EVALUATING CRITICAL METALS FOR JAPAN AND A LOW CARBON FUTURE

by

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ABSTRACT

Concern about availability and access to mineral resources has increased beginning the21st Century as technological advancement increased the demand for mineral resources.Besides changing the demand landscape by altering the quantity and the composition for metals demanded,the increase in demand pushed mineral prices up, further increasing the anxiety about mineral resource availability and access. The minerals supply landscape, too, has changed. The resurgence of resource nationalism indicates a return to protectionist thinking, which has led to tension between mineral consuming and mineral producing countries.

Meanwhile, the need to reduce carbon emissions to mitigate climate change could further accelerate mineral resource availability concerns. The amount of mineral resources demanded by low carbon technologies could increase rapidly and put significant pressure on the mineral demand-supply dynamics.

Therefore, it is necessary to investigate the metals that have a higher chance of experiencing supply-demand tensions in the medium term and the long term, given these developments.

In the medium term, Japan is one of the countries that could be heavily affected if there is a disruption to the supply of mineral resources. Japan has created a competitive manufacturing industry that relies significantly on mineral resources despite Japan lacking a meaningful domestic supply. Despite this reliance on minerals resources by Japan's manufacturing sector, few studies not initiated by the government exist to understand Japan's critical minerals—mineral resources with high economic importance and a high risk of supply disruption. In other major economies, concerns about the availability of and access to mineral resources have prompted researchers to suggest multiple methods to identify critical materials. However,the methods proposed so far, though sensible, should be improved.

This study proposes a quasi-dynamic approach that incorporates probabilities to

measure the vulnerability of an economy to supply restriction of metals to improve the existing medium-term criticality methodologies. The study identifies unique probabilities for absolute price changes for 18 metals and, using economic data from Japan's economic input-output tables, identifies critical metals for Japan for 2000, 2005, 2011, and 2015. The results indicate that metal price changes follow different probability distributions.The study also finds that niobium, molybdenum, rare earths, vanadium, tungsten, and cobalt are critical metals for Japan, and they will remain critical for the medium term. Based on the finding for the medium-term critical metals, the study proposes several strategies for Japan to secure the supply of these critical metals, including strengthening the relationships with resource-rich countries, pushing for more recycling of valuable metals, and stockpiling.

Regarding the low carbon future, the International Energy Agency(IEA) has carried out extensive modeling of future energy and transport requirements and proposed pathways to a low carbon future. However, few studies investigate the mineral resource requirements to achieve this ideal low carbon future. Based on IEA's 2 degrees scenario(2DS)(which describes an energy system consistent with emissions trajectory that climate science research indicates would limit the global temperature increase to 2°C)this study quantifies the amount of metals required by renewable energy techniologies and electric vehicles necessary to achieve the 2DS scenario. The study analyzes eight metals necessary for running five major renewable energy technologies (hydropower, geothermal, wind, solar, electric vehicles) to understand the possible additional demand for the selected metals. The study uses systems dynamic analysis with STELLA software to investigate the demand-supply progression between 2019 and 2070. By investigating additional demand and factors such as available reserves, recycling rates, available substitutes, and environmental implications, the study identifies critical metals for the long term in the context of pursuing a low carbon future. The study found that Nickel, cobalt, rear-earth elements and molybdenum will experience the most significant additional demand. However, only cobalt, lithium, and rear-earth elements are critical in the long term after considering recycling rates, substitute availability, and environmental implications.

Although the study proposed improvements in measuring and displaying critical metals, it did not eliminate the need to estimate critical metals accurately. In the medium-term analysis, there is still a need to estimate the end-use application of metals accurately because the existing data on end-use and GDP are broadly aggregated, leading to overlaps in estimating metals' real economic contributions. Furthermore, important factors that could affect the metal supply's security such as recycling rates, available metal substitutes, improvements in mining technology, and metal co-production were left out, to avoid meaningless results because of aggregating too many factors. In the long-term study, recycling rates and available substitutes were discussed but not quantitatively measured. The system dynamics model could be improved further if such factors and others like impact on the environmental and the implications, improvements in technology, and metal co-production are quantitatively measured and incorporated into the model.

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CHAPTER 1

INTRODUCTION

This chapter discusses the context of the study,states the research problem and the goal of the study.The outline of the entire thesis is also highlighted.

1.1 Background

Going back to the beginning of the Holocene age, concern about raw materials availability and limits to availability has been a sporadic feature in the resources landscape. The earliest tussle between human needs and the available resources recorded by researchers is the food shortage 10000 years ago. Maurice and Smithson (1984) described how the rising population and climate changes that caused food shortages, triggered the agrarian revolution. At that time, people responded to the shortage by shifting from a hunter-gatherer lifestyle to communities that settled down and practiced agriculture. Also, as described by History.com editors (2018) ,ancient Greece made great efforts to balance resource availability vs. human needs. The wars around 1000BC interrupted trading routes, cutting off Greece from Tin's supply, which led ancient Greece to develop iron as an alternative.

Although there is a long history of struggle between human needs and available resources, worry about resource availability and access seems to have rebounded in the 20th century and intensified in the 21st century driven by the changing mineral resources landscape. There are several underlying forces that are driving the changes in the mineral resources demand landscape.Rapid technological advances over the years led to a rise in demand for diverse mineral resources as the technology permitted better mineral commodities serving a range of new needs. As an example, in the 1800s, about 9 metals were required to produce electricity. By the 1900s, 20 metals were used for electricity production, and the number had increased to at least 38 metals by the 2000s(Achzet et al. (2011)). Advances in technology also allowed the extraction of many mineral commodities at increasingly lower costs, promoting more mining.

Second, the world population has continued to surge. With rising population, more mineral resources are required to meet the increasing needs. Together with rising population, living standards improved meaning people required items with more functionalities, which required even more mineral commodities to manufacture. These changes—technological advancement, surging population, and improving lifestyles—put pressure on mineral demand-supply balance.

Although changes in prices may not reflect the whole story,the sudden rise in mineral resources' prices beginning 1950s points to the changing landscape. The increase in metals' demand put pressure on metal prices to rise in the late 20the century and early 21st century. For example, between 1960 and 2008, Tin and Molybdenum's real prices increased by 1000% and 2150%, respectively(U.S Geological Survey (2018)).Figures 1.1 and 1.2 show show the development of some selected metals prices since 1900. Metal prices increased significantly in the 1960s, dropped in the 1990s, and gained momentum from 2001.

On the supply side, the diversity of metal suppliers has shrunk compared to the beginning of the century. For example, share of total value of top 5 mining companies in the world increased from 18% in 2000 to 35% in 2008. As of 2019 it was 21%. (Humphreys (2015); S&P Global (2019)).This means a few companies control the supply of some metals, and there is a risk should the companies conspire to engage in activities such as forming oligopolies. Table 1.1 shows how the share of production of top 10 mining companies changed between 2000 and 2008.

Not only has the diversity of supplier shrunk, there is also significant shift in the geographical distribution of producer countries.The top largest individual producers of some important metals and their shareas of production has changed since 1950s.For example, in 1950, the top producers of iron ore were United States(47%),France(14%),Sweden(7),Germany(5%). Producer countries and their shares had changed to China(27%), Australia(21%),Brazil(17%) and India(11%) in 2010.Producers of Chromium in 1950 comprised of South Africa(29%),Turkey(25%),Zimbabwe(17%) and Phillines(15%).By 2010, Zimbabwe and

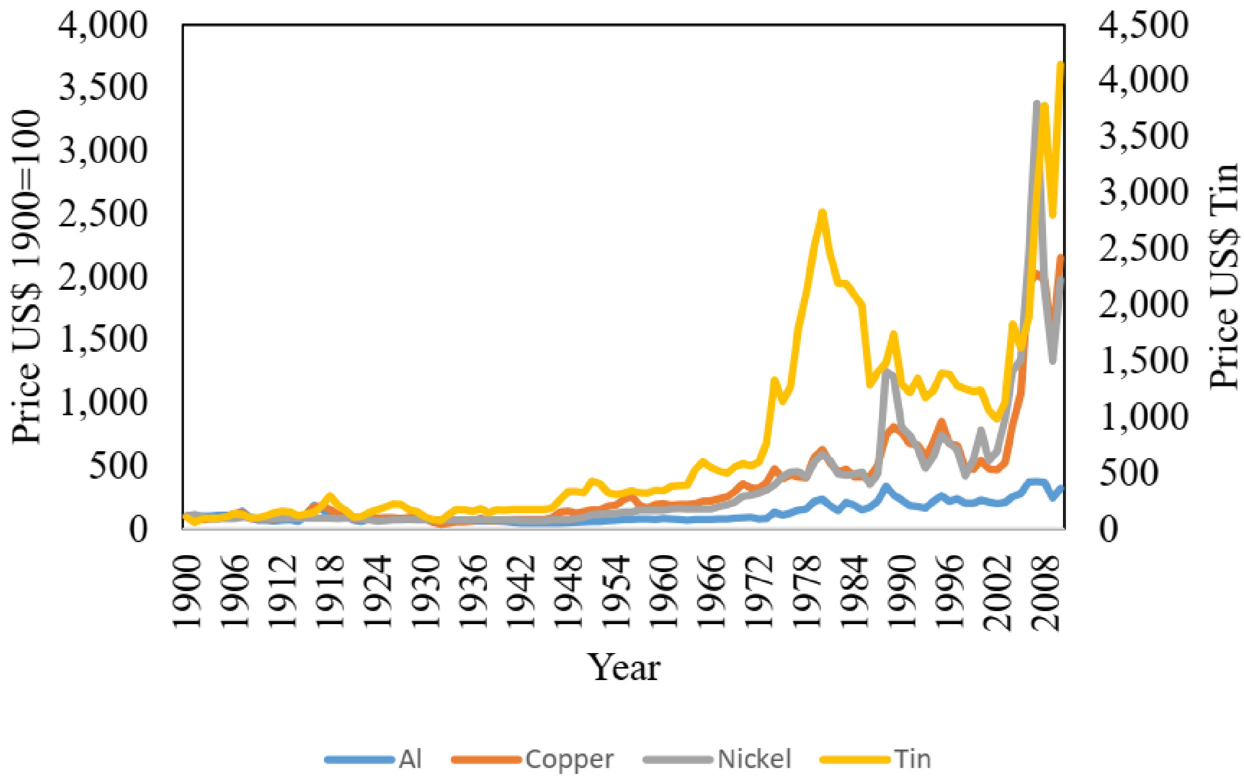

Figure 1.1: Changes in price of selected base metals 1990-2008. Source:United States Geological Survey(USGS)

Phillines were no longer among top producers and had been replaced by Kazakhstant(20%) and India(13%). The share of South Africa and Turkey had also changed to 43% and 7% respectively. For some minerals such as lithium, platinum, and niobium, close to the entire world production is limited to two or three mining countries. Australia and Chile produced 78% of Lithium in 2019, South Africa and Russia produced 84% of Platinum while 87% of Niobium was produced by Brazil.

Further, although mineral exploration and recovery technologies have improved, facilitating mining resources at a lower cost ,some essential minerals are produced mainly as by-products and have highly concentrated production. The resurgence of protectionist thinking as manifested in resource nationalism(as seen in 2011 for example, when China restricted export of rare-earth metals) and governments' considerable efforts to limit

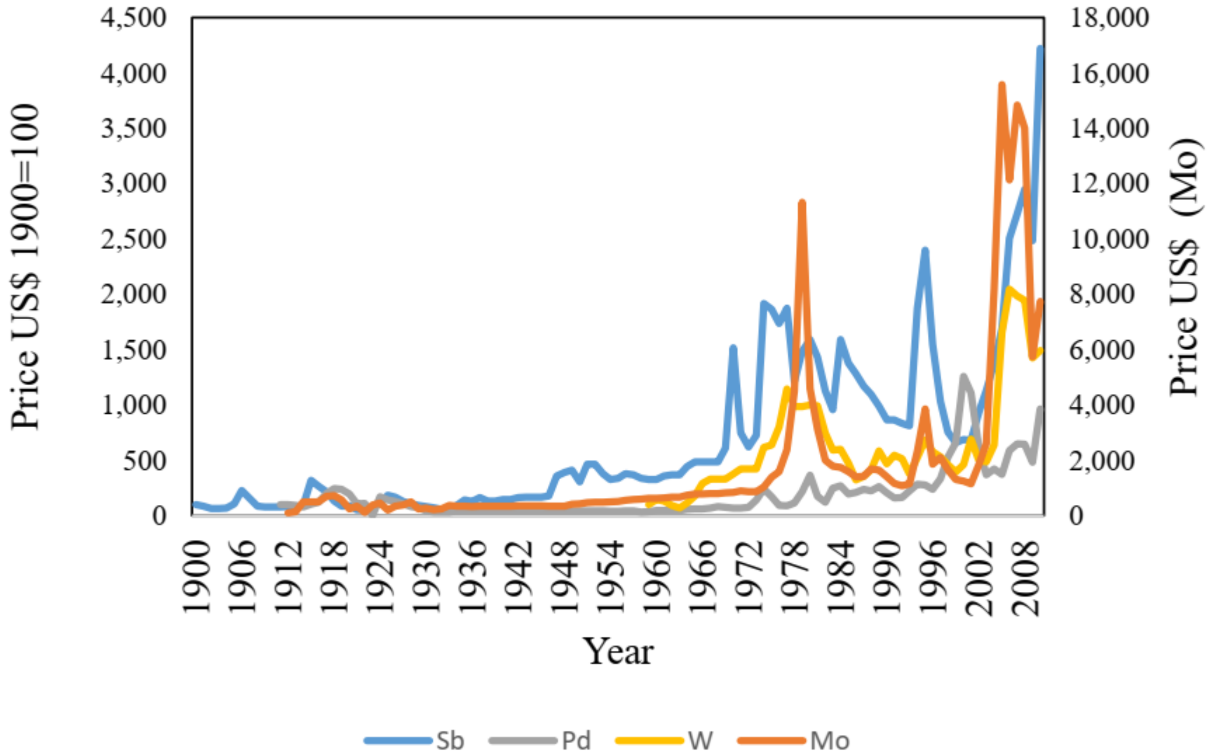

Figure 1.2: Changes in prices of selected rare metals 1900-2008. Source:United States Geological Survey(USGS)

mining's environmental impact also add stress to the changing landscape of mineral supply.

Meanwhile, the ongoing campaign for the transition to a low-carbon society will further change the mineral demand-supply landscape.Climate change brought about by rising average temperatures is a global emergency.Hoegh-Guldberg et al. (2018) reports on the impacts of letting the globe warm above pre-industrial levels.The need to transition to a low carbon future is therefore undeniable, a conclusion supported by Intergovernmental Panel on Climate Change(IPPC).Precisely, researchers place renewable energy technologies at the center of achieving a low carbon future. However,transition to a low carbon society requires investment in entirely new technologies that require a diverse quantity of mineral resources. The transition to using more renewable energy technologies could rapidly increase demand for metals and change the scale and composition of metals demanded.

Table 1.1: World's largest mining companies by value of production in 2000 and 2008. Data Source:Humphreys (2015); S&P Global (2019)

Company	Commodity	%Share (2000)	Company	Commodity	%share (2008)
Rio Tinto	Fe ore, Cu, coal	5.1	CVRD(Vale)	Fe ore,Ni	8
Anglo American	PGMs, diamonds,Coal	3.7	BHP Billiton	Fe ore,Cu,coal	5.9
Norilsk Nickel	PGMs,Ni,Cu	3.6	Rio Tinto	Fe ore,Cu,coal	4.6
CVRD(Vale)	Fe ore,Cu,coal	3	Anglo American	PGMs,diamonds,coal	3.5
BHP	Fe ore,Cu,coal	3	Freeport-McMoRan	Cu, Au	3
Codelco	Mo, Cu	3	Anglo American	PGMs,diamonds,coal	2.3
AngloGold	Au	2.1	Zstrata	coal,Cu,Ferroalloys	2.3
Phelps Dodge	Mo, Cu	1.9	Norlisk Nickel	Ni,PGMs,Cu	2.3
Grupo Mexico	Cu	1.7	Barrick Gold	Au	1.9
lnco	Ni	1.7	Newmont Mining	Au	1.2
Total Share		28.5			35

The projected drastic increase in quantity of mineral resources poses a challenge to availability and access because of limited reserves, long lead times before a new mine comes into production, and difficulty producing some metals independently because they are mined as co-products of some other metals and the high environmental impact of mining some metals.

The changing mineral resources landscape has elevated awareness by industries and governments of raw materials supply vulnerabilities and the possible resulting shortages. Especially for metals dependant economies, it is necessary to identify the mineral resources that might face demand-supply imbalances and find ways to secure such resources. Researchers are already developing a range of methods to evaluate such mineral resources,in studies that have adopted a framing commonly known as material criticality, but the task remains a significant intellectual challenge

1.1.1 Defining 'Critical material.'

There exists a considerable amount of literature on material criticality, but there still is no precise definition of a critical metal because different researchers understand the concept differently. The term "critical material" is understood to have been coined in 1939 by the "Strategic and Critical Materials Stock Piling Act" of the U.S..Since then, several researchers dealing with mineral resources' criticality have adopted various meanings for the term. For example, Buijs et al. (2012) propose that material is critical if it has "a comparatively high economic importance with a comparatively high risk of supply disruptions." Poulton et al. (2013) propose that material is critical if it is "essential to economic development but having limited supplies and being subject to supply-demand imbalances," while Gleich et al. (2013) stated that criticality "denotes the extent of current and future risks associated with a particular metal."

Although there is no standard definition of critical raw material, material criticality is associated with estimating whether a material has high economic importance and faces a significant risk of supply disruption. The implicit concern within criticality studies is ensuring access to mineral resources at an affordable cost and to show metals that pose economic or security risks should they experience extreme price increases. Economic risk can arise for several reasons, but the events contributing to creating a high risk for businesses and economies involve price changes and cutting off the supply of mineral resources. Therefore, ensuring an adequate supply at a reasonable cost is the primary concern across different industries and countries.

1.2 Problem statement

The mineral commodities landscape changes have led to renewed concerns about available mineral resources and the limits to access in countries that heavily depend on mineral resources for their economies, such as Japan. Japan has created competitive mineral resource-dependent industries such as the automobile, electronic equipment, and machine tools manufacturing industries, despite having no meaningful domestic supply of mineral resources. Notwithstanding the crucial role played by mineral resources, few studies have examined critical metals in Japan.

In other established economies, concerns about mineral resource availability have prompted scholars to propose methods to measure and show mineral resources with a high risk of supply disruption.Countries such as the united states, and regions such as the European union have all carried studies to map out their critical metals. However, there is little agreement on measuring such metals, and questions have arisen regarding the proposed methods.

Specifically, a prominent trend in metal criticality studies is to show the relative risk of supply disruption for metals that are important to the economy and elucidate the results of disruption.In efforts to measure the risk,criticality studies have consequently borrowed the idea of the risk matrix used in risk studies. In a traditional risk analysis, risk is tied to the concept of probability. However, current material criticality studies either overlook probability or make strong assumptions about probability functions by considering only the standard deviation of metal price changes (volatility) while attempting to measure criticality. The studies that use standard deviation assume that price all metals' price changes follow a normal distribution.This is a wide assumption since not all price changes may follow a normal distribution. There has been no attempt to find out the individual probability distributions of metals' prices, nor use unique probability functions to measure critical metals , to the best of our knowledge.

In the attempts to identify critical metals, the majority of the studies surveyed are predominantly static. They measure criticality for a single year. However, raw materials landscape is dynamic, and time should be an important consideration.The demand and supply of mineral resources changes depending on several factors such as technological progress and level of economic development. Further, when deciding which metals are critical, current criticality studies are subjective in the sense that researchers have no standard criteria to decide the criticality boundary.

The existing studies are also criticized because they use diverse methodologies and indicators, resulting in different results with different materials selected as critical. The materials studied, choice of the criticality indicators, measurement of the indicators, the indicators' weighting, the study's time frame (long term/ short term), and target audience(national, cooperate, and global) differs widely among the existing studies. Although different regions or countries will have different materials identified as critical based on their needs, the methodology to estimate the critical metals should fairly standard and comparable. In addition to diverse methodologies, there is a vague distinction between short-term and long-term indicators of criticality. The available studies generally use the same factors to measure criticality both for the short term and long term. They assume that the factors that make a metal critical in the short term or medium-term are the same factors that influence material criticality in the long term.

1.3 Purpose of the study

This study proposes work that addresses the gaps observed in the previous literature. First, this study attempts to incorporate a unique probability function of price changes for each metal to measure Japan's critical metals, and hence attempt to address the requirement of traditional risk assessment that probability should be used in risk assessment. Currently, criticality studies that try to incorporate probability make a strong assumption about risk probability . This study fills this gap by identifying unique probabilities for individual metals price changes to improve the results' accuracy. An accurate examination of essential metals in Japan is required to protect its resource-dependent manufacturing industries.

Second, this study proposes a quasi-dynamic approach to identifying critical metals for the medium term for Japan, in efforts to move from static study to dynamic analysis. The study analyzes 18 metals–aluminum, chromium, cobalt, copper, gold, iron, lead, lithium, manganese, molybdenum, nickel, niobium, platinum, rare earths, silver, tungsten, vanadium, and zinc–chosen based on data availability, between 2000 and 2015 . The study also uses a system dynamics approach to evaluate critical metals in pursuing a low carbon future.

Lastly, this study proposes identifying critical metals based on their criticality level and distance from the criticalaity matrix's origin, thus providing a clear criticality boundary.

The study offers originality in:

1. As pointed out previously, current criticality researches assume all metal price changes follow a normal distribution. This study identifies unique probability distribution for each metal's price changes and proposes a unique equation to measure critical metals.
2. Current criticality studies focus on single years, making them static. This study proposes a quasi-dynamic approach to identify critical metals for the medium term (for Japan) and using a system dynamics approach to identify critical metals in the long term (in the context of pursuing a low carbon future).
3. Apart from government-initiated studies, no available study explicitly identifies critical metals for Japan except Hatayama and Tahara (2015). This study identifies critical metals for Japan in 2000,2005,2011 and 2015.

4. This study is the first to use the Input-Output tables to study critical metals. It is possible to measure each industry's economy-wide effects (multiplier effect) using Input-Output tables, and therefore estimate metals criticality accurately.

1.4 Significance of the study

The study proposes methodologies to measure critical metals in the medium term and long term. It then uses the proposed methodologies to examine Japan's critical metals in the medium term and critical metals for a low carbon future in the long term. The medium-term criticality methodology incorporates probability to estimate vulnerability and distinguishes criticality through criticality levels. Using Probability to gauge critical materials will help to analyze supply risk scenarios rationally. The raw materials industry is full of uncertainties that can lead to unfounded anxieties about raw materials supply. Through probabilities, it is possible to analyze different scenarios and outcomes systematically. Comparing the risk curves can help to determine critical raw materials and help prioritize risk management efforts. Knowing which materials are critical can help reduce dependence on particular materials and prioritize the research agenda. Identifying critical materials can also help promote efficiency in the use of some materials, prompt producers to increase production by, for example, reviving previously uneconomic sources, and stir technological innovation.

The study will also contribute to the literature on long-term raw materials criticality assessments. Currently, few studies are available that propose ways to estimate long-term critical metals. As a result, many researchers are striving to formulate a standard tool to evaluate critical raw materials for the future that corporations, governments, and other interested parties can use. Our study contributes to these efforts by proposing a system dynamics model that can help understand different mineral industry players' interactions and estimate critical metals.

Japan can benefit from the study. The short-term criticality analysis points out critical metals for Japan. The Japanese government can use the information to put measures to avert any possible supply disruption. Policy analysts and stakeholders pushing for a low carbon future can also benefit from the study. The results of long-term criticality are based on global institutions' scenarios to mitigate climate change. Understanding which metals could prevent realizing this goal can help policymakers put measures to address the possible shortfalls.

1.5 Outline of the study

Chapter 1 gives the background of the study. Critical material is defined, the study's objectives are stated, and the study's significance is emphasized. Chapter two address the theoretical frameworks used to measure and identify critical metals. The chapter is divided into two sections: methodologies for analyzing critical metals in the medium term and methodologies to analyze critical metals in the long run. Literature about the available methodologies is also extensively reviewed. Chapter 3 focuses on medium-term criticality analysis. A methodology to estimate the critical metals in the medium is proposed, and using the proposed methodology, we identify critical metals for Japan in the medium-term. Chapter 4 shifts to the long term analysis and identifies critical metals for the long term, in the context of achieving a low carbon future. A system dynamics model is proposed, and the model is applied to estimate long-term critical metals. Chapter 5 ties the findings of chapter three and chapter four and offers the study's overall conclusions.

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CHAPTER 2

THE THEORETICAL FRAMEWORKS FOR MEASURING CRITICAL METALS

This chapter discusses the literature on evaluating critical materials. Attention is devoted to indicators used to measure critical metals and how material criticality studies display the results. Criticisms on existing methodologies are discussed.

2.1 Indicators used to measure critical metals

Criticality studies consider a wide range of metrics to identify and quantify the relative risks associated with a particular metal. These indicators can be grouped into Geological-technical factors, Economic factors, and socio-political factors.

2.1.1 Technical Factors

Issues that could lead to physical supply difficulties of a particular metal because of reasons such as physical unavailability of the metal(does the mineral exist in adequate quantity?) or production and processing difficulties(do we know how to extract and process a particular metal?) are considered as geological and technical factors. Inadequate secondary resources such as laabour and poor infrasctures(construction of infrasture such as water, electricity and road roads could be hampered but severe bad terrain) could also be considered as technical factors.However, the main technical and geological factors that could affect material criticality are ore grades, metal reserves, metals coproduction,substitutability of metals, and recycling rates.

Mineral resources are unequally distributed across the globe, as determined by nature. Therefore, it is reasonable to conceptualize and quantify available mineral resources to estimate the relative risk to supply. Through understanding the fundamental relationship of factors such as ore grades and how the grades are changing over time in relation to mineral reserves, we could understand which metals face a higher potential of experiencing supply disruptions. For example, primary production ore grades could influence product and recovery costs, making the mineral potentially less economically available (Dewulf et al. (2016))

Reserve is a standard measure of geological availability of raw materials. USGS defines reserves as resources that have been fully geologically evaluated and are commercially available and legally mineable at the current economic prices. In analyzing which metals is critical, available reserves is good indicators of whether adequate minerals and metals are available to meet our current and future needs. However, since the measurement of reserves depends on the prevailing economic conditions, reserves change frequently. Mining companies usually invest based on the short to medium-term needs and use reserves to justify investment for say 20 years. Therefore, reserves do not reflect the total amount of mineral resources potential and global reserve data are not reliable indicators of criticality. As a result, while some studies reserve data directly to estimate criticality (see, for example, Graedel et al. (2012)), many studies avoid the use of reserves.

Another technical factor that could influence criticality is the co-production of metals. Some metals could face supply challenges because they do not have independent production infrastructure but are mined as by-products from ores of primary carrier metals. The economic driver of mining is the carrier metals, and therefore, the availability of co-products depends on the carrier metals' prices. Co-products are only mined if they can generate additional revenue; otherwise, they are discarded. For example, it would not be economical to increase zinc production(a carrier metal) to meet germanium's (a by-product) increased demand. Some metals, such as germanium, could have high economic importance, but they are mined as by-products/ co-products. Such metals are critical because their production is highly dependent on the price of the carrier metal.Figure 2.1 shows how metals are linked in their production.

Substitute performance and substitute availability could also influence whether a metal is critical or not.Should materials availability constraints occur and there is not material that can offer similar or superior functionalities at a comparable cost, severe consequences could occur. A material may have a substitute, but the price could be inhibit access, or the performance poor. Developing a perfect substitute for a metal is perceived to be difficult and takes a long time since each metal has unique properties that make them suitable for certain

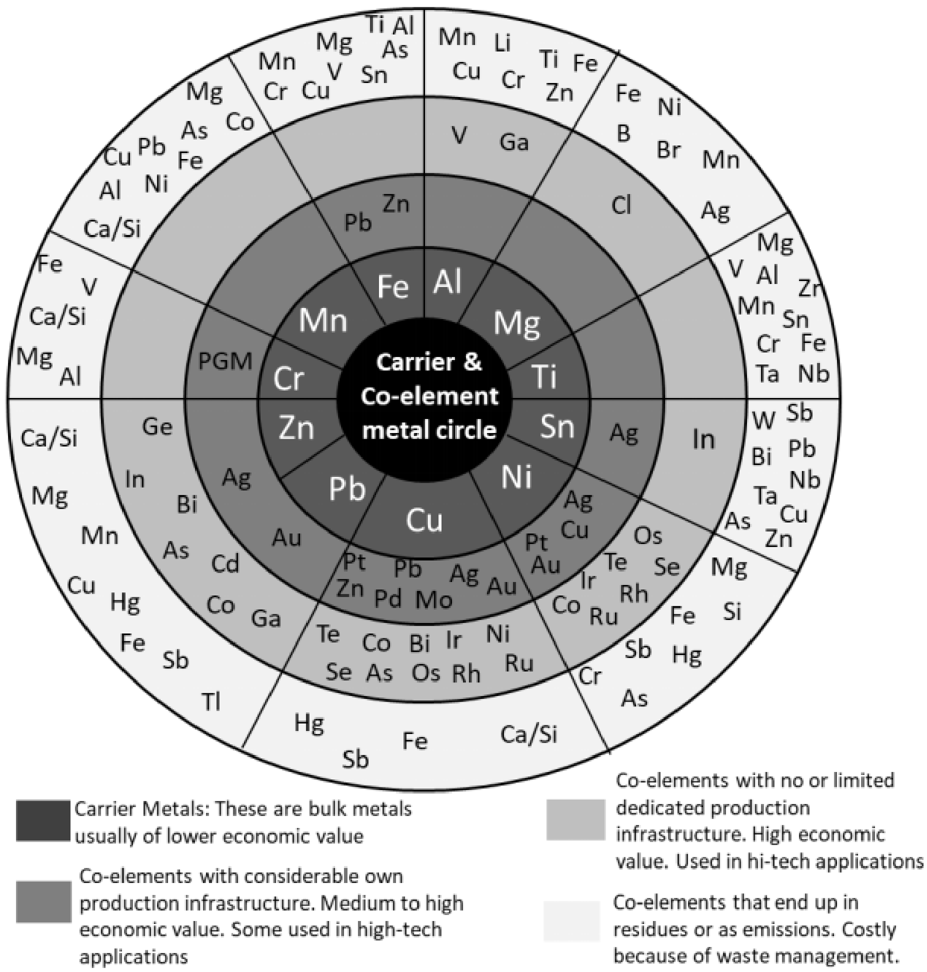

Figure 2.1: Co-production of metals. Source: Verhoef et al. (2004)

functions.Whether a there is a technology to recycle a particular metal, could influence material criticality.However, recycling of some metals is complex, can lead to accumulation of toxic wastes, or is too costly to be economical.

In summary, technical and geological factors can influence whether a metal is critical or not, and such factors ought to be considered while determining material criticality.

2.1.2 Economic Factors

Economic factors considers market forces and issues and issues with economic motivation such as resource nationalism, and how they could influence supply of essential metals. Several factors fall under economic factors.For example, Concentration of producer countries,concentration of producer companies, and concentration of import partner countries.Other economic factors are competition for a particular metal but different sectors of the economy,price changes and fluctuations, mining costs,trade barriers and embargoes. These factors influence how much of a metal is produced, and how much metal is available to end users such as companies or countries.

