博士論文

Global Metal Cycles in a Carbon-Constrained World

（炭素制約下における世界規模の金属資源循環）

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東京大学大学院

新領域創成科学研究科　環境システム学専攻

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Doctoral Thesis

Global Metal Cycles in a Carbon-Constrained World

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Abstract

Climate change mitigation strategies could fundamentally alter future metal cycles through two drivers—implementation of decarbonization technologies and carbon constraints on production activities. The question thus arises as to how the global metal cycle will change in the future in a carbon-constrained world, and what interventions are needed to reconcile climate change mitigation with sustainable metal use. This thesis aims to provide scientific support for discussions in such areas through a series of analyses. After describing the research background in Chapter 1, Chapter 2 explores the state of research and research gaps by conducting a systematic review of more than 150 published studies. This review will serve to clarify the purpose and contribution of the thesis. The thesis is then divided into two main sections. The first (Chapters 3 and 4) examines the impact of deployed decarbonization technologies on the future global metal cycle, while the second (Chapters 5, 6, and 7) explores the impact of carbon constraints on the future global metal cycle. Together, these sections aim to model the *global metal cycles in a carbon-constrained world*.

Chapters 3 and 4 aim to identify the total extraction of materials, including mine waste, associated with the deployment of decarbonization technologies and the role of a circular economy in the energy transition. By linking global energy scenarios with material demand-supply models on a country-by-country basis, the analysis shows that the decarbonization of both the electricity and transport sectors will curtail fossil fuel production. However, paradoxically, this reduction in fossil fuel production is expected to increase material extraction associated with metal production by a factor of more than 7 by 2050 relative to 2015 levels. This substantial increase is primarily due to increases in the extraction of iron, copper, nickel, silver, tellurium, cobalt, and lithium used for the production of solar photovoltaics and electric vehicles (i.e., plug-in hybrid electric vehicles and battery electric vehicles). Specifically, around 70-95% of material extraction in 2050 is attributed to these metals and technologies. The analysis also shows that

approximately 32–40% of the increase in material extraction is expected to occur in countries with weak, poor, and failing resource governance, implying that there is a high risk of improper management of the extracted materials. Countries with high levels of material extraction and insufficient governance include DR Congo, Guatemala, Iran, Venezuela, Cuba, Madagascar, and Zimbabwe. The analysis confirms the considerable potential of circular economy strategies regarding such issues. However, implementing a suite of circular economy strategies, including lifetime extension, servitization, and recycling, will not entirely offset the concomitant increase in material extraction. Responsible sourcing will be required in areas where supply cannot be met by circular material flows. In the absence of such action from the consumption side, the decarbonization of the electricity and transport sectors may face an ethical conundrum in which global carbon emissions are reduced at the expense of an increase in socio-environmental risks at local mining sites. In this study, a series of analyses underscore the importance of proper management of extracted materials, which will increase rapidly following the deployment of decarbonization technologies.

Chapters 5, 6, and 7 clarify the scale and timing of the impact of carbon constraints on production activities on future metal flows and stocks. Chapter 5 first explores the historical flows and stock dynamics of six major metals (iron, aluminum, copper, zinc, lead, and nickel) in 231 countries and regions over a 110-year period using a newly constructed dynamic metal cycle model. The analysis shows that substantial inequality exists in international metal stocks. Notably, in terms of per capita metal use, the top 20% of the population accounts for 60-75% of the world's total metal stock, while the bottom 20% accounts for only about 1%. International inequality in metal stocks has decreased over time due to the strong growth in developing countries, mainly those in Asia. However, the analysis shows that the continued reduction of metal stock inequality through this growth-led pathway will lead to an increase in global metal demand by a factor of 2 to 3 by the mid-21st century. Building upon these results, Chapters 6 and 7 explore the impacts of carbon constraints on global metal flows and stocks using an optimization routine coupled with a dynamic metal cycle model. The analysis shows that, under carbon constraints, primary production of all six metals will peak by 2030, and secondary production will surpass primary production by at least 2050. Consequently, cumulative ore requirements over the 21st century will remain below currently identified resources, implying that natural ore extraction will be limited by carbon constraints before existing resources can be depleted. In this case, the global in-use metal stocks will converge from the current level of about 4 t/capita to about 7 t/capita, on average, which is lower than the 12 t/capita that is currently used in high-income countries. This implies a need for increased material efficiency to meet the same demand for goods and services with less metal use. Importantly, realizing such system changes will require urgent and concerted international efforts involving all countries, but specific responsibilities will vary according to income level. Wealthy countries will need to use existing metal stocks more intensively and for longer periods to reduce stock replacement demand, while poor countries will need to develop long-lasting and material-efficient infrastructure to curtail stock expansion demand in the first half of the 21st century.

Finally, Chapter 8 summarizes the highlights of the preceding chapters and presents an outlook for future study. The thesis highlights the need for proper management of the extracted materials along with the deployment of decarbonization technologies, and the need to improve material efficiency to meet basic needs using metals that can be produced and used under the existing carbon constraints. The synthesis of the findings also suggests that these interventions are strongly interconnected and that both need to be addressed simultaneously. The approach presented in this thesis can be extended to a broad range of materials, including cement, biomass, and plastic, and can thus contribute to exploring future scenarios for a wide array of materials.

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Attribution

Chapter 2:

- **Takuma Watari**, Keisuke Nansai and Kenichi Nakajima (2020) "Review of critical metal dynamics to 2050 for 48 elements" *Resource Conservation and Recycling*, 155, 104669
- **Takuma Watari**, Keisuke Nansai and Kenichi Nakajima (2021) "Major metals demand, supply, and environmental impacts to 2100: A critical review" *Resource Conservation and Recycling*, 164, 105107

Chapter 3:

- **Takuma Watari**, Benjamin McLellan, Damien Giurco, Elsa Dominish, Eiji Yamasue and Keisuke Nansai (2019) "Total material requirement for the global energy transition to 2050: A Focus on transport and electricity" *Resource Conservation and Recycling*, 148, 91-103

Chapter 4:

- **Takuma Watari**, Keisuke Nansai, Kenichi Nakajima and Damien Giurco (2021) "Sustainable energy transitions require enhanced resource governance" *Journal of Cleaner Production*, 312, 127698

Chapter 5:

- **Takuma Watari** and Ryosuke Yokoi (2021) "International inequality in in-use metal stocks: What it portends for the future" *Resources Policy*, 70, 101968

Chapter 6:

- **Takuma Watari**, Keisuke Nansai, Damien Giurco, Kenichi Nakajima, Benjamin McLellan and Christoph Helbig (2020) "Global metal use targets in line with climate goals" *Environmental Science and Technology*, 54, 12476–12483

Chapter 7:

- **Takuma Watari**, Keisuke Nansai and Kenichi Nakajima (2021) "Contraction and convergence of in-use metal stocks to meet climate goals" *Global Environmental Change*, 69, 102284

Contents

Chapter 1

Introduction

1.1 Metals and the environment

Metals are an integral part of modern life. Our basic needs, including shelter, mobility, communication, are all supported by the metals accumulated in society as buildings, machines, consumer goods, and infrastructure. Such contributions by metals to modern society are realized through a variety of functions, including mechanical (e.g., strength), thermal (e.g., high-temperature resistance), electrical/electronic (e.g., photoelectric conversion), and magnetic (e.g., ferromagnetic). Consequently, the primary input of metals to society increased 22-fold from 55 Mt to 1200 Mt between 1900 and 2010 (Krausmann et al., 2017). Over the same period, the global in-use stock of metals grew 32-fold from 1 Gt to 28 Gt, faster than the 27-fold increase in the global gross domestic product (GDP). The number of elements used in products is also increasing over time, with about 40 elements being used in modern energy technologies such as solar photovoltaics and wind turbines (Zepf et al., 2014). Clearly, the sustainable use of metals is the foundation of human activity.

While the use of metals has brought tremendous benefits to modern society, their production activities have caused various environmental problems, and significantly, the nature of these problems has changed over time. The main concerns in the 19th and 20th centuries were health hazards caused by local pollution such as water and soil contamination, especially in the context of today's high-income countries (Oosterhuis et al., 1996). Localized and immediate effects characterized these problems, and the victims and perpetrators of the impacts were apparent. Therefore, end-of-pipe measures that regulate the exit of the pollutants causing the individual issues worked effectively (Oosterhuis et al., 1996). On the other hand, global environmental problems such as climate change and resource depletion, which have been the primary concerns since the latter half of the 20th century and the beginning of the 21st century, are entirely different in nature from localized pollution. Namely, the causes and impacts of the problems are long-term and wide-ranging, and the victims and perpetrators of the effects are unspecified and numerous. Thus, it involves inter-generational and intra-generational equity issues, as the consequences extend to the next generation and other regions. Moreover, unlike localized pollution, where the pollutants directly affect the human body, this type of problem is characterized by indirect effects such as increased natural disasters due to global warming. All of these features limit the effectiveness of end-of-pipe strategies and pose fundamental sustainability challenges to humanity.

1.2 Climate change mitigation as a driver of future metal cycles

Climate change, in particular, will essentially threaten human survival. The climate system is already approaching a critical point that triggers irreversible large-scale changes (Steffen et al., 2015), impacting multiple domains, including ecosystems, water, and food (Yokohata et al., 2019). In response, the Intergovernmental Panel on Climate Change (IPCC) has pointed out that averting devastating climate change impacts will require limiting global temperature rise to within 1.5-2 °C compared to pre-industrial levels (IPCC, 2018, 2014). This challenge will require deep reductions in greenhouse gas (GHG) emissions, dominated mainly by carbon dioxide (CO_2), during this century.

In this context, metals play two crucial roles. The first is to reduce GHG emissions from the production process. Despite significant efforts to improve energy efficiency in the metals industry (Wang et al., 2021), increased production has led to an increase in GHG emissions associated with metal production from 1.9 Gt-CO_2e in 1995 to 4.4 Gt-CO_2e in 2016 (Figure 1- 1) (Hertwich, 2021). Consequently, its share of overall GHG emissions increased from 7% to 11% over the same period. A deep and rapid reduction in GHG emissions from metal production is clearly a fundamental condition for achieving the climate goal.

The second important role is to support the functionality of decarbonization technologies. According to the International Energy Agency (IEA) (IEA, 2017), approximately 60% of the expected CO_2 emissions reduction by 2060 is projected due to the electricity and transport sectors. Such massive decreases will be made possible by the massive introduction of decarbonization technologies such as renewable energy and electric vehicles, which utilize a wide range of metals in vast quantities (Zepf et al., 2014). That is, the success of effective climate change mitigation strongly depends on a stable supply of metals needed for the decarbonization of these sectors.

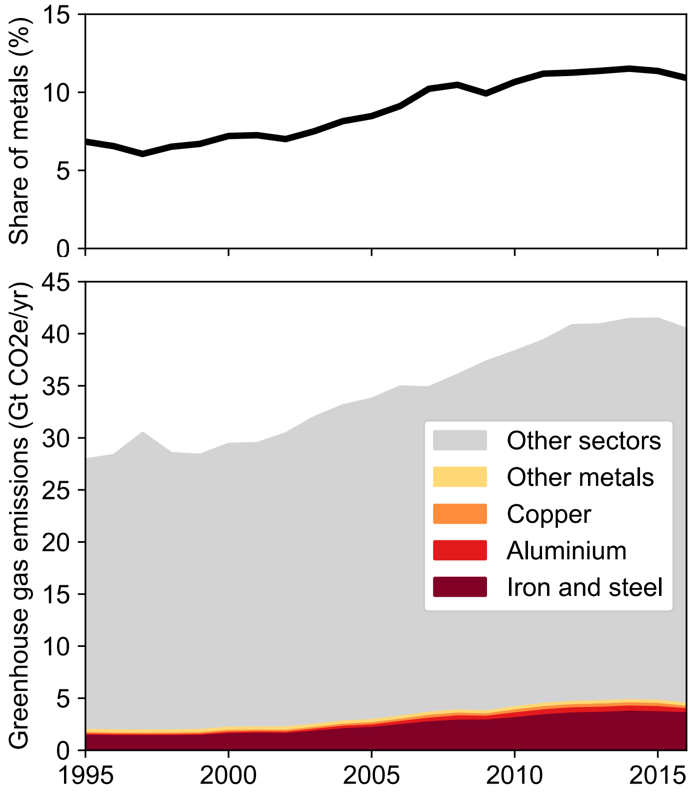

Figure 1- 1 GHG emission from metal production, 1995-2016. (Data: Hertwich (2021))

These perspectives suggest that carbon constraints and decarbonization technology deployment as key mitigation strategies for climate change could be the main drivers of future metal cycles. The key questions here are: How will the global metal cycle change in the future in a carbon-constrained world? What are the necessary conditions for climate change mitigation supported by sustainable metal use?

