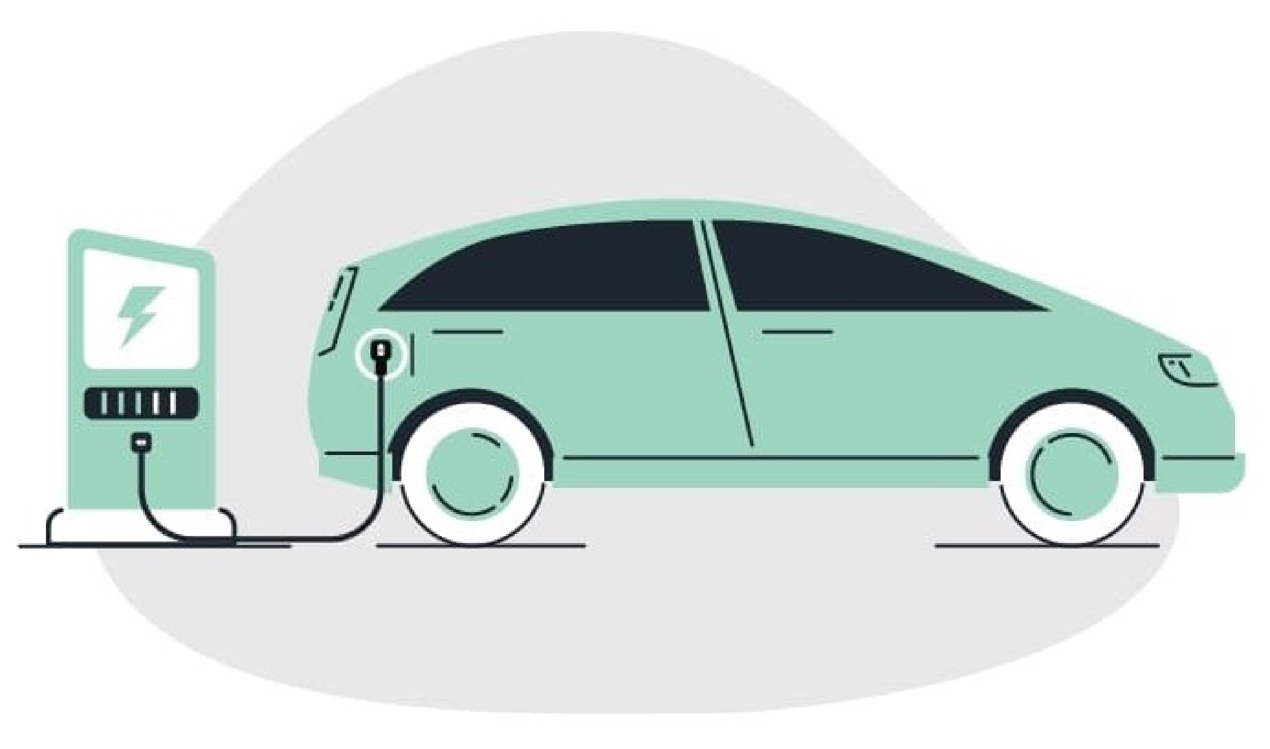
The Future of Critical Metals in Electric Vehicles

Impact of The Exponentially Increasing Number of Electric Vehicles On The Supply of Critical Metals

Nithin Harish



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Thesis report submitted to Delft University of Technology in partial fulfilment of requirements for the degree of *Master of Science in Sustainable Energy Technology*

by

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Executive Summary

Climate change is one of the most significant environmental challenges faced by the world today, with its impacts already being observed globally. In the transportation sector, the carbon-intensive nature of petroleum-based vehicles, the finite nature of fossil fuel supply, and advancements in technologies like batteries, fuel cells, power electronics, and electric motors have accelerated the adoption of electric vehicles (EVs) in the traditional automobile market.

The increasing demand for critical metals in the renewable energy technology industries has raised concerns about supply chain security.Further efforts are needed to ensure a sustainable and secure supply of the metals critical for this technology, for the future of EVs. Many countries have obliged to meet net zero emissions by 2050. Hence, there would be a boom in renewables by 2050, which makes it important for EVs to secure the supply of metals in order to meet demand in 2050 among other competing technologies.

There are several knowledge gaps and challenges related to the impact of electric vehicles (EVs) on critical metal resources. Existing studies on critical metal scarcity focus on different scenarios, but there is limited research specifically addressing the exponentially increasing demand for these metals due to the rise of EVs. Geological reserve perspectives have been analyzed to assess the criticality of metals for EVs, but this approach does not provide a holistic view, as factors like geopolitics and competitive demand also play important roles in determining criticality. Furthermore, there is limited research on alternative solutions that can reduce dependence on critical metals in EVs and their impact on the metal supply chain. The feasibility of these alternatives is also tied to their impact on vehicle performance, which is a crucial consideration for widespread adoption.

The intended outcome of this research is to answer the Research Question: ***How does the rapidly growing number of electric vehicles (EVs) impact the supply of critical metals, and what solutions can be employed to mitigate any potential supply bottlenecks?***

This research question is answered in 4 steps. The first step focuses on defining criticality for EVs and designing an analysis model that considers various perspectives beyond geological reserves. A desk review is conducted to identify useful socio-technical metrics for determining criticality and how these metrics contribute to criticality of metals for EVs. An analysis model to find the criticality of metals for EVs is developed based on existing frameworks to determine criticality. The model is used to analyze the criticality of metals for EVs, and the results are validated through expert interviews. The second step involves identifying potential bottlenecks in the supply of critical metals. Firstly, the metals which are critical for the functioning of an EV are identified using literature research. The research then builds on a previous study by Habib et al. to analyze geopolitical reserves and incorporates scenarios for future demand. Each metal within the scope of the research is analyzed individually using the analysis model designed in step 1, considering factors such as geopolitics and competitive demand, using literature reviews. The aim is to determine the potential bottlenecks in the supply of these metals by 2050. The third step focuses on identifying the critical metals from the results of the analysis model and determining alternate paths to mitigate supply bottlenecks. Interviews with experts from academia and industry are conducted to gather insights on the feasibility of alternative technologies and their impact on critical metal consumption. The different battery configurations and trade-offs in critical metal consumption are also examined. The interview methodology follows a semi-structured approach to ensure comprehensive data collection. The last step aims to realize alternate paths to mitigate potential supply bottlenecks. The research investigates existing practices

that threaten the proposed alternate solutions and explores promising solutions to these threats. The technology readiness level of these solutions is assessed, considering their impact on EV design and performance. Policy approaches by global leaders are also examined, and recommendations are provided based on identified bottlenecks and realized solutions.

The important factors contributing to criticality of metals for EVs were identified as Geological Reserve availability to meet EV demand by 2050, Competing Demand Sectors for EVs,Political, Economical, Social, Technological, Environmental and Legal factors. An analysis model was designed which analyses the criticality of a metal from the perspective of each of these factors.Lithium is a crucial component in the production of electric vehicles (EVs) as it is used in the batteries that power them.Copper is another essential component in EVs, primarily used for electrical wiring, motors, and charging infrastructure. Aluminum is used in various aspects of EVs, including the body and frame, battery systems, and wheels.Nickel and Cobalt are in EV batteries and motors. Rare Earth Metals (Neodymium and Dysprosium) are used in permanent magnets in EV motors. Hence the metals deemed important for functioning of EVs are Lithium, Nickel, Cobalt, Copper, Aluminium and REEs. The analysis model was implemented on these metals.

From the results of analysis, it was identified that there are potential supply bottlenecks of Lithium, Nickel, Cobalt and REEs due to different combinations of factors mentioned in the analysis model. Using interviews of experts from academia and industry, a set of alternative paths to avoid these bottlenecks were identified. These included replacing PSM motors with other motor technologies which do not contain REEs, adopting LFP and LMO batteries in the short term, and adopting battery chemistries like Na-ion, K-ion and Solid State Electrolyte batteries in the long term.

The readiness level of these technologies was researched upon and along with analysis of policies surrounding Critical Raw material supply and Net-zero emissions of global leaders like the EU is studied. Based on this, a list of recommendations is provided to Global policymakers, EV manufacturers and EV users in order to accelerate the adoption of these alternate technologies into the Electric Vehicle Industry. The proposed alternate paths to move away from metals that have potential supply bottlenecks for EVs are tabulated below. Based on these proposed solutions, recommendations are made to EV users, EV manufacturers and policy makers in this research.

Critical Metal	Alternate Paths	Technological Readiness Level (TRL)	Future Outlook
Rare Earth Metals (Neodymium & Dysprosium)	Replacing PSMs in Evs with motors which use less REEs like ASM and EESM which are free of REEs	Already used in serial BEVs and PHEVs by leading car manufacturers	There are various options to eliminate REEs in serial EVs. EESM, PSM with low cost magnets and ASMs are the most promising alternatives with an already high TRL. An increase in prices of REEs will see more EV manufactures adopting these technologies due to their low cost and high performance. High probability for adoption in short -term.
Nickel	Replacing NMC batteries with LFP Batteries	Already in use in latest models of Tesla and BYD cars	Tesla being the biggest Electric car manufacturer has led the way with LFP Batteries making other OEMs following this path. There is scope for further improvement in this technology to improve battery recyclability by almost 90% by decreasing costs and improving cycle life. High probability to replace NMC batteries in the short-term.
Cobalt	Replacing LCA and NMC batteries with LFP and LMO Batteries	▪LFP - Already in use in latest models of Tesla and BYD cars ▪LMO - Already in use in the latest model of the Nissan Leaf EV	LFP has high probability of short-term adoption by OEMs. LMO has limitations due to low energy density and can be used only for applications for smaller cars with very long charging times (Overnight charging). More OEMs targeting this sector of EVs can adopt LMO Batteries in the short-term. Will require more R&D for wide scale adoption in the long-term.
Lithium	▪ Replacing LIBs with Na, K and Mg-ion batteries. ▪ Replacing Liquid Eletrolyte batteries with Solid-State Batteries	Still in R&D and Prototyping stage, and have not been adopted in a large scale commercially yet.	K-ion batteries are the most promising replacement for Lithium-free chemistries due to comparable volumetric energy densities. But these technologies will not see market adoption in the short-term since they are far from ready to be viable replacements of LIBs. Hence, more amount of R&D needs to happen to make these technologies commercially and technologically feasible.

Table 1: Overview of technological alternatives to mitigate potential supply bottlenecks of critical metals

Contents

Nomenclature

List of Abbreviations

Al	Aluminium
ASM	Aynchronous motor
BEV	Battery Electric Vehicles
Co	Cobalt
CPSR	Constant Power Speed Range
Cu	Copper
DOD	Depth of Discharge
DRC	Democratic Republic of Congo
DRC	People’s Republic of China
Dy	Dysprosium
EESM	Externally Excited Synchronous Motor
EESM	Switched Reluctance Motor
EoL	End of Life
EU	European Union
EV	Electric Vehicles
FCEV	Fuel Cell Electric vehicles
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
IEA	International Energy Agency
K	Potassium
LCA	Life Cycle Assessment
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
Li	Lithium
LIB	Lithium-ion Batteries
LiFePO4	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LNO	Lithium Nickel Oxide
Mn	Manganese
Na	Sodium
NCA	Nickel Cadmium Aluminium
Nd	Neodymium
NdFeB	Neodymium-Iron-Boron
NGO	Non-Governmental Organisation
NGO	Non-governmental organization
Ni	Nickel
NiCd	Nickel-Cadmium
NiMH	Nickel-Metal Hydride
NMC	Nickel Manganese Cobalt
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment manufacturers
PbA	Lead Acetate
PESTEL	Political, Economic, Social, Technological, Environmental and Legal
PHEV	Plug-In Hybrid Electric Vehicles
PSM	Permanent-Magnet Synchronous Motor
REE	Rare Earth Elements
RES	Renewable Energy Sources
SiC	Silicon Carbide
SoC	State of Charge

SR	Supply Risks
SSB	Solid State Batteries
SSE	Solid State Electrolyte
SSP	Shared Socio-Economic Pathway
SUV	Sport Utility Vehicle
TRL	Technology Readiness Level
USGS	United States Geological Survey
VSR	Vulnerability to Supply Restrictions

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Introduction

Climate change is one of the greatest environmental challenges the world is facing today, and its impacts are already being felt around the globe. The scientific consensus is clear: human activities, particularly the burning of fossil fuels, are driving global warming. The effects of climate change include rising sea levels, more frequent and intense extreme weather events, and the loss of biodiversity (Hannappel, 2017). Climate change is a global challenge that requires immediate action to mitigate its impacts and adapt to the changes already underway. The statistics on climate change highlight the urgency of the situation, but they also underscore the need for collective action and international cooperation to address this issue, as explained below.

In order to realise these targets the global superpowers must focus on transforming their countries into low-carbon economies. There are a number of possible paths that can be taken to facilitate these climate goals (Hannappel, 2017). Irrespective of the path chosen, it is definite that there will be a huge increase in the number of renewable energy generation sources which would replace the traditional fossil-fuel based sources. The promotion of these renewable energy sources (RES) in an energy efficient manner relies on technologies that depend on critical metals for its components and electronics (Grandell et al., 2016). Hence, the transition to a low carbon energy sector will result in an increased demand for these metals.

Focusing on the transportation sector, over the years the highly carbon emissive nature of petroleum-based vehicles, the finite and price elastic nature of fossil fuel supply, and advancements in technologies such as batteries, fuel cells, power electronics and electric motors has propelled the inculcation of electric vehicles into the traditional automobile market. Experts agree that electric vehicles will be the path chosen by the transportation sector internationally to achieve net zero emissions (Juan et al., 2016). This indeed will be a fruitful path to reduce carbon emissions and also to solve the oil crisis. However, we might also be introducing a new problem of affecting and maybe even depleting the critical metal resources due to the above-mentioned acceleration in energy transition. Critical metals are experiencing a rapidly increasing usage by electric vehicles. Examples are lithium, nickel and cobalt in lithium-ion batteries (LIB),and neodymium and dysprosium in electric motors (Grandell et al., 2016).

For example, for the longest time, lithium-ion batteries (LIBs) had a market that was driven by their use in portable electronics (Narins, 2017). This is no longer the case as a rise in demand for batteries particularly those having a large form factor used in electric vehicles and storage has catalysed a new supply chain for the manufacturing of LIBs. In 2016, Lithium has been dubbed as the world's hottest commodity due to the predicted scarcity issues surrounding this metal (Serghei and Elena, 2016). Hence, considering the high demand growth for LIBs and the intention of the transportation sector to decarbonize itself, there is a crucial need to understand the potential risks associated with the availability and supply of this metal (Narins, 2017).

Additionally, many critical metals are only produced in a few countries, which can create a dependency on foreign sources and a vulnerability to supply disruptions. This has led to calls for more sustainable sourcing of these metals and the development of recycling and substitution technologies (Grandell et al., 2016).

Governments and industries have started to take steps to address this problem by investing in critical metal exploration and production, as well as recycling and substitution technologies. Additionally, international organizations are working to develop a more sustainable and secure supply chain for critical metals (Jetin, 2020). However, much more needs to be done to ensure a sustainable and secure supply of these metals for the future.

Literature suggests that there are several ways of mitigating risks of securing critical metal supply due to electric vehicles in particular (Burd et al., 2021). These include increasing primary supply, reusing/recycling and substitution. Furthermore, due to the rapidly advancing technologies in the field of electric vehicles, there will be a major change in vehicle recycling practices in the upcoming years. The most important components considered for this criterion are traction batteries, power electronics, electric motors and fuel cells. In addition, the evolution in design can also alter traditional manufacturing ad recycling practices. For example, the usage of wheel-hub motors by automotive OEMs like Lightyear will result in new design and recycling practices (Afaga and Cheng, 2022). This could even possibly lead to a revamp of the existing recycling infrastructure for the automobile industry. These recycling technologies are not only necessary from an environmental and safety point of view, but also to provide security for the long-term supply of the required critical metals (T. E. Graedel et al., 2012).

1.1. Background

There is an increasing demand for renewable technologies in the recent years due to the extensive incorporation of goals to mitigate climate change.Considering the example of the European Union (EU), the EU has been one of the forerunners in deploying measures in order to be climate neutral by 2050, in line with the Paris agreement to prevent climate change and its negative consequences. In order to achieve this, all the sectors of the EU economy and society like power , transportation, buildings, forestry, agriculture, etc. will play a pivotal role (Peake et al., 2018).

1.1.1. Increase in Renewable Technologies

The Paris Agreement is an international treaty aimed at combating climate change by reducing global greenhouse gas emissions. The main goal of the Paris Agreement is to limit global warming to well below 2 degrees Celsius above pre-industrial levels, while pursuing efforts to limit the temperature increase to 1.5 degrees Celsius (United Nations, 2023). Some examples of countries that have signed and ratified the Paris Agreement are:

- **United States:** The United States is one of the original signatories of the Paris Agreement and ratified it in 2016
- **China:** China is the world’s largest emitter of greenhouse gases and ratified the Paris Agreement in 2016

- **European Union:** The European Union ratified the Paris Agreement in 2016, and all 27 member states have also ratified it individually
- **India:** India ratified the Paris Agreement in 2016 and has committed to reducing its emissions intensity by 33-35% below 2005 levels by 2030
- **Japan:** Japan ratified the Paris Agreement in 2016 and has committed to reducing its greenhouse gas emissions by 26% below 2013 levels by 2030
- **Brazil:** Brazil ratified the Paris Agreement in 2016 and has committed to reducing its greenhouse gas emissions by 37% below 2005 levels by 2025
- **Canada:** Canada ratified the Paris Agreement in 2016 and has committed to reducing its greenhouse gas emissions by 30% below 2005 levels by 2030
- **Russia:** Russia ratified the Paris Agreement in 2019 and has committed to reducing its greenhouse gas emissions by 30% below 1990 levels by 2030

Overall, the Paris Agreement represents a global effort to combat climate change, with countries from all regions of the world coming together to address this critical issue. As of April 2023, there are 197 signatories to the Paris Agreement, including 196 countries and the European Union (United Nations, 2023).The below statistics in Figure 1.1 showing the increase in renewable energy over the last few years proves to cement energy transition, as the green energy generation technologies have significantly increased as expected. This trend will only further increase in the future with these countries depending or more renewable technologies in order to achieve their targets. The key takeaway from this is that all these countries will aim to achieve net zero emissions by the year 2050 and the dependence of renewable technologies will be at an all time high beyond 2050.

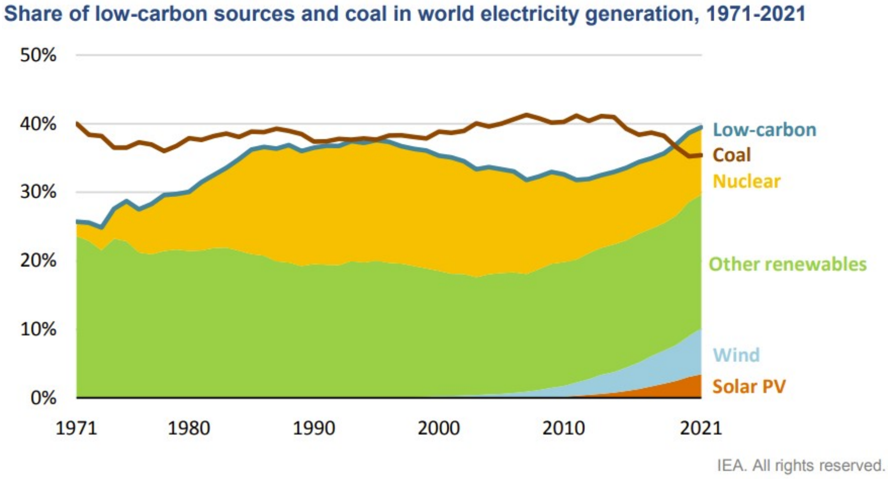


Figure 1.1: Share of low-carbon sources and coal in world electricity generation from 1971-2021 (International Energy Agency, 2022)

According to the International Energy Agency (IEA), in 2019, renewable energy sources accounted for 26% of the global electricity generation. Hydro-power is the largest source of renewable electricity, followed by wind, solar, and bio-energy. The use of renewable energy has been increasing in recent years, with the share of renewable energy in the global energy mix rising from 13% in 2010 to 18% in 2019. However, the rate of growth of renewable energy has slowed down in recent years due to a decline in the cost of fossil fuels and lack of policy support (International Energy Agency, 2022).

1.1.2. Critical Metals

Critical metals are a group of metals that are essential for the production of various technologies, including renewable energy, electronics, and transportation. These metals are considered critical because they are not abundant, are often only produced in a few countries, and have a high economic value.A metal can be deemed to be a critical metal if it has a scarce geological occurrence and is crucial for green energy technologies (Habib et al., 2020).

The inclination towards efficient and renewable sources of energy in order to incorporate more green technologies like electric vehicles (EVs), solar panels and wind turbines has led to the usage of several metals like cobalt, lanthanum and lithium, as these technologies heavily depend on these critical metals. The critical metals list is revised every three years by the US Geological Survey. The latest final list has been issued in the year 2022. These metals are termed critical metals by considering their importance in national security or economic development. Additionally, fuel minerals are excluded from the list of critical metals. Some examples of critical metals include lithium, cobalt, nickel, and rare earth elements. As per the latest list of 2022, there are 50 minerals which are deemed critical as shown in Figure 9.1 in section A1 in the Appendix (International Energy Agency, 2022).

One of the main uses of critical metals is in the production of renewable energy technologies such as electric vehicles, wind turbines and solar panels. These technologies require large amounts of rare earth elements, such as neodymium and dysprosium, for the production of permanent magnets used in wind turbine generators and electric vehicle motors. Lithium, which is used in lithium-ion batteries, is also a critical metal for the storage of renewable energy.

1.2. Knowledge Gap and Research Questions

Although there exists studies on critical metal scarcity based on different scenarios in the future (Watari et al., 2020 , Grandell et al., 2016), there are still knowledge gaps on the impact on critical metal resources specifically due to the exponentially increasing number of electric vehicles. Habib et al., 2020 analyses criticality of metals strictly from a geological reserve perspective, and determines if this reserve is sufficient to meet global EV demand by 2050. However, this research does not provide a holistic picture of criticality, since factors like geopolitics also play an important role in estimating if a metal is indeed critical or not for an industry. This coupled with the Paris goals of the Netherlands to achieve net zero emissions by 2050 makes this cause for electric vehicles even more critical, since there are additional factors which come into play regarding criticality of these metals, such as competitive demand by another renewable technology that could threaten availability of a certain metal for EVs by 2050. Criticality as a concept cannot be defined only in terms of available geological reserves. It is much more complex than this. Criticality can be defined by means of other factors as well such as geopolitics and competitive demand in the future. Hence, it is important to define criticality specifically in the context of electric vehicles. There exists no framework to estimate the criticality of metals for electric vehicles. There is a knowledge gap in the demand scenarios for the types of metals that are critical for the functioning of electric vehicles in specific.

There is also a knowledge gap on the alternative solutions that electric vehicles can accommodate in order to reduce the dependency on critical metal resources. Habib et al., 2020 analyses the scenarios for critical metals by 2050 but does not look into the alternative strategies that can be adopted to reduce dependencies on these critical metals. There is little to no research on the impact of these alternative solutions on the supply chain of metals used. Ultimately, the feasibility of these alternatives also depends on the impact on vehicle performance, as this is the priority for the common man.The intended outcome of this project is the prediction of the potential bottlenecks in the supply of critical metals. In addition, a set of solutions, based on the outcomes of the analysis, will be provided on how to tackle the resource scarcity and recommendations on how to achieve these solutions will be explained.

1.3. Research Objective

The objective of this research is to determine potential bottlenecks in the supply of metals that are critical to electric vehicles in specific, by a multi-category analysis that gives a holistic view on the criticality of metals specific to EVs. The outcome of this analysis would be the list of metals that could have supply bottlenecks by 2050. A set of strategies to overcome these bottlenecks will be recommended based on literature reviews and interviews of experts in industry and academia.

This paper will aim to answer the following research question:

Main research question: How does the rapidly growing number of electric vehicles (EVs) impact the supply of critical metals, and what solutions can be employed to mitigate any potential supply bottlenecks?

In order to answer the main research question, the following sub-questions are established:

RQ1: *What are the factors that contribute to criticality of a metal for the Electric Vehicle Industry?*

RQ2: *What according to literature is the current scenario of global critical metal supply, and what are the potential bottlenecks in the supply of critical metals due to electric vehicles by the year 2050?*

RQ3: *What are the current developments in manufacturing and recycling of traction batteries, electric motors and power electronics that can help the transportation industry to move away from critical metals?*

RQ4: *What are the ways to redesign the manufacturing of Electric Vehicle components in order to mitigate supply risks for critical metals?*

1.4. Scope of Research

Literature research was done to determine which metals are crucial for EVs in Chapter 4. Based on this, the scope of this research is limited to analysis of criticality for the metals used in electric vehicles (Ortar and Ryghaug, 2019). The metals which are considered for analysis in this report are:

1. Lithium
2. Cobalt
3. Nickel
4. Copper
5. Aluminium
6. Rare Earth metals

1.5. Alignment with Sustainable Energy Technology Masters Program

The MSc Sustainable energy technology program offered at the TU Delft explores a socio-technical aspect of the complex energy transition process. Electric Mobility is spear heading the energy transition in the transportation sector. Since it is a technology that is low on emissions, it would indeed solve the oil and carbon crisis. But in doing so, it may actually be introducing the new problem of impacting the supply of critical metals. This project solely focuses on this impact due to electric vehicles. Hence, the energy transition by means of electric mobility needs to be done in a more sustainable manner to prevent this while maintaining the efficiency and performance of these vehicles.This research project is done as a part of the E-Mobility, Power and Economics track of the Sustainable Energy Technology master's program of TU Delft.

For this project, the knowledge gained from courses such as Electric Vehicles and Charging Technology (SET3100), Electric Machines and Drives (ET4117), Economic Policy for Sustainable Energy (WM0637SET), Economics and Regulation of Sustainable Energy Systems (SET3055) and Sustainable Energy Innovations and Transitions (WM0931SET) will be implemented.

1.6. Thesis Outline

The structure of this report is as defined below.

Chapter 1: Introduction

The first chapter of this thesis serves as an introduction, providing essential background information on climate change, electric vehicles (EVs), and critical metals. It aims to highlight the significance of these topics and address the existing knowledge gaps. Additionally, this chapter outlines the research questions that are addressed throughout the master's thesis.

Chapter 2: Methodology

In Chapter 2, the methodology used to determine the criticality of metals within the context of EVs is defined. This chapter also outlines the methodology employed to answer the research questions identified in the introduction. The chosen approach and analytical tools are explained, ensuring transparency and reproducibility of the study.

Chapter 3: Defining Criticality of Metals for Electric Vehicles

In this chapter, the analysis model to determine criticality of metals for EVs is designed by studying existing methods and frameworks to determine criticality, and translating it into the context of EVs by designing an analysis model.

Chapter 4: Metals Used in Electric Vehicles

In this chapter, the metals to be analysed using the analysis model are determined by researching on the metals which are crucial for the functioning of EVs. These metals are then subjected to criticality analysis in the subsequent chapters.

Chapter 5:Demand Scenarios for Electric Vehicles

Chapter 5 delves into the insights gained from conducting a scenario analysis. This analysis focuses on forecasting the demand for each metal critical to EVs as well as the available supply of geological reserves of these metals by the year 2050. Through scenario-based modeling, this chapter explores various potential future scenarios, assessing their implications for metal demand.

Chapter 6: Criticality Analysis of Metals

Chapter 6 presents the criticality analysis of the metals within the scope of this thesis. Building upon the methodology defined in Chapter 2, this chapter applies the analysis model to each metal individually. The objective is to evaluate the metals based on their criticality within the context of electric vehicles.

Chapter 7: Results

Chapter 7 provides an in-depth presentation of the results obtained from the criticality analysis conducted in Chapter 6, as well as the results obtained from the exert interviews. It showcases the metals that are identified as critical for electric vehicles based on the implemented analysis model. This chapter offers a comprehensive overview of the criticality assessment outcomes.

Chapter 8: Discussions

Chapter 8 builds on the results obtained from chapter 7 along with inputs from expert interviews to identify and define alternate paths which can be taken by the EV industry to mitigate the supply risks of the critical metals. The feasibility of these technologies along with an analysis of barriers and current policies are provided in this chapter. This chapter also discusses the limitations, scientific contribution and future scope of this research.

Chapter 9: Conclusion and Recommendations

The final chapter of this thesis, Chapter 9, summarizes the report's findings and draws conclusions based on the results and findings presented in Chapter 7 and 8. It also includes recommendations derived from an extensive review of relevant literature and expert interviews. These recommendations aim to address potential supply bottlenecks related to the critical metals identified, suggesting strategies to mitigate any challenges and ensure a sustainable supply chain for electric vehicles.

By following this chapter outline, the thesis report will provide a structured and comprehensive analysis of the criticality of metals for electric vehicles, from introduction to conclusion, while addressing the research questions and providing valuable recommendations for future considerations.

2

Methodology

This study adopts a multi-disciplinary approach, incorporating elements of economics, environmental science, and electrical engineering. Data was collected through a comprehensive review of the literature and interviews with industry experts. The methodology used to answer each sub-research question is explained in detail below.

2.1. Research Question 1 - Defining Criticality for EVs and Designing an Analysis Model

The first research question is answered by means of developing an analysis model which encapsulates criticality of a metal from various perspectives such as geopolitical, technological advancements, etc., apart from the fundamental geological reserve capacities of these metals. This is due to the fact that, as explained in section 1.2 in the previous chapter, the existing studies for criticality of metals for electric vehicles are single-dimensional and only measure criticality in-terms of available geological supply in order to meet demand in the future. In order to obtain a more accurate idea of criticality for EVs, a literature review is conducted to determine which socio-technical metrics are most useful to identify the criticality of critical metals for the automotive industry as well as other sources of competitive demand for critical metals in electric vehicles, like solar panels. This is done by reading publications on the available methodologies to define criticality, along with its applications. From these existing methodologies, the one that is best suitable for this research is selected based on factors such as geographical scale, time period, etc. Research is conducted on various existing frameworks for determination of criticality, and the same is adapted in such a manner that the research goals of this project is met.

The analysis model was designed on the basis of conceptual research on which factors are important to define the criticality of a metal, and how these factors contribute to criticality. The metals in the scope of this project were analysed individually for each criteria in order to determine criticality for electric vehicles, using the analysis model built. The search engines used for all the literature survey done in this research are Google Scholar, ScienceDirect and ResearchGate. By using Keywords *”Criticality Frameworks”* and *”Criticality Methods”*, various existing methods for determining criticality was collected and compared. Finally, the reference conceptual framework based on the method that was the most suitable for this research was chosen as inspiration, and the indicators of this reference framework were identified. Based on these indicators, an analysis model was developed which is used to analyse the criticality of a metal from several perspectives, specifically for the context of EVs by ensuring all the factors contributing to criticality in the chosen method for inspiration are included.

Finally, the results obtained from analysis of all the metals in the scope of this research are tabulated in order to compare the criticalities of these metals. This is also essential to identify which metals could be a matter of concern for EVs and which are not. These were also validated using the inputs of experts during the interviews on the criticalities of these metals, by asking their opinion on the results obtained. The interview methodology will be explained in the following sections.

2.2. Research Question 2 - Identifying Potential Bottlenecks

The second research question used the scenarios created in the research paper by Habib et al., 2020 as a basis for analysis of geopolitical reserves. This is done since analysing available geological reserves available in the future is an important step in identifying criticality, though not the only one. This research paper in particular was chosen during the preliminary literature review as it deals with the forecasting of demand of critical metals used in Electric Vehicles. The timeline of forecast scenarios in this research paper (till 2050) also matched with the time period of research of this thesis. The results obtained from this framework were verified with other similar criticality analysis of these metals and incorporated in the analysis model developed in research question 1 as explained in the earlier section.

The metals within the scope of this research are determined as follows. An in-depth analysis on which are the components of electric vehicles that require specific critical metals is conducted in order to determine which are the metals crucial for the functioning of EVs. This is again done by using the same search engines mentioned above using keywords like *”Metal Composition of EVs”* and *”Metals in EVs”*. From preliminary literature research, the components of an EV which use critical metals were observed to be the traction batteries, electric motors and power electronics (Moss et al., 2013). More about this is researched on in Chapter 4. The outcome of this is the metals which are crucial for the functioning of EVs. These metals are subjected to the analysis model in order to determine their criticalities.

The metals in the scope of this research were then analysed using the framework developed in research question 1 in order to determine the potential bottlenecks in supply of these metals by 2050. This analysis was be done using literature review for each factor, for each metal. For example, in order to analyse the Political Factors influencing the criticality of Lithium, an extensive research on the past, present and future of the politics around Lithium is conducted using the search engines *Google Scholar*, *ScienceDirect* and *ResearchGate*. The keywords used are *”Lithium + Politics”* and *”Lithium + Political Factors”*. The year 2050 was chosen since we already know that the use of renewables will peak by 2050 due to the actions taken by numerous countries complying to the Paris climate goals. Hence it would be a matter of curiosity to understand the situation of critical metal demand beyond 2050. The scope of the research is Global, and is not region-specific.

In this manner, criticality of each metal is analysed from the perspective of each factor in the designed analysis model in order to obtain an in-depth idea of the criticality of each metal for electric vehicles. By understanding the impact each factor has on the criticality of the metal, the potential bottlenecks are determined and results are compared.

2.3. Research Question 3 - Identifying Current Developments and Alternate Paths

From the previous section, the net criticalities of each metal for EVs is determined. It is now important to determine the alternate paths which would ideally let us move away from depending on these metals for EVs. This is done using interviews of experts from academia and industry. The methodology followed for conducting interviews is explained below. Though primarily driven by social issues such as the exploitation of lithium mining in Congo, the industry is already aware of the lack of security in lithium supply. Hence the feasibility of current trends in manufacturing and recycling of these components and their impact on the criticalities of these metals needs to be analysed with the help of interviews of academic experts. It is important to have inputs of experts in academia and industry, on the feasibility of a particular Lithium-free or Cobalt-free technology for example, to become a reality and realising the barriers surrounding this technology. Hence interviews are used as a tool to obtain direction of further research on the analysis of technologies that can prove to be alternate paths to mitigate supply bottlenecks of these metals. In addition, the different battery configurations opted by industry leading electric vehicles and their trade-offs in terms of critical metal consumption versus efficiencies are realised (Grandell et al., 2016).

2.3.1. Interview Methodology

Keeping in mind the primary objective of this research, and in order to gather comprehensive insights as mentioned above, interviews were conducted using a semi-structured method on experts from industry and academia. This allows for a systematic comparison of respondents' viewpoints by asking similar questions on each topic. In total, 4 interviews were conducted to acquire information on alternate solutions to tackle supply bottlenecks of critical metals for EVs from both academic as well as industrial perspective.

The interview is an important step of qualitative research, and can take the researcher into the mental world of the interviewee and help understand how they see the world (McCracken, 1988). The interview framework consists of several steps to ensure an effective and organized data collection process as explained below.

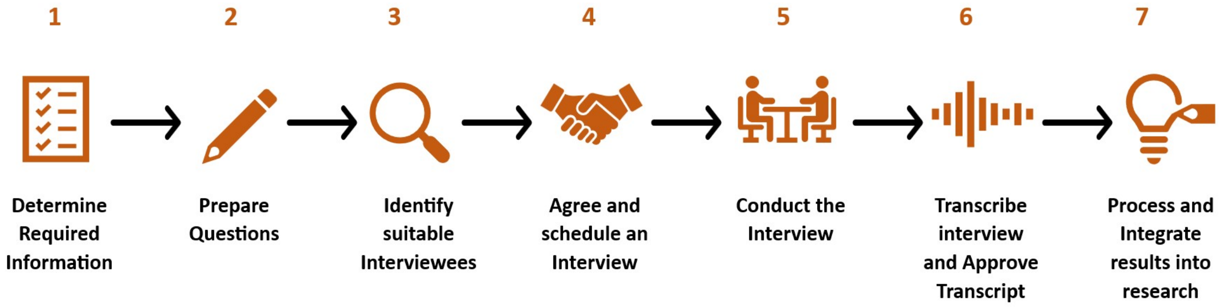
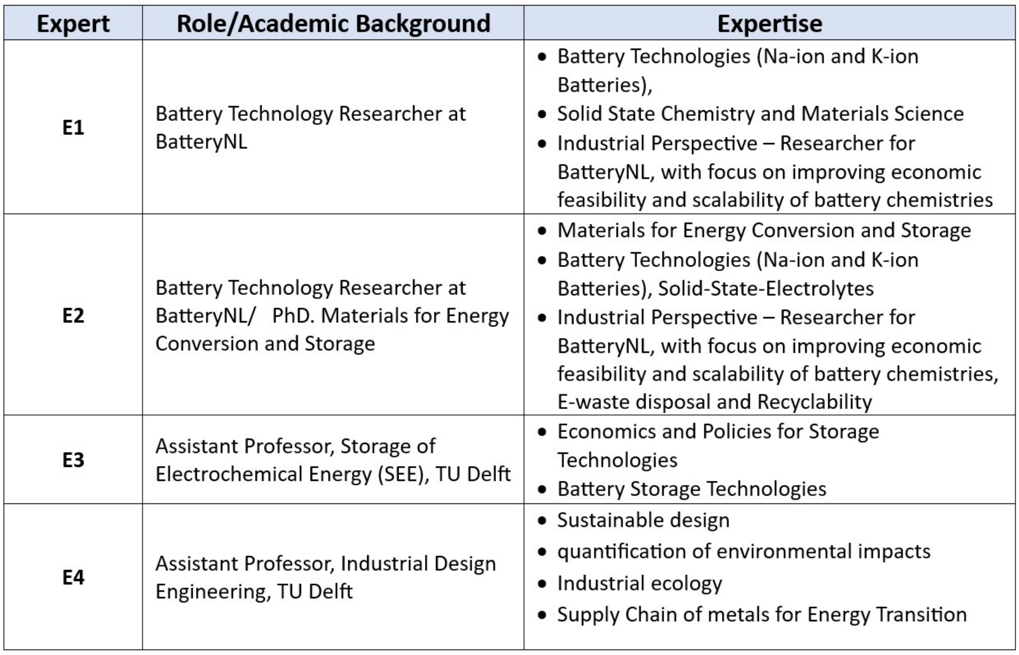


Figure 2.1: Interview Process

First, the necessary information required for the research is determined based on the desk research conducted for the research objectives and results obtained from the analysis model. This helps in identifying the key areas to focus on during the interviews. The second step involves composing suitable interview questions derived from the results obtained from the analysis model.

The third step is finding suitable candidates for the interviews. Experts in battery technologies, critical materials, and circular design were identified as potential respondents. The head of the Storage of Electrochemical Energy (SEE) department of TU Delft was reached out to for leads on experts who would be available for an interview. This was done by sending a mail stating the requirements of the research and describing the field of expertise and academical backgrounds of the ideal candidate for the interview. The head of the SEE department provided the names of the suitable candidates for interviews, and each of these candidates were reached out to individually via mail to schedule an interview. In addition, few of the candidates were recommended by the thesis committee based on the research conducted. Once they agree to take part in an interview, practical arrangements are made, including scheduling the interview, determining the location, and specifying the length and setup of the interview, which is the fourth step. It is important to seek permission from the respondents to record the interviews for accurate transcription and analysis purposes. The interviewees were selected based on academic and industrial expertise on Battery Technologies, Circular Economy and Industrial Ecology.The list of interviewees along with their backgrounds and expertise is tabulated below.



Expert	Role/Academic Background	Expertise
E1	Battery Technology Researcher at BatteryNL	• Battery Technologies (Na-ion and K-ion Batteries), • Solid State Chemistry and Materials Science • Industrial Perspective – Researcher for BatteryNL, with focus on improving economic feasibility and scalability of battery chemistries
E2	Battery Technology Researcher at BatteryNL/ PhD. Materials for Energy Conversion and Storage	• Materials for Energy Conversion and Storage • Battery Technologies (Na-ion and K-ion Batteries), Solid-State-Electrolytes • Industrial Perspective – Researcher for BatteryNL, with focus on improving economic feasibility and scalability of battery chemistries, E-waste disposal and Recyclability
E3	Assistant Professor, Storage of Electrochemical Energy (SEE), TU Delft	• Economics and Policies for Storage Technologies • Battery Storage Technologies
E4	Assistant Professor, Industrial Design Engineering, TU Delft	• Sustainable design • quantification of environmental impacts • Industrial ecology • Supply Chain of metals for Energy Transition

Table 2.1: List of Experts Interviewed for This Research

Step 5 involves conducting the interviews. The interviews were conducted in the following manner. During the introduction, the purpose and goals of the interview are clearly explained to the candidates, emphasizing the significance of their expertise and insights for the research. Some of the questions were asked in every interview which were based on the results obtained from the analysis model. Then, further questions were asked based on the academic and professional expertise of the interviewee. Other questions are more detailed which specifically concern papers which the interviewees have written or from which the interviewee has expertise in or knowledge about. The results obtained from analysis were also presented to obtain reflection on these results from interviewees without any bias.

Following the completion of the interviews, Step 6 involves transcribing the recorded interviews. Transcription enables a thorough review and analysis of the acquired knowledge, ensuring that the content is accurately captured and interpreted. The transcript prepared after each interview is shared to the interviewee for approval to eliminate misinterpretation.

Since the Interviews are intended to be anonymous, each interviewee is labelled a code (eg. E1), which is then used to refer points mentioned by that interviewee in the report. The insights gained from the interviews are then integrated into the research findings and discussed in subsequent chapters in the last step. This is done by first summarizing the insights obtained from each interview. For each metal that is deemed ”critical” as an outcome of the analysis model, the interviewees provide inputs on which are the most feasible alternate technologies to tackle this criticality. Further research was be conducted on defining paths to realise these alternate paths in the next research question.

By employing this interview framework, the research aims to gather in-depth knowledge and perspectives from experts in battery technologies, critical materials, and circular design. This semi-structured approach ensures that the research questions are adequately addressed and that a comprehensive understanding of the potential solutions to supply bottlenecks is achieved. The results from the interviews will be used to determine alternate scenarios to mitigate dependency of EVs on the critical metals as explained in the next sections.

2.4. Research Question 4 - Realising alternate paths to mitigate potential supply bottlenecks

The fourth research question was be answered in the following way. After identifying the existing practices that threaten the supply of critical metals and the promising solutions to mitigate supply risks of metals for EVs with the help of expert interviews, research is conducted on the technology readiness level for each of these technologies in order to obtain an outlook of the future of these technologies by 2050. This information can be used to improve ways to design and recycle EVs (Electric Vehicles) in order to reduce demand for critical metals and prevent raw material supply bottlenecks while ensuring sustainability (Elwert et al., 2015). This research along with the inputs from interviews with industry experts was used to understand the current and future practices in improving EV component recyclability that are being adopted by industries.

The impact of incorporating the design methods observed on the performance of EVs was researched upon, as it is important that new problems aren’t being created by attempting to solve existing ones. Hence it must be ensured that the proposed solutions do not involve other critical metals, and can be adopted by industries within a short span of time. It can also be assumed that matching the performance standards of EVs having current technologies such as Lithium-ion batteries to EVs running on batteries having less or no critical metals will be difficult. The performance trade-offs resulting from adopting these newer technologies will be touched upon in this chapter as well (Mususa et al., 2021).

The existing policy approaches by global leaders such as the European Union were also researched upon to understand what is the current approach being taken to secure critical metal supply, and what needs to change in these approaches. The search engines used for this research were Google Scholar, ScienceDirect and ResearchGate. The names of the technologies are used as keywords for the technology part, and keywords like ”Critical metal policy” are used to research on the policy part.

Finally, a set of recommendations are provided based on the identified bottlenecks in critical metal supply and the realised solutions obtained by following the methodology mentioned above which can be implemented by EV users, policy makers and/or EV industrial leaders in order to ensure that the supply of critical metals for EVs are secured beyond 2050.

3

Defining Criticality of Metals for Electric Vehicles

The aim of this section is to design and implement an analysis model in order to determine criticality of metals for EVs. Popular opinion is that geological reserves is the only factor which determines criticality of metals. However, this is not the case. Criticality requires a multi-factor analysis that needs to be performed. The supply of critical metals used in the manufacturing and operation of EVs is determined by several factors as identified below along with references:

1. **Geological availability:** The abundance and geographic distribution of a metal in the Earth's crust can affect its criticality. Metals that are rare or located in a small number of countries may be considered more critical (Mouloudi and Evrard Samuel, 2022).

2. **Production concentration:** Metals that are produced by a limited number of countries or companies may be considered more critical, as supply disruptions or price fluctuations in those regions can have a significant impact on global supply (Peiró et al., 2022).

3. **Recycling and substitution:** Metals that have low recycling rates or limited substitution options may be considered more critical, as this can lead to a greater dependence on primary production (T. Graedel et al., 2015).

4. **Environmental and social concerns:** The environmental and social impacts of metal production, such as pollution, land use, and labor practices, can affect the criticality of a metal (Jowitt et al., 2018).

5. **Political stability:** The political stability of countries that produce or supply metals can also affect their criticality, as political instability or conflicts can disrupt supply chains (J. Wang et al., 2020)

6. **Price volatility:** Fluctuations in the prices of critical metals can influence the supply and demand for these metals, impacting their availability for EVs (Peiró et al., 2022).

7. **Competition from other industries:** The demand for critical metals from other industries such as electronics, aerospace, and renewable energy can also impact their supply for EVs (T. Graedel et al., 2015).

8.**Technology advancements:** Technological advancements in the extraction and refining processes of critical metals can increase their supply, reduce waste and enhance sustainability (Jowitt et al., 2018).

In order to organize the effects of each of these factors into designing a framework for criticality, there are several approaches to defining criticality. Resource criticality is context-dependent and defined differently by various organizations. The European Union defines it as materials that display a high risk of supply shortage in the next ten years and are particularly important for the value chain. The assessment of resource criticality involves measuring supply risk and vulnerability to supply restriction. Substitutability of a resource is an important indicator in determining vulnerability to supply disruption and is also considered an indicator in the supply risk dimension. Nine different approaches to determine criticality was researched upon, and a summary of the same is provided below in Table 3.1 (Sonnemann et al., 2015).

As shown in Table 3.1, each of the approaches have been classified based on factors such as geographical scope, Time horizon, Objectives and Indicators. Since the aim is to define an approach to determine the criticality of metals for electric vehicles, the focus on selecting an approach for reference was based on factors such as Scope, Time Horizon and Objective. Resource criticality is often evaluated based on its availability and importance in use. Supply risk refers to the abundance of resources, as well as their economic, technological, geopolitical, and social availability, while vulnerability to supply restriction measures how much a resource's supply disruption could affect its final use in the value chain (Blengini G.A. and de Matos., 2017). The substitutability of a resource is an important indicator in determining vulnerability to supply disruption or importance in use (Sonnemann et al., 2015). Measuring substitution factors usually requires expert judgment or mathematical algorithms. Despite its difficulty, resource substitutability is still an important indicator in criticality assessment. Different criticality assessment methods compare various raw materials using measurable indicators relevant to the definition of criticality, such as geological availability, substitutability, and market concentration. However, these methods vary in the indicators they use to assess the potential risk of supply and its consequences.Each of the criticality assessment methods listed uses measurable indicators to compare different raw materials and determine their level of criticality (Sonnemann et al., 2015).