For example, the concentration of producer countries or producer companies may lead to supply disruption should an accident occur in a major producer, or should the suppliers take deliberate steps to limit a mineral resource's supply.The often cited metal with concentrated production is Cobalt. With 70 percent of Cobalt production in Democratic Republic of Congo(DRC), past and recent events have led to supply bottlenecks of the metal. In 1970d civil war in Congo led to severe supply disruption, and recently, the spread of COVID-19 pandemic led to closure of several cobalt mines and disruption of supply routes, leading to disruption of supply of Cobalt(Green car congress (2020)). Some producer countries might resort to resource nationalism as a means to boost their economies. As Anderson 2015 points out, governments in producer countries could benefit by engaging in resource nationalism by increasing state ownership and control over some mineral resources.Example of resource nationalism include Iranian government's nationalization of the Anglo–Iranian Oil Company (now known as BP) in 1951, and China's restriction of rare-earth exports in 2011. Changes in the price of metal could also influence criticality as mining companies adjust their exploration and production schedules based on the prevailing prices.Price may also influence the investment decisions by mining companies. Investment is greenfield mines is very costly,especially the initial capital costs, and if the returns are not high enough to compensate for the risk of investment, mining companies are deterred from investing in new mines or expansion of existing ones.

2.1.3 Socio-political Factors

Socio-political factors include regulatory and governance issues of the producer countries and environmental implications of mining a particular metal. Potential environmental implication of using a particular metal may lead to supply disruption. Mining of a particular metals may be accompanies by disposal of toxic substances as by products, which might affect the neighboring communities or even entire regions, if the toxic waste are absorbed into the waterbeds. Weak environmental performance of producer countries could also endanger the supply of raw material because of risks during accidents due to hazards to humans and the environment. There is a possibility that producer countries may implement policies to protect the environment, leading to the limited supply of some raw materials as some mining companies may fail to meet the often stringent measures(Ku and Hung (2014), Buijs and Sievers (2011)).

Geopolitical issues could also arise if an element is produced in locations subject to political instability. Other socio-political considerations include land-use restrictions as communities push for preservation of nature, and community acceptance issues(Social license to operate).

2.2 Studies Measuring Critical Metals for the Short and Medium-term

The earliest known attempt to explicitly study and point out critical metals was by the United States National Research Council in 2008. The study identified minerals with high economic importance and high supply risk for the U.S. economy's automotive, aerospace, electronics, and energy sectors. It proposed measuring the importance of a metal by its substitutability (if substitutes for a particular metal were readily available, it was relatively unimportant). If no materials could provide the same functionality at a comparable cost, the metal ranked high in importance. The study approximated supply risk by combining several factors, including the quantity of mineral resources available, policies and actions of producer countries that could affect the supply, and the price consumers are willing to pay for the metal (Committee on Critical Mineral Impacts of the U.S. Economy (2008))

The study combined these factors—the metal's importance as measured by the availability of a substitute and the supply risk—into a criticality matrix. A critical metal was one that sat in the upper right corner of the matrix. The metal's criticality increased as one moved from B to A, as shown in figure 2.2. As outlined by Glöser et al. (2015), the representation of the criticality matrix results seems to have been borrowed from the classical display of risk, where the probability of damage occurring is multiplied by the scale of the damage to estimate the risk.

Following the National Research Council study, several studies (see,for example, European Commission (2010),US Department of Energy (2011),Ku (2012), Graedel et al. (2015)) were published that retained the concept of a criticality matrix as proposed by the National Research Council but changed the factors used to measure criticality.

Among these subsequent studies, the study by the European Commission (2010) is widely known because it attempted to identify critical metal for the whole European Union.The study focuses on two sources of risk that may lead to supply disruption, and matches these risks against the economic importance of the individual metals to determine critical metals.The risks considered are supply risk and environmental country risk. Supply

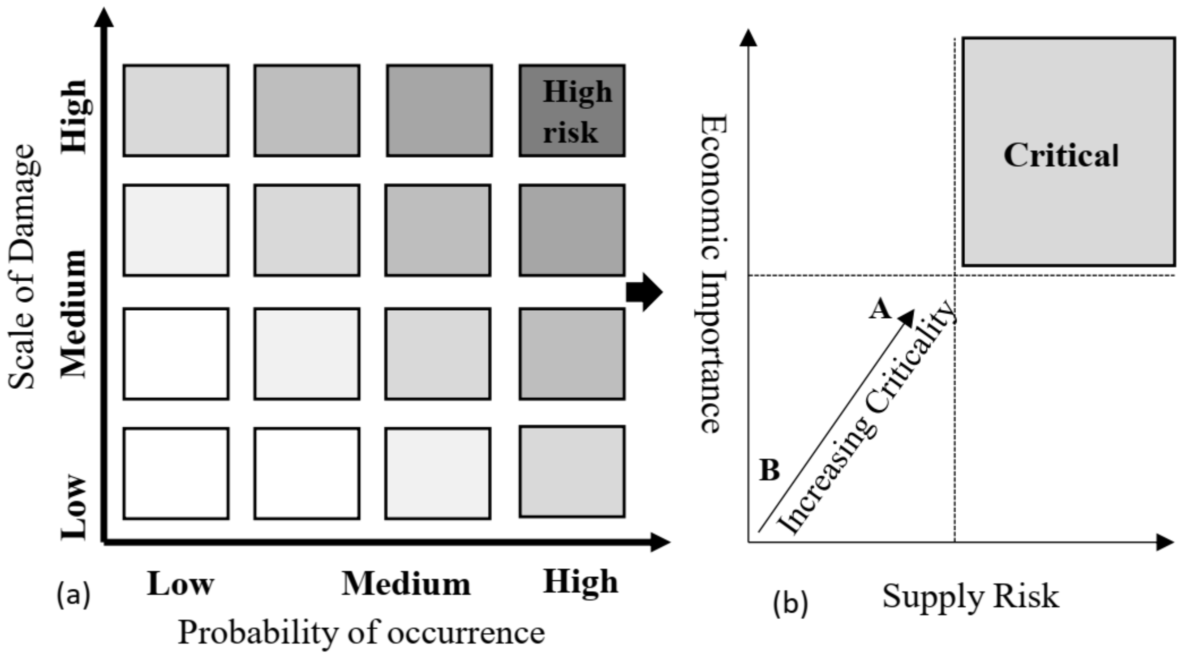

Figure 2.2: Criticality matrix as an abstraction of the risk matrix. The display of criticality in the United States National Research Council study is comparable to the risk matrix used in risk studies.

risk takes into account the political and economic stability of producer countries, concentration of the producers, and the substitution and recycling pf the metals(which could offset supply pressures). Environmental risk considers the fact that some producer countries might take measures to protect the environment and therefore endanger the supply of come metals.The study suggests measuring the economic importance of metals by considering the value added to the economy by the end use application of the metals.the results are displayed in a criticality matrix. Figure 2.3 show the results of the study. Critical metals sit in the upper right corner of the supply risk versus economic importance graph.

Aside from the criticality matrix approach to display results, a number of approaches to measure and display critical metals have been suggested. One study proposed a modified version of the criticality matrix and suggested criticality zones to measure and display critical metals.The authors combined numerous factors(to measure vulnerability and supply risks,

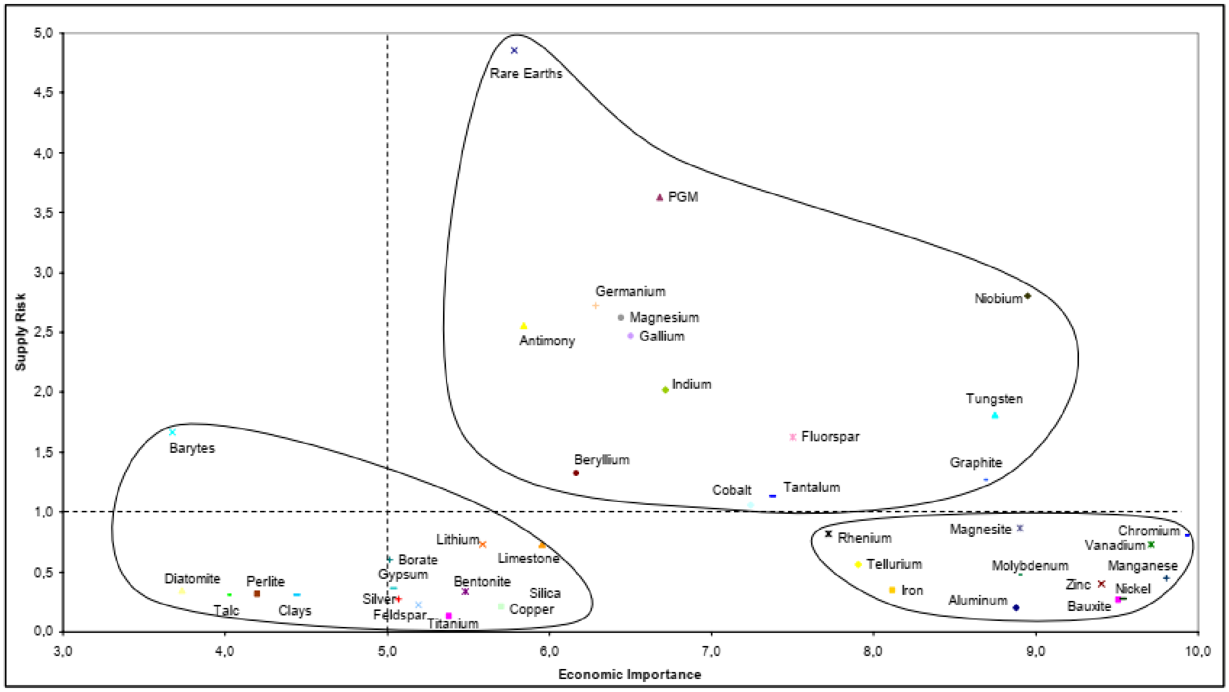

Figure 2.3: Critical metals for the EU in 2010. Source:European Commission (2010)

and displayed the results in zones as opposed to a criticality matrix. The zones had different polygonal shapes and indicated criticality (Erdmann and Behrendt (2011)).Figure 2.4 shows the proposed criticality zones.

Graedel et al. (2012) proposed another unique approach which was also adopted by Nuss et al. (2014); it combined three principal indicators to display critical materials: supply risks, vulnerability, and environmental implications. The method was novel because it went beyond the standard two-dimensional approach and incorporated the third axis that measured a particular metal's environmental load. The study measured criticality by vector length from the origin in the criticality space. A metal was critical if it sat further from the origin. This alternative approach had enlightening implications for manufacturers in highlighting the possibility of environmental considerations restricting access to mineral resources.

As a result, these subsequent studies have considerable methodological similarities and some notable differences.For example, majority of the studies investigate critical metals for

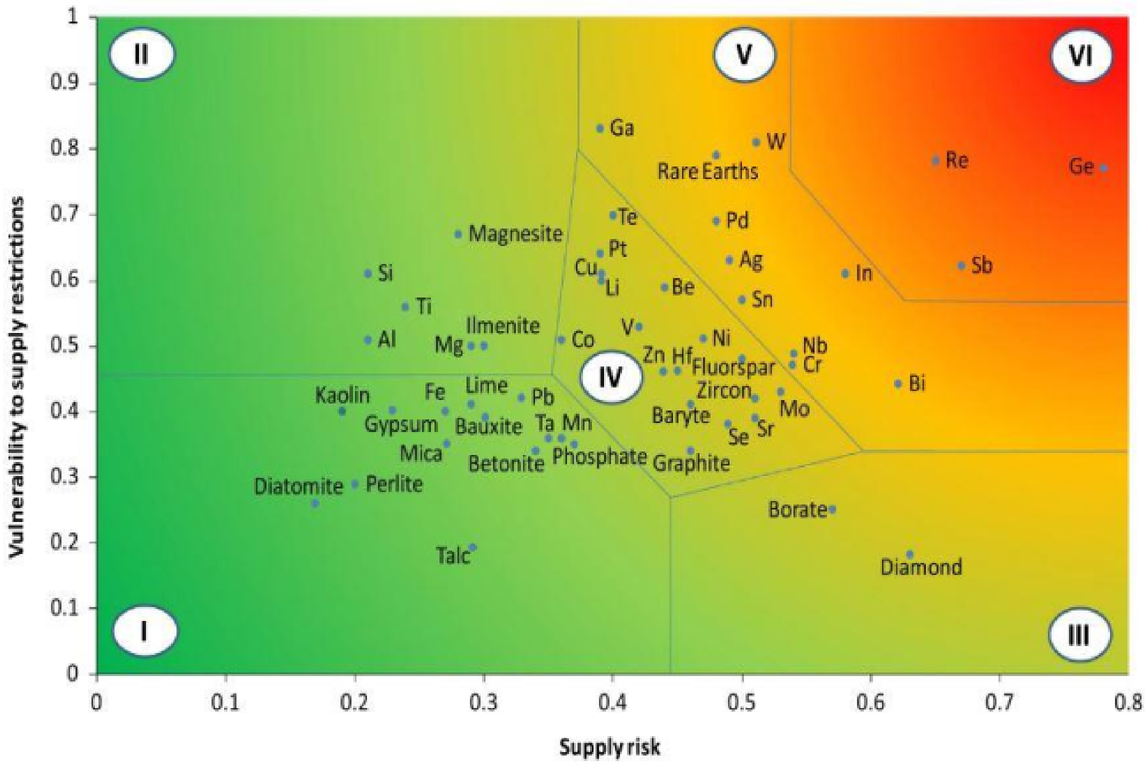

Figure 2.4: Criticality Zones. Source:Erdmann and Graedel (2011)

one year, and for a particular territory.The studies also use many factors to measure critical metals. The factors are however simplified to one or two final scores, which is used to show criticality.The differences appear especially in the indicators' choice and weighting.The studies apply different weighting of the indicators, some researchers assigning indicators arbitrary scores such 1 or 0 to indicate lowest risk and 3 or 4 to indicate highest risk.Just as weighting of the indicators vary, so does the number of indicators, and how the final results are displayed. However, criticality matrix is the frequently method to display the results.Table B.1 in Appendix B contains additional studies and the methodologies of metal criticality determination.

2.2.1 Criticism of existing criticality studies

The models developed so far and discussed above are sufficiently sensible in themselves, but they are unsatisfactory in some ways. First, the studies aggregated many factors to

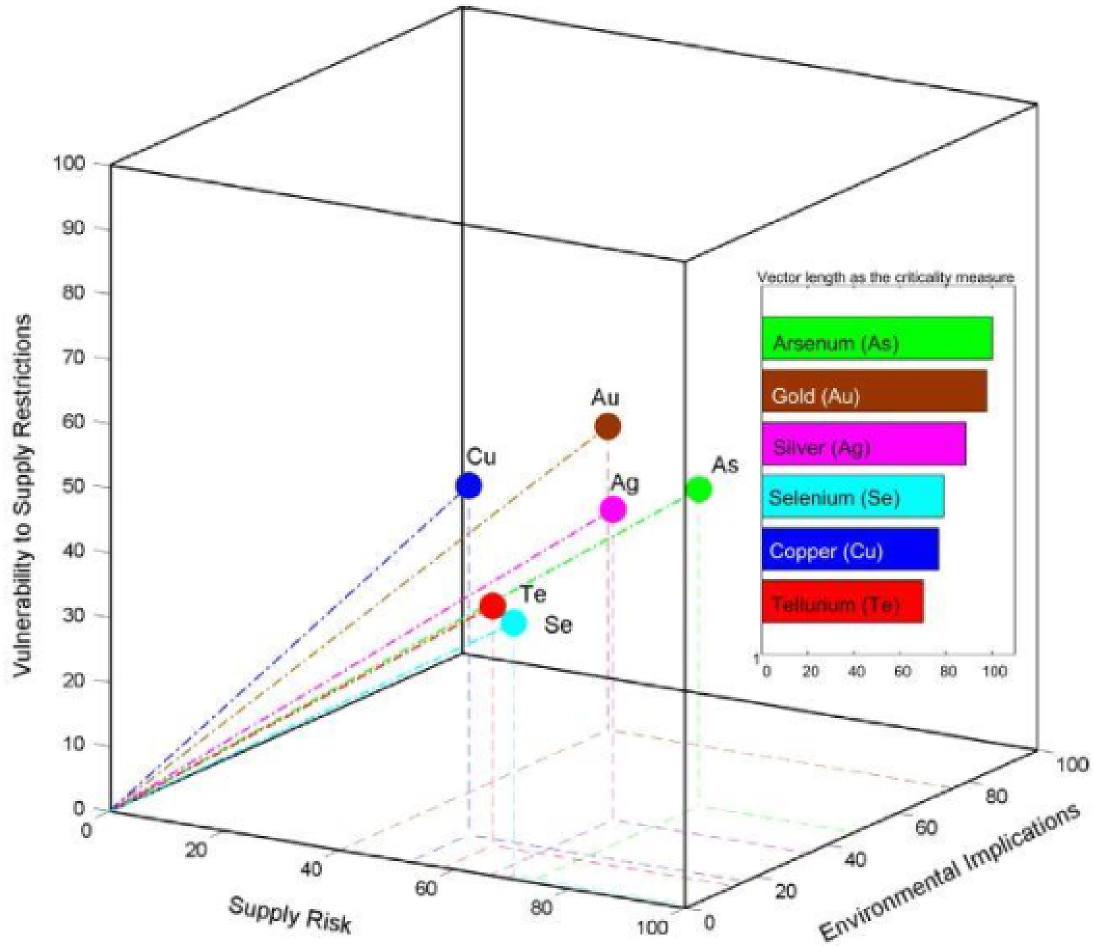

Figure 2.5: Criticality space. Source:Graedel et al. (2012)

end up with two leading indicators—supply risk and vulnerability—to measure a resource's criticality. Such an aggregate concept of criticality could distort the assessment of where significant risks might appear. It has been observed that lumping several concerns together in one overall "criticality" value, as opposed to addressing them separately, might cause extra confusion(Buijs and Sievers (2011)). Evaluating resource risk is a sensitive topic, mainly when conducted by governments, so sometimes it might help to express the results as aggregates in the form of one score or a two-axis matrix to blur the evaluation process. However, keeping the evaluation process a secret should not override the need for useful results.

Another critical aspect that seems to be overlooked by existing criticality studies is how to measure risk. In the traditional sense, the risk is an outcome of the sum of quantitative losses multiplied by their probabilities of occurrence. Despite criticality studies borrowing the idea of a risk matrix from risk studies, none of the works discussed considered using probabilities in measuring material criticality. Only Mayer and Gleich (2015) and Nuss et al. (2014) used standard deviation, a form of probability, while estimating metals' economic importance. Overlooking the fundamental way to measure risk may lead to unreliable results.

Lastly, the identifying and ordering (display) of critical metals, indicator choice, and aggregation and assessment dimensions vary across studies, which implies a lack of consensus among researchers on the correct way to measure and display critical materials. A study by Glöser et al. (2015) correctly pointed out that indicators ought to have empirically demonstrable and statistically significant relationships, and weighting and aggregating should reflect those relationships. It also showed how sensitive the display of criticality results is. It superimposed different materials considered critical by several studies on a figure with uniform criticality levels. Some studies indicated materials that should have been critical because they sat on the same criticality level as not critical. This contradiction casts doubt on the truthfulness of the results.

2.3 Measuring critical metals in the long term

From the outset, the discussion about long-term critical metals is confronted by two main problems. First, many studies attempting to study critical metals in the long term focus on mineral resource flows and stocks. The studies end their analysis at the available stocks of metals and assume a fixed stock of a certain amount of mineral resources. The studies model the development of demand or supply of metals into the future, identifying the possible supply risks measured by the reserve to production ratio. Metals with a declining production to reserve ratio are designated as critical (see, for example, (Watari et al. (2018) , Rosenau-Tornow et al. (2009) ,Van Vuuren et al. (1999) , Sohn (2005) ,Moss, Tzimas, Kara, Willis, and Kooroshy (Moss et al.) , Knoeri et al. (2013)).

However, as rightly criticized, the fixed stock paradigm fails to consider the amount of resources for future exploitation changes as technology and other considerations such as costs evolve. Tilton and Lagos (2007), when assessing the long-run availability of copper, argue convincingly that the amount of copper currently considered available will change considerably in the future depending on the opportunity cost of using copper. They point out that additions to reserves come about in two ways: through exploration that discovers previously unknown but economic deposits. Through technology, it can make previously uneconomical reserves economical to mine. The tendency for cumulative extraction to grow faster than cumulative discovery could indicate that it is cheaper to use reserves via new technology rather than exploration, and not that we are running out of resources.Although the study focused on copper, the conclusion applies to other metals as well.

Second, the few studies determining critical metals in the long-term, like their medium-term counterparts, use varying methodologies and indicators. While they provide useful insights into the metrics that could be of use to measure long-term criticality, the lack of consensus on the leading indicators creates a challenge to isolate indicators that could lead to useful results.Graedel et al. (2012) suggested a comprehensive methodology to determine critical metals for the medium term (5-10 years) and the long term (10-50 years) by combining several indicators to measure supply risk, vulnerability to supply restrictions, and environmental implications. The methodology for medium-term critical metals and long-term critical metals is the same, except for slight differences in the medium term and long-term criticality indicators. In estimating supply risk, Geopolitical (World governance index, global supply concentration), Social and regulatory (policy potential index, human development index), and Geological, Technological and Economic (depletion time, companion metal fraction) indicators are used to estimate the medium-term critical metals. Only the Geological, Technological and Economic index is used to assess long-term criticality in the long term. The environmental implications indicator and vulnerability to supply restrictions indicator are similar for both the medium-term and long-term criticality analysis. Both medium-term and long-term criticality results are displayed in the criticality space.

By dropping specific indicators when estimating critical metals for the future, the authors acknowledge that different factors influence criticality in the medium term and the long term. Morley and Eatherley (2008) add voice to the idea that different factors influence long-term criticality. They observe that in the short term, factors such as price are important – materials prices respond to supply and demand, and financial speculators could influence prices–but not significant in the long term. Prices may not be necessary for the long term because technology reduces production costs, and recycling may set in when prices are high enough. Bastein and Rietveld (2015) conducted a study to examine the Dutch economy's reliance on selected 64 minerals and metals. Part of their study examined the long-term (more than ten years after 2015) security of supply of these metals. The study measured long-term supply risks using the number of years of uninterrupted supply (reserves overproduction ratio(R/P)), the degree to which a material is a by-product (companionability), and the concentration of raw materials reserves. Long-term criticality is calculated by adding the three indicators.

The straight forward method by Bastein and Rietveld (2015) is desirable, but the methodology takes a broad view and misses some essential components that could influence criticality in the long term. The main index of the study is reserves. However, relying majorly on reserves as an indicator is unreliable because reserves change with time. Reserves could provide useful insights into the supply of mineral resources, but since the primary determinant of available reserves is whether the mineral resources can be mined economically or not at present, changes in prevailing mineral prices mean reserves are subject to change. Reserves data could be a pointer to where supply bottlenecks could arise, but relying exclusively on reserves to measure critical metals in the long term could be misleading. Buijs and Sievers (2011) discusses the dynamic nature of reserves more exhaustively. Because of the two challenges discussed above, our study attempts to identify critical minerals in the long term using a novel model that considers the existing criticism.

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CHAPTER 3

JAPAN'S CRITICAL METALS IN THE MEDIUM TERM

This chapter focuses on identifying critical metals for Japan.After a short background, the methodology applied is discussed. The results and discussion sections points out the critical metals, and highlight some strategies to secure supply of the metals identified as critical.

3.1 Lack of critical materials studies in Japan

Mineral resources are critical to Japan's economy. Japan has created competitive industries with strong connections to mineral resources, such as high-tech equipment and consumer electronics manufacturing. For example, Japan is among the leaders in lithium-ion battery manufacturing and next-generation cars, fuel cells,and solar panel technology. The manufacturing industry is the single most significant contributor to Japan's economy, with sub-sectors consuming many metals contributing considerably to the economy. Also, Japan accounts for a considerable share of global metal consumption, and the metals' productivity (quantity of metal used to produce a unit of gross domestic product [GDP]) is rising. Consequently, Japan relies heavily on mineral resources to sustain its economy and requires a stable and predictable mineral resource supply. Figure 3.1 shows the main industries in Japan and figure 3.2 shows the breakdown of these the major sectors. Figures 3.3 and 3.4 show that the the productivity of metals (such as cobalt) has increased since 2000 and consumption of some metals(such as rare earths) has remained above 10% since 2009.

Despite the central role of metals in Japan's economy, few published studies have investigated critical metals in Japan. While the study of critical metals began in the 1980s, when the country started a program to stockpile metals thought to be vulnerable to supply disruptions as reported by Japan oil gas and metals national corporation JOGMEC (JOGMEC), few scholars (see, for example, Glöser-Chahoud et al. (2016), Hatayama and Tahara (2015a), Hatayama and Tahara (2015b)) joined efforts by government institutions

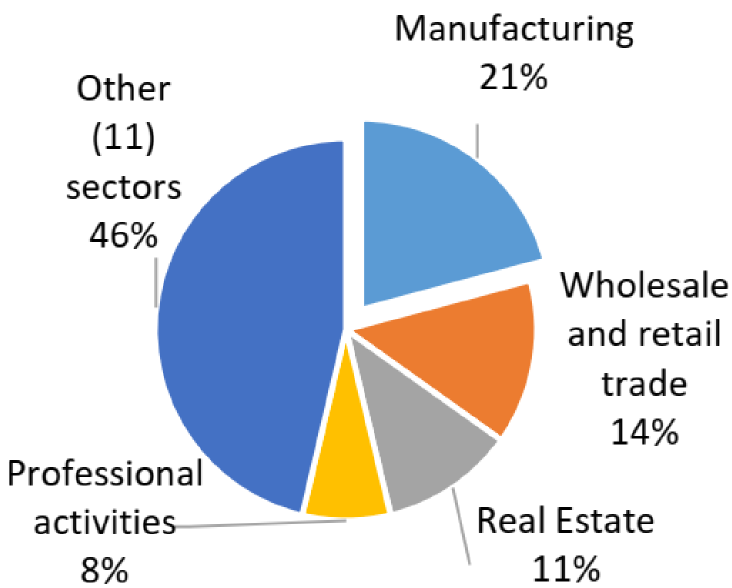

Figure 3.1: Industries making up Japan's economy. Source Ministry of Internal Affairs and Communications Japan (2019)

such as the New Energy and Industrial Technology Development Organization and the Japan Metal Economic Research Institute to conduct risk assessments of metals for the Japanese economy. These studies identified critical materials for a single year; therefore,the studies are a statistic. Our study suggests a quasi-dynamic method to screen critical metals for Japan and propose critical metals for the medium term by analyzing the trends in material criticality from 2000 to 2015.

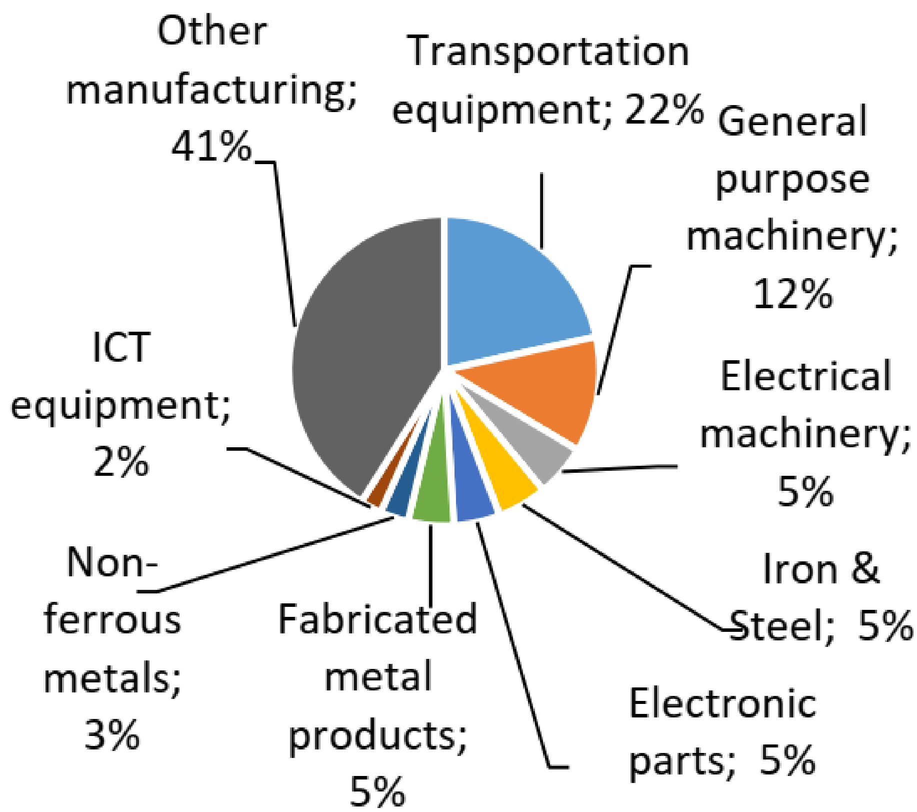

Figure 3.2: The share of contribution the manufacturing industry to Japans GDP in 2017. Source: Ministry of Internal Affairs and Communications Japan (2019)

3.2 Methodology and data

Following in the footsteps of existing material criticality research, we combined several indicators to measure a critical metal. The final indicators used in this study measured the relative advantage of a particular metal's supply stability and the risk to Japan's economic system should a particular metal supply disruption occur. We avoided combining too many indicators to avoid meaningless results by choosing the most relevant indicators that were easy to quantify based on a literature review. Figure 3.5 presents an overview of the study's methodological framework.