1.3 Systems modeling approach

One important approach to support the discussion in this domain, which requires a global scale and long-term perspective, is systems modeling. Systems modeling is a suitable tool for understanding the flow of materials and energy in society and identifying the interactions among the system elements to extract the critical variables for problem-solving. There is a long history of this type of approach focusing on resource depletion, which has been used to evaluate the peak year of oil production and identify the limits of economic growth based on mass production and consumption (Hubbert, 1956; Meadows et al., 1972). However, these models do not capture the relevance of the climate change perspective. While various energy system models fill this gap, they do not capture the physical interconnection in the series of metal cycles, including material production, manufacturing, in-use stock, and recycling (Pauliuk et al., 2017). In addition, most non-ferrous metals, which are essential for emerging technologies, are not included in the analysis, resulting in limited implications for sustainable metal use.

These challenges can be overcome by material flow analysis, which quantifies the flow and stock of materials throughout the material cycles based on the law of mass conservation at defined boundaries and times (Graedel, 2019). In particular, dynamic material flow analysis, which analyses material cycles over a long period, can encompass all aspects of temporal and spatial expansions, climate change mitigation strategies, and physical linkages in material cycles (Pauliuk and Müller, 2014). Thus, the approach in this thesis employs the principles of dynamic material flow analysis.

1.4 Scope of the thesis

The thesis aims to model the global metal cycles in a world where large-scale decarbonization technologies have been deployed, and strict carbon constraints on production activities have become apparent. This objective is achieved through an approach based on the principles of dynamic material flow analysis. Chapter 2 examines the state of research and research gaps by conducting a systematic review of existing studies in this domain. This review will serve to clarify the purpose and contribution of the thesis. The thesis is then divided into two main sections. The first (Chapters 3 and 4) examines the impact of deployed decarbonization technologies on the future global metal cycle, while the second (Chapters 5, 6, and 7) explores the impact of carbon constraints on the future global metal cycle. Finally, Chapter 8 brings together the highlights of the preceding chapters in a summary and presents an outlook for a prospective study. Together, these sections aim to model the *global metal cycles in a carbon-constrained world*.

Chapter 2

State of research and research gaps

This chapter explores the state of research and research gaps, focusing on (1) the impact of decarbonization technology deployment on the metal cycle and (2) the impact of carbon constraints on production activities on the metal cycle. The findings should provide a better understanding of the current situation and highlight previously overlooked viewpoints in existing studies.

2.1 Decarbonization technology and metal cycles

In assembling the information for literature review in this area, an attempt was made to compile a comprehensive list of long-term outlook studies that have examined the future cycles of metals and metalloids (hereafter termed "metals" for simplicity of exposition). The resulting review contains articles published between 1998 and June 2019 that were identified in search of two databases—Web of Science and Scopus—using the keywords "critical", "metal", "material", "demand", "material flow analysis", "scenario", "availability", "dynamic", "long-term", and "outlook". These keywords were selected subjectively to search for articles that matched the scope of this study. From the searched articles that were produced, papers were screened for review based on the following selection criteria: (1) the paper provides an analysis of future status (after 2020), not just the past, (2) the paper considers energy technology-driven scenarios for metals rather than superficial relationships between economic activities and metal demand, (3) the paper is a peer-reviewed journal article. Among the various sectors and related technologies in the decarbonization process, this section focuses on electricity and automotive technologies because of their significant contribution to decarbonization (approximately 60% of the expected CO_2 emissions reduction by 2060 is projected due to the electricity and transport sectors (IEA, 2017)).

2.1.1 Overview and trends

In all, 88 studies were selected, covering a total of 50 metals. Of the 88 studies, 77% investigate future metal cycles globally; the rest focus on the national and regional levels, including the U.S. (6%), Europe (6%), and China (4%). Temporal scales range from 2020 to 2200, with 12% of the studies providing analysis through 2030 and 52% giving analysis through 2050. Figure 2- 1 shows a drastic increase in the number of publications in this domain, especially over the last decade. The most significant number of publications were related to lithium and neodymium, followed by dysprosium, tellurium, copper, platinum, gallium, aluminum, cadmium, cobalt, and nickel.

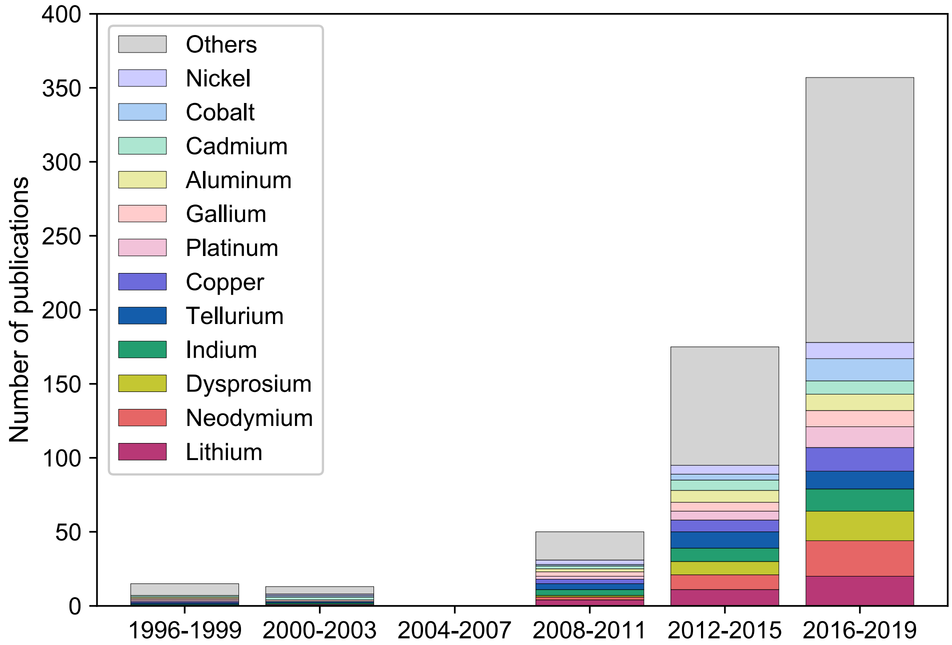

Figure 2- 1 Number of publications on the long-term outlook for the metal cycles associated with decarbonization technology deployments.

When looking at the number of studies by technology type (Figure 2- 2), metals related to solar photovoltaics (PV), wind power, and electric vehicles (EVs) have been investigated more than other technologies. This is perhaps due to the fact that these are the leading technologies for decarbonization (IEA, 2017), leading to deeper concerns regarding metal supply constraints. However, other technologies such as concentrated solar power, fuel cells, and biomass power plants are also expected to increase their capacity significantly over time. Thus, the trends here indicate that an analysis encompassing comprehensive decarbonization technologies remains an important area for further research.

In Figure 2- 2, the metals are arranged in order of decreasing criticality from the left, based on a criticality evaluation at the global level using the Yale University methodology (Graedel et al., 2015). Criticality determines which metals that flow through industry or economy have the highest supply risk, environmental impact, and vulnerability to supply restriction. Together with this information, a closer look reveals that most high criticality metals used in solar PV, such as indium, silver, and selenium, are well-explored. However, metals such as platinum used as a coating for panel glass and lead with high toxicity are less frequently investigated. On the other hand, analyses in the case of wind and EVs tend to focus on metals with relatively low criticality elements such as lithium, leading to the possibility of overlooking higher criticality metals. With regard to fuel cells, interest has been concentrated on platinum, with little attention paid to high criticality metals such as rhenium. There are also many studies on copper in nuclear, geothermal, and biomass power plants. Importantly, these trends indicate the potential lack of understanding of the impacts of the large-scale deployment of decarbonization technologies on the comprehensive metal cycle.

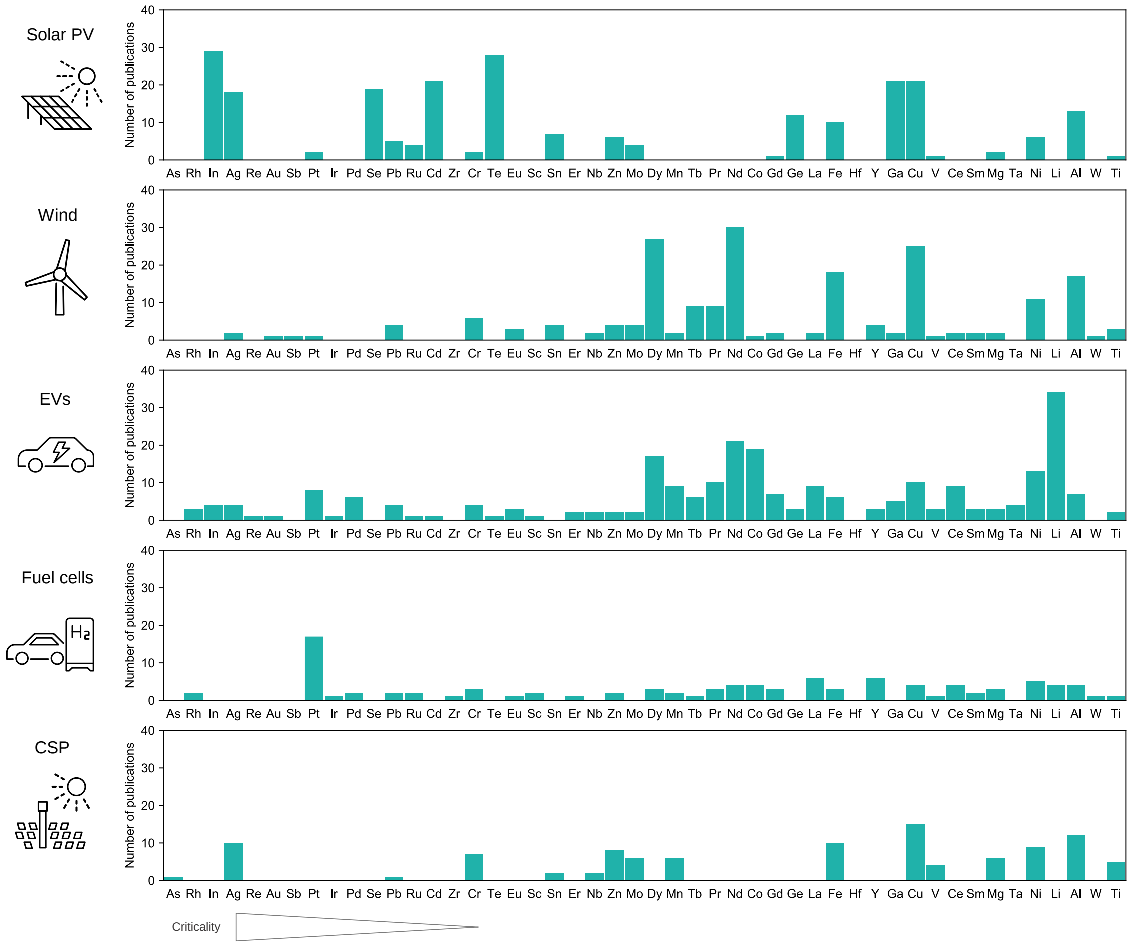

Figure 2- 2 Number of publications related to metal outlook by considered technology type. Ten technologies are included: solar photovoltaics (PV), wind power plant, electric vehicles (EVs), fuel cells, concentrated solar power (CSP), nuclear power plant, geothermal power plant, biomass power plant, carbon capture and storage (CCS) and storage battery. The metals are arranged in order of decreasing criticality from the left, based on a criticality evaluation at the global level using the Yale University methodology (Graedel et al., 2015). Criticality determines which metals that flow through industry or economy have the highest supply risk, environmental impact, and vulnerability to supply restriction.

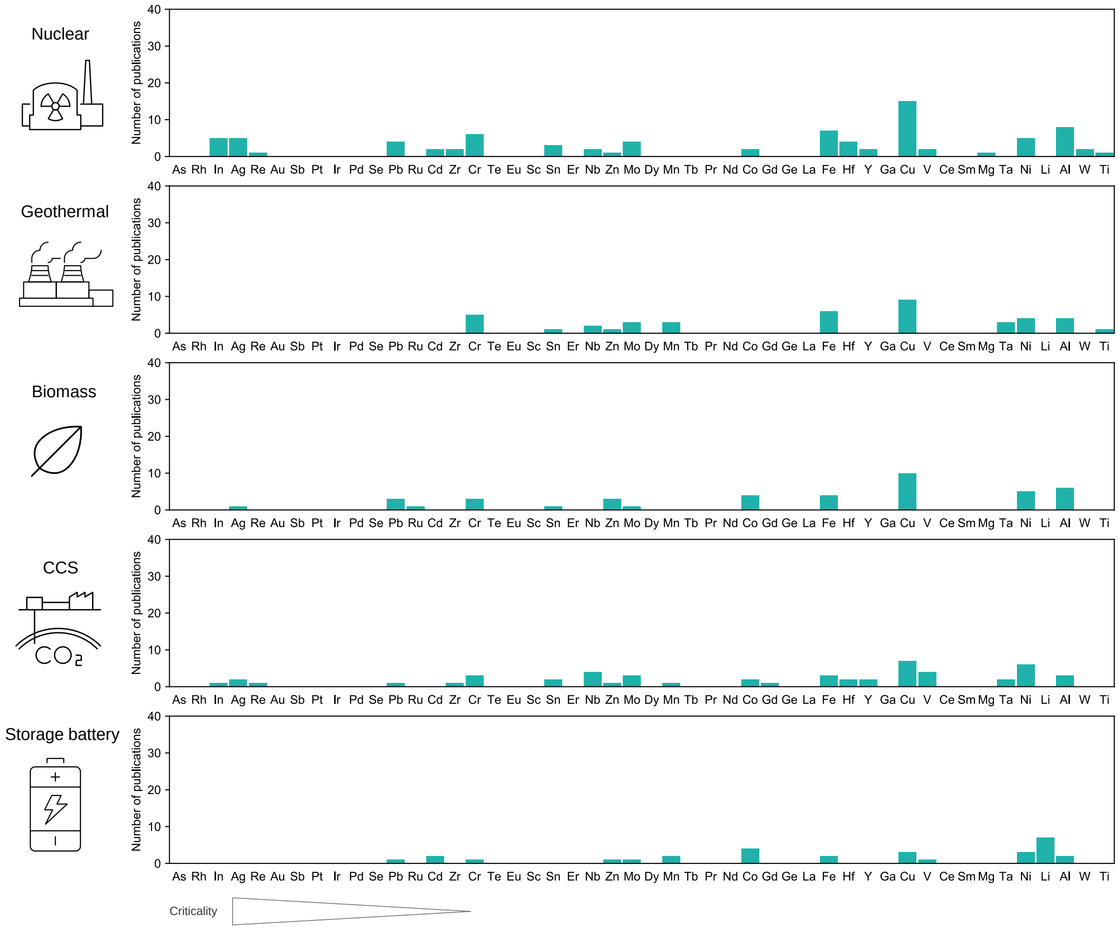

Figure 2-2 Continued.