METHOD	SCOPE	TIME HORIZON	OBJECTIVES	MATERIALS COVERED	CRITICALITY CONCEPT	INDICATORS
AEA Technology (2010)	National (UK)	0-5 years for shortterm 5-20 years for medium-term Greater than 20 for long-term	To review future resource risks faced by UK business	Ag, Al, Au, Co, Cu, In, Li, Mo, Ni, P, Pb, Pt, REE, Sb, Sn, Ta, Te, Ti and Zn	- Criticality matrix - Demand - Supply	- Combined availability to scarcity - Availability of alternatives - Supply distribution - Supply domination - Extent of geopolitical influences - Press coverage - Price fluctuation
DOE (2011)	Global	Present e 2015 for short-term 2015-2025 for medium-term	To analyze risk and opportunities, continue the public dialogue and identify programmatic directions through examining the role of REE and other key materials in the clean energy economy	Ce, Co, Dy, Eu, Ga, In, La, Li, Mn, Nd, Ni, Pr, Sm, Tb, Te and Y	- Criticality matrix	- Clean energy Demand - Substitutability limitation - Basic availability - Competing technology Demand - Political, regulatory and social factors - Co-dependence on other markets - Producer diversity
Erdmann et al. (2011)	National (Germany)	Up to 5 years shortterm 5-10 years medium-term 10-20 long-term (2008 base year)	To provide a complete picture of raw materials whose supply are proven to be critical to Germany in the medium to long term time horizon.	- Bentonite, Kaolin, Gypsum, Calcium carbonate - Diatomite, Mica, Talk, Vermiculite & Perlite - Bauxite, Magnesite, Ilmenite and rutile, Barite, Borate, Diamond, Fluorspar, Graphite, Phosphate, REE, Zircon - Al, Co, Cr, Cu, Fe, Mn, Mo, Nb, Ag, Ni, Pb, Sb, Sn, Sr, Ta, Ti, W, Zn - Be, Bi, Ga, Ge, Hf, In, Li, Mg, Pd, Pt, Re, Se, Si, Te, V	- Criticality matrix - Vulnerability - Supply risk	- Germany's share of world consumption - Change in share - Change in import in Ge - Sensitivity of the value chain in Germany - Global demand increase by future technologies - Substitutability - Country risk for Germany's import - Country risk for global production - Country concentration for global reserves - Corporate concentration of global production - Global reserves to global production ratio - Share of global primary and secondary production
BGS (2012)	Global	Specific year 2011	To supply a new supply risk index for chemical elements or element groups for UK's economy in 2011	Ag, Al, As, Au, Ba, Be, Bi, Diamond, Graphite, Cd, Co, Cr, Cu, F, Fe, Ga, Ge, Hg, In, Li, Mg, Mn, Mo, Nb, Ni, Pb, Platinum Group elements (Ru, Pd, Os, Ir and Pt), Re, REE (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu), Sb, Se, Sn, Sr, Ta, Th, Ti, U, V, W, Zn and Zr	- Supply risk	- Scarcity - Production concentration - Reserve distribution - Recycling rate - Substitutability - Governance (top producing nation) - Governance (top reserve-hosting nation)
Graedle et al. (2012), Nassar et al. (2012) and (Nuss et al., 2014)	Corporate (Solar Future, Inc.) National (US) Global	0-5 years for Corporate 5-10 years for National 10-100 years for Global	To propose a new methodological approach for metal criticality analysis (Graedel et al., 2012) and to apply it for geological copper family (Nassar et al., 2012)	Ag, As, Au, Cr, Cu, Fe, Mn, Nb, Se, Te and V	Criticality space - Supply risk - Vulnerability to supply restriction - Environmental implication (cradle-to-gate analysis)	- Depletion time (reserves) - Companion metal fraction - Policy potential index - Human development index - Worldwide governance indicators (Political stability) - Global Supply concentration - Percent of revenue impacted - Ability to pass-through cost increases - Importance to corporate strategy - Substitute performance - Substitute availability - Environmental impact ratio - Price ratio - Corporate innovation - National economic importance - Percentage of population utilizing - Net import reliance ratio - Net import reliance - Global innovation index - LCA cradle-to-gate: ‘human health’ & ‘ecosystems’
Moss et al. (2013)	Continental (EU)	20 years 2010-2030	To identify critical metals that could become a bottleneck to supply-chain of different low-carbon energy technologies in EU	Ag, Au, Cd, Ce, Co, Cr, Cu, Dy, Eu, Ga, Gd, Ge, Graphite, Hf, La, Li, Ln, Mo, Nb, Ndepr, Ni, Pb, Pt, Re, Se, Sm, Sn, Ta, Tb, Te, V, Y	- Supply chain bottleneck risk (Supply risk)	- Market factors - Limitations to expanding Supply capacity - Likelihood of rapid Global Demand growth. - Geopolitical factors - Cross-country concentration of Supply - Political risk related to major supplying countries
Goe and Gaustad (2014)	Country	Over a 20-year period	To quantify and compare criticality metrics for silicon-based and thin-film photovoltaic materials that focus on a more comprehensive systems approach	Al, As, Cd, Cu, Fe, Ga, Ge, Au, In, Mo, Pt, Se, Si, Ag, Te, Sn and Zn	- Criticality matrix - Supply risk - Economic risk - Environmental risk	- Net import reliance - HirfindahleHirshmann index of primary material and ore producers - Recycling rate - Ratio of production to reserves - CERCLA points - Primary embodied energy - Energy savings - Primary material price - Domestic consumption - Economic value by sector
Roelich et al. (2014)	National (UK)	2012-2050	To develop a dynamic criticality assessment method that allows the identification of potential policy responses in transition towards a lowcarbon infrastructure goal to reduce criticality	Nd	- Criticality matrix - Supply disruption potential - Exposure to disruption	- Companion fraction - Access - Environmental constraints - Production requirements imbalance - Goal sensitivity - Price sensitivity
Zepf et al. (2014)	Global	Long-term	To identify materials that are constraints to the main energy pathway	Ag, Cd, Co, Cr, Cu, Ga, Ge, In, K, Li, Mo, Ni, Nb, P, Pd, Pt, Re, REE, Rh, Te, U, V and W	- Three scores for each indicators (High, Low and Medium)	- Reserves - Trade - Ecological impacts - Processing -A1:G10 SA1:G10ubstitutability - Recyclability

Table 3.1: Different Approaches to determine criticality

The approach determined by T. E. Graedel et al., 2012 was found to be the best suited for the use-case of this research, owing to it's global scope, versatile time horizon (10-100 years) and a matching objective to this research. The main challenge of criticality assessment methods is their limitation to address the dynamic nature of most indicators. The T. E. Graedel et al., 2012 criticality matrix introduces an environmental element in addition to the supply risk and vulnerability to supply restriction dimensions. Each dimension has several elements that are equally weighted to give a single score in defining criticality. The supply risk side has three major components, and the vulnerability to supply restriction dimension has three components. The environmental dimension is highly relevant due to the environmental damage caused by extraction and metal production. T. E. Graedel et al., 2012 method is mainly designed for metals but can be adapted for other abiotic resources . Resource issues for materials such as mineral metals should not stick to depletion, rather it has to address the issue of scarcity which should reflect not only the geological aspects, but also socioeconomic, regulatory and geopolitical aspects that affects accessibility as proposed in the T. E. Graedel et al., 2012 approach. Hence, this method was referred to in order to find out the factors which determine criticality and to establish a conceptual framework which defines how each of these factors contribute to criticality. The main components and relevant indicators of Graedel et al.'s criticality assessment method are summarized in Table 3.2.

3.1. Conceptual Framework

Criticality refers to the degree of importance and vulnerability of a particular metal or mineral to a country's economy, national security, and technological advancement (T. E. Graedel et al., 2012). Figure 3.1 and Table 3.2 illustrate and summarize the connections between Graedel et al's (2012) indicators and life cycle analysis (LCA) on a conceptual level. This method takes a three dimensional approach to define criticality.The three dimensions of criticality mentioned in this method are Supply risks, Vulnerability to supply Restrictions and Environmental Implications.

Criticality Axis	Components
Supply risk long-term	- Geological, Technological and Economic
Vulnerability to supply restriction - global	- Importance - Substitutability
Environmental implications (cradle-to-gate analysis)	- Damage to Human health - Damage to ecosystem

Table 3.2: Summary of criticality axes and components of T. E. Graedel et al., 2012 approach

The first dimension is Supply Risk. Geopolitics and political factors can indeed play a significant role in determining the supply risks of a metal. Geopolitical considerations can influence the availability, accessibility, and control of these resources, thereby impacting their criticality. Here are some ways in which geopolitics and political factors can affect the criticality of a metal. Geopolitical factors such as the geographical distribution of metal resources can shape their criticality. Countries or regions with abundant reserves of a particular metal may have a strategic advantage, as they can exert influence over global supply and demand dynamics. Trade Relations and Dependence can impact a country's access to critical metals. Reliance on imports or dependence on specific suppliers makes a country vulnerable to disruptions in the supply chain due to political tensions, trade disputes, or export restrictions imposed by producing nations. Geopolitical dynamics often lead to resource nationalism, where countries seek to protect and control their domestic metal resources. Governments may impose export restrictions, nationalize mines, or establish stringent regulations to secure critical metals for domestic use, potentially limiting global supply and increasing their criticality. Metals crucial to defense technologies and strategic industries, such as aerospace, electronics, and renewable energy, are often considered critical. Governments may prioritize the development and protection of domestic sources of these metals to maintain national security and technological advantage. Political conflicts, territorial disputes, and geopolitical rivalries can disrupt the production, transportation, and trade of critical metals. Regions affected by instability, conflicts, or sanctions may face challenges in exploiting their resources or exporting them, leading to potential shortages and increased criticality. Political factors, such as government policies, funding, and research priorities, can influence the development of new technologies and their demand for specific metals.

Supply and Demand: Economic factors strongly influence the supply and demand dynamics of metals. The criticality of a metal is often linked to its scarcity or limited availability relative to its demand. Factors such as population growth, industrialization, technological advancements, and emerging industries can drive the demand for certain metals, affecting their criticality. Economic factors can contribute to the concentration of market power in the mining and production of metals. When a small number of companies or countries dominate the supply chain of a metal, it can lead to market control, price manipulation, and potential supply disruptions. Such concentration increases the criticality of the metal, as any disruptions or changes in market conditions can have significant impacts on industries relying on that metal. These factors including speculation, investment trends, and global economic conditions, influence the price volatility of metals. Metals with high price volatility are often considered more critical because sudden price fluctuations can significantly impact industries and economies that rely on them. Price instability can be driven by factors like geopolitical events, economic crises, changes in supply and demand dynamics, and speculative trading. They also play a role in the development and adoption of substitutes for critical metals. If the price of a metal increases significantly or supply disruptions occur, industries may seek alternatives or invest in research and development to find substitute materials. Economic considerations, such as cost-effectiveness and availability of substitutes, can influence the criticality of a metal by affecting its demand and market dynamics. Economic factors impact investments in exploration, mining, and production of metals. The availability of financing, government policies, regulatory frameworks, and market conditions influence the level of investment in discovering and extracting metal resources. Limited investment in new mining projects or exploration can contribute to the criticality of metals by affecting future supply capacity and diversity.They can also influence the development and adoption of recycling technologies and the establishment of a circular economy for metals. Efficient recycling processes and incentives for recycling can reduce the dependence on primary metal production, mitigate supply risks, and decrease the criticality of certain metals. This dimension has indicators such as Geopolitical, Geological, Technological, Economic, Social and Regulatory factors (T. E. Graedel et al., 2015).

The second dimension is Vulnerability to Supply Restrictions. Technological factors play a significant role in contributing to the criticality of a metal. Technological advancements, emerging industries, and the demand for specific applications can increase the criticality of certain metals. Here are some ways in which technological factors contribute to the criticality of a metal. Technological factors influence the demand for metals based on their specific applications. Certain metals possess unique properties that make them essential for various industries. The demand for these metals increases with the growth of electric vehicle and battery technologies, contributing to their criticality. Technological advancements in manufacturing processes can impact the criticality of metals. New manufacturing techniques, such as additive manufacturing (3D printing), may require specific metals with precise properties. Metals suitable for these advanced manufacturing technologies can become critical due to their unique characteristics and the growing adoption of such manufacturing methods. Technological factors are closely tied to the criticality of metals used in renewable energy technologies. Metals such as copper, silver, and rare earth elements are crucial for solar panels, wind turbines, and energy storage systems. The transition to renewable energy sources has led to increased demand for these metals. Technological factors influence research and development efforts aimed at discovering new applications or improving the performance of metals. As new technologies and materials are developed, the demand for specific metals can increase, potentially raising their criticality. Additionally, research breakthroughs in extraction, refining, and recycling technologies can impact the availability and cost-effectiveness of metals, affecting their criticality. It's important to note that technological factors are interrelated with economic, geopolitical, and environmental considerations. The adoption of new technologies, market trends, government policies, and sustainability initiatives all influence the criticality of metals. Understanding the evolving technological landscape and its impact on metal demand is crucial for strategic resource planning, sustainable resource management, and mitigating supply risks. Hence, the indicators of this dimension are Importance, Substitutability and Susceptibility as shown in Figure 3.1.

The last dimension of the criticality space is Environmental Implications. Social and environmental factors play a significant role in influencing the criticality of a metal. These factors encompass various aspects related to societal values, public perception, environmental impact, and sustainability considerations. The environmental footprint associated with the extraction, processing, and use of metals is an important consideration. Social and environmental factors such as concerns over pollution, habitat destruction, water usage, and greenhouse gas emissions can influence the criticality of a metal. Metals with high environmental impacts may face stricter regulations, public opposition, or sustainability requirements, potentially affecting their availability and increasing their criticality. Social and environmental factors drive the demand for responsible mining practices. Stakeholders, including consumers, investors, and advocacy groups, increasingly expect transparency, ethical sourcing, and responsible labor practices in the mining industry. Metals sourced through environmentally and socially responsible methods, such as fair trade or certified mines, may gain preference and reduce their criticality due to improved sustainability credentials. They also promote the adoption of recycling and the establishment of a circular economy for metals. Recycling reduces the need for primary metal production and minimizes the environmental impact associated with mining and extraction. Increased emphasis on recycling and resource efficiency can decrease the criticality of certain metals by reducing reliance on virgin materials and mitigating supply risks. Metals sourced from regions associated with armed conflict, forced labor, or human rights abuses face scrutiny and potential legal restrictions. Efforts to trace and avoid the use of such metals in supply chains can impact their criticality. Consumer demand for products with lower environmental impacts or ethical sourcing practices can shape the market for metals. Public perception regarding the sustainability and social responsibility of a metal or its alternatives can affect its criticality by influencing purchasing decisions and industry practices.Hence the indicator of this dimension are Human Health and Ecosystems as shown in Figure 3.1 (T. E. Graedel et al., 2015).

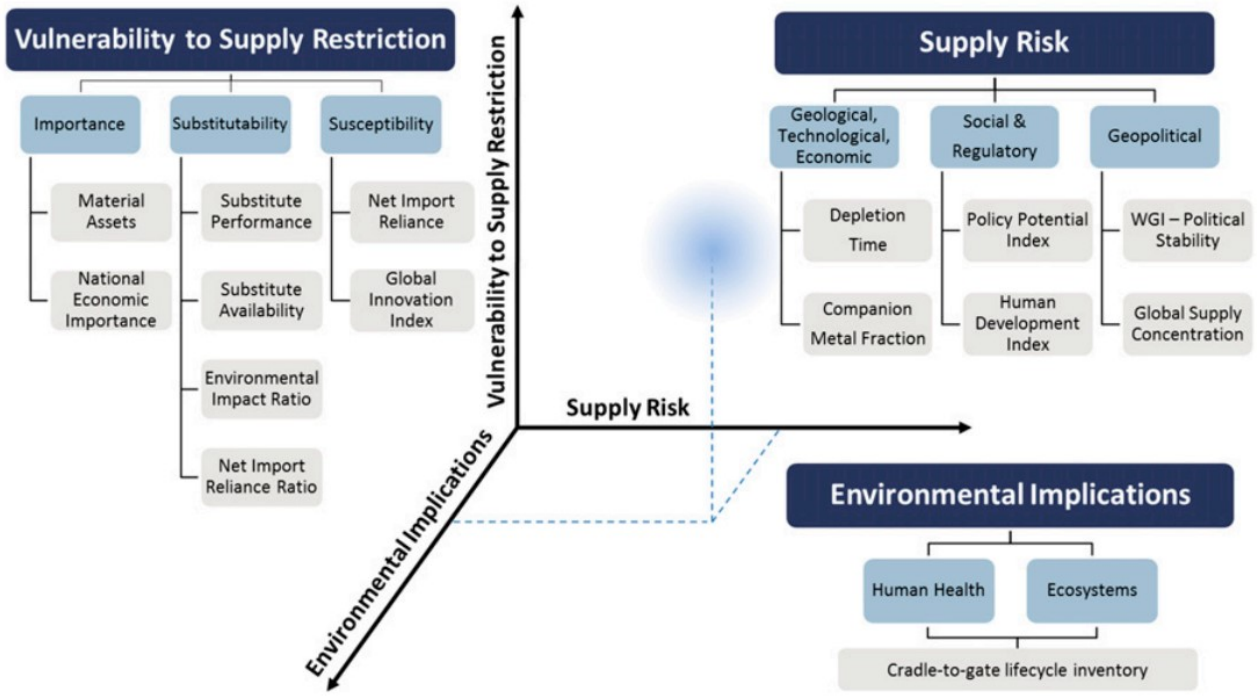


Figure 3.1: Conceptual Framework Model to determine Criticality of Metals (T. E. Graedel et al., 2015)

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Though this methodology is suitable for the scope of this research in terms of the global scope and time frame, it still does not take into account factors such EV demand by 2050, competitive demand, and ease of metal recyclability, which are very important for the scope of this research. Hence, certain changes need to be made to this framework and hence this conceptual framework is considered as an inspiration to design the analysis model to be used for this research.

3.2. Developing an Analysis Model

From the conceptual framework to determine criticality using With the above factors contributing towards criticality of a metal using the T. E. Graedel et al., 2015 method as shown in Figure 3.1, and based on the eight factors influencing criticality of a metal for EVs obtained from literature as defined in the beginning of this chapter, an analysis model is developed by ensuring all the indicators in the conceptual framework are translated into the EV context to ensure no factor contributing to criticality is missed in the model designed in this research.

3.2.1. PESTEL Analysis

The analysis framework that met the demands of this research the closest was the PESTEL framework as it covers most of the components mentioned in the T. E. Graedel et al., 2015 method. PESTEL analysis is a strategic framework used to analyze the external macro-environmental factors that can impact an organization's business operations and strategies (Issa et al., 2010). The acronym stands for Political, Economic, Social, Technological, Environmental, and Legal factors. Here's a brief overview of each factor:

Political Factors

Political factors refer to the influence of government policies and regulations on the business environment. This includes taxation policies, trade restrictions, labor laws, and government stability.The political factor refers to government regulations and legal issues that organizations must comply with. From a political standpoint, organizations should consider the laws and regulations of their own country. The government's impact on a country's infrastructure can have an effect on various factors. Political pressures can influence the stability of an industry's environment and the cost of operating. Political factors can also result in costs for organizations, such as taxes. Governments may attempt to shield companies in their country from foreign competition by imposing tariffs and import restrictions while promoting their growth by providing affordable loans and awarding significant government contracts. In summary, political factors play a significant role in shaping the business environment and affecting the cost of operations for organizations. They can impact taxes, tariffs, subsidies, and regulations that affect the behavior of companies. Therefore, it is important for businesses to consider the political environment when making decisions that will impact their operations (Issa et al., 2010).

Economic factors

These include the broader economic conditions in the region or country. The factors that impact the nature of competition in an industry can be categorized as local, national, or global economic factors. The economic growth rate, unemployment rate, and interest rates are important indicators that determine the spending power of both consumers and businesses. These factors have a direct impact on the buying capacity of individuals and companies, which in turn, affects the level of competition within an industry. In addition to these indicators, other economic factors, such as the supply and demand of key inputs, like oil, metals, minerals, and skilled labor, can also have an impact on the industry. For example, an increase in the cost of raw materials or a shortage of skilled labor can increase production costs, and this may lead to an increase in the price of goods or services, which in turn affects the demand for these goods or services. Therefore, it is important for businesses to keep a close eye on these economic factors to make informed decisions that will help them stay competitive in their respective industries (Issa et al., 2010).

Social Factors

Social factors refer to the cultural, demographic, and social trends in society that can impact a business. This includes changes in lifestyle and consumer behavior, population demographics, and cultural attitudes towards business.Society is an essential factor that influences projects in various ways. Social factors, such as growing consumer assertiveness and intolerance of poor quality, impact the project's success. Changes in the average household income and corresponding reduction in free time are also significant social factors. Additionally, cultural aspects, health, and safety consciousness, population growth rate, and age distribution are all factors that affect projects. For instance, cultural beliefs can influence how a product or service is received in a particular community, while population growth rate and age distribution can impact the demand for specific goods or services. Therefore, businesses must consider these social factors when designing and executing projects to ensure their success. Understanding these factors helps companies tailor their products or services to better meet the needs of their target consumers and remain competitive in the market (Issa et al., 2010).

Technological Factors

This is the stage which is the most crucial in the context of EVs. The main 2 factors considered here are ease of substitution and ease of recyclability. The ability to recycle and recover metals from end-of-life EVs and batteries is crucial for resource efficiency and reducing reliance on primary metal sources. Metals with efficient recycling systems in place have lower criticality. The potential for developing alternative materials or technologies that reduce or eliminate the need for certain metals can impact their criticality. Ongoing research and development efforts aim to find substitutes or improve the efficiency of metal usage in EVs (Issa et al., 2010).

A new and emerging technology has a significant impact on projects and organizations. Technological factors, such as the maturity of technology, competing technological developments, research funding, technology legislation, and new discoveries, all affect projects. For instance, the maturity of a technology can influence its adoption rate, while competing technological developments can impact market share. Additionally, research funding can drive innovation and new discoveries, leading to the development of new products or services. The increasing availability and accessibility of information technology, the internet, and global and local communications also contribute to the impact of technology on projects and organizations. It is now easier for users to access these technologies, which creates opportunities for businesses to connect with customers in new and innovative ways. Companies must consider these technological factors to remain competitive in the market and continue to innovate and grow. The ability to adapt to new technologies is crucial for businesses to thrive in today's fast-paced and ever-changing technological landscape (Issa et al., 2010).

Environmental Factors

Environmental factors refer to the impact of environmental issues on the business environment. This includes factors such as climate change, sustainability, and natural disasters.The impact of legislation is a crucial factor that affects projects. Organizations must adjust their products and operations to comply with the different regulatory and legislative frameworks that govern their product areas and the countries where they operate. Local, national, and global legislation can all have an impact on projects. For example, regulations related to product safety or environmental protection can significantly impact a project's timeline and budget. Organizations must also consider laws related to employment practices and intellectual property rights. In some cases, laws may require organizations to change their products or operations entirely. To remain compliant with legislation and regulations, organizations may need to invest in additional resources, such as legal expertise, training, and compliance management systems. Failure to comply with relevant legislation can result in fines, legal action, and damage to a company's reputation. Therefore, it is essential to consider the impact of legislation on a project and to ensure that all necessary measures are taken to comply with relevant laws and regulations (Issa et al., 2010).

Legal Factors

Legal factors include the impact of laws and regulations on business operations. This includes issues such as consumer protection laws, labor laws, and intellectual property laws.The factors include issues related to the environment at the local, national, and global levels. These factors can have significant effects on the way organizations operate and the products they offer. One major environmental issue is global warming and pollution, which is a concern that has led to a global agreement on the reduction of greenhouse gas emissions. Another important factor to consider is the impact of a project or organization on the community that surrounds it. This includes the effects on the natural environment and the health and safety of local residents. Overall, it is important for organizations to be aware of and address environmental factors to ensure their operations are sustainable and responsible (Issa et al., 2010).

PESTEL analysis is often used by organizations to identify potential opportunities and threats in their external environment. By analyzing these factors, organizations can develop strategies to mitigate risks and capitalize on opportunities. Due to the versatile nature of this framework, the PESTEL framework was used as inspiration in order to design an analysis framework for this research (Issa et al., 2010).

3.2.2. Analysis Model Design

As mentioned earlier, the PESTEL framework was used as an inspiration due to its versatility and relevance for this research. However, the PESTEL framework has a few shortcomings that are critical for the objective of this research. The PESTEL framework does not take into account the available geological supplies that is extremely fundamental while determining criticality of metals. Hence, an additional step involving scenario analysis of supply of the metals with respect to demand from EVs forecast to the year 2025 will be included in order to rectify this shortcoming. This scenario-wise analysis on metal demand for EVs from 2015 to 2050 will be explained in chapter 5

Another factor that the PESTEL framework does not consider is competitive demand. For each metal, Literature research will be conducted in order to determine the major demand sectors that could potentially grow/diminish in the future. This will provide an idea on the risk these demand sectors impose on EVs in the future.The resulting framework designed specifically for the purpose of this research is depicted in Figure 3.2 as shown below.The sequence of steps in the model does not affect the result obtained, as long as all the steps are executed for each metal.

The resulting analysis model which will be used for determining criticality of metals for EVs is shown in Figure 3.2. The Graedel et al (2012) method requires complex algorithms which are used to quantify the criticality of a metal with reference to each indicator. This is an elaborate process which is beyond the scope of this thesis. Hence, it is important to design a framework which uses the T. E. Graedel et al., 2015 methodology as an inspiration and captures all the factors used in this method, yet does not require any complex algorithms to quantify the results, since the purpose of quantification here is only to compare the criticalities of metals with each other. Each step of the designed analysis model is explained below.

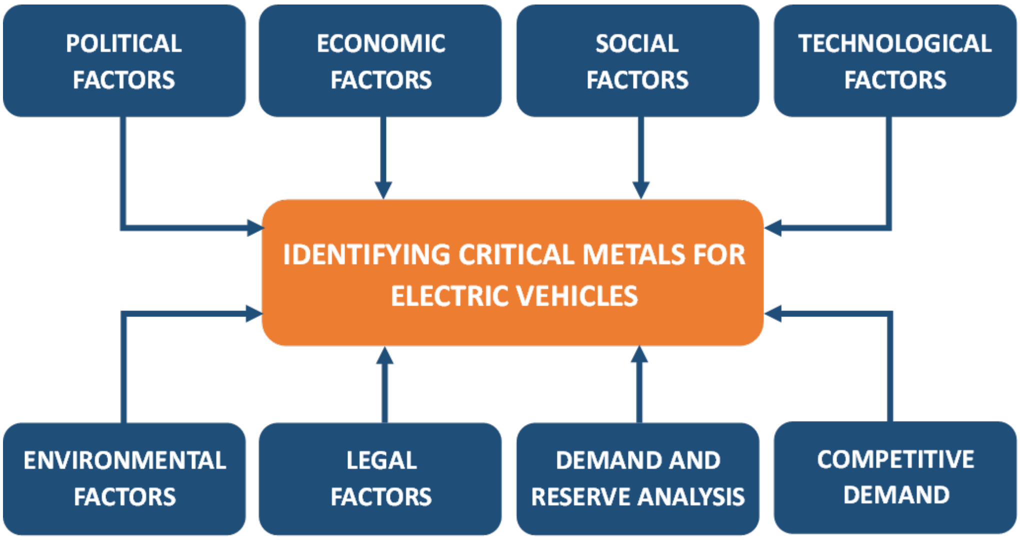

Figure 3.2: Analysis Model to define Criticality of Metals for Electric Vehicles

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Step 1: Analysing EV Demand and Available Geological Reserves of Metals by 2050

As defined in Chapter 2, this step will use the results from the scenarios created in the research paper by Habib et al., 2020 as a basis for analysis of geopolitical reserves. This is done since analysing available geological reserves available in the future is an important step in identifying criticality, though not the only one. This research paper in particular was chosen during the preliminary literature review as it deals with the forecasting of demand of critical metals used in Electric Vehicles. The timeline of forecast scenarios in this research paper (till 2050) also matched with the time period of research of this thesis. This step is performed and explained in Chapter 5.

Steps 2 to 7: Analysing Criticality of the Metal using PESTEL

In these steps, the Political, Economic, Social, Technological, Environmental and Legal factors explained in Section 3.2.1, contributing to the criticality of each metal is identified using literature. This is explained in detail in Chapter 6.

Step 8: Identifying Competitive Demand Sectors

This step involves identifying the demand sectors which compete with EVs for the same metal. This step is important since there might be other renewable technologies that might compete with EVs for a specific metal. And due to the growing trend of renewable technologies, this could pose a threat to the usage of this metal for the EV industry. Hence, Literature is used to determine the demand drivers and competing demand sector for each metal in this step. This has been performed in Chapter 6.

Hence the designed analysis model overcomes the disadvantages of the PESTEL analysis framework and the Graedel et al (2012) method for this research by providing a holistic view of criticality of metal for EVs. In this manner, criticality of each metal is analysed from the perspective of each factor in the designed analysis model in order to obtain an in-depth idea of the criticality of each metal for electric vehicles.

4

Metals Used In Electric Vehicles

Now that the Analysis model has been designed in Chapter 3, the metals which need to be analysed using this model needs to be identified. This chapter serves this purpose of identifying which metals are crucial for the functioning of EVs, in order to use them for criticality analysis using the model.

Electric vehicles (EVs) are becoming increasingly popular due to their low carbon emissions and fuel efficiency. The metals used in EVs play a vital role in their performance and sustainability. The most common types of electric vehicles are Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric vehicles (PHEVs) and Fuel Cell Electric vehicles (FCEV).In this subsection, we will explore the metal composition of EVs and their properties. The comparison of metal requirement for a conventional vehicle to that for an electric vehicle is shown in the figure below.By way of example, the IEA reports that a typical electric car requires six times the mineral inputs of a conventional car. Figure 4.1 below depicts the various metals used in EVs, compared to conventional vehicles. It must be noted that metals like stainless steel and aluminium have been excluded in the below figure, since they are a requirement for both conventional as well as electric vehicles.

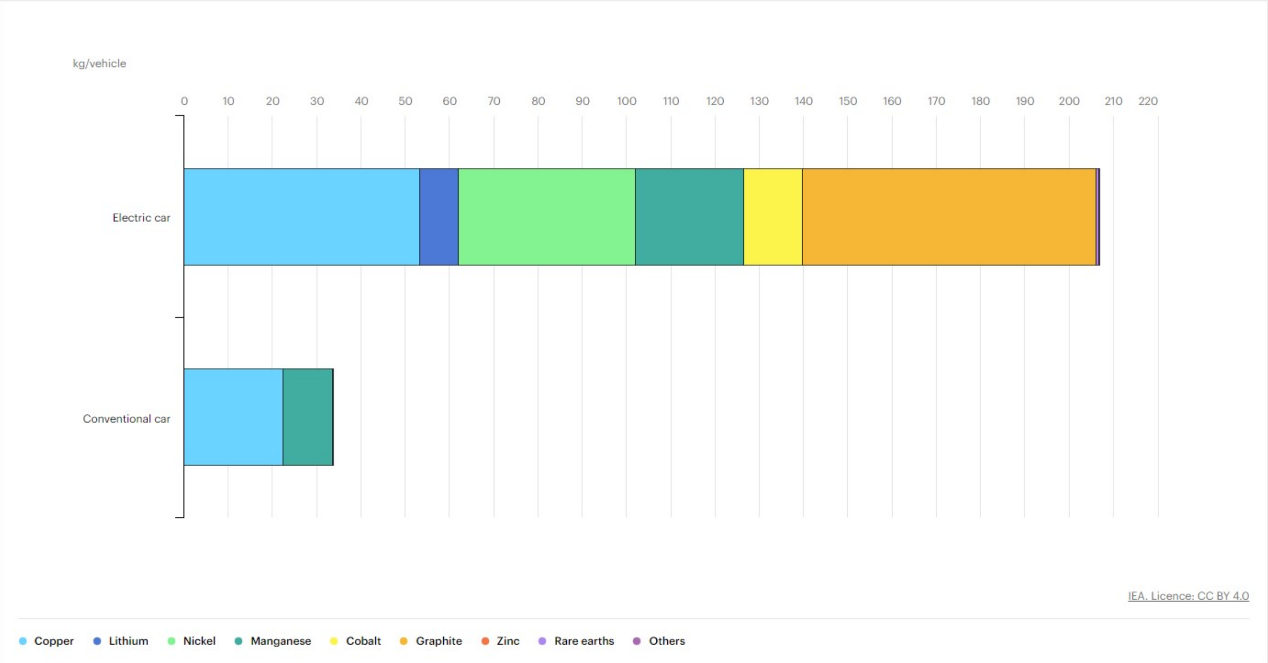

Figure 4.1: Minerals used in Electric Vehicles and Conventional Vehicles (International Energy Agency, 2022)

4.1. Lithium

Lithium is an essential component in the production of electric vehicles (EVs), specifically in the batteries that power them. The batteries used in EVs are typically lithium-ion batteries, which contain varying amounts of lithium depending on their size and capacity.Lithium is a highly reactive metal with atomic number 3 and atomic weight 6.94. It is the lightest metal and has a high electrochemical potential, which makes it an ideal candidate for battery applications. Lithium has a low density and a high energy density, which means that it can store a significant amount of energy in a small space. It is also highly conductive, which makes it an excellent material for use in batteries. This is particularly important for electric vehicles, which require a large amount of energy to operate. Lithium-ion batteries also have a longer cycle life than other battery types, which means that they can be recharged and used multiple times without a significant decrease in performance.Another advantage of lithium-ion batteries is that they have a lower self-discharge rate than other types of batteries. This means that they can hold their charge for longer periods, even when not in use. This is particularly important for electric vehicles, which may sit unused for extended periods. Despite its advantages, lithium-ion batteries also present some challenges for electric vehicles. One of the most significant challenges is their cost. Lithium-ion batteries are currently more expensive than other types of batteries, which can increase the cost of electric vehicles. However, as technology advances and production scales up, the cost of lithium-ion batteries is expected to decrease. Let's take a closer look at how lithium is used in electric vehicles (Li et al., 2022).

Lithium-Ion Batteries: Lithium-ion batteries used in EVs typically contain lithium cobalt oxide, lithium iron phosphate, or lithium manganese oxide. These materials have high energy densities, allowing EVs to travel longer distances on a single charge. There are several types of lithium batteries used in EVs. They are tabulated below in Table 4.1. Lithium Cobalt Oxide (LCO) is the most commonly used cathode material in EV batteries. LCO has a high energy density, providing long-range driving capabilities. However, LCO is also the most expensive cathode material, and it has a relatively short lifespan compared to other cathode materials.Lithium iron phosphate (LFP) is another popular cathode material used in EV batteries. LFP has a lower energy density than LCO but has a longer lifespan and is less expensive. LFP batteries are also more stable than LCO batteries, reducing the risk of thermal runaway and fire.Lithium manganese oxide (LMO) is a third cathode material used in EV batteries. LMO has a higher thermal stability than LCO and LFP and is less prone to thermal runaway. However, LMO has a lower energy density than LCO and LFP, limiting its range.Among all these types of batteries, the specific capacity of lithium is the same in theory. But the amount of lithium used varies among different types. For example, the lithium content in Li-metal batteries is higher than Li-ion batteries (Råde and Andersson, 2001).

Battery Pack Design: Lithium is also used in the design of battery packs for electric vehicles. The battery pack is made up of many individual cells, and the design of the pack affects its overall performance. Lithium is a lightweight material, which means it can be used to make battery packs that are both lighter and more compact than traditional battery packs (Gruber et al., 2011).

4.2. Copper

Copper is an excellent conductor of electricity and is commonly used in EVs for electrical wiring, motors, and charging infrastructure.Copper is a critical component in the production of electric vehicles (EVs), playing a vital role in both the car's performance and sustainability. From electric motors to charging stations, copper is used in various aspects of EVs. Let's take a closer look at how copper is utilized in electric vehicles (Elwert et al., 2015).

Electric Motors: Electric vehicles rely on electric motors to power their wheels, and copper is a

Table 4.1: Popular Battery Chemistries used in EVs (Råde and Andersson, 2001)

Battery type	Ni	Li	Co	V	Mm	Cd	Pb
Li-metal(V)		X		X			
Li-ion(Mn)		X					
Li-ion(Ni)	X	X					
Li-ion(Co)		X	X				
NaNiCl	X						
NiMH(AB2)	X		X	X			
NiMH(AB5)	X		X		X		
NiCd	X					X	
PbA							X

critical component in these motors. Copper is an excellent conductor of electricity, which means it can deliver the high currents needed to power the motor efficiently. Copper wire coils are used in the construction of electric motors, with more copper required for larger and more powerful motors.

Battery Systems:Copper is also used in the battery systems of electric vehicles. Copper is a vital component in the wiring that connects the battery cells to the vehicle's control systems. Copper bus-bars are used to connect the battery cells in series and parallel configurations, delivering the required voltage and current to power the motor.

Charging Infrastructure: Copper is used extensively in the charging infrastructure for electric vehicles, including charging stations and connectors. Copper is used in the cables that carry the electric current from the power source to the vehicle's battery, as well as the connectors that link the cables to the vehicle.

Thermal Management Systems: Thermal management systems are crucial in electric vehicles to maintain the temperature of the battery and other components. Copper is used in these systems to dissipate heat efficiently, ensuring that the battery and other critical components operate within their optimal temperature range.

Sustainable Manufacturing: Copper is also essential for sustainable manufacturing of electric vehicles. The production of copper itself is energy-intensive, but it is a highly recyclable material. Copper can be reused in EVs and other applications, reducing the need for new copper mining and lowering the environmental impact of EV production.

Copper is a vital component in the production of electric vehicles. It is used in various aspects of EVs, from electric motors to charging stations and sustainable manufacturing. With the increasing demand for electric vehicles, the demand for copper is also likely to rise, making copper an essential material for the future of sustainable transportationRåde and Andersson, 2001.

4.3. Aluminum

Aluminum is an important component in the production of electric vehicles (EVs). It is used in various aspects of EVs, including the body and frame, wheels, and battery systems. Let's take a closer look at how aluminum is utilized in electric vehicles (Shaffer et al., 2021).

Chasis: Aluminum is a lightweight material, making it an ideal choice for EVs that require high energy efficiency. By using aluminum in the body and frame of an EV, manufacturers can reduce the weight of the vehicle, improving its range and overall performance.

Battery Systems: Aluminum is also used in the battery systems of electric vehicles. The casing for the battery pack is typically made of aluminum, providing protection for the battery cells and helping to dissipate heat from the battery. Aluminum is also used in battery connectors, which link the battery cells together and transmit power to the electric motor.

Wheels: Aluminum is a popular material for the wheels of electric vehicles due to its lightweight and durable nature. Aluminum wheels can help reduce the weight of the vehicle, improving its range and energy efficiency. Additionally, aluminum wheels can improve the overall performance of the vehicle, providing better handling and a smoother ride.

Aluminum is a versatile material that can be easily molded and shaped, making it ideal for complex EV designs. By using aluminum in the body and frame of an EV, manufacturers can create more aerodynamic designs and improve the overall efficiency of the vehicle (Shaffer et al., 2021).

4.4. Nickel

Nickel is an important metal used in the production of electric vehicles (EVs) due to its ability to enhance the performance and longevity of EV batteries. In this article, we will explore the various applications of nickel in EVs and the reasons why it is a crucial component of the electric vehicle industry.

Electric Vehicle Batteries: Nickel is an essential component of the cathode of many EV batteries, which is the positive electrode that receives the electrons during charging. Referring to Table 4.1, we see that nickel is typically combined with other metals such as cobalt and manganese to create cathode materials, such as nickel-cobalt-manganese (NCM) or nickel-manganese-cobalt (NMC) oxide.These cathode materials are used in many types of EV batteries, including lithium-ion batteries, which are the most common type of battery used in EVs. Nickel-based cathodes are preferred in EV batteries because they offer a high energy density, which means that they can store more energy per unit of volume than other cathode materials. Additionally, nickel-based cathodes have a longer lifespan than other cathode materials, which means that they can withstand more charge and discharge cycles without degrading. This is important because the lifespan of an EV battery is a critical factor in determining the overall cost and environmental impact of the vehicle.

Electric Vehicle Motors: Nickel is also used in the production of electric vehicle motors. Specifically, nickel is used in the production of the motor's rotor, which is the rotating component that generates the mechanical energy to power the vehicle. Nickel is preferred for this application because it is a strong and durable metal that can withstand the high temperatures and stresses that are generated during the operation of an electric vehicle. Additionally, nickel is a magnetic material, which means that it can be used to enhance the performance of the motor.

Electric Vehicle Charging Infrastructure: Nickel is also used in the production of electric vehicle charging infrastructure, specifically in the wiring and connectors that are used to transfer electrical power from the charging station to the vehicle. Nickel is used in this application because it is a highly conductive material that can transfer electrical energy efficiently.

Hence, Nickel plays a critical role in the production and operation of electric vehicles. It is used in the cathodes of EV batteries to increase their energy density and lifespan, in the rotors of EV motors to enhance their performance and durability, and in the wiring and connectors of EV charging infrastructure to facilitate efficient energy transfer. As the demand for electric vehicles continues to grow, the importance of nickel in the EV industry is only expected to increase (Elwert et al., 2015).

4.5. Cobalt

Cobalt is an essential metal used in the production of electric vehicles (EVs) due to its ability to enhance the performance and safety of EV batteries. In this section, we will explore the various applications of cobalt in EVs and the reasons why it is a crucial component of the electric vehicle industry.

Electric Vehicle Batteries: Cobalt is an essential component of the cathode of many EV batteries, which is the positive electrode that receives the electrons during charging. Cobalt is typically combined with other metals such as nickel and manganese to create cathode materials, such as nickel-cobalt-manganese (NCM) or lithium-cobalt-oxide (LCO). Cobalt-based cathode materials are preferred in some types of EV batteries because they offer a high energy density and high specific power, which means that they can deliver high power in a short amount of time. Additionally, cobalt-based cathodes have a longer lifespan than other cathode materials, which means that they can withstand more charge and discharge cycles without degrading. Examples of battery chemistries that use cobalt can be seen in Table 4.1.

Electric Vehicle Motors: Cobalt is also used in the production of electric vehicle motors. Specifically, cobalt is used in the production of the motor's magnets, which are essential components that generate the magnetic field that drives the motor. Cobalt-based magnets are preferred in this application because they offer a high magnetic energy density, which means that they can generate a strong magnetic field with a relatively small amount of material. Additionally, cobalt-based magnets have a high Curie temperature, which means that they can maintain their magnetic properties at high temperatures, making them suitable for use in high-performance EV motors.

Electric Vehicle Safety: Cobalt is also used in the production of EV batteries to enhance their safety. Specifically, cobalt is used in the separator, which is a component that separates the cathode and anode of the battery to prevent short circuits. Cobalt-based separators are preferred in this application because they offer a high thermal stability, which means that they can withstand high temperatures without degrading or melting. This is important because one of the main safety concerns with EV batteries is the risk of thermal runaway, which can occur when the battery overheats and causes a chemical reaction that releases heat and potentially causes a fire or explosion.

Cobalt plays a critical role in the production and operation of electric vehicles. It is used in the cathodes of some EV batteries to increase their energy density, in the magnets of EV motors to enhance their performance, and in the separators of EV batteries to improve their safety. While the use of cobalt in EVs has raised concerns about its environmental and ethical impacts, it remains an important and widely used metal in the electric vehicle industry (K. H. Chan et al., 2021).

4.6. Rare Earth Elements (REEs)

Rare earth metals are a group of 17 chemical elements that are essential components of many modern technologies, including electric vehicles (EVs). In this section, we will explore the various applications of rare earth metals in EVs and the reasons why they are crucial components of the electric vehicle industry.

Electric Vehicle Motors: Rare earth metals are essential components of the permanent magnets used in many electric vehicle motors. Specifically, the rare earth metals neodymium, praseodymium, and dysprosium are commonly used to create neodymium-iron-boron (NdFeB) magnets, which are the most powerful magnets available.

NdFeB magnets are preferred in this application because they offer a high magnetic energy density, which means that they can generate a strong magnetic field with a relatively small amount of material. Additionally, NdFeB magnets have a high Curie temperature, which means that they can maintain their magnetic properties at high temperatures, making them suitable for use in high-performance EV motors.

While the use of rare earth metals in EV motors has enabled significant improvements in efficiency and performance, it has also raised concerns about the environmental and social impacts of their mining and production. Most rare earth metals are currently mined and processed in China, where there have been reports of environmental damage and labor rights violations.

Electric Vehicle Batteries: Rare earth metals are also used in the production of some types of electric vehicle batteries, specifically nickel-metal-hydride (NiMH) batteries. Rare earth metals such as lanthanum and cerium are used as catalysts in the production of the nickel electrode of NiMH batteries, which are used in some hybrid electric vehicles (HEVs).The Table 4.1 shows the battery chemistries which use mischmetal (Mm) which is a combination of rare earths.

However, the use of NiMH batteries in EVs has declined in recent years, as they have lower energy density and lifespan than lithium-ion batteries, which are now the most common type of battery used in EVs. Additionally, the production of NiMH batteries requires significant amounts of nickel, which can have environmental and social impacts similar to those associated with the mining and production of other metals used in EVs.

Electric Vehicle Charging Infrastructure: Rare earth metals are also used in the production of electric vehicle charging infrastructure, specifically in the magnets used in the motors of charging stations. While charging stations do not require the same level of performance as EV motors, the use of rare earth magnets can help to increase efficiency and reduce costs.

Rare earth metals play a critical role in the production and operation of electric vehicles. They are used in the magnets of EV motors to enhance their performance, in some types of EV batteries to improve their efficiency, and in the motors of EV charging infrastructure to increase efficiency and reduce costs (Alonso et al., 2012).

In conclusion, the metals that are considered to be crucial for the functioning of EVs are Lithium, Nickel, Cobalt, Copper, Aluminium and REEs. These metals will be passed through the analysis model in order to determine the criticality of each of these metals for EVs.

5

Demand Scenarios for Electric Vehicles

In the previous chapter, the metals in the scope of this research were decided based on importance for the functioning of EVs. In this chapter, the first step of the analysis model as shown in Figure 3.2 is performed to understand the available geological reserves for each of these metals by 2050, and what the demand for each of these metals due to EVs will look like by 2050. The demand for critical metals is expected to increase significantly by 2050. This is driven by various factors such as the growing adoption of clean energy technologies, electrification of transportation, and the increasing demand for consumer electronics.

5.1. Current Scenario of the EV Market

It is known by now that the EV market has been making huge strides in both sales as well as investments in the automotive industry. Original Equipment manufacturers (OEMs) have been making investments in the range of billions to launch electrified models in the market.

On studying the current scenario of the Electric Vehicle Market Worldwide, conclusions can be derived on how the market will take shape in the future. The significant growth of EVs leading up to 2030 will present major opportunities and challenges for traditional original equipment manufacturers (OEMs), new-entrant OEMs, captive finance companies and dealerships (International Energy Agency, 2022).

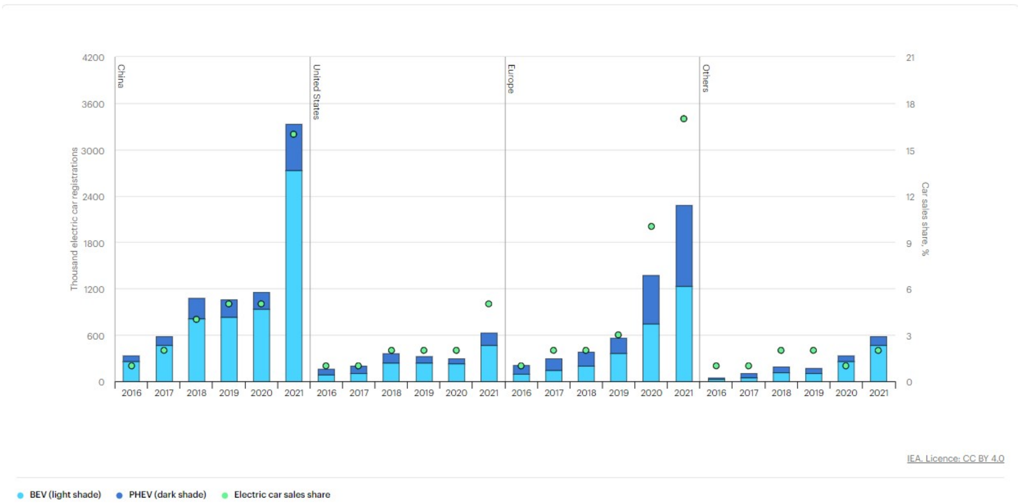

Figure 5.1: Electric car registrations and sales share in China, United States, Europe and other regions, 2016-2021 (International Energy Agency, 2022)

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Figure 5.1 depicts the rise in sales of two of the most popular types of electric vehicles, the Battery Electric Vehicle (BEV) and the Plug-in Hybrid Electric Vehicles (PHEV) in major global EV markets such as China, Europe and USA from 2016 to 2021. We can see a drastic rise in EV sales between 2016 to 2021. As of 2021, there were over 7 million EVs on the roads globally. China is the largest market for EVs, followed by Europe and the US as depicted in figure 5.1 above. The global EV market is projected to continue to grow in the coming years, driven by declining costs and increased government support. BEVs make up the majority of the EV market, followed by PHEVs. The demand for lithium, cobalt, nickel and other critical metals used in EV batteries is expected to increase as the EV market grows.

5.1.1. China

China are market leaders in the EV segment, accounting for half of global EV sales (Wen et al., 2021). In the second half of 2019, sales turned out to be lower than expected due to the reason that some of the subsidies offered to Chinese customers were halved, which resulted in a decline in EV sales that year. PHEVs fell by an estimation of 9% and BEV sales declined by 17% from 2018 to 2019.The silver lining to this incident is that the sales of ICE vehicles in China fell as well, which can be interpreted as the EV market in China actually increasing proportionally. Holistically, considering the course for the year 2023, it can be seen that this decline in sales in China in the year 2019 has affected the global EV Sales figures, but this impact does not sustain for a long term. Similarly, the impact of COVID-19 on global EV sales can also be seen as a short term effect.Responding to this incident, the Chinese government announced that such slashes in subsidies would not recur in the year 2020. However they continued to implement incentives to EV purchasing customers such as number plate credits in Tier 1 cities remained. Furthermore, investments have continuously been made in the charging infrastructure of China. There is also a strong focus on encouraging EV manufacturers in China to market and produce EVs (Wen et al., 2021).

The COVID-19 pandemic resulted in the decline of passenger car sales in China by a staggering 45% in the first quarter of 2020. EV sales were also hit by a massive decline of 56% as customers stayed indoors and EV showrooms were not operational. However, the recovery rate of the EV market in China was swift. Within March of 2020, the automotive industries in China worked towards achieving 75% of sales growth as 86% of their workforce returned to work. In the duration of a month, i.e, by April 2020 the production level of the industry was the same as that during the pre-pandemic period. The sales however, remained low in certain provinces of China. The Chinese government has attempted to recover sales in these provinces by means of favourable policies, pent-up demand, and establishing e-commerce platforms enabling customers to purchase EVs online. The release of new models have benefited several Chinese OEMs as well and this paves the path for a 'V-shaped' recovery of the EV market in China (Wen et al., 2021).

5.1.2. Europe

The EV market in Europe saw more growth than other regions of the world in 2019. Netherlands and the Nordics continued to be torchbearers for the cause of EVs in Europe. Norway took up 56% of the European market share. In the Netherlands, two of the top ten selling cars that year were BEVs. Countries like UK reported triple digit growth in sales in 2019. The catalysts for this significant rise in sales were attributed to favourable government policies and a change in consumer attitude primarily driven by growing concerns about climate change. This is also due to the major European countries setting goals in response to climate change. For example, the United Kingdom has a target of achieving net zero emissions by 2050, and has proposed a ban on the sale of all ICE vehicles by 2035. In Europe, the adoption of EVs in a mainstream context have been limited due to a number of obstacles such as a limited number of models available in the European market and perceptions by customers regarding the charging infrastructure capabilities in certain areas of Europe.

Though the COVID-19 outbreak had hindered automobile sales in Europe, EV sales still held up pretty well in comparison with ICE vehicles. In the first quarter of 2020, the passenger car sales in Europe saw a decline of 38.5%. Post April 2020, after the imposition of restrictions due to the pandemic were initiated, the passenger car sales saw a staggering decline of 76.3% compared to 2019. However, the sales of EVs in particular fell by only 31% in April 2020 in Western Europe. Some European countries even showed a modest sales growth compared to 2019 (Gersdorf et al., 2020).

5.1.3. United States

In 2019, the EV market in USA saw an encouraging head start in EV sales. However, customers in USA saw falling fuel prices which impacted EV sales in the second half of 2019.Tesla have been the market leaders in the EV segment in USA by a huge margin, owing particularly to the success of the Tesla Model 3 which accounted for half of all EV sales.