3.2.1 Vulnerability

This study proposes a method for calculating vulnerability that uses unique probability distributions for individual metal price changes. We defined vulnerability as the relative

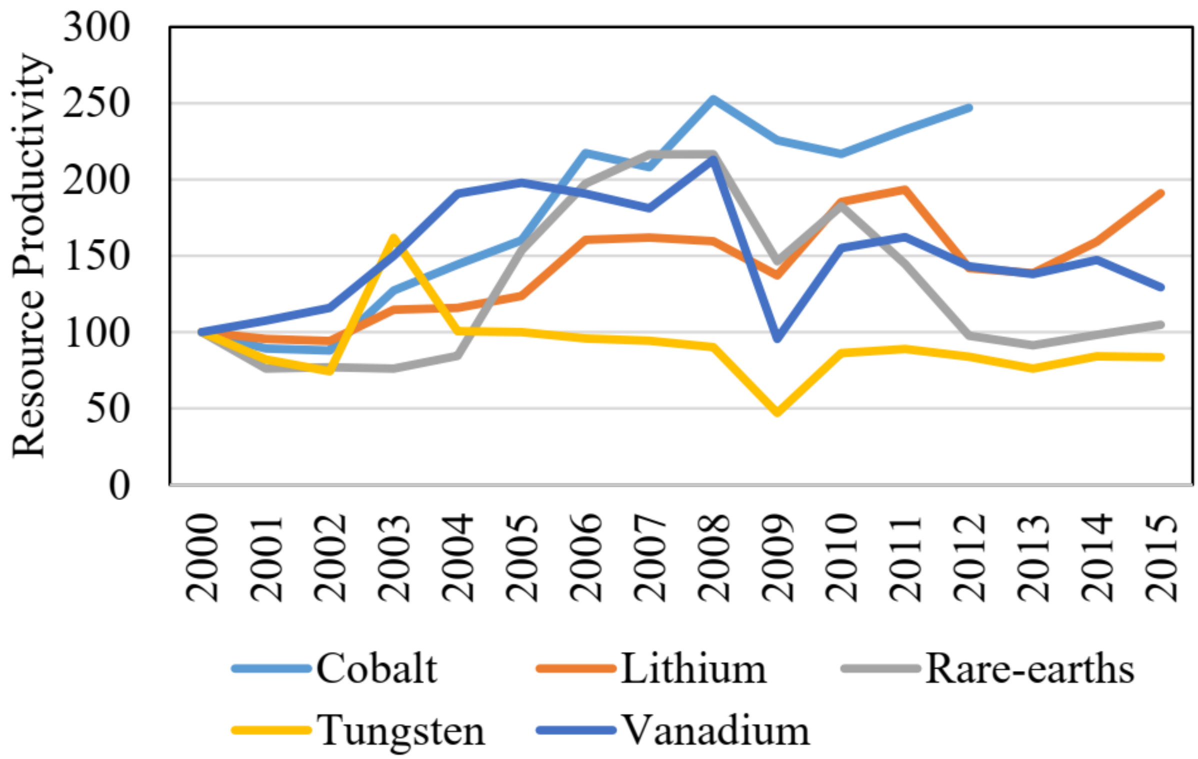

Figure 3.3: The productivity of metals in Japan from 2000 to 2015. Source: Metal consumption data from the Japan Oil, Gas and Metals National Corporation (JOGMEC) annual materials flow reports.GDP Data source:World Bank open data

damage to the economy when a metal's price changes. It was calculated by examining a metal's contribution to Japan's gross domestic product for the specified year and the metal's value, derived by multiplying the apparent consumption by the total possible price change weighted by the price changing probability. To calculate the economic contribution (see equation 3.1), we modified European Commission (2010)'s method by adding a factor that measured each industry's multiplier effect and using sectors' total output instead of the value-added approach. The multiplier effect was estimated using each sector's inverse matrix coefficients obtained from Japan's input-output tables.The addition of the multiplier effect is important because it helps it helps to capture better the contribution of each sector to the economy. It is agreed by economists that an increase in the output of a certain sector in an economy influences how the other sectors perform. Sectors of the economy have linkages

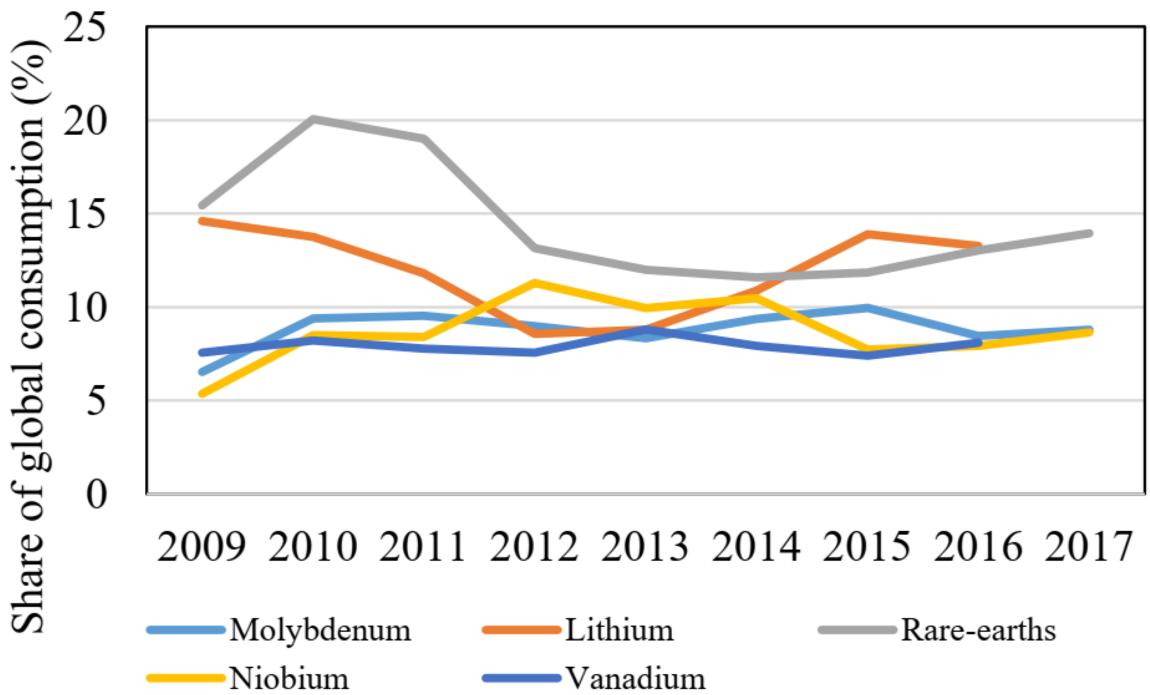

Figure 3.4: Japan's share of global consumption of selected metals 2009-2017. Source: JOGMEC annual material flow reports.

an are not stand alone units. A value-added approach is a commendable and valuable approach but risk underestimating the contribution of individual sectors , and consequently misrepresenting the results. Besides, there were no enough data to accurately estimate each end application value addition in the case of Japan.

Using material flow reports published yearly by JOGMEC, we identified each metal's end-use applications and grouped them into industries defined by Japan's input-output tables, which classify the Japanese economy into 38 sectors. Each sector contributes a particular share of output to the final gross domestic product of Japan. Each sector of the input-output table has a unique coefficient generally referred to as the inverse matrix coefficient. The inverse matrix coefficient indicates how each sector's output will change or how much production will be ultimately induced if total demand in the economy increases by one unit. Tanaka (2011) provides a detailed explanation of input-output tables and

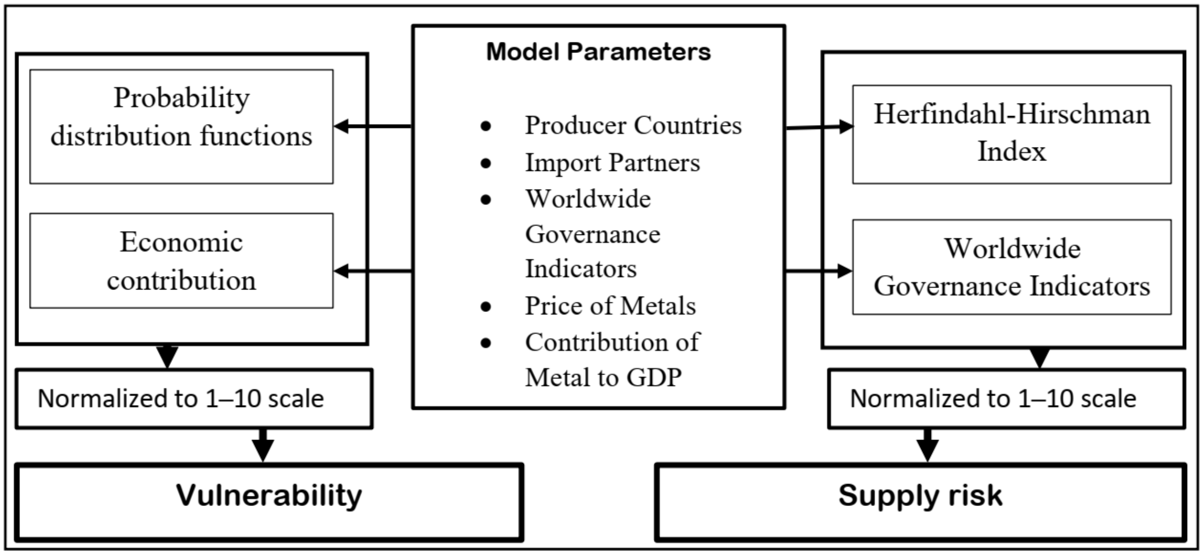

Figure 3.5: Methodological framework for determining critical metals for Japan

inverse matrix coefficients. The economic input-output data and the corresponding inverse matrix figures was obtained from E-Stat (2016)(e-stat), Japan's official portal site for government statistics , while we estimated the share of metal consumption per sector and the total amount of specific metal consumed in Japan in a particular year from JOGMEC's annual reports.

$$Economic \quad Contribution(EC_i) = \frac{1}{GDP}\sum_{s} A_s * Q_s * Z_s \tag{3.1}$$

Where, EC_i is the economic contribution of metal i to Japan's GDP, GDP is the gross domestic product of Japan, A_s is the percentage share of metal used in sector s, Q_s is the output of sector s, and Z_s is the inverse matrix coefficient of sectors. The economic contribution value is fed into the equation to calculate the vulnerability to supply restriction, as equation (3.2) shows.

$$Vul_i = EC_i * C_i \sum_{x=0}^{\infty}[log[(Price_i * x) * Prob_i(x)]] \tag{3.2}$$

Where Vul_i is the vulnerability of metal i in Japan's economy, EC_i is the economic contribution of metal i to Japan's GDP, C_i is the quantity of metal i consumed in Japan in a particular year,$Price_i$ is the price of metal i, x is the percentage change in the price of a metal, and $Prob_i$ (x) is the probability that the price of metal i changes by x percent.

We used metal prices in our study because prices carry informative value about the demand-supply landscape of metal resources. Market prices offer more information beyond geological scarcity and reflect how resources are extracted, the level of technology required to achieve these metals' functionalities, and the value placed upon the metals by consumers (Olivetti et al. (2015)). In addition, price changes could prompt changes in the industry, such as moving to using substitutes or increasing metal use efficiency by redesigning products to use less metals (Graedel et al. (2013)), which could influence a metal's criticality. Frenzel et al. (2017) also observed that, generally, price hikes are the main event that contributes to the risk of material criticality. They acknowledged that price and severe physical disruption of supply are the two main events that criticality is concerned with, and severe physical disruption can be understood as the upper end of prohibitively high costs (prices), which is equivalent to no availability. These views conform to our study, which estimated the potential risk posed by metal by summing the product of the metal's economic contribution by the possible price changes, weighted by the probability of such price changes occurring.

We used U.S. historical real annual metal price data to estimate probability distributions for different metals' absolute price changes. Since both positive and negative price changes influence both producers' and consumers' decisions, we used absolute price changes to estimate the probability of price changes. We obtained the metal price data from the US Department of the Interior and US Geological Society (2013). We then used Minitab software to test the data against 16 different distributions to identify a suitable probability distribution. Minitab uses the Anderson- Darling test to determine whether a given sample of data was drawn from a given probability distribution. We used a 95.0 confidence level (0.05 significance level) to test our hypothesis that the data followed a particular distribution. A lower p-value (<0.05) indicated that we could reject the null hypothesis and conclude that the data did not follow the distribution. In comparison, a higher p-value indicated that we did not have enough evidence to reject the null hypothesis and could assume that the data followed the distribution tested.

Finally, we normalized the results to obtain a vulnerability value on a scale between 0 and 10.

3.2.2 Supply Restriction

We combined the Herfindahl–Hirschman Index (HHI) for global mineral producers, the HHI Index for Japan's mineral import partners, and the Worldwide Governance Indicators (WGI) for the import partners to measure each metal's supply disruption. The HHI Index has become one of the standard tools for measuring market concentration and is used as a proxy to measure the diversity of mineral resource supply. Consequently, numerous studies (e.g., Achzet and Helbig (2013),European Commission (2010),Fortier et al. (2018),Sievers and Tercero (2012)) have used the HHI Index to evaluate material criticality. In this study, supply restriction measured the relative advantage of a particular metal over others in terms of supplier diversity. The more suppliers, the greater the supply stability. The HHI measures market concentration and is calculated by squaring each player's share of the market and summing the result. We adapted the HHI Index to calculate the concentration of global mineral producers and the concentration of countries from which Japan imports its mineral resources as shown in equations 3.3 and 3.4.We obtained the import data for the years 2000, 2005, 2011, and 2015 from Japan's material flow reports published annually by JOGMEC. If Japan imports a particular metal from a few countries, then the HHI Index is high, indicating a higher level of concern about the metal's supply. If Japan imports a particular metal from several countries, the HHI Index is low, implying a low supply hazard.

$$SupplyHazard = HHI(globalproducers) * HHI(importpartners) * WGI(importpartners) \tag{3.3}$$

$$HHI = \sum_{i=1}^{n} (S_i)^2 \tag{3.4}$$

S_i is the percentage share of country i

The WGI show how countries rank based on a combination of political stability, government effectiveness, control of corruption, rule of law, regulatory quality, absence of violence, and voice and accountability. A country scores between -2.5 and +2.5 based on the views of the quality of governance provided by large enterprises, citizens, and experts (World Bank, 2019). We obtained the WGI data from the The World Bank (2019).

For this study, a high governance index indicated that a country was reliable in fulfilling its metal supply contracts and would not abruptly change laws during, say, political transitions. A high score on the governance index implied that the chances of cutting the supply of a particular metal were low for such countries. On the contrary, a country that ranked low in the WGI had a higher possibility of abruptly cutting the supply of metals to its trade partners.

We multiplied the three indicators for each metal and normalized the results to a score of 0–10. A high score indicated a higher potential of experiencing supply restriction. This means that the global producers of such metals are few, and a significant share of Japan's imports of metals comes from a few countries, which rank low in the governance index. Such countries have a higher chance of abruptly changing laws related to mineral resource supply. Therefore, Japan faces uncertainty regarding the stable supply of the metals it imports from such countries.

3.3 Results of the medium term study

3.3.1 Supply restrictions for the metals under study

Policy trends in resource-supplying countries could significantly affect the supply of metals, thereby creating a supply hazard. Some supplier countries may engage in resource nationalism as resource prices continue to rise, and high-income resource-producing countries, which depend less on mining revenues, could tighten regulations for the sake of environmental protection, affecting the supply of the resources they produce.

In Japan, some essential metals that support vital industries could be subject to a sudden disruption in supply because most of the imports of these essential metals come from a few countries, some of which have weak governance systems. Over 90% of the total imports of metals such as vanadium, tungsten, niobium, chromium, lithium, and manganese into Japan come from only three countries, presenting a potential impact to the economy should an interruption in their supply, whether accidental or intentional, occur. Figure 3.6 shows the metals under study and their supply restrictions score. Tungsten, platinum, lithium, manganese, and rare earths had the highest scores between 2000 and 2015. Table B.1 in appendix B shows the global production share and Japan's import partners for 2015 and 2018 for the metals studied.

3.3.2 The probability distribution functions for metals price changes

Table 3.1 presents the summary statistics for the probability distributions. The study found that most of the price changes for the metals under study followed an exponential distribution, and a few followed a log-normal distribution. This is in contrast to previous research that assumed metal prices followed a Gaussian distribution (see, for example, Mayer and Gleich (2015),McCullough and Nassar (2017)).Cobalt and rare-earth metals had the highest standard deviation of absolute price changes, while iron and chromium had the lowest standard deviation among the metals in this study. A high standard deviation suggests high price volatility, and implies prices are less predictable. Glöser et al. (2015) observed that the high uncertainty could be because these metals have a relatively small market, with few

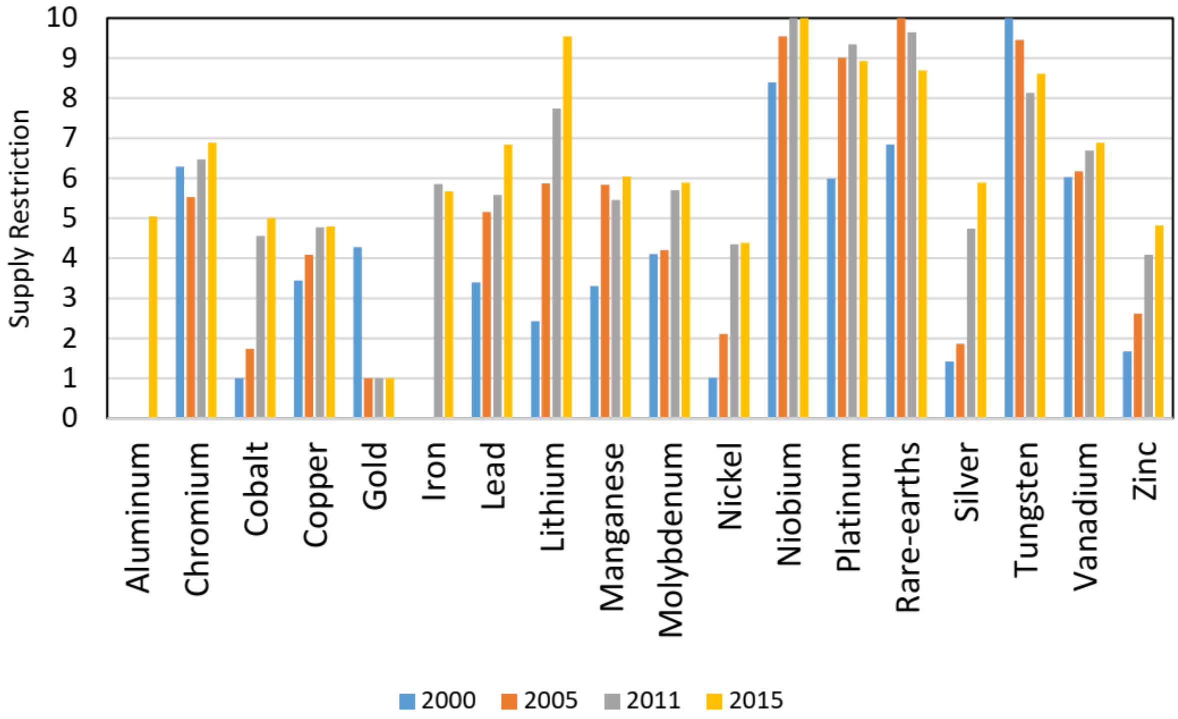

Figure 3.6: Supply restriction scores for the metals studied in the years 2000,2005,2011 and 2015.

players .

3.3.3 Economic contribution of metals and the vulnerability of Japan's GDP

Figure 3.7 shows the share of the contribution to Japan's GDP by various metals in the years 2000, 2005, 2011, and 2015. The economic contributions of individual metals changed across the years under study, but iron, lead, manganese, niobium, platinum, copper, and chromium had significant contributions between 2000 and 2015. In 2000, lead, platinum, and copper had the most significant economic contributions, but that share dropped consistently in consecutive years. In 2005, iron, manganese, and chromium contributed significantly. In 2015, iron had the biggest economic contribution.

3.3.4 Vulnerability to supply disruption

Figure 3.8 shows the vulnerability of Japan's economy resulting from the various metals under study. Vulnerability measures the risk that Japan's economy faces because of changes

Table 3.1: Summary statistics and probability distributions

Metal	Probability distribution	Sample (years)	Mean	Standard deviation	P-value
Aluminum	Exponential	60	0.15	0.18	0.615
Chromium	Exponential	46	0.12	0.16	0.438
Cobalt	Log-normal	55	0.33	0.49	0.199
Copper	Exponential	54	0.17	0.19	0.845
Gold	Exponential	42	0.19	0.23	0.354
Iron	Exponential	52	0.13	0.16	0.445
Lead	Exponential	54	0.17	0.18	0.445
Lithium	Exponential	36	0.10	0.16	0.107
Manganese	Log-normal	57	0.19	0.41	0.907
Molybdenum	Log-normal	57	0.28	0.40	0.484
Nickel	Exponential	51	0.24	0.30	0.771
Niobium	Log-normal	35	0.24	0.30	0.213
Platinum	Exponential	51	0.19	0.20	0.913
Rare earths	Lognormal	34	0.22	0.48	0.591
Silver	Exponential	54	0.22	0.25	0.448
Tungsten	Exponential	46	0.27	0.28	0.553
Vanadium	Log-normal	44	0.33	0.41	0.388
Zinc	Log-normal	53	0.19	0.24	0.275

in the economic contribution of metals resulting from changes in the prices of these metals. The vulnerability of metals varied over the years, but rare metals such as cobalt, vanadium, niobium, molybdenum, and rare earths had the highest vulnerabilities.

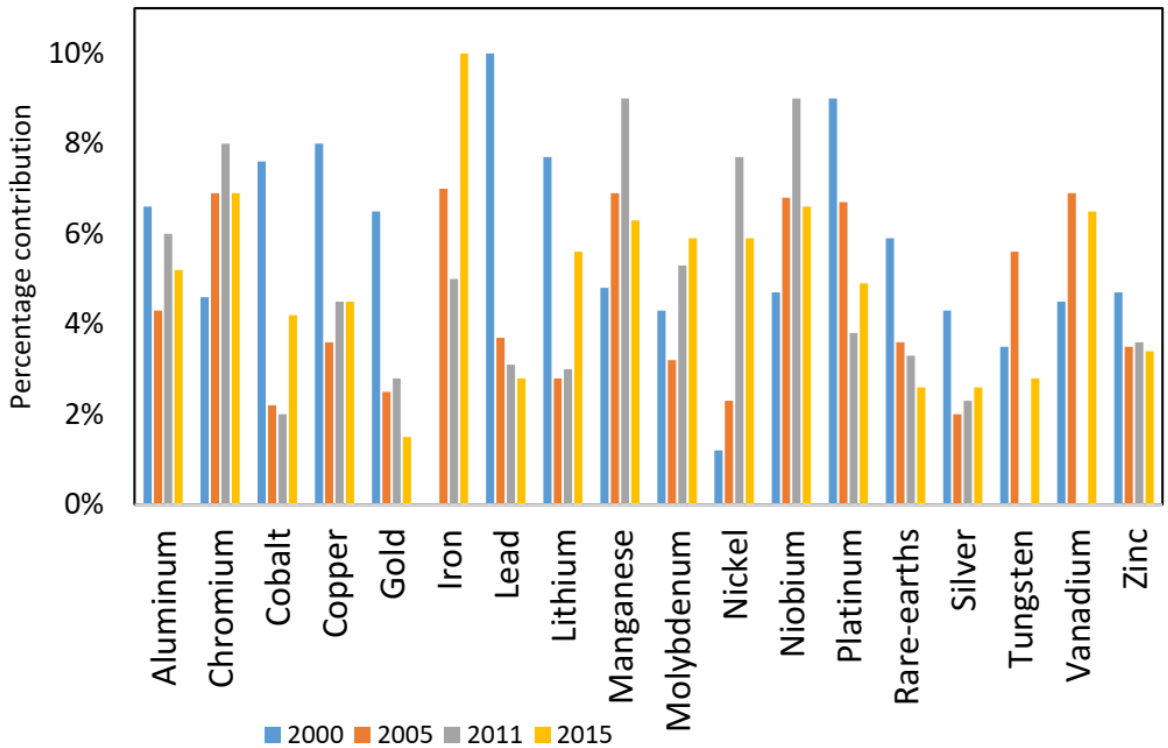

Figure 3.7: Economic contributions of the metals studied. Source: Economic data for particular years from Japan's input-output tables. Sector's metal consumption data from JOGMEC reports

3.3.5 Critical metals for Japan in the medium term

Figures 3.9,3.10,3.11 and 3.12 shows the critical metals for Japan in the years 2015, 2011, 2005, and 2000. Critical metals for Japan were identified by combining supply restriction and vulnerability to supply disruption scores into a criticality matrix. Metals that scored high in vulnerability to supply disruption and supply restriction were considered critical, and identified by how far they seat from the origin, as shown by figure 3.2. The curves distinguished the criticality level. Each point on a particular curve indicated equal positions from the origin. Metals on the highest level—the longest distance from the origin—had a higher criticality than those on the first level. Consequently, cobalt, lithium, molybdenum, manganese, niobium, platinum, rare earths, tungsten, and vanadium are critical metals for Japan. These metals are consumed in large quantities and are essential for Japan's crucial

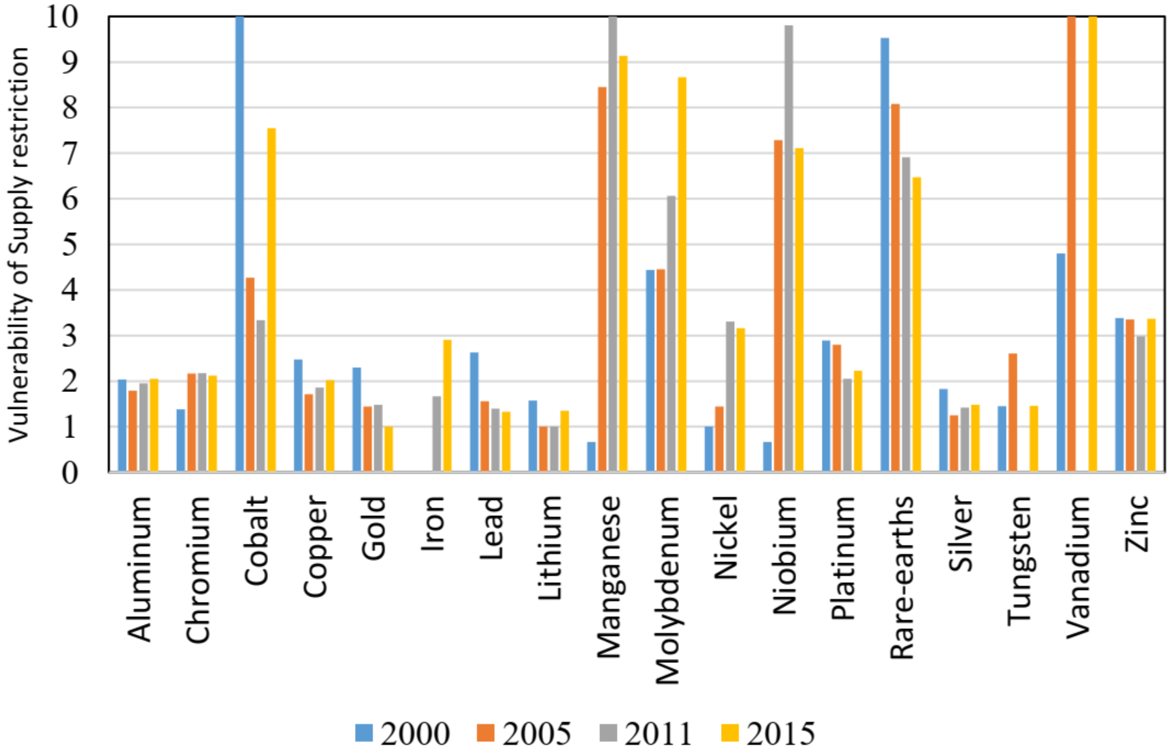

Figure 3.8: Vulnerability to supply restriction scores for the metals studied.

industries, but their supply is threatened because of suppliers' concentration.

Cobalt is known for several uses, including as an essential catalyst for increasing polymerization and oxidation rates in plastics manufacturing and removing sulfur from crude oil in the oil refinery industry (Cobalt Institute (2017)). However, its use in Li-ion batteries and magnet alloys is necessary in the automotive industry, and the rechargeable battery cathodes widely used in electric vehicles is probably the most important use of cobalt in Japan (Japan Oil Gas and Metals National Corporation (2016)). Japan is a crucial player in the electric vehicle market and a global leader in automobiles.

Despite its high economic importance, cobalt's market is known for volatility because of its small size and the complexities in its supply chain. Only a few countries mine and refine cobalt, with 74% of global production coming from DR Congo, Russia, and Cuba. Coupled with environmental, social, and governance concerns, cobalt's supply chain is full

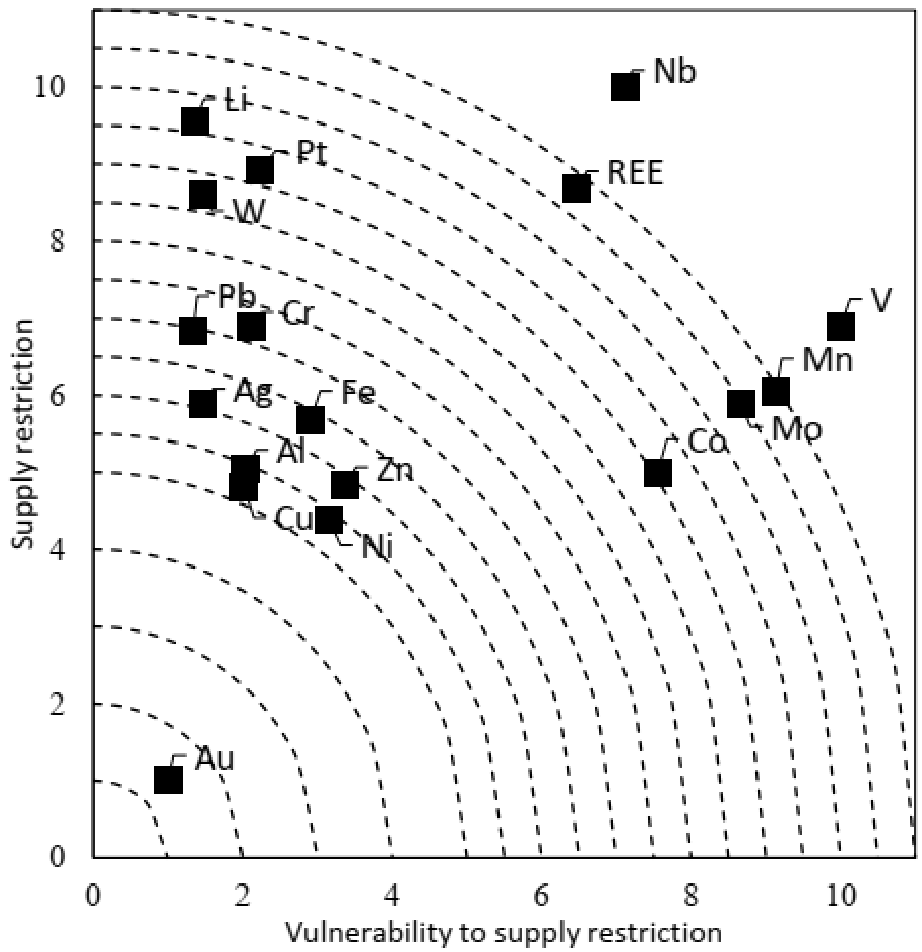

Figure 3.9: Critical metals in 2015

of potential supply risks. Furthermore, there is no substitute for cobalt, especially as used in medical diagnostics and the pharmaceutical industry, which keeps pressure on the demand for cobalt (Cobalt Institute (2017)).