2.1.2 Limited knowledge of total extracted materials to be managed

Figure 2- 3 summarizes the estimated metal demand through 2030 and 2050 on a global scale, with 546 data points covering 22 metals. Overall, the number of data points that could be collected varies widely, with lithium at a maximum of 67, followed by indium at 54, dysprosium at 52, and neodymium at 45. Metals used for thin-film solar PV, such as tellurium, selenium, and gallium, have many data points for decarbonization technologies. All these data give an essential perspective on how future metal demand will change over time with the energy transition involving the mass deployment of various decarbonization technologies.

However, a significant research gap is the lack of understanding of the total amount of materials to be managed, including hidden flows such as mine wastes. As shown in Figure 2- 3, while the existing studies vigorously captured the quantities of metals directly used for decarbonization technologies, none of them quantified the total extracted materials to be managed, including stripped soil and sediment disposed of in the mining and processing stages. This deficit in our understanding will likely mask the total amount of materials that need to be carefully managed along with the energy transition, which can lead to increased risk of various adverse impacts such as destructive tailings dam failure, soil contamination, and supply disruptions due to inappropriate management (Lèbre et al., 2019; Mancini and Sala, 2018). A critical step for responsible management is understanding how the extracted materials will change over time and which technologies and metals will drive it. Such information will allow decision-makers to discuss "hot spots" where priority measures should be taken.

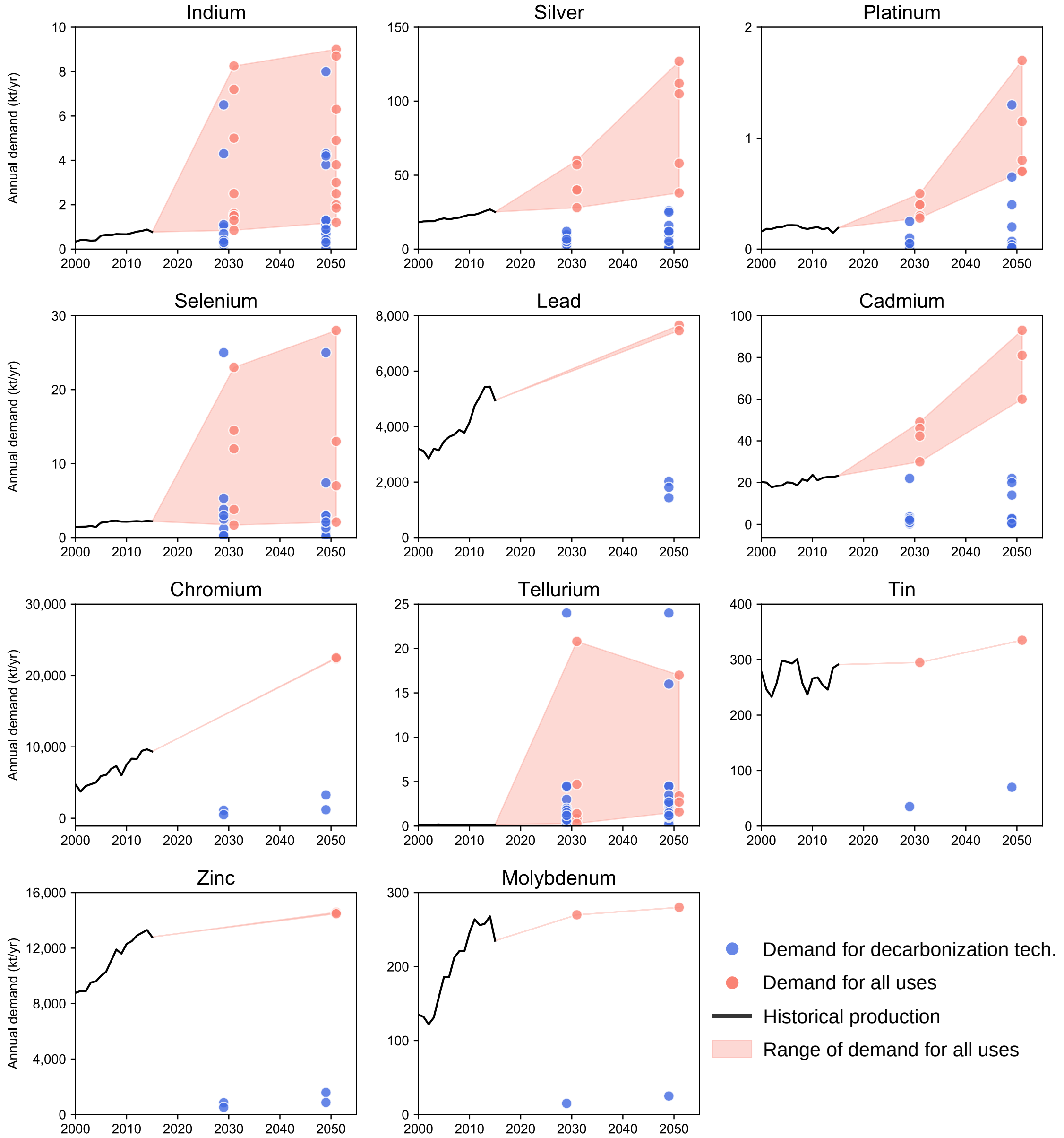

Figure 2- 3 Summary of estimated metal demand through 2030 and 2050 at the global scale; 546 data points are included. Twenty-two metals for which data could be obtained are presented for all end-uses and decarbonization technologies.

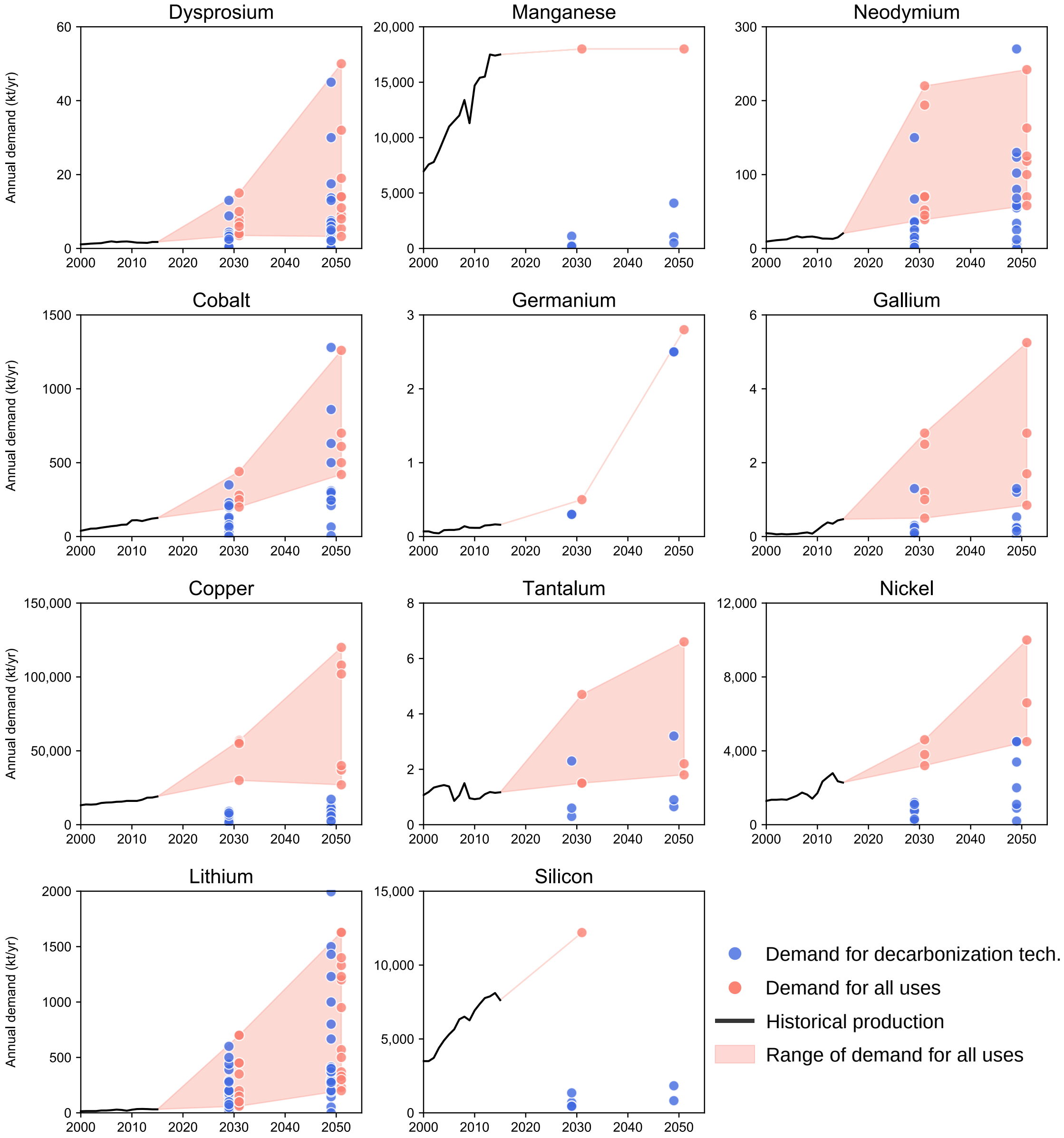

Figure 2- 3 Continued.

2.1.3 Limited regional resolution in mining activities

Another limitation of the previous studies is that they largely lack the geographical resolution to identify which countries will support the global energy transition through material extraction. Without this information, it is challenging to discuss areas of concern where interventions will be most needed (Lèbre et al., 2020). Only 9 of the 88 studies have a regional resolution for mine development (Table 2- 1), and all of them are analyzed for a single metal (e.g., lithium, indium, rare earth elements). As mining countries include various developing and low-income countries with lower environmental awareness and regulations (Natural Resource Governance Institute, 2017), scientific support for formulating a proper framework and establishing mutual relationships between consuming and producing countries is essential for responsible materials management. Thus, there is a need to identify the regions where the metals needed for decarbonization technologies could be mined in the future to extract areas of particular concern.

Table 2- 1 Modelling approaches implemented in the reviewed articles for estimating mine development by region and its target metals.

References	Target metal	Modeling approach
(Liu et al., 2019)	Lithium	System dynamics
(Sun et al., 2019)	Lithium	System dynamics
(Imholte et al., 2018)	Rare Earths	System dynamics
(Choi et al., 2018)	Indium	Genetic mixed-integer linear programming
(Olivetti et al., 2017)	Lithium	Regression analysis
(Roelich et al., 2014)	Neodymium	Regression analysis
(Miedema and Moll, 2013)	Lithium	Regression analysis
(Hoenderdaal et al., 2013)	Dysprosium	Data from industry reports
(Mohr et al., 2012)	Lithium	Scheduling model

2.1.4 Limited scope for circular economy strategy

The expectations of many studies regarding the circular economy strategies required for sustainable material use are very high (Stahel, 2016); however, despite the potential of the circular economy, empirical analyses of its effect have been heavily biased toward end-of-life (EoL) recycling. Consequently, a full range of other possibilities, such as reuse, remanufacturing, and servitization, have been overlooked (Figure 2- 4).

Figure 2- 4 shows a wheel diagram demonstrating the number of times each circular economy strategy has been investigated; the most explored elements appear in the inner circle. With reference to previous studies (Dominish et al., 2018; Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017), this study summarized the following main circular economy strategies: recycling, reusing, remanufacturing, lifetime extension, and servitization. Alarmingly, there is little attention given to reuse, remanufacturing, lifetime extension, and servitization, while recycling is heavily examined as circular economy strategies. With respect to each of the various elements, metals related to batteries and motors, including lithium and neodymium, have been widely examined in studies involving the recycling strategy. A relatively few studies explicitly deal with other strategies, including component reuse and remanufacturing. As an exception, Busch et al. (2014) quantitatively evaluate the effect of component reuse and remanufacturing by constructing a dynamic model with multiple layers of infrastructures, technologies, and materials. The significance of this attempt is that it clearly distinguishes recycle, reuse, and remanufacturing and handles these quantitatively in the model. In the case of indium tin oxide (ITO) manufactured using the sputtering method, Werner et al. (2018) found that a large amount of process loss occurs, resulting in a much smaller indium content in the final product relative to the inputs into the manufacturing process. In this case, perhaps more attention should be given to improving the recovery rate of process scrap in each life cycle rather than end-

of-life recycling accompanied by a substantial amount of energy consumption and waste liquid.