In 2020, the pandemic impacted sales of passenger cars in USA as well, similar to Europe and China. The was a natural decline in demand, increase in job losses and lockdown impositions in certain regions. The recovery of EV sales in USA was observed to be slower than that in China and Europe due to the low fuel prices and a limited number of options in EV models (Hao et al., 2020).

5.1.4. Rest Of The World

Apart from the market leaders in EV sales such as China, Europe and USA, the EV market sales in the rest of the world is still lagging behind. This can be mainly attributed to lack of commitment from governments towards EVs, lack of capable charging infrastructures, cultural differences towards EV models and lack of purchasing power. Japan are leaders in ICE vehicle manufacturing. However, their EV market is dominated by domestic OEMs who have not yet been able to match up to the EV performance of the EVs manufactured by Chinese, European and American OEMs. In India, the EVs are required to be of low cost and a mass production is required. This is an area where EVs are still in the research and development stage, with very few domestic OEMs like Tata and Mahindra successfully launching low cost PHEVs that are slowly gaining popularity. The charging infrastructure is also still on the developing stage (Bibra et al., 2021).

5.2. Future Demand Scenarios

This section is attributed to the contribution of electric vehicles to the demand on critical metals in the future.The number of electric vehicles (EVs) on the roads globally has been increasing rapidly in recent years. This growth is driven by a combination of factors, including declining costs of EVs, advancements in battery technology, and increasing government support. In many countries, governments are offering incentives for consumers to purchase EVs, such as tax credits and grants, in an effort to reduce greenhouse gas emissions and promote sustainable transportation. This support, combined with the growing demand for EVs due to their lower operating costs and environmental benefits, is driving the growth of the EV market.

As a result of this growth, the EV market is projected to continue to expand in the coming years. According to market research, the global EV market is expected to reach over 300 million vehicles by 2030, with electric cars accounting for 60% of market sales in the automotive industry (International Energy Agency, 2022). This growth will be driven by continued advancements in battery technology, increasing consumer demand, and supportive government policies. The increasing number of EVs on the road will also have a significant impact on the demand for critical metals used in EV batteries, such as lithium, cobalt, nickel, and others. This demand is expected to increase as the market for EVs continues to grow.

5.2.1. Demand Scenarios for Electric Vehicles for 2050

We can already see the increasing trend in EV sales during the past five to seven years, across the world as shown in figure 5.1 above. Based on these existing trends and market studies,we can forecast certain demand scenarios for electric vehicles.As mentioned earlier, the demand for electric vehicles (EVs) is influenced by various factors such as government policies, consumer preferences, technological advancements, and economic conditions.From Figure 5.1 we can see that BEVs already globally outperform PHEVs in the EV market.

It is estimated that BEVs will account for about 81% (25.3 million) of the EV market share in terms of new sales by 2030. On the other hand, PHEVs are estimated to reach 5.8 million by 2030. As the world returns to normalcy, we will see a recovery in ICE sales till 2025. However, this growth will be less compared to the trends of ICE sales in the past due to public awareness on the ban that will be imposed on these vehicles in the future by several countries. Post 2025, there will be a decline in sales of ICE vehicles. The global EV sales will grow from 11.2 million in 2025 to 31.1 million in 2030. It is estimated that by then EV sales would secure 32% of the total new car sales market shares. Hence in the recovery phase post the pandemic, the sales of ICE is expected to slow down while EVs will continue to show an upward trajectory in sales worldwide. By 2030 China is expected to hold 49% of the global EV market, Europe is expected to hold 27% and USA is expected to hold 14%. Domestically, China is expected to achieve a market share of around 48% by 2030. Europe is expected to obtain 42% of the domestic market share by 2030, and USA is expected to obtain 27% of the domestic market share (about half of that of China) by 2030.

Scenario Predictions for Electric Vehicles by 2050

Based on the current trends in EV sales described, the factors influencing consumer behavior the sales of EV in the future can be projected by describing three scenarios that apply to the case of electric vehicles.

Baseline Scenario: The first scenario is the baseline scenario. The SSP2 narrative is used for the baseline scenario. This is a scenario that defines a world with challenges that are intermediate, which allows for both adaptation as well as mitigation. This scenario has a target of keeping the temperature rise at or below $2.4°C$ (Habib et al., 2020).

Moderate Scenario: The second scenario is a moderate scenario. This scenario has a target of keeping CO_2 emissions below 550 ppm. In this scenario, there will be a moderate increase in the demand for EVs due to the introduction of supportive policies such as subsidies, tax incentives, and stricter emissions regulations. Consumers are also assumed to become more aware of the environmental benefits of EVs and more willing to switch from conventional vehicles to EVs. Under this scenario, EVs are expected to reach around 15% of global new car sales by 2030 (Habib et al., 2020).

Stringent Scenario: The last scenario is the stringent scenario. It is aimed at accomplishing the $2°C$ goal aligning with the Paris agreement (Riahi et al., 2017). In this scenario, there will be a rapid increase in the demand for EVs due to aggressive policies, such as banning the sale of new gasoline and diesel cars in major markets and increasing investments in EV charging infrastructure. This scenario assumes that consumers will also become more willing to pay higher upfront costs for EVs due to the environmental benefits and lower operating costs. Under this scenario, EVs are expected to reach around 30% of global new car sales by 2030 (Habib et al., 2020).

Figure 5.2 below depicts the demand predictions of different types of electric vehicles namely; Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs) based on three scenario narratives, since these vehicles contribute to a majority of the market shared as analysed earlier. The SSPs (Shared Socioeconomic Pathway) are narratives developed by a team of international climate scientists, energy systems modelers and economists. These pathways are being used in climate models, and greenhouse gas emission predictions. It must be noted that this analysis has been conducted only for passenger EVs.

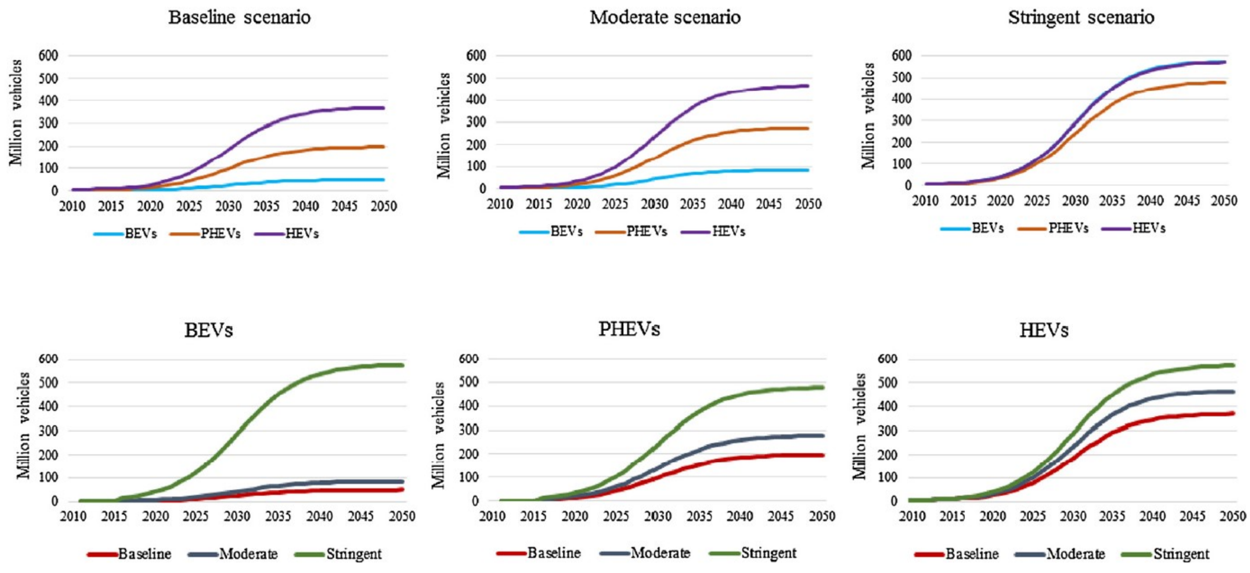

Figure 5.2: Annual growth of three different types of EV stocks in three scenarios, 2010-2050 (Habib et al., 2020)

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As shown in Figure 5.2, the growth rate of EV sales is expected to slow down, resulting in a plateau in the number of EV sales. This is due to the fact that not all countries will be able to support the energy transition into EVs the same way as the wealthier nations over the next decade. Charging infrastructures require humongous capital investments that can be achieved only through a combination of public and private investments in these countries. This cannot be achieved uniformly throughout the world. In the countries that are unable to achieve this feat in time, the market for ICE is predicted to sustain for a while till this charging infrastructure is established (Habib et al., 2020).

5.3. Critical Metal Demand Scenarios

This chapter is attributed to the contribution of electric vehicles to the demand on critical metals in the future. The number of electric vehicles (EVs) on the roads globally has been increasing rapidly in recent years. This growth is driven by a combination of factors, including declining costs of EVs, advancements in battery technology, and increasing government support. In many countries, governments are offering incentives for consumers to purchase EVs, such as tax credits and grants, in an effort to reduce greenhouse gas emissions and promote sustainable transportation. This support, combined with the growing demand for EVs due to their lower operating costs and environmental benefits, is driving the growth of the EV market.

As a result of this growth, the EV market is projected to continue to expand in the coming years. According to market research, the global EV market is expected to reach over 40 million vehicles by 2030 (Cazzola et al., 2016). This growth will be driven by continued advancements in battery technology, increasing consumer demand, and supportive government policies. The increasing number of EVs on the road will also have a significant impact on the demand for critical metals used in EV batteries, such as lithium, cobalt, nickel, and others. This demand is expected to increase as the market for EVs continues to grow. The demand for lithium, cobalt, nickel and other critical metals used in EV batteries is expected to increase as the EV market grows (Jetin, 2020).

Figure 5.3 below depicts the annual metal demand as well as the available geological reserves for nine metals namely aluminium, cobalt, copper, iron, lithium, manganese, nickel, neodymium and dysprosium, since these are the metals primarily associated with electric vehicles (Habib et al., 2020).

We can see in Figure 5.3 that the growth in critical metal demand peaks at around the year 2035 for all three scenarios. Conversely, the critical metal demand generated by the EVs in 2015 and 2050 is significantly lower. As explained earlier, this is because the scenario development model follows the s-curve growth trend, where most of the growth happens from 2015 until 2035 and then it stabilises by 2050. The estimated cumulative demand of metals from 2015 to 2050 ranges from baseline to stringent scenarios as: aluminium: 185–562 million tons; cobalt: 1–10 million tons; copper: 52–182 million tons; iron: 615–1630 million tons; lithium: 1.8–11 million tons; manganese: 8–20 million tons; nickel: 13–68 million tons; neodymium: 1.4–2.8 million tons; and dysprosium: 0.04–0.1 million tons (Habib et al., 2020).

Figure 5.3 also reveals that the demand for cobalt, lithium and nickel is in orders of magnitude higher in the stringent scenario compared to the baseline and moderate scenarios. This is primarily because all these metals are used in the NCA-G (where the G stands for gas) battery that is part of the BEVs, and since the share of BEVs is almost five times higher in stringent scenario compared to the other two, the result is high demand of these metals. Nickel is different in the sense that it is an important constituent of Ni- MH batteries as well that are used in the HEVs, and HEVs follow a similar trend as of BEVs in the stringent scenario, hence resulting in even higher demand. The demand for aluminium, copper and iron mainly comes from the EVs body as well as from different batteries. For example, in case of aluminium, the demand is also generated from NCA-G batteries used in BEVs, which explains the significantly higher demand of aluminium in the stringent scenario as compared to the other two scenarios. Manganese demand originates from LMO-G batteries used in the PHEVs, and since the demand of PHEVs grows 2 and 3 times higher in the stringent scenario in comparison to the moderate and baseline scenarios respectively, the resulting manganese demand also follows the same growth curve.

The demand for neodymium and dysprosium mainly comes from the permanent magnets founds in the motors contained in EVs, and only a little demand is generated by the NiMH batteries found in HEVs. Figure 5.3 also shows the amount of remaining geological reserves for all the nine metals considered in this study, which corresponds to the geological supply risk factor of resource criticality assessment by highlighting the depletion issue of non-renewable resources such as metals The effect of mining on each metal's geological reserves can be seen in the Figure, where the remaining number of reserves in million tons are shown until 2050 for the three scenarios. The effects are different from scenario to scenario but the baseline scenario has the least consequences for the reserve size and the stringent has the biggest impact, due to the lowest and highest number of EVs demand respectively. The geological supply risk results for cobalt are striking, as it seems that the geological reserves will already be depleted by 2035 in the stringent scenario. However, it is important here to mention that geological reserves are only a small part of the total geological resources of a particular metal and geological reserves grow over time because of changing technological and economic conditions in future. The depletion of geological reserves of cobalt, lithium and nickel occurs at a faster rate in the stringent scenario in comparison to the other two scenarios (Habib et al., 2020).

Figure 5.3 shows that even considering the stringent scenario, more than 90% of the geological reserves are still remaining in 2050 for the metals mainly used in the car body such as aluminium and iron, which are one of the most widely abundant metals found in earth's crust. For copper, the amount of remaining reserve considering the stringent case is almost 74% in 2050. Regarding the two REEs namely neodymium and dysprosium, considered to be as critical elements (Blengini G.A. and de Matos., 2017), the amount of remaining geological reserves is 78% and 89% respectively in 2050. Although these results show that the REEs do not seem to face geological supply risk in the mid-to-long term future, one has to bear in mind that this study did not consider any other end-uses of these metals than the passenger vehicles.

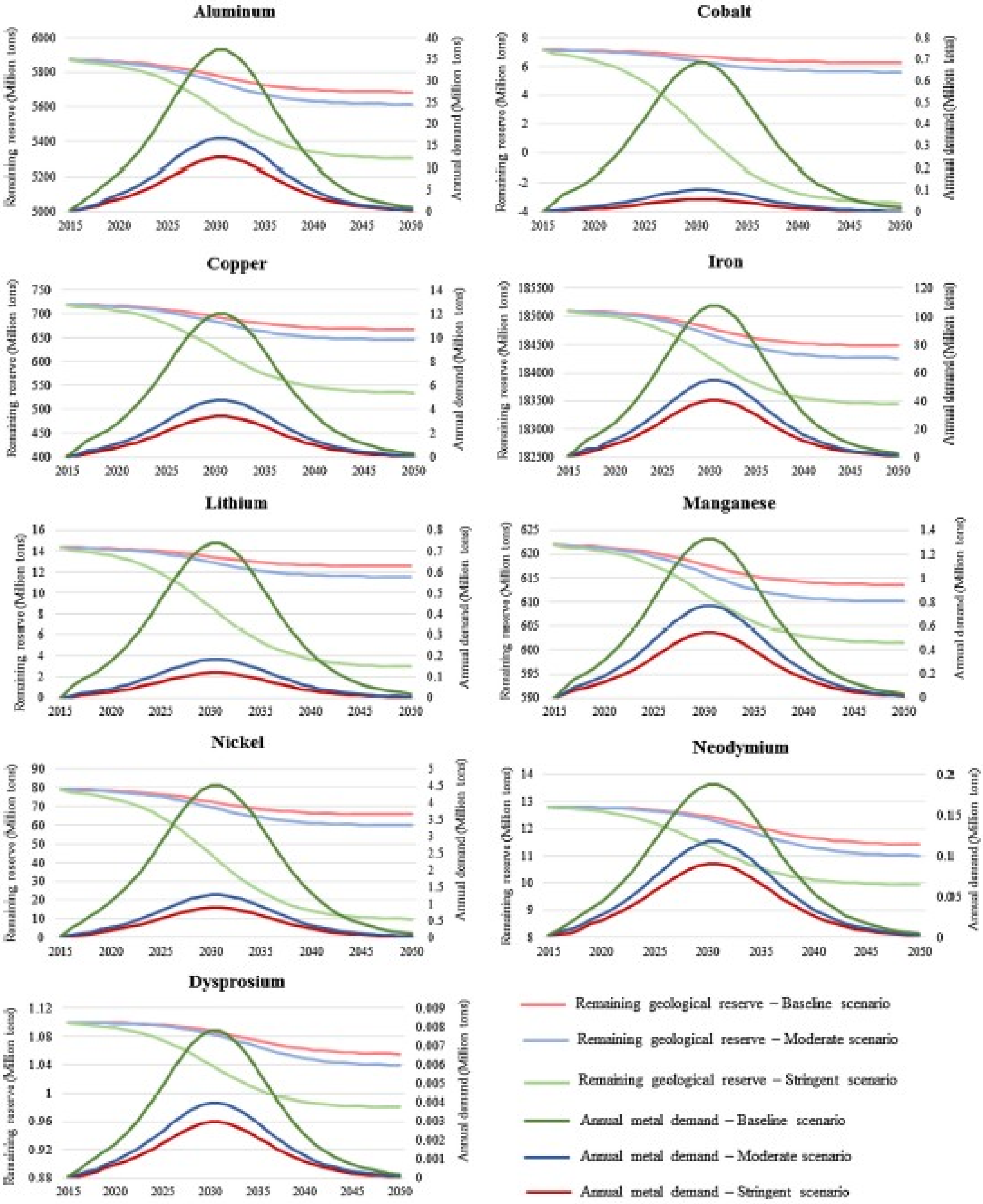

Figure 5.3: Critical Metal Demand due to EVs and Remaining Geological Reserves for 9 critical metals from 2015 to 2050 (Habib et al., 2020)

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6

Criticality Analysis of Metals

The previous chapter dealt with the first step of the analysis model. This chapter deals with steps 2 to 8 of the analysis model. This chapter deals with the PESTEL analysis and identifying competitive demand sectors of the metals used in EVs within the scope of this research as defined in chapter 2. By examining the political, economic, social, technological, environmental,legal and competitive demand factors that influence the use of these metals in EVs, this chapter aims to provide insights into the future prospects of the EV market and the role of these metals in sustainable transportation. It must be noted that the prices mentioned in this chapter have not been adjusted for inflation.

6.1. Criticality Analysis of Lithium

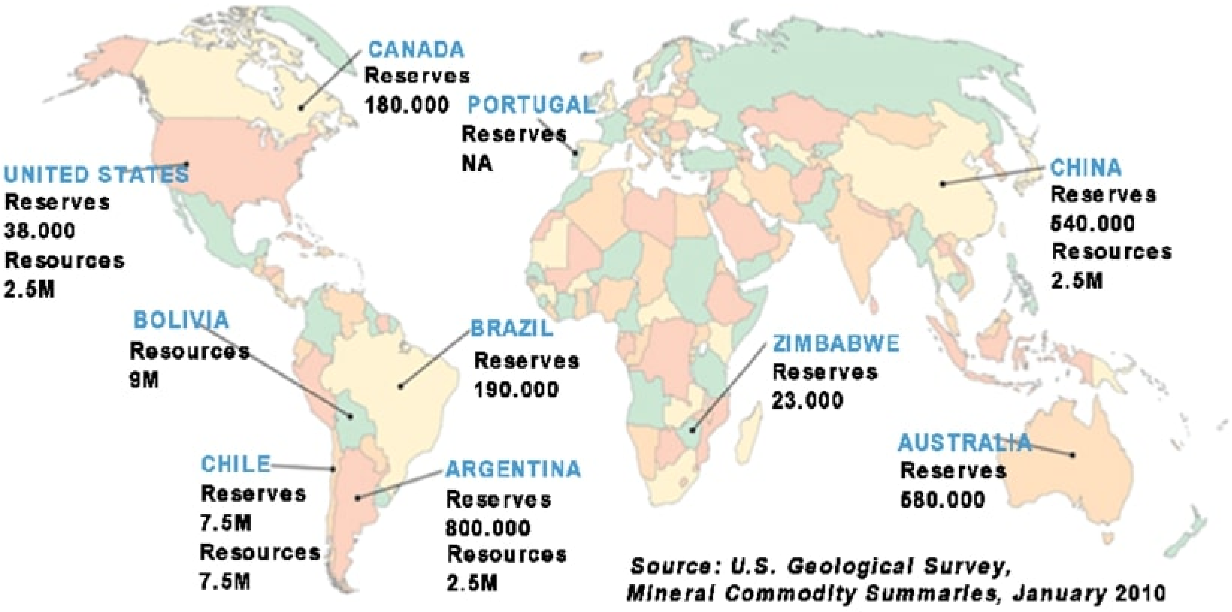
Lithium is one of the most critical components of the batteries used in electric vehicles (EVs). As the demand for EVs continues to rise, so does the demand for lithium, leading to an increased focus on the external factors that impact its production and availability. This section will provide a PESTEL analysis of lithium for EVs, examining the key external factors that affect its production, supply, and demand by analyzing these factors, to provide insights into the future prospects of the lithium market and its role in the transition to sustainable transportation.

6.1.1. Political Factors

The 20th century was characterized by a heavy reliance on fossil fuels, or ”black gold,” for energy production. However, with the onset of climate change and increasing concerns about sustainability, the focus has shifted towards cleaner forms of energy production. As a result, it has been suggested that the 21st century will be the era of metals. In particular, there has been a growing interest in lithium, which is an essential component in the production of rechargeable batteries used in electric vehicles and other electronic devices (International Energy Agency, 2022).

Lithium reserves are highly concentrated in South America, particularly in Argentina, Bolivia, and Chile, which collectively make up the ”lithium triangle.” Bolivia has the largest untapped lithium reserves, with an estimated 21 million tons. Argentina has 17 million tons of reserves, while Chile has 9 million tons. Australia is the fourth largest producer, with 6.8 million tons of identified resources. China also has significant lithium resources, with an estimated 4.5 million tons (Jaskula, 2020). The worldwide distribution of Lithium mines is as shown in Figure 6.1.

Chinese companies have been actively pursuing mine investments in both South America and Australia to maintain their dominant position in downstream industries and the overall supply chain. For example, Tianqi Lithium, a company listed on the Shenzhen Stock Exchange, became the second largest shareholder in Sociedad Química y Minera (SQM), a Chilean mining company, in 2018. The company also holds a 51 percent stake in the world’s largest hard-rock lithium mine at Greenbushes in Western Australia. Tianqi Lithium is fully verticalized, meaning it engages in all stages of the



Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2010

Figure 6.1: Worldwide Lithium Resources (Kim, 2018)

lithium industry, including mining, downstream production, processing, and sales of a wide range of high-quality lithium products (Kalantzakos, 2020).

In 2010, the discovery of vast mineral resources in Afghanistan marked a turning point for the country. The presence of metals such as lithium, copper, cobalt, and rare-earth elements, estimated to be worth over USD 1 trillion, sparked hope that Afghanistan could emerge as a major player in the mining industry. However, more than a decade later, these resources remain largely untapped. The departure of US forces from Afghanistan has led to concerns about the fate of these minerals, with neighboring countries such as China expressing interest in exploiting them. The potential of these resources is enormous, and if properly developed, they could provide a much-needed boost to Afghanistan's economy and help the country break free from its dependence on foreign aid (Jaskula, 2020).

Meanwhile, the world has seen a growing push towards carbon neutrality and the adoption of renewable energy sources. The United States' return to the Paris Agreement and President Biden's executive order to make the federal government carbon neutral by 2050 are significant steps in this direction. The European Union's European Green Deal, which aims to achieve the same goal by 2050, has also set a precedent for other countries to follow. The automobile sector has been one of the industries at the forefront of this shift, with Norway and the UK announcing a ban on the sale of new petrol and diesel cars by 2025 and 2030, respectively (Pitron, 2022).

China is a dominant player in the lithium cell manufacturing industry, producing 73 percent of global lithium cell manufacturing capacity. As the world shifts towards electric cars to reduce greenhouse gas emissions, the demand for lithium, graphite, cobalt, and rare-earth metals has skyrocketed. The production of these materials needs to increase by staggering amounts to meet the goals of the Paris Agreement. However, mining these materials often comes at a cost to the environment and local communities. For example, global mining group Rio Tinto's announcement of a lithium mine in Western Serbia led to protests due to concerns about environmental degradation, resulting in the indefinite postponement of the project (J. Lee et al., 2020).

In response to the growing demand for these materials, there has been a surge in lithium extraction projects around the world. The United States reopened the Californian Mountain Pass Mine in 2018, and France's Minister of the Ecological Transition has discussed the possibility of opening lithium mines in France. The EU is also prioritizing the development of its own mining industry to reduce dependence on other countries. However, this trend has not been without controversy. Indigenous communities in Atacama, Chile, have protested against mining projects, citing social inequality and environmental degradation (J. Lee et al., 2020).

The mining industry is not only a significant contributor to global energy use but also exacerbates water stress. Seventy percent of the mining projects operated by the six largest companies are located in regions that already face water scarcity. Therefore, it is essential to strike a balance between the need for these critical materials and the need to protect the environment and local communities. Initiatives such as sustainable mining practices and responsible sourcing of materials can help to mitigate the negative impacts of the mining industry (J. Lee et al., 2020).

6.1.2. Economic Factors

The recycling of lithium-ion batteries (LIBs) presents numerous economic and financial challenges that hinder the development of a thriving market for this technology. One of the most significant barriers to the recycling of LIBs is the apparent lack of economic incentives. Studies have identified several factors contributing to these economic barriers, such as the high treatment costs of LIBs, the low supply of used LIBs, the lower mining costs for raw materials compared to extracting them from end-of-life (EoL) LIBs, and the practically non-existent second-hand LIB market. These factors deter stakeholders from investing their time, money, and effort in developing a successful LIB recycling market.

In addition to economic barriers, there are also social barriers that prevent the efficient recycling of LIBs. For example, the lack of willingness to return used LIBs from the consumer side and inadequate coordination and collaboration among various actors in the reverse logistics supply chain limit the efficiency of LIB recycling. Furthermore, the awareness about the adverse effects of toxicity from metals during LIB recycling to human health negatively impacts recycling activities. Another social barrier is the poor acceptability or sellability of recycled LIBs. These factors are connected to behaviors surrounding LIB EoL management, values attributed to used LIBs, or even attitudes and buying behavior of electric vehicle consumers (Bhuyan et al., 2022).

Despite these barriers, the demand for lithium-ion batteries has continued to grow, driven by their increased use in portable electronic devices, electric vehicles, and grid storage applications. This growth has resulted in a surge in lithium production, with companies like Tesla securing rights to thousands of acres of land for this purpose. However, it is essential to consider the economic evaluation results that indicate the break even price for spent LIBs is estimated at 2.87 USD per kilogram, and the elasticity of the total costs to the spent battery price is approximately 21.30 percent. These results suggest that while battery recovering is beneficial in the current battery market, the break even price marks the upper limit for re-manufacturing costs, and it is not likely but still possible.

The price of lithium has fluctuated significantly between 2017 and 2022, reflecting the changing demand for lithium-ion batteries in a variety of industries, including electric vehicles and energy storage. From Figure 6.2 we see that the price of lithium began to surge, driven by a growing demand for electric vehicles and energy storage systems in 2017. Lithium prices increased by more than 50% in just a few months, peaking at around $21,000 per metric tonne in January 2018. However, the rapid price increase led to an oversupply of lithium, causing prices to drop sharply in late 2018 and 2019. In addition, the COVID-19 pandemic caused a global economic slowdown in 2020, which further impacted the demand for lithium and led to lower prices. Despite these fluctuations, the overall trend in lithium prices has been upward, reflecting the long-term growth in demand for electric vehicles and energy storage systems. As of 2022, the price of lithium was around $10,000 per metric tonne, although this can vary depending on the specific grade and source of the lithium. Overall, the

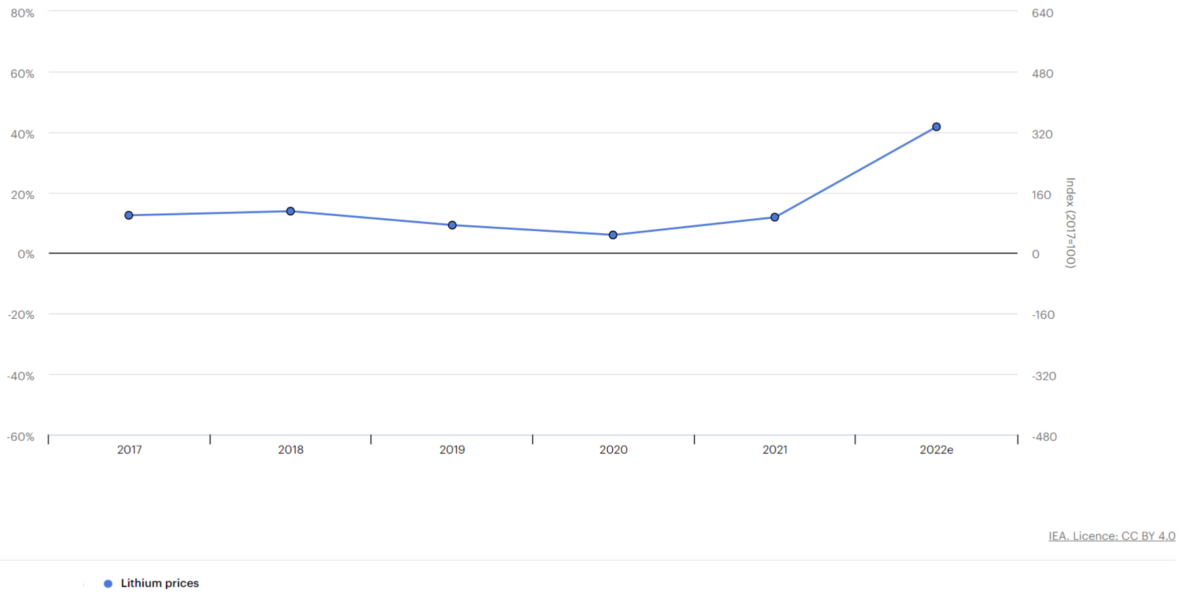


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Figure 6.2: Lithium Prices between 2017 and 2022 (International Energy Agency, 2022)

price of lithium is expected to remain volatile in the coming years, reflecting the changing dynamics of the global lithium market and the ongoing growth of electric vehicle and energy storage industries.

In conclusion, the development of a thriving market for LIB recycling faces several economic and financial challenges that deter stakeholders from investing their resources. Addressing these challenges requires collaborative efforts among various actors in the reverse logistics supply chain, improved awareness about the adverse effects of toxicity from metals during LIB recycling to human health, and an increase in the acceptability and sellability of recycled LIBs. Moreover, as demand for lithium-ion batteries continues to grow, it is crucial to consider the economic evaluation results to ensure that LIB recycling remains a viable and sustainable solution (Bhuyan et al., 2022).

6.1.3. Social Factors

According to the United States Geological Survey (USGS), world production in 2015 was 31,500 tons, while in 2018 it reached 85,000 tons. The recycling of lithium-ion batteries (LIBs) is essential for reducing the environmental impact of these batteries and promoting a circular economy. However, the recycling process faces significant social barriers that limit its effectiveness. These barriers are related to the interaction among different stakeholders, behaviors surrounding LIB end-of-life (EoL) management, values attributed to used LIBs, and even attitudes and buying behavior of electric vehicle consumers. All of these factors fall within the social dimension of the PESTEL analysis framework.

One of the most significant social barriers to LIB recycling is the lack of willingness to return used batteries from the consumer side. Many consumers are not aware of the importance of recycling their batteries or do not see the benefits of doing so. Inadequate coordination and collaboration among various actors in the reverse logistics supply chain, such as collectors, transporters, and recyclers, further limit the effectiveness of the recycling process. This lack of coordination results in inefficiencies, increased costs, and lower recycling rates.

Another social barrier to LIB recycling is the awareness about the adverse effects of the toxicity from metals during LIB recycling to human health. The recycling process involves the use of hazardous chemicals and high temperatures that can cause harm to workers and the environment. This awareness negatively impacts recycling activities and slows down the adoption of new recycling technologies.

Finally, poor acceptability or sellability of recycled LIB is another significant social barrier to recycling. This issue arises because recycled batteries are often seen as inferior to new batteries and may have a lower performance level. This perception affects the demand for recycled batteries, and without a market demand, the recycling industry cannot thrive. To overcome these social barriers, stakeholders need to raise awareness of the importance of recycling batteries, collaborate more effectively to streamline the recycling process, and invest in developing new technologies that reduce the environmental impact of recycling (Bhuyan et al., 2022).

6.1.4. Technological Factors

Lithium-ion batteries (LIBs) are widely recognized for their high energy and power densities, making them the most preferred rechargeable battery type. This technology relies on the properties of lithium, which is the lightest metal, offering a high electrochemical potential in combination with cost advantages. LIBs are known for their advantages such as quick recharge rate, low weight, low self-discharge, and long cycling life. These features make LIBs the go-to power source for a broad range of applications, including portable electronic devices, electric tools, electric vehicles, and grid storage applications. The high energy density of LIBs enables them to pack more energy into a smaller volume, making them ideal for applications where size and weight are critical factors.

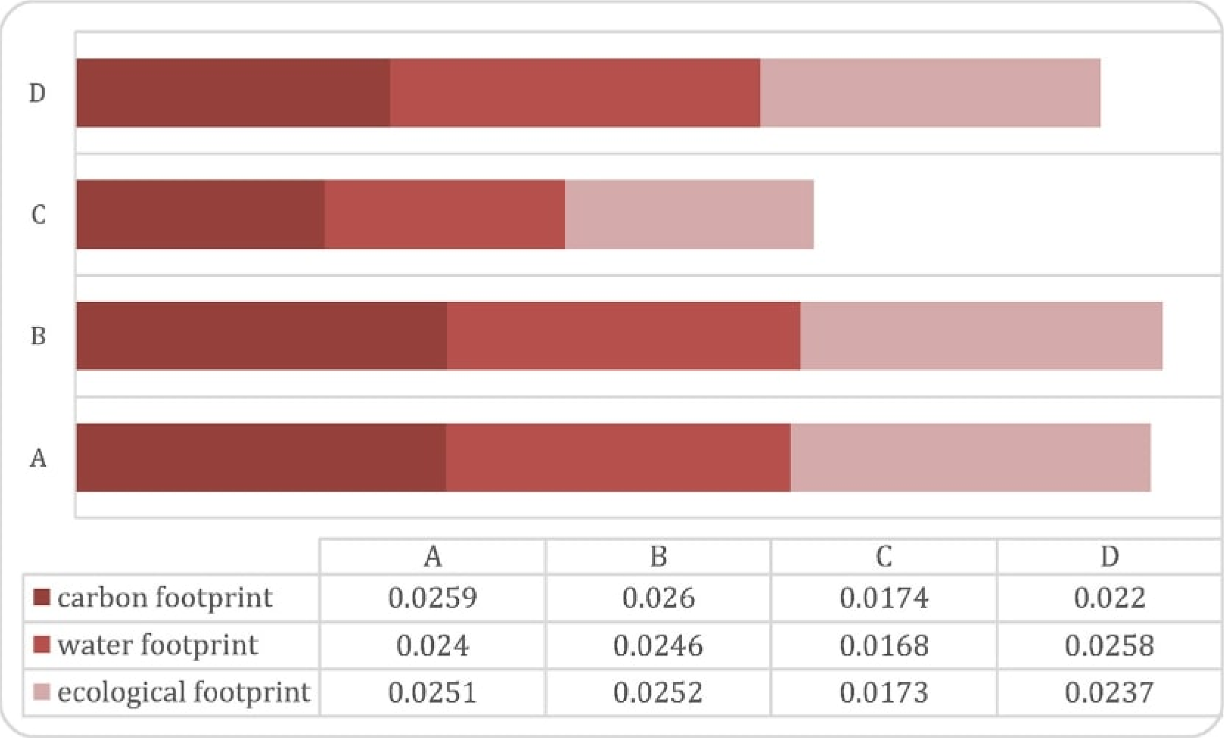
Another crucial benefit of LIBs is their minimal maintenance requirement. Unlike other battery types, LIBs require very little, if any, maintenance, and they do not have the so-called ”memory effect.” This property ensures that the battery retains its full capacity even after partial discharge and recharge cycles, eliminating the need for full discharge before charging. Additionally, LIBs have a lower self-discharge rate, which means they can hold their charge for a longer time, making them more convenient for applications where infrequent use is expected. With these advantages, LIBs are becoming one of the most promising solutions for energy-related issues, offering a reliable and efficient power source for various applications.These properties make it hard to substitute Lithium by other materials in battery technologies.

6.1.5. Environmental Factors

Lithium-ion batteries (LIBs) are widely used in the automotive industry and have gained a lot of attention due to their advantages over primary batteries. However, they present significant environmental issues, including pollution from exploration and processing of metals, natural resource pressure, and careless disposal of batteries containing toxic materials. Lithium, cobalt, and nickel, which are required for energy storage, are scarce resources, and their demand is rapidly increasing. The readily available lithium reserves may soon run out, and its price will rise, leading to additional environmental damage due to mining, extraction, and purification processes that rely on energy consumption and production of industrial wastes.

Recycling strategies are essential to mitigate these issues. Still, global recycling of LIBs is about 10%, meaning that the remaining 90% ends up in landfills, making valuable materials unrecoverable. This situation needs to change because natural lithium reserves alone cannot support the foreseeable future demand. The growth of the electric vehicle (EV) market, which intends to replace conventional internal combustion engine vehicles (ICE), will drive this demand. EVs have significantly lower emissions than ICEs, particularly when the charge relies on renewable energy sources.

Despite their advantages, LIBs present different environmental impacts, especially during production and at the end of their life cycle. Recycling, in combination with renewable energy sources, can



	A	B	C	D
■ carbon footprint	0.0259	0.026	0.0174	0.022
■ water footprint	0.024	0.0246	0.0168	0.0258
■ ecological footprint	0.0251	0.0252	0.0173	0.0237

Figure 6.3: Environmental Impact indices for four types of Lithium Battery (Gong et al., 2018)

reduce the environmental footprint of the LIB industry. Recycling mainly protects the environment in two ways by reducing the dependence on mining and refining, which minimises the amount of waste that is often toxic or non-biodegradable.

Clean and efficient energy sources are necessary to decarbonise the economy and reduce greenhouse gas emissions. Charging batteries during high production hours to discharge them during periods of higher demand will be possible with such systems. Life Cycle Assessment (LCA) of LIBs is a powerful tool in the product development phase to identify potential hazards, environmental impacts, and relevant stages in the product life cycle so that appropriate measures can be adopted at each stage. Interactions are shown between the different phases, considering their normal lifespan flow, as well as new possibilities that recycling and second-life utilisation bring to the life cycle assessment (Costa et al., 2021).

Figure 6.3 shows the environmental impact of 4 types of Lithium batteries namely, A ($LiFePO_4$/C), B ($LiFe_{0.98}Mn_{0.02}PO_4$/C), C ($FeF_3(H2O)_3$/C) and D ($LiMn_2O_4$/C) (Gong et al., 2018).

The environmental impact of battery products has become increasingly important, given the global concern for reducing greenhouse gas emissions and protecting the environment. In this section, we compare the environmental performance index of four battery products and analyse their environmental impact. Fig. 2 presents the comparison of the four battery products. The higher the index value, the lower the corresponding environmental performance is (Gong et al., 2018).

Among the four battery products, the C battery has the smallest carbon footprint, water footprint, and ecological footprint index values, as shown in Fig. 3. This indicates that the synthesis technology for the C battery is the most simple and environmentally friendly, with minimal carbon, water, and energy consumption. The novel cathode carbon-metal fluoride composite material of the C battery was prepared through mechanical milling with acetylene black, using non-polluting raw materials and synthetic processes, as depicted in Fig. 1.

In contrast, the A and B battery index values are relatively large, implying that the synthesis technology for these two types of batteries is more complex, requiring more raw materials. The D battery index value is relatively small compared to the A and B batteries. This is likely due to the environmental impact of the iron contained in the raw materials of the A and B batteries during the early production process. Moreover, the B battery index value is maximal, although the synthesis process of the other two batteries is not very different. The manganese in the raw materials of the B battery also has an influence on the environment (Gong et al., 2018).

When synthesising 1 kg of battery material, the A battery has the greatest impact on human health, ecosystems, and natural resources. The environmental disadvantage of this material is quite apparent. Therefore, reducing the use of heavy metals and hazardous materials and exploring alternative green new materials are critical directions for future lithium-ion battery technology development (Gong et al., 2018).

6.1.6. Legal Factors

The legal implications of lithium mining are complex and varied across different countries. In many cases, governments have significant control over the extraction of lithium resources, either through state-owned enterprises or private firms operating under presidential decree. For example, in Chile, the exploitation of lithium deposits is restricted to the state, its enterprises, or private firms authorized by presidential decree. US-based Albemarle Corporation and Chile's Sociedad Química y Minera de Chile S.A. (SQM) are the two companies responsible for lithium exploitation in Chile.

Foreign investment in the extraction of lithium resources is also subject to various legal considerations. Some countries, such as Argentina, have established legal frameworks for the acquisition of exploration and extraction rights, while others, like China, may restrict foreign investment for national security reasons. In Australia, the federal government has tightened the screening of foreign investment in critical minerals like lithium on national security grounds.

While international trade agreements limit the imposition of export restrictions or domestic content requirements, countries may be tempted to invoke self-judging exceptions for essential security interests, particularly in the context of energy security and supply chain security for critical minerals. Legal disputes arising from lithium mining operations may also involve considerations of human rights, environmental protection, and the rights of indigenous peoples, which offer a legal framework for supply chain justice. Investor-state arbitration of lithium disputes must consider relevant obligations of the host state and the multifaceted agenda of supply chain justice, rather than merely value deprivation or investor expectations (Hailes, 2022).

6.1.7. Competitive demand for Lithium

Figure 6.4 shows that there is no competition for Lithium among renewable technologies, meaning that the growth in other renewable technologies will not affect the supply of Lithium for EVs. However, Lithium is used in various industries, including electronics, energy storage, transportation, and medicine. In recent years, the demand for lithium has grown rapidly, and the sector has become highly competitive.

The electronics industry is one of the major consumers of lithium. Lithium is used in batteries for smartphones, laptops, and other portable devices. With the increasing popularity of electric vehicles, the demand for lithium-ion batteries has also increased, driving up demand for lithium. In addition, the growing renewable energy sector has created demand for lithium-ion batteries to store energy from solar and wind power.

The transportation sector is another major consumer of lithium. Electric vehicles are becoming increasingly popular as countries seek to reduce their carbon emissions and move towards more

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium
Solar PV	🔴	🔵	🔵	🔵	🔵	🔵	🔵	🔵	🔴
Wind	🔴	🔵	🟡	🔵	🔴	🟡	🔴	🔵	🟡
Hydro	🟡	🔵	🔵	🔵	🔵	🟡	🟡	🔵	🟡
CSP	🟡	🔵	🟡	🔵	🔵	🔴	🟡	🔵	🔴
Bioenergy	🔴	🔵	🔵	🔵	🔵	🔵	🟡	🔵	🟡
Geothermal	🔵	🔵	🔴	🔵	🔵	🔴	🔵	🔵	🔵
Nuclear	🟡	🔵	🟡	🔵	🔵	🟡	🔵	🔵	🔵
Electricity networks	🔴	🔵	🔵	🔵	🔵	🔵	🔵	🔵	🔴
EVs and battery storage	🔴	🔴	🔴	🔴	🔴	🔵	🔵	🔵	🔴
Hydrogen	🔵	🔵	🔴	🔵	🟡	🔵	🔵	🔴	🟡

Relative importance of minerals for a particular clean energy technology: High: 🔴 Moderate: 🟡 Low: 🔵

Figure 6.4: Competitive Demand for metals within different types of Renewable Technologies (International Energy Agency, 2022)

sustainable modes of transportation. Lithium-ion batteries are used in electric vehicles, making them a critical component of the transportation sector.

The medical industry is also a consumer of lithium. Lithium is used as a treatment for bipolar disorder and other mental health conditions. The demand for lithium in the medical sector is relatively small compared to other sectors, but it remains an important demand sector. The primary demand sector for Lithium will continue to be EVs in the future (Gong et al., 2018).

6.2. Criticality Analysis of Cobalt

The use of electric vehicles is being increasingly advocated as a necessary step in making society greener. Various countries, including China, Germany, and other European governments, have set targets to increase the production and use of electric vehicles. Lithium availability has been a material of concern and study, but cobalt is also needed in the batteries and has a long history of supply disruption, so its availability is a concern as well.

Moreover, lithium-ion battery use is not limited to electric vehicles. Personal electronic devices and power storage needed with renewable energy sources (wind and solar) are also growing areas of consumption of lithium-ion batteries. The cobalt market, which has a history of supply problems, is still facing supply crises after 40 years, as per a recent report.

Concerns have increased about the ability of the producers of cobalt to meet the needs of a potentially rapid increase in the production of electric vehicles and other battery uses. Cobalt is mostly produced as a byproduct of nickel and copper mining, and cobalt production is largely driven by the market for those two metals and not cobalt's market. Cobalt has a sizeable amount of production occurring in the Democratic Republic of the Congo, which is politically unstable and has ethical source concerns about its production.

Several factors drive this growing concern about the risk of limited cobalt supply availability. The increasing demand for cobalt in lithium-ion batteries used to power electric vehicles is one such factor. Cobalt is included on China's list of critical minerals due to its use in lithium-ion batteries, as has the

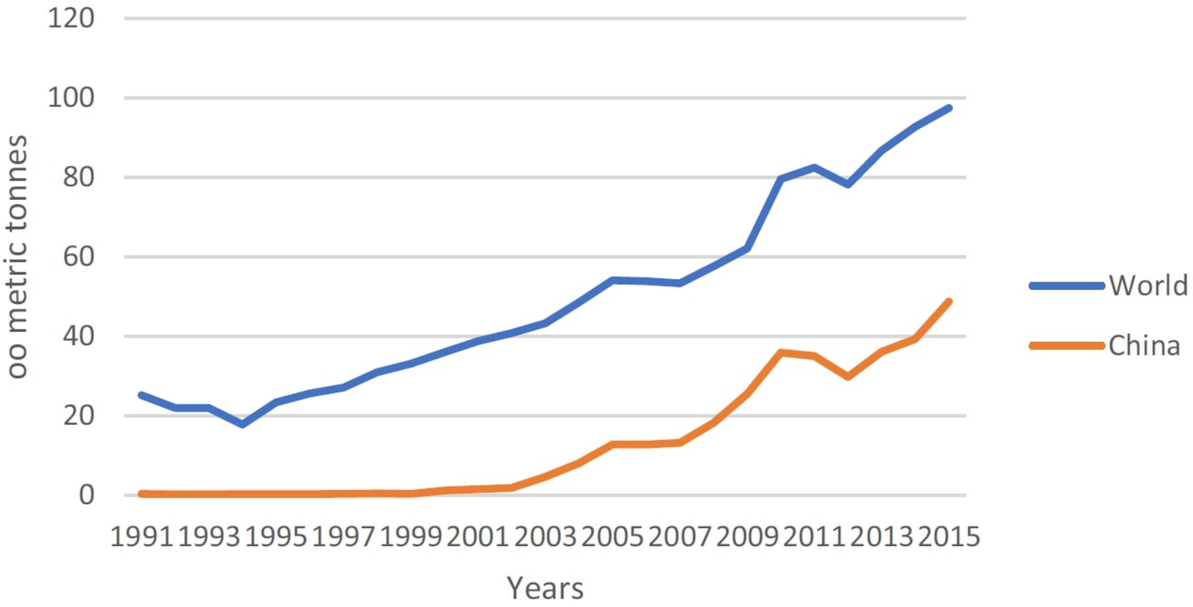


Figure 6.5: Comparison of Global and Chinese Cobalt Refinery Shares (Campbell, 2020)

United States government. Past studies by the European Union have found cobalt to be a critical mineral, but with most of the concern being on economic importance (price) and less on supply risk (Li et al., 2022).

6.2.1. Political Factors

The Democratic Republic of Congo (DRC) plays a vital role in the global supply of cobalt, providing 60 percent of the world's supply. China has made significant strides in the DRC's cobalt mining market over the past fifteen years, buying out European and North American companies and now controlling a majority of the cobalt mines in the southern DRC. As of 2020, fifteen out of the nineteen cobalt-producing mines in Congo were owned or financed by Chinese companies. This has resulted in China having control over 70 percent of the DRC's cobalt.

The world's increasing demand for metals used in clean energy technologies, such as lithium, graphite, cobalt, and rare-earth metals, is staggering. The Paris Agreement goals necessitate producing 42 times more lithium, 25 times more graphite, 21 times more cobalt, and 7 times more rare-earth metals in 2040 compared to 2020. This highlights the importance of secure and sustainable supply chains for these minerals.

China's influence in the DRC's cobalt mining industry is undeniable. In October 2019, China's GEM Co. signed a 5-year sales agreement with Glencore, through which it would purchase a minimum of 61,200 tons of cobalt between 2020 and 2024. China has also established a 35-member Union of Mining Companies with Chinese capital and the blessings of both the PRC and DRC governments, securing its position of influence over the industry to ensure that it remains the dominant actor in cobalt mining there. China is also the leading supplier of cobalt imports to the US and the world's leading consumer of cobalt, with more than 80 percent of its consumption used by the rechargeable battery industry. This can be seen in Figure 6.5 above.

Although Australia is capable of providing some level of diversification of supply, cobalt production there was only 5,100 tons in 2019, compared to the DRC's output of 100,000 tons. This makes the DRC the most critical player in the sourcing of the mineral and a hot-spot of contention. The world's increasing demand for cobalt, coupled with China's domination of the market, has led to concerns about the sustainability and ethics of cobalt mining in the DRC. There is a pressing need for responsible and sustainable mining practices to ensure a secure and ethical supply of the mineral for the clean energy technologies of the future (Li et al., 2022).

6.2.2. Economic Factors

There are different ways to classify supply risk for cobalt, but two general reasons for inadequate cobalt supplies exist. One is a ”burning out” of physical cobalt availability caused by a decline in output due to production costs and technological limitations or an unexpected rise in demand without a corresponding increase in supply output.In an attempt to measure this risk for materials in lithium-ion batteries found that cobalt supply reduction risk was modest. Geological evidence suggests that there is an adequate supply of cobalt resources to meet future demands (Gautneb et al., 2019). However, the risk of supply not being able to meet an increase in demand due to by-product dependence, future demand trends, and substitution is much higher. The by-product nature of primary cobalt production poses a significant risk to supply availability since it depends on copper and nickel production, rather than the cobalt market itself. During 2000-2016, cobalt consumption grew at a much faster rate (over 8% annually) than copper (2.5%) or nickel (3.9%) consumption (Gulley et al., 2019). Despite this growth, the physical availability of cobalt did not pose a major concern.