Lithium has several uses, such as in metallurgical processes, glass ceramics, and pharmaceuticals, but the biggest use is in Li-ion batteries and other primary batteries, with mobile phones using approximately 3g of lithium carbonate in their batteries and notebooks 30–40 grams. Motor vehicles require 0.6kg per kilowatt-hour, while a fully electric car requires 22kg of lithium carbonate (Evans (2014)). Lithium is therefore indispensable in the manufacture of motor vehicles, which is a significant sector in the

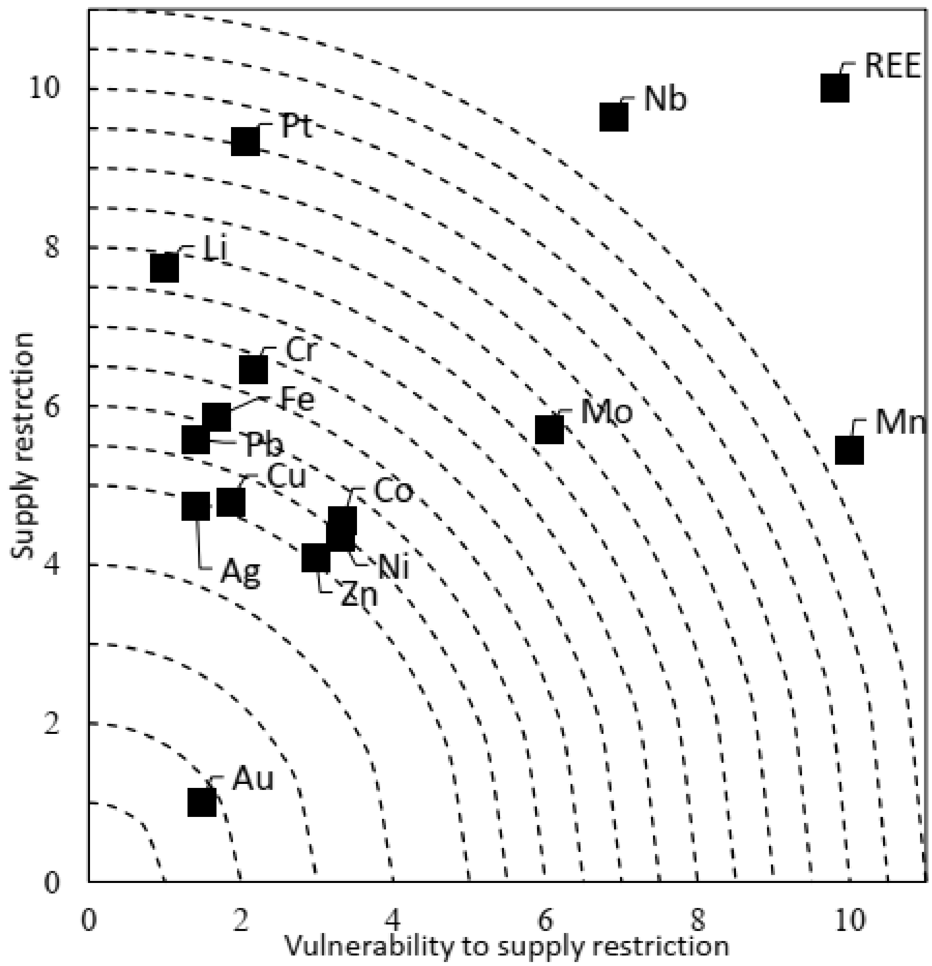

Figure 3.10: Critical metals in 2011

Japanese economy. Despite its crucial role, the supply of lithium is worrying. Japan imports all of its lithium from only three countries: Chile, Argentina, and China.

Niobium's significant uses are in developing infrastructures such as automobiles, railways, and pipelines because of its ability to increase strength and reduce weight. Recently, niobium has also been used in electronics to make computer chips and superconductors (Linnen et al. (2014)). Japan's primary use of niobium is in the automobile industry and building infrastructure, such as skyscrapers and pipelines Japan Oil Gas and Metals National Corporation (2016). Notwithstanding its crucial uses, niobium is supplied almost exclusively by Brazil (89%) and Canada (10%), yet its demand

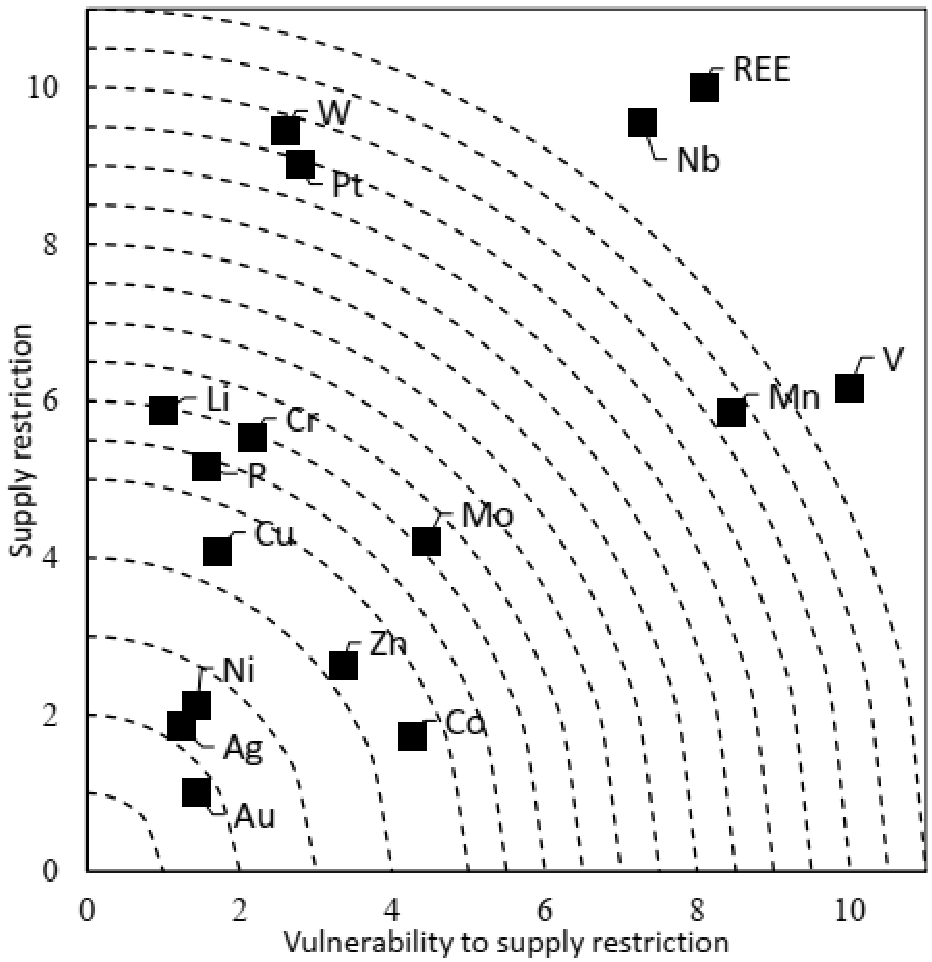

Figure 3.11: Critical metals in 2005

has expanded rapidly as major economies, including the U.S., China, and Japan, compete for the available resources abroad (Fortier et al. (2018)).

Platinum remains a critical metal for Japan's auto industry because it is used as an auto catalyst for converting noxious emissions from car exhaust systems into harmless, non-toxic products (Japan Oil Gas and Metals National Corporation (2018)). Following legislation setting standards for emissions from motor vehicles introduced by Japan and the U.S. in the 1970s, the demand for platinum multiplied (Gunn (2014)). However, supply has stagnated, with South Africa and Russia remaining the significant platinum suppliers, accounting for over 80% of the global supply. South Africa held 91% of all platinum group metals reserves

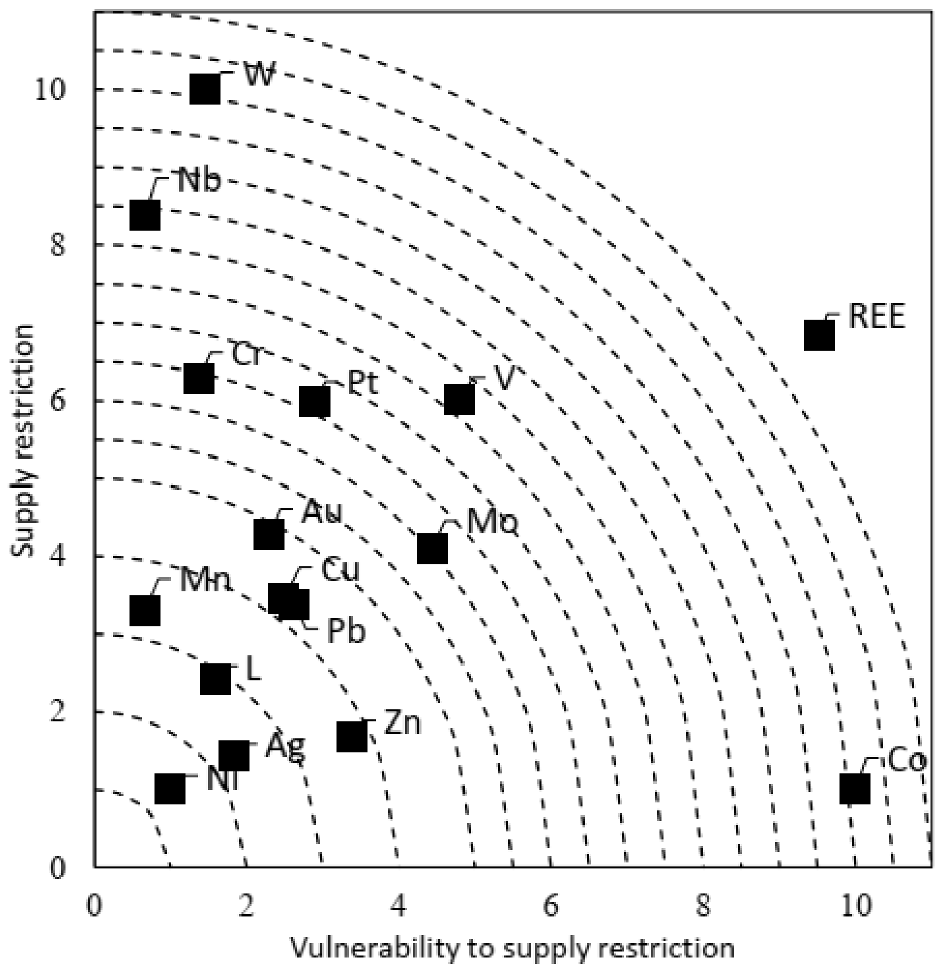

Figure 3.12: Critical metals in 2000

in 2018 (United States Geological Survey (USGS) (2020)). Although the domestic recycling of platinum in Japan is significant (in 2017, the recycling rate for platinum was 37%((Japan Oil Gas and Metals National Corporation (2018))), 80% of Japan's platinum imports were from South Africa in 2017, presenting a threat to its stable and predictable supply.

A trend has emerged where metals identified as critical to Japan support its key manufacturing industries, mainly the automobiles sector. This is supported by data that shows the manufacturing sector is the single most significant contributor to Japan's GDP, contributing 21% of the total output in 2017 (Ministry of Internal Affairs and Communications Japan (2019)). Figure 8 and 9 shows the contribution of different sectors

Table 3.2: Distance from the origin scores of metals studied

Metal	2000	2005	2011	2015
Aluminium	***	***	***	5.4
Chromium	6.4	5.9	6.8	7.2
Cobalt	10.0	4.6	5.7	9.1
Copper	4.2	4.4	5.1	5.2
Gold	4.9	1.8	1.8	1.4
Iron	***	***	6.1	6.4
Lead	4.3	5.4	5.8	7.0
Lithium	2.9	6.0	7.8	9.6
Manganese	3.4	10.3	11.4	11.0
Molybdenum	6.0	6.1	8.3	10.5
Nickel	1.4	2.6	5.5	5.4
Niobium	8.4	12.0	14.0	12.3
Platinum	6.7	9.4	9.6	9.2
Rare-earths	11.7	12.9	11.9	10.8
Silver	2.3	2.2	4.9	6.1
Tungsten	10.1	9.8	***	8.7
Vanadium	7.7	11.8	***	12.1
Zinc	3.8	4.3	5.1	5.9

to the Japanese economy in 2017, and the manufacturing sub-sectors' contributions.

Automotive-related manufacturing, which consumes a significant amount of metals such as rare earths, cobalt, platinum, and lithium, constitutes Japan's largest manufacturing sector: the transportation machinery industry. In total, 5.5 million people (8.7% of Japan's workforce) worked in the automotive manufacturing and related industries in 2017 (JAMA (2017)).

While critical metals are indispensable for Japan's economy, their prices have soared in recent years because of increasing demand from emerging economies such as China, increasing fears about access and availability. For example, between 2000 and the end of 2007, platinum prices increased by around 400%, probably because of emissions control legislation, which boosted platinum's demand as an autocatalyst. The price fell dramatically following the financial crisis, which reduced demand, but it has since recovered. The price of tungsten increased sharply between late 2004 and early 2006, jumping from USD $100 per metric ton in late 2004 to $250 per metric ton in late 2055.

Table 3.3: Cumulative distance from origin scores(2000-2015) and the average distance from the origin

Metal	Cumulative score	Average score
Rare-earths	47.3	11.8
Niobium	46.7	11.7
Manganese	36.0	9.0
Platinum	34.9	8.7
Vanadium	31.6	10.5
Molybdenum	31.0	7.8
Cobalt	29.4	7.4
Tungsten	28.6	9.5
Chromium	26.4	6.6
Lithium	26.3	6.6
Lead	22.4	5.6
Copper	19.0	4.8
Zinc	19.0	4.8
Silver	15.6	3.9
Nickel	14.8	3.7
Iron	12.5	6.3
Gold	9.8	2.5
Aluminium	5.4	5.4

The prices remained at this high level (compared to before 2004) through 2008, declined slightly in 2009 because of the global recession, and increased sharply again to $450 in early 2011. Collectively, between 2004 and 2011, tungsten (ammonium paratungstate) prices rose by 500%(S&P Global (2019)).

Metals with high economic importance also have fewer suppliers, presenting a risk of disruption to their supply. The risk of supply disruption is not exaggerated, as there is some evidence for Japan that relying too much on a country for the supply of essential minerals can be disastrous. The Chinese government's measures related to rare earths had an unusually large impact on Japan. In 2011, China introduced a de-facto ban on rare-earth exports to Japan because of a dispute over the Senkaku Islands. From 2006, China started implementing policies meant to promote the domestic metallurgical industry's development. The policies affected rare earths, tungsten, tin, and antimony. Under this policy, export tariffs were implemented and gradually expanded to control resource exports. Under the same policies, rare metals are subject to the "E/L (Export License) system," which sets a quota for the export quantity, and China changes the quota every year. Because of this sudden policy shift, manufacturers in Japan were severely affected by the disruption of the supply of rare-earth metals. Some rear-earth prices, such as lanthanum and cerium, jumped by 900% between 2009 and 2011 (Silberglitt et al. (2013)).

While some critical metals, such as rare earths, are used in small amounts, they are essential for manufacturing new generation electronic appliances such as LCD TVs, mobile phones, and automobiles. The stable supply of these minerals is vital from the viewpoint of maintaining and strengthening international competitiveness in the Japanese manufacturing industry.

3.3.6 Significance of probability in criticality determination

There is no objective standard to compare criticality of metals if probability is not Incorporated in the studies.Different metal's prices experience volatility at different levels. For example, while it is possible for the price of rare earths to change by as as much as 600 percent in one year, it is statistically impractical to expect the price of copper to change by that margin.Without probability to weight the price changes of metals, criticality results could underestimate or over estimate the vulnerability to supply restriction of a metal. Figures 3.13 and 3.14 show the implications of ignoring probability in criticality studies.

For comparison purposes, we assumed price changes up to 300 percent, and measured criticality with probability and without probability.From the figures criticality of some metals is significantly misleading.Take for example, the exaggerated criticality of Iron. has been. Even with probability, and the price changes up to 300 percent, the criticality of iron is overestimated.historical price of iron has not changed by more than 70 percent on year to year comparison.Assuming that the price could go up to 300 in the medium term is therefore misleading.At the same time, criticality for metals such as vanadium, manganese and molybdenum has been underestimated.

Standard deviation has been applied as a tool to objectively measure the price changes, but as stated earlier, using standard deviation assumes that metal prices follow a normal distribution. As our results show, not all metal prices follow a normal distribution.

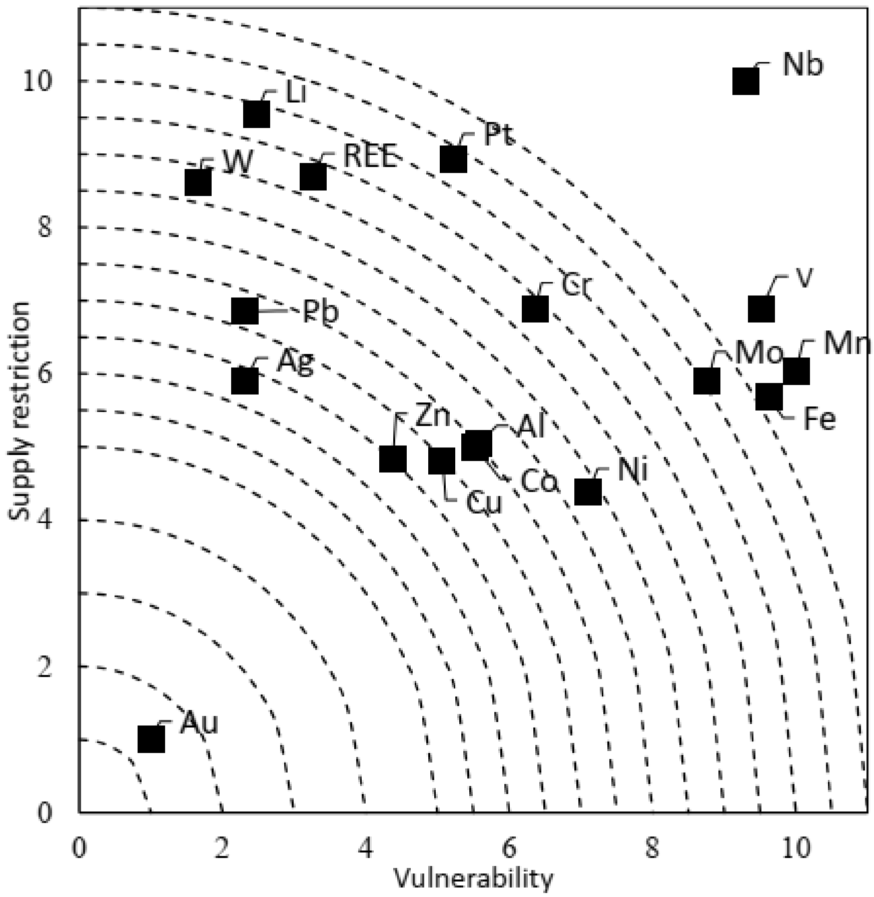

Figure 3.13: 2015 criticality of metals with probability for price changes up to 300%

3.3.7 Changes in the relative importance of metals

The criticality scores of most metals studied changed during the years of the study. Figure 3.15 shows the changes in the relative advantage of the metal supply restrictions and vulnerability to supply restrictions for the five selected metals. Following each metal line, we can track the changes in the relative advantages from 2000 to 2005 to 2011 and finally to 2015.

The implication of the changes for Japan is that critical metals will continue to shift even in the medium term as competition for different metals changes and suppliers change. For

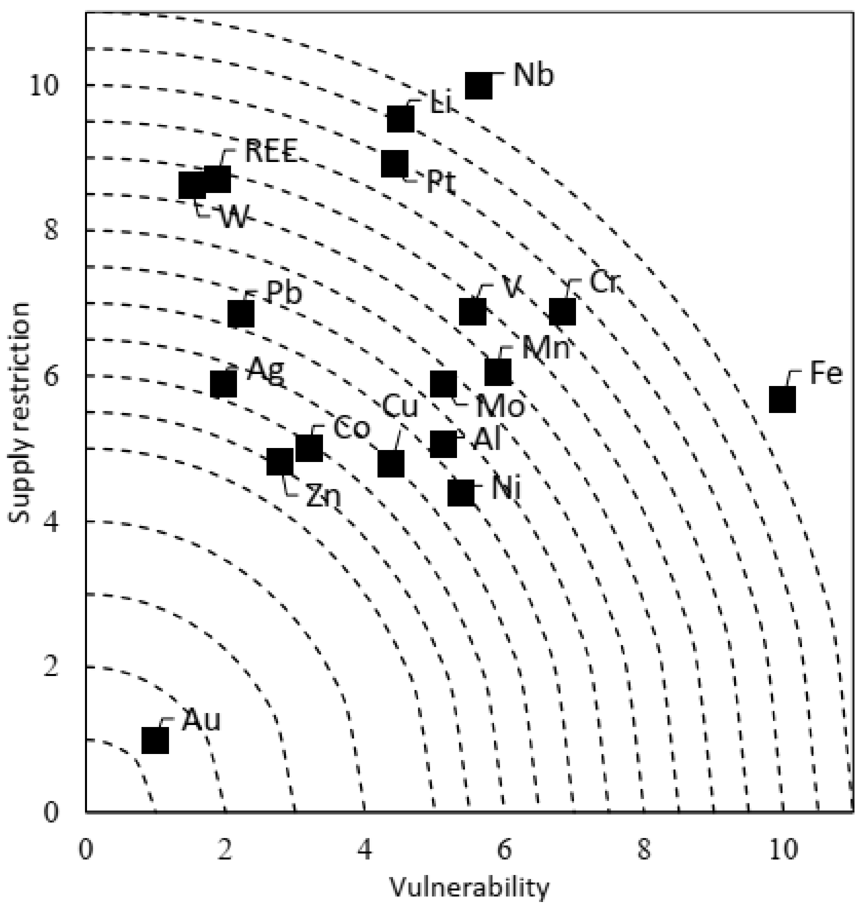

Figure 3.14: 2015 criticality of metals without probability for price changes up to 300%

example, with the efforts to build a low-carbon society, we expect the demand for metals such as cobalt, lithium, and rare earths to grow in the fields of next-generation automobile motor storage batteries, which we anticipate will become widespread. In addition to the growing demand for these metals in the motor industry, we expect their use in renewable energy technologies to increase in response to growing concerns about climate change. Such changes will increase the relative importance of these metals, and depending on their supply situation, their criticality will also change. Therefore, putting in place measures to ensure the stable supply of critical metals is a policy issue that Japan should consider amending every few years. Based on the likelihood of the demand for some critical metals increasing in response to calls for a low-carbon future, this study predicts that cobalt, lithium, molybdenum,

Table 3.4: Comparison of criticality levels

With probability		Without probability	
Iron	11.5	Niobium	13.6
Niobium	11.5	Vanadium	11.7
Lithium	10.6	Manganese	11.7
Platinum	10.0	Iron	11.2
Chromium	9.7	Molybdenum	10.6
Rare-earths	8.9	Platinum	10.3
Vanadium	8.8	Lithium	9.8
Tungsten	8.7	Chromium	9.4
Manganese	8.4	Rare-earths	9.3
Molybdenum	7.8	Tungsten	8.8
Lead	7.2	Nickel	8.3
Aluminum	7.2	Aluminum	7.5
Nickel	6.9	Cobalt	7.4
Copper	6.5	Lead	7.2
Silver	6.2	Copper	7.0
Cobalt	5.9	Zinc	6.5
Zinc	5.6	Silver	6.3
Gold	1.4	Gold	1.4

niobium, platinum, rare earths, and vanadium will remain critical metals for Japan for the medium term.

3.3.8 Strategies to secure the supply of critical metals for Japan

Japan can secure the supply of essential resources by strengthening its relationships with resource-rich countries that produce critical metals. Securing resources abroad through activities such as investing in mining projects, human resource development, infrastructure development, and industrial promotion can be a useful strategy to protect against disruption of the supply of essential resources for the medium to long term. This study established that lithium, niobium, platinum, vanadium, and manganese are critical metals, and they will remain critical for the medium term. To secure the supply of these metals, Japan should strengthen relations with Argentina and Chile, which produce lithium; Brazil and Canada, which produce niobium; and Australia for manganese. South Africa produces platinum, manganese, and vanadium, all of which are critical metals for Japan, and the country can protect its supply of these metals by reinforcing its relations with South Africa.

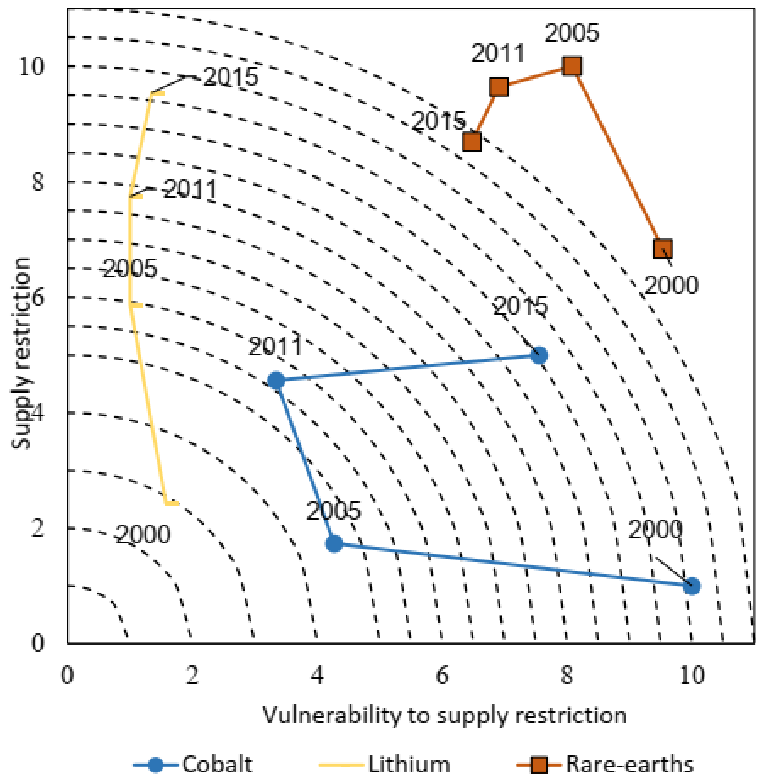

Figure 3.15: Changes in relative importance of selected metals between 2000 and 2015.

Despite Africa having the potential to supply many valuable resources,as Dempsey (2019) observes, the current relationship between Japan and Africa remains tentative, with Japanese investment commitments to Africa regularly undershot. Nonetheless, there is a real opportunity to gain more by consolidating relationships with more African countries such as Zambia and DR Congo (cobalt), Guinea (aluminum), Zimbabwe (platinum), and Rwanda (tungsten).

For many years, Japan has been renowned for its comparative advantage in advanced technologies. For example, as the world warms up to nanotechnology, Japan has been promoting national nanotechnology projects, with concrete achievements such as the Hayashi Ultrafine Particles project in the 1980s (Japan Science and Technology Agency (1986)). Japan should increase its efforts by consolidating its most advanced technologies, such as nanotechnology, to engineer substitutes for critical metals and therefore decrease its reliance on metals as we know them. There exist studies that suggest some critical metals for Japan (for example, vanadium and manganese) can be substituted by more abundant materials. Reijnders (2016) discusses the possibility of using aluminum, magnesium, nitrogen, and silicon to substitute chromium, manganese, molybdenum, niobium, nickel, vanadium, and tungsten in steel making.

Japan can also push for the recycling of valuable metals to secure the supply of critical metals. Japan is a leader in the recycling of many products. The same efforts can be applied to recycling critical metals, for which recycling technology is already available, by promoting the collection of used products containing critical metals and utilizing existing systems, or creating new recycling systems, for critical metals. Manufacturers that use critical metals in their products can promote recycling by introducing environmentally friendly designs that are easy to recycle and sharing information, such as the amount of critical metals used in the products they manufacture, to boost the recycling of critical metals. There is currently little information about the content of essential metals used in manufactured items, as most manufacturers choose not to share such information for various reasons.

Potential problems with recycling could include an inadequate quantity of materials to recycle, which makes recycling uneconomical, and a lack of technology to recycle critical metals. Encouraging people to send out items with critical metals for recycling and sealing the loopholes that allow items sent for recycling to be shipped abroad as second-hand products could increase the quantity of domestic recycling. Targeted efforts toward research on recycling technology can increase the pace of the development of such technologies.

Stockpiling critical metals and increasing the intensity of exploration of resources in Japan could help to secure the supply of some of the needed critical metals. Japan already has a system for stockpiling essential resources, but creating a flexible stockpiling and release system that is integrated with the industry is essential. Research has shown that systematic efforts toward exploration activities can bear fruit. So far, seafloor hydrothermal deposits in the waters around Japan have shown positive results and proved that it is possible to cultivate some mineral resources such as copper from hydrothermal fluids (Nozaki et al. (2016)). Extending exploration activities could lead to further discoveries.

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CHAPTER 4

CRITICAL METALS IN THE LONG TERM: CONSIDERING A LOW CARBON FUTURE

This chapter shifts the attention to identifying critical metals for the long term. After the background,the methodology applied is discussed. The results and discussion sections points out the critical metals in the efforts towards a low carbon future.

4.1 Introduction

Through global organizations such as the United Nations, the world has set out several goals for the future among them promoting sustainable development. One objective of the sustainable development goals(goal 7) is to ensure "access to affordable, reliable, sustainable and modern energy for all". To achieve this goal, universal access to affordable and reliable energy services, improved energy efficiency, and an increased share of renewable energy in the global energy mix is necessary (UN DESA (2020)).

Another objective related to sustainable development is limiting climate change, as captured in the Paris agreement, a legally binding framework for coordinated efforts to mitigate climate change adopted by 196 parties. The Paris agreement's overarching aim is to limit the global mean temperature increases to below 2 degrees Celcius above the pre-industrial global temperatures and to achieve net-zero emissions in the second half of the century (United Nations (2015)).

Accelerating the use of renewable energy and related technologies like electric vehicles lies at the heart of achieving these objectives (International Energy Agency (2030)). In addition to mitigating climate change, a shift to using more renewable energy brings several other benefits. For example, enhancing technological and structural efficiency by avoiding transmission and transportation costs, energy independence(renewable energy is mostly obtained locally or regionally), and new opportunities for jobs in the resulting newly created industries such as bio fuels (Scheer (2006)).Therefore, accelerated renewable energy use is seen as the foundation for a sustainable future, a priority for the human condition and directly linked to a low carbon future.

However, accelerated production of renewable energy means accelerated demand for mineral resources. It follows that mining more mineral resources is unavoidable to keep up with the pace of increasing demand from new technologies required in the renewable energy strategy to meet climate change and sustainable development challenges. Consequently, it is vital to explore the implications of the rapid uptake of climate-friendly technologies for the minerals industry. This chapter examines the additional demand for metals that might arise due to achieving a low carbon future in the long term and proposes metals that might be a bottleneck to achieving the ambitious low carbon future because of disruption of their supply.

4.2 Low carbon future and the implications for Mineral Resources

Many researchers and organizations have studied the bottlenecks that could impede the progress towards a low carbon future(e.g Roelich et al. (2014),Habib and Wenzel (2014), Busch et al. (2017), Mohr et al. (2012),Moss et al. (2013),Nansai et al. (2015a), Vidal et al. (2013)). A common theme across these studies is the realization that achieving a low carbon future is tied to significantly scaling up clean energy technologies. However, to realize the full benefits of renewable energy, several factors need to fall in place for these technologies to be ready, including accelerated innovation and unconstrained access to mineral resources.

Some organizations leading in the research of transitioning to low carbon future and the implication to the society, are the International Energy Agency(IEA) and the International renewable energy agency(IRENA). In their 2015 report, International Energy Agency (2015), lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C (The 2-degree Celsius scenario). The 2-degree scenario reduces CO2 emissions (including emissions from fuel combustion and process and feed stock emissions in the industry) by almost 60% by 2050 (compared with 2013), with carbon emissions being projected to decline after 2050 until carbon neutrality is reached.

International Renewable Energy Agency (2019) on its part sets out a path to a decarbonized energy system based on energy efficiency and renewable energy in their 2018 report. The study analyzes two scenarios. A reference case scenario, representing the business as usual perspective, considered countries' current and planned policies concerning energy efficiency and renewable energy. The other scenario is REmap Case, which analyses the deployment of low carbon technologies and energy efficiency to limit the rise of global temperatures to below 2 degrees above pre-industrial levels by the end of the century. The findings indicate that the scale of renewable energy implementation needs to be scaled up to more than six times faster to limit the average global temperature rise to below 2 degrees. Figure 4.1 shows the required changes in the electricity mix to achieve a low carbon future.