These trends suggest a limited scope in strategy considerations. Namely, most of the existing studies restrict potential strategies to only recycling at the analysis design stage. Little attention is given to assessing the full range of opportunities that span the entire life cycle. The omission of other possibilities prevents decision makers from understanding the true potential and/or limitations of circular economy strategies. What is needed is a comprehensive and comparative assessment of various potential strategies to design a strategic mix for sustainable metal use.

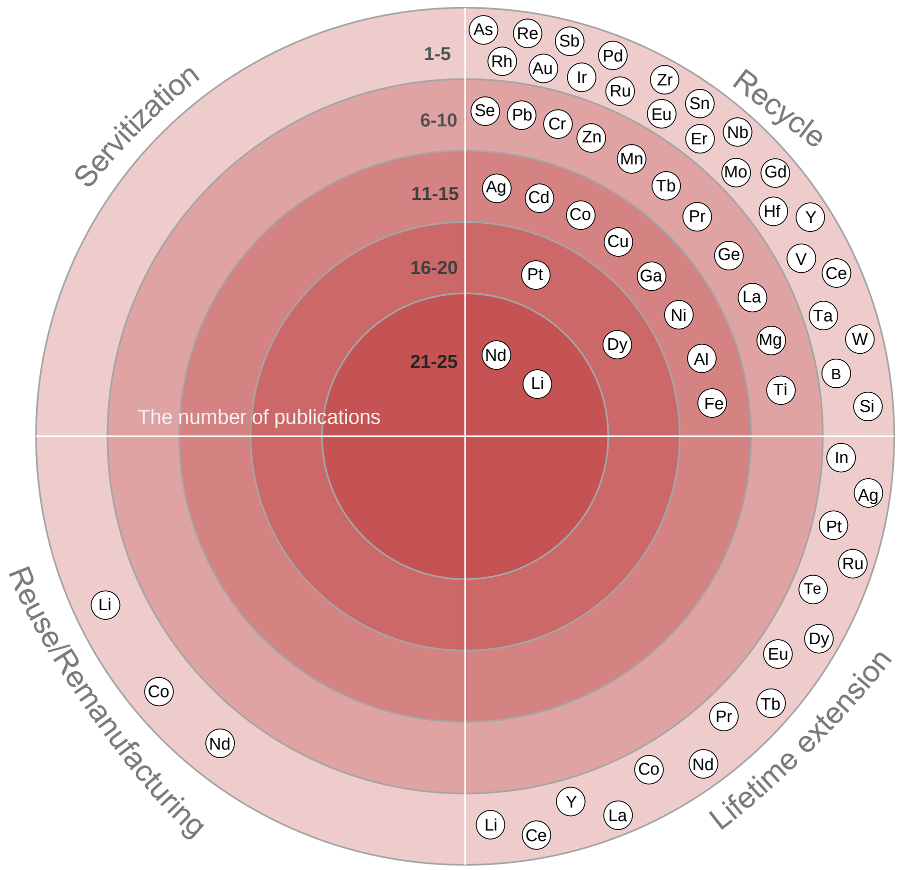

Figure 2- 4 Wheel diagram indicating the number of publications covering each circular economy strategy; the most explored elements appear in the inner circle.

2.1.5 Summary of research gaps

The critical review revealed a rapid increase in the publication of scientific articles in this domain. However, existing studies have the following important, yet seemingly not well addressed, challenges: (I) they overlook the total amount of materials to be managed, including hidden flows such as mine waste, (II) they largely lack the geographical resolution to identify which countries will support the global energy transition through material extraction, and (III) they scarcely model the effects of key circular economy strategies such as lifetime extension and servitization. Closing these research gaps is critical to exploring the interventions needed to reconcile climate change mitigation with the sustainable use of metals. Accordingly, Chapters 3 and 4 address these issues to identify the total extraction of materials, including mine waste, associated with the deployment of decarbonization technologies and the role of a circular economy in the energy transition.

Table 2- 2 List of articles that were subjected to systematic review.

References	Hidden flows	Regional resolution of mining activities	A series of circular economy strategies
(Elshkaki and Shen, 2019)			
(Liu et al., 2019)		✓	
(Shammugam et al., 2019)			
(Hache et al., 2019)			
(Fishman and Graedel, 2019)			
(Li et al., 2019)			
(Moreau et al., 2019)			
(Beylot et al., 2019)			
(Sun et al., 2019)		✓	
(Tokimatsu et al., 2018)			
(Valero et al., 2018b)			
(Valero et al., 2018a)			
(Månberger and Stenqvist, 2018)			
(Li and Adachi, 2019)			✓
(Watari et al., 2018)			
(Imholte et al., 2018)		✓	
(Deetman et al., 2018)			
(Ziemann et al., 2018)			
(de Koning et al., 2018)			
(Fishman et al., 2018)			
(Schipper et al., 2018)			
(Harvey, 2018)			
(Choi et al., 2018)		✓	
(Zhou et al., 2017)			
(Olivetti et al., 2017)		✓	
(Tokimatsu et al., 2017b)			
(Davidsson and Höök, 2017)			
(Vidal et al., 2017)			
(Martin et al., 2017)			
(Jasiński et al., 2018)			
(Busch et al., 2017)			✓
(Pavel et al., 2017)			
(Pehlken et al., 2017)			
(Sverdrup, 2016)			✓
(Zhang et al., 2016)			
(Nassar et al., 2016)			
(Choi et al., 2016)			
(Løvik et al., 2016)			
(Schulze and Buchert, 2016)			
(McLellan et al., 2016)			
(Grandell et al., 2016)			✓
(Rollat et al., 2016)			
(Simon et al., 2015)			

References	Hidden flows	Regional resolution of mining activities	A series of circular economy strategies
(Elshkaki and Graedel, 2015)			
(Kavlak et al., 2015a)			
(Kim et al., 2015)			
(Viebahn et al., 2015)			
(Elshkaki and Graedel, 2014)		✓	
(Davidsson et al., 2014)			
(Stamp et al., 2014)			✓
(Richa et al., 2014)			
(Busch et al., 2014)			
(Bustamante and Gaustad, 2014)			
(Habib and Wenzel, 2014)			
(Speirs and Contestabile, 2014)			
(Roelich et al., 2014)		✓	
(Houari et al., 2013)			
(Vidal et al., 2013)			
(Elshkaki and Graedel, 2013)			
(Elshkaki, 2013)			
(Fizaine, 2013)			
(Miedema and Moll, 2013)		✓	
(Vikström et al., 2013)			
(Moss et al., 2013)			
(Rademaker et al., 2013)			
(Hoenderdaal et al., 2013)		✓	
(Zimmermann et al., 2013)			
(Ravikumar and Malghan, 2013)			
(Hatayama et al., 2012)			
(Mohr et al., 2012)		✓	
(Kushnir and Sandén, 2012)			
(Pihl et al., 2012)			
(Fthenakis, 2012)			
(García-Olivares et al., 2012)			
(Alonso et al., 2012a)			
(Alonso et al., 2012b)			
(Zuser and Rechberger, 2011)			
(Sun et al., 2011)			
(Gruber et al., 2011)			
(Wanger, 2011)			
(US Department of Energy, 2011)			
(Kleijn et al., 2011)			
(Kleijn and Van Der Voet, 2010)			
(Yaksic and Tilton, 2009)			
(Fthenakis, 2009)			
(Andersson and Råde, 2001)			
(Andersson, 2000)			
(Andersson et al., 1998)			

2.2 Carbon constraints and metal cycles

This section reviews extant information on the long-term scenario analysis for future metal cycles, focusing on carbon emissions from the production process. Among the various metals and their unique applications, the focus is on iron, aluminum, copper, zinc, lead, and nickel—which account for more than 98% by mass of all metal production (U.S. Geological Survey, 2020). They are also responsible for approximately 95% of the GHG emissions associated with the production of all metals (Hertwich, 2021).

General articles in this area were collected using two databases: Web of Science and Scopus. This study firstly extracted the articles published from 1995 to May 2020 using the keywords "metal", "material", "mineral", "demand", "supply", "environmental", "material flow analysis", "scenario", "availability", "dynamic", "long-term", and "outlook". These keywords were selected subjectively to search for articles that matched the scope of this study. The retrieved articles were then screened using the following criteria: (1) the study provides an analysis of future status (after 2020), not just historical trends, (2) the study covers a comprehensive sector that drives future metal flows and stocks rather than specific limited products, (3) the study is a peer-reviewed journal article. For the selected articles, basic information, including target metals, geographical boundaries, and temporal scale, were collected. This study also organized the modeling approaches employed in each study based on a previous review article summarizing the methodologies used in dynamic material flow analysis (Müller et al., 2014).

2.2.1 Overview and trends

Figure 2- 5 shows a drastic increase in the number of publications on long-term scenarios for major metals, especially over the last five years. The most significant number of publications were related to iron, followed by copper, aluminum, zinc, nickel, and lead. Of the 70 studies selected, 73% explored future scenarios globally; the remaining 27% of studies focused on national and regional levels, including China (19%) and the U.S. (3%). Temporal scales ranged from 2030 to 2400, with 51% of the selected studies providing analyses through 2050 and 24% providing analyses through 2100.

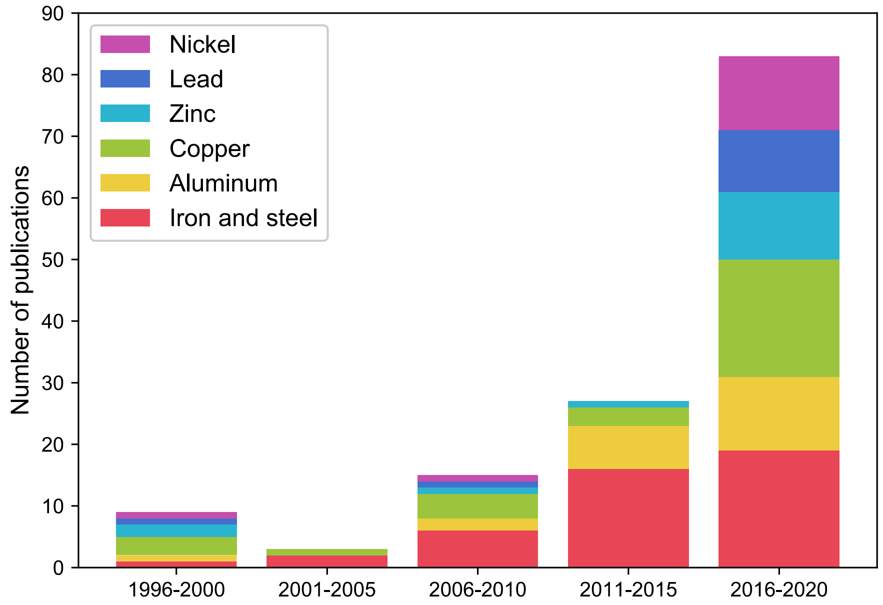

Figure 2- 5 Number of publications on the long-term outlook for major metal cycles.

From these studies, this study obtained a total of 197 data points indicating future major metal demand for the years 2030, 2050, and 2100 at a global scale (Figure 2- 6). The key finding here was that the demand for all major metals, except lead, is likely to increase continuously over the 21st century. Based on the median of the data points, the largest growth rate in 2050 relative to 2010 can be seen in aluminum (215%), followed by copper (140%), nickel (140%), iron (86%), zinc (81%), and lead (46%). This study can also confirm that demand for all major metals, except lead, is expected to increase continuously by the end of this century, with the largest growth rate for aluminum (470%), followed by copper (330%), zinc (130%), and iron (100%). In this case, demand for nickel by 2100 could not be inferred from existing studies. These results imply that demand for major metals is likely to increase by 2-6-fold over the 21st century in a 'business as usual' scenario, which does not consider environmental constraints.

Clearly, projected metal demands are subject to significant uncertainties due to various factors, including methodology choices, assumed socio-economic variables, and the year used to initiate projections. This study found that two general modeling approaches were used to estimate future demand—inflow-driven and stock-driven approaches. Inflow-driven approaches attempt to determine directly future metal demand or inflows by using socio-economic variables, such as GDP and urbanization. This method includes regression models, specific growth rate models, logistic consumption models, intensity of use models, computable general equilibrium models, constant consumption models, and linear consumption models (see Table 2- 3 for correspondence between existing studies and each model). All of these methods try to explain directly future metal inflows based on socio-economic parameters.