Despite the slower growth rate for copper and nickel, cobalt production has been able to increase due to technological advances and better recovery rates from nickel laterite ores in the DR Congo. The availability of stockpiled cobalt materials and an increase in artisanal cobalt mining in the DRC also contributed to the growth. However, it is unclear how much more growth can be achieved through these methods, and there are uncertainties about the availability of cobalt from ocean resources. There is a concern that the demand for cobalt in lithium-ion batteries for electric vehicles may outpace production due to its by-product nature. If this were to happen, there could be a short-term adjustment crisis with a sharp price spike, but the market could adjust over time with higher prices. The political instability of the DRC raises ethical concerns about using cobalt materials mined in the region, and there are several possible market responses to price spikes and supply risk, including seeking new sources of cobalt, developing new technologies, finding substitutes for cobalt, and creating and keeping inventories and stockpiles.

The market price has replaced the 1978 producer's price, and the market has diversified in the supply of cobalt due to technical advancements in processing, some new sources, more artisanal mining, and more secondary recovery since 1978. However, this gain in supply has been offset by rising consumption of cobalt, leaving the overall dependence on the DR Congo for cobalt largely unchanged. The market price fluctuation for Cobalt is shown in Figure 6.6 below.

Ownership of the cobalt resources in the DR Congo has broadened since 1978, and the firm concentration for cobalt is not particularly high relative to other metal markets. Private firms still must face the risk of interacting and negotiating with the DR Congo government though. In 2018, the government of the Congo declared cobalt a ”strategic” material, and the government's tariff has risen from 2 to 10%. The market diversification in cobalt supply has not kept up with the growth of cobalt demand. The end use of cobalt has become less diverse as the use of cobalt in lithium-ion batteries has come increasingly to dominate the end-use market.

The cobalt markets of 1978 and 2018 are similar in that the supply of cobalt is by-product based and dependent on the DR Congo. However, the potential is there for a significant change in the dynamics of the cobalt market from its situation over the last 40 years. If there is a large shift to electric vehicles requiring lithium-ion batteries, there could be a large rise in consumption for cobalt largely based on one end use. This demand could exceed the amount of cobalt that could be produced as a

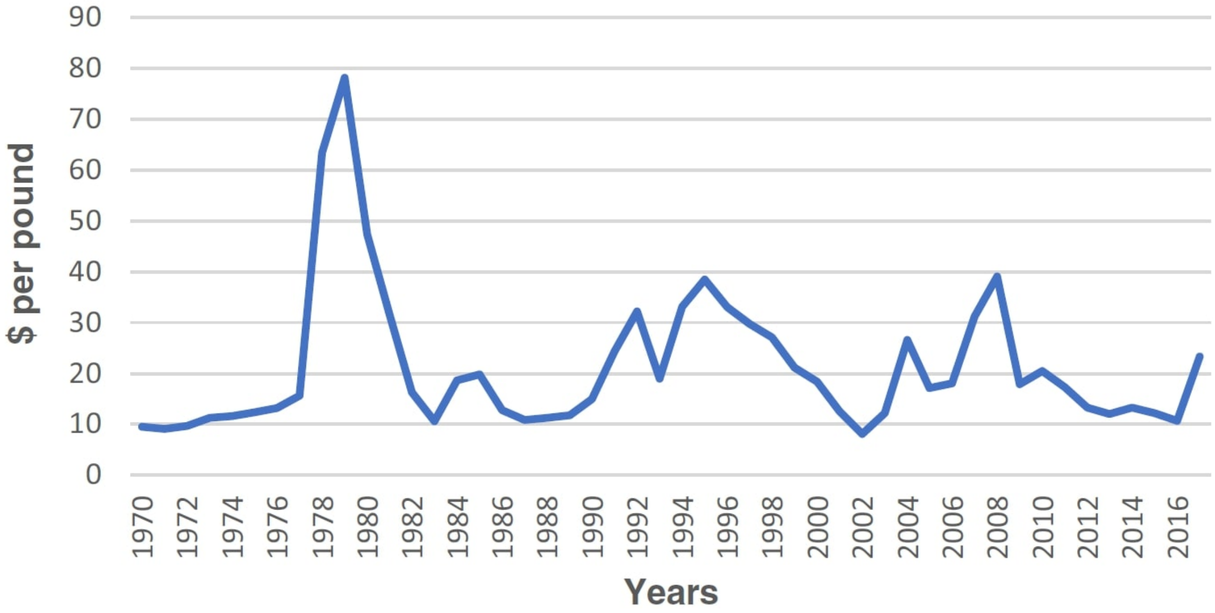


Figure 6.6: Cobalt Prices over the years (Campbell, 2020)

by-product of copper and nickel mining. One possible response to this is to increase potential cobalt supplies through deep-sea mining if such mining becomes commercial but this option is uncertain about its likelihood and timing.

Over the 40 years since the cobalt market crisis of 1978, market adjustments have occurred as predicted by economic theory. However, the market signal to make these adjustments (long-run price trend) has not been strong enough to offset significantly the cobalt market characteristics that largely drive its market behavior: by-product supply and the large amount of low-cost material in the DR Congo, and the technical advantages of using cobalt in its applications over potential substitutes.

In 2018, the demand for cobalt is changing and that change seems poised to accelerate. China's (and other countries) large bet on electric vehicles is the key driving force for this change. The demand for cobalt is moving toward a dominant use (lithium-ion batteries) that could grow rapidly and is not particularly linked to the markets of copper and nickel that are the main sources of cobalt. Other non-by-product sources of cobalt are not adequate to make much of a difference in supply (although increased recycling would be a help). Commercial deep-sea mining offers the potential for an increase in the supply of cobalt in the future, but this source of cobalt is also by-product dependent on the other metals in the raw material and may not be that responsive to cobalt market conditions either (Campbell, 2020).

6.2.3. Social Factors

Extractive activities, such as mining, have a significant impact on natural habitats both within and outside the mining lease. Mining infrastructure built to access and transport the ore creates large corridors that expand the disturbance beyond the mining area. This poses risks to critical biodiversity preservation areas that are not currently under strict legal protection, leaving them potentially exposed to mining development and other human land uses.

People living or working in the vicinity of a mining project are the key stakeholders and bearers of social risk. People who were present before the mine's development have had to make way and adapt to mining-induced social, economic and environmental changes. The European Commission's

Global Human Settlement Layer is used to assess the population density value in direct proximity to the mining project, providing an indication of the presence of directly affected communities. In addition, population density in a 100 km buffer around the mine is assessed to account for indirect or chronic impacts in the wider area of influence. Some social groups are affected more than others, and indigenous peoples often experience higher levels of poverty, marginalisation and discrimination, while maintaining deep spiritual, cultural and sometimes legal ties to their land. The location of a mine on indigenous land adds a degree of complexity to the social context and involves additional risks during the land access and acquisition process and throughout project expansion.

The Democratic Republic of Congo (DRC) has been the focus of media attention as the dominant producer of cobalt, a key mineral used in rechargeable batteries for electronic devices. This attention was heightened following a 2016 Amnesty International report that raised questions about the ethical mining practices employed in the country (Amnesty International, 2016). The report exposed the harsh realities of the mining industry in the DRC, where thousands of artisanal miners, including children, work without safety precautions to extract cobalt from deep within the earth. These miners work long hours in hazardous conditions, often for meagre wages, and are exposed to various health hazards, including lung diseases, due to the lack of protective equipment and poor ventilation.

The plight of the artisanal miners in the DRC highlights the need for a concerted effort to ensure that the mining industry operates ethically and responsibly. It is important to ensure that workers in the sector are protected from harm and are not subjected to exploitative practices. Moreover, given the critical role that cobalt plays in powering electronic devices, there is a growing need to promote sustainable practices in the mining sector to reduce the environmental impact of mining activities. Efforts to address these issues will require a collaborative approach involving governments, the private sector, civil society, and international organizations (Lèbre et al., 2020).

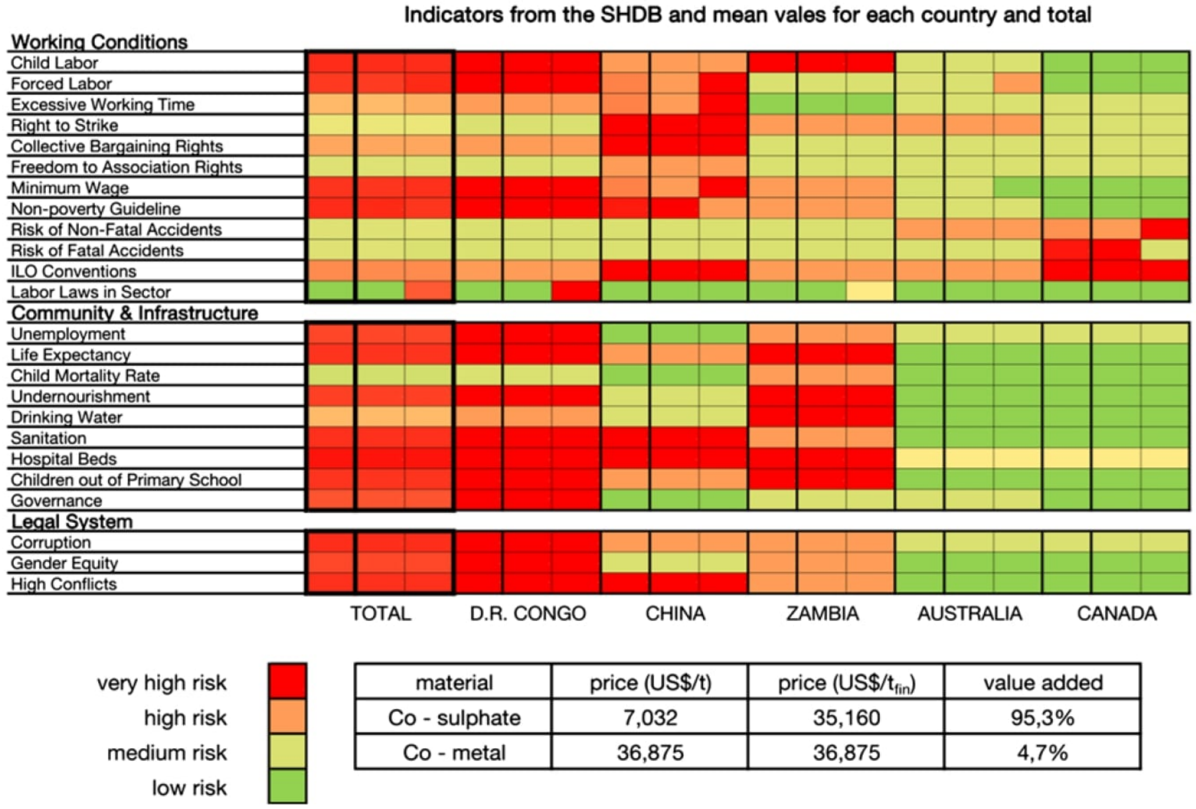
Hence, The cobalt situation is the most concerning among the materials studied due to several reasons. Firstly, a significant portion of the global cobalt value is produced in one country, the Democratic Republic of Congo (DRC). Unfortunately, the DRC has very low living conditions as reflected by its 176th out of 188 ranking on the Human Development Index according to the UN. Additionally, the Social Hotspots Database reports high or very high risks of negative social conditions for most economic sectors, particularly for child and forced labor, insufficient wages, and the legal system. The armed conflict in the DRC and the risks associated with conflict minerals entering the supply chain are also serious concerns. The social risk profile sheet for cobalt, shown in Figure 6.7, presents the most alarming results among all the materials studied (Reuter, 2016).

6.2.4. Technological Factors

It is commonly believed that cobalt is necessary in battery production to balance the charge and reduce the negative effects of manganese, which can cause nickel formation and impede lithium diffusion. The below Figure 6.8 shows the weightage of Cobalt in different battery chemistries.

However, researchers have found that alternative materials like aluminum, magnesium, and manganese can provide similar benefits to cobalt, particularly in stabilizing high-nickel cathodes.The prevailing belief is that Co^{3+} is essential for charge balancing to alleviate the negative effect of Mn^{4+} in inducing Ni^{2+} formation. Ni^{2+} has a tendency to occupy the Li^{+} site, which results in Li/Ni mixing. This mixing of lithium and nickel blocks lithium diffusion pathways, and slows the charge/discharge kinetics.

Due to this issue, researchers have been making efforts to replace Mn4+ with Al3+. The substitution of Mn4+ with Al^{3+} offers some of the same benefits as Co^{3+} in reducing Li/Ni mixing, enhancing charge/discharge rate capability, improving thermal stability, and lowering surface reactivity.Recent research has shown that cobalt-free cathodes with high energy density and durability can be achieved



material	price (US\$/t)	price (US\$/t_{fin})	value added
Co - sulphate	7,032	35,160	95,3%
Co - metal	36,875	36,875	4,7%

Figure 6.7: Social Impact Analysis of Cobalt (Reuter, 2016)

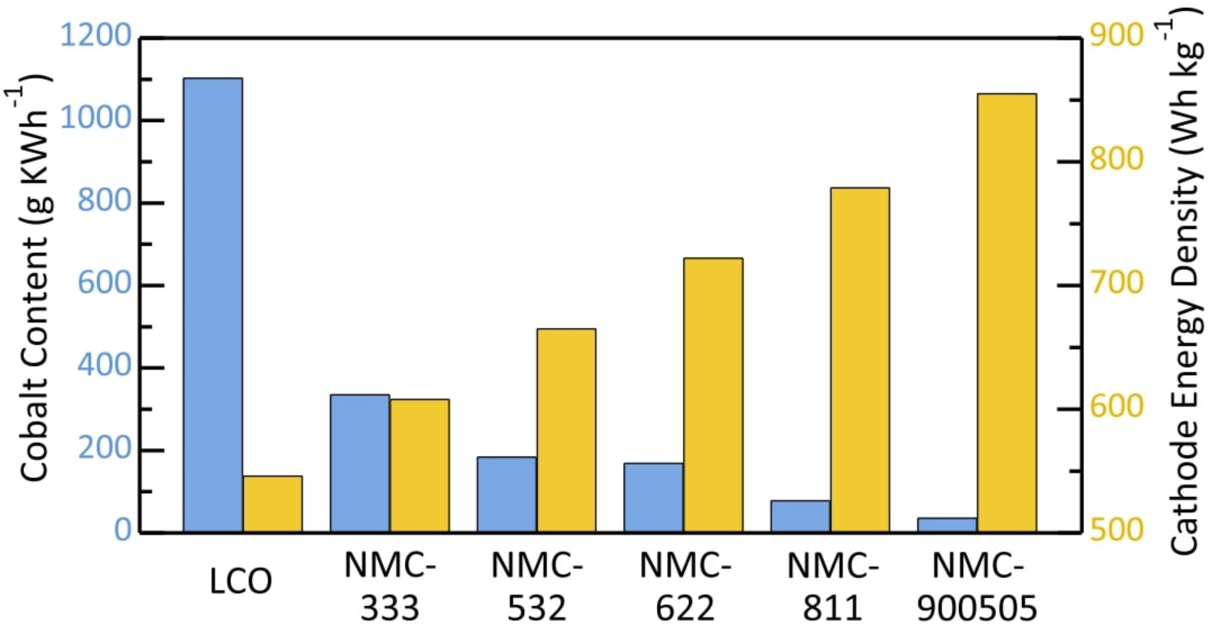


Figure 6.8: Energy density and cobalt content of typical layered oxides (S. Lee and Manthiram, 2022)

by doping nickel with manganese, aluminum, and magnesium, and by using titanium to create a protective surface coating. These cobalt-free cathodes offer a promising low-cost alternative to traditional cobalt-containing cathodes in the EV battery market (S. Lee and Manthiram, 2022).

6.2.5. Environmental Factors

Mining projects involve massive material movements, creating waste stocks and mining voids, which are the primary cause of direct land disturbance. Tailings storage facilities can occupy almost half of the disturbed land area, while waste rock dumps and voids, including open pits and underground workings, occupy the rest. To minimise the impacts of mining activities on the environment, mine owners are responsible for rehabilitating disturbed areas and effectively containing or neutralising polluting substances. However, natural conditions surrounding mine sites, such as reactive substances within unearthed material and void walls, pose challenges to the design, construction, and maintenance of waste facilities and mining voids. Wind, rain, and oxygen can favour their reaction and the diffusion of pollution through dust or acid drainage, requiring long-term containment and structural integrity of waste facilities. In some cases, a tailings dam failure can cause significant impacts on local communities and ecosystems due to multiple causes, including human and management errors and external factors such as heavy rains and earthquakes (S. Lee and Manthiram, 2022).

The Katanga Province in the DRC is one of the world's largest cobalt-producing regions where the nearby rivers and groundwater have been polluted, leading to soil and water contamination. Cobalt mining in Bou Azzer, Morocco, has caused significant environmental damage. The mining activities have led to soil erosion and degradation, deforestation, and water pollution. The mining activities in Cobalt, Ontario, Canada, have caused significant environmental damage. The mining waste has polluted nearby water resources, leading to the contamination of fish and other aquatic life (S. Lee and Manthiram, 2022).

Mining and mineral processing activities at mine sites usually require high fresh water usage. Fresh water is high-quality water suitable for human consumption or that requires minimal treatment to make it suitable for human consumption. However, accessing fresh water can be challenging in water-scarce contexts or where competing water uses exist. Poor mine water management, including high water withdrawal, low water reuse rates, and discharge of contaminated water, can significantly impact local water resources and surrounding ecosystems and communities. Therefore, efficient mine water management is crucial to minimise the impact of mining activities on water resources and ecosystems. Overall, the mining industry must prioritise sustainable mining practices, including waste and water management, to reduce the environmental impact of mining activities and ensure the long-term viability of the industry (S. Lee and Manthiram, 2022).

6.2.6. Legal Factors

In recent years, there have been significant changes in the laws governing mining activities, particularly in resource-rich countries such as the Democratic Republic of Congo (DRC). In March 2018, the DRC signed a new law that increased taxes on mining companies and doubled government royalties from the mining industry. The new law was aimed at generating more revenue for the government and ensuring that the country's natural resources were being used to benefit its citizens.

However, such laws have been a cause of tension between countries that are sites of production and those wishing to access resources and clients. For instance, a 2020 study by the OECD (Organisation for Economic Co-operation and Development) analyzing global export restrictions on industrial raw materials from 2009 to 2019 reported that metals such as copper or cobalt have consistently been the object of export restrictions during this ten-year period in nations such as China, Indonesia, Argentina, the DRC, and even Zambia. This indicates a growing trend where the balance of power is no longer systematically in favor of the latter, but increasingly in favor of the former.

Moreover, the issue of child labor in the mining industry has drawn attention to the need for reforms in the sector. In response to the outcry over child labor, a new mining code raised royalties for cobalt in the DRC from 2 to 10 percent in 2018, causing an uproar among foreign investors. This move was aimed at ensuring that mining activities were carried out in a responsible and sustainable manner, and that the country's resources were being used to benefit its people (Prause, 2020).

The secure supply of various metals is crucial for the energy transition, which currently requires the opening up of new mining regions until recycling processes are improved. The Global South is where many essential raw materials for the energy transition are mined, leading to conflicts around the expansion of the mining frontier. The production of cobalt is closely linked to conflicts arising from the energy transition, specifically the electrification of the transport sector. The increase in demand for cobalt for lithium-ion batteries has caused an expansion of industrial and artisanal cobalt mining in the Democratic Republic of Congo (DRC), leading to physical, economic, and social transformation of copper-cobalt mining areas and sparking conflicts (Prause, 2020).

Two types of conflicts have been identified in the DRC related to cobalt mining: conflicts between artisanal miners and industrial companies over access to artisanal mining sites and conflicts between local host communities and industrial mining companies over the distribution of benefits derived from industrial mining. Conflicts related to cobalt mining are not limited to the DRC; international NGOs are also initiating campaigns for responsible sourcing of minerals and demanding due diligence from car manufacturers. The different struggles related to cobalt mining are connected, especially around the distribution of mining profits and stopping human rights violations perpetrated by multinational mining companies. Artisanal mining is a key source of livelihood in the DRC, leading to defensive struggles around access to land for artisanal mining, while due diligence campaigns advocate the regulation and formalization of artisanal mining to end child labor (Prause, 2020).

The energy transition is linked to conflicts around the raw materials required for green technologies, with different actors involved, including protest actors contesting the expansion of industrial mining in the Global South and NGOs and social movements in the Global North. These actors can exert pressure on companies and states within the global production network to shape changing relations of production related to the energy transition (Prause, 2020).

6.2.7. Competitive Demand

Figure 6.4 shows that among the renewable technologies, there is no competition for consumption of Cobalt as it is relatively important only for EVs and battery storage technologies. However, Cobalt is a crucial metal used in various industries, including aerospace, defense, energy, and transportation. The demand for cobalt has increased significantly in recent years, primarily due to the growing popularity of electric vehicles (EVs) and rechargeable batteries. The following text discusses the different demand sectors for cobalt (Alves Dias et al., 2018).

The battery sector is the most significant demand sector for cobalt, accounting for approximately 60% of the global cobalt demand. Cobalt is a crucial component in the production of lithium-ion batteries, which are used in a wide range of applications, including EVs, laptops, smartphones, and other electronic devices. The high energy density and stability of cobalt make it an ideal material for battery production.The transportation sector is another significant demand sector for cobalt. Cobalt is used in the production of automotive parts and components, including gears, bearings, and superalloys. The demand for cobalt in this sector has increased significantly due to the growing popularity of EVs and hybrid vehicles (Alves Dias et al., 2018).

The aerospace sector is another significant demand sector for cobalt. Cobalt is used in the production of jet engine turbines, where its high-temperature strength and resistance to corrosion make it an ideal material. Cobalt alloys are also used in the production of aircraft parts and components due to their high strength and durability (Alves Dias et al., 2018).

The defense sector is another significant demand sector for cobalt. Cobalt is used in the production of missile and rocket parts, as well as in the production of armor and ammunition. Cobalt alloys are also used in the production of helicopter and fighter jet parts due to their high strength and heat resistance (Alves Dias et al., 2018).

The energy sector is another significant demand sector for cobalt. Cobalt is used in the production of gas turbines and steam turbines due to its high-temperature strength and resistance to corrosion. Cobalt alloys are also used in the production of nuclear reactor parts due to their high resistance to radiation (Alves Dias et al., 2018).

6.3. Criticality Analysis of Nickel

Nickel, a versatile and abundant transition metal, plays an indispensable role in the production and performance of electric vehicles. Its application spans across various components, from rechargeable batteries to electric motors, power electronics, and charging infrastructure. As governments and industries alike continue to accelerate the transition towards EV adoption, understanding the criticality of nickel within this context becomes paramount. This section delves into the intricate realm of criticality analysis for nickel in the context of electric vehicles using the analysis model.

6.3.1. Political Factors

There are two primary types of nickel products: high-purity Class 1 products and lower-purity Class 2 products. Class 1 products contain 99.8% nickel or above and are used in the synthesis of nickel sulfate, which is essential for battery cathodes. The relationship between different resource types (sulfide, saprolite, and limonite) and product types is complex.

Sulfide deposits, which have been the main source of nickel supply for over a century, are primarily located in Russia, Canada, and Australia. These deposits contain relatively high-grade nickel ore, typically ranging from 0.4% to 3.2%. On the other hand, oxide resources, known as laterites, such as saprolite and limonite, are mainly found in Indonesia, the Philippines, and New Caledonia. Laterite resources are formed through weathering in a high-temperature and humid climate. This is shown in Figure 6.9 below.

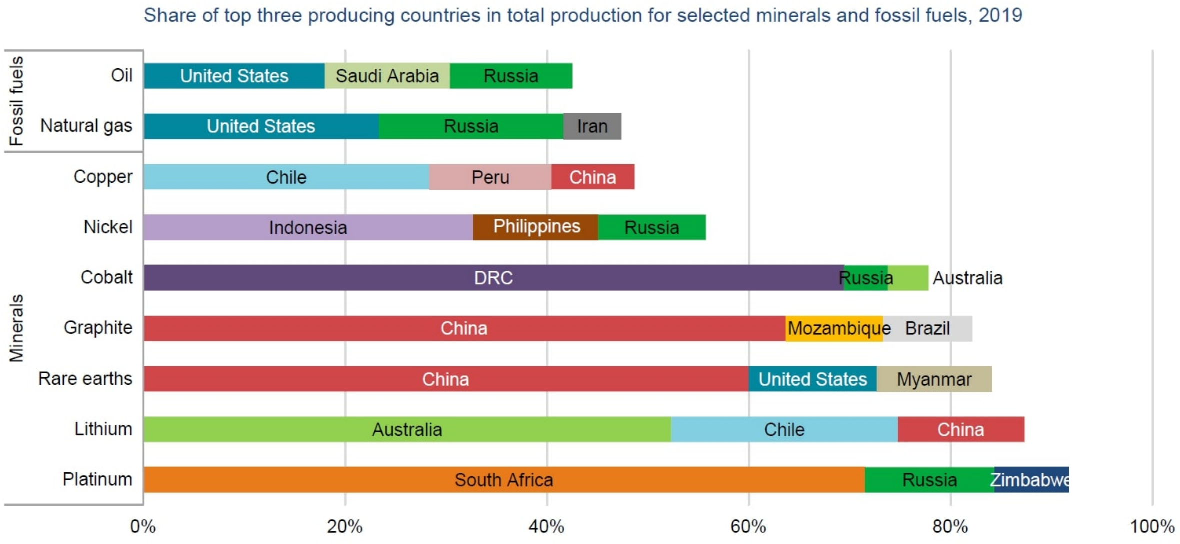


Figure 6.9: Share of top three producing countries for selected critical metals, (International Energy Agency, 2021)

China plays a significant role in the refining and processing of nickel. It accounts for approximately 35% of global nickel refining, and its involvement extends to Indonesian operations as well. Chinese companies have a strong presence in the nickel industry, with a high level of concentration in refining and processing operations as shown in Figure 6.10 below.

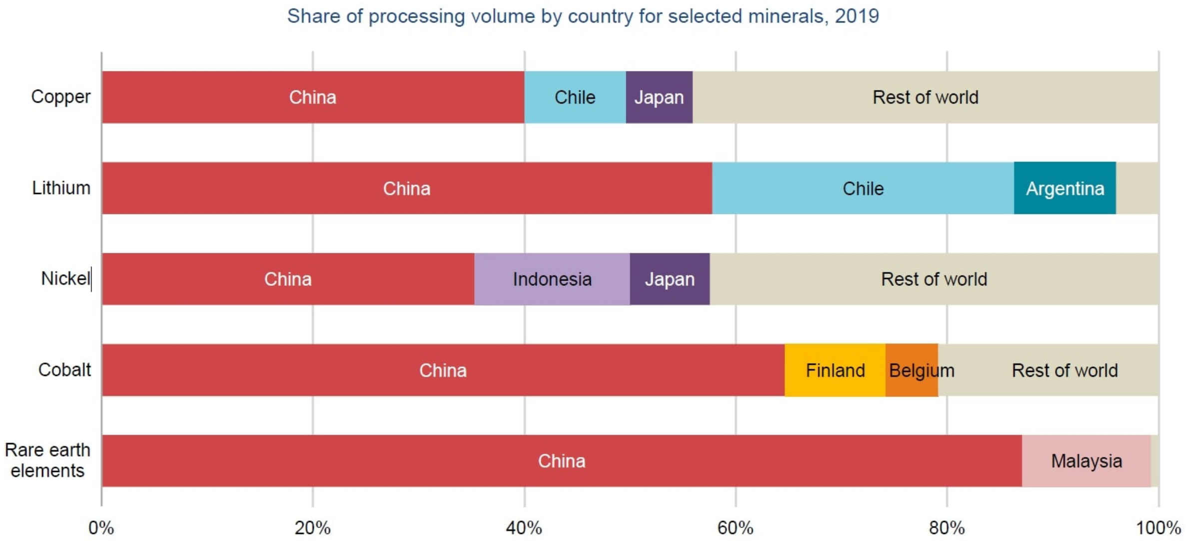


Figure 6.10: Share of processing countries for selected critical metals, (International Energy Agency, 2021)

Global nickel production has seen a 20% increase in the past five years, primarily driven by expansion projects in the Asia Pacific region, particularly Indonesia and the Philippines. These two countries currently represent 45% of global nickel output. Looking ahead, their dominance in nickel production is expected to intensify, contributing to around 70% of global production growth until 2025. Indonesia alone accounts for about half of this growth. However, other projects outside Indonesia, such as the Kabanga project in Tanzania and the Wingellina project in Australia, are also being planned.

This suggests that the future supply of nickel will heavily depend on developments in Indonesia. Any physical events or policy changes in Indonesia could significantly impact global nickel supply chains. In 2020, Indonesia implemented an earlier-than-expected ban on nickel ore exports, redirecting its focus to processing ore domestically instead of exporting to China. This led to a sharp decline in nickel ore exports to China and an increase in nickel pig iron exports. Chinese refiners had to seek new sources of ore supply from the Philippines or New Caledonia and also explore investment opportunities in Indonesia. Chinese companies have invested approximately USD 30 billion in the Indonesian nickel supply chain, with notable examples being Tshingshan's investments in the Morowali and Weda Bay industrial parks (International Energy Agency, 2021).

6.3.2. Economic Factors

The historical view of nickel prices, as depicted in Figure 1, reveals distinct patterns and fluctuations. From 1990 to 1996, the price of nickel underwent a relatively smooth fluctuation process, ranging from $4,376 to $10,957 per ton. However, the Asian financial crisis in 1997 had a significant impact, leading to a continuous and substantial decline of 51% and indicating a bubble characteristic in the market. With the subsequent economic recovery, the price started to exhibit a flat upward trend (X. Q. Wang et al., 2023).

Driven by the boom in stainless steel production, the price of nickel embarked on a sustained

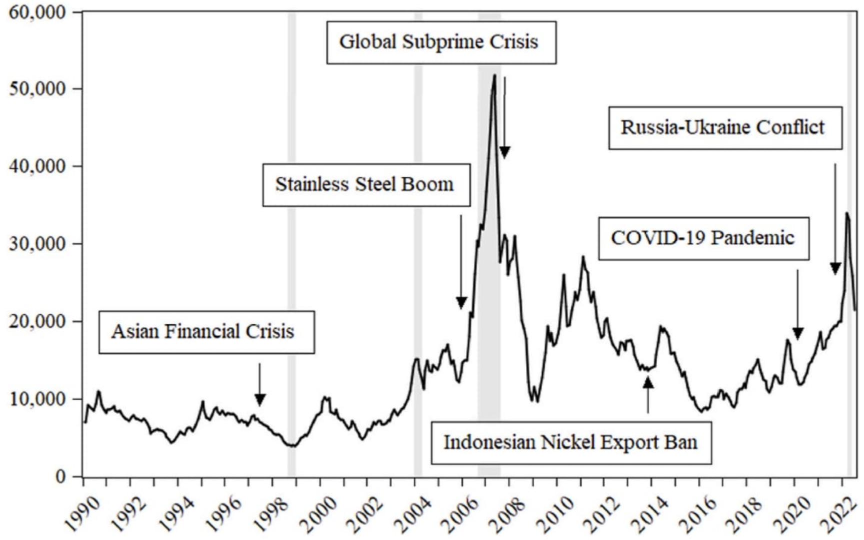


Figure 6.11: Price Fluctuation of Nickel From 1990 to 2022 in USD (X. Q. Wang et al., 2023)

and massive rally, eventually reaching a remarkable all-time high of $51,783 per ton in May 2007. This phase represented an explosive bubble cycle. However, the global subprime crisis that followed caused the price to plummet by 81%. Subsequently, from 2009 to 2014, the price experienced a highly oscillating process.

After a temporary decline in 2015, the nickel price initiated a continuous and substantial upward movement, characterized by high volatility. This rise was influenced by various external events, including the COVID-19 pandemic and the Russia-Ukraine conflict.

Supply and demand factors, along with geopolitical shifts, have gained significant influence in the dynamics of the nickel market, which are profoundly impacted by changes in geopolitics due to the high dependence on key mineral resources. The demand for nickel is experiencing rapid growth driven by the decarbonization target of the energy system, while resources continue to become scarce. Nickel resources, which were previously not prominently considered in diplomatic decision-making, are now increasingly becoming the focal point of strategic competition. Major economies are placing great importance on the security of critical minerals and strengthening their control over nickel resources. Geopolitics significantly contribute to the additional volatility of the nickel market, especially in unstable bilateral and multilateral relations, posing the risk of supply interruptions. The geopolitical conflict between Russia and Ukraine has intensified the fluctuation of nickel prices (X. Q. Wang et al., 2023) , (International Energy Agency, 2021).

6.3.3. Social Factors

Indonesia, as one of the largest nickel-producing countries globally, has faced concerns regarding labor practices in small-scale nickel mining operations. Specifically, there have been reports highlighting issues such as child labor and forced labor. These concerns shed light on the need for improved labor standards and practices within the Indonesian nickel industry.

Similarly, the Philippines, another significant player in the nickel production sector, has also faced reports of labor abuses. The industry has been associated with hazardous working conditions and inadequate pay, raising concerns about the well-being and safety of workers. These labor abuses emphasize the importance of ensuring fair and safe working environments in the Philippine nickel mining operations.

In New Caledonia, labor abuses have been reported in nickel mining operations as well. Workers have faced unsafe working conditions, inadequate remuneration, and the exploitation of migrant labor. These concerns highlight the need for better labor protections and fair treatment of workers within the New Caledonian nickel industry.

In Russia, there have also been reports of labor abuses within the nickel mining sector. These include the use of forced labor and unsafe working conditions, which raise significant ethical and humanitarian concerns. It is essential to address these issues and prioritize the well-being and rights of workers in the Russian nickel mining industry.

Overall, labor abuses in the nickel mining operations of Indonesia, the Philippines, New Caledonia, and Russia highlight the importance of ensuring fair and safe working conditions, protecting workers' rights, and eliminating exploitative labor practices throughout the global nickel supply chain. Efforts to promote responsible and sustainable mining practices should include robust labor standards and effective enforcement mechanisms to safeguard the well-being and dignity of workers in these industries (Nguyen et al., 2021).

6.3.4. Technological Factors

The advancement of lithium-ion battery technology goes beyond enhancing energy density, durability, safety, and cost. It also encompasses minimizing the environmental, social, and political costs associated with sourcing the materials used in these batteries.

In response to price spikes and concerns about ethical mining practices during the 2010s, electric vehicle (EV) producers have been actively working to reduce the reliance on cobalt in batteries. This has led to an increase in the usage of nickel in many cases. For instance, NCA (nickel-cobalt-aluminum) batteries have transitioned to NCA^+, a nickel-rich variant, while NMC (nickel-manganese-cobalt) 111 batteries have been shifting towards NMC 532, NMC 622, and NMC 811, and could potentially adopt even more nickel-rich chemistries like NMC 9.5.5. This trend of reducing cobalt content could significantly impact the demand for nickel in the battery industry International Energy Agency, 2021.

Layered lithium nickel oxide (LNO) has been explored as an alternative to lithium cobalt oxide (LCO) due to its high theoretical capacity and lower costs. However, synthesizing stoichiometric LNO with a 1:1 Li/Ni ratio is challenging as it often results in Li-deficient $Li_{1-x}Ni_{1+x}O_2$. Heteroatom doping, such as introducing elements like Co, Mn, or Al, has proven to be an effective solution to enhance the cycle stability and address synthesis issues. For instance, lithium nickel cobalt aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, NCA) can be prepared by doping Co and Al into the LNO structure. Al incorporation helps stabilize the crystal structure and improve thermal stability, while Co substitution reduces cation mixing and stabilizes the layered structure. NCA demonstrates superior structural stability and electrochemical performance. A doping amount of 5% Al is sufficient to stabilize the layer structure, and with Co (15 mol%) and Al (5 mol%), NCA achieves a discharge capacity of around 200 mAh g−1 and excellent cycling stability even at elevated temperatures.

In comparison to lithium manganese oxide (LMO), NCA is more expensive but offers advantages such as higher specific capacity (200 mAh g−1), higher energy density (>200 Wh kg−1 at the cell level), and longer life (calendar life: >15 years). It has been successfully utilized in electric vehicles, including Tesla products like Model X, Model S, and Model 3. The energy density of NCA is projected to reach 300 Wh kg−1 and 700 Wh L−1 at the cell level by 2025.

The combination of nickel manganese cobalt oxide (NMC) is a successful cathode chemistry used in the automotive battery industry. NMC, such as $LiNi_{1-x-y}Mn_xCo_yO_2$, offers similar specific capacity and operating voltage to LCO (lithium cobalt oxide) but at lower costs due to reduced cobalt content. The most common forms of NMC are NMC-111 and NMC-532. Combining nickel and manganese in NMC improves their individual characteristics, with nickel providing high energy density and manganese offering low internal resistance. NMC-based battery technology is well-suited for electric vehicle (EV) applications due to its low self-heating rate.

There is a shift towards using NMC-blended Li-ion chemistry in battery systems due to its economic feasibility and overall performance. The combination of nickel, manganese, and cobalt in varying proportions allows for versatility in automotive and energy storage applications that require frequent cycling. Currently, NMC-111, NMC-442, and NMC-532 are considered state-of-the-art cathode materials for lithium-ion batteries (LIBs). In the future, Ni-rich NMC cathodes like NMC-811 and NMC-622, which offer higher specific energy and lower costs, are expected to be adopted in the automotive industry. However, it is challenging to surpass the theoretical limitation of Ni-rich NMC, which is 350 Wh kg−1 at the cell level.

In the long run, high-voltage spinel $LiNi_{0.5}Mn_{1.5}O_4$ (HV-spinel) is a promising alternative as a high-energy cathode material for EVs. HV-spinel operates at a high voltage of 4.7 V and has a specific capacity of 130 mAh g−1, resulting in a specific energy of approximately 580 Wh kg−1 at the cathode level. HV-spinel is attractive due to its easy synthesis, low costs, environmental friendliness, good safety, and excellent rate capability. The disordered HV-spinel phase exhibits significantly higher rate capability compared to the ordered phase. However, HV-spinel faces challenges such as capacity fading at elevated temperatures and electrolyte decomposition due to its higher operating voltage. Developing a high-voltage electrolyte is crucial for the future application of HV-spinel.

Another alternative cathode material with long-term potential is high-energy NMC (HE-NMC) layered-layered composite materials, which have a general formula of $xLi_2MnO_3{\cdot}(1{-}x)LiMO_2$ (M=Ni, Mn, Co). HE-NMC materials have garnered attention in the automotive industry due to their highest specific energy (900 Wh kg−1) among all cathode materials. They consist of LiMO2 (M=Ni, Mn, Co) and Li2MnO3, with the latter stabilizing the layered LiMO2 component. This composite structure allows for greater delithiation compared to pure layer LCO. However, HE-NMC faces challenges in terms of cycling stability and voltage fading, particularly at high current densities. Improved electronic conductivities and tap densities are necessary for HE-NMC to become a potential battery technology for next-generation EV applications (Ding et al., 2019).

6.3.5. Environmental Factors

Two major types of solid waste generated during nickel production are smelter slags and leaching residues, which pose significant risks to human health and the environment if not properly managed. Smelter slags are granulated wastes formed during the smelting process and contain various oxides. The global production of nickel slags is estimated to be around 150 million tons per year, and their disposal in surface dumps or under the sea can lead to the release of toxic and leachable heavy metal(loid)s into the environment. Leaching residues, generated during hydrometallurgical processing, also contain toxic metals and precipitates formed under specific conditions. These residues can seriously endanger the environment and human health.

Treatment methods for nickel leaching residues have been proposed, but upcycling these materials is challenging due to their complex structure and low metal content. Circular economy principles should be followed to extract additional metal values and manage these secondary materials effectively. However, upcycling efforts are still limited to pilot trials, and the extraction process is hindered by the inherent mineralogical characteristics and low metal content of the residues.

The disposal of nickel smelter slags and leaching residues has had significant environmental impacts in the past, as they were often disposed of at poorly protected or abandoned sites without proper monitoring. Examples include large stockpiles of Ni-bearing silicate smelter slags in Poland and the deposition of NiCu sulfide smelter slags in Canada. These uncontrolled disposals led to the release of toxic metals into the environment.

The nickel industry and research community are facing challenges in managing the environmental impacts associated with the disposal of these waste materials. Proper environmental management and monitoring plans are necessary to prevent the release of toxic metals and metalloids into the environment during waste disposal (Bartzas et al., 2021).

6.3.6. Legal Factors

The availability and prices of nickel are susceptible to various factors, including physical disruptions and regulatory or geopolitical events in major producing countries. Natural disasters like earthquakes, tsunamis, and flooding can cause significant disruptions in the production and supply chain of nickel. These events can damage mining facilities, transportation infrastructure, and processing plants, leading to a decrease in nickel output. As a result, the availability of nickel in the market can be greatly affected, causing fluctuations in prices.

In addition to natural disasters, regulatory and geopolitical events also play a crucial role in shaping the nickel market. Government policies and regulations in major producing countries can impact the export and import of nickel ore, refined nickel, and nickel products. Changes in these policies can lead to restrictions or bans on nickel ore exports, as seen in the case of Indonesia. When a major nickel-producing country enforces such measures, it disrupts the global supply chain, affecting the availability of nickel and subsequently influencing its prices.

Indonesia’s ban on nickel ore exports serves as a significant example of how regulatory decisions can have far-reaching consequences. As one of the world’s largest nickel producers, Indonesia’s export ban had a substantial impact on the global nickel market. The restriction created a shortage of nickel ore in the market, leading to a rise in prices. This event highlighted the vulnerability of the nickel industry to policy changes and demonstrated how geopolitical factors can disrupt the availability and pricing of this crucial metal.

Therefore, it is crucial for market participants and stakeholders to closely monitor these factors and their potential impacts on the nickel market. Understanding the interplay between physical disruptions, regulatory actions, and geopolitical events can help anticipate market dynamics and make informed decisions. Additionally, diversifying nickel supply sources and promoting sustainable mining practices can contribute to a more resilient and stable nickel market in the face of such uncertainties (International Energy Agency, 2021).

6.3.7. Competitive Demand

The effect for competitive demand is observed to be severe in the case of Nickel. Among renewable technologies, Nickel is seen to be a crucial component for Hydrogen storage, EV Batteries and Geothermal energy generation. It is also seen as moderately important in technologies such as Wind, Concentrated Solar Power and Nuclear energy generation. Hence there will be fierce competition to secure Nickel supply within these technologies. To worsen the case of Nickel, Stainless Steel Production (Demand Drivers) accounts for approximately two-thirds of global nickel demand. The chemical industry is the fourth-largest consumer of nickel, and demand for nickel in this sector is expected to grow as the global population continues to increase.Due to high competition for demand, the Demand for class 1 Nickel is projected to be around 1.5 million tonnes by 2025. The supply for 2025 is estimated to be 1.2 million tonnes which will not be sufficient to meet the demand needs (International Energy Agency, 2021).

6.4. Criticality Analysis of Copper

Copper, with its exceptional conductivity and durability, plays a vital role in the production and functioning of electric vehicles. In this chapter, we delve into a comprehensive analysis using the Criticality Framework to assess the various external factors influencing the criticality of copper for electric vehicles. Analysis of Political, Economic, Social, Technological, Environmental, Legal, and Competitive Demand Sector factors, provides a structured approach to evaluate the external macro-environmental factors affecting a specific industry or sector.

Let us now explore the intricacies of each PESTEL factor and their impact on the criticality of copper for electric vehicles. By doing so, we can better comprehend the evolving landscape and make well-informed decisions to foster the sustainable growth of the electric vehicle industry while ensuring the availability and responsible use of copper.

6.4.1. Political Factors

The western part of South America, particularly Chile and Peru, stands as the primary powerhouse in global copper production, contributing a staggering 40% to the total output. However, other significant copper-producing countries include China, the Democratic Republic of the Congo (DRC), the United States, and Australia (International Energy Agency, 2021).

Copper ore exists in two main forms: copper sulfide, which comprises approximately 80% of production, and copper oxide, which accounts for the remaining 20% (International Energy Agency, 2021). The pyro-metallurgical process, known as smelting, is employed for sulfide ore processing. This process involves crushing and grinding the ore, transforming it into concentrates, and subsequently exporting them to China and other countries for the production of refined copper through electro-refining. Notably, China holds the largest market share in copper refining, approximately 40%, followed by Chile, Japan, and Russia. However, due to China's substantial demand for refined copper, the country also imports refined copper products from abroad, further solidifying its position in the global copper market (Nassar et al., 2012).

Several notable projects, such as Quellaveco in Peru and Kamoa-Kakula in the DRC, are currently under construction, offering the potential for significant near-term supply increases if completed on schedule. Additionally, expansion projects like Oyu Tolgoi in Mongolia are in progress, further contributing to the future supply outlook. This will help diversify the supply of copper in the future. This can be seen in Figure 6.12 below Jing et al., 2021.

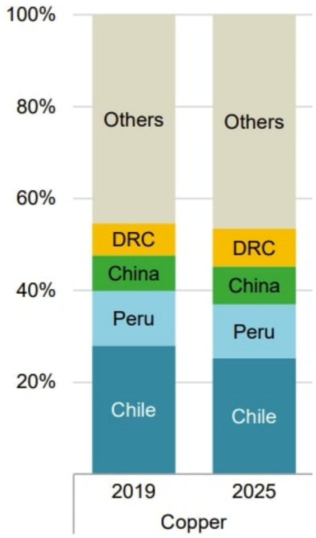


Figure 6.12: Comparison of Major global Copper in 2025 and 1990 (International Energy Agency, 2021)

Although Chile and Peru are expected to retain their positions as the largest copper producers until 2025, the landscape is anticipated to become more diversified, with the DRC and Indonesia increasing their production capacities. Regarding processing, China is projected to maintain its dominant position in the near term, with its capacity growth until 2025 accounting for nearly half of all planned additions to global capacity. As China's processing share expands (while its mining share remains stable), the nation is poised to exert greater influence over the trade and pricing of intermediate copper products (Mróz, 2022),(International Energy Agency, 2021).

6.4.2. Economic Factors

Economic factors play a significant role in determining the criticality of copper for electric vehicles. While copper reserves have witnessed a 30% increase over the past decade, the development of new projects has become increasingly challenging, primarily due to the declining ore quality in major producing regions. Notably, the average grades of copper concentrate in Chile have decreased by 30% since 2005, while the quality of the feed for hydro-metallurgical processes has also deteriorated. Presently, the average copper content in Chilean ore stands at approximately 0.7%. Furthermore, as mining operations move towards the peripheries of exploited deposits and extract metal content from lower-grade ores, additional costs and energy consumption are incurred, not only for on-site processing but also along the entire value chain, including activities like dust suppression and reclamation. Moreover, deeper production sites require higher costs and energy inputs, further impacting the economic viability of copper extraction (International Energy Agency, 2021),(Valenta et al., 2019).

While cost escalations pose a significant challenge for the copper industry, the impacts of resource depletion can be mitigated through technological innovation. Over time, average ore grades have declined from 10-20% in the late 19th century to 2-3% in the early 20th century. However, advancements in technology have played a vital role in unlocking new supplies in a cost-effective manner. Aerial surveys, satellite imagery, geographic information systems, and computer models have enabled the industry to achieve a dramatic increase in copper output. One notable development has been the emergence of solvent extraction-electrowinning (Sx-Ew) processes since the 1970s, allowing for greater efficiency in dealing with oxide resources. Today, this process accounts for approximately 20 of global copper production. Continued technology innovation remains pivotal for sustaining an affordable and reliable supply of copper, similar to other minerals (Valenta et al., 2019).The price volatility of copper between 2010 and 2022 can be seen below. Copper is one of the least price volatile metal in comparison with other metals shown in Figure 6.13.

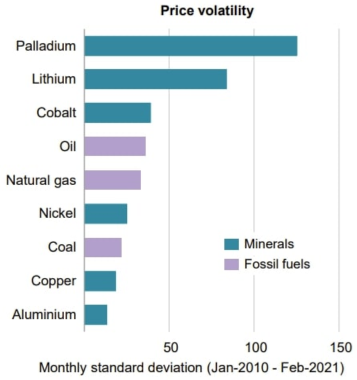


Figure 6.13: Price Volatility of selected metals between 2010 and 2021 (International Energy Agency, 2021)

In summary, economic factors such as declining ore quality, escalating costs, and resource depletion pose challenges to the criticality of copper for electric vehicles. However, technological advancements have proven instrumental in overcoming these challenges, unlocking new supplies and improving efficiency in copper production. Ongoing innovation in technologies and processes will be crucial to ensuring a sustainable and affordable supply of copper for the growing electric vehicle industry (International Energy Agency, 2021).

6.4.3. Social Factors

Copper production in Peru, the second-largest global producer, has been affected by social unrest across the country. The early phase of democratisation in Peru saw the emergence of major social movements that challenged China-backed projects such as the Myitsone dam, the China-Myanmar pipelines, and the Letpadaung copper mine. The Peruvian government faced a dilemma, as proceeding with these projects would lead to political costs domestically, while canceling them would offend Beijing. As a result, the Myitsone dam project was shelved in 2011, and the Letpadaung copper mine project experienced temporary suspension in 2012 before restarting under a revised contract the following year. Scholars and analysts attribute the disruption of Chinese projects to the rapprochement between the United States and Myanmar. Some Chinese scholars criticized Washington for causing economic setbacks in Myanmar, suggesting that US actions were behind the challenges faced by Chinese projects. The perception was that the US influenced the outcome of projects such as the Myitsone dam, the Letpadaung copper mine, and the China-Myanmar oil and gas pipelines. Chinese representatives from state-owned enterprises (SoEs) in Myanmar echoed these views, claiming that local people were manipulated and highlighting the role of education levels in Myanmar (D. S. W. Chan and Pun, 2020).