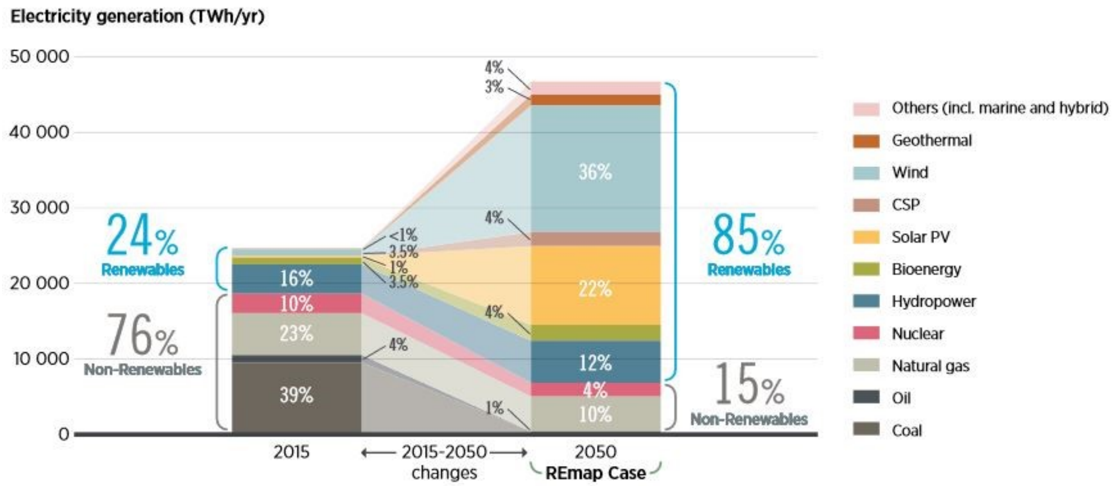

Figure 4.1: Contribution of renewable energy technologies in the energy mix between 2015 and 2050. The share of renewable energy sources' contribution should increase significantly between 2015 and 2050 to limit global temperatures to below 2 degrees. Wind Power and Solar P.V. will account for the most significant share of electricity generation. Source: International Renewable Energy Agency

The studies and reports mentioned above make it clear that moving towards a low carbon future has implications for the mineral resources industry. The international resource panel (IRP (2017)) conducted two related studies to examine the environmental and resource implications of low carbon technologies and the benefits, risks, and trade offs of low carbon technologies used for electricity production. Using an integrated Life Cycle Assessment framework, the report quantifies the environmental and natural resources implication for 36 low carbon technologies across buildings, industry and transportation sectors, and four electricity generation technologies. The study results indicate that low carbon technologies require over 600 million tons of metal resources by 2050, which will go into additional infrastructure and wiring needs. This additional amount of metals is dwarfed by the related consumption of metals caused by the rest of the economy.

World Bank Group (2017) also conducted a study to examine minerals and metal's role for a low carbon future. The study, based on IEAs Energy Technology Perspective scenarios– 2°C (2DS), 4°C (4DS), and 6°C (6DS) global temperature warming scenarios–

examines material requirements for three leading technologies: wind, solar, and batteries for energy storage, and concludes that the demand for metals used in these technologies will increase. The overall implication is that transitioning to a low carbon future leads to a rise in some metals' demand, which could have ripple effects for the resources landscape. A follow up study in 2018 by Hund et al. (2020) confirmed that demand for metals would increase significantly. The World Bank projected that some metals' demand would increase by as much as 500 percent compared to the 2018 annual production. Figure 4.2 shows the 2050 projected annual demand from energy technologies as a percent of the 2018 annual production.

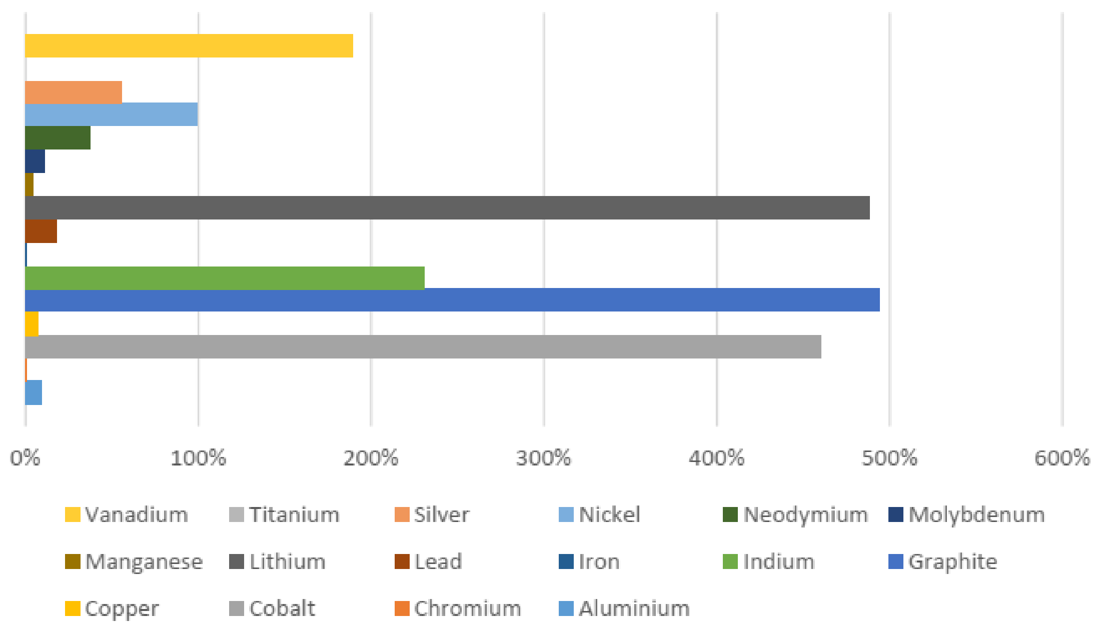

Figure 4.2: Change in demand for some selected metals used in clean energy technologies. Data Source: World Bank

Other studies have also studied the implications of a shift to a low carbon future for the minerals resources landscape. Nansai et al. (2015b) analyzes the material footprint– the amount of resources mined in order to support a nation's final consumption –of three metals (Neodymium, Cobalt, and Platinum) necessary for low carbon technologies, and acknowledges a low carbon future shift will increase the demand for these specific metals.

They study conclude that adopting low carbon technologies could shift 'the risk' from carbon resources to metals and create a trade off between increased mining risk and the deployment of low carbon technologies.

In the same vein, Vidal et al. (2013) argue that a shift to a low carbon future has significant consequences for the minerals producing and consuming countries and the resources industry. Agreeing that a low carbon future hinges on shifting to renewable energy, they argue that the shift will replace one none renewable resource (fossil fuel) with another (metals and minerals). They continue that a shift to a low carbon future will be less beneficial if the energy transition to renewables is not managed simultaneously as an integral whole since mineral resources carry similar geopolitical and environmental issues as fossil fuels. The authors express concerns about the carbon footprints from increased mining to meet metals' demand for a low carbon future.

The study by Watari et al. (2018) focuses on understanding the metals that could impede shifting to a low carbon future. Using the International Energy agency low carbon energy scenario as the basis, they analyze the metals required by solar power, wind power, and next-generation vehicle technologies and the possibility that the metals' supply constraints could affect the introduction of the three technologies. They subsequently identify (critical) metals that require priority measures. They conclude that, first, the spread of solar power and next-generation vehicles could be hindered because of resource depletion. Second, the expansion of low carbon technologies will mostly affect rare metals' demand instead of common metals and that recycling could cut metals' demand by up to 70 percent by 2060.

The studies highlighted above bring to light two main facts. First, that the minerals demand landscape will change drastically as the world pursues a low carbon future and second, demand for some specific metals will increase as green technologies spread. It is therefore important to understand which among these metals are critical to achieving the low carbon future. That is, they are crucial for the transition to a low carbon future but they may face supply bottlenecks.

4.3 Methodology and data to examine critical metals in the long term

Some metals required for a low carbon future(hence have strategic or economic importance) may face a risk of supply shortage.Such metals are called critical metals. This section discusses the methodology employed to identify critical metals in the context of a low carbon future. The study builds on the foundations of previous studies to identify critical metals in the context of achieving a low carbon future.

The methodology for this study is based on a simple flow diagram shown in figure 4.3. Reserves are mined to get mineral ores, and the ores are processed to obtain metals, which form the metals stock. Manufacturers of low carbon technologies draw from this stock to manufacture low carbon technologies like electric cars and solar power panels. The technologies containing the metals are retired after their productive use and form end of life material. A percentage of the end of life material is recycled and processed back to useful metals, while the remaining amount is dumped into the environment. The mining process also produces some waste that is dumped back into the environment.

Based on the flow diagram in figure 4.3, we develop a dynamic system model using the STELLA software to model the demand-supply dynamics of specific metals necessary to achieving a low carbon future. The system dynamics model combines several types of analysis: First, analysis of metals demand based on the spread of low carbon technology.Second, interaction between metals' demands, and decline in the statistical availability of metals reserves.Third, analysis of the interaction between population growth, global gross domestic product(GDP), and metal demand.Based on the system dynamics model results, we examine the production-requirement imbalances of selected metals and the additional demand for metals studied. We then discuss how recycling,substitutes' availability and the implications for the environment could affect the additional demand. From the discussion, we propose critical metals for the long-term in the context of a low carbon future.

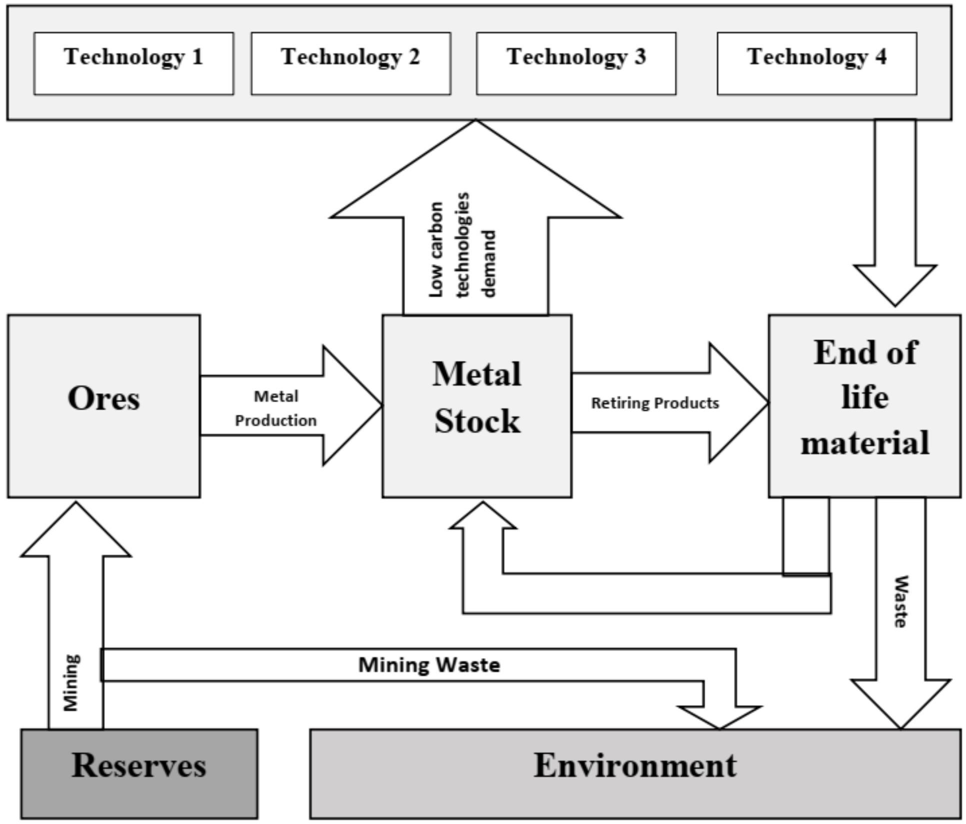

Figure 4.3: Simplified flow of metal resources

4.3.1 System Dynamics

A confluence of several factors influences material criticality. Creating a method of assessment that can incorporate these complex dynamics and, at the same time, maintain the necessary simplicity to provide useful guidance to players interested in mitigating criticality risks creates a challenge.Understanding the interactions among many technological, geophysical, and economic systems is necessary to understand and evaluate risks for the long term. System Dynamics could help understand the interaction.

Systems dynamics is an approach to help understand the behavior of complex systems over time. The approach attempts to understand the fundamental behavior of a system by modelling the system's basic structures. With the help of computers, simulations can help us understand the developments in a complex system, which can help us see how a system changes over time. Ford (1999) explains that 'dynamics' in system dynamics refer to these fundamental patterns of change, and system dynamics help us understand why these patterns occur. Ford (1999) emphasizes that the fundamental use of a system dynamics analysis is for improved understanding, not for prediction.

According to System Dynamics Society (2020),the fundamental ideas of System Dynamics originated from the works of Jay Forrester in the 1960s, who applied the concepts from feedback control theory to the study of industrial systems. Since then, the ideas have been adopted by other researchers such as Meadows et al. (1972) in their work “The Limits to Growth”. Although studies applying system dynamics in estimating long-term critical metals are scarce, we believe it could be a useful tool to modell and understand how the different factors interact to influence material criticality.

4.4 The model and data

Prior to simulating the model, we conducted several preliminary steps. First we identified the low carbon technologies to study. Many technologies fall under low carbon technologies, such as hydropower, nuclear power, geothermal power, and carbon capture and storage. This study focused on seven technologies: Hydro power, Geothermal, Wind, Solar PV and Electric vehicles chosen based on their possibility to contribute to a low carbon future(determined through literature review)and data availability.The rapid growth of especially wind, solar and electric cars has shown the potential of new clean energy technologies to bring down emissions.Net-zero emissions will require these technologies to be deployed on a far greater scale. In addition to data availability, the study considered whether the technology uses renewable energy or not. Only technologies that use renewable energy in the strict sense were selected and therefore technologies such as nuclear and carbon capture and storage are not considered in this study.

We focus mainly on electricity generating technologies because cutting carbon emissions especially from the electricity sector is essential to achieving the desired low carbon future(International Energy Agency (2020)).International Energy Agency(IEA) points out that that the acceleration of the electrification of the world economy is a central pillar of the clean energy transition and that final electricity demand will more than double, driven by demand for electricity to power cars, buses and trucks, to recycle metals, and to supply the energy required for heating, cooking and other house appliances.In fact,the share of electricity in final energy uses has been growing steadily for decades. For instance, in the period 1990-2019, global annual electricity demand grew on average by 3.0%, an average annual increase roughly equivalent to the total amount of electricity generated annually in Italy and Sweden combined. IEA estimates that the share of electricity in the final energy use will keep growing , driven by growing demand for electrical appliances and an expansion of electricity into new sectors, which reflects the environmental and practical advantages of electricity over other forms of energy in final applications. Final electricity demand will expand by around 30 000 TWh through to 2070, equivalent to around 135% more of current consumption, and the share of electricity in the global final energy demand grows from 19% today to 47% in 2070 if the world commits fully to a low carbon future that keeps temperature rise below 2 degree that of pre-industrial temperature (IEA (2017))

Second, we identify the metals used in the selected technologies. The study estimates the amount of metal required to run a particular technology based on available literature. Studies such as those by Moss et al. (2011) Moss et al. (2013) and World Bank Group (2017) report on metals required to run different low carbon technologies.Table 4.1 summarizes the metal requirements by the different technologies.This study focuses on metals used in more that three technologies, i.e copper, chromium, manganese, molybdenum,nickel, titanium, in addition to cobalt, lithium and rare-earths because of their importance for manufacturing electric vehicles.

The last preliminary step is identifying the historical usage of the metals studied, and modelling the future use in what we call business as usual(BAU) consumption of metals. We use regression analysis to determine the relationship between global Gross Domestic product(GDP), population, and metal consumption and and use the derived function to model business as usual consumption up to 2070.The general equation for estimating the

Table 4.1: Metal requirements for various low carbon technologies. Kg/MW for electricity generating sources, and kg/vehicle for electric vehicles. Source: Moss et al. (2013)

Metal	Electric Vehicles	Solar PV	Wind	Geothermal	Hydropower
Aluminum (Al)		10593			
Boron (B)	0.09		7		
Cerium (Ce)	1.03				
Chromium (Cr)			902	64,405	12.5
Cobalt (Co)	13.91				
Copper (Cu)	71.08	2741	3,000	3,605	67
Dysprosium (Dy)	0.43		25		
Gallium (Ga)	0.001				
Germanium (Ge)	0.00005				
Gold (Au)	0.0002				
Indium (In)	0.00005				
Iron (Fe)			24,355		
Lanthanum (La)	1.16				
Lead (Fe)	12	366			5.36
Lithium (Li)	12.7				
Magnesium (Mg)		53.5			1.92
Manganese (Mn)	91.5		80.5	4,325	1.7
Molybdenum (Mo)			136	7,209	2.9
Neodymium (Nd)	2.91		186		
Nickel (Ni)	46.5		663	120,155	31
Niobium (Nb)				128	
Palladium (Pd)	0.0008				
Platinum (Pt)					
Praseodymium (Pr)	0.08		35		
Ruthenium (Ru)					
Samarium (Sm)	0.08				
Silicon (Si)		3,653			
Silver (Ag)	0.007	24			
Tantalum (Ta)				64	
Terbium (Tb)	0.021		7		
Tin (Sn)		577			0.00308
Titanium (Ti)	38.78			1,634	0.24
Zinc (Zn)			5,750		5
Zirconium (Zr)					0.000013

future business as usual metal consumption is given by equation 4.1

$$Quantity \quad of \quad Metal_i \quad consumed \quad in \quad year_x = \alpha + \beta GDP/Capita \quad in \quad year_x \tag{4.1}$$

Data on metal consumption is scarce. To estimate the quantity of metal consumed every year, we use the quantity of metal available for consumption, implied by the production quantities. We acknowledge that not all metals produced in a certain year is consumed as some of the produced quantity is kept as stock, but for modelling purpose, we assume that all of the metal produced in a certain year is consumed in that particular year.Table A.5 in appendix A shows the historical production of metals studied while tables B.20 to B.27 in the appendix B shows the regression statistics.

4.4.1 The model

Figure 4.4 shows the general model for analyzing the dynamics in the demand and supply of a particular metal. The description and measurement of the parameters and the data source is summarized in table 4.2

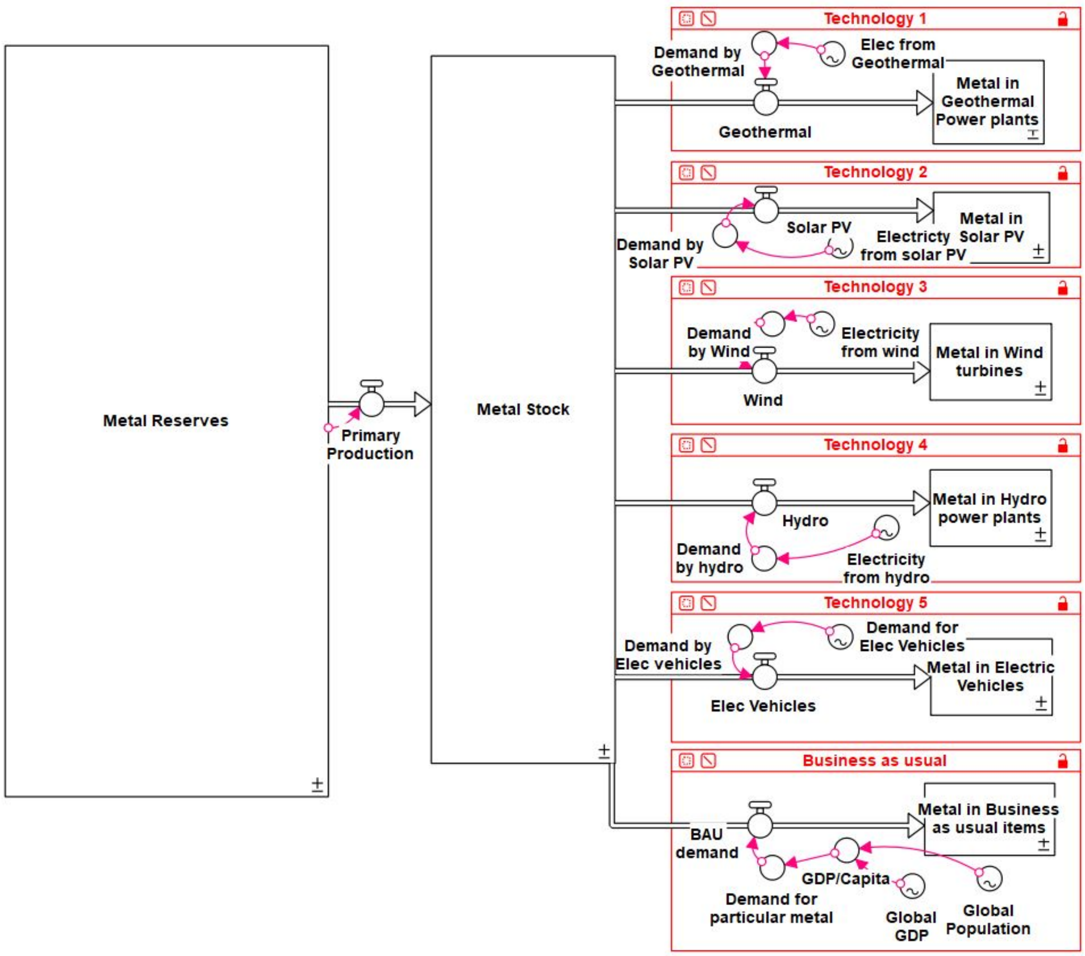

Figure 4.4: General system dynamics model

4.4.2 Identifying critical metals in the long term

To Point out long term critical metals accurately is a challenge because of the many factors that ought to be considered, limited data, and the general difficulty in forecasting how the changes will happen.However this study attempts to estimates the relative criticality of metal in the context of a low carbon future by considering the additional metals required to meet the achieve the low carbon future, the potential environmental

Parameter	Description	units	Data Source
Metal Reserve	Estimate the statistical availability of a metal. The amount of resources that can be economically mined.	tonnes	United States Geological Survey (USGS) (2020)
Primary Production	Amount of ore that is converted to metal	tonnes	
Production Rate	Amount of ore that is converted to metal as a Percentage of the reserve.	tonnes	United States Geological Survey (USGS) (2020)
Metal stock	Total amount of metal available to manufacturers	tonnes	Endogenous
Consumption of Metal by technology i	Amount of metal demanded by a particular technology	tonnes	Endogenous
Stock of metal in technology i	Amount of metal that is contained in technologies that are currently in use	tonnes	Endogenous
Metal demand by technology i	Quantity of metal required for a particular technology to run/	tonnes	World Bank Group (2017),Moss et al. (2011),Moss et al. (2013)
Electricity produced by technology i	Amount of power derived from a particular technology	Gigawatt hour(GWh)	IEA (2017)
GDP/Capita	Economic productivity per head	US $	Endogenous
Global Population	Population of the world	People	ONU (2019),World Bank (2017)
Global GDP	Global Economic productivity	US $	World Bank (2019)

Table 4.2: Summary of the Parameters used in the studies system dynamic model and the relevant units and data sources

implications of utilizing a particular metal on the additional demand, and the effects of substitutes and recycling rates. Additional metal demand is estimated by simulations from the STELLA model between the years 2019 to 2070.Environmental implications, substitutes availability, and recycling rates are qualitative measures based on literature review. Considering the above indicators in totality, the study proposes critical metals.

4.5 Additional demand for metals studied

4.5.1 Nickel

Nickel's demand will increase significantly in the pursuit of a low carbon future. The demand will rise by 100% above the business as usual demand in the year 2033,and the additional demand could increase by 290% of the BAU demand by 2070.Demand for nickel by geothermal power plants is the biggest driver of the increased demand, followed by electric vehicles, then wind power plants.Figures 4.5 and 4.6 shows the development of nickel demand up to 2070 and the breakdown of the demand respectively.

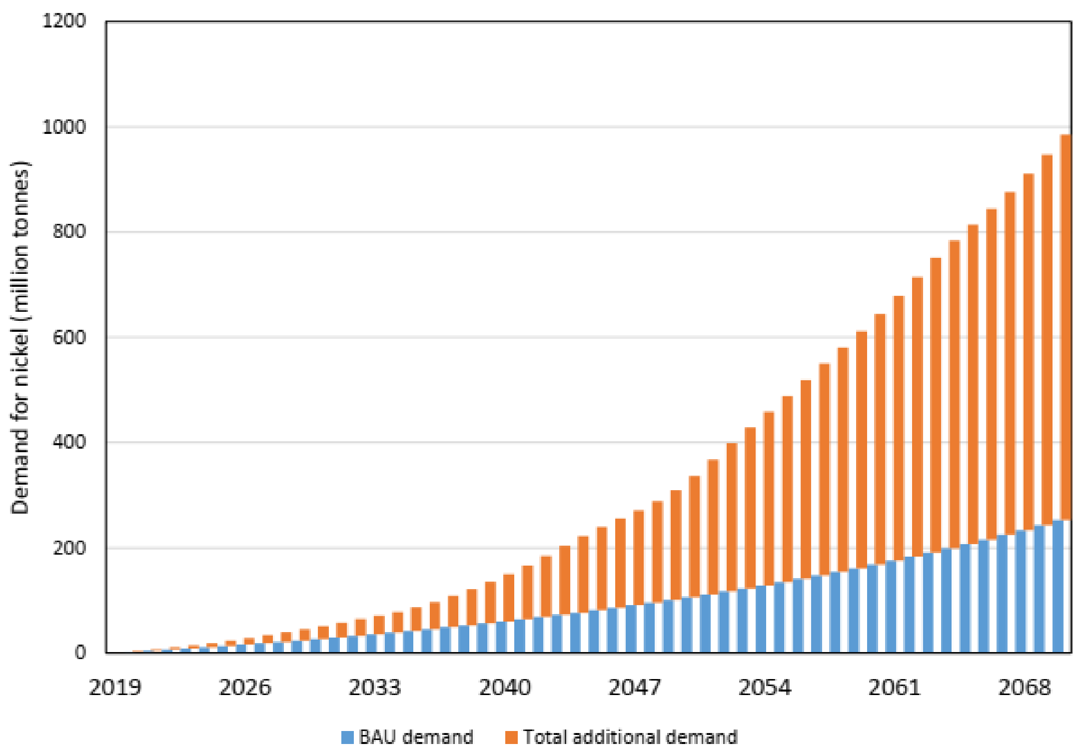

Figure 4.5: Demand for nickel.

Nickel is used in four low carbon technologies(Geothermal power plants, wind turbines, hydro power plants, and electric vehicles) making it an essential metal for a low carbon future.Geothermal energy is mostly generated in areas where there is volcanic or seismic activity. These environments are usually saline and the hot water needed to run geothermal

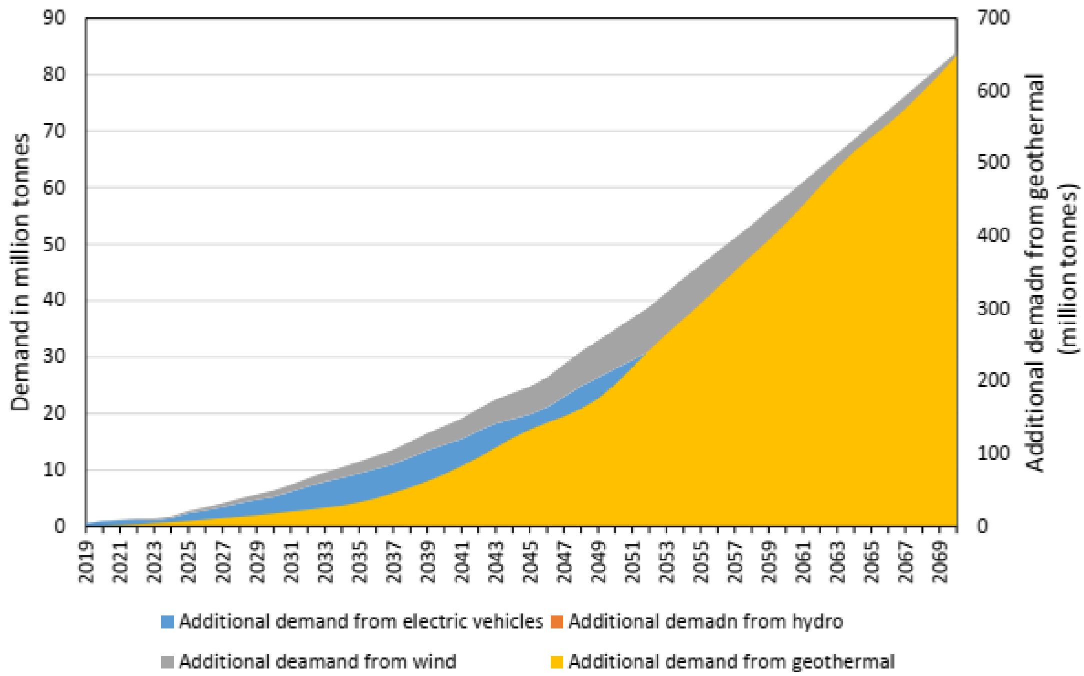

Figure 4.6: Breakdown of the additional demand for nickel.

power plants is usually highly corrosive.Consequently, corrosion-resistant nickel alloys are needed to withstand these conditions.For wind power generation,nickel is used mainly in the gearing and generator components of the wind turbines.Nickel is also used to manufacture corrosion resistant stainless steel used in offshore wind turbines that need to withstand the corrosive sea environment.Similarly for hydro power generation, nickel is essential to manufacture erosion and corrosion resistant nickel alloys used in the building hydro power plants to ensure the longevity of the power plants.

Hybrid and Electric vehicles need to store electricity using rechargeable batteries.Nickel is used to manufacture NMC (nickel-manganese-cobalt) lithium-ion batteries which are widely used in electric vehicles and other portable electric equipment.

4.5.2 Cobalt

Roberts and Gunn (2015) identifies the main use of cobalt, at present, to be in batteries(30 percent), super alloys and magnet alloys(27 percent) and in catalytic processes(10 percent). The proliferation of electric cars in pursuit of a low carbon future is expected to increase change the demand landscape of Cobalt significantly.Electric vehicles is the single technology accounting for the drastic increase in cobalt demand as seen in figure 4.7.Cobalt metal offer qualities that make them desirable as a component in EV batteries including the high energy density which allows light weight and energy dense batteries, thermal stability and safety.Additional demand as a percentage of the business as usual demand for cobalt will increase from 80 percent in 2027 to 100 percent by 2063 if the plans to actualize a low carbon future stand.