On the other hand, the stock-driven approach is based on the concept that future metal inflows are driven by stock dynamics. Therefore, this approach first estimates the future stock growth based on the per capita stock saturation or the relationship with socioeconomic variables and then explores the future inflows required to create that stock growth. Of the 65 studies that projected future demand, 43 (66%) employed an inflow-driven approach, 17 (26%) employed a stock-driven approach, and the remaining five (8%) utilized both approaches.

Although it is challenging to verify the impact of different model choices on outcomes and their validity, Schipper et al. (2018) pointed out that each approach has its advantages and disadvantages. Namely, long-term scenarios, such as those undertaken in studies that estimated future demand by the year 2100 using the inflow-driven approach, may lead to overestimating future demand due to the lack of mechanistic explanations of the metal cycle and service provision. Conversely, the stock-driven approach can capture such mechanisms, although it tends to be data-intensive, making it difficult to conduct the analysis efficiently. For example, steel demand in 2100 estimated by the stock-driven approach is in the range of 2,200-2,500 Mt (Morfeldt et al., 2015; Pauliuk et al., 2013a; Xylia et al., 2018), while the median value estimated by the inflow-driven approach is approximately 4,200 Mt (Morfeldt et al., 2015; Van der Voet et al., 2019; Vuuren et al., 1999). Based on the comparative analysis of the inflow-driven and stock-driven approach, Schipper et al. (2018) conjectured that the stock-driven approach could give a more reliable picture in the long run.

In addition, most of the inflow-driven approaches do not quantify the stock phase, where metals are retained in society as products and infrastructure, and thus provide little insight into the use of metals in society (Pauliuk and Müller, 2014). Unlike energy, which acts only at the moment of consumption, metals continue to function as long as they remain in society as products and infrastructure. From this perspective, Hatayama et al. (2010) point out that it is vital to capture both the flow and the stock phase to discuss the future use of metals.

Together, these perspectives suggest the importance of selecting a method according to the scope and illustrate the need to choose the stock-driven approach in order to obtain implications for the impact of carbon constraints on long-term metal use, which is the focus of the thesis.

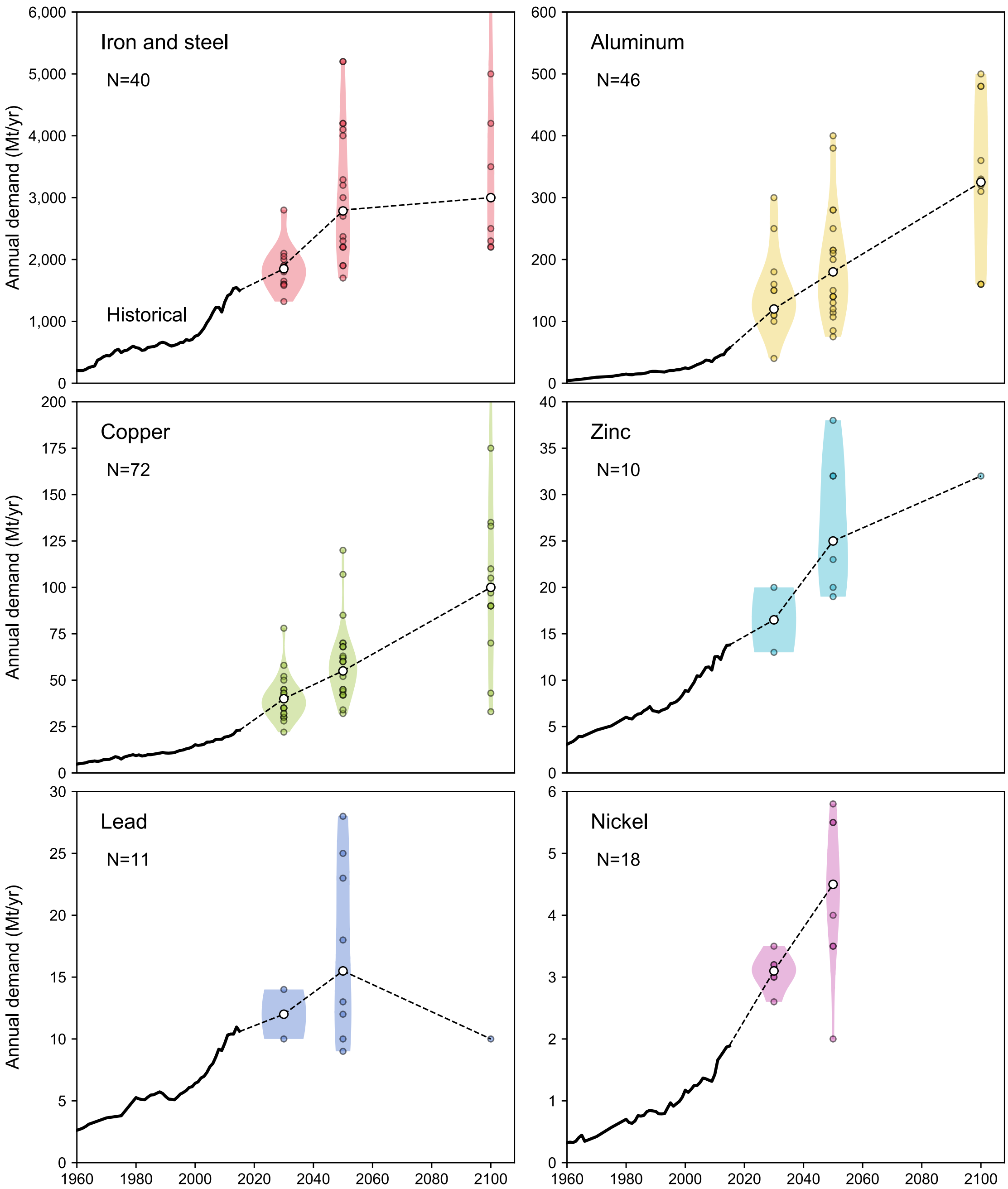

Figure 2- 6 Summary of demand outlook for major metals through 2030, 2050, and 2100 at the global scale. N indicates the number of data points; a total of 197 data points are included. Open circles represent the median of the data. Historical data are obtained from World Bureau Metal Statistics (2015).

Table 2- 3 Modeling approaches implemented in the reviewed articles for estimating future major metal demand. Model names are principally based on Müller et al. (2014)

Modeling approach	References
Regression model	(Ciacci et al., 2020; Dhar et al., 2020; Dong et al., 2019; Edelenbosch et al., 2017; Elshkaki et al., 2020, 2018, 2017, 2016; Kesicki and Yanagisawa, 2014; Kuipers et al., 2018; Schipper et al., 2018; Van der Voet et al., 2019; Xuan and Yue, 2016)
Specific growth rate model	(de Koning et al., 2018; Graus et al., 2011; Hoogwijk et al., 2010; Karali et al., 2016; Kermeli et al., 2015, 2014; Legarth, 1996; Li and Zhu, 2014; Morfeldt et al., 2015; Northey et al., 2014; Wang et al., 2014; Yellishetty et al., 2010)
Logistic consumption model	(Akashi et al., 2014, 2011; Allwood et al., 2010; Gauffin et al., 2017; Giurco and Petrie, 2007; Oda et al., 2013, 2007; Van Ruijven et al., 2016; Zeltner et al., 1999; Zeng et al., 2018)
Intensity of use model	(Halada et al., 2008; Hidalgo et al., 2005; Kapur, 2006, 2005; Tokimatsu et al., 2017a; Vuuren et al., 1999; Watari et al., 2018; Zhou et al., 2013)
Computable general equilibrium model	(Gielen and Moriguchi, 2002; Hatfield-Dodds et al., 2017; Schandl et al., 2020, 2016)
Constant consumption model	(Valero et al., 2018a; Yokoi et al., 2018)
Linear consumption model	(Legarth, 1996; Zeltner et al., 1999)
Stock saturation model	(Daigo et al., 2014; Hatayama et al., 2012, 2010; Liu et al., 2013; Milford et al., 2013; Morfeldt et al., 2015; Pauliuk et al., 2013a, 2012; Song et al., 2020; Xylia et al., 2018; Yokoi et al., 2018; Yoshimura and Matsuno, 2018; Yu et al., 2020; Zhang et al., 2015a)
Individual stock models for metal-containing technologies	(Chen et al., 2014; de Koning et al., 2018; Dong et al., 2019; Gerst, 2009; Schipper et al., 2018; Valero et al., 2018a; Watari et al., 2018; Zhang et al., 2015b)

2.2.2 Limited links between metal cycles and carbon constraints

Figure 2- 7 shows the number of times each type of environmental implication associated with metal production has been examined in existing studies. The greatest concern clearly lies in the areas of energy requirements and greenhouse gas (GHG) emissions. Of the 70 studies, 31 (44%) and 29 (41%) explicitly considered energy requirements and GHGs in their scenarios, suggesting a strong concern about climate change impacts induced by the production of major metals. A closer examination of the 29 studies on GHG emissions revealed that 45% did not have specific emission

constraints, while the remaining 55% set restrictions in line with the 1.5-2°C climate goals (UNFCCC, 2015). Namely, only 16 of the 70 studies explicitly explore the link between metal cycles and carbon constraints in line with climate goals. More importantly, 14 studies capture only metal flows and not stocks. As mentioned earlier, this type of approach lacks mechanistic explanations of metal use and service provision, which is essential to consider the nature of metal use in society.

This critical research gap has been filled by two important studies based on dynamic material flow analysis (Liu et al., 2013; Milford et al., 2013). However, these studies do not consider the time-series or cumulative emission constraints, meaning that the scenarios do not guarantee alignment with the emission reduction requirements to achieve climate goals. In fact, although Liu et al. (2013) set a benchmark of 50% reduction in 2050 compared to 2000 levels, some scenarios show a significant increase in carbon emissions before then, even if they are close to that benchmark. This observation suggests the possibility of overshooting, which would impose more stringent reduction obligations in the second half of the 21st century (Rogelj et al., 2019).

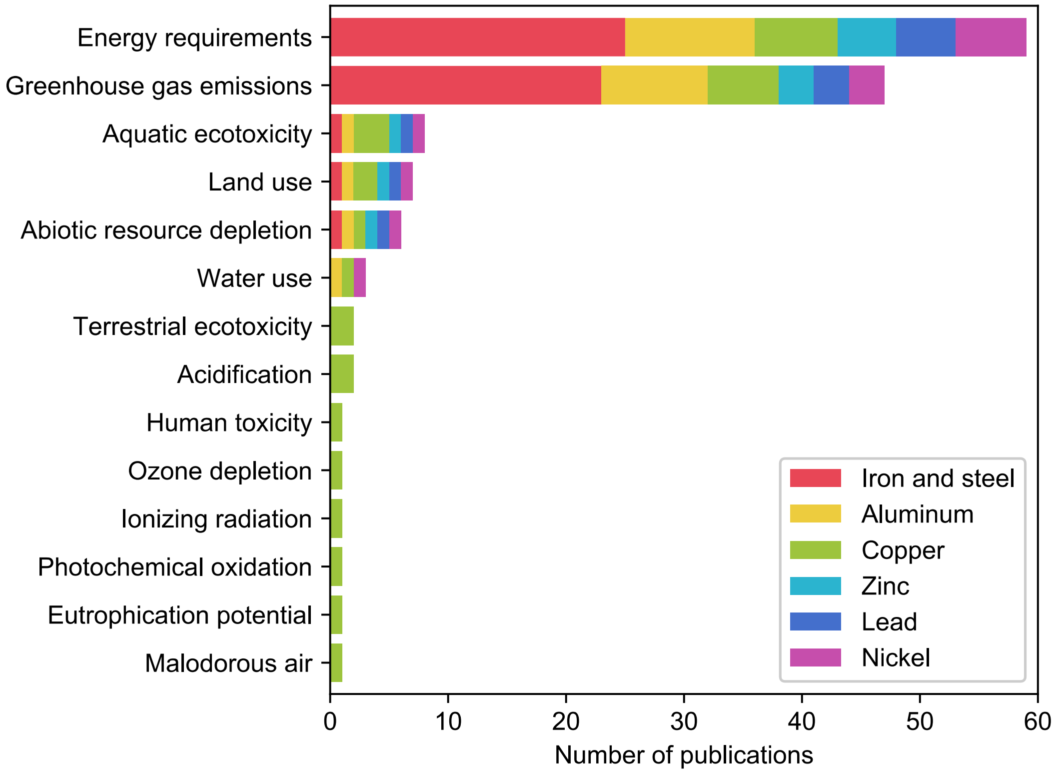

Figure 2- 7 Number of publications covering each environmental implication associated with metal extraction and processing.

2.2.3 Summary of research gaps

The critical review revealed a rapid increase in the publication of scientific articles in this domain. Yet, previous studies provide no quantitative information on the impact of time-series carbon constraints on long-term metal flows and stocks. This gap prevents a better understanding of the relationship between carbon constraints and metal cycles. Accordingly, Chapters 5, 6, and 7 aim to identify the scale and timing of the impacts of carbon constraints on production activities on future metal flows and stocks.

Table 2- 4 List of articles that were subjected to systematic review.