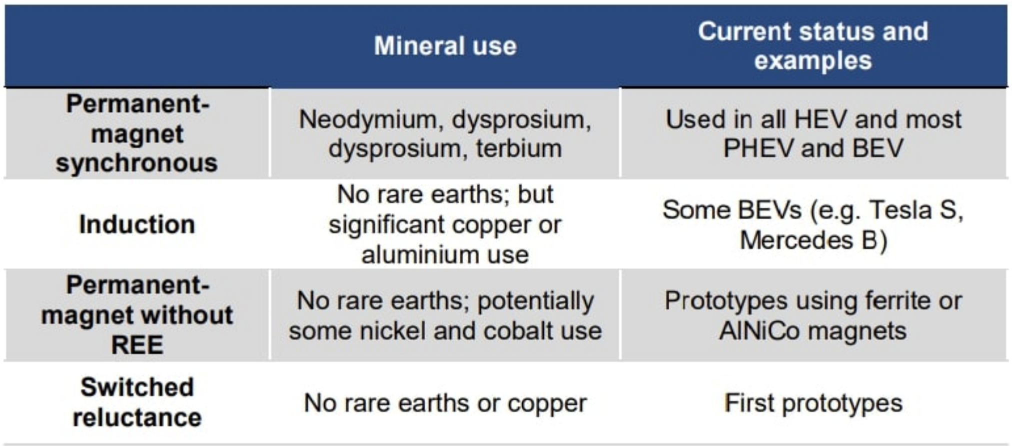
Similar social conflicts have arisen in other copper-producing countries as well. In Peru, the mining company Las Bambas has faced protests and social conflicts from local communities who argue that the mine has resulted in environmental damage and disrupted their way of life. In Chile, the mining company Codelco has encountered criticism from workers and labor unions regarding working conditions, safety measures, and labor rights (Fiscor, 2023).

These social factors pose challenges to the criticality of copper for electric vehicles. Local communities and labor groups demand greater accountability from mining companies and express concerns about the environmental impact of copper mining activities. Such conflicts can disrupt production and supply chains, leading to delays and additional costs. Resolving these social issues requires addressing environmental concerns, engaging with local communities, and ensuring fair working conditions and labor rights.

In summary, social factors, including protests, environmental concerns, and labor disputes, affect the criticality of copper for electric vehicles. Countries like Peru and Chile have experienced social unrest related to copper mining projects, with communities and labor groups raising issues of environmental damage, disruption of livelihoods, and labor rights. Managing these social conflicts is crucial for the sustainable and responsible production of copper, ensuring a reliable supply for the growing demand in the electric vehicle industry (Kolala and Bwalya Umar, 2019).

6.4.4. Technological Factors

Technological factors play a significant role in determining the criticality of copper for electric vehicles. The choice of electric motor technology directly impacts the amount of copper and other resources required. The two most common electric motor technologies for plug-in electric vehicles (EVs) are permanent-magnet synchronous motors and asynchronous induction motors, as shown in Figure 6.14 below. Permanent-magnet motors offer high efficiency and power density, but their use of rare earth metals (REMs) makes them costly compared to other technologies. Additionally, they require a significant amount of copper, approximately 3-6 kg per vehicle. On the other hand, induction motors have lower costs but moderate efficiencies due to electrical losses in copper windings. While they do not require REMs, they rely heavily on copper, with approximately 11-24 kg per vehicle for the rotor cage and copper stator (Mahesh et al., 2021),(Yao et al., 2021).



	Mineral use	Current status and examples
Permanent-magnet synchronous	Neodymium, dysprosium, dysprosium, terbium	Used in all HEV and most PHEV and BEV
Induction	No rare earths; but significant copper or aluminium use	Some BEVs (e.g. Tesla S, Mercedes B)
Permanent-magnet without REE	No rare earths; potentially some nickel and cobalt use	Prototypes using ferrite or AlNiCo magnets
Switched reluctance	No rare earths or copper	First prototypes

Figure 6.14: Types of motors used in different EV Drivetrains (Agamloh et al., 2020),(Widmer et al., 2015)

When it comes to batteries, the mineral requirements vary depending on the cathode and anode chemistries. For instance, nickel manganese cobalt oxide (NMC) 111 batteries typically require significantly more cobalt than nickel cobalt aluminum oxide (NCA^{+}) batteries but half as much nickel. On the other hand, lithium iron phosphate (LFP) batteries do not need nickel, cobalt, or manganese but rely on approximately 50% more copper compared to NMC batteries (International Energy Agency, 2021).

Furthermore, the adoption of EV wireless charging, also known as inductive charging, has the potential to reduce copper consumption per vehicle by 18%. Inductive charging eliminates the need for cables and charging pins, further reducing the reliance on copper (Yao et al., 2021).

These technological factors highlight the importance of optimizing electric motor technologies and battery chemistries to minimize the overall demand for copper in electric vehicles. Balancing efficiency, performance, and cost considerations while reducing the reliance on REMs and optimizing copper usage is crucial for the sustainable development of electric vehicles (Dericioglu et al., 2018).

6.4.5. Environmental Factors

The Figure 6.15 below illustrates the share of production volumes and the corresponding water stress levels for the production of selected metals. One significant inference drawn from the figure is that copper production has the highest impact on water stress levels when compared to other metals. The data suggests that the extraction and processing of copper place substantial pressure on water resources, leading to increased water stress in regions where copper mining operations are prevalent. This finding underscores the criticality of addressing water management practices in the copper industry to minimize the environmental impact and ensure sustainable water usage. Efforts to implement water conservation measures and promote responsible water stewardship are imperative to mitigate the water stress associated with copper production and maintain the long-term viability of this essential metal.

Environmental factors play a crucial role in the criticality of copper for electric vehicles, with several notable issues arising in different regions around the world. In the United States, the Berkeley Pit copper mine located in Montana has caused significant water pollution due to acid mine drainage.

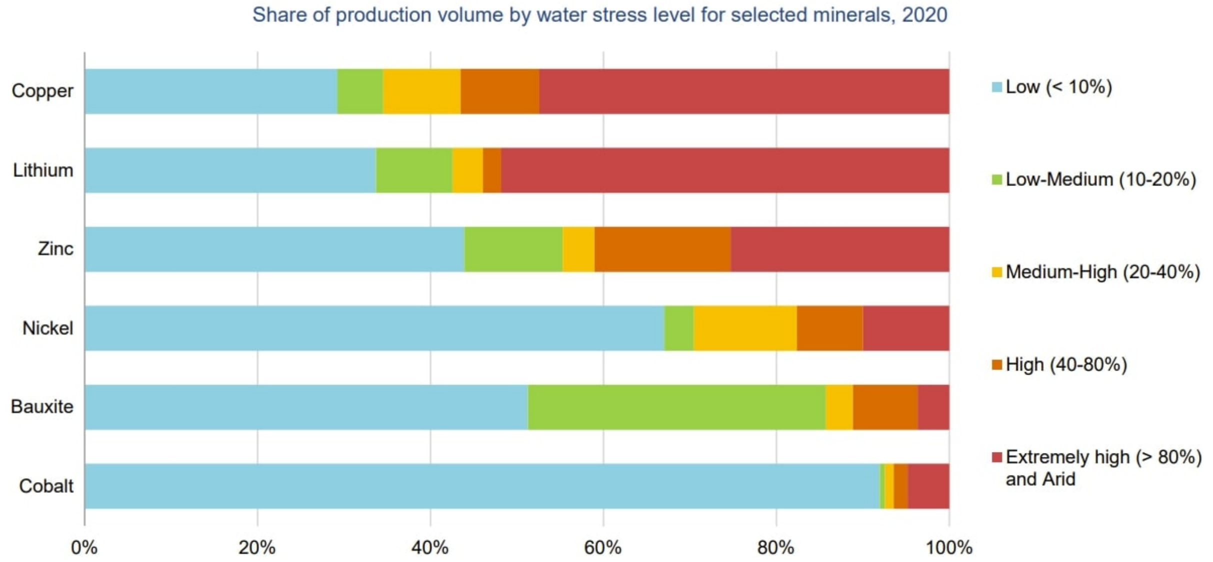


Figure 6.15: Share of Production volumes and Water Stress levels for selected metals (International Energy Agency, 2021)

This occurs when water flows through the mine, picking up heavy metals and chemicals along the way, resulting in environmental contamination and damage.

In Indonesia, the Grasberg copper mine, renowned as one of the largest in the world, has contributed to deforestation on a substantial scale. The clearing of significant forest areas to make room for the mine has resulted in habitat loss for endangered species and has had adverse effects on the local environment. Additionally, the deforestation associated with the Grasberg mine has contributed to climate change, further exacerbating environmental concerns.

The Democratic Republic of Congo (DRC), a major producer of copper, is plagued by ongoing conflicts that raise concerns about the ethical sourcing of copper. The tumultuous situation in the DRC has led to questions about the mining practices and supply chains associated with copper extraction in the region. Ethical sourcing of copper is paramount, given its critical role in the production of electric vehicles, and ensuring responsible mining practices is vital for sustainability.

These environmental factors highlight the need for stringent environmental regulations and responsible mining practices in the copper industry. Minimizing water pollution, mitigating deforestation, protecting biodiversity, and promoting ethical sourcing are key considerations in reducing the environmental impact associated with copper mining and its use in electric vehicles. Efforts to address these concerns are essential for the sustainable development of the electric vehicle industry and the conservation of the environment (Bridge, 2000).

6.4.6. Legal Factors

Regulatory and legal factors play a significant role in shaping the criticality of copper for electric vehicles, with the European Union's Restriction of Hazardous Substances (RoHS) directive being a notable example. The RoHS directive imposes restrictions on the use of hazardous substances in electronic and electrical equipment, including lead and cadmium. This regulation aims to protect human health and the environment by limiting the presence of harmful substances in products, including those utilizing copper components. Compliance with RoHS requirements is crucial for manufacturers and suppliers in the electric vehicle industry to ensure their products meet the necessary standards and can be marketed and sold within the EU market.

In addition to the RoHS directive, various other regulations and legal frameworks govern the production, use, and disposal of copper in electric vehicles. These regulations may cover areas such as emissions standards, waste management, recycling requirements, and worker safety. Compliance with these regulations is essential to ensure the environmentally sound and sustainable production of copper components for electric vehicles. Adhering to legal requirements not only helps mitigate the potential negative environmental and health impacts associated with copper mining and processing but also promotes responsible and ethical practices throughout the supply chain.

Furthermore, regulatory and legal factors can influence the sourcing of copper, particularly in terms of ethical considerations. Increasingly, there is a growing focus on responsible sourcing and supply chain transparency to prevent the use of copper from conflict-affected regions or areas associated with human rights abuses. Legal frameworks, such as conflict mineral regulations, aim to address these concerns and promote the ethical procurement of copper and other minerals used in electric vehicles.

To ensure the sustainable use of copper in electric vehicles, governments and regulatory bodies need to continue developing and implementing robust regulations that promote environmental protection, worker safety, and ethical sourcing practices. Collaboration between industry stakeholders, policymakers, and advocacy groups is crucial to create a regulatory framework that strikes a balance between meeting the demand for copper and minimizing its potential negative impacts on the environment, society, and human health (Sepúlveda et al., 2010).

6.4.7. Competitive Demand

Though Electric Vehicles are the primary demand drivers for Copper, Within renewable technologies, there is heavy competition for Copper consumption. The technologies in competition are Solar PVs, Wind, Bio-energy, electricity networks and EVs and batteries as shown in Figure 6.4.It is definite that all these technologies will boom exponentially by 2050 and this will add to the cause of criticality of copper for EVs. Apart from Renewable Technologies, The EV Sector currently is and is likely to remain the primary driver for Lithium demand, as it is used in electrical wiring, motors, transformers, and other electronic components in vehicles (International Energy Agency, 2021).

6.5. Criticality Analysis of Aluminium

This section embarks on a comprehensive exploration of the criticality analysis of aluminum within the context of electric vehicles. As EV adoption surges and governments worldwide set ambitious emission reduction targets, understanding the intricate dynamics of aluminum's role becomes paramount. Criticality analysis of aluminum for EVs is performed using the analysis model in this section.

6.5.1. Political Factors

The criticality of aluminum for electric vehicles is influenced by various political factors. One key aspect is the geographical distribution of bauxite resources, which are the primary source of aluminum. According to the United States Geological Survey (USGS), bauxite resources are abundant worldwide, with estimates ranging from 55 to 75 billion tonnes. These resources are concentrated in different regions, with Africa holding 32%, Oceania 23%, South America and the Caribbean 21%, Asia 18%, and the rest of the world 6%. Guinea and Australia possess the largest bauxite reserves, accounting for 24% and 20% respectively. Other significant bauxite-rich countries include Vietnam, Brazil, and Jamaica (United States Geological Survey, 2020).

In the European Union, Greece is known to possess substantial exploitable bauxite deposits, with an estimated 250 million tonnes of ore reserves. Additionally, bauxite resources can be found in countries such as France, Hungary, Romania, and Italy. These reserves contribute to the overall supply of aluminum in the EU (United States Geological Survey, 2020).

Political conflicts between major aluminum-producing countries can significantly impact the supply chain and the criticality of aluminum. Currently, Ukraine and Russia jointly meet 10% of the global aluminum demand. Any conflict or disruptions in trade between these two nations can lead to supply chain disruptions and a surge in aluminum prices. For instance, the ongoing Russia-Ukraine war has resulted in soaring aluminum prices, reaching record highs (Perchard and MacKenzie, 2021).

In addition to the mentioned points, other political factors that can influence the criticality of aluminum for electric vehicles include trade policies, tariffs, and regulations imposed by governments. These measures can affect the availability, pricing, and accessibility of aluminum, thereby impacting its use in the production of electric vehicles. Political stability, international relations, and geopolitical dynamics also play a significant role in determining the long-term supply and demand of aluminum for the automotive industry (Alexander, 2021).

6.5.2. Economic Factors

The criticality of aluminum for electric vehicles is influenced by several economic factors. One key factor is the cost of electricity, which has a significant impact on the price and availability of aluminum. The cost of electricity accounts for a substantial portion of the total price of aluminum, with estimates ranging from 30% in the United States to 45% in China. Producing aluminum requires a large amount of electricity, with approximately 15,000 kilowatt-hours (kWh) needed to produce 1 ton of aluminum. The demand for aluminum is influenced by various industries and applications, including automotive, aerospace, construction, refrigeration, packaging, and machinery. Technological advancements and the increasing importance of green energy in transportation can drive the demand for aluminum as a lightweight alternative to steel (Montijo, 2022).

Global demand also plays a crucial role in the criticality of aluminum. The industry operates within a globalized market, where countries both contribute to the demand and supply of aluminum. Events in any country, especially those accounting for a significant share of production or consumption, can affect the commodity's price. The top producers and consumers of aluminum, such as Australia, China, Brazil, the United States, Japan, and Germany, have a considerable influence on the global demand and pricing of aluminum.

The state of the world economy is another factor that affects the criticality of aluminum. Metals like iron ore, copper, aluminum, and nickel are essential for industrial production and construction globally. Shifts in supply and demand for these metals often indicate changes in the world economy. Economic growth, particularly in developing countries that require infrastructure development, can significantly impact the demand for metals like aluminum (Bartoš et al., 2022).

Current trends in aluminum prices are monitored and analyzed by organizations such as the United States Geological Survey (USGS). Factors such as global shutdowns, changed consumer behavior, and economic uncertainties, as seen during the COVID-19 pandemic, can cause fluctuations in aluminum prices. For instance, the pandemic led to a drop in demand and prices for aluminum in April 2020. However, as the automotive, packaging, and construction sectors recover, the demand for aluminum is increasing, resulting in rising prices (Montijo, 2022).

These economic factors, including the cost of electricity, global demand, and the state of the world economy, collectively influence the criticality of aluminum for electric vehicles. Understanding and monitoring these factors are crucial for assessing the availability, pricing, and sustainability of aluminum as a key material in the electric vehicle industry.

6.5.3. Social Factors

The criticality of aluminum in various industries, including electric vehicles, is not only influenced by economic and environmental factors but also by social considerations. The impact of aluminum mining on local communities and their livelihoods has raised concerns regarding human rights, environmental destruction, and the fair distribution of benefits.

In rural communities such as those in Boké, where aluminum mining activities are prominent, residents have expressed grievances regarding the negative consequences they experience. The destruction of land, which has been their source of sustenance for generations, and the harm inflicted on the natural environment crucial for their food and livelihoods have been significant issues. Reports from organizations like Human Rights Watch and Inclusive Development International have highlighted these concerns, shedding light on the disconnect between the expanding mining industry and the well-being of local communities.

The lack of access to basic services such as water and electricity, along with a perceived lack of local benefits from the mining industry, has fueled tensions in the Boké region. The World Bank's report in October 2020 acknowledged these tensions, emphasizing the need for improved socio-economic welfare and more inclusive benefits for local communities. The report called for mitigating the negative environmental impacts of mining and transitioning towards sustainable and diversified economic activities to ensure long-term development (McDonough, 2022).

Instances of human rights abuses within the aluminum supply chains of major companies have also come to light. Apple and Microsoft, among others, have faced scrutiny for sourcing aluminum from companies operating in China, where human rights violations have been reported. The concerns range from labor rights issues to environmental degradation associated with mining operations. These cases highlight the importance of responsible sourcing and supply chain management to address human rights abuses and ensure ethical practices throughout the aluminum industry (McDonough, 2022).

To promote sustainable and socially responsible aluminum production, stakeholders need to prioritize the well-being of local communities and the protection of human rights. Collaborative efforts between mining companies, governments, international organizations, and local communities are necessary to address the environmental impacts, improve socio-economic conditions, and establish fair and inclusive practices in the aluminum supply chain. Real-world examples of companies adopting responsible sourcing policies, engaging in community development initiatives, and supporting environmental conservation can serve as positive models for the industry as a whole (Osama et al., 2022).

6.5.4. Technological Factors

Aluminum plays a crucial technological role in the development and production of electric vehicles (EVs). While the battery cells primarily consist of minerals such as lithium, nickel, cobalt, and manganese, the remaining components, including modules and pack components, heavily rely on aluminum, steel, coolants, and electronic parts. These materials contribute to the lightweight and efficient design of EVs.

The advancement of aluminum alloy design has been instrumental in the EV industry. The development of stronger and lighter aluminum alloys has enabled the manufacturing of components that are well-suited for electric vehicles, such as battery housings and structural elements. These alloys offer high strength-to-weight ratios, enhancing the overall performance and safety of EVs while reducing their weight. Lightweight aluminum components contribute to increased energy efficiency and extended driving range (Hirsch, 2014).

Technological innovations, such as 3D printing, have further revolutionized the production of aluminum components for electric vehicles. 3D printing allows for intricate and complex designs, customization, and rapid prototyping. This technology enables more efficient and cost-effective manufacturing processes for aluminum parts, leading to reduced production time and waste. The use of 3D printing in aluminum component production contributes to the overall advancement and feasibility of electric vehicles (Hirsch, 2014).

The prices of rare earth elements, which are essential for permanent-magnet motors commonly used in EVs, have been subject to fluctuations and supply constraints. In response to these challenges, there is a growing interest in induction motors as an alternative to permanent-magnet motors. Induction motors do not require rare earth elements and can utilize aluminum components. This shift in motor technology could result in increased demand for aluminum in the EV industry, as induction motors become more prevalent (Hirsch, 2014).

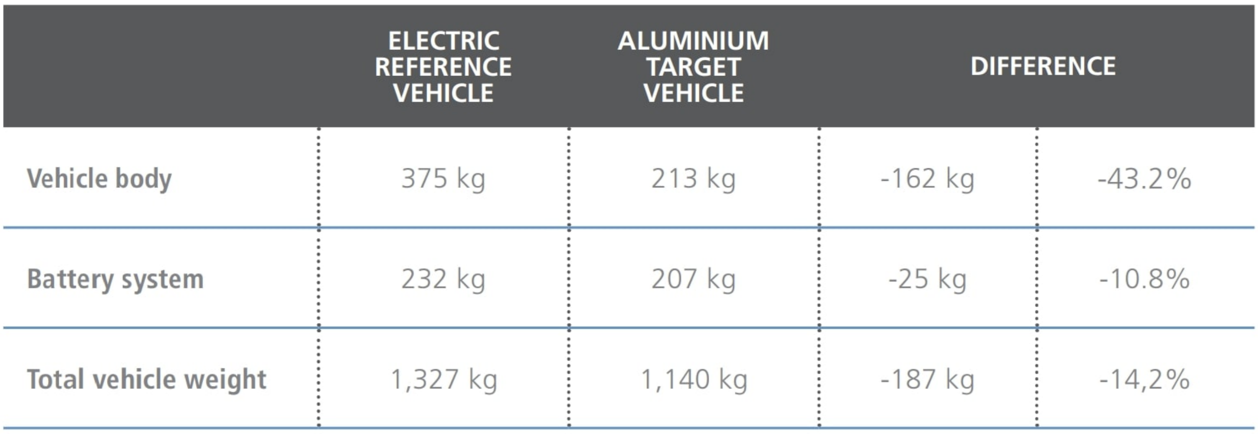
In addition to these factors, it's worth noting that aluminum is highly recyclable, making it an environmentally sustainable choice for the EV industry. The recycling process for aluminum requires significantly less energy compared to primary production, reducing greenhouse gas emissions. The recyclability of aluminum contributes to the circular economy and reduces the reliance on primary aluminum production. Recycling high-strength, heat-treatable aluminium alloys used in electric vehicles (EVs) faces a significant challenge regarding the varying presence of unwanted elements like iron and copper in the recycled metal chips. Several proposed solutions aim to address this issue. These include advancements in sorting techniques like color sorting and laser-induced breakdown spectroscopy, which can effectively separate different types of aluminium alloys. Other methods involve purifying the materials through fluxing or segregation, as well as solid-state recycling based on severe plastic deformation. Solid-state recycling offers advantages such as energy efficiency and maximum material utilization compared to conventional remelting processes. Various techniques are available for solid-state recycling, including hot extrusion, equal channel angular pressing, and high-pressure torsion. These methods can achieve mechanical properties equal to or higher than the original products. To further enhance mechanical properties, the semisolid extrusion process has been developed, where pre-compacted chips are heated to a specific semisolid temperature prior to final extrusion. Additionally, suitable heat treatments have been studied to improve mechanical properties. However, the widespread adoption of solid-state recycling has been limited due to potential issues such as the dispersion of the second phase and the formation of micro-voids. Therefore, it is crucial to focus more on the development of aluminium recycling techniques for high-performance aluminium alloys (Hirsch, 2014).

In addition, the European Aluminium Association has set the below targets for electric vehicles weights to the weights mentioned in Figure 6.16 below. This can be achieved by using aluminium bodies with revised structures in order to minimize the energy consumed to move the vehicle.

Overall, the technological importance of aluminum for electric vehicles is undeniable. Advances in aluminum alloy design, coupled with innovative manufacturing techniques like 3D printing, contribute to lightweight and efficient EV components. Additionally, the potential shift towards induction motors presents an opportunity for increased aluminum demand. As the EV industry continues to grow and evolve, aluminum will remain a key material in the pursuit of sustainable and technologically advanced electric vehicles (International Energy Agency, 2021).

6.5.5. Environmental Factors

The production of aluminum has several environmental impacts, as highlighted in the provided hints. One of the significant impacts is acidification potential, which refers to emissions that cause acidifying effects on the environment. Nitrogen oxides (NOx), sulfur dioxide (SO2), and ammonia (NH3) are the main acidifying emissions from aluminum production. The majority of these emissions, approximately 77%, are associated with the electrolysis process, while electricity generation contributes to 74% of



	ELECTRIC REFERENCE VEHICLE	ALUMINIUM TARGET VEHICLE	DIFFERENCE	
Vehicle body	375 kg	213 kg	-162 kg	-43.2%
Battery system	232 kg	207 kg	-25 kg	-10.8%
Total vehicle weight	1,327 kg	1,140 kg	-187 kg	-14,2%

Figure 6.16: Aluminium Targets for EVs (European Aluminium Association, 2013)

all acidification emissions (Brough and Jouhara, 2020).

Another environmental impact is the depletion of fossil energy resources. The refining process for alumina, a precursor to aluminum, requires a substantial amount of energy. In 2018, it took an average of 11,359 MJ per tonne of alumina produced for refining. The worldwide fuel energy consumption for refining alumina was over 1,336,249 TJ, with the actual figure likely higher due to under reported data (Brough and Jouhara, 2020).

Eutrophication potential is another concern associated with aluminum production. Eutrophication refers to the excessive growth of plants, such as algal blooms, due to the presence of compounds like nitrogen and phosphorus in watercourses. The primary industry's eutrophication potential is mainly attributed to nitrogen oxide (NOx) emissions, accounting for 95% of the total eutrophication potential from the US primary aluminum industry. The production of one US ton of primary aluminum ingot results in approximately 2.35 kg of phosphate equivalent emissions (Brough and Jouhara, 2020).

The production of aluminum also contributes to photo-chemical ozone creation potential (POCP), which measures emissions that can contribute to low-level smog. Compounds such as sulfur dioxide (SO2), volatile organic compounds (VOCs), nitrogen oxides (NOx), and methane (CH4) react with sunlight in the atmosphere, leading to the formation of photo-chemical ozone. The primary industry's emissions contribute approximately 3.06 kg ethene equivalents (C2H6) per tonne of aluminum produced (Brough and Jouhara, 2020).

Water scarcity footprint (WSFP) is another environmental impact associated with primary aluminum production. It measures the environmental impact on water availability. Freshwater consumption from mining, refining, and smelters, as well as ancillary materials, fuel, and electricity, contribute to the water scarcity footprint. The WSFP for global primary aluminum production is estimated at 18.2 m3 H2O eq.tAl-1, or 9.6 m3 H2O eq.tAl-1 without considering China's contribution, which heavily affects the calculations (Brough and Jouhara, 2020).

Furthermore, the production of aluminum results in the generation of red mud, a residue from the Bayer process. Red mud is highly alkaline and has historically been disposed of in landfills. However, researchers have been exploring ways to treat red mud to extract value from it. Various studies have investigated its potential use in concrete production, geopolymers, gallium extraction, ceramic tiles, road bases, and more (Brough and Jouhara, 2020).

Overall, aluminum production has significant environmental impacts, including acidification potential, depletion of fossil energy resources, eutrophication potential, photo-chemical ozone creation potential, water scarcity footprint, and the generation of red mud. These impacts highlight the importance of considering sustainable practices and exploring alternative methods in the aluminum industry to mitigate its environmental footprint.

6.5.6. Legal Factors

The EU's CO_2 emissions regulations have had a significant impact on the use of aluminum in electric vehicle designs. The emphasis on reducing weight and improving efficiency has driven automakers to increase the incorporation of aluminum in their vehicles. To address the issue of vehicle mass, it is crucial to achieve weight reduction without compromising functionality or safety. Aluminum offers a unique advantage in light weighting without downsizing the vehicles or compromising their safety.

Innovative, safe, and cost-efficient aluminum components such as bonnets, fenders, doors, and bumpers are already being used in various car models. Switching to aluminum for these parts is relatively straightforward and does not require extensive re-engineering of the vehicles. Collectively, these lightweight aluminum components can exceed 40 kg per car in weight reduction potential. However, the market penetration of aluminum components in this regard is still less than 20%. Exploiting this potential can immediately contribute to reducing average emissions from future cars by 3-4 g CO_2/km.

In practice, material substitution often occurs during model changes, which involve significant redesigning. Incorporating mixed materials, including aluminum, does not pose significant challenges as long as appropriate design and manufacturing measures are implemented. This opens up the possibility of even greater weight savings.

Tesla's Model S electric car and Audi's e-tron electric SUV are examples of vehicles that utilize a high-strength aluminum structure to reduce weight and improve range. These companies recognize the benefits of aluminum in achieving their goals of enhanced performance and efficiency in electric vehicles (European Aluminium Association, 2013).

6.5.7. Competitive Demand

Within renewables, there is heavy competition for usage of Aluminium. Aluminium is crucial for technologies like Solar Energy, electrical networks, EVs and batteries, Wind, Hydro, hydrogen and Bio energy as shown in Figure 6.4. The other less significant demand sectors are Construction, Packaging, Electrical wiring and cables, and Consumer Goods.

6.6. Criticality Analysis of Rare Earth Metals

This section deals with the Criticality analysis of Rare Earth Metals. Considering the scope of this thesis, only Neodymium and Dysprosium were used as representatives to the Rare-Earth Metals group, owing to their importance in permanent magnet motors which are critical for the functioning of EVs.

6.6.1. Political Factors

The criticality of rare earth metals for electric vehicles is heavily influenced by various political factors, with China's dominant control over the world's supply playing a central role. China currently holds over 90% of the global rare earth metals supply, giving it significant leverage in international trade as shown in Figure 6.17 below. This was exemplified by China's decision to impose an export ban on rare earths to Japan in 2010. The ban had severe implications for Japan's economy, as key sectors heavily relied on these minerals. The incident raised concerns among businesses and policymakers in major importing countries like Japan, the United States, and Germany, as it highlighted China's willingness to use its economic influence as a political bargaining chip (Law, 2019),(Vekasi, 2019).

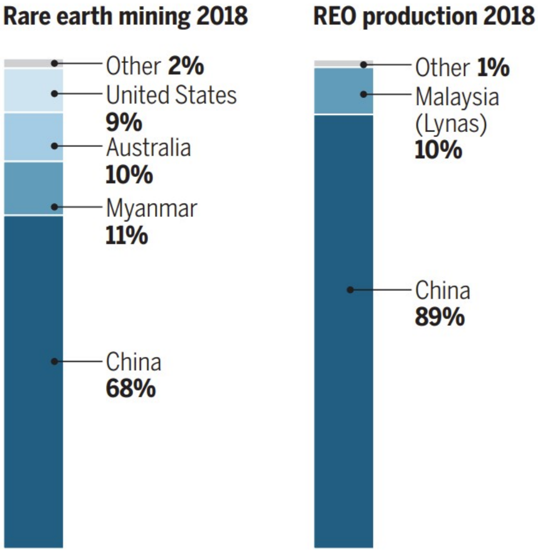


Figure 6.17: Global Rare Earth Mining and Production Shares (Law, 2019)

To mitigate the risks associated with China's monopoly, Japan initiated diversification efforts to secure alternative sources of rare earth elements (REEs). Non-Chinese Asian imports of REEs primarily rely on shipments from Vietnam and Malaysia. However, it is worth noting that many Vietnamese imports actually originate from Chinese mines, and Malaysian imports are sourced from the Australia-based Lynas Corporation. These complexities in supply chains underscore the challenges faced in reducing dependence on China and achieving true diversification.

The heightened risk perception surrounding rare earth metals in Japan was further exacerbated by tensions and uncertainties prevailing in the Chinese market. Multinational companies operating in China had to interpret opaque Chinese policies and make strategic decisions accordingly. Factors such as export quotas, industrial rationalization, China's monopoly in production, technological advantages, and the absence of viable natural or synthetic alternatives contributed to the perceived risks associated with rare earth metals. This perception made these minerals an even more potent tool for economic statecraft, raising concerns about the possibility of their use as diplomatic leverage.

The mere perception that rare earth metals could be employed as a means of diplomatic manipulation was deeply troubling. It further highlighted the vulnerability of countries and companies heavily reliant on these critical minerals and the urgent need to explore alternative strategies. Governments and industries alike are compelled to develop long-term plans to diversify supply chains, invest in research and development of substitute materials, and promote international cooperation to ensure a stable and sustainable supply of rare earth metals for electric vehicles and other critical industries.

6.6.2. Economic Factors

The economic impact on the global market of rare earth metals (REEs) has been characterized by an unstable balance between demand and supply. In the 1980s, developed countries experienced a rapid increase in demand for REMs, which then somewhat decreased in 1991-1993. This fluctuation in demand affected the REMs market, particularly due to the significant increase in production in China and the presence of large reserves in countries of the former Soviet Union. These factors played a role in shaping the market dynamics for REMs during that period.

A substantial increase in prices occurred between 2009 and 2011, as evidenced by the data presented in Table 1. However, more recently in 2012, there was a sudden and significant fall in prices

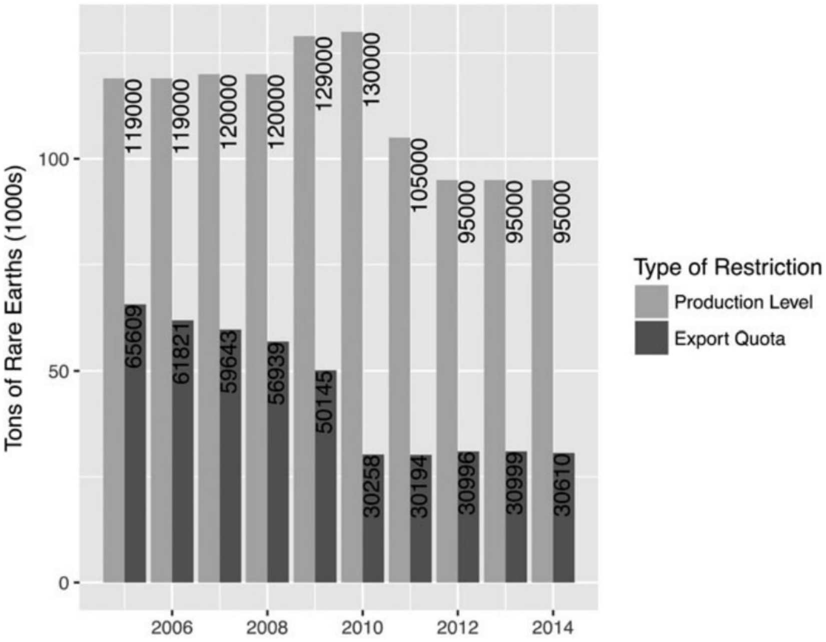


Figure 6.18: Produced Vs Exported Quantities of REEs by China (Vekasi, 2019)

according to Metal-Pages quotations. Various factors likely contributed to these changes in trend. The persistent economic crisis in industrialized countries, the contraction of hi-tech consumption, and the release of large stocks of rare earth oxides (REOs) by certain Chinese private operators who feared potential inspections and confiscations by the Chinese government all played a part in the price fluctuations.

Germany has recognized the need to secure a diversified supply of rare earth elements (REEs) and has made diplomatic efforts in this regard, including engaging with resource-rich countries like Australia. It is becoming increasingly evident that countries such as China and India have strategically oriented their raw materials policies and implemented measures to meet their own needs for raw materials. This development can potentially impact the access of German and European companies to these sources of raw materials in the medium term, emphasizing the importance of securing alternative supply chains.

In Greece, there are significant reserves of rare earth elements found in alluvial deposits in the coastal and groundwater environment of the Strymona Gulf, between the Strymona River and the Kavala region in northern Greece. Detailed research estimates indicate ore reserves of 485 million tons with an average rare earth content of 1.7%. Furthermore, bauxites and lateritic bauxites in central Greece also contain representative concentrations of rare earths, ranging from 3,275 to 6,378 grams per ton. It is worth noting that there is emerging interest in the red mud generated by aluminum metallurgy. Rare earth elements in Greece are found in various environments, including igneous, sedimentary, or metamorphic rocks of different ages. Secondary rocks, which have undergone further concentration through sedimentary processes or weathering, are economically the most significant types of rare earth deposits in Greece.

The economic factors affecting the criticality of rare earth metals for electric vehicles are characterized by the historical instability in the demand and supply balance, price fluctuations influenced by global economic conditions, and the exploration of alternative sources and reserves in different countries. These factors underline the importance of diversifying supply chains and fostering international collaboration to ensure a stable and sustainable supply of rare earth metals for the electric vehicle industry and other sectors reliant on these critical minerals (Charalampides et al., 2016).

Strategically, the objective is to diversify the supply chain of rare earth metals outside of China over time. This goal is supported by the Chinese government, at least for mining and early-stage processing, as they recognize the need to secure new sources due to the expected increase in domestic consumption. However, this diversification may initially result in higher processing costs and face opposition due to environmental concerns. The ability to diversify outside of China depends on other countries' willingness to bear the cost and environmental risks associated with rare earth metal production. The easiest solution would be to continue relying on China for production and processing, allowing China to maintain its control over the market.

Creating a complete supply chain is challenging for any government, making market forces the best response in this situation. Interestingly, the development of China's rare earth metal industry has largely been market-driven, with government intervention only occurring in recent years. Despite occasional rhetoric and panics, China has consistently maintained low prices and sufficient supply in the market. The primary concern is that China may become the dominant producer of key products utilizing rare earth metals in green, high-tech, and military applications. China openly acknowledges this as a major aim of its rare earth metal policies.

The focus should be on the products utilizing rare earth metals, rather than the metals themselves. It is strategically unsound to allow any single region to dominate the production of these crucial products for various industries. If there is a need and sufficient resources and skills, the market will develop rare earth resources and processing capacity outside of China. However, this requires significant effort in development and investment. Government policies should promote the growth of viable industries in green technologies and high-tech applications outside of China. Such investments will be costly and long-term, and relying solely on the market is less likely to achieve this outcome. Government intervention can mitigate financial risks for the private sector and help develop these industries, reducing the strategic risk of excessive dependence on a single source (Campbell, 2014).

6.6.3. Social Factors

Concerns regarding public health in relation to REE mining primarily stem from worries about radiation from thorium-containing waste. The available epidemiological evidence on the health impact of REE mining is still somewhat limited due to the lack of publicly accessible monitoring of the processing carried out in China. One comprehensive study on the toxicity of REEs was conducted by Hirano and Suzuki in the early 1990s, which yielded data similar to concerns about the toxicity of heavy metals. The available data on the health effects of thorium is also very limited, and any observed negative health impacts are constrained by small sample sizes, making it difficult to establish statistically significant causation.

Continued monitoring of public health is crucial and should be an integral part of the community engagement plan for the LAMP site. This is particularly important considering that much of the environmental conflict surrounding the site arises from differing perceptions of what constitutes an ”acceptable dose” of radiation. Effectively demonstrating, through comprehensive and statistically significant sample sizes, that there are no long-term health impacts associated with the plant can render such arguments irrelevant and address public concerns about the potential health risks.

The question of whether sites contaminated by rare earth mineral processing can be effectively rehabilitated for alternative post-mining uses is closely tied to concerns about health risks and the technical feasibility of site remediation. The potential for such impacts has also played a crucial role in protests against the Lynas Corporation plant in Malaysia, fueled in part by negative experiences associated with a previous rare earth processing site on the peninsula.

Social opposition to rare earth mining is also driven by arguments related to environmental justice.

Processing sites often face greater difficulties in obtaining permits in developed countries, leading to their establishment in developing countries. In fact, environmental regulations played a significant role in the closure of rare earth operations in the USA. Much of the resistance against the Lynas plant in Malaysia questioned whether the company's decision to locate the site in Malaysia was solely driven by economic factors or due to the anticipation of strong social resistance in Australia. Addressing such concerns about differentiated standards and environmental justice will be crucial in preventing further escalation of socio-environmental conflicts (Ali, 2014).

6.6.4. Technological Factors

Two primary battery technologies were evaluated for the hybrid vehicle. The lithium battery does not contain any rare earth materials, while the nickel metal hydride battery was found to have a rare earth content of over 3.5 kg. Aside from the battery, rare earths are also present in the hybrid motor/generator system. In a representative hybrid vehicle, approximately 0.6 kg of rare earths were identified in the motor/generator system, mainly due to the large Ne-Fe-B permanent magnet used in the motor/generator (Alonso et al., 2012).

Thus, the total mass of rare earths in a hybrid electric vehicle equipped with a nickel metal hydride battery is approximately 4.5 kg, whereas a hybrid electric vehicle with a lithium-ion battery contains approximately 1 kg of rare earth elements. Figures 1 and 2 illustrate the distribution of rare earths by mass in a hypothetical conventional vehicle and a hybrid vehicle with a lithium battery, respectively. The mass fractions of rare earths in the NiMH battery were not available for further description. The motor/generator system is considered part of the transmission, and as depicted in Figure 2, the hybrid vehicle contains around 61% of its rare earth content in this system (Alonso et al., 2012).

Although many current electric motors in hybrid electric vehicles (HEVs) and fully electric vehicles utilize rare-earth permanent magnets, there are alternative options to develop rare-earth-free electric motors for specific applications. Research indicates that some of the reviewed rare-earth-free motors can achieve similar performance in terms of torque density, efficiency, or mechanical power compared to state-of-the-art rare-earth-based electric motors. Furthermore, some of these motors offer additional benefits such as lower cost, improved ruggedness, higher temperature operation, resistance to demagnetization, broader constant power speed range (CPSR), or enhanced efficiency, which is particularly advantageous for extending the vehicle's range. Due to the higher complexity and component count in HEVs and plug-in hybrid electric vehicles (PHEVs), they require more compact motors than FEVs. Therefore, when considering a specific application, a detailed analysis is necessary to determine which motor type can meet the desired performance criteria (Riba et al., 2016).

6.6.5. Environmental Factors

Environmental factors play a crucial role in the criticality of rare earth metals for electric vehicles, and monitoring these factors is essential to ensure the safe and sustainable operation of rare earth facilities. Similar to other large industrial operations, rare earth processing facilities require diligent wastewater treatment systems and secondary containment measures to prevent environmental harm in the event of failure. For instance, the Lynas Advanced Materials Plant (LAMP) facility has implemented secondary containment measures, learning from past incidents of pipe leakage. Additionally, the new Molycorp expansion at Mountain Pass, California, has adopted stringent environmental monitoring practices in response to historical issues.

Environmental monitoring primarily focuses on the refinery level, as the extraction of rare earth ores constitutes only a small portion of the production process. Refining rare earth minerals into marketable products is the major aspect of production. Carbonate rare earth minerals naturally act as a buffer against hyper-acidity that can result from various acidic leaching processes during refinement.

However, excessive carbonate presence can lead to alkalinity, necessitating pH monitoring of treated effluent to maintain appropriate environmental conditions.

Rare earth elements themselves contain radioactive isotopes that require monitoring, depending on the ore grade. Lessons can be drawn from the uranium mining sector, particularly from the monitoring protocols used in high-grade Athabascan uranium deposits in Saskatchewan, Canada. These protocols can provide valuable insights into radiation monitoring, considering the similarities in monitoring pitchblende ore for uranium mines.

The processing of rare earth ores is often a major concern due to the potential production of thorium, which can emit alpha particles. Monitoring plans should specifically address alpha-emitting sources since alpha particles do not travel far but can cause significant cellular damage, especially if inhaled. Extensive literature exists on monitoring alpha emissions from radon, a naturally occurring radioactive gas that has raised significant public health concerns regarding indoor air pollution in North American basements.

To ensure the environmental sustainability of rare earth metal production for electric vehicles, comprehensive monitoring and mitigation measures must be in place. By closely monitoring wastewater treatment systems, acidity levels, radioactivity, and alpha emissions, the industry can mitigate potential environmental risks and promote the safe and responsible production of rare earth metals (Ali, 2014).

6.6.6. Legal Factors

China has maintained a virtual monopoly on the global production of rare-earth elements for many years, with over 90% control of the current global supply and about 30% of the known reserves worldwide. Japan and the United States, the two main importers of rare earths, relied on China for over 90% of their supply by the 1990s. Rare earths, consisting of 17 elements including lanthanides, scandium, and yttrium, are crucial for various high-tech products such as hybrid car engines, cellphone batteries, and missile guidance systems.

The demand for rare-earth resources increased in the 1980s, primarily in Japan, the United States, and Germany, and has further risen due to the growing economies of China and India. While the United States dominated rare-earth production in the 1980s, China surpassed it within a decade, mainly due to lower production costs, lax environmental regulations, and significant state investment in the industry. China's monopoly is upheld by its abundant reserves, technical expertise, and control over multiple stages of the rare-earth processing chain.

Although China's rare-earth monopoly poses a significant trade dependence for advanced industrialized nations, it is not insurmountable. Japan is the largest consumer and importer of rare-earth elements and accounted for a significant portion of Chinese rare-earth exports. The dependency of Japan and the United States on Chinese rare-earth imports can be observed through market diversification measures.

China implemented production and export quotas in the early 2000s to regulate the rare-earth industry, aiming to stabilize the domestic market and limit exports. These policies, combined with efforts to centralize and consolidate the industry, have resulted in a situation similar to resource nationalism. China's policies effectively shift economic advantages from foreign buyers to domestic producers and the state, encouraging high-end manufacturers to invest in China.

The interpretation of Chinese rare-earth policy as economic statecraft for geopolitical leverage remains contested. Some argue that China used rare earths as a tool for economic resource nationalism, while others believe that environmental concerns or promoting the interests of domestic stakeholders were the primary motivations. Evidence suggests that an export ban occurred, leading to concerns about China's use of natural resources for political leverage.

The use of economic coercion in China's foreign relations extends beyond rare earths, undermining the credibility of China's denials. Previous studies have shown that political tensions between China and its trading partners can affect economic relations, supporting the notion that rare earths could have been used as a political bargaining tool (Vekasi, 2019).

6.6.7. Competitive Demand

Within renewables, there is competition for usage of REMs between EVs and storage, Wind Energy and Hydrogen energy as shown in Figure 6.4. The other less significant demand sectors are consumer Electronics, alloys in aerospace components, and as a control rod in nuclear reactors.

7

Results

Chapters 5 and 6 explains the implementation of steps 1 to 8 of the analysis model on the metals Lithium, Cobalt, Nickel, Copper, Aluminium and REEs. This chapter presents the results obtained from the analysis of criticality factors for metals used in electric vehicles (EVs) using the analysis model, and the interviews conducted on how to move away from the potential bottlenecks of critical metals. The results of criticality analysis of various metals, including Lithium, Cobalt, REEs (Neodymium and Dysprosium), and Nickel shown in the Tables below. This chapter also discusses the implications of the criticalities of these metals and sets the stage for exploring alternative paths to mitigate potential supply bottlenecks.

7.1. Results from Analysis Model

Table 7.1, 7.2, 7.3, 7.4, 7.5 and 7.6 shows of the 6 metals after implementing analysis using the criticality framework for each metal. The justifications for the impact column for each metal is found in the relevant subsection of text in this report mentioned in the corresponding row of the ”Section/Subsection” column. The color coding in the ”Impact” column was done in the following manner. If the contribution of a particular factor to the criticality of a certain metal is positive for electric vehicles, the corresponding row in the ”Impact” column is indicated as ”Low” by using the color green. If the contribution of a particular factor to the criticality of a certain metal is negative for electric vehicles, but there is already literature suggesting measures being implemented to solve the same, the corresponding row in the ”Impact” column is indicated as ”Moderate” by using the color white. If the contribution of a particular factor to the criticality of a certain metal is negative for electric vehicles, the corresponding row in the ”Impact” column is indicated as ”High” by using the color red. In this way, the ”Impact” column indicates the impact the particular factor has on the criticality of a particular metal for EVs.

The analysis reveals that certain metals exhibit high criticalities, indicating a higher level of risk of bottleneck in their supply chains. Among these metals, Nickel emerges as the most critical due to the combined influence of geological, political, economic, social, technological, environmental, legal, and competitive demand factors as mentioned in Chapter 6. The results further highlight the significance of Lithium, Cobalt, and REEs (Neodymium and Dysprosium) as metals with elevated criticalities. These findings underscore the need for proactive measures to ensure a secure and sustainable supply of these critical metals for the growing EV industry.

The high criticalities observed for Lithium, Cobalt, REEs, and Nickel necessitate a comprehensive examination of alternate paths that can minimize potential supply bottlenecks. This chapter investigates potential strategies by combining insights from literature research and expert interviews. The objective is to explore feasible solutions that address the identified challenges and provide recommendations for mitigating supply risks in the EV metal value chain.

The results obtained from analysis for copper and Aluminium indicate the following. For copper, the only factor that had a high impact on criticality is Competitive demand. However, this shouldn’t be a problem as the Reserve analysis by 2050 shows that there will be an abundant supply of copper even by 2050 despite considering the stringent scenario, which will be very well sufficient to meet this demand. For Aluminium, the contribution of Economic and Legal factors contribute to criticality. However, technological breakthroughs like solid-state recycling, low geopolitical tension and abundance of geological reserves by 2050 even in the stringent scenario makes Aluminium a non-critical metal for EVs.