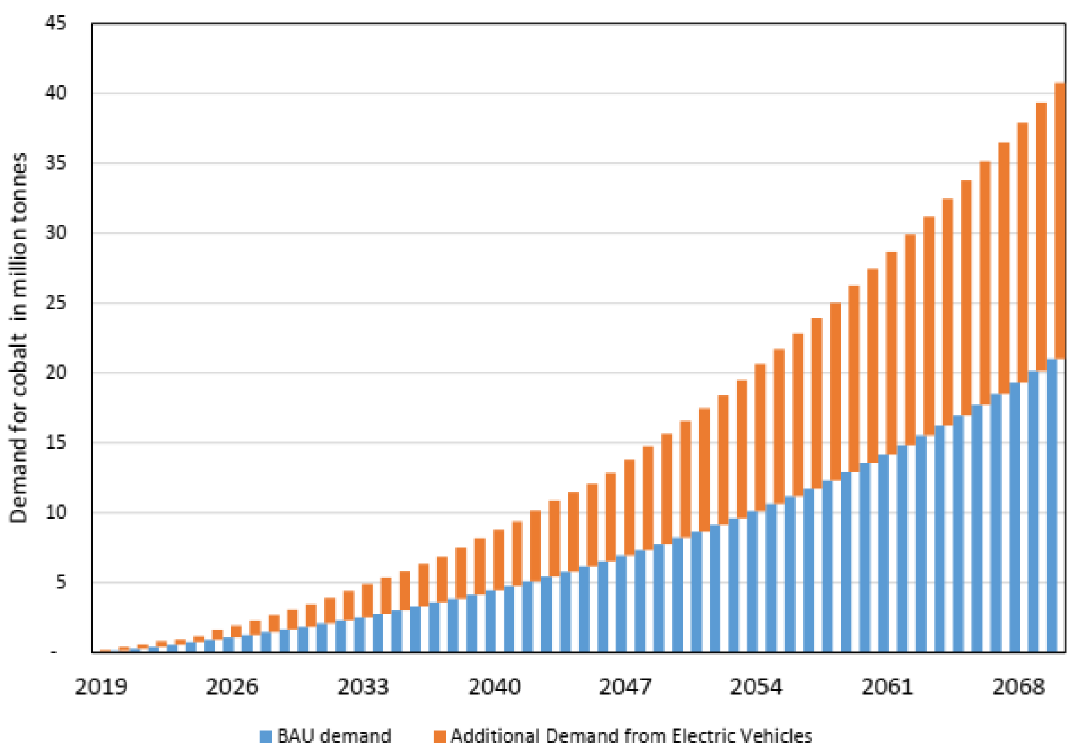

Figure 4.7: Demand for Cobalt.

4.5.3 Rare earth elements

The rare -earth elements studied are Dysprosium (Dy), Lanthanum (La),Neodymium (Nd), Praseodymium (Pr),Terbium (Tb), and Yttrium (Y).Collectively, the rare earths are integral to the manufacturer of a wide range of technologies that are central to the transition to a low-carbon economy.In technologies covered in this study, rare earths are critical in wind power generation and electric vehicles.

A transition to low-carbon energy and transportation systems will increase the demand for rare earth metals drastically.In order for clean technologies to contribute significantly to a reduction in greenhouse gases, the demand for REE will increase by 46 percent over the business as usual demand in 2025 and by over 85 percent percent by 2063.Figures 4.8 and 4.9 show the development of REE demand and the breakdown of the demand respectively.

The main driver of the increased demand will come from manufacture of electric vehicles.Rare earth elements are used in small quantities, in a large number of components of electric cars, including magnets and catalytic converters.The mass of rare earths in a full hybrid electric vehicle with a nickel metal hydride battery is approximately 4.5 kg. A full hybrid electric vehicle with a lithium-ion battery contains approximately 1kg of rare earth elements(Alonso et al. (2012))

Despite this crucial role of rare earths, securing supply is particularly challenging, because rare earth metals are not commonly found in sufficient concentrations to be mined profitably.(ref required)

4.5.4 Molybdenum

Molybdenum is used in three technologies considered in this study: geothermal, wind and hydro.It is therefore an important metal to aid the shift to renewable energy.Percentage additional demand for Molybdenum increases from 19 percent in 2020 to 99 percent in 2065 mostly because of demand for geothermal power plants construction.Figures 4.10 and 4.11 shows the development of molybdenum demand and the breakdown of this demand respectively.Development of geothermal energy will contribute to the majority of molybdenum's additional demand.

Molybdenum is combined with other metals and with appropriate thermo-mechanical processing to provide superior material performance such as strength, toughness, fatigue and wear resistance necessary for geothermal power generation.In offshore wind power installations, a foundation anchoring the tower to the sea floor is necessary. Molybdenum

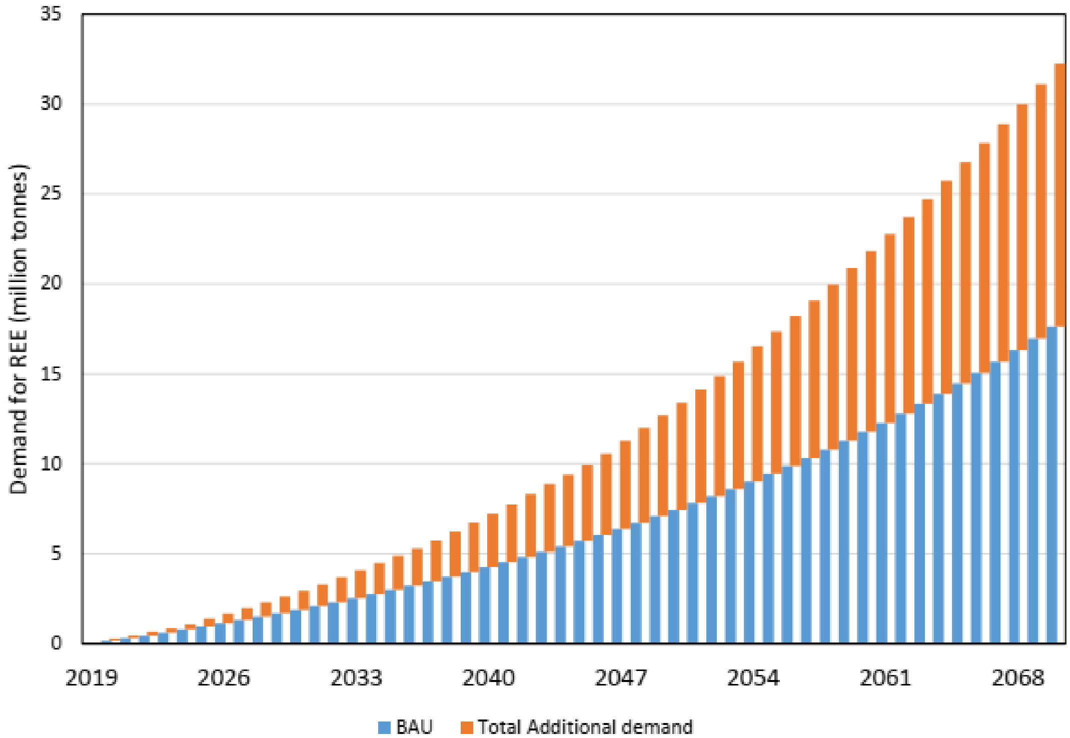

Figure 4.8: Demand for Rare-earth minerals

alloying is used to provide extra strength for these bases.Molybdenum is also used to manufacture the gearbox, the generator, and rotor hub.

4.5.5 Titanium

Titanium is necessary to run three technologies considered in this study:Geothermal power plants, hydro power plants, and electric vehicles. To achieve the low carbon future vision, additional demand for titanium as a percentage of the business as usual demand increases progressively from 17 percent in 2022 to 44 percent in 2070.The biggest driver of the additional demand is from electric vehicles and the second heaviest consumer of titanium is the construction of geothermal power plants.Figures 4.12 and 4.13 summarizes titanium's demand development and the major technologies contributing to the additional demand.

Some geothermal environments are so corrosive that titanium is one of the few candidate materials that can survive in these environment. The ability to survive these

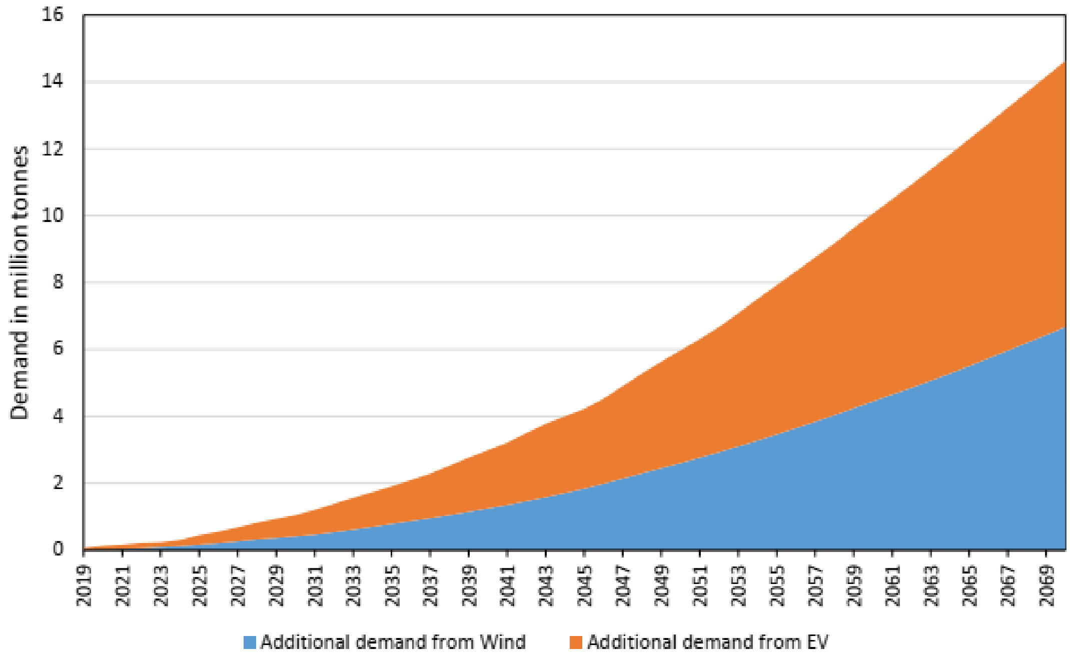

Figure 4.9: Breakdown of additional demand for rare-earth elements

environments is critical when the design life spans of geothermal power plants are typically over 20 years.Titanium is used to manufacture turbine components such as blades and rotors, to make heat ex changers and production well casings.

The lithium titanium oxide (LTO) anode is widely accepted as one of the best anodes for the future lithium ion batteries in electric vehicles (EVs). Within the field of battery research and development, titanium-based anode materials have recently attracted widespread attention due to their significantly better thermal stability

4.5.6 Copper

Copper's ability to conducts both heat and electricity be drawn into wires makes it a common metal in electric and electrical appliances and applications. Copper is used by all the technologies considered in this study, making it an essential metal. However,the additional demand as a result of ramping up the low carbon technologies does not change drastically relative to other metals studied.The additional demand changes from 5 percent of the business as usual demand in 2020 to 10 percent in 2070 as figure 4.14 shows.Demand by

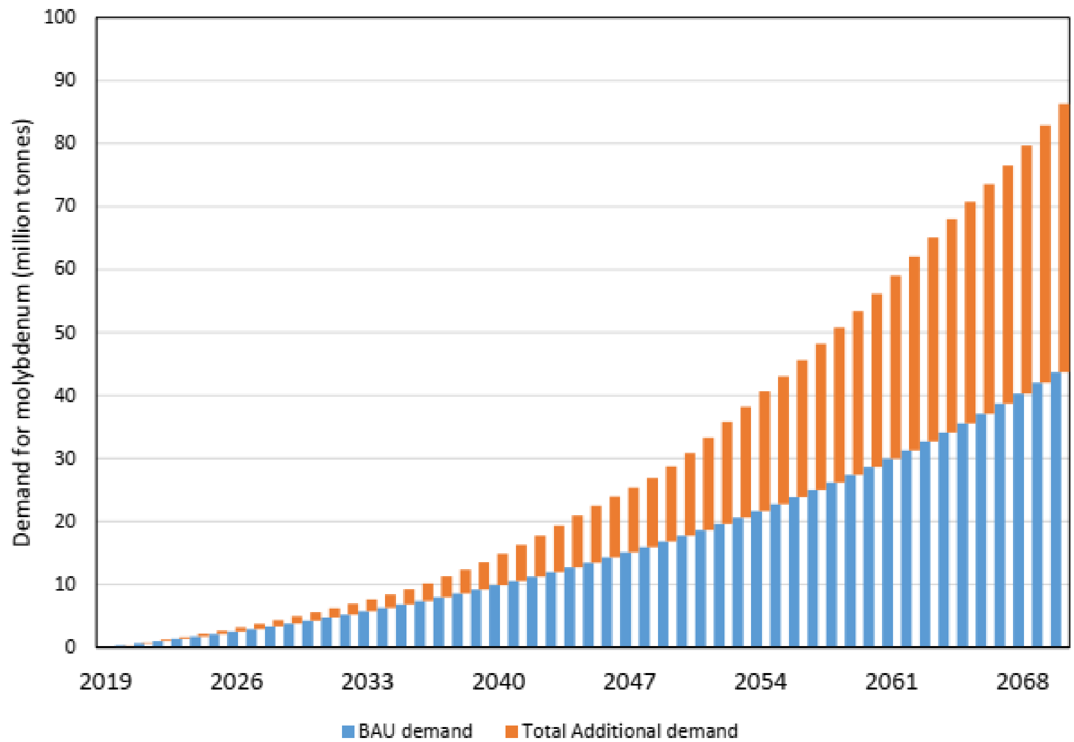

Figure 4.10: Demand for Molybdenum

electric vehicles and wind power power plants are the biggest contributors of the additional demand, as figure 4.15 shows.

Copper is used throughout the electric vehicle(EV) from the motor to the invert er and the electrical wiring because of its high electrical conductivity, durability and malleability.More copper is used to support the infrastructure required by elect vehicles, such as charging stations and in supporting electrical grid infrastructure. EVs can use up to three and a half times as much copper when compared to an internal combustion engine (ICE) passenger car. Copper is therefore critical to the functioning of electrical vehicles.

In wind power stations, , copper is consumed in wind turbine's generator, power transformers, gearbox and tower cabling.Copper is also used to connect onshore turbines through collector cables, which are linked to a substation and then the electrical and transmission network. Copper is essential to powering solar PV systems. It is relied upon

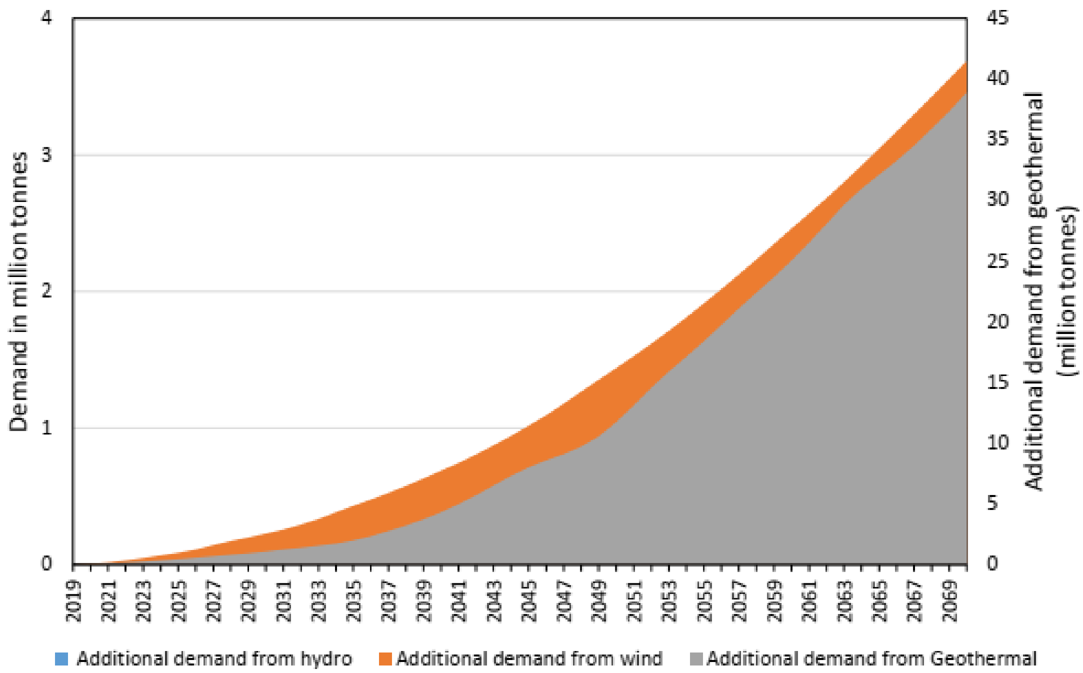

Figure 4.11: Breakdown of additional demand for molybdenum

to conduct amperes and to connect voltages to the grid; in some cases, copper is needed to drive motors that tilt the solar panels toward the sun.

4.5.7 Lithium

The biggest use of lithium is in rechargeable batteries for mobile phones, laptops, digital cameras and electric vehicles.Lithium is used by electric vehicles only among the technologies considered in this study.The percentage change in additional demand for lithium appears insignificant. However, the main use of lithium of lithium in business as usual situation(current situation) is similar to the use in technologies promoting a low carbon future.Significant amount of Lithium's current use is in the low carbon technologies, even though these technologies are not mainstream yet. Nevertheless, the total demand for lithium changes by as much as 7000 percent by the year 2070 mostly because of increased demand for electric vehicles.Figure 4.16 shows the development of lithium's demand until 2070 in the context of pursuing a low carbon future.

Lithium is used mostly to manufacture lithium-ion and lithium polymer batteries used in

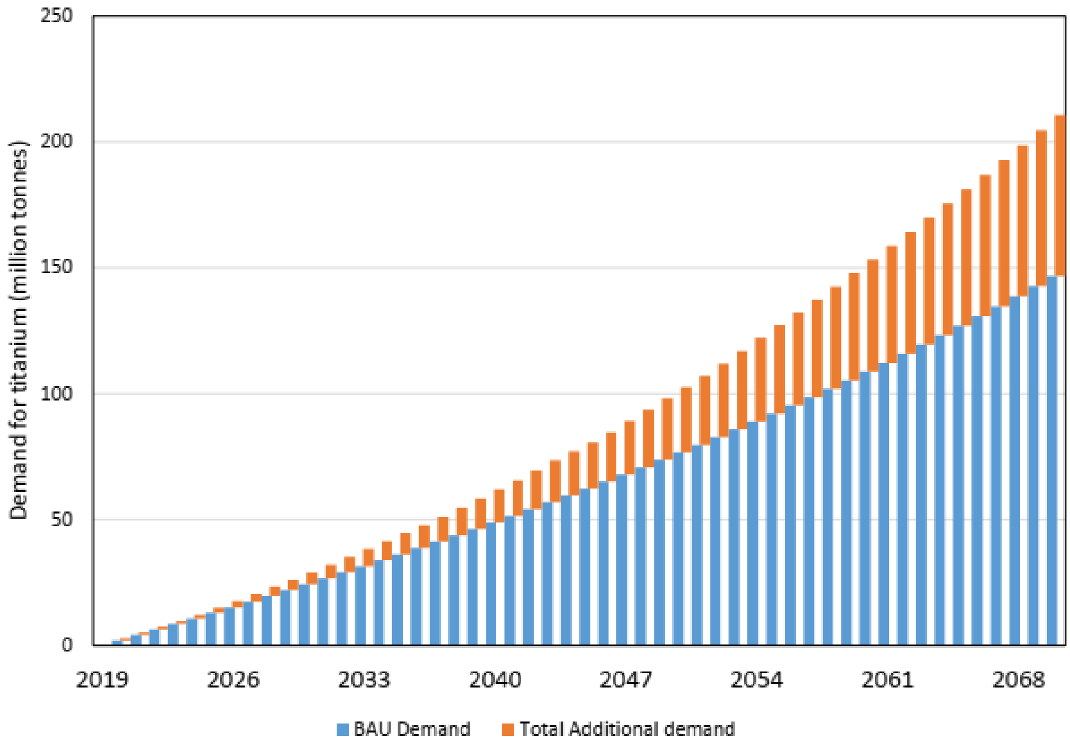

Figure 4.12: Demand for titanium.

electric cars. If the trend toward replacing internal combustion engine vehicles with electric vehicles continues and lithium-ion batteries become the preferred power source for electric vehicles, then a large demand for lithium carbonate could potentially be generated.

4.5.8 Chromium

Chromium is used in three technologies considered in this study:Hydro power generation, wind turbines and geothermal.Chromium is used for structural purposes by combining with other metals to form strong steel. There is an emerging use of chromium as Iron-Chromium flow batteries used for energy storage in renewable energy generation. Because of the limited use of chromium in the renewable sector, the additional demand is relatively insignificant. Demand for chromium as a percentage of the business as usual quantity changes from 1 percent in 2020 to only 8 percent in 2070 as figure 4.17 shows.As indicated in figure 4.18, the significant additional demand comes from geothermal power plants construction.

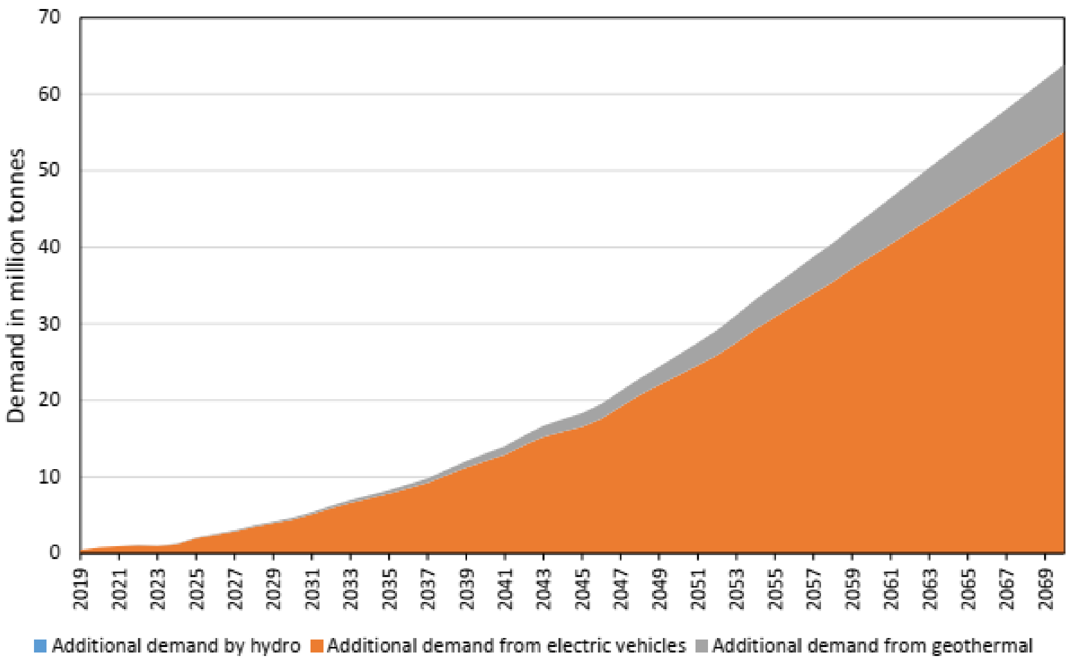

Figure 4.13: Breakdown of additional demand for titanium

4.5.9 Manganese

Aside from iron, manganese is the most essential mineral in the production of steel.Steel is an essential material in construction of renewable energy power plants such as geothermal, hydro and wind mills.Despite this, additional demand for manganese in the context of pursuing a low carbon future is low. The additional demand as a percentage of the business as usual demand remains at an average of 6 percent from 2020 to 2070 as figure 4.19 shows.

Manganese serves as an electrode in many lithium batteries.Manganese's use in the newest generation of batteries for electric vehicles is likely to grab the most attention.In fact, the biggest contributor of additional manganese demand between 2019 and 2070 in the context of pursuing a low carbon future is demand by electric vehicles as figure 4.20 indicates.There is no substitute for manganese, and in some aspects, manganese has itself become a substitute in certain alloy applications.

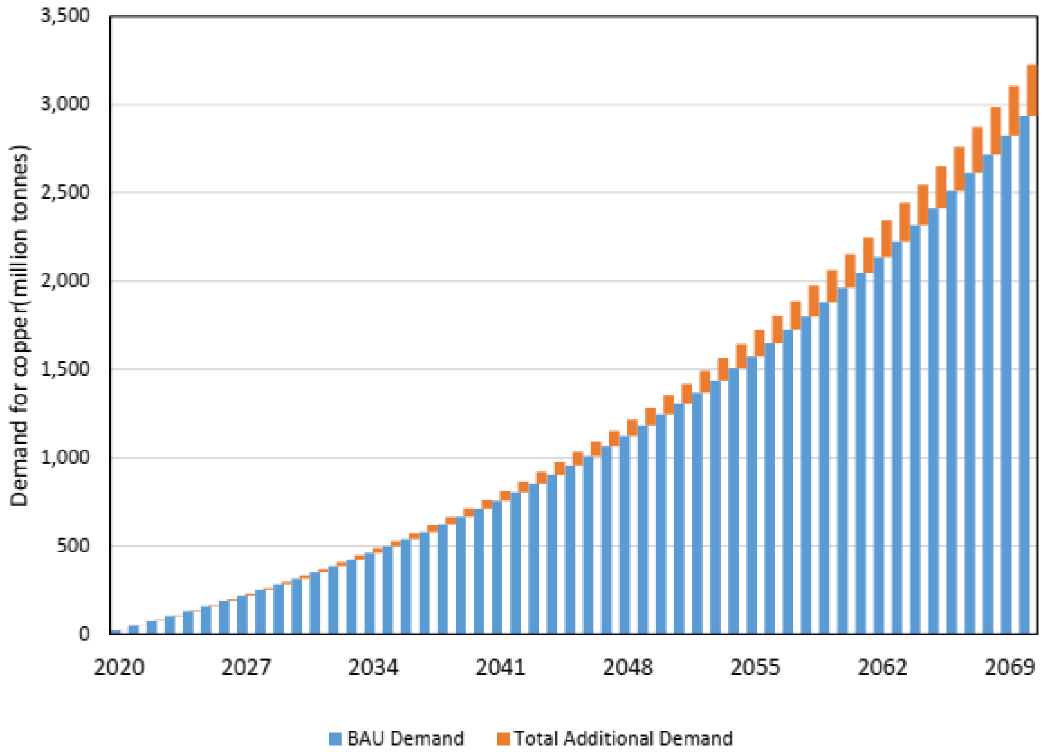

Figure 4.14: Demand for copper.

4.6 How will environmental implications of mining the required additional metals affect the supply of these metals?

Transition to a low carbon future could increase mineral production significantly, as the results above indicate. However,although mining and processing of mineral resources is an integral part of economic development, it is also associated with significant environmental and social impacts.By extension, the additional demand by low carbon technologies could magnify the environmental and social impacts.Past evidence has shown that uncontrolled mining can have drastic effects on the environment and the society.

Among the metals studied, the most discussed example of social and environmental effect from mining activities occur from mining cobalt.Mining of Cobalt has led to heavy mineral contamination of air water, and soil in DRC Congo, with severe health implications for the miners health and the surrounding communities.As reported by researchers such as Tsurukawa et al. (2011) and Amnesty international (2017) small scale

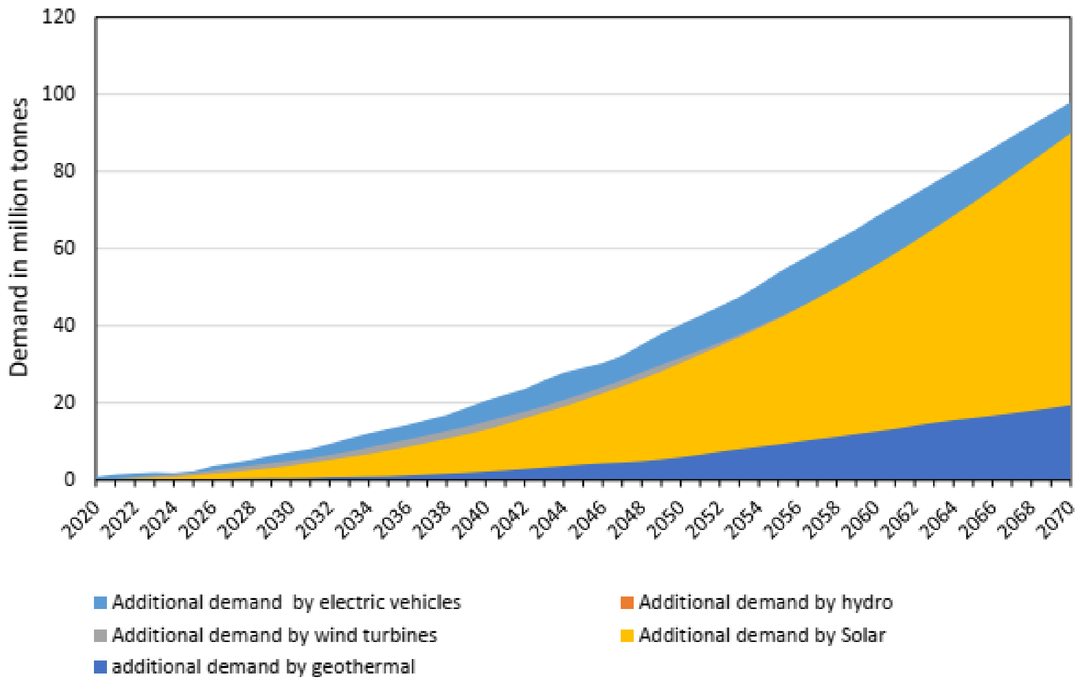

Figure 4.15: Breakdown of additional demand for copper

miners work in dangerous conditions such as hand dug caves that are at a risk of carving in or landslides and there exists exists extensive child labour.Copper mining can lead to long lasting heavy mineral contamination of soils and water as seen in Brazil, Chile, India and China(Stowhas et al. (2018)), and exposure to arsenic for smeleter workers in China has had health impact on miners(Sun et al. (2015)).Nickelsulphide mining has had historical environmental impacts including damaging lakes and wetlands as reported by Mudd (2010).Mining and processing Rare earths is complex and requires large amounts of chemicals that may be harmful to to human health if not managed properly(McLellan et al. (2013). Bontron (2012) also reports that REE mining produces large volumes of solid waste, gas and wastewater which can pollute ground water leading to crop failures and displacement of communicates as seen in China .Although lithium mining is generally considered less risky than many other minerals, there are concerns over water contamination and shortages in the lithium triangle of Argentina, Bolivia and Chile, and the inadequate compensation for affected local communities (Wanger (2011))

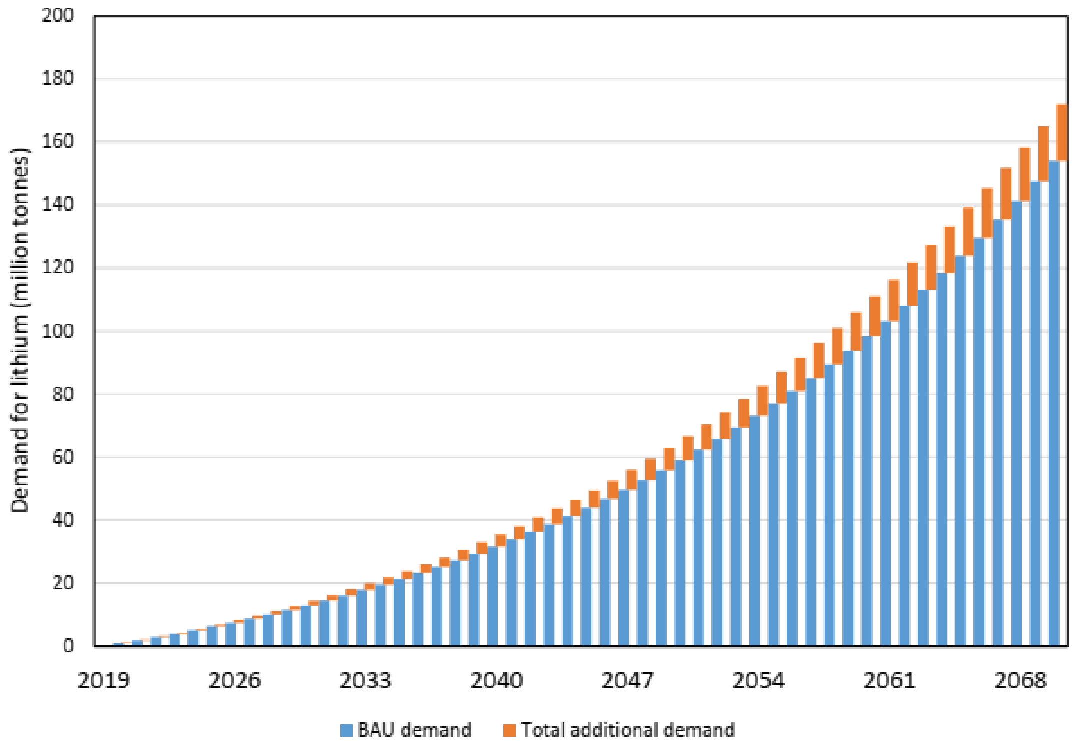

Figure 4.16: Demand for Lithium.