References	Relationship between stock dynamics and single-year emission reduction targets	Relationship between stock dynamics and time-series emission reduction targets
(Ciacci et al., 2020)		
(Schandl et al., 2020)		
(Song et al., 2020)		
(Elshkaki et al., 2020)		
(Yu et al., 2020)		
(Dhar et al., 2020)		
(Dong et al., 2019)		
(Van der Voet et al., 2019)		
(Schipper et al., 2018)		
(Elshkaki et al., 2018)		
(Zeng et al., 2018)		
(Watari et al., 2018)		
(Valero et al., 2018a)		
(Yoshimura and Matsuno, 2018)		
(Yokoi et al., 2018)		
(de Koning et al., 2018)		
(Xylia et al., 2018)		
(Kuipers et al., 2018)		
(Mohr et al., 2018)		
(Ali et al., 2017)		
(Elshkaki et al., 2017)		
(Hatfield-Dodds et al., 2017)		
(Edelenbosch et al., 2017)		
(Gauffin et al., 2017)		
(Tokimatsu et al., 2017a)		
(Calvo et al., 2017)		
(Sverdrup et al., 2017)		
(Van Ruijven et al., 2016)		
(Xuan and Yue, 2016)		
(Schandl et al., 2016)		
(Elshkaki et al., 2016)		
(Zhang et al., 2015a)		
(Zhang et al., 2015b)		
(Kermeli et al., 2015)		
(Morfeldt et al., 2015)		
(Sverdrup et al., 2015)		
(Mohr et al., 2015)		
(Daigo et al., 2014)		
(Northey et al., 2014)		
(Kermeli et al., 2014)		
(Akashi et al., 2014)		

References	Relationship between stock dynamics and single-year emission reduction targets	Relationship between stock dynamics and time-series emission reduction targets
(Chen et al., 2014)		
(Li and Zhu, 2014)		
(Wang et al., 2014)		
(Kesicki and Yanagisawa, 2014)		
(Karali et al., 2016)		
(Milford et al., 2013)	✓	
(Pauliuk et al., 2013a)		
(Liu et al., 2013)	✓	
(Zhou et al., 2013)		
(Oda et al., 2013)		
(Pauliuk et al., 2012)		
(Hatayama et al., 2012)		
(Akashi et al., 2011)		
(Graus et al., 2011)		
(Hatayama et al., 2010)		
(Allwood et al., 2010)		
(Yellishetty et al., 2010)		
(Hoogwijk et al., 2010)		
(Gerst, 2009)		
(Halada et al., 2008)		
(Oda et al., 2007)		
(Giurco and Petrie, 2007)		
(Kapur, 2006)		
(Hidalgo et al., 2005)		
(Kapur, 2005)		
(Gielen and Moriguchi, 2002)		
(Vuuren et al., 1999)		
(Zeltner et al., 1999)		
(Legarth, 1996)		

2.3 Aims and contribution of the thesis

Building upon the research gaps identified in the previous sections, Chapters 3 and 4 aim to identify the total extraction of materials, including mine waste, associated with the deployment of decarbonization technologies and the role of a circular economy in the energy transition. Chapters 5, 6, and 7 aim to identify the scale and timing of the impacts of carbon constraints on production activities on future metal flows and stocks. They collectively aim to identify the interventions needed to reconcile climate change mitigation with the sustainable use of metals.

Chapter 3 demonstrates a modeling approach that can quantify the total extraction of materials to be managed associated with both metals and fossil fuels production under the global energy transition by using a dynamic stock-flow model and the concept of Total Material Requirement. The approach is applied to the International Energy Agency's scenarios up to 2050, targeting 15 electricity generation and 5 transport technologies. **Chapter 4** extends the capabilities of the modeling approach by linking global energy scenarios with material demand-supply models on a country-by-country basis. A series of circular economy strategies (i.e., lifetime extension, servitization, and EoL recycling) are also linked to the models to obtain a quantitative understanding of the potential roles of such strategies in the sustainable energy transition.

Chapter 5 constructs a global metal cycle model that tracks entire metal flows and stock dynamics for 231 countries and regions over a 110-year period from 1900 to 2010. The model is applied to six major metals (iron, aluminum, copper, zinc, lead, and nickel) to explore the global distribution patterns of historical in-use stocks. **Chapter 6** then develops a new modeling approach that combines the global metal cycle model with an optimization routine to explore the metal cycle under carbon constraints. This attempt provides a benchmark for the specific scale and timing of the impact of carbon constraints in the production process on metal flows and stocks over the 21st century.

Chapter 7 links the model to a framework that can derive metal flows and stocks for four country income groups based on the principle of contraction and convergence. This analysis highlights the common but differentiated responsibilities around the world based on income levels.

Finally, **Chapter 8** connects the findings of the previous chapters and puts them into a broader context. It also gives an outlook on follow-up work.

Chapter 3

Total material requirement for the global energy transition to 2050

3.1 Introduction

Avoiding the catastrophic impacts of climate change will require, inter alia, the transformation of both the electricity supply and transport systems on an unprecedented scale in the coming decades (International Energy Agency (IEA), 2017). Such a transition will fundamentally alter the existing flows of metals as well as fossil fuels. Reflecting the importance and urgency of this topic is the emergence of large-scale studies in this domain, as shown in Chapter 2. However, an extensive review of 88 studies revealed that while the existing studies vigorously captured the quantities of metals directly used for decarbonization technologies, none of them quantified the total amount of extracted materials to be managed, including hidden flows such as waste rock and overburden. This deficit in our understanding will likely mask the entire materials that need to be carefully managed along with the energy transition, which can lead to increased risk of various adverse impacts such as land degradation (Werner et al., 2020), biodiversity loss (Sonter et al., 2020), damage to human health (Banza Lubaba Nkulu et al., 2018), and the catastrophic collapse of tailings dams (Owen et al., 2020). An essential step for responsible materials management is to understand how the extracted materials will change over time and which technologies and metals will drive the change.

Accordingly, this chapter addresses this knowledge gap by linking global energy scenarios with a dynamic stock-flow model and a material intensity dataset containing over 200 data points. Our approach captures all used and unused material extraction by using the Total Material Requirement indicator (Bringezu et al., 2004), which can be used to estimate the total weight of materials spent in mining and processing stages. Among the various sectors and related technologies in the decarbonization process, this study focuses on electricity and automotive technologies because of their considerable contribution to decarbonization, as discussed in Chapter 2.

3.2 Methodology

The approach for quantifying total extracted materials under a global energy transition scenario consists of the following steps:

Step 1: Estimate technology flows under long-term energy scenarios.

Step 2: Transform technology flows into metal and fossil fuel demand.

Step 3: Convert metal and fossil fuel demand to used and unused material extraction.

The details of each step are described in detail below.

3.2.1 Estimating technology flows under long-term energy scenarios

The starting points of the analysis are the future electricity generation capacity and vehicle ownership (in-use stock) described in the energy scenario. When assuming that the inflow in year t is $I(t)$, and the outflow in year t is $O(t)$, then the change in in-use stock in year t, $\Delta S(t)$, can be expressed by the simple balance:

$$\Delta S(t) = I(t) - O(t) \tag{3-1}$$

where t is a discrete value in one-year steps.

In this case, expressing the technology lifetime distribution as a function $\phi(t-t')$ with the number of years of use $(t-t')$ as a variable, $O(t)$ can be calculated by equation (3-2).

$$O(t) = \sum_{t'=0}^{t} I(t')\phi(t-t') \tag{3-2}$$

Thus, equation (3-1) can be rewritten as follows:

$$\Delta S(t) = I(t) - \sum_{t'=0}^{t} I(t')\phi(t-t') \tag{3-3}$$

Let τ be a discrete value representing a point in time at the end of the observation year t, $\Delta S(t)$ can be expressed as the difference in stock.

$$\Delta S(t) = S(\tau) - S(\tau - 1) \tag{3-4}$$

Therefore, $I(t)$ can be obtained by equation (3-5).

$$I(t) = S(\tau) - S(\tau - 1) + \sum_{t'=0}^{t} I(t')\phi(t - t') \quad (3\text{-}5)$$

In this case, the lifetime distribution is usually approximated by parametric distributions such as normal (Gaussian), lognormal, gamma, and Weibull distributions (Müller et al., 2014). In this study, the lifetime distribution was approximated by the normal distribution, referring to the previous studies (Fishman et al., 2018; Fishman and Graedel, 2019). Thus, equation (3-5) can be rewritten as follows:

$$I(t) = S(\tau) - S(\tau - 1) + \sum_{t'=0}^{t} \left(I(t') \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(t - t' - \mu)^2}{2\sigma^2} \right) \right) \quad (3\text{-}6)$$

where μ is the mean lifetime and σ is the standard deviation of the lifetime distribution. The sensitivity of the model to the choice of distribution function was assessed by comparing the results with those estimated using the Weibull distribution (see Section 3.2.6 for more details.).

In this study, S of decarbonization technologies up to 2050 was obtained from the Energy Technology Perspectives 2017 (IEA, 2017), which was the latest long-term energy scenario published by the IEA, and historical S was collected from various sources (Earth Policy Institute, 2018; Global Wind Energy Council, 2018; U.S. Energy Information Administration, 2018). Target technologies are 15 electricity generation technologies (oil, coal, coal with carbon capture and storage (CCS), natural gas, natural gas with CCS, nuclear, biomass and waste, biomass and waste with CCS, hydro, geothermal, wind onshore, wind offshore, solar photovoltaics (solar PV), concentrating solar thermal power, and ocean power), and 5 vehicle types (internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), electric battery vehicles (BAV), and fuel cell vehicles (FCV)). The mean lifetime of each technology assumed here is provided in Table 3- 1.

Table 3- 1 Mean lifetime of each technology (Ashby, 2012).

Technologies	Distribution function	Standard deviation	Mean lifetime
Oil	Normal	30% of the mean	40
Coal			40
Coal with CCS			40
Natural gas			40
Natural gas with CCS			40
Nuclear			40
Biomass and waste			40
Biomass with CCS			40
Hydro			100
Geothermal			40
Wind onshore			25
Wind offshore			25
Solar PV			20
Solar CSP			20
Ocean			30
Vehicle			15

3.2.2 Transform technology flows into metal and fossil fuel demand

Metal demand for the energy transition can be calculated by multiplying the technology flow (GW or cars/year) by the material intensity, MI (t/GW or car). This study used data from 37 sources (Table 3- 2) to obtain the material intensity for 20 technologies. This leads to a total of 36 metals being considered, with 209 data points. If multiple values were available for the same data, their average was used. This study assumed that the compiled material intensities were constant over time, meaning that the analysis here provides an upper bound estimate that does not consider any potential decrease in material intensity due to developments in engineering and design.

The metal demands are obtained from both mine production (P) and EoL scrap (E) as shown in equations (3-7) and (3-8):

$$P(t) = I(t)\mathrm{MI}(t) - E(t) \tag{3-7}$$

$$E(t) = \gamma(t) \sum_{t'=0}^{t} I(t')\mathrm{MI}(t')\phi(t-t') \tag{3-8}$$

where γ denotes the EoL recycling rate (scrap collection rate $\times$ recycling yield).

Table 3- 2 Correspondence between the material intensities and references.

Technologies	References
Oil, Coal, Natural gas	(Vidal et al., 2013)
Carbon Capture and Storage	(Moss et al., 2011; R.L. Moss et al., 2013)
Nuclear	(Moss et al., 2011; R. L. Moss et al., 2013)
Biomass and Waste	(Ashby, 2012)
Hydro	(Ashby, 2012)
Geothermal	(Ashby, 2012; Moss et al., 2011; R. L. Moss et al., 2013)
Wind (onshore and offshore)	(Ashby, 2012; Bodeker et al., 2010; Falconer, 2009; Fizaine and Court, 2015; García-Olivares et al., 2012; Guezuraga et al., 2012; Habib et al., 2016; Habib and Wenzel, 2016, 2014; Hoenderdaal et al., 2013; Kleijn and Van Der Voet, 2010; Lacal-Arantegui, 2015; Martínez et al., 2009; McLellan et al., 2016; R. L. Moss et al., 2013; Roelich et al., 2014; Teske et al., 2016; U.S. Department of Energy, 2011; VESTAS, 2006; Wilburn, 2011; World Bank Group, 2017; Zimmermann, 2013)
Solar PV (c-Si, CIGS, CdTe)	(Andersson and Jacobsson, 2000; Ashby, 2012; Berry, 2012; Bleiwas, 2010; Bodeker et al., 2010; Elshkaki and Graedel, 2013; Fizaine and Court, 2015; Fthenakis, 2012; Kavlak et al., 2015b; McLellan et al., 2016; R. L. Moss et al., 2013; Stamp et al., 2014; Teske et al., 2016; The Warren Centre, 2016; U.S. Department of Energy, 2011; Valero et al., 2018a; Woodhouse et al., 2013; World Bank Group, 2017)
Solar CSP	(Ashby, 2012; Bodeker et al., 2010; Moss et al., 2011; Pihl et al., 2012; Teske et al., 2016; World Bank Group, 2017)
Ocean	(Ashby, 2012)
Vehicles (ICEV, HEV, PHEV, EV, FCV)	(Fishman et al., 2018; R.L. Moss et al., 2013; Rutherford, 2011; U.S. Department of Energy, 2011; Valero et al., 2018a; World Bank Group, 2017)

Fossil fuel demand for operating electric technologies can be obtained directly from the original scenario (IEA, 2017). The fossil fuel demand for vehicle operation $Q\ (t)$ can be estimated by multiplying the vehicle stock $S(\tau)$ (car/year) by the annual mileage $\theta(t)$ (km/car-year) and fuel consumption $\psi(t)$ (MJ/km), which can be obtained from the literatures (IEA, 2018, 2010) (Table 3- 3).

$$Q(t) = S(\tau)\theta(t)\psi(t) \tag{3-9}$$

Table 3- 3 Assumptions for calculating energy consumption for vehicle operations (IEA, 2018, 2010).