Category	Cause	Event	Consequence		Impact on Criticality
Political	Lithium is mainly mined in a few countries, including Chile, Argentina, and Australia. Political instability or changes in government policies in these countries could affect the supply of lithium.	China possesses 73% of global lithium cell manufacturing capacity. Chinese companies have pursued mine investments in these countries to maintain a dominant position in lithium supply chain.	Governments may introduce regulations to nationalise lithium mining to prevent exploitation of workers and reduce the environmental impact of mining.	**6.1.1**	**High**
Economic	The demand for lithium has increased significantly due to the growing popularity of electric vehicles. This has led to price volatility and supply chain concerns.	The cost of lithium can significantly impact the cost of producing electric vehicles and the profitability of companies.	This could slow down the innovation and adoption of electric vehicles by consumers. This could also delay the transition to a more sustainable transportation system.	**6.1.2**	**Moderate**
Social	There is increasing awareness of the environmental impact of Lithium mining and this could drive demand for electric vehicles and lithium.	Consumers may be concerned about the environmental impact of lithium mining and could push for more sustainable and environmentally friendly mining practices. There is also a lack of social acceptance of recycled Lithium.	This could increase pressure on companies to find more sustainable and environmentally friendly ways to produce electric vehicle batteries. It could be used to create interest in the use of recycled or reused materials in the production of electric vehicle batteries.	**6.1.3**	**Moderate**
Technological	Lithium ion batteries demonstrate the highest combination of energy and power densities among rechargeable batteries. Lithium batteries also have advantages such as high recharge rate, low weight, low maintenance and high cycling life.	Lithium is a critical component in the batteries used in electric vehicles.	As battery technology evolves, it is possible that the reliance on lithium could decrease, reducing the criticality of lithium in the long term.	**6.1.4**	**High**
Environmental	Mining lithium can have a significant environmental impact, including water consumption, soil pollution, and habitat destruction.	There have been reports of water scarcity and pollution due to lithium mining in Chile's Atacama Desert. The mining of lithium in Argentina's Salinas Grandes salt flats has been criticized for causing soil erosion and desertification. The mining of lithium in Nevada's Thacker Pass has raised concerns about the impact on the local sage-grouse population.	Governments and consumers may push for more sustainable and environmentally friendly mining practices.	**6.1.5**	**High**
Legal	Companies may face legal challenges if they are found to be sourcing lithium unethically or using child labor in their supply chain.	China is a significant producer of lithium, and there have been reports of unethical practices in the country's Tibet Autonomous Region. Mining operations in the region have been linked to human rights violations, including forced labor and the displacement of local communities.	If a company is found to be engaging in unethical practices, it may face increased scrutiny from consumers, investors, and regulatory bodies. This could lead to increased reporting requirements and costs associated with supply chain audits and due diligence.	**6.1.6**	**Low**
Category	**Sectors**	**Event**	**Consequence**		**Impact on Criticality**
Competitive Demand	Energy Storage Systems, Air Treatment, Continuous Casting and Aluminium Production.	The EV Sector currently is and is likely to remain the primary driver for Lithium demand.	There will be no significant impact on EVS due to demand from other sectors as the impact of these demand sectors is not significant when compared to EVs which are the primary drivers of demand.	**6.1.7**	**Low**

Table 7.1: Criticality Analysis of Lithium

Category	Description			Section / Subsection	Impact on Criticality
Reserve Capacity by 2050	From the scenario analysis, we see that the depletion of cobalt occurs at a faster rate in the stringent scenario in comparison to the other two scenarios with an increase in cumulative demand of upto 10 million tonnes by 2050, peaking between years 2030 and 2035. This results in an estimated depletion of cobalt resources by the year 2035.			**5.3**	**High**
Category	**Cause**	**Event**	**Consequence**		**Impact On Criticality**
Political	Cobalt is mainly mined in the Democratic Republic of Congo (DRC), which has a history of political instability and conflict. This can create challenges for companies trying to secure a stable supply chain.	Cobalt Production in DRC increased from 63,000 tons in 2015 to 100,000 tons in 2019. This makes the DRC the most critical player in the sourcing of Cobalt and a hotspot of contention and exploitation.	Governments may introduce regulations to ensure ethical sourcing of cobalt to prevent exploitation of workers and reduce the environmental impact of mining.	**6.2.1**	**High**
Economic	DRC accounts for 60% of Global Cobalt production. The supply of cobalt can be affected by various factors, such as political instability, labor disputes, and environmental regulations.	The price of cobalt is highly volatile due to its limited supply and high demand. The price of cobalt has risen sharply in recent years due to the increasing demand for electric vehicle batteries. Price volatility can affect the affordability and availability of cobalt, which can impact the production of electric vehicles.	Cobalt can be substituted by other metals, such as nickel and manganese, in the production of electric vehicle batteries. The availability and cost-effectiveness of these substitutes can influence the criticality of cobalt for electric vehicles.	**6.2.2**	**High**
Social	There is increasing consumer awareness of the ethical and environmental implications of mining cobalt.	The Democratic Republic of Congo (DRC) which has very low living conditions. Additionally, there are very high risks of negative social conditions for most economic sectors, particularly for child and forced labor, insufficient wages, and the legal system.	This could impact the supply of Cobalt for electric vehicles and the reputation of companies that use cobalt in their products.	**6.2.3**	**High**
Technological	Cobalt is a critical component in the batteries used in electric vehicles. As battery technology evolves, it is possible that the reliance on cobalt could decrease, reducing the criticality of cobalt in the long term.	Cobalt is a key component in many rechargeable batteries, but it is also expensive and has ethical concerns related to mining practices. Companies are developing cobalt-free batteries that use alternative materials such as nickel, manganese, and aluminum.	Researchers are exploring the use of alternative materials that can replace cobalt in battery production.	**6.2.4**	**Low**
Environmental	Mining cobalt can have a significant environmental impact, including deforestation, soil erosion, and water pollution. Governments and consumers may push for more sustainable and environmentally friendly mining practices.	There have been multiple reports of exploitation of environmental resources due to Cobalt mining globally. These activities have resulted in significant impact to the environment and the communities around these refineries.	Mining companies are increasingly investing in research and development of new technologies aimed at reducing the environmental impact of mining and improving social practices. Criticism on cobalt mining has led to a shift towards alternative materials or technologies that do not rely on cobalt.	**6.2.5**	**Low**
Legal	Companies may face legal challenges if they are found to be sourcing cobalt unethically or using child labor in their supply chain.	The DRC signed a new law in March 2018 which increased taxes on mining companies and doubled government royalties from the mining industry. Metals such as copper or cobalt have consistently been the object of export restrictions during 2009-2019 in nations such as China, Indonesia, Argentina, the DRC, and even Zambia.	Governments may introduce regulations around the sourcing and use of cobalt in batteries, which could impact the cost of production for companies. Tensions are abounding between countries that are sites of production and countries wishing to access resources and clients. The balance of power is no longer systematically in favor of the latter, but increasingly in favor of the former.	**6.2.6**	**Low**
Category	**Sectors**	**Event**	**Consequence**		**Impact On Criticality**
Competitive Demand	Batteries, Electric Vehicle Components, Aerospace, Defence and Energy Sector.	EV Batteries are the primary drivers for Cobalt demand and is likely to remain the same in the future.	There will be no significant impact on Electric vehicles due to competetive demand for Cobalt from other demand sectors.	**6.2.7**	**Low**

Table 7.2: Criticality Analysis of Cobalt

Category	Description			Section / Subsection	Impact On Criticality
Reserve Capacity by 2050	From the scenario analysis, we see that the depletion of nickel occurs at a faster rate in the stringent scenario in comparison to the other two scenarios with an increase in cumulative demand of upto 68 million tonnes by 2050, peaking between years 2030 and 2035. This results in an estimated remaining reserve of 10 million tonnes by 2050.			**5.3**	**Moderate**
Category	**Cause**	**Event**	**Consequence**		**Impact On Criticality**
Political	Nickel is mainly mined in a few countries, including Indonesia, the Philippines, and Russia. Political instability or changes in government policies in these countries could affect the supply of nickel.	In 2020, Indonesia implemented an earlier-than-expected ban on nickel ore export. This led to a sharp decline in nickel ore exports to China and an increase in nickel pig iron exports.	The future supply of nickel will heavily depend on developments in Indonesia. Any physical events or policy changes in Indonesia could significantly impact global nickel supply chains.	**6.3.1**	**High**
Economic	Supply and demand factors, along with geopolitical shifts, have gained significant influence in the dynamics of the nickel market.	The nickel price initiated a continuous and substantial upward movement, characterized by high volatility. This rise was influenced by various external events, including the COVID-19 pandemic and the Russia-Ukraine conflict.	Major economies are placing great importance on the security of critical minerals and strengthening their control over nickel resources.	**6.3.2**	**High**
Social	There is increasing consumer awareness of the ethical and environmental implications of mining Nickel.	Indonesia is one of the largest nickel-producing countries in the world, where there have been concerns about child labor and forced labor in small-scale nickel mining operations. The Philippines , Russia and New Caledonia have reported similar cases as well.	This could impact the demand for electric vehicles and the reputation of companies that use Nickel in their products.	**6.3.3**	**Moderate**
Technological	Nickel is a critical component in the batteries used in electric vehicles. As battery technology improves, the efficiency of batteries is likely to increase.Nickel based battery chemistries are being adopted to move away from Lithium in batteries.	NCA is more expensive than LMO batteries but offers advantages such as higher specific capacity , higher energy density , and longer life compared to . It has been successfully utilized in electric vehicles, including Tesla products like Model X, Model S, and Model 3.	These new battery chemistries could further increase demand for nickel in the long term.	**6.3.4**	**High**
Environmental	Mining nickel can have a significant environmental impact, including deforestation, soil erosion, and water pollution.	In 2019, nickel mining operations in Sulawesi, Indonesia, were found to have caused deforestation, soil erosion, and water pollution, affecting the livelihoods of nearby communities and damaging local ecosystems. Similar effects were observed in New Caledonia , and Norlilsk (Russia) as well.	Governments and consumers may push for more sustainable and environmentally friendly mining practices.	**6.3.5**	**Low**
Legal	Icountries wish to secure their critical metal resources to avoid exploitation by foreign superpowers.	As one of the world's largest nickel producers, Indonesia's export ban had a substantial impact on the global nickel market.	The restriction created a shortage of nickel ore in the market, leading to a rise in prices. This event highlighted the vulnerability of the nickel industry to policy changes and demonstrated how geopolitical factors can disrupt the availability and pricing of this crucial metal.	**6.3.6**	**High**
Category	**Demand Sectors**	**Event**	**Consequence**		**Impact On Criticality**
Competitive Demand	Stainless Steel Production (Demand Drivers) accounts for approximately two-thirds of global nickel demand. The chemical industry is the fourth-largest consumer of nickel, and demand for nickel in this sector is expected to grow as the global population continues to increase.Nickel is also used in some renewable energy technologies, such as wind turbines and solar panels.	The global Nickel market is in a changing phase. The primary drivers of demand is and has historically been the production of stainless steel. However, growing EV industry and competition within renewable technologies such as Geothermal, Hydrogen, Wind and Nuclear energy will assure high competition for accessing Nickel supplies for these technologies.	Due to high competition for demand, the Demand for class 1 Nickel is projected to be around 1.5 million tonnes by 2025. The supply for 2025 is estimated to be 1.2 million tonnes which will not be sufficient to meet the demand needs.	**6.3.7**	**High**

Table 7.3: Criticality Analysis of Nickel

Category	**Description**			**Section / Subsection**	**Impact On Criticality**
Reserve Capacity by 2030	From scenario analysis, it is predicted that there will still be an abundance of copper by 2050 despite considering the stringent scenario. There is estimated to be a cumulative demand for copper of 182 million tonnes and about 540 million tonnes of copper in geological reserves by the year 2050.			**5.3**	**Low**
Category	**Cause**	**Event**	**Consequence**		**Impact On Criticality**
Political	Political instability and conflicts in some copper-producing countries can disrupt the supply chain and lead to price volatility.	The US-China trade war has had a significant impact on the global copper market. China is the world's largest consumer of copper, and the trade war has led to a decrease in demand for copper from China, which has led to a drop in copper prices.	The increase in EVs globally will spread the demand for copper, compensating the price volatility due to geo-political tensions.	**6.4.1**	**Low**
Economic	The price of copper is highly dependent on global demand and supply.According to the International Copper Association, an electric vehicle uses four times as much copper as a conventional vehicle.	In 2021, the price of copper reached a record high, owing to the increase in copper demand by the EV industry.	This can increase the cost of electric vehicles and make them less affordable for consumers.	**6.4.2**	**Low**
Social	There is increasing consumer awareness of the social implications of mining Copper.	In Peru, the copper mining company, Las Bambas, has faced protests and social conflicts from local communities who claim that the mine has caused environmental damage and disrupted their way of life. In Chile, the copper mining company, Codelco, has faced criticism from workers and labor unions over working conditions, safety measures, and labor rights.	Mining companies are committing to a range of social responsibility initiatives, such as improving safety and health standards for its workers, reducing its carbon emissions, and supporting local communities for the mining of copper.	**6.4.3**	**Low**
Technological	The development of new technologies can impact the demand for copper.	The development of wireless charging technology eliminates the reduce the need for copper in charging infrastructure such as in the cables and charging pins.	The development of new technologies can influence the criticality of copper for EVs.	**6.4.4**	**Moderate**
Environmental	The production of copper can have a significant impact on the environment. The mining and processing of copper can lead to water pollution, soil contamination, and deforestation.	In USA, the Berkeley Pit copper mine in Montana has resulted in significant water pollution due to copper mining. Similar environmental impacts due to copper mining have been observed in Indonesia and The Democratic Republic of Congo.	Governments and consumers may push for more sustainable and environmentally friendly mining practices.	**6.4.5**	**Moderate**
Legal	The use of copper in electric vehicles can also be impacted by regulations on the use of hazardous materials.	The EU's Restriction of Hazardous Substances (RoHS) directive restricts the use of certain hazardous substances, including lead and cadmium, in electronic and electrical equipment.	Such regulations would force EV manufacturers to move away from copper usage in the vehicles.	**6.4.6**	**Low**
Category	**Demand Sectors**	**Event**	**Consequence**		**Impact On Criticality**
Competitive Demand	Electrical and Electronics, Construction, Solar Panels, Transportation (ICE vehicles) and Industrial machinery, Wind, Solar PV, Bio-energy, Electrical Networks and EVs.	The EV Sector currently is and is likely to remain the primary driver for Copper demand, as it is used in electrical wiring, motors, transformers, and other electronic components in vehicles. However, there is heavy competition for Copper among renewable technologies such as Wind, Solar and Bio-energy.	With the growing popularity of Renewable Technologies, there would be heavy competition for the demand of Copper.	**6.4.7**	**High**

Table 7.4: Criticality Analysis of Copper

Category	Description			Section / Subsection	Impact on Criticality
Reserve Capacity by 2030	From scenario analysis, it is predicted that there will still be an abundance of aluminium by 2050 despite considering the stringent scenario. There is estimated to be a cumulative demand for copper of 562 million tonnes and about 5300 million tonnes of copper in geological reserves by the year 2050.			**5.3**	**Low**
Category	**Cause**	**Event**	**Consequence**		**Impact on Criticality**
Political	10% of the global aluminium demand is met by Ukraine and Russia. A conflict between these countries would lead to supply chain disruptions in aluminium trade.	The Russia - Ukraine war has resulting in aluminium prices soaring at a record high	As a solution to the difficult circumstances ranging from COVID-19 to the Russia-Ukraine war, the top aluminum producing companies focused their efforts on secondary (recycled) aluminum as a less expensive option during the difficult period.	**6.5.1**	**Low**
Economic	The demand for aluminium has increased significantly due to the growing popularity of electric vehicles. This has led to price volatility and supply chain concerns.	For example, the demand for electric vehicles has been growing rapidly in China, which has driven up the demand for aluminum in the automotive industry.	Fluctuations in the price of aluminum can impact the cost of producing electric vehicles, affecting their affordability for consumers.	**6.5.2**	**High**
Social	Aluminium mining has been associated with human rights abuses, such as forced labor, child labor, and violations of workers' rights.	There have been instances of human rights abuses in the supply chains of several major companies, including Apple and Microsoft, which source aluminium from companies in China.	This could increase pressure on companies to find more sustainable and environmentally friendly ways to produce aluminium.	**6.5.3**	**Low**
Technological	Technological advancements in the production and use of aluminum can significantly impact the electric vehicle industry.	Advances in aluminum alloy design have led to the development of stronger and more lightweight aluminum alloys that are well-suited for use in electric vehicle components such as battery housings and structural components. Additionally, innovations in manufacturing processes such as 3D printing can increase the efficiency and cost-effectiveness of producing aluminum components for electric vehicles.	These advancements could drive up aluminium demand in the future	**6.5.4**	**Moderate**
Environmental	Aluminium production is energy intensive and requires the most amount of energy for production which results in significant greenhouse gas emissions, particularly if the electricity used to power the process comes from fossil fuels.	According to the International Energy Agency, the aluminium sector accounted for about 1% of global greenhouse gas emissions in 2018.	Governments and consumers may push for more sustainable and environmentally friendly production practices.	**6.5.5**	**Moderate**
Legal	Government policies and regulations can significantly impact the production and demand for aluminum in the electric vehicle industry.	The EU's CO2 emissions regulations have driven automakers to increase the use of aluminum in their electric vehicle designs to reduce weight and improve efficiency.	Tesla's Model S electric car and Audi's e-tron electric SUV uses a high-strength aluminum structure to reduce weight and improve range of the vehicle.	**6.5.6**	**High**
Category	**Demand Sectors**	**Event**	**Consequence**		**Impact on Criticality**
Competitive Demand	Transportation, Construction, Packaging, Electrical wiring and cables, and Consumer Goods.	Transportation Industry is the primary driver for aluminium demand.	The increase in EVs will not have a significant impact on aluminium demand, since these EVs will replace ICE vehicles which also use aluminium in their chasis.	**6.5.7**	**Low**

Table 7.5: Criticality Analysis of Aluminium

Category	Description			Section / Subsection	Impact on Criticality
Reserve Capacity by 2030	Though there seems to be a sufficient amount of Neodymium in 2050, the same cannot be said for Dysprosium considering the stringent scenario for both metals. The cumulative demand for Dysprosium between 2015 and 2050 is estimated to be 0.1 million tons. The available geological reserve by the end of 2050 is predicted to be a meagre 0.97 million tonnes. For Neodymium, there is estimated to be a cumulative demand for copper of 2.8 million tonnes and about 10 million tonnes of copper in geological reserves by the year 2050.			5.3	High
Category	Cause	Event	Consequence		Impact on Criticality
Political	Political factors play a crucial role in determining the criticality of REMs for EVs. China has a monopoly on the production and supply of REMs, accounting for over 90% of the world's total production.	The geopolitical tensions and trade policies between countries significantly affect the supply and demand of these metals. The Chinese government has also imposed export quotas and taxes, limiting the availability of these metals for other countries.	Political stability and cooperation among countries are crucial to ensure a consistent supply of REMs for EVs.	6.6.1	High
Economic	The increasing demand for EVs and the limited availability of REMs can cause a significant rise in their prices. This, in turn, can lead to an increase in the cost of EV production and affect their affordability for consumers. Moreover, the lack of domestic production of these metals in some countries can also impact their economies negatively.	The COVID-19 pandemic has impacted global supply chains and disrupted the production of rare earth metals, leading to a shortage and driving up the prices. Furthermore, geopolitical tensions between China and other countries have also impacted the prices of rare earth metals.	Countries need to invest in domestic production and recycling technologies to reduce their reliance on imports and ensure the affordability of EVs.	6.6.2	Low
Social	The increasing awareness and concern for environmental sustainability have led to a surge in demand for EVs. However, the negative impacts of REM mining on the environment and communities can also affect the acceptance and adoption of EVs.	Radioactive and non-radioactive contamination in areas of China have been raised as a major concern. There have also been protests at the Lynas Corporation plant in Malaysia due to people being aware of the negative experiences that a previous RE processing site had on the peninsula. the RE sector.	Recycling technologies for micro-retrieval of REMs need to improve.	6.6.3	Low
Technological	Technological advancements in the production and recycling of REMs can significantly impact the criticality of these metals for EVs. Moreover, advancements in recycling technologies can improve the availability of these metals and reduce the environmental impacts of mining.	Neodymium is a rare earth metal that is used in powerful magnets. Researchers are exploring the use of alternative materials such as iron, cobalt, and nickel to create magnets with similar properties.There is also ongoing research on Rare-Earth free magnets for Electric Vehicles.	Investment in research and development of new technologies is crucial to ensure the sustainable production and supply of REMs for EVs.	6.6.4	Low
Environmental	Environmental factors such as the impacts of REM mining and disposal can also affect the criticality of these metals for EVs. REM mining and processing can cause significant environmental damage, including soil and water pollution and habitat destruction. Moreover, the disposal of used batteries and electronics containing REMs can also lead to environmental contamination.	Baotou is one of the largest REM mining and processing centers in China. The mining and processing of REMs have caused severe environmental damage, including water and soil pollution, deforestation, and habitat destruction. The Yellow River, which flows through Baotou, has been severely contaminated with heavy metals, acids, and other pollutants from REM processing plants. Similar instances of environmental damage have been reported in REE mines in Malaysia and Canada.	Sustainable and ethical mining practices and proper disposal and recycling of these metals are crucial to reduce their environmental impacts and ensure their availability for the EV industry.	6.6.5	Moderate
Legal	The Global Supply for Rare Earths is concentrated in countries like China.	Countries are implementing export bans to empower resource nationalism and for geopolitical benefits.	There needs to be urgent diversification of supply of REEs globally to prevent dependence on countries like China.	6.6.6	High
Category	Demand Sectors	Event	Consequence		Impact on Criticality
Competitive Demand	Clean Energy Technologies like wind turbines use permanent magnets made with Dysprosium. They are also used in Consumer Electronics, alloys in Aerospace components, and as a control rod in nuclear reactors.	The EV Sector is likely to be the primary driver for Dysprosium demand.	With an increase in renewables being implemented globally in order to comply with agreements to mitigate climate change such as the Paris Goals, there is expected to be a competiton within these renewable technologies for Dysprosium, especially considering the already small availability of the metal in the stringent scenario.	6.6.7	High

Table 7.6: Criticality Analysis of Rare Earths

From these tables, it can be seen that the metal that is the most critical for EVs is Nickel. Lithium, Cobalt, Neodymium and Dysprosium also have high net criticalities in the EV context. Hence, this section will discuss the alternate paths which will reduce the dependencies of EVs on these metals, with the help of interviews conducted with experts (Appendix: Section A2) and literature research.

7.2. Results from Interviews

Expert interviews were conducted based on these results in order to identify alternate paths to mitigate these bottlenecks. The take-aways of these interviews are as shown below.

7.2.1. Interview with Experts 1 and 2

This interview provided the opportunity to engage with two anonymous experts from the battery research group at TU Delft. These experts, referred to as E1 and E2 in the transcript below, are highly knowledgeable and experienced in the field of battery technologies. They are actively involved in cutting-edge research and development, focusing on alternative battery chemistries, including Potassium and Sodium-ion batteries. Additionally, both experts have industrial expertise as they work closely with BatteryNL, an organization with a range of objectives related to advancing battery technology. BatteryNL is a company that operates with several objectives in mind. Firstly, they aim to unravel the complex interface processes in next-generation lithium battery chemistries using novel and state-of-the-art methodologies. Their research is specifically targeted at newly developed 2D and 3D model interfaces and representative battery morphologies. Another objective of BatteryNL is to develop new scalable and economically viable interface strategies that can mitigate performance degradation in batteries. BatteryNL also places importance on supporting the integration of new battery technologies through techno-economic and sustainability evaluations. They actively engage with society to assess the impact and feasibility of implementing these technologies in real-world applications. By evaluating the techno-economic aspects and addressing sustainability concerns, BatteryNL aims to drive the adoption and successful integration of new battery technologies. Lastly, BatteryNL strives to stimulate battery technology developments and collaborations in the Netherlands. They establish roadmaps and exploitation plans to guide the advancement of battery technologies and foster collaboration among stakeholders. By organizing interactions and networking opportunities, BatteryNL creates an environment conducive to innovation and knowledge exchange within the battery technology domain.

The insights and expertise shared by Expert 1 and Expert 2 in this interview provide valuable perspectives on the research, development, and potential applications of alternative battery technologies. Their contributions shed light on the advancements, challenges, and the overall landscape of the battery industry, aligning with the objectives of BatteryNL and contributing to the broader field of energy storage. Expert 1 also shared content from a seminar he had given on critical metals in batteries, which was shared and was very valuable for this research.

The detailed interview can be found in section A2.1 in the Appendix. Both Experts 1 and 2 agreed that traditional lithium, nickel, and cobalt-based battery chemistries face challenges related to limited availability, environmental and social impacts of mining, fluctuating costs, and safety concerns. Potassium and Sodium-ion batteries are emerging alternatives to traditional chemistries, utilizing larger ions and potentially more abundant metals like potassium and sodium. Their performance, energy density, and cost profiles are still being explored and optimized. Ongoing research efforts focus on finding new materials for batteries, including alternative cathode materials and improved anode materials and electrolytes. The goal is to reduce or eliminate the use of critical metals and enhance sustainability. Potential applications for Potassium and Sodium-ion batteries include stationary energy storage systems and electric vehicles, where they can help balance intermittent renewable energy sources and provide cost-effective solutions. They also mentioned that challenges to overcome for commercial viability include improving energy density and cycle life, optimizing manufacturing processes, ensuring safety and reliability, and establishing robust supply chains for potassium and sodium materials. The commercial availability timeline for Potassium and Sodium-ion batteries is uncertain and depends on research progress, funding, technological breakthroughs, and market demand. Widespread adoption of alternative battery technologies could diversify the battery market, reduce reliance on critical metals, accelerate the clean energy transition, and enable better matching of energy storage technologies to specific applications. Other emerging battery technologies mentioned in the interview include solid-state batteries, lithium-sulfur batteries, and flow batteries, each with their own potential impact on the energy storage landscape. Policymakers and industry players can support the development and deployment of alternative battery technologies through funding, regulatory frameworks, standards, incentives, and collaboration among stakeholders. Assigning equal importance to factors contributing to criticality, such as availability, geopolitical factors, supply chain risks, and environmental impacts, ensures a comprehensive and unbiased assessment of criticality in the battery industry.

Overall, the interview provides valuable insights into alternative battery technologies, their potential applications, challenges, and the broader implications for the battery industry and the clean energy transition. The experts' perspectives contribute to advancing sustainable and innovative approaches to energy storage.

7.2.2. Interview with Expert 3

The following interview was conducted with an Assistant Professor in the Storage of Electrochemical Energy (SEE) group at the Reactor institute Delft. With a background in Applied Physics and Financial Economics, as well as a PhD in Chiral Magnetism, the interviewee brings a diverse range of expertise to their research. Their current focus lies in studying thin film materials for sustainable applications and exploring the interfacial properties of battery materials. Additionally, they hold the role of instrument scientist for a neutron reflectometer, a powerful experimental technique for studying thin films. The expert is referred to as E3 in the transcript, and has also has been researching on understanding the interfacial properties of battery materials, which is crucial for enhancing battery performance. The interviewee employs in-operando neutron scattering and other experimental techniques to investigate the nanoscale ionic transport across various interfaces within batteries. By studying these interfaces non-destructively, they aim to unravel the factors that influence battery performance and contribute to advancements in battery technology.

The detailed interview can be found in section A2.2 in the Appendix. Expert 3 had the opinion that the dominance of lithium-ion batteries, especially in electric vehicles (EVs), makes lithium a critical metal. However, the importance of specific metals varies globally, and it is essential to consider all factors without bias. Iron phosphate-based batteries are being explored as an alternative to nickel-based batteries for specific applications, but they have limitations such as shorter lifetime. Sodium-ion and potassium-ion batteries are being researched as alternatives, but their commercial readiness level may not be as high yet. They could be suitable for low-power applications like city vehicles. The performance of recycled nickel and cobalt in batteries depends on the purity obtained through recycling processes. However, until sufficient recycled sources are available, new nickel production will still be needed. Iron phosphate batteries may not be the future for electric vehicles due to lower energy and power densities compared to current chemistries. Ongoing research is exploring alternative chemistries, anode materials, and solid-state electrolytes. Rare earth elements are used more commonly in battery management systems rather than in the core of the battery. It is possible to make batteries work without rare earths, but their absence may impact efficiency. Ongoing battery research focuses on exploring alternative chemistries, increasing energy density through anode materials, and developing solid-state electrolytes to enhance safety and energy density. Battery weight impacts parameters like energy density and power density, but a comprehensive analysis of the entire battery system is necessary to evaluate overall energy efficiency. Policies and regulations are being implemented by the European Union and the United States to become more self-sufficient in critical metals, promote sustainable practices, and reduce dependence on them. The criticality of metals is determined by a combination of factors, including ease of substitution and availability of alternatives. The application itself plays a crucial role in assessing metal criticality. Polymer-based electrolytes in batteries are not preferred due to challenges in recycling, energy-intensive production, environmental impact, and safety risks. Solid-state electrolytes are explored as alternatives.

The interview provides insights into the current status and future directions of battery technologies, exploring the criticality of metals, alternative chemistries, recycling, and environmental considerations in the design process.

7.2.3. Interview with Expert 4

This interview an Assistant Professor at the Faculty of Industrial Design Engineering at TU Delft who is referred to as E4 in the interview transcript. With a strong focus on sustainable design, quantification of environmental impacts, and industrial ecology, E4's expertise lies in understanding how environmental considerations can shape the field of design and contribute to a more sustainable future. With a background in critical raw materials and supply chain resilience, E4 brings a unique perspective to the conversation, exploring the intersection of sustainable design and the challenges associated with material sourcing and resource management.

This interview delved into E4's current research interests, which revolve around the quantification of environmental impacts and how this knowledge can inform sustainable design decisions. Furthermore, the crucial role of critical raw materials in the design process and the need for resilient supply chains to ensure sustainability was explored.

E4's extensive experience in the field of industrial ecology allows for insightful discussions on topics such as circular economy and system-level concepts. By understanding the interplay between product design choices and broader system-level implications, E4 sheds light on the importance of considering lifecycle assessments, environmental footprints, and circularity in the design process.

The detailed interview can be found in section A2.3 in the Appendix. E4's research interests focus on the quantification of environmental impacts to inform sustainable design decisions and the challenges associated with material sourcing and resource management. Recycling lithium in electric vehicle (EV) batteries is technically feasible and relatively cheap compared to other metals. However, the organizational aspects of collection and transportation to recycling facilities pose challenges. Substitution options for metals like cobalt and nickel are being explored, such as LFP batteries or sodium batteries. Recycling remains an area of ongoing research. Large-scale adoption of alternative batteries may face supply chain challenges that require significant efforts to establish. Consumer demand for clean energy solutions can create market incentives for the development and commercialization of new technologies. Circular business models will play a crucial role in reducing the consumption of critical metals in EVs. Legislation and regulations that promote recycling, extended product lifespan, and improved recyclability are essential. Government policies are crucial in reducing car dependency, promoting alternatives, and driving transitions to sustainable practices. Fewer cars overall can be achieved through car sharing and improved public transport systems. The main challenges in incorporating transitions to reduce dependency on critical metals include economic feasibility within the current system, lobbying against transitions, insufficient resource availability, political tensions, and varying interests among countries. Geopolitics and potential disruptions in critical metal supply chains pose significant risks. Reducing dependency on critical metals is important due to geopolitical factors and the potential impact of conflicts on markets and supply chains. Cobalt faces the highest risks among critical metals due to China's dominant position in scaling up its capacity. While lithium has a relatively lower risk, the geopolitical landscape remains a concern. Consumer behavior changes are challenging to achieve without policies and incentives. Encouraging practices like carpooling requires policy interventions to drive consumer behavior. Overall, the interview highlights the importance of considering environmental impacts and sustainable practices in design decisions, the challenges of material sourcing and recycling, the role of circular business models, the need for government policies and regulations, and the risks associated with dependency on critical metals in the transition to sustainable technologies.

Based on the results obtained from analysis and interviews, alternate paths to mitigate the dependence of EVs on these vehicles will be explained in the next chapter.

8

Discussions

From chapter 7, it can be seen that the analysis and interviews have yielded valuable insights into the criticalities of various metals within the context of electric vehicles (EVs). These criticalities are indicative of potential supply bottlenecks, with certain metals demonstrating elevated levels of risk. Notably, Nickel emerges as the most critical metal due to a convergence of geological, political, economic, social, technological, environmental, legal, and competitive demand factors, as detailed in Chapter 6.

Lithium, Cobalt, and Rare Earth Elements (Neodymium and Dysprosium) also exhibit elevated net criticalities, emphasizing their importance within the EV supply chain. These findings underscore the necessity for proactive measures to ensure a stable and sustainable supply of these critical metals to support the burgeoning EV industry.

The elevated net criticalities observed for these metals necessitate a comprehensive exploration of alternative pathways that can mitigate potential supply bottlenecks. This chapter delves into potential strategies derived from a synthesis of scholarly research and expert interviews. The aim is to uncover viable solutions that address the identified challenges and provide practical recommendations for alleviating supply risks within the EV metal value chain.

Furthermore, the outcomes of the analysis regarding Copper and Aluminium are as follows. For Copper, competitive demand emerges as the primary influential factor for criticality. However, a comprehensive Reserve analysis up to 2050 indicates a substantial surplus in copper supply, even under stringent scenarios. This projection reassures an ample supply to meet demand. Conversely, Aluminium's criticality is attributed to contributions from Economic and Legal factors. Notably, the advent of solid-state recycling, low geopolitical tension, and abundant geological reserves by 2050, even under stringent conditions, renders Aluminium a non-critical metal for EVs.

Upon careful examination, it becomes evident that Nickel is the most critical metal for EVs, followed by Lithium, Cobalt, Neodymium, and Dysprosium. Consequently, this section will elaborate on alternative pathways to diminish EV dependency on these metals. These insights are gleaned from expert interviews conducted, coupled with thorough literature research.

In the subsequent subsection, the chapter delves into the results stemming from these insightful interviews. Expert perspectives are invaluable in uncovering viable strategies for mitigating identified bottlenecks. The interviews provide a holistic view of alternative battery technologies, challenges associated with critical metals, emerging chemistries, recycling prospects, environmental considerations, and regulatory influences.

Expert 1 and Expert 2, distinguished members of the battery research group at TU Delft, expound upon alternative battery chemistries, particularly Potassium and Sodium-ion batteries. These experts, deeply embedded in pioneering research and development, shed light on the advancements, challenges, and the broader battery industry landscape. Their insights encompass the potential of emerging technologies, their applications, challenges in scaling, and prospective timelines for commercial viability.

The following interview, involving Expert 3 from the Storage of Electrochemical Energy (SEE) group at the Reactor Institute Delft, uncovers critical considerations concerning alternative chemistries, recycling, and environmental impacts. This expert provides an intricate understanding of how specific battery technologies impact critical metal dependencies, recycling processes, and sustainable design.

In a subsequent interview, Expert 4, an Assistant Professor in the Faculty of Industrial Design Engineering at TU Delft, draws attention to the intersection of sustainable design, material sourcing challenges, and resource management. Their expertise elucidates the role of circular business models, regulatory frameworks, and geopolitical factors in shaping the trajectory of critical metal usage in EVs.

Collectively, the analysis and interviews offer a comprehensive framework for mitigating critical metal dependencies in the EV ecosystem. Informed by these insights, the upcoming sections will delve into elucidating the strategies and recommendations derived from this rich repository of knowledge.

8.1. Alternate Paths to minimize Supply Bottlenecks

The analysis of existing literature offers valuable insights into the current state of research and industry practices related to mitigating supply bottlenecks. Various studies, reports, and academic publications are reviewed to identify emerging technologies, innovative approaches, and policy interventions aimed at securing critical metal supplies for EVs. The literature research serves as a foundation for assessing the viability and effectiveness of potential alternative paths. In addition to the literature research, expert interviews play a crucial role in understanding the practical aspects and real-world implications of alternative paths. Interviews with experts in battery technologies, critical materials, and circular design provided valuable perspectives on the feasibility, scalability, and potential challenges associated with different strategies as explained in chapter7. These interviews help validate and refine the findings from the literature research, contributing to a comprehensive understanding of the available options for addressing supply bottlenecks. The section below is a result of literature research done based on results from the interviews conducted with experts from academia and industries.

Current developments in manufacturing and recycling of traction batteries, electric motors, and power electronics are driving efforts to reduce or eliminate the need for critical metals in electric vehicles (EVs). Recycling processes for traction batteries and other EV components are being improved to enhance the recovery of valuable metals and minimize the reliance on new raw materials. By implementing advanced recycling techniques, the industry aims to close the material loop, reducing the environmental impact associated with critical metal extraction and promoting a more sustainable circular economy for EVs. Researchers are actively exploring alternative battery technologies as a means to decrease the reliance on critical metals. One promising avenue is the development of solid-state batteries, which offer the potential to replace conventional lithium-ion batteries and significantly reduce the use of critical metals. Solid-state batteries employ solid electrolytes instead of liquid ones, providing improved energy density, enhanced safety, and the possibility of utilizing more abundant and environmentally friendly materials. These advancements in battery technology could revolutionize the EV industry by reducing the criticality of metals and paving the way for more sustainable energy storage solutions.

Efforts are also focused on developing electric motors that are more efficient and require fewer critical metals. Researchers are exploring innovative motor designs and materials to optimize performance and minimize reliance on scarce resources. For instance, advancements in motor technologies incorporating aluminum in place of copper for certain components can reduce the demand for critical metals while maintaining or even improving motor efficiency. By pursuing these motor alternatives, the EV industry aims to enhance resource efficiency and reduce the environmental impact associated with critical metal extraction and utilization.

Power electronics, a crucial component of EVs, are also being targeted for alternative material solutions to reduce the need for critical metals. Silicon carbide (SiC), a wide-band gap semiconductor, is gaining attention as a substitute for conventional materials like silicon in power electronics. SiC offers superior thermal conductivity and higher operating temperatures, enabling more efficient and compact designs. By leveraging SiC and other alternative materials, the industry aims to minimize the reliance on critical metals like cobalt, which is often used in power electronic devices. This shift towards alternative materials in power electronics contributes to the overall goal of reducing criticality in the EV supply chain.

Material substitution plays a significant role in mitigating the criticality of metals in EVs. Researchers and industry stakeholders are actively seeking alternative materials that can replace critical metals in various components. For example, aluminum is being explored as a substitute for copper in electric motors and inverters, offering similar electrical conductivity while being more abundant and less critical. Similarly, manganese is being investigated as a potential replacement for cobalt in battery cathodes, addressing concerns related to cobalt sourcing and reducing supply chain vulnerabilities. These material substitution efforts contribute to the overall objective of diversifying and securing the supply of critical metals, thereby enhancing the sustainability and resilience of the EV industry (Grandell et al., 2016).

These are the directions in which the literature research and interviews will be conducted. Based on the results of the literature research and expert interviews, recommendations for tackling the identified supply bottlenecks will be provided. The recommendations encompass a range of approaches, including technological advancements, diversification of supply sources, recycling and circular economy initiatives, sustainable sourcing practices, policy and regulatory interventions, and collaborative efforts among stakeholders. The proposed recommendations aim to ensure the long-term availability, affordability, and sustainability of critical metals for the EV industry, thereby mitigating potential supply disruptions and supporting the transition to a greener transportation sector.

8.1.1. Rare Earths in EV Motors

The main source of demand for Neodymium and Dysprosium (REEs) in EVs are in the permanent magnets used in EV motors as mentioned in Chapter4. The criticality of rare earth metals in electric vehicles (EVs) can potentially be alleviated in the future through advancements in material efficiency, motor design, and component substitution. Experts anticipate improvements in the utilization of rare earths for the production of NdFeB magnets, which are commonly used in electric motors. Table 8.1 shows the various types of Electric Motors currently adopted or under development in the EV Industry. This table also shows the Rare-Earth Content for each type of Motor. While complete substitution of rare earths may not occur in the near term, it is believed that the proportion of Nd and Pr in NdFeB composition could decrease from 30% to 26.5% by 2020. Additionally, the Dy content in NdFeB magnets, currently at around 7.5%, could potentially be reduced to approximately 5% for plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs). Optimized motor designs, such as the hybrid design utilized in BMW's i3 motor, could lead to the usage of fewer NdFeB magnets (Ballinger et al., 2020).

Furthermore, some manufacturers may opt to continue using or switch to motors that do not rely on rare earths for battery electric vehicles (BEVs). Pilot concepts for rare earths-free motors in hybrid vehicles (PHEVs and HEVs) are also being explored and show promising potential for commercialization. However, the precise rate of substitution penetration remains uncertain due to various parameters and the unpredictability of future technological and economic developments. Currently, the availability of rare earths at low prices and sufficient supply does not provide a strong incentive to transition to rare earths-free motors, unless they become more cost-effective and performance-efficient (Pavel et al., 2017).

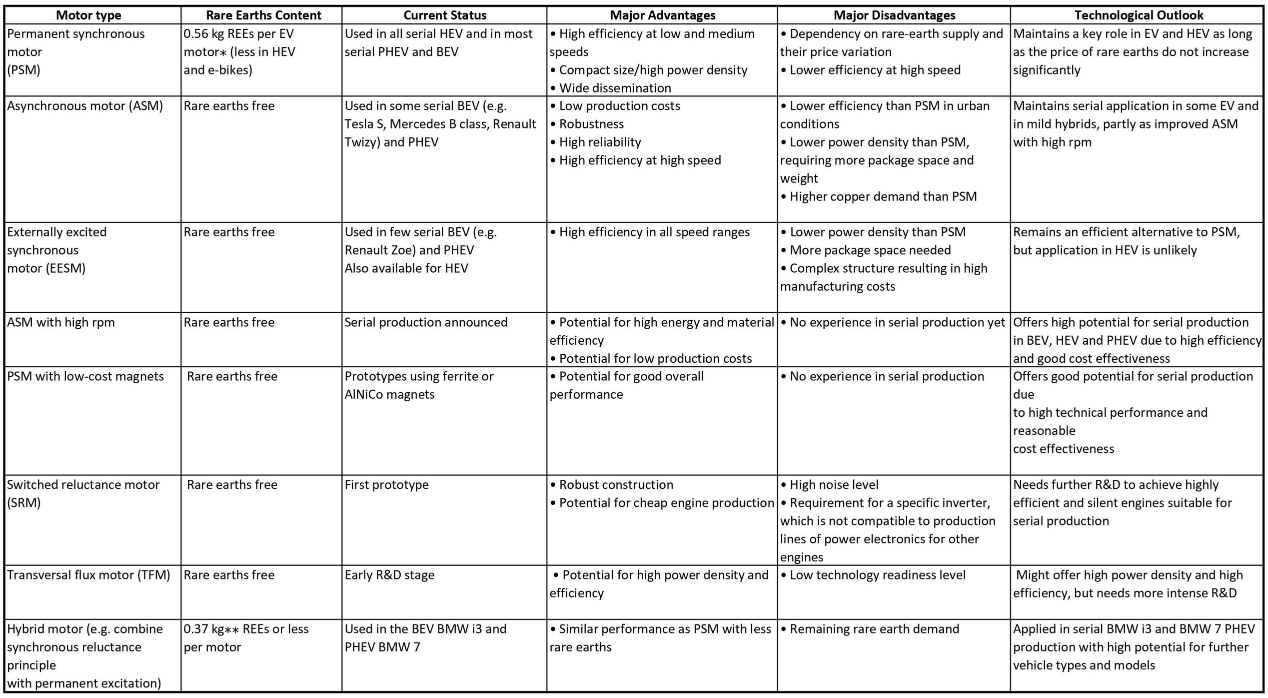
In this context, experts see promise in the development of high rpm axial flux synchronous motors (ASM) which exhibit high efficiency and could be produced at lower costs. Considering possible technological advancements and insights from experts, this study analyzes different substitution scenarios based on three main parameters: materials efficiency, dematerialization (reducing NdFeB content), and component substitution (replacing permanent magnet synchronous motors with other rare earths-free technologies). During the interview with Expert 3 (7.2.2), it was also mentioned that the REEs that are used in battery management systems can easily be replaced with a small impact on battery performance.

Despite the potential benefits in terms of mitigating climate change and achieving fuel savings, several barriers hinder the widespread adoption of rare earths substitutes in EVs. The combined sectors of hybrid and electric vehicles and e-bikes are estimated to require more than twice the amount of NdFeB magnets in 2020 compared to 2015 (between 11,500-34,500 tonnes NdFeB), accounting for up to 30% of the projected global NdFeB supply in 2020. Moreover, the demand for rare earths-based permanent magnets is expected to increase in other applications, such as high-tech devices and energy-related devices. The growing demand for NdFeB magnets can significantly impact the rare earth supply chain and lead to price fluctuations. Among the rare earths, Dy poses the highest supply risk as up to 75% of its 2020 supply may be required to meet global electric road transport needs. Mitigating the potential supply risks associated with rare earths in electric road transport applications is challenging since there are no effective substitutes for the rare earths used in permanent magnets. However, enhancing material efficiency, reducing NdFeB content, and adopting alternative components, such as rare earths-free electric traction motors, can help alleviate the increasing demand for rare earths. Different substitution paths should be pursued simultaneously, as there is no dominant method of substitution (Pavel et al., 2017).

8.1.2. Nickel-Free Battery Chemistry - (Lithium Iron Phosphate)

The main source of demand for Nickel in EVs is by the battery as mentioned in chapter 4. In the EV industry, as of 2021, NMC (nickel-manganese-cobalt) technology dominates the market, accounting for 71% of EV sales. Tesla models predominantly use NCA (nickel-cobalt-aluminum) cells, while LFP (lithium iron phosphate) batteries represent less than 4% of the market share [47]. LFP batteries have advantages such as longer cycling life and power density compared to NMC batteries. However, their lower energy density requires more space and weight to achieve the same capacity as NMC batteries, limiting their widespread adoption in the EV industry. LFP batteries have typically been used in low-range inexpensive cars, as well as in applications such as uninterruptible power supply (UPS) and home storage systems, where size and weight constraints are less significant. Nevertheless, the mass adoption of LFP cells in the EV industry is becoming more feasible due to cost and safety considerations (Houache et al., 2022).

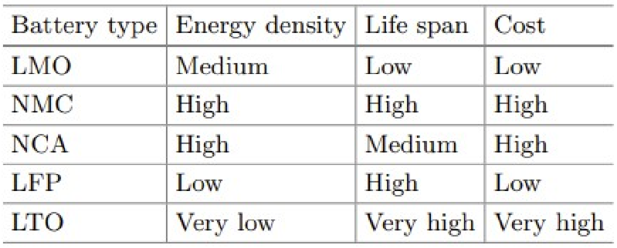
Leading battery manufacturers, including Tesla, Panasonic, and LG, are developing new Li-ion batteries with longer lifespans, fewer charging times, and higher energy density. Their aim is to eliminate or significantly reduce the use of nickel and cobalt in batteries, making them more eco-friendly, safer to dispose of, and easier to recycle. This technological shift could potentially reduce the cost of EVs by at least 20%, as the cost of batteries constitutes nearly 40% of the total EV cost. The cost of LFP batteries are significantly lower than other chemistries as shown in Figure 8.1. Recently,



Motor type	Rare Earths Content	Current Status	Major Advantages	Major Disadvantages	Technological Outlook
Permanent synchronous motor (PSM)	0.56 kg REEs per EV motor∗ (less in HEV and e-bikes)	Used in all serial HEV and in most serial PHEV and BEV	• High efficiency at low and medium speeds • Compact size/high power density • Wide dissemination	• Dependency on rare-earth supply and their price variation • Lower efficiency at high speed	Maintains a key role in EV and HEV as long as the price of rare earths do not increase significantly
Asynchronous motor (ASM)	Rare earths free	Used in some serial BEV (e.g. Tesla S, Mercedes B class, Renault Twizy) and PHEV	• Low production costs • Robustness • High reliability • High efficiency at high speed	• Lower efficiency than PSM in urban conditions • Lower power density than PSM, requiring more package space and weight • Higher copper demand than PSM	Maintains serial application in some EV and in mild hybrids, partly as improved ASM with high rpm
Externally excited synchronous motor (EESM)	Rare earths free	Used in few serial BEV (e.g. Renault Zoe) and PHEV Also available for HEV	• High efficiency in all speed ranges	• Lower power density than PSM • More package space needed • Complex structure resulting in high manufacturing costs	Remains an efficient alternative to PSM, but application in HEV is unlikely
ASM with high rpm	Rare earths free	Serial production announced	• Potential for high energy and material efficiency • Potential for low production costs	• No experience in serial production yet	Offers high potential for serial production in BEV, HEV and PHEV due to high efficiency and good cost effectiveness
PSM with low-cost magnets	Rare earths free	Prototypes using ferrite or AlNiCo magnets	• Potential for good overall performance	• No experience in serial production	Offers good potential for serial production due to high technical performance and reasonable cost effectiveness
Switched reluctance motor (SRM)	Rare earths free	First prototype	• Robust construction • Potential for cheap engine production	• High noise level • Requirement for a specific inverter, which is not compatible to production lines of power electronics for other engines	Needs further R&D to achieve highly efficient and silent engines suitable for serial production
Transversal flux motor (TFM)	Rare earths free	Early R&D stage	• Potential for high power density and efficiency	• Low technology readiness level	Might offer high power density and high efficiency, but needs more intense R&D
Hybrid motor (e.g. combine synchronous reluctance principle with permanent excitation)	0.37 kg∗∗ REEs or less per motor	Used in the BEV BMW i3 and PHEV BMW 7	• Similar performance as PSM with less rare earths	• Remaining rare earth demand	Applied in serial BMW i3 and BMW 7 PHEV production with high potential for further vehicle types and models

Table 8.1: Main component substitutes for PSM in EVs and HEVs, and comparison to current state-of-the art PSM (Zheng et al., 2022)

Tesla introduced cobalt-free LFP batteries with improved energy density, manufactured by LG and China's Amprex technology. This switch has reduced the cost of EVs by 20%, as cobalt is the most expensive component in batteries. Additionally, Tesla is transitioning from nickel cathodes to iron cathodes to eliminate the need for nickel in batteries. The comparison of performance parameters of these chemistries in comparison to traditional chemistries like NMC is shown in Figure 8.1.



Battery type	Energy density	Life span	Cost
LMO	Medium	Low	Low
NMC	High	High	High
NCA	High	Medium	High
LFP	Low	High	Low
LTO	Very low	Very high	Very high

Figure 8.1: Comparison of Parameters of Various Battery Chemistries (Horiba, 2014)

The surge in demand for EV batteries has caused a significant increase in nickel prices, rising over 16% in the past year. To address this issue, Tesla is working on eliminating cobalt in their new LFP batteries, aiming for a 90% recyclability rate and a lifespan of over 10,000 charging cycles. These cobalt- and nickel-free batteries are not only more affordable, but they also offer advantages such as easier and safer recycling, lower internal resistance for faster charging, and improved vehicle acceleration.

The shift towards LFP batteries is driven by their ability to avoid using scarce metals like nickel and cobalt, relying primarily on abundant and lower-cost iron, according to the interviewed Experts 1 and 2 (7.2.1). In 2021, the average cost of LFP cells was approximately 30% lower than that of NMC cells, resulting in overall cost reductions for batteries. The use of LFP batteries also aligns with the goals of EV manufacturers to improve profit margins and produce cost-competitive vehicles. Additionally, the availability of LFP batteries can free up nickel for use in high-energy-density batteries, reducing the cost and supply chain concerns associated with nickel (Walvekar et al., 2022).

Furthermore, the expiration of major LFP-related patents outside China has created favorable conditions for manufacturing LFP batteries. The expiration of these patents allows for increased adoption of LFP batteries in EVs globally. Currently, Tesla faces additional costs when purchasing LFP batteries from China due to import tariffs, shipping costs, and licensing fees. However, once the patents expire, Tesla will be able to manufacture its own batteries, leading to significant cost savings and aligning with its strategy of localizing key parts of vehicle production (Houache et al., 2022).