As the example above indicate, there is a possibility that the transition to a low carbon future could have have adverse effects on the environment, especially in resource extracting countries if mining is left uncontrolled.The impact could be significant in a small number of developing countries because high grade deposits of many rare metals are concentrated in these countries yet they tend to have insufficient environmental regulations. Accelerated resource extraction could lead to adverse effects on local communities.

Estimating accurately the full environmental impact of mining is impossible because some impact can not be quantified.However one way commonly accepted as a measure the environmental effects of mining is evaluating the total material requirement(TMR).TMR was developed by Wuppertal Insitutte and measures the total mass of resources flows caused by economic and non economic activities.TMR can be used as an indicator of the potential impacts on the environment from the total mass of natural resources as shown by Halada et al. (2001) . Authors such as Watari et al. (2019a) have carried carried out studies applying

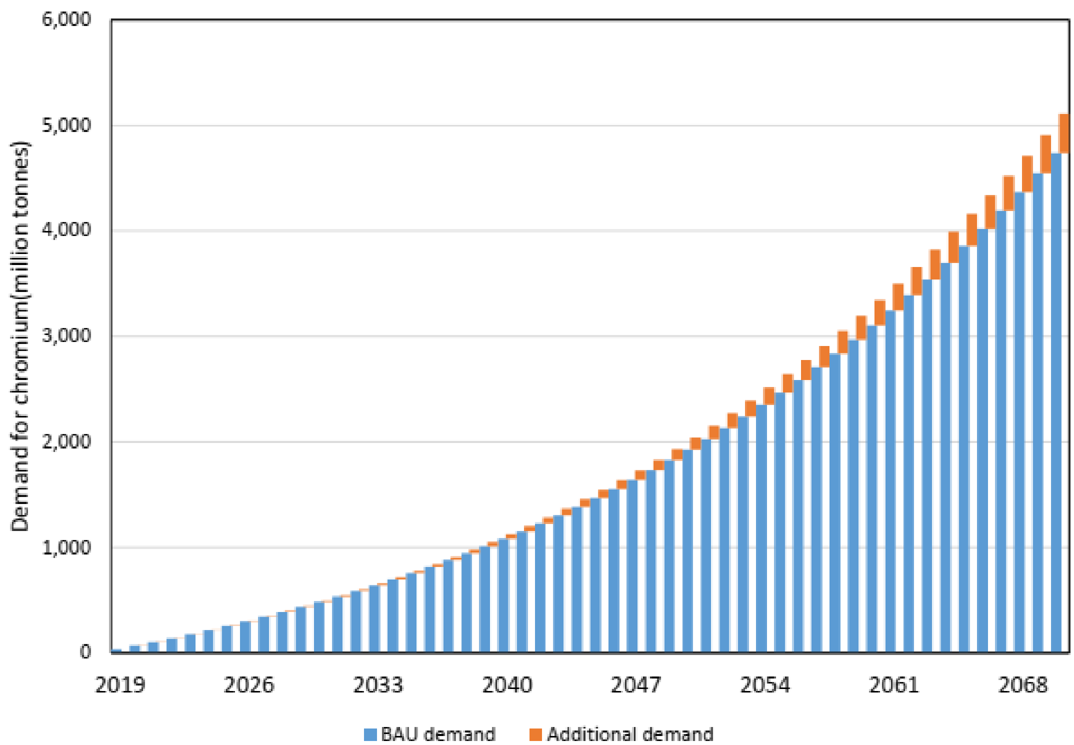

Figure 4.17: Demand for chromium.

Table 4.3: Total material requirement(TMR) intensity of selected metals in 2015 at the global level. Source: Watari et al. (2019b)

Metal	TMR Ranking
Rear earth elements	1
Lithium	2
Cobalt	3
Copper	4
Nickel	5
Manganese	6
Titanium	7
Chromium	8

TMR to evaluate the requirements for the global transition to a low carbon future and found that resource flows will increase significantly over time and TMR "increased by around 450% to 500% from 2015 and 2050 in the electricity and transport sectors". Table 4.3 ranks the metals according to their TMR, based on the study by Watari et al. (2019a)

As table 4.3 indicates,mineral resources that have the potential to lead to the greatest

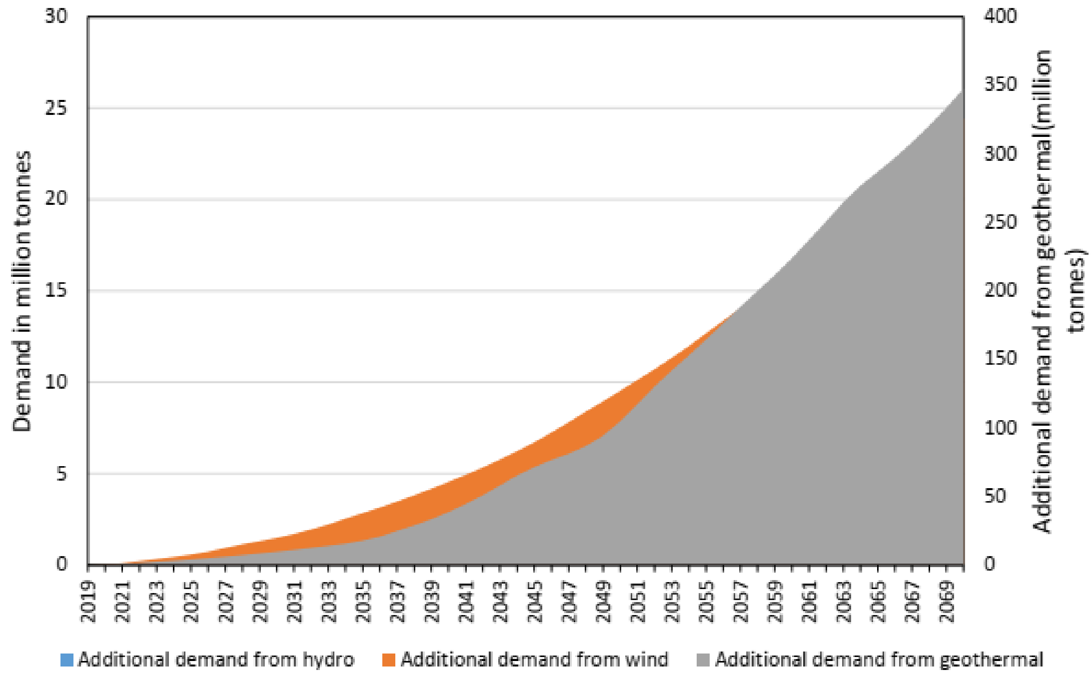

Figure 4.18: Breakdown of additional demand for chromium

environmental impacts through the expansion of mining activities are rare-earths, lithium, and cobalt.Balancing between the environmental impacts of these metals and the additional demand for a low carbon future is necessary.The growing public awareness of problems and impacts of mining means environmental aspects of mining are more relevant for raw material policy-making and responsible sourcing strategies now than before.Prominent mining disasters like dam failures such as in Kolontár,Hungary in October 2010 and in Bento Rodriguez, Brazil in November 2015 reinforces the idea that mining is accompanied with substantial environmental impacts and risks for the local environments, increasing the potential for for communities around the world to oppose the development of new and the expansion of existing mines. In other words, metals associated with high environmental impact face a higher risk of supply disruption.

4.7 Substitution in light of the additional demand

Substitution could be a useful strategy to meet the potential additional demand of metals in the context of pursuing a low carbon future. However, substitution often comes at

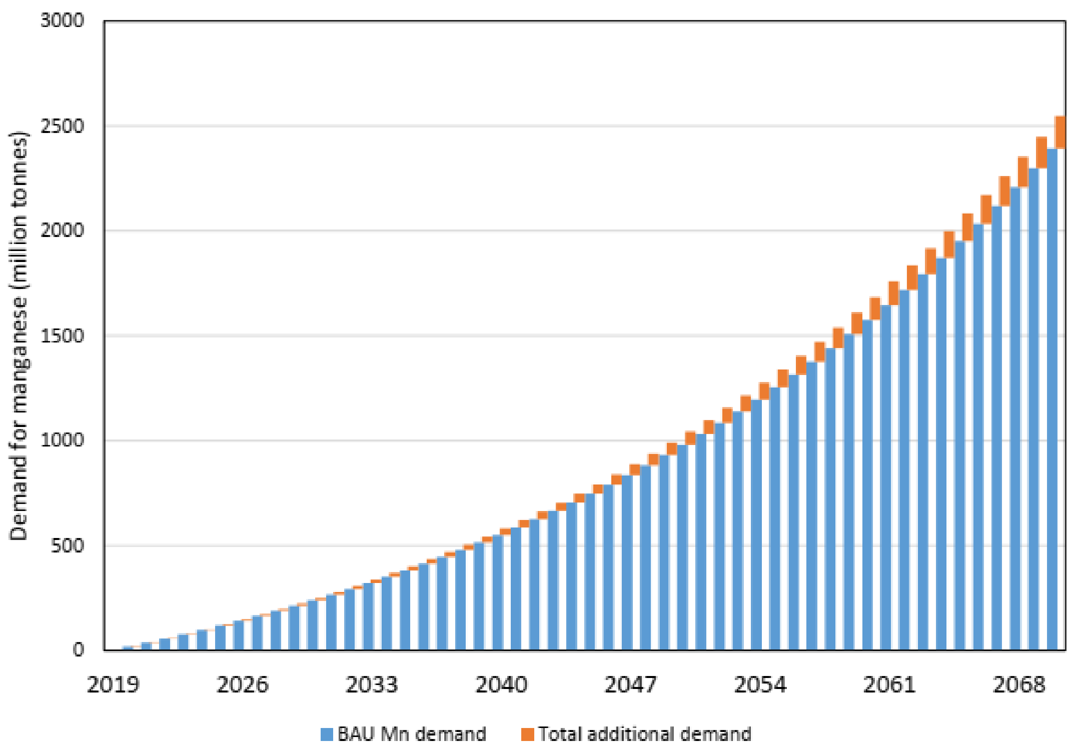

Figure 4.19: Demand for Manganese.

a price, economic or otherwise, and requires consideration of the substitute‘s performance, it's availability, the price changes a substitute would involve, and, from a more holistic perspective, the substitute‘s environmental impact as compared to that of the metal in question.

Although multiple substitutes can be identified for each end-use application, and sometimes an ideal substitute may even exist, the substitute might not be found in sufficient quantity, or its supply might not be reliable to meet the demand.Further, in case the substitute is co-mined with the metal in question,in the event of a supply restriction of the main metal in question, the substitute would also suffer from the supply restriction and would thus not be available.

Nonetheless, there is some evidence that substitutes can be found.In 1970s, when civil war caused a sharp decrease in the supply Cobalt, scientists at General motors successfully developed magnets that did not require cobalt (Congress of United States (1982)). Scientists

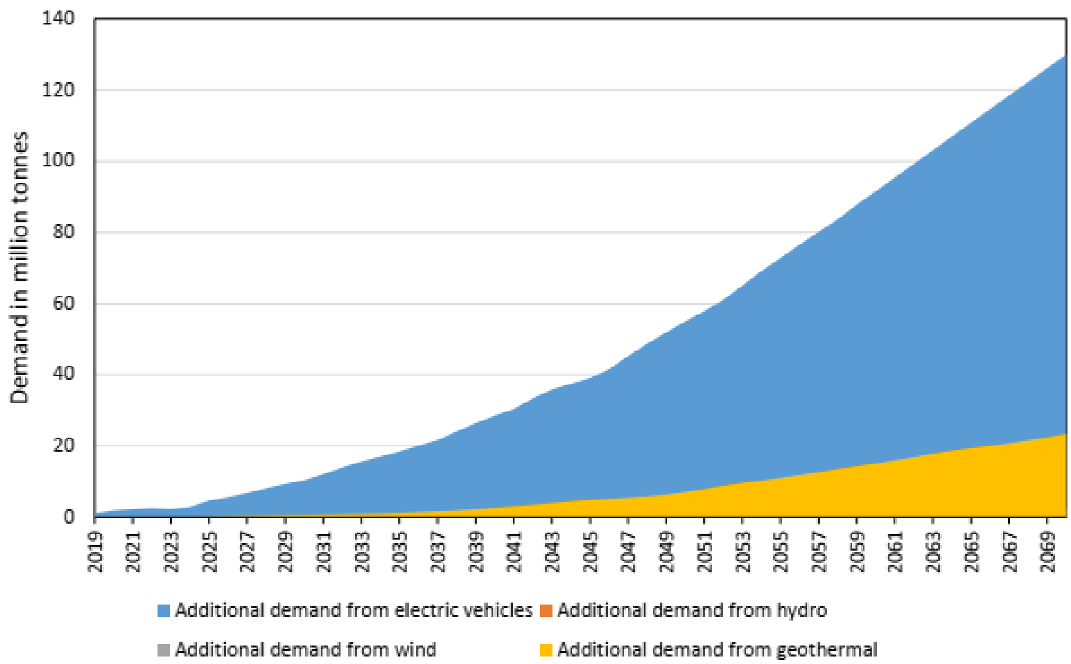

Figure 4.20: Breakdown of additional demand for manganese

at General motors also developed super-alloys used in gas turbines requiring little or no rhenium to respond to the supply shortage of rhenium(Duclos et al. (2010)).But, these metal to metal substitution are rare, and can not be counted on to lessen the burden of additional demand of metals for required for the low carbon future.

Graedel et al. (2015) examined the substitutability of 62 metals of the periodic table and concluded that "absolutely none of the 62 metals have substitutes that provide exemplary performance across all its major applications[and] it seems very clear that substitution in the face of metal scarcity is not a general panacea" Table 4.4 shows the substitute scores for the metals studied.

Overall, substitution can not be a reliable option to manage a possible supply disruption. Based solely on the substitute scores on table 4.4, manganese,chromium, copper rare earth elements and titanium have a relatively high risk should a supply disruption happen because there are no reliable substitutes.

Table 4.4: Substitute performance of metals studied scaled from 0 to 100, with 0 indicating that exemplary substitutes exist for all major uses and 100 indicating that no substitute with even adequate performance exists for any of the major uses Source:Graedel et al. (2015)

Metal	Substitute performance
Rear earth elements	69
Lithium	41
Cobalt	54
Copper	70
Nickel	62
Manganese	96
Titanium	63
Chromium	76

4.8 Recycling as a strategy to meet the additional demand

Recycling of metals is widely viewed as a fruitful sustainability strategy.Recycling can save energy and minimize the (environmental)challenges related to the extraction and processing of virgin metals and with adequate recycling, concern about metals supply disruption can decrease.

Several factors, including economic, technology, and social norms, determine if recycling can be effective in easing the demand supply tensions in the path towards decarbonization. The economics of recycling is important because the net intrinsic value of materials ready for recycling must be high enough to cover the cost and efforts of recycling. Recycling technology to separate joined or alloyed materials must be available, and the discarded products design should not require too much efforts to separate.Lastly, if the society is educated through public campaigns and encouraged to adopt the habit of recycling, and legislation, and other recycling policies, including recycling fees are put in place, recycling could help meet the huge demand for the metals required to achieve the low carbon future.

Currently, the recycling rate of the metals studied is above 50 percent for all the metals studied, except for rare-earth elements and Lithium.The rates will keep changing in the future depending on factors such as product lifetimes, product composition and recycling efficiencies

However, recycling alone will not help reduce pressure on the the metals required for

Table 4.5: Global average of end of life recycling rates of metals studied. Source:Graedel et al. (2011)

Metal	End of life recycling rate
Rear earth elements	$< 1\%$
Lithium	$< 1\%$
Cobalt	$> 50\%$
Copper	$> 50\%$
Nickel	$> 50\%$
Manganese	$> 50\%$
Titanium	$> 50\%$
Chromium	$> 50\%$

the low carbon future.The availability of secondary metals (new or old scrap) is limited due to the often long lifetimes of metals in use (Atherton (2007)), currently, the efficiency in collection and processing of most discarded products is low,and at the moment, primary material is relatively abundant and low cost keeping the price of scrap low.(Reference) To increase the chances of recycling easing the pressure on the supply of metals required for the low carbon future, in-depth research is necessary to develop new re- cycling technologies and infrastructures for specific applications,especially the low carbon technologies.

4.9 What can we understand from the long term study

1.Metals reserves are unlikely to constraint the shift to a low carbon future.However,reserves and annual mining rates are likely to influence the technological mix and maximum growth rates of some sub-technologies.

2. Mining of several metals needs to increase, assuming future metal demand will resemble current levels, and the projected additional demand. Nevertheless, metal intensities have improved historically and if this continues, the required growth in mining rates and cumulative demand might be lower than the projected demand. Improved intensity would also enable recycled metals to meet a portion of the demand by the end of the studied period.

3.Cumulative demand and growth rates for the metals studied differed widely between the during the period of study. Whether a metal will remain critical will therefore depend on the mix of sub-technologies for most metals.

4.Most technologies can be substituted by back-stop technologies with slightly lower performance (or higher cost), but constructed from non-critical metals for which additional demand is low compared to current mining rates. The exception is lithium batteries, which are superior to current rivals as a result of higher energy and power density.

4.10 Limitations of the long term study and future research

Although this study has proposed system dynamics to gauge possible critical metals, the model still needs a lot of work to make it better.One aspect is incorporating factors such as recycling,technological improvements, substitutes and measures of environmental impact into the model. In this study, such factors are discussed qualitatively. Expanding the model to include feedback loops may lead to better results.

The long term study did not conduct sensitivity analysis of the resulting additional demand. Future research could improve the research and provide more in-depth results by consulting a sensitivity analysis of the various scenarios.Further research is also necessary to understand the dynamic progress of production rates. This study assumed constant production rates between 2020 and 2070. The wide assumption about production rates is unrealistic.

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CHAPTER 5

STUDY CONCLUSION

As concern about availability and access to mineral resources increases, many researchers have proposed meaningful ways to measure and identify critical minerals in what are often referred to as criticality studies.The studies make meaningful recommendation on how to measure critical metals, but in some ways, these studies are unsatisfactory. For one, majority of the studies are subjective, and use diverse methods to aggregate and weight indicators, thus making criticality results unreliable. Another important aspect overlooked by existing criticality studies is the incorporation of probability to weight the damages that could arise from mineral resource supply disruption. The strong assumption about probability functions and the subjective manner in displaying the results makes criticality results unreliable.

Our study proposed a method to incorporate probability in measuring criticality. It also responded to criticism about the subjective display of results and suggested displaying results as criticality levels.

Consequently, this study has proposed two methods that fill the gaps identified in the literature. The first is a quasi-dynamic method that incorporate probability in measuring criticality in the medium term, using Japan as a case study.Japan is a country that could be severely affected by a disruption in the supply of metal resources because its economy depends heavily on such resources. However, there has been little effort outside of government institutions to analyze critical metals in Japan. The second is a system dynamics model that estimates criticality in the long term in the context of pursuing a low carbon future to limit climate change.The study analyzed the additional demand for mineral resources that could arise if the world seriously pursues a low carbon future.

The results indicate show that metal price changes follow different probability distributions. This is against the prevailing assumption that all metal price changes follow a normal distribution. This implies that the accuracy of estimating critical metals improved. For Japan, the study suggested that cobalt, niobium, rare earths, platinum, and tungsten are among Japan's critical metals. Industrial demand for these metals is expected to increase in the future as changes such as a shift to green technologies occur. Therefore, ensuring a stable supply of these metals is a policy issue for Japan.

The study also suggested strategies that Japan could employ to secure the supply of these critical metals. They included strengthening bilateral relationships with resource-producing countries,especially in Africa where Japan's presence is overshadowed by other countries such as China.Japan Could also ramp up efforts to engineer substitutes for critical metals, put in more efforts to recycle metals, and exerting more effort toward resource exploration in Japan.

In the context of pursuing a low carbon future,the study highlighted the important role to be played by emerging technologies such as electric vehicles in efforts to solve the global climate change emergency. Using system dynamics to analyze additional demand for metals, and how factors such as recycling might impact this future demand, the study found that Nickel, cobalt, rear-earth elements and molybdenum will experience the most significant additional demand in the push for a low carbon future. However, only cobalt and rear-earth elements are classified as critical when other factors like recycling rates, substitutes availability, and environmental considerations are considered.

Metals criticality is a sensitive topic, with economies putting in measures to preserve their economies. Metals may therefore be perceived as more critical in the medium to long-term today than is actually the case if policies that reduce vulnerabilities are implemented. Policymakers and researchers examining metals criticality should consider these findings not as alarming, but a prompt to focus on how to reduce vulnerability by developing technologies that utilise abundant metals, improve metal intensity and/or increase recycling and prioritise technological diversity. There is also need for more research collaboration between energy sector and the mineral sectors inf efforts to meet to meet the desired low carbon future. These options would provide synergies with a circular economy.

Although the study proposed improvements in measuring and displaying critical metals, it did not eliminate the need to estimate critical metals accurately. There is still a need to estimate the end use application of metals accurately because the existing data on end use and GDP are broadly aggregated, leading to overlaps in estimating metals' real economic contributions. Often, one product is an input for another product and, therefore, it is difficult to identify each metal's real product. Furthermore, to avoid getting meaningless results due to aggregating too many factors (it is hard to mix them, and therefore, if one is not careful, the results could be meaningless), some factors such as recycling rates, available metal substitutes, improvements in mining technology, and metal co-production that could affect the security of the metal supply were left out.

The amount of metals studied in the long term was limited to 8 metals. Extending the study to cover other metals, and improving the model to measure and incorporate other criticality indicators such as recycling rates and the substitutes availability might lead to more meaningful and comparable results.

APPENDIX A

SUPPLEMENT DATA

Appendix A shows the information that was too long to fit in the main body of the thesis and some data that was used.

Table A.1: Selected studies and the methodologies applied to determine critical metals

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
Committee on Critical Mineral Impacts of the U.S. Economy (2008) "Minerals, Critical Minerals and the US Economy"	2008	**Supply risk:** ▪ Geological availability ▪ Technical availability ▪ Environmental and social availability ▪ Political availability ▪ Economic availability **Impact of supply restriction** ▪ Consumption share of sectors ▪ Specific impact	Not explicitly explained	criticality matrix	U.S

Author Title	**Year**	**Variables considered**	**Variable weighting and aggregation**	**Display of results**	**Target audience**
Morley and Eatherley (2008) "Material security:Ensuring resource availability for the UK economy"	2008	**Material risk:** ▪ Global consumption levels ▪ Lack of substitutes ▪ Global warming potential ▪ Total material requirement **Supply risk criteria** ▪ Sarcity ▪ monopoly supply ▪ Political instability in supplying regions ▪ Vulnerability to the efects of climate change in key supplying regions	Qualitative judgement is used to assign a score of 1(low) to 3(high) to each component for each material	materials are ranked based on total score	U.k

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
United Nations Environment Programme (2009) "Critical metals for future sustainable technologies and their recycling potential"	2009	**Material risk:** ▪ Rapid demand growth ▪ Moderate demand growth **Supply risks** ▪ Regional concentration ▪ Physical stability ▪ Temporary scarcity ▪ Structural or technical scarcity **Recycling restrictions** ▪ High scale of dissipative applications ▪ Physical or chemical limitations for recycling ▪ Lack of suitable recyling technologies ▪ Lack of incentives for recycling	Subjective judgement. MEtals meeting several of the indicators used in teh study are labelled 'serious supply risks'	None	Global

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
US Department of Energy (2010) "Critical Materials Strategy"	2010	**Importance to clean energy** ▪ clean energy demand (75) ▪ Substitutability limitations(25) **Supply risk** ▪ basic availability ▪ competing technology demand(10) ▪ political,regulatory and social factors(20) ▪ co-dependance on other markets(10) ▪ producer diversity(20)	No mention of how weights for different categories were arrived at.	Plotted on a two axis matrix.Attributes assigned qualitative factors between 1(least critical) and 4(most critical). Criticality scores are averages of the two attributes	U.S

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
European Commission (2010) “Defining critical raw materials Critical raw materials for the EU”	2010	**Economic importance:** The weighted sum of individual mega sectors(expressed as gross value added) divided EU GDP **Supply risk:** ▪ stability of producing countries (measured using HHI index) ▪ substitutability(experts opinion) ▪ recycling (ration of recycling from old scrap to EU consumption) **Environmental country risk:** Based on environemtnal performance index of each country	supply risk variables aggregated through multiplication	Graph of supply risk vs economic importance. Environmental country risk displayed indipently on a linear scale	E.U

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
Duclos et al. (2010) "Design in an era of constrained resources"	2010	**Impact of supply restriction (on GE):** ▪ G.E percent of global supply ▪ impact on revenues ▪ substitutability of the element(within G.E) ▪ ability to pass costs to consumers **Supply and price risk:** ▪ Abudance in earths crust ▪ Geographical concentration ▪ Co production of the material ▪ Demand growth ▪ historic price volatility ▪ market substitutability	Each indicator is (subjectively) allocated a value ranging from 1(very low risk) to 5(very high risk)	criticality matrix	General electric company
Thomason et al. (2010) "From National Defense Stockpile (NDS) to Strategic Materials Security Program (SMSP): Evidence and Analytic Support"	2010	**Supply:** ▪ U.S Supply ▪ Foreign supplies(including decrements and delyas) **Demand** ▪ Defense investment ▪ civilian demand **Stockpile balance:** ▪ shortfalls inventory	Not explicitly explained	criticality measured by demand supply ratio	U.S

Author Title	**Year**	**Variables considered**	**Variable weighting and aggregation**	**Display of results**	**Target audience**
Moss et al. (2011) "Critical metals in strategic energy technologies"	2011	Indicators considered: ▪ The likelihood of rapid global demand growth ▪ Limitations on expanding supply in the short to medium term ▪ Cross country concentration of supply ▪ Political risks associated with the major producer countries	Extensive interviews with key companies and industry experts	None	Energy industry

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
Hatayama and Tahara (2015) "Criticality assemssment for Japans resource strategy"	2015	Based on NEDOS approach but added sufficiency of mineral interests. Supply risk: ▪ Depletion time ▪ Concentration of reserves ▪ Concentration of pre-production ▪ concentration of import trade partners ▪ sufficiency of mineral interest **Price risk:** ▪ price change ▪ price variation **Demand risk** ▪ mine production change ▪ domestic demand growth ▪ domestic demand growth for specific uses **Recycling restriction** ▪ stock piles ▪ Recyclability Potential risk ▪ possibility of usage restrictions	Each indicator is (subjectively) allocated a value ranging from 0(very low risk) to 3(very high risk). Final figures are summed to indicate material criticality.Weighting of indicators not clear	Materials ranked according to criticality scores	Japan

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
Graedel et al. (2015) "Criticaltiy of metals and mettaloids"	2015	**Vulnerability to Supply restriction:** ▪ Material access ▪ National economic importance ▪ Substitute performace ▪ substitute availability ▪ Environmental impact ratio ▪ Net import reliance ratio ▪ Global innovation index **Supply risk:** ▪ Depletion times ▪ Companion metal fraction ▪ policy potential index ▪ human development index ▪ WGI political stability ▪ Global supply concentration **Environmental implications** ▪ Cradle to gate lifecycle inventory	Indexes measured on a sclae of 1-100 and weighted equally	3D criticality space	global, national and corporate levels

Author Title	Year	Variables considered	Variable weighting and aggregation	Display of results	Target audience
Bastein and Rietveld (2015) "Materials in the Dutch economy- a vulnerability assessment"	2015	**Long term supply(>10 years):** ▪ Geoeconomic: Reserve over production (R/P) ▪ Geoeconomic: Companionality(extent to which raw material is a by-product) ▪ Geopolitics:Concentration of reserves **Short term security of supply :** ▪ Geopolitics: Concentration of production ▪ Geopolitics: Stability and the quality of the administration of producer countries (WGI) ▪ Existing export restrictions ▪ End of life recycling rate **Operating profit** ▪ Price volatility of raw materials **Corporate reputation** ▪ Environmental impact ▪ performance of source countries for human development index ▪ regulations with respect to confilct minerals	$\text{Criticality}_{KT} = HHI_{prod} * (WGI_{weighted} + OECDrestrictions_{weighted}) * (1 - \%EOL - RR)$		National and corporate level in the Netherlands

Author Title	**Year**	**Variables considered**	**Variable weighting and aggregation**	**Display of results**	**Target audience**
NSTC (2016) "Assessment of critical minerals:Screening methodology and initial application"	2016	C = $\sqrt[3]{R * G * M}$ where R= supply risk, G= Production growth and M= Market dynamics	Single value for each material on a scale of 0-1	Blank	blank

Author Title	**Year**	**Variables considered**	**Variable weighting and aggregation**	**Display of results**	**Target audience**
Dewulf et al. (2017) "Methodology for establishing the EU list of critical raw materials"	2017	EI = $$\Sigma_s(A_s * Q_s) * SIEI$$ where EI denotes economic importance, A_s denotes share of end use of raw material in a NACE sector, Q_s denotes each sector's value added at the NACE level and SIEI denotes the substitution index of a raw material related to economic importance. s denoted sector SIEI = $$\Sigma_i\Sigma_a SCP_{i,aa}{*}Subshare_{i,a}{*}Share_a$$ i denotes an individual substitute material, a denotes an individual application of the candidate material, SCP is the substitute cost performance parameter, Share is the share f the raw material in an application, and Sub-share is the sub-share of each substitute within each application.	Blank	Blank	European Union

Table A.2: HHI scores for metals studied

	Global				Japans Import partners			
Metal	2000	2005	2011	2015	2000	2005	2011	2015
Aluminum	783	1001	2044	3114	***	***	***	1230
Chromium	2308	2189	2327	2523	5388	4394	3372	3153
Cobalt	1375	2037	3054	2704	2678	1863	2399	2779
Copper	1557	1547	1373	1255	3027	2973	3105	2796
Gold	828	671	587	567	3324	2616	2193	1495
Iron	1185	1386	1766	1919	***	***	4734	4527
Lead	1335	1800	2842	2559	2910	3600	2498	3498
Lithium	2128	2710	5008	5790	4341	4674	3517	6359
Manganese	1257	1238	1433	1876	3793	8178	4256	3048
Molybdenum	2126	2231	2434	2263	3483	2920	3838	3607
Nickel	1275	1098	1272	1123	1646	2121	2596	3003
Niobium	7954	8260	8188	8064	8369	8558	9160	9669
Platinum	5537	6257	5592	5605	4010	6321	7050	6467
Rare-earths	6862	9382	8151	6678	3488	7001	4980	3710
Silver	840	942	1028	1038	2660	2242	5005	7530
Tungsten	7152	7620	7038	6723	6600	9392	4001	4679
Vanadium	4027	3311	3833	3717	4549	3412	3421	2608
Zinc	1073	1177	1466	1561	2356	1980	2221	2029