Type	Energy consumption (MJ/km)	Annual mileage (km/year)	Mean (km/year)	(MJ/year)
ICEV	2.38			32,487
HEV	1.67			22,796
PHEV	0.98	8,500–18,800	13,650	13,377
BEV	0.69			9,419
FCV	0.98			13,377

Importantly, there has been no inclusion of feedback loops in the modeling of fossil fuel demand. That is, there is no modeling of the additional energy demand required to provide the additional required metals (mining through to production), nor is there a secondary feedback mechanism to more closely examine the additional metal requirements for providing this extra energy; this is something that could be considered in future studies.

3.2.3 Convert metal and fossil fuel demand to used and unused material extraction

The main objective of this study is to quantify the future changes in total material flows including mine waste (e.g., shavings, mine waters, tailings, and slag) for responsible management. Various indicators have been proposed to quantify material flows in a defined space and time in this context. Still, as mentioned in Chapter 2, existing studies only estimated direct material input (DMI) or raw material input (RMI) (Figure 3- 1). Therefore, the scale of the total material flows, including unused extraction, which should be carefully managed over the long term, remains poorly understood. For this issue, the Land Use Change indicator partially contains unused extraction in terms of area. Still, it has the disadvantage that it does not capture material flows that do not involve changes in surface area, such as in the case of underground mining (Murakami et al., 2020). Total Material Requirement (TMR) is positioned to overcome these challenges by capturing the total material flows, including unused extraction associated with mining and processing as weight (Bringezu, 2015). Indeed, TMR has been widely adopted in studies that attempt to evaluate emerging technologies from the perspective of material use (Kosai et al., 2021, 2020). This is supported by data availability for a comprehensive set of metals (Halada et al., 2001; Nakajima et al., 2019). Therefore, this study also employs TMR as an effective indicator to achieve the objective of this study. However, it should be noted that TMR generally does not consider the impact on water (e.g., intrusion control water) or air (e.g., CO_2) and thus captures only the unused extraction as soil and rocks. This point is further discussed in Section 3.4.

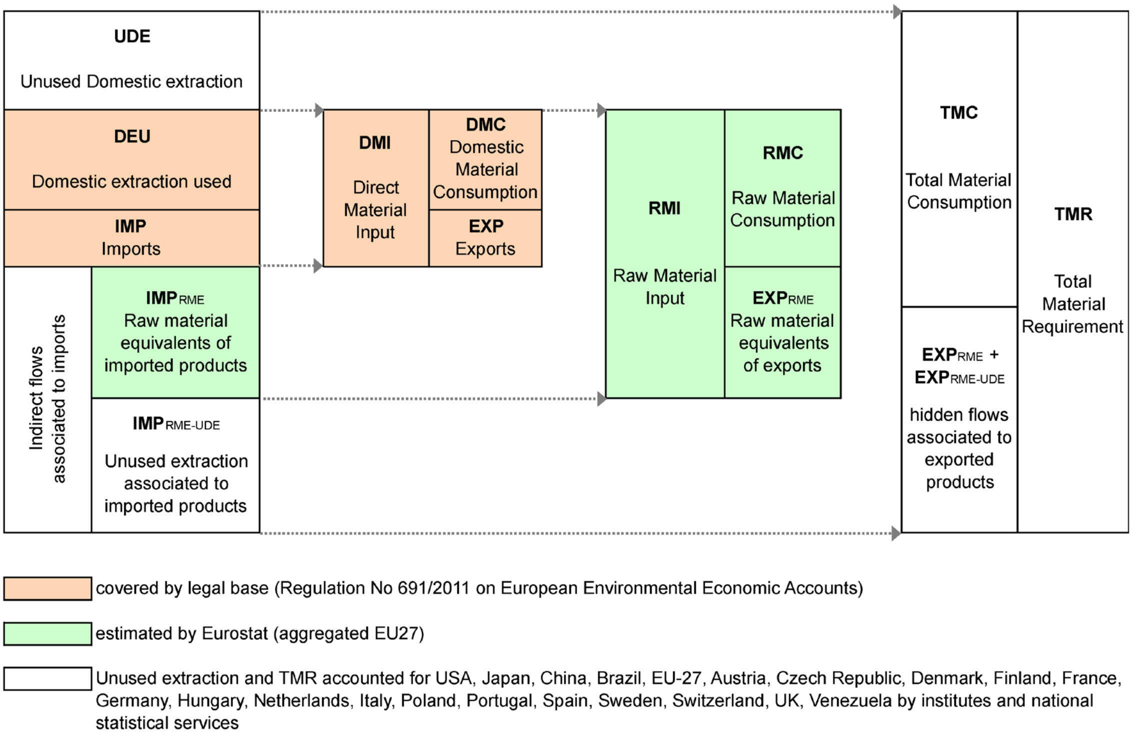

Figure 3- 1 Overview scheme of material flow indicators (Bringezu, 2015)

TMR can be expressed through the following equation:

$$\mathrm{TMR} = \sum M_{\mathrm{direct}} + \sum M_{\mathrm{indirect}} + \sum M_{\mathrm{hidden}} \tag{3-10}$$

where M_{direct} is direct materials inputs, M_{indirect} indicates indirect materials inputs and M_{hidden} expresses hidden flows. Specifically, in addition to direct material inputs (extracted ore), fuels and reducing agents are required to produce concentrate, and energy is used for transportation which can be defined as indirect material inputs. Furthermore, mining involves removing overburden or waste rock to access the ore, which may also require land clearing that removes vegetation. Additionally, waste is produced in the form of tailings. These flows are not typically incorporated into statistical data because they are non-economic activities. In TMR, these are referred to as hidden flows, and are included to evaluate all extracted materials comprehensively (Halada et al., 2001).

Here, TMR associated with metal production $\mathrm{TMR}_{\mathrm{metal}}(t)$ were calculated using equation (3-11).

$$\mathrm{TMR}_{\mathrm{metal}}(t) = \sum_{m\in M}\sum_{n\in N} P_{m,n}(t)\,\mathrm{TMR}_{m}(t) \tag{3-11}$$

where $P_{m,n}(t)$ represents primary production of metal type m for technology n, and M and N are the set of target metals and technologies, respectively. $\mathrm{TMR}_{m}(t)$ indicates TMR factor (tonnes-TMR/tonne) in the production of each element from cradle to refinery gate.

Since TMR factor of each metal highly relates to their ore grades (Halada et al., 2001), the value of some metals is expected to increase in the future, reflecting future ore grade declines (Van der Voet et al., 2019). This study also considers this potential change by estimating ore grade declines with equation (3-12).

$$\text{Ore grades}(t) = \alpha \times t^{\beta} \tag{3-12}$$

where α and β represent constants, which determine the shape of the trendline fitted to historical data. Based on the literature survey (Van der Voet et al., 2019), only the case of copper, zinc, lead and nickel show decline trends in the past and there is no evidence to justify that all metals' ore grades will decline. This study, therefore, estimated the TMR factor taking into consideration the future decline in ore grades only in the case of these metals (Figure 3- 11 and Figure 3- 12). Figure 3- 2 shows the TMR factor of each metal in 2015.

In this case, the stripping ratio may also significantly impact the calculation of the TMR factor. However, due to the unavailability of sufficient time-series data, only the change in ore grade is considered in this study. The increase in the TMR factor due to the change in ore grade is attributed entirely to the host metal, without any allocation to by-product metals.

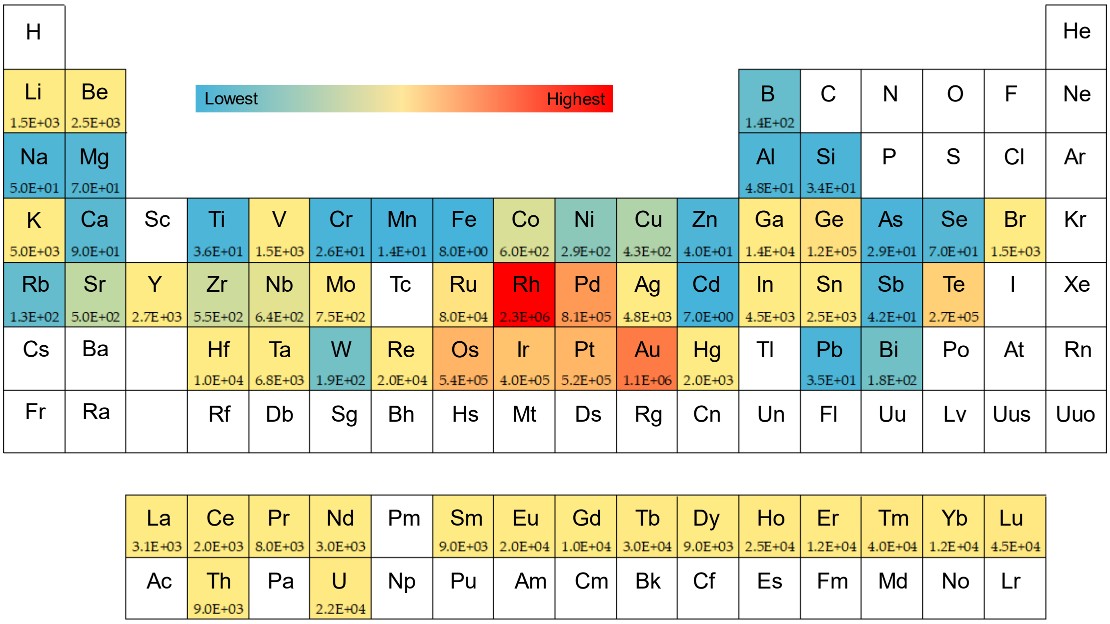

Figure 3- 2 Total Material Requirement (TMR) factor of each metal in 2015 at the global level. The values for Cu, Zn, Pb and Ni were calculated by the authors, and the other metals were obtained from (Halada et al., 2001). Note: TMR intensity of Cu, Zn, Pb and Ni are changing over time, reflecting ore grade projections.

In addition to metal production, the energy transition could change flows of fossil fuels for generating electricity and running vehicles because each energy technology requires different types of fossil fuels which have their own TMR factor (tonnes-TMR/TWh or tonnes-TMR/MJ). This study also considers this change by estimating TMR associated with fossil fuel production under the transition to a decarbonized energy system. TMR of fossil fuels used for electricity generation and vehicle use in year t is estimated by the following equation:

$$\mathrm{TMR}_{\mathrm{fossil}}(t) = \sum_{f \in F} \sum_{n \in N} Q_{f,n}(t) \mathrm{TMR}_f(t) \tag{3-13}$$

where $Q_{f,m}(t)$ represents the fossil fuel consumption of fossil fuel type f by technology type n in year t, and F expresses the set of target fuels. $\mathrm{TMR}_f(t)$ expresses the TMR factor of the fossil fuel type f (Table 3- 4).

Table 3- 4 Total material requirement factors of each fossil fuel production (Unit: kg-TMR/kWh). Data is obtained from (Nakajima et al., 2006).

	TMR factor
Oil	1.7
Coal	4.8
Natural gas	0.3

3.2.4 Scenario setting

In this study, changes in total extracted materials expressed by TMR were quantified under various energy scenarios. Namely, the Reference Technology Scenario (RTS), 2 °C Scenario (2DS) and Beyond 2 °C Scenario (B2DS), which were set based on IEA publications (IEA, 2017). In this case, the RTS takes into account the current energy system, and voluntary targets of each country pledged in the Paris Agreement, which will lead to a temperature rise of 2.7 °C by 2100. In contrast, the 2DS can be considered as a major climate change mitigation scenario from the IEA, delineating a path to keep global temperature rise below 2 °C in 2100. The B2DS is the most ambitious scenario, which lays out an energy system pathway achieving only 1.75°C temperature increase. Scenario analysis allows us to quantitatively and dynamically evaluate the difference in the impact of each energy scenario from the perspective of material extraction.

Note that this study employs scenario analysis rather than future predictions. Scenarios are hypotheses, and are tools for examining future possibilities. As such, the results should always be interpreted relative to 'what-if descriptions'.

3.2.5 Validity of the model and parameters

The approach adopted here is standard dynamic stock-flow modeling, which has been continuously developed and refined in the field of industrial ecology (Müller et al., 2014). It has been used and validated in multiple studies to estimate the impact of emerging technology introduction on material flows (Deetman et al., 2018; Fishman and Graedel, 2019). A possible problem is the setting of parameters. Thus, the validity of the parameter settings was tested by comparing the estimated and actual consumption of copper and steel for vehicles, given the data availability. In this case, time-series data on copper was obtained directly from the Copper Alliance (2020). The information on steel was approximated using the 2008 end-use breakdown and overall consumption (Cullen et al., 2012; World Bureau Metal Statistics, 2015).