In conclusion, the adoption of LFP batteries in the EV industry offers cost advantages, eliminates the need for scarce metals like nickel and cobalt, and contributes to safer and more sustainable battery technology. The shift towards LFP batteries, combined with the expiration of related patents, is expected to increase the prevalence of LFP batteries in EVs, enabling car manufacturers to reduce costs, increase profit.

8.1.3. Cobalt-Free Battery Chemistries - Lithium Iron Phosphate (LFP) and Lithium Manganese Oxide (LMO)

The main source of demand for Cobalt in EVs is by the batteries as mentioned in Chapter 4. The earlier section explains about the LFP Battery chemistry, which is a cobalt-free battery chemistry. Similarly, there are other battery chemistries which use reduced or no cobalt in order for them to function. LFP is attractive due to its high thermal stability, excellent cycle life, flat charge/discharge profile, and high electrochemical stability over the entire depth of discharge (DOD) of 100%. However, it has not gained much traction in Western markets because of its low energy density and nominal voltage (3.3 V versus graphite anode), which directly impacts the driving range of electric vehicles (EVs) (Gourley et al., 2020).

Nevertheless, LFP technology has garnered significant interest in China due to its cobalt-free composition and has been adopted by major EV manufacturers like BYD Company and Wanxiang Group Corporation. LFP batteries are predominantly used in electric buses, with around 99% of the global stock concentrated in China. Therefore, it is speculated that LFP will play a crucial role in public transportation and stationary energy storage, where safety and stability are more critical than energy density.

One area for improvement in LFP is reducing the production cost associated with its complex synthesis methods to achieve a favorable cost/performance ratio. The electrochemical performance of LFP is highly dependent on the preparation method, requiring strict control over morphology, particle size distribution, coating homogeneity, and reagent purity, while ensuring that Fe^{2+} is not oxidized to Fe^{3+} to maintain consistent performance, according to Experts 1 and 2 (7.2.1).

Similarly, spinel $LiMn_2O_4$ (LMO) is a cobalt-free cathode that gained commercial relevance after being reported in 1983. The 3D solid-state diffusion of Li^+ in its host structure enables high-rate performance in lithium-ion batteries (LIBs). However, LMO's main drawback is its low practical capacity and cycle stability due to the presence of Mn^{3+}. The electronic configuration of Mn^{3+} induces Jahn-Teller distortion, which can lead to lattice changes and hinder Li^+ diffusion, especially at high discharge rates. Additionally, Mn3+ generates soluble Mn^{2+} through the disproportionation reaction: $2Mn^{3+}$(solid) → Mn^{4+}(solid) + Mn^{2+}(solution). Researchers have addressed the Jahn-Teller distortion by partially substituting Mn with other cations and exploring various coatings to suppress the dissolution of Mn. However, the poor reliability of LMO limits its applications to niche uses (Gourley et al., 2020).

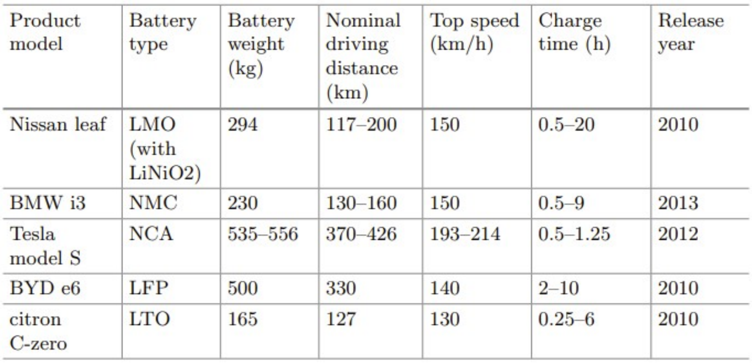
LMO (lithium manganese oxide) batteries are not preferred in modern electric vehicles (EVs) for several reasons. Firstly, LMO batteries have a relatively low capacity, with a theoretical capacity of 148 mAh/g. This means they can store and deliver less energy compared to other cathode materials, resulting in shorter driving ranges for EVs. Another drawback of LMO batteries is their short lifetime due to the dissolution of manganese (Mn) and structural instability during cycling in the electrolyte. This can lead to reduced performance and reliability over time, making them less suitable for long-term use in EV applications.

Furthermore, while LMO batteries offer high power output, which is beneficial for acceleration and performance, they have lower energy density compared to other cathode materials. Energy density refers to the amount of energy that can be stored in a given volume or weight, and higher energy density is desirable for EVs to achieve longer driving ranges.

Due to these limitations, LMO batteries are often not the preferred choice for modern EVs. Instead, EV manufacturers tend to utilize composite cathode materials, such as a blend of 70% NMC (nickel manganese cobalt oxide) and LMO. This combination leverages the advantages of both materials, including extended lifetime, enhanced capacity, and cost-effectiveness (Houache et al., 2022).

Layered mixed-type cathodes, particularly NMC-type compositions like NMC111, are considered the most suitable for meeting the high-energy requirements of EVs. NMC111 is well-established and known for its stability and safety. The capacity of NMC-type cathodes primarily relies on the Ni^{2+}/Ni^{4+} redox couple, while Mn^{4+} enhances thermal and electrochemical stability, and Co^{3+} contributes to electronic conductivity and prevents cation mixing between Ni^{2+} and Li^{+}. To increase capacity and reduce cobalt dependence, researchers are exploring higher nickel content NMC cathodes like NMC532 and even higher nickel content formulations like NMC811. However, these high-nickel-content cathodes face challenges related to thermal stability and capacity fade, which are being actively addressed through material modifications and coatings.

In summary, different cathode materials offer unique advantages and face specific challenges in the development of advanced lithium-ion batteries. While LFP and LMO provide cobalt-free alternatives with enhanced safety and stability, NMC-type cathodes offer high-energy density solutions. The ongoing research and development efforts aim to improve the performance and cost-effectiveness of these cathode materials, making them more suitable for various applications in the rapidly evolving landscape of electric vehicles and energy storage systems Gourley et al., 2020. The practical applications are performances that these battery chemistries can achieve in comparison with other mainstream chemistries can be seen in Figure 8.2 below (Camargos et al., 2022).



Product model	Battery type	Battery weight (kg)	Nominal driving distance (km)	Top speed (km/h)	Charge time (h)	Release year
Nissan leaf	LMO (with LiNiO2)	294	117–200	150	0.5–20	2010
BMW i3	NMC	230	130–160	150	0.5–9	2013
Tesla model S	NCA	535–556	370–426	193–214	0.5–1.25	2012
BYD e6	LFP	500	330	140	2–10	2010
citron C-zero	LTO	165	127	130	0.25–6	2010

Figure 8.2: Practical Applications Various Battery Chemistries (Horiba, 2014)

8.1.4. Beyond Li-Ion Batteries - Sodium, Potassium and Magnesium ion Batteries

The main source of demand for Lithium in EVs is by the battery as mentioned in chapter 4. Lithium in particular is very crucial because the battery chemistries than could be used to move away from

Cobalt and Nickel also are Lithium based chemistries.

Current Status and Challenges In Developing Beyond Li-ion Technology

Battery chemistries beyond Li-ion tend to either deploy metallic Li at the anode or substitute Li ions entirely, but both approaches face challenges. Li-metal anodes could allow access to energy densities an order of magnitude higher than current LIBs, but dendrite growth on the metal surface can lead to premature performance fade or, worse, explosive failure. These safety issues can be addressed and energy density further improved by pairing Li-metal anodes with solid electrolytes (SEs) in Li solid-state (LiSS) batteries.

However, SEs (typically ceramic- or polymer-based) can struggle to provide sufficient ionic conductivity, and in the case of ceramic electrolytes, many contain critical elements such as Ge, La, Zr, or Ti, although newer sustainable alternatives based on sulfides have emerged. A LiSS configuration still typically employs conventional Li-ion cathodes, which are also dependent on critical elements, but these could be avoided with alternative cathode pairings such as Li-S and Li-O2. However, although low-cost and abundant, sulfur cathodes suffer premature capacity loss from uncontrolled shuttling of soluble polysulfide intermediates, and Li-O2 batteries are compromised by a lack of cathode structures that allow constant flow of uncontaminated oxygen throughout cycling, with suitable catalysts to promote nucleation of Li2O2 over irreversible Li2O formation.

Systems that substitute lithium with more abundant Earth elements such as Na and K operate analogously to LIBs, but incompatibility with particular Li electrodes has necessitated the development of new, higher-capacity materials. Hard carbons have long been the anode of choice (up to 400 mAh g1), but alloying materials such as Sn (847 mAh g1) or Sb (660 mAh g1) could offer potentially higher capacity, although effective methods of accommodating the large volume expansion must be developed to ensure electrode integrity.

Cathodes based on layered metal oxides, polyanions, or Prussian blue analogs enable the replacement of Co and Ni with non-critical redox species such as Mn or Fe, and switching from Cu to Al current collectors is expected to further reduce the total cell cost. However, energy densities are limited by the larger ionic radius of Na and K ions, limiting uptake to applications where battery size is less critical.

Multivalent-ion chemistries could be attractive for EVs and portable electronics by offering specific and volumetric energy densities beyond the current state of the art. However, higher charge density on the mobile ion will likely complicate their practical application. The ability of metal oxides, chevrel, and spinel structures to facilitate fast ion diffusion has been explored, but the discovery of cathodes able to accommodate highly polarizing ions, and electrolytes that avoid anode passivation and corrosion, with sufficient ionic conductivity, remains challenging.

Solid-State Batteries

Solid-state batteries (SSBs) are an alternative to lithium-ion batteries (LIBs) that use ceramics or other solid materials as electrolytes instead of liquid electrolytes. The development of SSBs has gained significant interest due to their potential to surpass the ionic conductivity of liquid electrolytes. However, oxide-based SEs can be combined with liquid-polymer electrolytes in hybrid concepts to improve their conductivity. Disperse polymer-based electrolytes with low levels of liquids are also being explored. Sulfide-based composites, which offer high ionic conductivity and low mechanical moduli, are the primary focus in the development of SSBs for room-temperature operation. However, achieving conductivity comparable to that of liquid electrolytes is not sufficient because the microstructure of electrodes in solid-state composites introduces additional resistive components. The tortuosity and particle size distributions in the solid composite create a longer pathway for ions, requiring faster ionic transport to match the lithium-ion transport in liquid-electrolyte-based cathodes (Janek and Zeier, 2023).

For commercial implementation of high energy density SSBs with thick electrode configurations, a minimum effective ionic conductivity of 10 mS cm–1 is required. Lowering the lithium content in SEs is considered important but only provides a minor contribution to lithium criticality since cathode and anode materials still require lithium. Sodium-based SSBs are being explored as an alternative to lithium, but challenges such as sintering and the decomposition of certain materials need to be addressed. Sodium halides have shown limited ionic transport, and further research is needed to protect the SE and develop high-performance anodes (Feng et al., 2022).

When considering cost and potential applications, it is important to reduce the lithium content in SEs. Inorganic SEs require a significant amount of lithium, while polymer SEs offer a potential compromise by using less lithium if their ionic mobility can be improved. Designing ionic conductors by tailoring known materials or finding novel materials with higher intrinsic ionic mobility and lower charge-carrier density is crucial.

Regarding other alkali metals, potassium cells are unlikely to find broad application due to safety concerns and lower energy density. Magnesium and calcium cells have gained attention, but their energy densities are lower than lithium cells. Exploring alternative anode materials is necessary to improve safety and round-trip energy cycling efficiencies. The challenge lies in finding methods to plate metals without dendrite or mossy metal formation (Ellis and Nazar, 2012).

The lower energy density performance of lead-acid, nickel metal-hydride, and electrochemical capacitors are not the sole reason for their full replacement with Li-ion batteries. While cost reduction and energy densities play a significant role, other factors such as material abundance, economy, manufacturability, and productivity should also be considered, as depicted in Figure 14b. Developing Na-ion and K-ion batteries involves using similar battery materials as Li-ion batteries and utilizing existing production lines, which minimizes initial investment and ensures high manufacturability (Ellis and Nazar, 2012). These metals are considered as worthy successors to Lithium-Ion due to their high energy density capacities as sown in Figure 8.3.

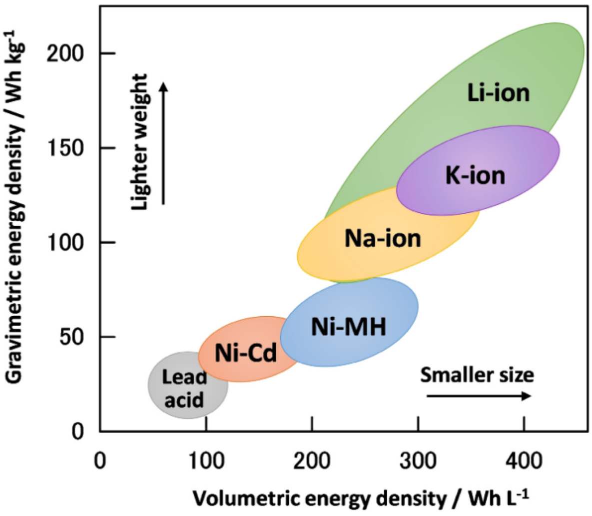


Figure 8.3: Energy density of rechargeable batteries (Kubota et al., 2018)

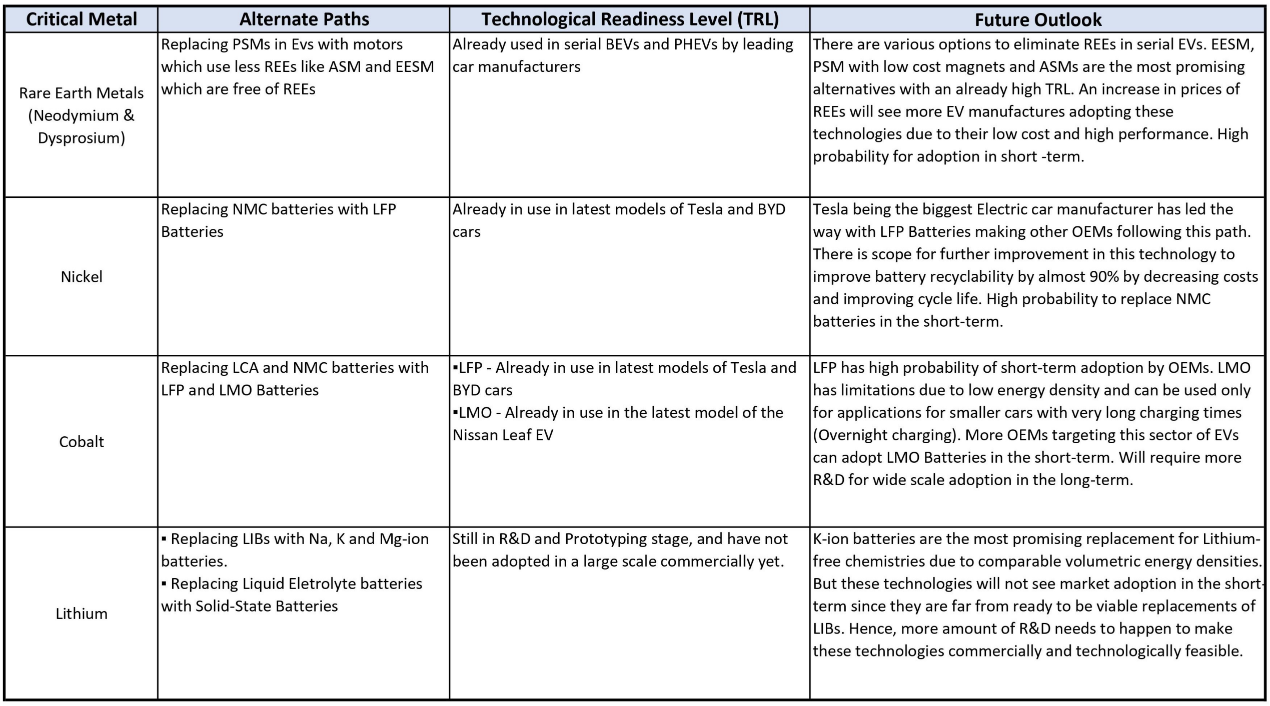
Sodium-Ion Batteries

The transition from Li to Na brings about changes in the distribution sites and diffusion paths in solid-state electrolytes (SSEs) due to the larger size of Na^+. Additionally, the stabilities and challenges faced by Na all-solid-state batteries (ASSBs) are not identical. The transition from Li to Na influences the distribution sites and diffusion paths in SSEs. The Na3AB4 and NASICON-type SSEs, such as Na3PS4, exhibit temperature-dependent phase transitions and varying ionic conductivities. Sodium vacancies and the motion of Na^+ ions play crucial roles in the ionic conduction of these systems. Doping with Cl^-, Si^{4+}, Ca^{2+}, Sb^{5+}, or W^{6+} can further enhance the ionic conductivity and stability of the cubic phase. Careful control of defects and doping can lead to improved Na^+ conductivity in ASSBs.

Potassium-Ion Batteries

Studying potassium chemistry and cells can provide valuable insights into lithium, sodium, magnesium, and calcium. However, it is important to be realistic about the prospects of commercial cells based on potassium. Due to its high hazard potential and relatively low energy density, potassium does not offer significant advantages in battery applications. In contrast, there has been limited research on magnesium and calcium cells since the 1970s, but recent developments have sparked interest in magnesium as a potential next-generation battery material. Understanding these limitations is crucial. Calcium, being closer to lithium in terms of cell potential and having larger ions that diffuse faster through solid lattices, could be a viable alternative to magnesium. However, addressing challenges related to calcium plating and finding suitable electrolytes may prove even more difficult than for magnesium. Exploring calcium reactions is necessary to gain a deeper scientific understanding of intercalation processes (Mohan et al., 2022).

It's worth noting that large-format Na-ion and K-ion batteries are expected to gain attention as low-cost options for stationary energy storage systems, given their abundance of materials. Currently, Li-ion and lead-acid batteries are commercially used for stationary applications like load levelling and sustainable energy storage (e.g., wind and solar energy). On the other hand, Na-ion and K-ion batteries are predominantly studied in universities and research institutes (Au et al., 2022). To make Na-ion and K-ion batteries a reality, further development is necessary to improve not only their energy density but also cycle life and safety for stationary use. Moreover, it is desirable for these batteries to possess unique advantages and distinctive performance characteristics compared to Li-ion batteries. Maximizing the potential of Na-ion and K-ion batteries relies on leveraging the low Lewis acidity and weak ionic interaction of Na^+ and K^+ ions, which are key factors in optimizing their characteristics (Feng et al., 2022). An overview of the technological paths that can be taken to mitigate the potential bottlenecks on critical metals for EVs is as shown in Table 8.2 below.



Critical Metal	Alternate Paths	Technological Readiness Level (TRL)	Future Outlook
Rare Earth Metals (Neodymium & Dysprosium)	Replacing PSMs in Evs with motors which use less REEs like ASM and EESM which are free of REEs	Already used in serial BEVs and PHEVs by leading car manufacturers	There are various options to eliminate REEs in serial EVs. EESM, PSM with low cost magnets and ASMs are the most promising alternatives with an already high TRL. An increase in prices of REEs will see more EV manufactures adopting these technologies due to their low cost and high performance. High probability for adoption in short -term.
Nickel	Replacing NMC batteries with LFP Batteries	Already in use in latest models of Tesla and BYD cars	Tesla being the biggest Electric car manufacturer has led the way with LFP Batteries making other OEMs following this path. There is scope for further improvement in this technology to improve battery recyclability by almost 90% by decreasing costs and improving cycle life. High probability to replace NMC batteries in the short-term.
Cobalt	Replacing LCA and NMC batteries with LFP and LMO Batteries	▪LFP - Already in use in latest models of Tesla and BYD cars ▪LMO - Already in use in the latest model of the Nissan Leaf EV	LFP has high probability of short-term adoption by OEMs. LMO has limitations due to low energy density and can be used only for applications for smaller cars with very long charging times (Overnight charging). More OEMs targeting this sector of EVs can adopt LMO Batteries in the short-term. Will require more R&D for wide scale adoption in the long-term.
Lithium	▪ Replacing LIBs with Na, K and Mg-ion batteries. ▪ Replacing Liquid Eletrolyte batteries with Solid-State Batteries	Still in R&D and Prototyping stage, and have not been adopted in a large scale commercially yet.	K-ion batteries are the most promising replacement for Lithium-free chemistries due to comparable volumetric energy densities. But these technologies will not see market adoption in the short-term since they are far from ready to be viable replacements of LIBs. Hence, more amount of R&D needs to happen to make these technologies commercially and technologically feasible.

Table 8.2: Overview of technological alternatives to mitigate potential supply bottlenecks of critical metals

8.1.5. Recycling Potential

Recycling companies emphasize the importance of understanding the expected volume of batteries to be recycled in order to adapt their processes accordingly. This study estimates the future recycling potential of raw materials such as lithium, cobalt, and nickel to determine the amount of potentially available material for recycling. Assuming an average lifetime of 10 years for EV LIBs, the recycling potential for the year 2040 can be projected. It is important to note that this recycling potential only considers the mass of materials present in end-of-life batteries and does not account for recycling efficiencies, which are typically less than 100%. Nevertheless, recycling is expected to make a significant contribution to the resource supply for Li-batteries within the timeframe of this study. Quantifying the recycling efficiency would require additional assumptions regarding factors such as collection rates, second-life options, losses during dismantling, pre-processing, smelting, and refining. However, this study consciously chose not to provide a specific quantification of recycling efficiency. The current recycling rate percentage for popular metals are as shown in Figure 8.4 below. It can be seen that as of 2021, the recycling rate percentages are very low for Lithium and REEs (Harper et al., 2019).

The level of recycling is typically assessed using two indicators: end-of-life (EOL) recycling rates and recycling input rates. EOL recycling rates measure the proportion of material in waste streams that is actually recycled, while recycling input rates assess the share of secondary sources in the total supply. EOL recycling rates vary significantly depending on the metal. Base metals such as copper, nickel, and aluminum, which are used in large volumes, have achieved high EOL recycling rates. Precious metals like platinum, palladium, and gold also exhibit higher rates of recycling due to their high global prices, which incentivize both collection and product recycling. However, lithium and rare earth elements (REEs) have limited global recycling capabilities, primarily due to challenges like limited collection infrastructure and technical constraints related to lithium's reactivity in thermodynamic and metallurgical recycling processes. Regional variances exist as well, with

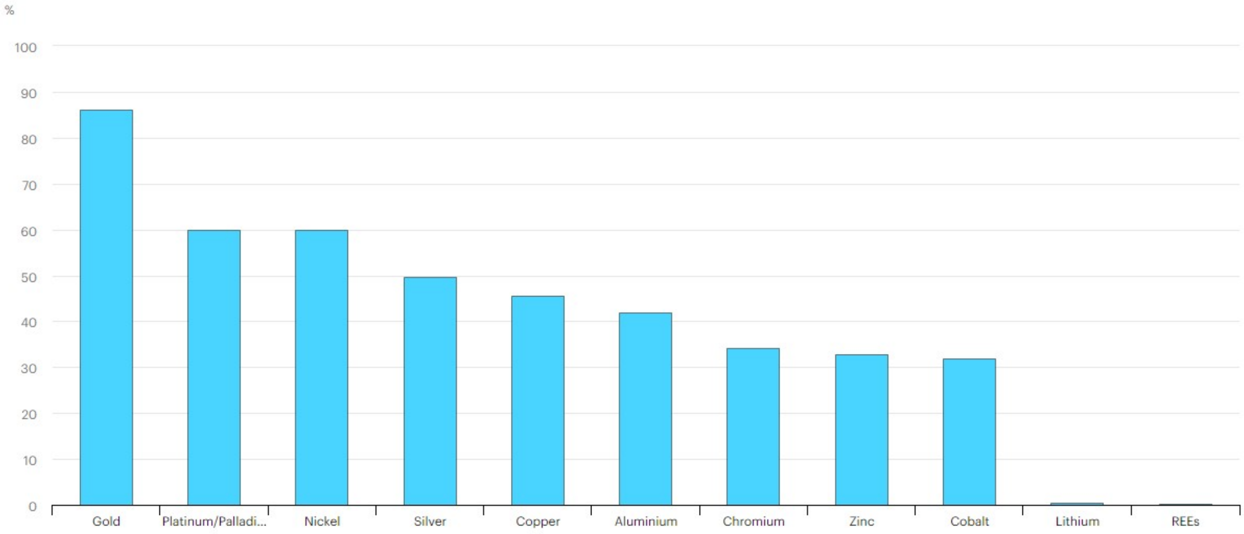


Figure 8.4: Recycling Rates of Popular Metals as of 2021 International Energy Agency, 2022

approximately 50% of total base metal production in the European Union relying on secondary production (recycled metals), compared to 18% in the rest of the world (Harper et al., 2019).

It's important to note that recycling does not eliminate the need for ongoing investment in primary mineral supply. According to a World Bank study, new investments in primary supply will still be necessary even if EOL recycling rates were to reach 100% by 2050. However, recycling can play a crucial role in alleviating the pressure on primary supply from virgin materials, particularly during periods of surging demand. For instance, the anticipated exponential growth in spent electric vehicle (EV) batteries reaching the end of their first life after 2030 offers the potential to reduce the strain on primary supply investment.

While the recycling industry faces various commercial and environmental challenges, its competitiveness is expected to improve over time as economies of scale are realized and technology advancements occur, attracting more players to the field. The relative advantages of recycling are likely to be further reinforced by potential upward pressure on production costs for virgin resources. Additionally, regions with greater deployment of clean energy technologies can benefit significantly from economies of scale in recycling. This underscores the substantial security benefits that recycling can bring to importing regions and emphasizes the importance of incorporating a circular approach within the framework of mineral security International Energy Agency, 2022.

The proposal for the new battery directive includes clear targets for recycling efficiencies and material recovery rates of batteries by 2025 and 2030. The recycling efficiencies are projected to range from 65% to 70%, while the material recovery rates for cobalt, nickel, lithium, and copper are expected to range from 90%, 90%, 35%, and 90% in 2025 to 95%, 95%, 70%, and 95% in 2030, according to the European Commission. Fig. 5 illustrates the future demand for raw materials (lithium, cobalt, and nickel) compared to the corresponding recycling potential in both the critical material and abundant material scenarios. The recycling potential for lithium and nickel is estimated to exceed half of the raw material demand for LIBs in 2040. In the case of cobalt, the recycling potential even surpasses the raw material demand in 2040, particularly in the abundant material scenario. This is due to the assumption that the market share of cobalt-containing cathode materials will decrease until 2040 in the abundant material scenario. While several recycling capacities in the order of several hundred kilotonnes of battery packs per year have been announced globally, our data suggests that capacities in the range of several megatonnes per year will be required by 2040. To handle such large volumes of raw materials for recycling, the development of a large-scale recycling infrastructure is necessary. Consequently, new LIB recycling plants are planned throughout Europe, with announced annual recycling capacities per plant ranging from 8,000 to 125,000 tonnes Maisel et al., 2023.

As the use of LIBs in electric vehicles and electronic applications continues to grow, the demand for LIB production increases annually. Consequently, the generation of spent LIBs and their entry into the waste stream also increases. Recent developments have led to a multitude of alternative cathodes and anodes, expanding the range of electrode chemistries available for recycling. The adoption of efficient alternatives for the electrodes poses a challenge for the recycling industry, as it requires the development and modification of recycling processes for battery waste.

Understanding the advantages of choosing one recycling method over another is crucial for the effective recycling of spent LIBs. Consistency in the chemical composition of LIBs feed, appropriate pre-treatment without hazardous short-circuiting, and the choice between pyrometallurgical and hydrometallurgical routes are key factors influencing the overall development of the recycling process. Combining pyrometallurgical and hydrometallurgical routes can yield significant benefits. However, for a pilot-scale plant, a steady stream of relatively pure LIBs feed in the range of a few thousand tons per day is challenging to maintain due to the diverse nature of E-waste streams containing LIBs waste, making chemical composition and manufacturing-based isolation a significant challenge (Pražanová et al., 2022).

New Trends in Battery Recycling:

Despite the existence of current processes and technologies for LIB recycling, researchers have been conducting studies to evaluate new approaches. These studies aim to achieve various objectives, including enhancing safety during the dismantling step, recovering electricity prior to recycling, improving pre-treatment, implementing mechanical separation, and exploring different processing routes. To recover metals from LIBs, three main routes have been explored: pyrometallurgy, hydrometallurgy, and biohydrometallurgy.

The routes and processes mentioned above begin with the battery dismantling step, which can be done manually (e.g., Duesenfeld GmbH) or with the use of industrial equipment. Depending on the approach, the batteries may or may not undergo a discharging step. It is important to note that during this step, an exothermic reaction can occur between lithium and oxygen in the atmosphere, potentially leading to explosions.

Simultaneously, in the electrodes, water reacts with fluorinated salts, resulting in the formation of hydrofluoric acid. This byproduct is undesirable due to its high corrosive power and toxicity. At high temperatures (as observed in the Umicore process), reactions can take place inside the batteries, generating gases that can lead to battery combustion and the formation of toxic compounds like dioxins and halogenated organic compounds. Additionally, organic solvents used as electrolytes can ignite at 120 °C, producing flammable gases such as methane , and PVDF binders can also generate toxic gases (Martins et al., 2021).

Pretreatment:

The pretreatment of LIBs (Lithium-ion batteries) involves several steps to discharge, grind, and separate the main constituents before chemical processing (thermal or aqueous). This process is crucial to prevent environmental issues and safety problems, although it can lead to metal losses. Thermal degradation can occur if certain temperature limits are exceeded for different battery cathode materials such as LCO, NMC, LMO, and LFP, which can release gases like O2 and flammable gases like H2, CH4, and C2H4 from the electrolyte. The decomposition of the solid-electrolyte interface and electrolyte above certain temperatures can also generate flammable gases. To mitigate these risks, some EV (electric vehicle) and HEV (hybrid electric vehicle) batteries are designed with polymeric electrolytes instead. Additionally, discharged LIBs still retain residual energy, and improper pretreatment methods can cause short circuits and rapid temperature increases, leading to explosions. Therefore, it is essential to discharge the batteries safely, either through controlled short circuits or by using resistors, while keeping the temperature below 90°C to avoid high-temperature risks. Discharging LIBs in saline solutions is a common method due to its speed, simplicity, and low cost, although it can result in the formation of chlorine gas and undesired precipitates. Other alternatives, such as using graphite and Cu powder, exist but are not suitable for large-scale applications (Martins et al., 2021).

Separation: The separation of LIB components aims to concentrate materials with similar properties to improve the recovery rate. Manual disassembly is a commonly reported method, but it is time-consuming, labor-intensive, and costly, making it unsuitable for industrial-scale operations. Various equipment and approaches are used to achieve industrial viability. Separation after crushing the LIBs into streams facilitates the recovery of battery components. Magnetic and granulometric separation are widely employed, particularly for separating iron and aluminum/copper foils. Techniques involving organic solvents like N–N-dimethylformamide or N-methyl-2-pyrrolidone have been utilized to dissolve PVDF binders and separate aluminum foils from cathodes. Grinding with additives like ethylenediaminetetraacetic acid (EDTA) has shown promise in recovering Co and Li from LiCoO2 cathodes. Different grinding equipment can affect leaching performance, and particle size plays a role in separating metallic and non-metallic phases. Flotation separation is employed to classify components by separating the active material from the cathode and anode. Thermal methods are used to remove electrolytes, carbon impurities, and binders, but they can release toxic gases, requiring additional treatment. Industry 4.0 technologies, such as robotic systems, are also being explored to improve the control and screening of battery types, making the recycling process more efficient (Martins et al., 2021).

Pyrometallurgical route The pyrometallurgical route involves thermal processes at elevated temperatures to separate slag from the materials of interest. In LIB recycling, pyrometallurgy is used in conjunction with hydrometallurgy. Different reactions and conditions have been explored, such as heating LiCoO2 and graphite in an inert atmosphere to obtain lithium carbonate, cobalt ferromagnetic material, and residual carbon. Pyrolysis processes at specific temperatures and atmospheres have also been investigated to reduce the cathode and obtain various products. Nitration-roasting-leaching processes have shown promise for lithium recovery. Various other thermal processing methods have been studied to recover metals like lithium and cobalt (Martins et al., 2021).

An emerging recycling method known as direct recycling involves removing the cathode or anode from the electrode for reconditioning and reuse in a re-manufactured lithium-ion battery without breaking them down into individual material elements. Although this method avoids lengthy and expensive purification steps, there is a limitation that the recovered cathodes can only be used for manufacturing the same battery type.

Currently, the global capacity for battery recycling is approximately 180 kilo tonnes per year (kt/yr), with China accounting for almost 50% of this capacity. China is expected to maintain its dominant position due to the substantial additional capacity it has announced, amounting to 1,000 kt/yr. While most of the companies involved in battery recycling today are independent refiners, there is a growing interest from a broad spectrum of players, including battery manufacturers, original equipment manufacturers, miners, and processors, especially in Europe (Windisch-Kern et al., 2022).

At present, the global capacity for recycling batteries stands at approximately 180 kilo tonnes per year (kt/yr). China currently holds almost half of this capacity and is expected to maintain its leading position due to its substantial plans for additional capacity expansion, estimated at 1,000 kt/yr . Although most of the companies engaged in battery recycling are independent refiners, there is a growing interest from a diverse range of stakeholders, including battery manufacturers, original

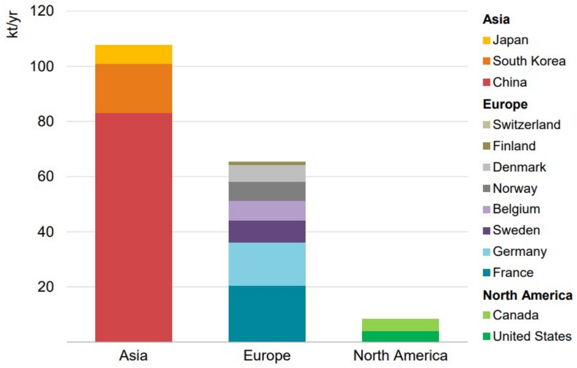


Figure 8.5: Existing and announced Global Lithium-ion Battery Recycling Capacity by 2021 (International Energy Agency, 2022)

equipment manufacturers, miners, and processors, to enter the market. This interest is particularly evident in Europe, indicating a trend towards increased participation and market diversification in the battery recycling industry as shown in Figure 8.5

8.1.6. Policies

Since the 1950s, policy makers have expressed concerns about critical minerals. However, it was China's introduction of export restrictions on Rare Earth Elements (REEs) in 2010 that spurred many countries to adopt formal strategies and implement measures to secure reliable supplies of minerals. Over the past decade, several countries, including the European Union, the United States, Japan, Canada, and Australia, have developed critical material strategies to address this issue (Richter, 2022).

The importance of critical minerals has gained even more prominence on the policy agenda due to the increasing momentum behind clean energy transitions. While ensuring uninterrupted supplies of critical minerals is a common objective across these strategies, the specific directions and policy priorities can vary depending on each nation's or region's circumstances. During the past few decades, China has emerged as a dominant player in global supply chains for critical minerals and clean energy technologies. This rise to prominence as the leading contributor to clean energy supply chains is primarily attributed to China's long-term industrial policies, such as its five-year plans for economic development, the ”Made in China” initiative, and the Belt and Road Initiatives (Habib et al., 2020).

In this context, it is essential to examine the major policy directions and approaches taken by different global regions to ensure mineral security. Each region may adopt specific strategies and prioritize different aspects of mineral security based on their unique requirements and available resources. By understanding and analyzing these diverse approaches, policymakers can gain insights into effective measures for securing critical minerals and supporting the development of clean energy technologies. As countries intensify their endeavors to reduce emissions, it is imperative that they also prioritize the resilience and security of their energy systems. The current international energy security mechanisms are primarily focused on mitigating the risks associated with disruptions or price spikes in hydrocarbon supplies, specifically oil. However, the growing significance of minerals in a decarbonizing energy system presents a different set of challenges that energy policymakers need to address (Martins et al., 2021).

In an electrified and renewables-rich energy system, concerns regarding price volatility and security of supply do not vanish. The transition to renewable energy sources introduces new factors that necessitate an expansion of perspectives for energy policy makers. They must recognize and evaluate potential vulnerabilities that may arise due to the increased reliance on minerals. While hydrocarbons play a dominant role in traditional energy security frameworks, minerals used in renewable technologies, such as lithium, cobalt, and rare earth elements, become crucial for the functioning of the decarbonized energy system. Therefore, energy policy makers must broaden their focus to include these minerals and consider strategies to ensure their availability, affordability, and secure supply chains (Jetin, 2020).

Addressing price volatility entails implementing measures to minimize fluctuations in mineral prices, which can impact the cost of renewable energy technologies. Enhancing the security of supply involves diversifying sources and suppliers, reducing dependence on a limited number of mineral-producing regions, and promoting responsible mining practices. This includes considerations of social and environmental sustainability throughout the mineral supply chain. Moreover, energy policy makers need to foster international cooperation and collaboration to address mineral-related challenges. This can involve engaging in strategic partnerships, sharing best practices, and establishing frameworks for information exchange on mineral resources, production, and trade. By adopting a holistic and proactive approach to energy security, which encompasses both hydrocarbons and minerals, countries can better navigate the complexities of a decarbonized energy system while safeguarding against potential vulnerabilities. LIBs for electric vehicles (EV) and hybrid electric vehicles (HEV) are expected to comply with the same regulations as current lead-acid batteries. Manufacturers will collect the batteries at the end of their useful life and replace them with new ones to prevent inappropriate disposal or accidents. This approach is likely to result in higher collection and recycling rates for LIBs compared to other waste from electrical and electronic equipment (WEEE) (Jetin, 2020).

In 2020, the European Union proposed a new battery regulation that aims to address various issues related to electric vehicles. This regulation seeks to increase transparency, traceability, and accountability throughout the battery life-cycle. It includes requirements for access to battery management systems, mandates digital passports, carbon footprint declarations, and maximum thresholds. The regulation also sets specific recycling rates for lithium, cobalt, and nickel, and encourages the use of recycled materials in new batteries to stimulate demand. There have been concerns that these ambitious rules for electric vehicle batteries may lead to increased costs and slow down the adoption of electric cars. However, it is argued that increased supply-chain transparency should be incentivized in general. The transition to electric vehicles should be primarily driven by policies phasing out fossil fuel vehicles, and the potential trade-offs should be addressed through policy mixes and a systems approach. Increased costs could also encourage sufficiency measures in transportation and minimize rebound effects in the transition to electric vehicles.

When designing circular economy policies and strategies for electric vehicles, it is crucial to consider the distribution of value and costs. Digital product passports have been proposed as a means to provide better data, enhance supply chain transparency, and facilitate collaboration among value-chain actors. These passports could potentially include recycling fees that follow the vehicle or component throughout its lifecycle, ensuring proper waste and resource management. By doing so, longer vehicle lifetimes can be achieved without compromising environmental impacts due to inadequate waste management.

Circular economy strategies should also align with climate policies. Limiting cross-border flows of used and waste vehicles to prevent leakage of circular economy value needs to be considered while taking into account the transition needs of all countries from fossil fuels. These transfers of value can contribute to the development of sustainable mobility systems aligned with climate commitments. The economic competitiveness gains of circular economy strategies at the country and regional level should be balanced with global climate change goals. Ultimately, approaching the transition to electric vehicles from both climate and circular economy perspectives is likely to lead to a more sustainable outcome (Richter, 2022).

The EU approach is an example of the direction that global superpowers are taking in policy framework. This was mentioned as a valuable resource for this thesis by Expert 4 (7.2.3).

Critical Raw Materials Act

The Critical Raw Materials (CRM) Act of the European Union (EU) is a significant legislative initiative aimed at addressing the strategic importance and security of critical raw materials within the region. Critical raw materials are essential elements and compounds that play a vital role in the development and functioning of key sectors such as renewable energy, electronics, transportation, and advanced manufacturing.

The CRM Act recognizes the challenges posed by the increasing global demand, limited availability, and potential supply disruptions of critical raw materials. It aims to ensure the sustainable supply, responsible sourcing, and efficient use of these materials to safeguard the EU's economic competitiveness, technological advancements, and environmental goals.

One of the primary objectives of the CRM Act is the identification and monitoring of critical raw materials. The EU periodically assesses and updates a list of critical raw materials based on several factors, including economic importance, supply risk, and geopolitical considerations. This list serves as a basis for policy development, resource planning, and targeted research and innovation initiatives.

By categorizing materials as critical, the EU aims to gain a deeper understanding of their availability, concentration, extraction practices, and geopolitical dependencies. This knowledge enables the development of strategic measures to mitigate supply risks and diversify sourcing options. It also promotes responsible mining practices, sustainable extraction techniques, and resource-efficient processing methods.

The CRM Act advocates for enhanced resource efficiency and circular economy principles. It encourages the reduction of waste and the development of innovative recycling technologies to recover critical raw materials from end-of-life products. This approach not only conserves valuable resources but also reduces the environmental impact associated with primary extraction and promotes a more sustainable materials lifecycle.

To support the objectives of the CRM Act, the EU promotes research and innovation in critical raw materials. It fosters collaboration among member states, industry stakeholders, and research institutions to advance knowledge, technologies, and expertise in critical raw material supply chains. This includes exploring alternative materials, substitution technologies, and recycling methods that can reduce the demand for critical raw materials and enhance the EU's self-sufficiency.

Additionally, the CRM Act emphasizes the importance of international cooperation and responsible sourcing practices. The EU engages in dialogue with resource-rich countries and promotes sustainable mining practices, social responsibility, and environmental stewardship throughout the global supply chain. This collaborative approach aims to ensure fair access to critical raw materials while respecting human rights and environmental standards (European Commission, 2023a).

The Critical Raw Materials (CRM) Act does not introduce new sustainability standards at the European or global level. Instead, it is based on compliance with existing standards. However, the current waste management framework in Europe, specifically the 2006 Extractive Waste Directive, falls short of global best practices and should be promptly updated. It is crucial to prioritize strong environmental and social safeguards in all extraction and processing projects, whether within Europe or internationally. This objective hinges on the Corporate Sustainability Due Diligence Directive (CSDDD), which has not yet been agreed upon. The CSDDD aims to ensure that businesses, including those in the extractive sector, uphold human rights, protect the environment, and address climate concerns globally. However, certain negotiators seek to weaken the requirements of this directive. Failing to establish robust horizontal due diligence measures will erode trust among consumers, local communities, and civil society in the ”Strategic Project” label, ultimately hindering the progress and objectives of Europe’s critical metals strategy. The objective of the proposed Critical Raw Materials (CRM) Act by the European Commission is to achieve specific targets for meeting domestic demand. This includes sourcing 10 percent of domestic demand from domestic mining, 40 percent from domestic refining, and 15 percent from recycling. To facilitate these goals, the CRM Act would establish a common EU time limit for issuing permits to relevant industrial projects. The proposed act also addresses supply chain monitoring, stockpiling, and enhancing the recyclability of CRMs. Geological surveys and investigations would be conducted to identify domestic resources for mining and recycling of CRMs. While the provisions on recycling and information gathering are noteworthy, the CRM Act’s focus on import substitution fails to address the underlying challenge posed by Europe’s indirect exposure to CRM bottlenecks through global supply chains, which cannot be fully resolved by domestic mining and refining alone.

Therefore, international measures become crucial, although the draft CRM Act lacks clarity on this aspect. Free trade agreements (FTAs), such as those recently concluded by the EU with Chile and Australia, offer more concrete policies, including market access for EU investments and the prevention of export restrictions on CRMs. However, trade policy provides limited incentives for import diversification since the EU already applies low tariffs on CRMs. Tariffs on base metals are already zero for a third of them, with an average tariff rate of just 3.6 percent.

Considering these trade policy constraints, the EU’s main tools in this area will need to be investment through the Global Gateway (EU’s foreign investment policy) and export credits to facilitate private investments abroad. The Commission’s CRM strategy acknowledges these tools, but their application remains to be seen. They should be utilized to promote infrastructure investment and projects that diversify the mining and refining of CRMs outside the EU. This will require substantial investment not only from the EU but also from national governments. International cooperation with like-minded partners will be crucial in sharing the burden.

Foreign commercial policy tools are more challenging to implement effectively and have a less direct impact compared to domestic industrial policy. However, the dual challenge of meeting the high demand for CRMs in the green transition and addressing the lack of resilience in global commodity markets cannot be adequately met through domestic measures alone. The EU should support a trade policy environment and concrete investments abroad that diversify supply chains not only for its domestic market but also for the broader global context. Since all economies pursuing decarbonization face similar investment challenges, the aim should be to develop liquid and diversified global commodity markets, similar to existing markets for copper and aluminum, which are also crucial for the green transition (Guillaume, 2023a).

Net-Zero Industry Act

The Net Zero Industry Act of the European Commission is a crucial legislative initiative aimed at driving the transformation of industrial sectors towards carbon neutrality and sustainability. With the goal of achieving a net-zero greenhouse gas emissions economy by 2050, this act focuses on mobilizing industries to significantly reduce their carbon footprint and adopt clean and sustainable practices.

The Net Zero Industry Act recognizes the urgent need to decarbonize industrial processes and address the significant contribution of industrial activities to global greenhouse gas emissions. Industries such as manufacturing, energy, construction, and transportation play a pivotal role in the transition to a low-carbon economy and are key targets for emission reduction measures.

One of the primary objectives of the Net Zero Industry Act is to set ambitious emission reduction targets for industrial sectors. These targets are designed to drive the adoption of cleaner technologies, energy-efficient practices, and sustainable production processes. By establishing clear and measurable goals, the act provides a roadmap for industries to align their operations with the overall objective of achieving net-zero emissions.

The act also encourages innovation and research and development activities to support the transition to a net-zero industry. It promotes collaboration between industry stakeholders, research institutions, and policymakers to develop and deploy breakthrough technologies, such as renewable energy integration, carbon capture and storage, and sustainable materials and manufacturing processes. These innovations aim to enable industries to reduce their environmental impact while maintaining competitiveness and economic growth.

Furthermore, the Net Zero Industry Act emphasizes the importance of resource efficiency and circular economy principles. It encourages industries to optimize the use of raw materials, reduce waste generation, and promote recycling and reuse practices. By adopting circular economy approaches, industries can minimize resource consumption, minimize waste, and create value from by-products and end-of-life products, thus contributing to the overall sustainability goals.

The act also recognizes the need for strong policy frameworks and market incentives to drive the transition to a net-zero industry. It calls for the implementation of supportive measures, such as carbon pricing mechanisms, regulatory standards, and financial incentives, to accelerate the adoption of low-carbon technologies and practices. These policy tools create market signals that encourage investment in sustainable solutions and help industries overcome financial barriers to decarbonization.

Additionally, the Net Zero Industry Act emphasizes the importance of international cooperation and collaboration. It encourages knowledge sharing, best practices exchange, and joint initiatives with global partners to address common challenges and drive collective action towards a sustainable industrial sector. International cooperation can facilitate the transfer of clean technologies, promote sustainable supply chains, and ensure a level playing field for industries across different regions.

In conclusion, the Net Zero Industry Act of the European Commission is a comprehensive legislative framework that aims to transform industrial sectors into carbon-neutral and sustainable entities. Through ambitious emission reduction targets, innovation support, circular economy principles, policy frameworks, and international cooperation, the act provides a roadmap for industries to transition towards a net-zero emissions economy. By embracing these measures, industries can contribute significantly to global climate goals while fostering economic growth and competitiveness in a sustainable manner (European Commission, 2023b).

However, there are some Limitations to this act. Firstly, the Net-Zero Industries Act of the European Union is likely to impede rather than expedite the EU's green transition. Achieving decarbonization involves setting and swiftly achieving renewable energy production targets, which can be facilitated through international trade of clean energy goods. Over-reliance on a specific exporter should be avoided, as seen in the cautionary tale of dependence on Russian gas, which justifies industrial policy. However, an all-encompassing approach of import substitution, even from a diverse range of trading partners, is illogical and will increase the cost of the EU's energy transition.

Secondly, the Net-Zero Industries Act's approach could hamper efforts to enhance EU competitiveness. Similar to the special economic zones employed by developing countries with unfavorable business environments, the Net-Zero Industries Act diverts attention from the actual challenges faced by the EU, such as high energy prices and the lack of a truly unified single market, including limited progress in capital markets union. The Net-Zero Industries Act fails to address these obstacles; instead, it merely grants preferential treatment to specific projects.

Lastly, the Net-Zero Industries Act's approach would convey negative signals. It would appear equally detrimental to trading partners in the developing world who aim to ascend the value chain, just as the US' IRA did. Like China and the US, the EU would be indicating its lack of interest in importing clean technology, even from partners capable of producing at significantly lower costs. EU allies such as the US and Japan will take note that the import substitution objectives are as adversarial to them as they are to China. From the standpoint of EU policymaking, it would send a message that regulatory fairness and market-based outcomes, which are the pillars of the single market and EU economic strength, could be disregarded when an industry is labelled 'strategic,' even without any evaluation of the trade-offs between economic efficiency and geopolitical resilience (Guillaume, 2023b).

8.2. Limitations

In this section the limitations of the used study methodology are explained.

8.2.1. Rebound Effect

As outlined in the book "Introduction to Energy Analysis" by Blok and Nieuwlaar, 2020, an increase in energy usage might stem from enhanced efficiency under specific conditions. Rebound effects manifest in two forms: direct and indirect. The direct rebound effect transpires when an enhancement in the energy efficiency of equipment leads to reduced energy costs, potentially prompting greater utilization by consumers. Conversely, the indirect rebound effect explores the potential for savings generated by one process to be channelled into another process, resulting in heightened energy consumption (Davis, 2019). Typically, the rebound effect exerts a modest influence, representing 10 to 30 percent of the anticipated energy savings (Blok and Nieuwlaar, 2020). This effect could have an effect on the numbers obtained from demand analysis of EVs by 2050, as the actual demand could be higher that the numbers estimated in the study conducted by Habib et al., 2020 used in this study. The implications of the rebound effect on EV Demand and its long term effects by 2050 needs to be looked into .