Table A.3: World Governance Indicators

Metal	World Governance Indicators 2000	2005	2011	2015
Aluminum	***	***	***	59.3
Chromium	46.8	63.6	53.0	47.4
Cobalt	82.1	83.0	79.3	79.8
Copper	59.3	60.1	60.7	61.2
Gold	***	73.4	77.7	79.0
Iron	***	***	66.9	74.8
Lead	51.8	54.3	65.6	54.2
Lithium	86.7	67.9	62.0	52.7
Manganese	62.2	60.4	62.4	53.5
Molybdenum	65.6	70.2	72.4	69.9
Nickel	68.3	67.3	58.5	67.6
Niobium	75.2	70.6	74.4	71.4
Platinum	73.8	58.5	64.2	65.5
Rare-earths	64.9	61.2	60.0	55.5
Silver	64.4	67.6	68.0	68.5
Tungsten	29.6	72.1	71.5	66.4
Vanadium	67.9	58.8	68.8	56.7
Zinc	65.0	58.9	62.8	56.3

Table A.4: Power generation from renewable energy sources(in TWh), and quantity of electric vehicles(in million) required between 2019-2070 to achieve a low carbon future. 1990-2018 is real historical data

Year	Wind	Solar	Geothermal	Hydro	Electric Vehicles
1990	3.9	0.1	36.4	2191.7	
1991	4.2	0.1	37.4	2268.6	
1992	4.6	0.1	39.3	2267.2	
1993	5.6	0.2	40.2	2397.7	
1994	7.3	0.2	41.1	2419.7	
1995	8.0	0.2	39.9	2545.9	
1996	9.5	0.2	42.2	2583.2	
1997	12.1	0.3	42.4	2614.4	
1998	16.1	0.4	45.4	2628.6	
1999	21.6	0.6	48.7	2636.5	
2000	31.3	0.8	52.2	2695.6	
2001	38.5	1.1	51.8	2638.3	
2002	52.9	1.4	52.4	2711.4	
2003	64.6	1.8	54.1	2725.7	
2004	84.9	2.5	56.5	2894.2	
2005	104.5	3.7	58.3	3019.5	
2006	133.7	5.3	59.6	3124.3	
2007	171.6	7.3	62.3	3166.7	
2008	221.9	11.7	64.9	3286.5	
2009	278.2	19.9	67.0	3339.6	
2010	342.2	32.0	68.1	3535.3	
2011	437.4	63.7	69.3	3595.5	
2012	525.6	98.8	70.3	3759.3	
2013	648.0	139.4	71.7	3890.3	
2014	718.2	190.2	77.5	3966.7	
2015	833.7	250.1	80.6	3982.2	
2016	962.9	329.5	82.2	4151.3	
2017	1132.8	444.4	85.3	4186.4	
2018	1273.4	554.4		4325.1	
2019	908.2	812.4	129.3	4000.0	1056.0
2020	1111.1	1070.4	151.3	3881.7	1104.0
2021	2137.0	1070.4	173.3	3305.5	1152.0
2022	2178.6	1200.9	195.3	3669.4	1200.8
2023	2236.8	1237.3	217.3	4008.4	1248.4
2024	2581.3	2246.5	239.3	4643.5	1273.5
2025	3163.6	2735.4	261.3	5225.7	1294.5
2026	4057.1	2492.8	283.3	5220.9	1333.0
2027	3755.5	3282.5	305.3	4933.0	1365.8
2028	3532.3	3526.9	327.3	4730.1	1399.9
2029	3338.3	3839.0	349.3	4987.1	1442.6

Table A.4 Continued

Year	Wind	Solar	Geothermal	Hydro	Electric Vehicles
2030	3901.2	4799.9	371.3	5089.6	1472.1
2031	4648.8	4625.7	393.3	5171.7	1495.0
2032	5415.3	4719.6	415.3	5606.4	1532.8
2033	6186.4	5098.8	415.9	5995.1	1569.5
2034	6108.5	5686.7	630.8	6102.6	1590.6
2035	5984.8	6218.2	789.7	6185.7	1614.5
2036	6305.8	6554.6	1078.7	6186.4	1646.9
2037	6630.1	7034.2	1101.0	6150.1	1661.4
2038	6843.8	7263.6	1240.6	5907.4	1675.9
2039	7323.2	7737.1	1436.3	6005.2	1690.4
2040	7436.8	8897.5	1622.4	6519.0	1706.4
2041	7896.6	9759.4	1731.6	7004.2	1723.3
2042	8442.7	9760.0	1961.9	6832.9	1741.2
2043	8994.3	9926.3	1939.0	6827.4	1748.6
2044	9489.3	10822.1	1682.0	7249.9	1747.7
2045	10158.0	11335.3	1415.3	7579.4	1742.8
2046	10968.6	11480.9	1229.2	7749.2	1742.7
2047	11236.7	11998.0	1512.8	7668.4	1740.0
2048	11139.6	12861.8	2040.2	7565.9	1730.2
2049	11072.4	13553.9	2869.9	7368.3	1710.9
2050	11304.8	14017.1	3383.6	7157.7	1693.0
2051	11558.0	14225.3	3544.2	7240.0	1661.3
2052	12108.2	14610.1	3176.0	7655.9	1620.2
2053	12761.1	14995.0	3048.7	7753.7	1581.5
2054	13190.5	15621.8	3066.4	7724.0	1533.3
2055	13415.3	16834.8	3240.3	7740.2	1479.7
2056	13668.9	17485.5	3294.6	7961.7	1427.6
2057	14186.5	17551.0	3134.5	8133.0	1380.1
2058	14685.5	18096.9	3134.5	8248.6	1342.0
2059	14516.4	18825.9	3372.7	8378.5	1296.4
2060	14320.5	19474.2	3568.6	8549.7	1250.8
2061	14469.2	20244.5	3764.6	8717.6	1205.3
2062	14863.6	21140.3	3789.1	8927.9	1159.7
2063	15695.9	21459.2	3246.6	9313.6	1114.1
2064	15999.8	21418.5	2812.7	9631.4	1068.5
2065	16081.3	22159.6	2752.1	9813.4	1023.0
2066	16434.3	22789.5	3035.6	9898.3	977.4
2067	16597.1	23054.1	3387.1	9898.3	931.8
2068	16679.2	23321.4	3499.1	9898.3	886.2
2069	16815.1	23586.9	3770.8	10013.5	840.7
2070	16937.6	23852.8	4002.5	10075.4	795.1

Table A.5: Historical production of metals studied in tonnes. Copper in 1000 tons

Year	Copper	Chromium	Nickel	Manganese	Molybdenum	Titanium	Lithium	Rare-earths
1990	10,780	12,959	974,000	9,080,000	127,000	1,720,000	162,588	60,100
1991	10,695	13,320	991,000	7,640,000	115,000	1,510,000	148,210	49,800
1992	10,801	10,953	981,000	7,470,000	108,000	1,640,000	148,478	57,000
1993	10,994	10,001	905,000	7,280,000	93,600	1,550,000	167,442	59,500
1994	11,660	9,570	895,000	7,190,000	104,000	1,510,000	170,295	56,800
1995	12,147	10,600	927,000	7,970,000	136,000	1,810,000	177,433	75,700
1996	12,401	12,190	954,000	8,180,000	126,000	1,830,000	213,651	80,600
1997	13,020	12,000	1,010,000	7,520,000	139,000	1,950,000	212,677	68,300
1998	13,405	12,600	1,040,000	6,950,000	135,000	2,050,000	178,334	70,200
1999	13,830	13,500	1,050,000	6,990,000	129,000	2,120,000	180,300	80,400
2000	15,191	13,700	1,110,000	6,960,000	134,000	2,010,000	204,457	92,700
2001	14,686	12,400	1,170,000	7,580,000	133,000	2,040,000	209,949	89,500
2002	15,037	13,000	1,210,000	7,800,000	121,000	2,050,000	219,005	93,000
2003	15,315	15,500	1,230,000	8,730,000	125,000	1,880,000	251,858	97,100
2004	16,650	17,000	1,280,000	9,350,000	159,000	1,880,000	257,573	101,000
2005	16,670	19,300	1,300,000	11,000,000	186,000	1,880,000	343,723	122,000
2006	16,969	20,000	1,350,000	11,500,000	187,000	2,160,000	394,448	137,000
2007	18,096	21,500	1,440,000	12,100,000	209,000	2,260,000	380,851	124,000
2008	18,110	21,500	1,390,000	12,900,000	221,000	2,250,000	386,693	128,000
2009	18,141	19,300	1,380,000	11,300,000	223,000	1,850,000	301,038	132,000
2010	19,331	22,000	1,440,000	14,800,000	247,000	2,340,000	480,721	99,500
2011	19,566	23,300	1,560,000	15,700,000	264,000	2,220,000	610,271	104,000
2012	20,118	24,000	1,810,000	15,500,000	259,000	2,300,000	634,129	105,000
2013	20,981	30,100	1,980,000	16,900,000	281,000	2,070,000	581,759	107,000
2014	22,750	30,600	2,000,000	16,400,000	305,000	1,930,000	620,655	125,000
2015	22,893	28,000	2,000,000	17,000,000	288,000	1,650,000	610,551	129,000
2016	23,200	34,400	1,930,000		278,000	1,730,000	656,784	129,000
2017	23,280	35,700			297,000	1,670,000	1,952,138	132,000

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APPENDIX B

SUPPLEMENTAL INFORMATION

Information in appendix B gives additional information about concentration of suppliers of metals resources and the specif statistics regarding the methodology.Specifically, it gives the goodness of fit test statistics for each metal, and the regression analysis statistics for the individual metals.

Table B.1: The uses of metals studied, the top producer countries of these metals, and the import partner countries for Japan

Metal	Main uses	Global (ore) production				Japans import partner country			
		2015		2018		2015		2018	
		Top 3 countries	Global Production share(%)	Top 3 countries	Global Production share(%)	Top 3 countries	% of total imports	Top 3 countries	%of total imports
Al	Transportation, (automobile, railway) Food containers, civil engineering, and construction,	Australia China Brazil	62	Australia China Guinea	65	Australia(28%) Russia(15%) Brazil(15%)	58	Australia(23%) Russia(19%) Saudi Arabia(11%)	53
Cr	stainless steel, heat resistant alloys,	South Africa Kazakhstan India	78	South Africa Kazakhstan India	82	South Africa (52%) Kazakhstan (37%) India(6%)	95	South Africa (48%) Kazakhstan(36%) India(10%)	94
Co	Li-ion battery, industrial cutting tools(carbide tool)	DR Congo Canada Russia	60	DR Congo Russia Cuba	74	Finland (45%) Canada (24%) Zambia(10%)	79	Finland (52%) Canada(22%) China(4%)	78
Cu	Electrical wires	Chile Peru China	47	Chile Peru China	47	Chile (48%) Canada (11%) Peru/Indonesia(11%)	70	chile (47%) Peru(16%) Indonesia(11%)	74
Au	Telecommunications equipment, machine parts,jewellery	China Australia Russia	30	China Australia Russia	31	South Korea(12%) Hong Kong(16%) Taiwan(9%)	37	South Korea (32%) Hong Kong(21%) Taiwan(9%)	68
Fe	Plain(Rolled) steel, Special(rolled)Steel, Casting	China Australia Brazil	79	China Australia Brazil	78	Russia (39%) South Korea (21%) South Africa (12%)	72	Russia (50%) South Africa (20%) Brazil (8%)	78
Pb	Lead acid battery	China Peru Australia	66	China Australia Peru	61	Australia (53%) USA(21%) Bolivia (14%)	88	Australia (29%) USA (25%) Peru (19%)	73
Li	Lithium-ion battery, electrolyte	Australia Chile Argentina	90	australia Chile China	90	Chile (78%) Argentina(17%) China (5%)	100	chile (74%) Argentina (17%) China (8%)	99

Table B.1 Continued

Metal	Main uses	Global (ore) production				Japans import partner country			
		2015		2018		2015		2018	
		Top 3 countries	Global Production share(%)	Top 3 countries	Global Production share(%)	Top 3 countries	% of total imports	Top 3 countries	%of total imports
Mn	Manganese steel, battery electrodes	China South Africa Australia	76	China South Africa Australia	70	south Africa (69%) Australia(24%) Gabon (7%)	100	south Africa (66%) Australia (21%) Gabon (14%)	100
Mo	Steel materials, pigments, catalysts	China Chile USA	78	China Chile USA	78	Chile (66%) USA(9%) Mexico (9%)	84	Chile (71%) USA (13%) Mexico (7%)	91
Ni	Stainless steel, NiMH battery, NiCd battery	Russia Phillipines Canada	45	Indonesia Phillipines N.Caledonia	53	Madagascar (22%) Canada(18%) South Africa (15%)	55	Australia (32%) Madagascar (22%) Canada (19%)	73
Nb	High tensile steel, stainless steel for automotive construction pipeline	Brazil Canada	99	Brazil Canada	99	Brazil (98%) Canada(1%) China (0.2%)	99	Brazil (98%) Canada (2%) China (0.18%)	100
Pt	Automotive catalyst, Jewelry,	South Africa Russia Zimbabwe	92	south Africa Russia Zimbabwe	92	South Africa(80%) USA(5.4%) Russia(3.2%)	89	South Africa (81%) USA(5%) Taiwan(3.5%)	90
Rare-earths	Motor magnets, glass polishing, exhaust gas catalyst phosphors	China Australia USA	95	China Australia USA	91	China(57%) Vietnam(13%) France(17%)	87	China(58%) Vietnam(17%) Malaysia(10%)	85
Ag	Photographic material(X-ray film, printing plate film, movie film,general color film),Electrical parts(connectors)	Mexico Peru China	49	Mexico Peru China	54	South Korea(87%) Mexico(4%) USA(3%)	94	South Korea(76%) Mexico(15%) USA(3%)	94
W	carbide tools, special steel, (for molds, castings)	China Vietnam Rwanda	89	China Vietnam North Korea	93	China(56%) Vietnam(44%) Germany(0.24%)	87	China(89%) Vietnam(11%) India(0.39%)	100

Table B.1 Continued

Metal	Main uses	Global (ore) production				Japans import partner country			
		2015		2018		2015		2018	
		Top 3 countries	Global Production share(%)	Top 3 countries	Global Production share(%)	Top 3 countries	% of total imports	Top 3 countries	%of total imports
V	Steel making additive, catalyst	China Russia south Africa	91	China russia South Africa	92	South Africa(43%) China(32%) Czech(19%)	94	South Africa(13%) China(41%) Czech(24%)	78
Zn	Galvanized steel sheet for automobiles, building materials, home appliances	China Peru Australia	59	China Australia Australia	54	Peru(22%) Bolivia(22%) Australia(26%)	70	Peru(29%) Bolivia(27%) Australia(17%)	73

Table B.2: Goodness of Fit Test for aluminum(Al)

Distribution	A.D.	P	LRT P
Normal	4.210	<0.005	
Box-Cox Transformation	0.264	0.686	
Lognormal	0.517	0.183	
3-Parameter Lognormal	0.336	*	0.266
Exponetial	0.411	0.615	
2-Parameter Exponential	0.417	>0.250	0.522
Weibull	0.329	>0.250	
3-Parameter Weibull	0.296	>0.500	0.273
Smallest Extreme value	8.061	<0.010	
Largest Extreme Value	1.878	<0.010	
Gamma	0.371	>0.250	
3-Parameter Gamma	0.331	*	0.287
Logistic	2.645	<0.005	
Loglogistic	0.431	0.243	
3-Parameter Loglogistic	0.433	*	0.983
Johnson Transformation	0.298	0.577	

Table B.3: Goodness of fit Test for iron(Fe)

Distribution	A.D	P	LRT P
Normal	4.657	<0.005	
Box-Cox Transformation	0.408	0.335	
Lognormal	0.408	0.335	
3-Parameter Lognormal	0.349	*	0.790
Exponetial	0.536	0.445	
2-Parameter Exponential	0.584	>0.250	0.137
Weibull	0.457	>0.250	
3-Parameter Weibull	0.341	>0.500	0.035
Smallest Extreme value	8.792	<0.010	
Largest Extreme Value	1.822	<0.010	
Gamma	0.514	0.225	
3-Parameter Gamma	0.384	*	0.037
Logistic	2.649	<0.005	
Loglogistic	0.325	0.250	
3-Parameter Loglogistic	0.433	*	0.619
Johnson Transformation	0.241	0.761	

Table B.4: Goodness of Fit Test for copper(Cu)

Distribution	A.D.	P	LRT P
Normal	3.812	<0.005	
Box-Cox Transformation	0.736	0.052	
Lognormal	0.566	0.136	
3-Parameter Lognormal	0.380	*	0.155
Exponetial	0.284	0.845	
2-Parameter Exponential	0.289	>0.250	1.000
Weibull	0.255	>0.250	
3-Parameter Weibull	0.274	>0.500	1.000
Smallest Extreme value	7.193	<0.010	
Largest Extreme Value	1.250	<0.010	
Gamma	0.274	>0.250	
3-Parameter Gamma	0.307	*	1.000
Logistic	2.023	<0.005	
Loglogistic	0.496	0.171	
3-Parameter Loglogistic	0.472	*	0.778
Johnson Transformation	0.256	0.712	

Table B.5: Goodness of fit Test for lead(Pb)

Distribution	A.D	P	LRT P
Normal	3.7910	<0.005	
Box-Cox Transformation	0.843	0.028	
Lognormal	0.843	0.028	
3-Parameter Lognormal	0.163	*	0.011
Exponetial	0.536	0.445	
2-Parameter Exponential	0.576	>0.250	1.000
Weibull	0.407	>0.250	
3-Parameter Weibull	0.430	>0.331	1.000
Smallest Extreme value	7.3211	<0.010	
Largest Extreme Value	1.013	<0.010	
Gamma	0.352	>0.250	
3-Parameter Gamma	0.376	*	1.000
Logistic	1.918	<0.005	
Loglogistic	0.357	0.250	
3-Parameter Loglogistic	0.173	*	0.219
Johnson Transformation	0.145	0.967	

Table B.6: Goodness of Fit Test for manganese(Mn)

Distribution	A.D.	P	LRT P
Normal	10.014	<0.005	
Box-Cox Transformation	0.183	0.907	
Lognormal	0.183	0.907	
3-Parameter Lognormal	0.204	*	0.281
Exponetial	3.433	0.003	
2-Parameter Exponential	3.797	>0.010	0.135
Weibull	1.315	>0.010	
3-Parameter Weibull	0.779	>0.045	0.001
Smallest Extreme value	14.655	<0.010	
Largest Extreme Value	4.324	<0.010	
Gamma	1.929	>0.005	
3-Parameter Gamma	1.314	*	0.001
Logistic	5.079	<0.005	
Loglogistic	0.152	0.250	
3-Parameter Loglogistic	0.185	*	0.121
Johnson Transformation	0.146	0.965	

Table B.7: Goodness of fit Test for nickel (Ni)

Distribution	A.D	P	LRT P
Normal	4.230	<0.005	
Box-Cox Transformation	0.535	0.163	
Lognormal	0.535	0.163	
3-Parameter Lognormal	0.305	*	0.197
Exponetial	0.328	0.771	
2-Parameter Exponential	0.332	>0.250	1.000
Weibull	0.312	>0.250	
3-Parameter Weibull	0.311	>0.500	0.777
Smallest Extreme value	8.803	<0.010	
Largest Extreme Value	1.259	<0.010	
Gamma	0.320	>0.250	
3-Parameter Gamma	0.326	*	1.000
Logistic	1.884	<0.005	
Loglogistic	0.414	0.250	
3-Parameter Loglogistic	0.388	*	0.803
Johnson Transformation	0.245	0.748	

Table B.8: Goodness of Fit test for molybdenum (Mo)

Distribution	A.D.	P	LRT P
Normal	5.862	<0.005	
Box-Cox Transformation	0.341	0.484	
Lognormal	0.341	0.484	
3-Parameter Lognormal	0.267	*	0.065
Exponetial	3.324	0.003	
2-Parameter Exponential	3.990	<0.010	0.141
Weibull	0.766	0.044	
3-Parameter Weibull	0.260	>0.500	0.001
Smallest Extreme value	8.572	<0.010	
Largest Extreme Value	3.828	<0.010	
Gamma	1.141	>0.008	
3-Parameter Gamma	0.444	*	0.000
Logistic	4.324	<0.005	
Loglogistic	0.456	0.215	
3-Parameter Loglogistic	0.319	*	0.033
Johnson Transformation	0.127	0.984	

Table B.9: Goodness of fit Test for niobium (Nb)

Distribution	A.D	P	LRT P
Normal	4.691	<0.005	
Box-Cox Transformation	0.485	0.213	
Lognormal	0.485	0.213	
3-Parameter Lognormal	0.236	*	0.082
Exponetial	1.448	0.034	
2-Parameter Exponential	1.428	>0.023	0.016
Weibull	1.410	<0.010	
3-Parameter Weibull	0.771	>0.047	0.003
Smallest Extreme value	5.767	<0.010	
Largest Extreme Value	2.747	<0.010	
Gamma	1.576	<0.005	
3-Parameter Gamma	1.004	*	0.006
Logistic	3.391	<0.005	
Loglogistic	0.367	0.250	
3-Parameter Loglogistic	0.181	*	0.058
Johnson Transformation	0.179	0.911	

Table B.10: Goodness of Fit test for platinum (Pt)

Distribution	A.D.	P	LRT P
Normal	3.269	<0.005	
Box-Cox Transformation	0.724	0.055	
Lognormal	0.387	0.375	
3-Parameter Lognormal	0.252	*	0.186
Exponetial	0.233	0.913	
2-Parameter Exponential	0.243	>0.250	1.000
Weibull	0.221	>0.250	
3-Parameter Weibull	0.246	>0.500	1.000
Smallest Extreme value	5.761	<0.010	
Largest Extreme Value	1.372	<0.010	
Gamma	0.241	>0.250	
3-Parameter Gamma	0.284	*	1.000
Logistic	2.059	<0.005	
Loglogistic	0.343	>0.250	
3-Parameter Loglogistic	0.333	*	0.843
Johnson Transformation	0.165	0.937	

Table B.11: Goodness of fit Test for zinc (Zn)

Distribution	A.D	P	LRT P
Normal	6.305	<0.005	
Box-Cox Transformation	0.444	0.275	
Lognormal	0.444	0.275	
3-Parameter Lognormal	0.318	*	0.084
Exponetial	1.336	0.047	
2-Parameter Exponential	1.374	0.033	1.000
Weibull	1.333	0.010	
3-Parameter Weibull	1.369	>0.500	1.000
Smallest Extreme value	9.837	<0.010	
Largest Extreme Value	2.234	<0.010	
Gamma	1.267	>0.005	
3-Parameter Gamma	1.384	*	1.000
Logistic	3.207	<0.005	
Loglogistic	0.186	>0.250	
3-Parameter Loglogistic	0.183	*	0.570
Johnson Transformation	0.145	0.966	

Table B.12: Goodness of Fit test for silver (Ag)

Distribution	A.D.	P	LRT P
Normal	4.401	<0.005	
Box-Cox Transformation	0.249	0.738	
Lognormal	0.449	0.268	
3-Parameter Lognormal	0.418	*	0.875
Exponetial	0.535	0.448	
2-Parameter Exponential	0.678	0.246	0.167
Weibull	0.315	>0.250	
3-Parameter Weibull	0.255	>0.500	0.028
Smallest Extreme value	6.733	<0.010	
Largest Extreme Value	1.921	<0.010	
Gamma	0.389	>0.250	
3-Parameter Gamma	0.250	*	0.016
Logistic	2.864	<0.005	
Loglogistic	0.388	0.250	
3-Parameter Loglogistic	0.585	*	0.445
Johnson Transformation	0.248	0.740	

Table B.13: Goodness of fit test for cobalt (Co)

Distribution	A.D	P	LRT P
Normal	6.979	<0.005	
Box-Cox Transformation	0.501	0.199	
Lognormal	0.501	0.199	
3-Parameter Lognormal	0.397	*	0.469
Exponetial	1.156	0.076	
2-Parameter Exponential	1.066	0.080	0.144
Weibull	1.172	<0.010	
3-Parameter Weibull	1.005	0.013	0.057
Smallest Extreme value	12.049	<0.010	
Largest Extreme Value	2.261	<0.010	
Gamma	1.158	0.008	
3-Parameter Gamma	1.045	*	0.122
Logistic	3.218	<0.005	
Loglogistic	0.333	>0.250	
3-Parameter Loglogistic	0.333	*	0.998
Johnson Transformation	0.298	0.573	

Table B.14: Goodness of Fit test for lithium (Li)

Distribution	A.D.	P	LRT P
Normal	5.609	¡0.005	
Box-Cox Transformation	1.688	<0.005	
Lognormal	1.688	<0.005	
3-Parameter Lognormal	0.697	*	0.040
Exponetial	1.025	0.107	
2-Parameter Exponential	1.027	0.081	1.000
Weibull	1.112	<0.010	
3-Parameter Weibull	1.113	0.007	0.819
Smallest Extreme value	9.479	<0.010	
Largest Extreme Value	1.193	<0.010	
Gamma	1.042	0.014	
3-Parameter Gamma	1.026	*	1.000
Logistic	1.796	<0.005	
Loglogistic	1.074	<0.005	
3-Parameter Loglogistic	0.539	*	0.163
Johnson Transformation	0.407	0.334	

Table B.15: Goodness of fit test for tungsten (W)

Distribution	A.D	P	LRT P
Normal	2.815	<0.005	
Box-Cox Transformation	0.450	0.264	
Lognormal	1.042	0.009	
3-Parameter Lognormal	0.381	*	0.090
Exponetial	0.447	0.553	
2-Parameter Exponential	0.418	>0.250	0.410
Weibull	0.335	>0.250	
3-Parameter Weibull	0.336	>0.500	0.702
Smallest Extreme value	6.478	<0.010	
Largest Extreme Value	0.566	0.150	
Gamma	0.320	>0.250	
3-Parameter Gamma	0.311	*	1.000
Logistic	1.215	<0.005	
Loglogistic	0.727	0.034	
3-Parameter Loglogistic	0.395	*	0.356
Johnson Transformation	0.230	0.796	

Table B.16: Goodness of Fit test for rare-earths (REE)

Distribution	A.D.	P	LRT P
Normal	4.185	<0.005	
Box-Cox Transformation	0.288	0.591	
Lognormal	0.288	0.591	
3-Parameter Lognormal	0.148	*	0.103
Exponetial	1.883	0.011	
2-Parameter Exponential	2.132	<0.010	0.209
Weibull	0.905	0.019	
3-Parameter Weibull	0.460	0.273	0.007
Smallest Extreme value	5.521	<0.010	
Largest Extreme Value	2.472	<0.010	
Gamma	1.222	0.005	
3-Parameter Gamma	0.722	*	0.005
Logistic	2.774	<0.005	
Loglogistic	0.256	>0.250	
3-Parameter Loglogistic	0.162	*	0.063
Johnson Transformation	0.128	0.981	

Table B.17: Goodness of fit test for gold (Au)

Distribution	A.D	P	LRT P
Normal	4.652	<0.005	
Box-Cox Transformation	1.112	0.006	
Lognormal	1.774	0.005	
3-Parameter Lognormal	0.283	*	0.001
Exponetial	0.715	0.260	
2-Parameter Exponential	0.578	>0.250	1.000
Weibull	0.557	0.159	
3-Parameter Weibull	0.505	0.214	1.000
Smallest Extreme value	6.964	<0.010	
Largest Extreme Value	1.852	<0.010	
Gamma	0.586	0.162	
3-Parameter Gamma	0.545	*	1.000
Logistic	2.865	<0.005	
Loglogistic	0.720	0.035	
3-Parameter Loglogistic	0.273	*	0.114
Johnson Transformation	0.232	0.791	

Table B.18: Goodness of Fit test for chromium (Cr)

Distribution	A.D.	P	LRT P
Normal	4.256	<0.005	
Box-Cox Transformation	0.282	0.624	
Lognormal	0.964	0.014	
3-Parameter Lognormal	0.636	*	0.229
Exponetial	0.541	0.438	
2-Parameter Exponential	0.467	>0.250	1.000
Weibull	0.292	>0.250	
3-Parameter Weibull	0.292	>0.500	1.000
Smallest Extreme value	8.949	<0.010	
Largest Extreme Value	1.180	<0.010	
Gamma	0.296	>0.250	
3-Parameter Gamma	0.293	*	0.548
Logistic	1.864	<0.005	
Loglogistic	0.795	0.022	
3-Parameter Loglogistic	0.791	*	0.982
Johnson Transformation	0.387	0.377	

Table B.19: Goodness of fit test for vanadium (V)

Distribution	A.D	P	LRT P
Normal	4.602	<0.005	
Box-Cox Transformation	0.340	0.485	
Lognormal	0.382	0.388	
3-Parameter Lognormal	0.368	*	0.876
Exponetial	1.467	0.033	
2-Parameter Exponential	1.462	0.024	1.000
Weibull	0.419	>0.250	
3-Parameter Weibull	0.325	>0.500	0.090
Smallest Extreme value	6.437	<0.010	
Largest Extreme Value	2.794	<0.010	
Gamma	0.573	0.174	
3-Parameter Gamma	0.405	*	0.043
Logistic	3.433	<0.005	
Loglogistic	0.359	>0.250	
3-Parameter Loglogistic	0.470	*	0.381
Johnson Transformation	0.271	0.661	

Table B.20: Regression Statistics for copper

Observations	28
R Square	0.8016
Adjusted R Square	0.7939
Intercept P-Value	5.8850E-16
X Variable P-Value	2.0458E-24

Table B.21: Regression Statistics for chromium

Observations	28
R Square	0.8996
Adjusted R Square	0.8957
Intercept P-Value	2.3464E-10
V Variable P-Value	1.7194E-14

Table B.22: Regression Statistics for nickel

Observations	27
R Square	0.9002
Adjusted R Square	0.8962
Intercept P-Value	6.9882E-08
X variable P-Value	5.0994E-14

Table B.23: Regression Statistics for manganese

Observations	26
R Square	0.8378
Adjusted R Square	0.8310
Intercept P-Value	7.7876E-07
X Variable P-Value	5.8163E-11

Table B.24: Regression Statistics for molybdenum

Observations	28
R Square	0.9112
Adjusted R Square	0.9078
Intercept P-Value	1.3781E-10
X Variable P-Value	3.4537E-15

Table B.25: Regression Statistics for titanium

Observations	28
R Square	0.1489
Adjusted R Square	0.1162
Intercept P-Value	1.0790E-03
X Variable P-Value	4.2559E-02

Table B.26: Regression Statistics for lithium

Observations	28
R Square	0.5377
Adjusted R Square	0.5199
Intercept P-Value	1.8245E-04
X Variable P-Value	9.0580E-06

Table B.27: Regression Statistics for rare-earths

Observations	28
R Square	0.8016
Adjusted R Square	0.7939
Intercept P-Value	5.7067E-05
X Variable P-Value	1.2704E-10