8.2.2. Perspectives Gained from Interviews

Conducting interviews served the dual purpose of acquiring fresh insights and confirming findings from the desk research phase. The research engaged a relatively small sample of four individuals, which may be considered limited. Although contact was established with a total of 15 potential interviewees, only four demonstrated willingness or availability to participate in interviews and contribute to the study.

The interviewees shared a common trait: expertise in battery technologies and circular economy. Moreover, they were affiliated with universities, research institutes, or public organizations. A constraint of the study is the absence of multiple interviewees from the vehicle industry. While most interviewees possessed some level of familiarity with vehicle industry operations, only 2 had experience within a vehicle manufacturing context. Numerous attempts were made to secure interviews with several vehicle manufacturers, all of which declined cooperation. Despite reaching knowledge saturation in various instances, the possibility of uncovering additional insights remains feasible through a broader pool of participants.

8.2.3. Performance Degradation Of Battery Technologies over time

The alternate paths proposed by this study to move away from critical metals involves adoption of ASMs and EESMs instead of PSMs, as well as adoption of battery chemistries like LFP, LMO, Na-ion, K-ion and SSBs. However the performance degradation of these batteries over a long period of usage has not been researched on in this study. Factors like residual capacity, easy of recycling and resale value of these batteries needs to be looked into, as these factors can also affect the adoption of these technologies positively or negatively.

8.3. Future Research

Some of the future research can be in the following areas:

1. Research can be conducted to determine the capacity of companies involved in recycling EV motors and batteries, as well as the number of such companies. This research aims to assess their ability to handle the increasing volume of end-of-life (EoL) motors and batteries generated from electric vehicles (EVs).
2. This research can be extended beyond passenger electric vehicles, to Heavy-Duty electric vehicles, electric boats, planes and bikes.
3. Investigate the utilization of silicon-based materials, such as silicon nanowires or silicon-carbon composites, as anodes in lithium-ion batteries and assess their performance in terms of capacity, cycling stability, and compatibility with existing battery manufacturing processes.
4. Investigate novel hydro-metallurgical processes further for the recovery of critical metals from spent lithium-ion batteries. Explore techniques such as leaching, solvent extraction, and precipitation to efficiently recover metals like cobalt, nickel, and lithium.
5. Explore the development of metal-free catalysts for key electrochemical processes in batteries, such as oxygen reduction reactions (ORR) or hydrogen evolution reactions (HER). Investigate the performance and stability of alternative catalyst materials, such as carbon-based or organic compounds, for improved resource sustainability.

8.4. Scientific Contribution

As mentioned in section 1.2, there is a lock of comprehensive research on this thesis topic. This research provides new knowledge on the potential bottlenecks in supply of metals that are currently essential for the functioning of this technology. Existing studies determine criticality for EVs strictly from a geological reserves and geopolitics perspective. However, this research was successful in identifying the factors contributing to criticality for EVs. Factors such as competitive demand for the same metals among different renewable technologies was not used in any research to determine potential supply bottlenecks for EVs by 2050. This proves to be extremely crucial with all these renewable technologies booming together to achieve net zero emissions by 2050.

The analysis model developed in this research shown in Figure 3.2 can be used for other renewable technologies identify critical metals for that technology in order to conduct a similar study for different renewable technologies as well. The model designed is extremely versatile and simple, and provides an opportunity to conduct criticality analysis for renewable technologies with a holistic context for criticality.

This research also provides technological solutions to the potential bottlenecks which could hinder the energy transition of the transportation industry as shown in Table 8.2. The research provides new knowledge on the alternate paths which can be taken to move away from critical metals by looking into the technology readiness level of these technologies. Adoption of these technologies will ensure that e-Mobility technologies are protected from critical metal supply risks, while also maintaining operational and performance requirements of these vehicles.

9

Conclusion and Recommendations

9.1. Conclusion

This study encompasses a comprehensive analysis and evaluation of data, research findings, and expert interviews to derive several key conclusions regarding the criticality of metals for electric vehicles (EVs). These conclusions offer valuable insights into the present state of affairs, underscore significant trends, and shed light on crucial implications for future actions. The subsequent section will present recommendations based on these conclusions. The main research question is answered by answering the following sub-research questions :

RQ1: What are the factors that contribute to criticality of a metal for the Electric Vehicle Industry?

To ascertain the factors contributing to metal criticality in the electric vehicle industry, an extensive research effort was undertaken to understand the various methodologies employed by scientists in determining criticality and how these factors influence it. Most of the existing criticality analysis of materials for EVs were single dimensional as they only focused available geological reserves and/or geopolitics. It was important to also include factors such as competitive demand among renewables, primary demand sectors, technological substitutability and recyclability.

Drawing from the industrial application, scope, and time horizon of this framework, the factors contributing to metal criticality were determined using the approach explained in Graedel et al's (2012) framework. This framework was chosen as inspiration because it suited the time-frame and application of this research. However, this framework cannot be directly used as it requires complex algorithms and provides a quantitative output which is time consuming and not suitable for the scope of this research. The factors taken into consideration in this framework for analysing niche technologies were studied. Based on desk research, the factors that were not taken into account in this framework were also identified.

Key factors identified as contributing to metal criticality include available *geological reserves, sectors with competitive demand, and political, economic, social, technological, environmental, and legal factors*. A comprehensive framework was developed, addressing all these factors to assess metal criticality for electric vehicles. Based on these factors, the analysis model to determine criticality of metals for EVs was designed and implemented as shown in Figure 3.2.

RQ2: What according to literature is the current scenario of global critical metal supply, and what are the potential bottlenecks in the supply of critical metals due to electric vehicles by the year 2050?

This study focused on identifying the metals that play a pivotal role in the functioning of electric vehicles. It was confirmed from desk research that lithium, cobalt, nickel, copper, aluminum, and rare earth metals (Neodymium and Dysprosium) are deemed essential for the operation of EVs.

A scenario-based analysis was conducted to forecast the demand for these metals until 2050. This year 2050 was chosen since most countries in cohesion with the Paris Agreement aim to reach net zero emissions by 2050. Hence the renewable technologies would be peaking till 2050. To estimate the demand of each metal by 2050, a scenario analysis was studied on the growth of EVs by 2050. The quantity of electric vehicles (EVs) operating globally has been experiencing rapid growth in recent times. This expansion is propelled by a combination of factors, encompassing reduced costs of EVs, progressions in battery technology, and amplified governmental backing. Numerous nations are introducing incentives to encourage EV purchases, comprising tax incentives and grants, aimed at diminishing greenhouse gas emissions and fostering ecologically sustainable transportation. This backing, in conjunction with the escalating desire for EVs due to their economical operational expenses and environmental advantages, is steering the surge of the EV market. Consequently, the EV market is anticipated to sustain its expansion trajectory in the forthcoming years. According to market analysis, the worldwide EV market is predicted to exceed 40 million vehicles by 2030. This surge will be propelled by ongoing enhancements in battery technology, mounting consumer requisition, and supportive governmental protocols. The escalating presence of EVs on roadways will also notably influence the requisition for vital metals employed in EV batteries, such as lithium, cobalt, nickel, and others. This demand is foreseen to amplify as the EV market continues to burgeon. The necessity for lithium, cobalt, nickel, and other essential metals used in EV batteries is projected to grow with the proliferation of the EV market.

The estimated cumulative demand of metals from 2015 to 2050 ranges from baseline to stringent scenarios as: aluminium: 185–562 million tons; cobalt: 1–10 million tons; copper: 52–182 million tons; iron: 615–1630 million tons; lithium: 1.8–11 million tons; manganese: 8–20 million tons; nickel: 13–68 million tons; neodymium: 1.4–2.8 million tons; and dysprosium: 0.04–0.1 million tons.

The research revealed striking geological supply risk results for cobalt, indicating that the reserves may be depleted as early as 2035 under stringent scenarios. Furthermore, it was observed that the demand for cobalt, lithium, and nickel in the stringent scenario was orders of magnitude higher compared to the baseline and moderate scenarios. Conversely, the study indicated that REEs (Neodymium and Dysprosium) do not face geological supply risks in the medium-to-long term future.

Each metal was then subjected to the analysis model, and the results obtained by implementing the analysis model for each metal were tabulated. From these results. the metals which have potential supply bottlenecks for EVs by 2050 were identified. Notably, nickel was the most critical of all metals for EVs, followed by cobalt, lithium and REEs (neodymium and dysprosium).

RQ3: What are the current developments in manufacturing and recycling of traction batteries, electric motors and power electronics that can help the transportation industry to move away from critical metals?

The results obtained by answering the previous sub-research question formed the basis for identifying alternative paths to reduce reliance on these metals in EVs. These results were shared with experts and interviews were conducted to identify the promising solutions which could help mitigate the negative impact of these potential bottlenecks due to dependence on Nickel, Cobalt, Lithium and REEs by EVs.

Literature research and expert interviews in battery technologies, materials, and circular economy provided valuable insights on the feasibility of these alternative paths. Battery chemistries like LFP, which eliminates the usage of nickel and cobalt, and LMO, which eliminates cobalt usage, were explored. The feasibility and long-term impact of these chemistries were analyzed through research and interviews. LFP, already adopted by industry leaders like Tesla, not only reduces the usage of nickel and cobalt in batteries but also lowers the cost, thus accelerating the transition from internal combustion engine vehicles to EVs. Lithium-free battery technologies like potassium-ion and sodium-ion batteries were also examined at the research and development level, showing promise as solutions for lithium-free batteries, as affirmed by experts in interviews. Additionally, research on electric motors that do not rely on REEs indicated their suitability for specific applications, accompanied by a feasibility outlook. Motor technologies such as EESM, ASM, and PSM, featuring low-cost magnets, emerged as promising solutions for reducing dependence on REEs in EV motors. These promising technologies along with an outlook for each technology is tabulated in Table 8.2.

RQ4: What are the ways to redesign the manufacturing of Electric Vehicle components in order to mitigate supply risks for critical metals?

Based on the readiness of the alternate technologies narrowed down from the previous sub-research question, it was concluded that EVs must immediately replace NMC and LCA batteries with chemistries like LFP and LMO which will eliminate dependence on nickel and cobalt. There is very less impact on the driving range of EVs and battery wights due to incorporation of these chemistries, which is a boost for these technologies. However, though LMO batteries are cheaper than existing chemistries, they have longer charging duration of upto 20 hours, and hence must be used in vehicles which use overnight charging majorly. Further research needs to be done on Lithium free battery chemistries like Na-ion,K-ion, Mg-ion and SSBs in order to improve their performance and scalability to meet industrial standards both commercially and technologically. It was also concluded that OEMs can avoid usage of PSM motors which use REEs for the permanent magnets, with alternate technologies like ASM, EESM and PSM with low cost magnets in EV motors which do not use REEs at all. It can be noted that the impact in performance due to incorporation of these technologies is negligible in terms of rpm and power output which is why they are already being used in serial BEVs by EV market giants like Tesla and BMW.

Finally, the study explored current recycling technologies and emerging trends that provide secondary supplies of metals like cobalt and nickel. It examined existing policies, their weaknesses and potential policy changes that facilitate battery second life, secondary supplies of critical metals through recycling, and ensure access to such metals. These findings will inform the recommendations presented in the subsequent section.

In conclusion, this study's extensive analysis of data, research findings, and expert insights has led to valuable conclusions regarding the criticality of metals for electric vehicles. These conclusions, encompassing factors contributing to criticality, crucial metals for EVs, demand forecasts, and net criticality scores, provide a solid foundation for formulating recommendations on future actions.

Main research question: How does the rapidly growing number of electric vehicles (EVs) impact the supply of critical metals, and what solutions can be employed to mitigate any potential supply bottlenecks?

The transition to low-carbon economies, especially among global superpowers, is crucial for combating climate change, leading to a surge in demand for critical metals essential for renewable energy technologies. Electric vehicles (EVs) are central to this transition, aiding the transportation sector in achieving net-zero emissions. However, the accelerated adoption of EVs raises concerns about potential scarcities of critical metals like lithium and cobalt, necessitating sustainable sourcing, recycling, and substitution strategies. Hence it is very important to protect this technology by ensuring there are no supply bottlenecks in the metals that are crucial for the functioning of EVs.

In order to understand the impact of potential bottlenecks of metals crucial to EVs, firstly there had to be a fundamental understanding of what criticality means for the context of EVs, and how a metal can be deemed critical for EVs. This effort aimed to comprehend the diverse methodologies used to determine criticality and their impact. While existing analyses often focused solely on geological reserves and geopolitics, this study sought to encompass competitive demand among renewables, primary demand sectors, technological substitutability, and recyclability. Drawing inspiration from

Graedel et al.'s (2012) framework, the factors driving metal criticality were identified, although direct application was impractical due to complexity and time constraints.

The factors identified which need to be taken into account to understand the criticality of a metal for EVs are: Political Factors, Economic Factors, Social Factors, Technological Factors, Environmental Factors, Legal Factors, Available Geological Reserves by 2050 and Competitive Demand among renewable technologies. An analysis model encompassing all these factors was designed for the sake of this research. The metals lithium, cobalt, nickel, copper, aluminum, and rare earth metals (Neodymium and Dysprosium) were analysed for criticality using this analysis model, and the results were tabulated and compared. Hence the impact of the rapidly growing number of EVs on metals was found to be that there are potential supply bottlenecks for metals Nickel, Cobalt, Lithium and REEs (Neodymium and Dysprosium). Hence it is important for EVs to move away from these metals to ensure that this technology survives these supply bottlenecks.

The outcomes derived from addressing the preceding sub-research inquiry laid the groundwork for identifying alternative strategies to decrease dependence on these metals in EVs. These findings were communicated to experts, and interviews were conducted to pinpoint viable solutions that could alleviate the adverse repercussions of potential bottlenecks linked to reliance on Nickel, Cobalt, Lithium, and REEs in EVs. Insightful inputs were garnered through literature exploration and expert interviews in battery technologies, materials, and circular economy, shedding light on the feasibility of these alternative paths. Battery compositions such as LFP, designed to exclude nickel and cobalt, and LMO, devised to eliminate cobalt usage, underwent exploration. Their viability and long-term ramifications were scrutinized through research and interviews. Notably, LFP, already adopted by industry leaders such as Tesla, not only curtails the use of nickel and cobalt in batteries but also reduces costs, thereby expediting the shift from internal combustion engine vehicles to EVs. The feasibility of lithium-free battery technologies like potassium-ion and sodium-ion batteries was also assessed, displaying promise as solutions for lithium-free batteries, a perspective echoed by experts during interviews. Furthermore, the evaluation of electric motor technologies devoid of REEs revealed their suitability for specific applications, accompanied by an assessment of feasibility. Promising motor technologies like EESM, ASM, and PSM, featuring cost-effective magnets, emerged as potential solutions to mitigate reliance on REEs in EV motors.

Building on the preparedness of the identified alternate technologies from the earlier sub-research investigation, the study concludes that EVs must promptly replace NMC and LCA batteries with chemistries like LFP and LMO to eliminate dependence on nickel and cobalt. The incorporation of these chemistries has minimal impact on EV driving range and battery weight, bolstering their prospects. However, LMO batteries, while cost-effective compared to existing options, have a longer charging duration of up to 20 hours, making them suitable primarily for overnight-charging vehicles. Additionally, further research is warranted on lithium-free battery chemistries such as Na-ion, K-ion, Mg-ion, and SSBs to enhance their performance and scalability in alignment with industrial standards both commercially and technologically. It is also determined that Original Equipment Manufacturers (OEMs) can circumvent the utilization of PSM motors relying on REEs for permanent magnets. Instead, alternate technologies like ASM, EESM, and PSM equipped with low-cost magnets can be employed in EV motors, eliminating the use of REEs altogether. Remarkably, the integration of these technologies has minimal impact on performance in terms of rpm and power output, a reason for their adoption in serial Battery Electric Vehicles (BEVs) by EV industry giants like Tesla and BMW.

Hence, it is important for OEMs, EV Users and Policy Makers to take actions which promote these alternate paths that will help EVs to move away from critical metals while growing in number, thereby enabling energy transition by 2050 without any supply bottlenecks. The next section will elaborate more on the recommendations to help mitigate supply bottlenecks for EVs.

9.2. Recommendations

The criticality of metals for the electric vehicle (EV) industry necessitates proactive measures to secure their reliable supply. In light of the extensive analysis and evaluation conducted in this study, it is evident that the availability of key metals, such as lithium, cobalt, nickel and rare earth metals, play a crucial role in the development and sustainability of EV technologies. In this section, a set of recommendations that can be implemented by global policymakers, EV manufacturers and users to address the challenges associated with securing the supply of these critical metals is presented.

9.2.1. For EV Users:

1. **Responsible Purchasing of EVs:** EV buyers must make efforts in getting to know the battery chemistries and motor specifications of the vehicles before buying in order to make responsible decisions by avoiding critical metal dependency in purchased EVs. This will not only help in mitigating supply bottlenecks of these metals, but will reduce the demand for these metals which also have serious social and environmental impacts on the planet.
2. **Embrace Vehicle Pooling and Shared Mobility Services:** Consider participating in vehicle pooling programs or utilizing shared mobility services that provide electric vehicles. By sharing a vehicle with others for daily commuting or transportation needs, multiple individuals can benefit from a single electric vehicle, reducing the overall number of vehicles on the road. This can help minimize the demand for new electric vehicles and, consequently, reduce the supply risks associated with critical metals used in EVs.

9.2.2. For EV Manufacturers:

1. **Invest in Research and Development for the Right Technologies:** EV manufacturers should allocate resources to support research and development efforts aimed at reducing the dependence on critical metals in electric vehicle technologies. There are promising technologies like SSB batteries and Na-ion, K-ion batteries that still require extensive research and development in order to be used in commercial vehicles. OEMs should allocate funding and resources towards these technologies, instead of further developing existing battery chemistries which use Lithium, Cobalt and Nickel.
2. **Responsible Selection of Motor Technology and Battery Chemistry:** EV manufacturers must prioritize the responsible selection of battery chemistries that utilize minimal amounts of critical metals for the intended vehicle application over extravagant performance targets. The usage of motor technologies like ASM, EESM and PSM with low cost magnets, and battery chemistries like LMO (over NMC and LCA) can be used in smaller vehicles having low cost, city-driving application for users who prefer overnight charging.
3. **Create Short-term goals for adoption of LFP batteries over NMC and LCA batteries:** EV manufacturers must realize that LFP batteries are already commercially and technically viable and must opt this chemistry over NMC and LCA which uses Nickel and Cobalt, in order to minimize the risk of creating supply bottlenecks in Nickel and Cobalt by 2050.

9.2.3. For Policy Makers:

1. **Enhance Metal Supply Chain Resilience:** Policymakers should actively promote the diversification of the metal supply chain by encouraging investments in various mining regions and reducing reliance on a single country or region for metal production. This can be achieved through fostering strategic partnerships and collaborations between countries, supporting exploration and development of new mining projects, and ensuring a stable and diversified supply of critical metals. This is a downside of the latest policies implemented by the EU like the Net-Zero

Industries act,

2. **Develop Robust Recycling Infrastructure:** Policymakers should prioritize the establishment and implementation of efficient recycling infrastructure for electric vehicle batteries. This involves developing regulations and standards for battery recycling, incentivizing the use of recycled metals in battery production, and driving research and development in battery recycling technologies. Collaboration between EV manufacturers and recycling companies is essential to ensure effective and environmentally responsible recovery of critical metals. Additionally, policies should incentivize the second life usage of batteries and encourage responsible battery usage for low-power applications.
3. **Invest in Research and Development:** Policymakers should allocate resources to support research and development efforts aimed at reducing the dependence on critical metals in electric vehicle technologies. This entails exploring alternative materials and technologies that can substitute or minimize the use of critical metals without compromising performance, like Na-ion batteries, K-ion batteries, SSB batteries and motor technologies which are free of REEs. By funding research projects and fostering collaboration between academia, industry, and government agencies, innovative solutions can be accelerated which can improve the TRL of these technologies.
4. **Promote Circular Economy Practices:** Policymakers should enact policies that encourage the adoption of circular economy approaches within the electric vehicle industry. This includes incentivizing the design of products and components for easy disassembly, reuse, and recycling. Extended producer responsibility programs can be implemented to ensure that EV manufacturers take full responsibility for the entire lifecycle of their products, including the responsible management of critical metals. Global leaders like the EU have already initiated this policy, which is a move in the right direction.
5. **Advocate for Responsible Mining Practices:** Policymakers should advocate for and enforce regulations that promote responsible mining practices, encompassing environmental sustainability, worker safety, and fair labor practices. By supporting and incentivizing responsible mining operations, policymakers can mitigate the environmental and social impacts associated with metal extraction while ensuring a reliable supply of critical metals.
6. **Foster Global Cooperation:** As stated in the Critical Raw Materials Act by the European Commission already, Policymakers throughout the globe as well should facilitate international cooperation and dialogue among governments, industry stakeholders, and research institutions to address the challenges of securing the supply of critical metals. This involves sharing best practices, data, and information on metal reserves, promoting technology transfer, and establishing global frameworks for sustainable metal sourcing. Collaborative efforts can enhance the resilience and sustainability of the metal supply chain. This has already been initiated by the EU in the Net-Zero Industries act, as mentioned earlier.
7. **Regulations to prevent disposal of Batteries:** As mentioned by Expert 4 in the interview, there currently exists no policy which holds companies responsible on how they dispose batteries. There must be a policy to provide incentives to these companies for recycling batteries instead of incinerating them, which is the current practice as mentioned by Expert 1 during the interview.
8. **Support Domestic Metal Production:** Policymakers can incentivize domestic metal production by providing financial incentives, tax breaks, and regulatory support for mining companies. By encouraging domestic metal production, the reliance on imports can be reduced, and the resilience of the electric vehicle industry to supply chain disruptions can be strengthened. The EU has already taken a step in this direction with the CRM act. The objective of the proposed Critical Raw Materials (CRM) Act by the European Commission is to achieve specific targets for meeting domestic demand. This includes sourcing 10 percent of domestic demand from

domestic mining, 40 percent from domestic refining, and 15 percent from recycling. To facilitate these goals, the CRM Act would establish a common EU time limit for issuing permits to relevant industrial projects.

By implementing these recommendations, policymakers, EV manufacturers and consumers can take proactive steps to secure the supply of critical metals, foster sustainability, and drive the transition to a more resilient and environmentally friendly electric vehicle industry.

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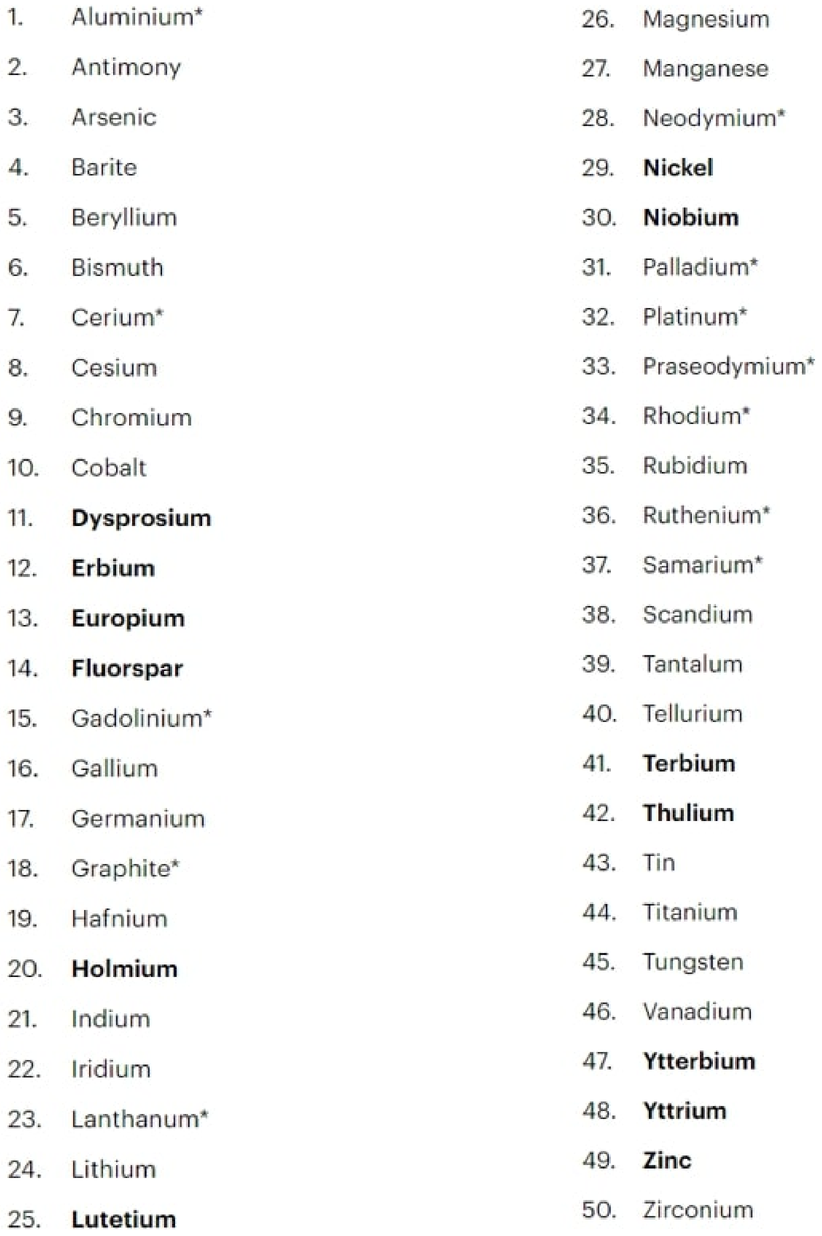
Appendix

A1. List of Critical Metals



1. Aluminium*
2. Antimony
3. Arsenic
4. Barite
5. Beryllium
6. Bismuth
7. Cerium*
8. Cesium
9. Chromium
10. Cobalt
11. **Dysprosium**
12. **Erbium**
13. **Europium**
14. **Fluorspar**
15. Gadolinium*
16. Gallium
17. Germanium
18. Graphite*
19. Hafnium
20. **Holmium**
21. Indium
22. Iridium
23. Lanthanum*
24. Lithium
25. **Lutetium**
26. Magnesium
27. Manganese
28. Neodymium*
29. **Nickel**
30. **Niobium**
31. Palladium*
32. Platinum*
33. Praseodymium*
34. Rhodium*
35. Rubidium
36. Ruthenium*
37. Samarium*
38. Scandium
39. Tantalum
40. Tellurium
41. **Terbium**
42. **Thulium**
43. Tin
44. Titanium
45. Tungsten
46. Vanadium
47. **Ytterbium**
48. **Yttrium**
49. **Zinc**
50. Zirconium

Figure 9.1: List of Critical Metals (International Energy Agency, 2022)

A2. Interview Log

A2.1 Interview with Expert 1 and Expert 2

This interview provided the opportunity to engage with two anonymous experts from the battery research group at TU Delft. These experts, referred to as E1 and E2 in the transcript below, are highly knowledgeable and experienced in the field of battery technologies. They are actively involved in cutting-edge research and development, focusing on alternative battery chemistries, including Potassium and Sodium-ion batteries. Additionally, both experts have industrial expertise as they work closely with BatteryNL, an organization with a range of objectives related to advancing battery technology.BatteryNL is a company that operates with several objectives in mind. Firstly, they aim to unravel the complex interface processes in next-generation lithium battery chemistries using novel and state-of-the-art methodologies. Their research is specifically targeted at newly developed 2D and 3D model interfaces and representative battery morphologies. Another objective of BatteryNL is to develop new scalable and economically viable interface strategies that can mitigate performance degradation in batteries. BatteryNL also places importance on supporting the integration of new battery technologies through techno-economic and sustainability evaluations. They actively engage with society to assess the impact and feasibility of implementing these technologies in real-world applications. By evaluating the techno-economic aspects and addressing sustainability concerns, BatteryNL aims to drive the adoption and successful integration of new battery technologies.Lastly, BatteryNL strives to stimulate battery technology developments and collaborations in the Netherlands. They establish roadmaps and exploitation plans to guide the advancement of battery technologies and foster collaboration among stakeholders. By organizing interactions and networking opportunities, BatteryNL creates an environment conducive to innovation and knowledge exchange within the battery technology domain.

The insights and expertise shared by Expert 1 and Expert 2 in this interview provide valuable perspectives on the research, development, and potential applications of alternative battery technologies. Their contributions shed light on the advancements, challenges, and the overall landscape of the battery industry, aligning with the objectives of BatteryNL and contributing to the broader field of energy storage. Expert 1 also shared content from a seminar he had given on critical metals in batteries, which was shared and was very valuable for this research.

Interview Transcript

Nithin Harish: What are some of the challenges associated with traditional lithium, nickel, and cobalt-based battery chemistries?

E1: Traditional lithium, nickel, and cobalt-based battery chemistries have several challenges. Firstly, there are concerns about the limited availability of these metals and their uneven geographical distribution, which can lead to supply chain issues. Secondly, the mining and extraction processes for these metals can have significant environmental and social impacts.

Additionally, cobalt mining has been associated with ethical concerns regarding child labor in certain regions. Furthermore, the cost of these metals can fluctuate based on market demand and supply. Lastly, there are concerns about the safety and stability of these chemistries, particularly in high-temperature or high-voltage conditions, which can lead to safety hazards such as thermal runaway.

Nithin Harish: What are Potassium and Sodium-ion batteries, and how do they differ from traditional lithium-ion batteries?

E2: Potassium and Sodium-ion batteries are alternative battery chemistries that aim to replace or reduce the reliance on lithium, nickel, and cobalt. Potassium-ion batteries use potassium ions instead of lithium ions for energy storage, while sodium-ion batteries use sodium ions.

One key difference is the size and mobility of the ions: potassium ions are larger than lithium ions, and sodium ions are even larger. This size difference affects the crystal structures and materials used in the battery's electrodes. Another difference is the abundance and geographic distribution of these metals compared to lithium. Sodium is more abundant and widely distributed, which can potentially alleviate some supply chain concerns associated with lithium.

Nithin Harish: How do Potassium and Sodium-ion batteries compare to traditional metals in terms of performance, energy density, and cost?

E1: Potassium and Sodium-ion batteries are still in the early stages of research and development, so their performance, energy density, and cost profiles are not yet fully established. However, from a theoretical perspective, Potassium-ion batteries could offer higher energy density compared to lithium-ion batteries due to the larger size of potassium ions. Sodium-ion batteries, on the other hand, may have slightly lower energy density compared to lithium-ion batteries.

As for cost, the availability and distribution of potassium and sodium could potentially make these battery chemistries more cost-effective than lithium, nickel, and cobalt. However, it's important to note that manufacturing these alternative batteries at scale and ensuring their long-term stability and safety could introduce additional cost considerations.

Nithin Harish: What is the Technology Readiness Level (TRL) of Potassium and Sodium-ion batteries?

E3: The Technology Readiness Level (TRL) of Potassium and Sodium-ion batteries can vary depending on the specific research and development efforts. Generally, Potassium-ion batteries are still in the early stages of exploration and fundamental research, so their TRL would be relatively low, possibly in the range of TRL 1-3. Sodium-ion batteries have progressed further, with some prototype and demonstration projects, but they are not yet commercially available for widespread use. Their TRL would be in the range of TRL 4-6. It's important to note that TRLs are subjective and can vary based on different sources and definitions.

Nithin Harish: Are there any ongoing research or development efforts focused on finding new materials for batteries? If yes, what are some promising candidates? Is it possible to reduce the percentage of critical metals used in these batteries?

E3: Yes, there are ongoing research and development efforts focused on finding new materials for batteries. One area of exploration is the development of alternative cathode materials that can host potassium or sodium ions, such as Prussian blue analogs and various transition metal oxides. These materials have shown promise in early studies, but further research is needed to optimize their performance and stability. Additionally, there is ongoing work to enhance the performance of anode materials and electrolytes for these battery systems. These efforts aim to reduce or eliminate the use of critical metals like cobalt, nickel, and lithium, making the batteries more sustainable and reducing supply chain concerns.

Nithin Harish: What are some of the potential applications for Potassium and Sodium-ion batteries?

E2: Potassium and Sodium-ion batteries have the potential to be used in various applications. They could find applications in stationary energy storage systems, such as grid-scale batteries or residential energy storage. These batteries could help balance the intermittent nature of renewable energy sources like solar and wind, enabling more efficient energy management. Additionally, they could be used in electric vehicles, particularly for applications that prioritize cost-effectiveness over high energy density. However, it's important to note that the specific application suitability would depend on the performance characteristics, cost, and safety of the battery technology when compared to existing alternatives.

Nithin Harish: What are some of the challenges that need to be overcome for Potassium and Sodium-ion batteries to become commercially viable?

E1: Several challenges need to be addressed for Potassium and Sodium-ion batteries to become commercially viable. One key challenge is improving the energy density and cycle life of these batteries. While research has shown promise in this regard, further advancements are needed to match or exceed the performance of lithium-ion batteries. Another challenge is optimizing the cost and manufacturing processes for these alternative battery chemistries.

Scaling up production and ensuring consistent quality can be complex tasks. Additionally, safety and reliability are critical factors that need to be thoroughly addressed to gain consumer and industry confidence. Lastly, establishing a robust supply chain for potassium and sodium materials, including mining, processing, and recycling, will be essential for long-term viability.

Nithin Harish: What is the expected timeline for the commercial availability of Potassium and Sodium-ion batteries?

E3: The timeline for the commercial availability of Potassium and Sodium-ion batteries is uncertain and can vary depending on the pace of research and development. Potassium-ion batteries are still in the early stages of exploration, and it could take several more years, possibly a decade or more, before they reach commercialization.

Sodium-ion batteries are further along in terms of development, but they still require additional optimization and validation before they can be mass-produced for commercial applications. It’s challenging to provide an exact timeline, as it depends on various factors such as funding, technological breakthroughs, and market demand.

Nithin Harish: How might the widespread adoption of Potassium and Sodium-ion batteries impact the battery industry and the clean energy transition?

E2: The widespread adoption of Potassium and Sodium-ion batteries could have several implications for the battery industry and the clean energy transition. Firstly, it could diversify the battery market and reduce dependence on critical metals like lithium, nickel, and cobalt, potentially making the battery supply chain more robust and sustainable.

Secondly, if these alternative batteries can achieve competitive performance and cost profiles, they could accelerate the adoption of renewable energy by providing more cost-effective and efficient energy storage solutions. Moreover, the availability of multiple battery chemistries would enable better matching of energy storage technologies to specific applications, further optimizing the overall energy system.

Nithin Harish: What are some other emerging battery technologies that could potentially impact the energy storage landscape?

E1: Apart from Potassium and Sodium-ion batteries, several other emerging battery technologies show promise for impacting the energy storage landscape. Solid-state batteries, which replace liquid electrolytes with solid electrolytes, offer the potential for higher energy density, improved safety, and longer cycle life. Lithium-sulfur batteries are another emerging technology that could provide significantly higher energy density than traditional lithium-ion batteries.

Additionally, flow batteries, such as vanadium redox flow batteries, are gaining attention for large-scale energy storage applications due to their scalability and long cycle life. However, it’s important to note that these technologies are still undergoing development and face their own set of challenges for commercialization.

Nithin Harish: How can policymakers and industry players support the development and deployment of alternative battery technologies?

E3: Policymakers and industry players can play a crucial role in supporting the development and deployment of alternative battery technologies. Firstly, they can allocate funding and resources for research and development, providing grants or incentives for projects focused on advancing these technologies. Secondly, they can establish regulatory frameworks and standards that promote the safety, reliability, and environmental sustainability of battery technologies.

Additionally, policymakers can implement policies that incentivize the adoption of alternative battery technologies, such as offering tax credits or subsidies for their use in specific applications. Collaboration between industry players, academia, and government institutions can also foster knowledge sharing and accelerate progress in this field.

Nithin Harish: I have one last question, which is a validation on the weights I have assigned to each of the factors that contribute to criticality. So, what do you think of these factors? Are they all equally important, or are some more critical than others?

E1: Yeah, I personally tackle the term criticality by imagining that I live in China. In such a case, China has a lot of reserves, so lithium wouldn't be critical for me. However, some other metals might be critical in that context. Therefore, it really depends on the specific case and geographical perspective.

Considering a global scope, I think it's wise to give equal importance to all factors in order to remove any bias. Each factor contributes to the overall criticality assessment, and neglecting any of them could lead to an incomplete understanding of the situation. It's important to take into account aspects such as availability, geopolitical factors, supply chain risks, and environmental impacts.

Assigning equal weights to all factors ensures that no single factor is overemphasized or overlooked. This approach promotes a holistic analysis that considers multiple dimensions of criticality. By giving equal importance to all factors, we avoid potential biases that could arise from prioritizing certain factors over others.

However, it's important to note that criticality assessments can vary depending on the specific context and objectives. Different stakeholders may have different priorities and perspectives. Therefore, it's crucial to have discussions and consultations with experts and stakeholders from various domains to reach a consensus on the relative importance of the factors.

In summary, while the specific importance of each factor may vary depending on the context, adopting an equal weighting approach on a global scale helps ensure a comprehensive and unbiased assessment of criticality. This allows for a more robust understanding of the factors contributing to criticality and enables informed decision-making in the field of battery technologies.

Nithin Harish: This concludes the list of questions I had for the both of you. Thank you so much for your valuable time and inputs. I already feel I have quite some directions to focus my further research in.

E1: Good luck with your thesis, and we are curious to see your results, as we feel it will be very useful for the both of us definitely!

A2.2 Interview with Expert 3

The following interview was conducted with an Assistant Professor in the Storage of Electrochemical Energy (SEE) group at the Reactor institute Delft. With a background in Applied Physics and Financial Economics, as well as a PhD in Chiral Magnetism, the interviewee brings a diverse range of expertise to their research. Their current focus lies in studying thin film materials for sustainable applications and exploring the interfacial properties of battery materials. Additionally, they hold the role of instrument scientist for a neutron reflectometer, a powerful experimental technique for studying thin films. The expert is referred to as E3 in the transcript, and has also has been researching on understanding the interfacial properties of battery materials, which is crucial for enhancing battery performance. The interviewee employs in-operando neutron scattering and other experimental techniques to investigate the nanoscale ionic transport across various interfaces within batteries. By studying these interfaces non-destructively, they aim to unravel the factors that influence battery performance and contribute to advancements in battery technology.

Interview Transcript

Nithin Harish: What do you feel about the criticality of metals in battery technologies? Do you think that this is going to be a factor that determines the direction in which innovations in this field will take place?

E3: The current scenario is almost completely dominated by Lithium-ion batteries, especially in the context of electric vehicles (EVs). As EVs gain traction and the demand for high-energy applications, such as electrification of heavy-duty vehicles, increases rapidly, lithium remains a critical metal. However, when we consider the global scale and different use cases, the importance of specific metals varies. For instance, in China, which has significant lithium reserves, lithium may not be as critical compared to other metals. In a global context, it is wise to give equal importance to all factors and avoid bias. The criticality of metals may influence the direction of innovations, but it also depends on the specific requirements and availability of alternative materials.

Nithin Harish: Do you see any viable alternatives in the context of electric vehicles that can help us move away from nickel? Are there certain applications, such as low-power city applications, where sodium or potassium batteries could be suitable?

E3: There are ongoing efforts to explore alternatives to nickel-based batteries for electric vehicles. One potential alternative is iron phosphate-based batteries, which are already being used in some applications in China. However, these batteries have certain limitations, such as shorter lifetime compared to nickel-based batteries. Sodium-ion and potassium-ion batteries are also being researched, but their technology readiness level for commercial implementation may not be as high yet. These alternative chemistries could be suitable for specific applications with lower power and energy requirements, such as city applications or low-end vehicles.

Nithin Harish: In the field of recycling, do you think that batteries can perform just as well with recycled nickel and cobalt? Or will there be a performance impact on the battery?

E3: The performance of recycled nickel and cobalt in batteries depends on the purity of the materials obtained through recycling processes. If the recycling can achieve high purity levels, there should not be a significant performance impact. However, at the moment, only a small percentage of cars are electric, and we need a much larger quantity of batteries, which requires a substantial amount of nickel. Until the point where we have sufficient recycled sources, there will still be a need for new nickel production. Additionally, recycling batteries can be energy-intensive, and certain components, such as polymer electrolytes, pose challenges in terms of chemical handling and recycling.

Nithin Harish: Do you see iron phosphate batteries as the future for electric vehicles? Are there other technologies like sodium-ion or fluoride-ion batteries that are emerging?

E3: Iron phosphate batteries are currently a viable alternative for specific applications, but they may not be the future for electric vehicles as they have certain downsides, such as lower energy density and power density compared to current battery chemistries. They are suitable for low-end applications or specific use cases, such as city bikes or scooters. As for sodium-ion or fluoride-ion batteries, it is still too early to determine their future in electric vehicles. Ongoing research is exploring alternative chemistries, energy density improvement through anode materials, and the development of solid-state electrolytes.

Nithin Harish: Some battery chemistries, especially lithium-ion batteries, contain a large amount of rare earth elements. Are there any ways to circumvent the usage of rare earths in batteries?

E3: Rare earth elements are more commonly used in the battery management system rather than in the core of the battery. In the context of our discussion, it is possible to make batteries work without rare earths. However, the efficiency may be lower without these elements. Rare earths are more critical in applications such as windmills and EV motors where strong permanent magnets are required. It's important to consider the overall system and application requirements when assessing the criticality of rare earths in batteries.

Nithin Harish: In your opinion, what are the ongoing areas of research for battery technologies? What aspects are researchers trying to optimize?

E3: Battery research can be categorized into three main directions. First, there is a focus on exploring alternative chemistries, particularly for stationary energy storage applications where moving away from nickel-based batteries is desirable. Second, researchers are working on increasing energy density, primarily by investigating anode materials. Graphite, which is widely used as an anode material, can potentially be replaced with materials like lithium or silicon, resulting in a significant increase in energy density and reduced reliance on other critical elements. Lastly, there is a shift towards solid-state electrolytes, which offer potential advantages in terms of safety, reduced use of unwanted chemicals, and the possibility of compact battery designs without extensive battery management systems, leading to increased energy density.

Nithin Harish: Literature suggests that sodium-ion batteries are much lighter than lithium-ion batteries. Does this lighter weight have a significant impact on the energy required to move the vehicle, considering that the battery itself contributes to a significant amount of weight compared to the vehicle?

E3: Weight is an important factor to consider in battery technologies, as it affects parameters like Ampere hours per gram, per cubic centimeter, or per area. However, it's essential to take a holistic view when assessing the impact of battery weight on overall vehicle energy consumption. While certain components of sodium-ion batteries may be lighter than those in lithium-ion batteries, other factors, such as the weight of the anode, also come into play. A comprehensive analysis of the entire battery system, including energy density and power density, is necessary to evaluate the overall energy efficiency.

Nithin Harish: Do you think there could be any policies or regulations that could help us move away from the usage of critical metals in batteries?

E3: Both the European Union (EU) and the United States (US) have already implemented policies to become more self-sufficient in critical metals and address the challenges associated with their usage. The EU, for example, is developing policies specifically focused on critical materials for the energy transition. These policies aim to promote sustainable practices, resource efficiency, and reduce dependence on critical metals. The existence of such policies reflects the importance of this topic and the need for strategic approaches to ensure a secure supply chain for battery technologies.

Nithin Harish: From your perspective as a materials expert, what do you think defines the criticality of metals the most? What do you consider the most crucial factor in deeming a metal to be critical?

E3: Criticality of metals is determined by a combination of factors. One important aspect is the ease of substituting a metal for a specific application. For example, lithium is considered critical due to its importance in current battery technologies, especially for electric vehicles. However, when we look at the overall picture, nickel becomes even more critical due to its widespread use in various applications, including batteries. The criticality of a metal depends on the specific requirements and availability of alternatives, making it a multifaceted consideration. The application itself plays a crucial role in assessing the criticality of metals.

Nithin Harish: When you mentioned that liquid electrolytes with polymers are not preferred, what are the reasons behind this preference?

E3: The preference for alternatives to liquid electrolytes with polymers stems from several factors. Firstly, polymer-based electrolytes are challenging to recycle, making the overall battery recycling process more complex. Additionally, their production is relatively energy-intensive, which adds to the environmental footprint of the battery manufacturing process. Moreover, in terms of environmental impact, if these polymers escape into the environment, they can have severe consequences on groundwater and soil. Finally, polymer electrolytes can also pose a safety risk due to their flammability. These factors contribute to the exploration of solid-state electrolytes as potential alternatives, as they offer improved safety, reduced environmental impact, and the potential for more compact battery designs.

Nithin Harish: I would like to express my gratitude for your valuable inputs. I am excited to share my findings with you and receive your feedback.

E3: You're welcome! It has been a pleasure to share my knowledge and insights with you. I look forward to reviewing your findings and providing feedback. Good luck with your thesis, and I'm genuinely interested to see the outcomes of your research.

A2.3 Interview with Expert 4

This interview an Assistant Professor at the Faculty of Industrial Design Engineering at TU Delft who is referred to as E4 in the interview transcript. With a strong focus on sustainable design, quantification of environmental impacts, and industrial ecology, E4's expertise lies in understanding how environmental considerations can shape the field of design and contribute to a more sustainable future. With a background in critical raw materials and supply chain resilience, E4 brings a unique perspective to the conversation, exploring the intersection of sustainable design and the challenges associated with material sourcing and resource management.

This interview delved into E4's current research interests, which revolve around the quantification of environmental impacts and how this knowledge can inform sustainable design decisions. Furthermore, the crucial role of critical raw materials in the design process and the need for resilient supply chains to ensure sustainability was explored.

E4's extensive experience in the field of industrial ecology allows for insightful discussions on topics such as circular economy and system-level concepts. By understanding the interplay between product design choices and broader system-level implications, E4 sheds light on the importance of considering lifecycle assessments, environmental footprints, and circularity in the design process.

Interview Transcript

Nithin Harish: How feasible do you believe it is to move away from metals like lithium, cobalt, nickel, and dysprosium in EVs? What technological or societal changes would be necessary to support this shift?

E4: Recycling lithium is relatively cheap compared to other metals, so technically, it is quite feasible to recycle them. However, the organizational aspects pose challenges. For instance, managing a large stack of lithium-containing batteries is easy, but ensuring their collection and transportation to the recycling facilities is more complex and costly.

Nithin Harish: With respect to other materials like cobalt or nickel, do you see markets already incorporating technologies that move away from these metals? Or is recycling still the main area of research?

E4: Actually, most people are exploring substitution options. For example, LFP batteries or sodium batteries are being considered. While sodium batteries may not dominate the market immediately, they provide an alternative. Recycling is also an area of ongoing research.

Nithin Harish: Do you think there could be certain technological or societal changes critical for a sodium battery or similar alternatives to emerge?

E4: It's difficult to pinpoint specific factors holding back sodium batteries. Large-scale adoption may primarily face supply chain issues that require significant efforts to establish. Ultimately, the acceptance and demand for sodium batteries or any new technology depend on consumer attitudes. Increased consumer demand for clean energy solutions can create market incentives for the development and commercialization of sodium batteries.

Nithin Harish: How important do you think circular business models will be in facilitating a shift away from critical metals in EVs? What circular solutions do you see as most promising in this regard?

E4: Circular business models will play a crucial role, especially considering the European Union's focus on increasing recycling. Legislation will drive recycling efforts, and circular models will support these initiatives. However, I believe that symbols and models may be overrated compared to the impact of legislation. For instance, France's law mandating certain reparability standards for products before they can be sold promotes circularity. Extending product lifespan and improving recyclability are key. For instance, if solar panels were designed to be easily disassembled, recycling them would be more efficient. We need to act urgently and make every effort to transition to sustainable practices.

Nithin Harish: From a global perspective, what role do you think government policies and regulations would play in driving a transition to reducing consumption of these metals for batteries?

E4: Government policies are crucial in reducing car dependency and promoting alternatives. The current focus is on transitioning from conventional to electric cars, but it's not enough. We need fewer cars overall, which can be achieved through car sharing and improved public transport systems. Government interventions are essential to bring about these changes.

Nithin Harish: From a business and societal perspective, what do you think are the most significant challenges in incorporating these transitions?

E4: The main challenge lies in the economic feasibility within the current system. Some companies lobby against such transitions, and there's often insufficient availability of resources. Additionally, political tensions and varying interests among countries hinder progress. For instance, in countries like India, the transition to renewable energy is slower due to a preference for coal-based energy generation. Overcoming these challenges requires long-term thinking and effective industrial policies to counter market shortages and ensure a sustainable transition.

Nithin Harish: Speaking of the political perspective, countries like China possess a major share of critical metals. Do you think countries in Europe or elsewhere have an incentive to reduce dependency on these metals and shift away from them?

E4: I highly recommend reading the Critical Raw Materials Act of the European Union and the Net-Zero Industry Act. These legislative initiatives provide insights into the European policy approach. However, implementation varies among countries. Some, like the Netherlands, face organizational challenges. The risk associated with dependency on critical metals, especially with geopolitical factors, is significant. Geopolitics and potential disruptions in supply chains pose the biggest risks. For instance, conflicts like the Russian invasion of Ukraine or a Chinese invasion of Taiwan could heavily impact critical metals markets and supply chains. Thus, reducing dependency on these metals becomes essential.

Nithin Harish: Based on your assessment, what do you believe is the most important risk associated with sticking to lithium or other critical metals for batteries?

E4: The energy transition needs to accelerate to meet the 2050 goals. Geopolitical factors play a critical role in resource provision, and recent events like the Russian invasion of Ukraine demonstrated the impact on markets. The price of nickel surged, and trade in this metal was temporarily halted on the London Metal Exchange. Uncertainty surrounds how critical material supply chains will adjust, and the risk of geopolitical conflicts disrupting these chains is substantial. Among the critical metals, cobalt faces the highest risks due to China's dominant position in scaling up its capacity. While lithium has a relatively lower risk, the geopolitical landscape remains a significant concern.

Nithin Harish: How important do you think consumer attitude changes are in this transition, such as adopting practices like carpooling?

E4: Consumer behavior changes are generally challenging to achieve without policies that enforce them. Consumers rarely change behavior voluntarily. Encouraging practices like carpooling to reduce the number of vehicles on the road would require policy interventions and incentives to drive consumer behavior.

Nithin Harish: Thank you! Those were all the questions I had. Thank you for your time and valuable inputs.

E4: No problem! All the best for your thesis!