Figure 3- 3 confirms that the actual values are generally consistent with the model estimates, suggesting that the parameters are set to reasonable values. However, since the data for most minor metals are not well organized, validation of the estimates for such metals remains a critical issue to be considered. The results of this study should always be interpreted with this point in mind.

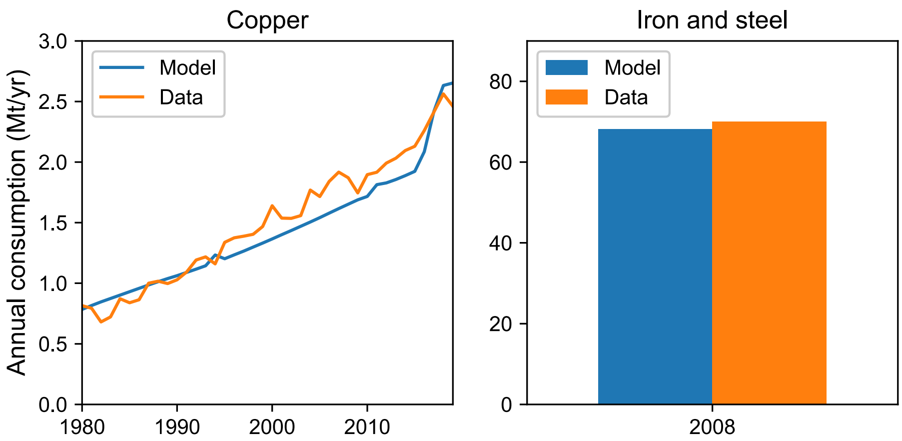

Figure 3- 3 Comparison of estimated and actual copper and steel consumption for vehicles.

3.2.6 Sensitivity and uncertainty analysis

Since the objective of the model is to explore the "future", some inherent uncertainty exists in the parameters considered. Therefore, this study investigated the impacts of our modeling assumptions by way of a one-factor-at-a-time sensitivity analysis. Investigated parameters included average lifetime, a standard deviation of lifetime distribution, type of probability distribution, material intensity, and TMR factor. In addition, a Monte Carlo simulation was conducted in which each parameter was randomly extracted from a specific probability distribution, and the model was run multiple times to derive the uncertainty ranges for the results. Hence, the model can be seen as a stochastic system, where each parameter is understood to be the mean μ of a normal distribution with an uncertainty parameter σ. In each model run, input parameters are randomly drawn from a distribution $X \sim \mathcal{N}(\mu, \sigma^2)$. Uncertainty ranges for each parameter were established based on a combination of multiple references and information about the reliability of the data sources.

Fishman et al. (2018) set the uncertainty ranges for all parameters, including material intensity and average lifetime, as follows: the uncertainty for each parameter follows a unique normal distribution, and the functional form of all normal distributions is $X \sim \mathcal{N}(\mu, (0.1\mu)^2)$, i.e., X is randomly selected from a normal distribution with mean μ and standard deviation σ that is one-tenth of the mean value. Wiedenhofer et al. (2019) assumed a maximum uncertainty of ±30% for the average lifetime, and a maximum uncertainty range of ±45% for material inputs (including three standard deviations) based on expert judgments on the reliability of information sources. Furthermore, for material intensity, the difference between the estimated mean value and the maximum and minimum values for Cu intensity for BEV, for which the most abundant data were obtained in this study, is ±45%. Based on such information, this study assumed an uncertainty range of ±30% for the average lifetime and ±45% for the material intensity.

While uncertainty information on TMR factors does not exist, Kosai et al. (2021) examined the uncertainty range for TMR factors for lithium-ion batteries (LIBs) associated with the uncertainty in the grade of copper ore. This was done by the Monte Carlo simulation using data for copper ore grades from 1991 to 2015. Their analysis confirmed that the range of TMR factors for LIBs is about 43–49 kg-TMR/kg, compared to the median of about 46 kg-TMR/kg. Considering that copper accounts for approximately 37% of that amount, the uncertainty range for the TMR factor for copper can be approximated to be about ±18%. Based on this assumption, this study simply employed an uncertainty range of ±18% for the TMR factors of all elements.

The uncertainty ranges set here all follow normal distributions and are expressed in terms of the relative variability of each parameter as a percentage, including three standard deviations. Each parameter has its own normal distribution function independent of the others (Fishman et al., 2018). Note that because the empirical uncertainty of the variables is unknown, the uncertainty range obtained by this analysis is only sufficient for determining whether the trend of the estimation results is robust or not.

3.3 Results

3.3.1 Total material requirement for the global energy transition

Future material extraction patterns driven by the energy transition show a paradoxical relationship between carbon emissions and material extraction (Figure 3- 4). The energy transition could mitigate material extraction in the electricity sector over time, reflecting the decreasing fossil fuel production. On the other hand, in the transport sector, increases in material extraction would be inevitable even if we introduce EVs (PHEV and EV), capable of decreasing fossil fuel production for vehicle operations. This is simply because that the increase in metal production offsets the decline in fossil fuel production.

A closer look at B2DS shows that decarbonizing electricity and transport systems will reduce material extraction caused by fossil fuel production by about 75% and 35%, respectively, from 2015 to 2050. On the other hand, material extraction associated with metal production will increase sharply in both sectors, increasing by more than a factor of 7 by 2050. Combining fossil fuels and metals, we can confirm that the decarbonization of the electricity sector will curtail material extraction by roughly 60% by 2050 relative to 2015 levels. Conversely, the decarbonization of the transport sector will double material extraction by counteracting the decline in fossil fuel production with a surge in metal production. These findings suggest that the energy transition may, paradoxically, result in a reduction of carbon emissions while increasing substantially material extraction.

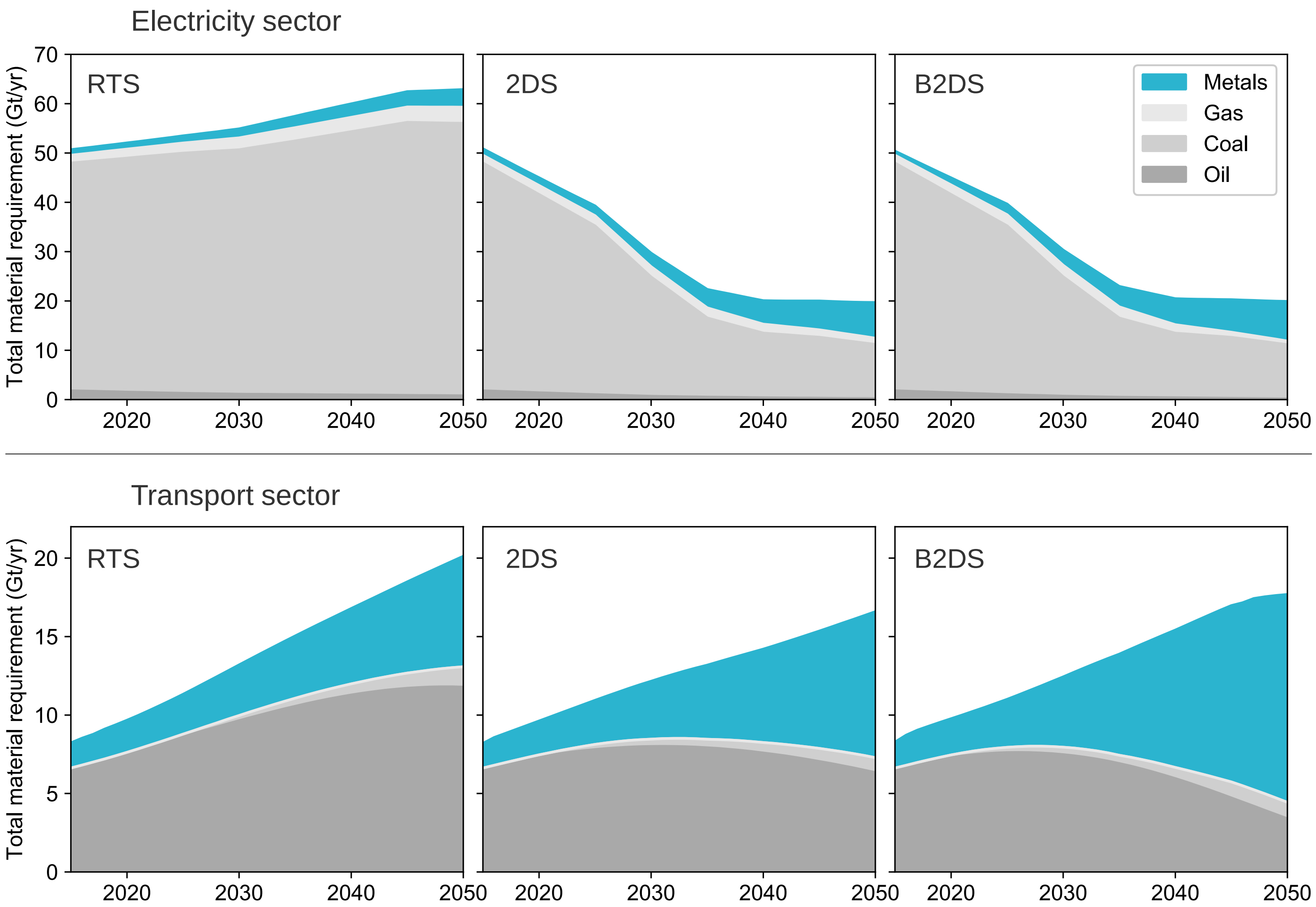

Figure 3- 4 Total material requirements associated with generating electricity and operating vehicles up to 2050 at the global level.

When considering the 'TMR/MWh or vehicle in-use' as shown in Figure 3- 5, all scenarios express a decreasing trend in the electricity sector. On the contrary, the transport sector suggests that the more decarbonization progresses, the more materials are extracted. That is, the decarbonization of the transport sector would lead to more significant material flows and increase the importance of the proper management of extracted materials. The value in the B2DS is decreasing since around 2045 because the number of vehicles in-use is continuing to increase despite the material extraction showing a saturation trend around that time. This could be due to the vehicles' average lifetime, which is assumed as more than 10 years in this study.

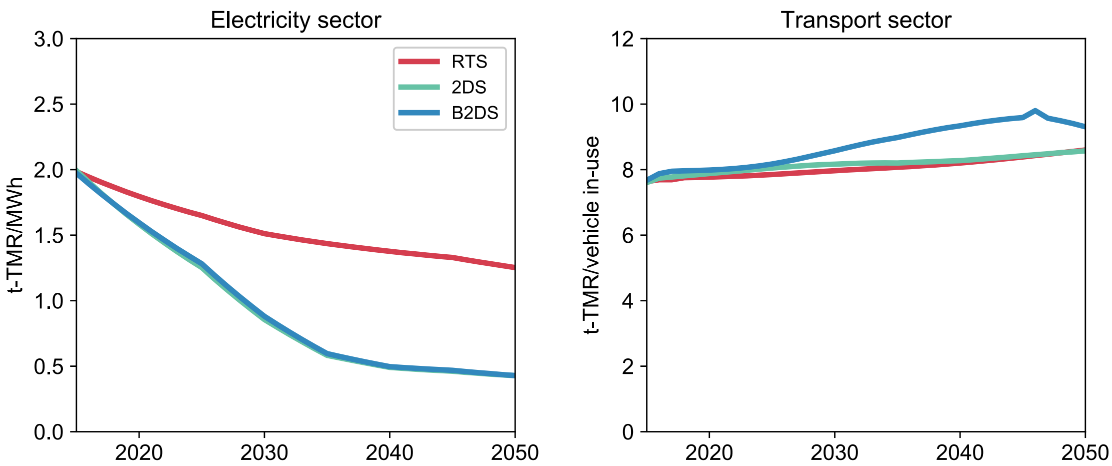

Figure 3- 5 Total material requirements per unit of electricity generated and the number of vehicles in-use to 2050 at the global level.

When examining the material extraction associated with metal production shown in Figure 3- 6 and Figure 3- 7 in more detail, all scenarios indicate that material extraction would increase drastically over time. In the 2DS, material extraction increases by a factor of 4 to 5 from 2015 and 2050 in the electricity and transport sectors, respectively, whereas in the RTS, it increases by a factor of 2 and 3, respectively. Moreover, in the B2DS, which is the most ambitious scenario, material extraction increases by a factor of 9 and 7 from 2015 to 2050 in the electricity and transport sectors, respectively. Such drastic increases in material extraction are mostly from emerging technologies such as solar PV and EVs. Solar PV, for example, dominates around 70% of material extraction in 2050 in the case of the B2DS electricity sector. Additionally, about 95% of material extraction in 2050 is induced by EVs in the case of the B2DS transport sector.

Regarding the fractional contribution of each of the metals, copper flows are increasing over time and play a prominent role in pushing up the material extraction in both sectors. The remaining extracted materials are primarily from iron, nickel, silver, tellurium, cobalt and lithium. Specifically, more than 90% of material extraction in 2050 comes from these metals.

The validity of the estimates was assessed using the final demand for ore from the existing studies collected in Chapter 2. Figure 3- 8 confirms that the estimates in this study are generally within the range of estimates in existing studies.

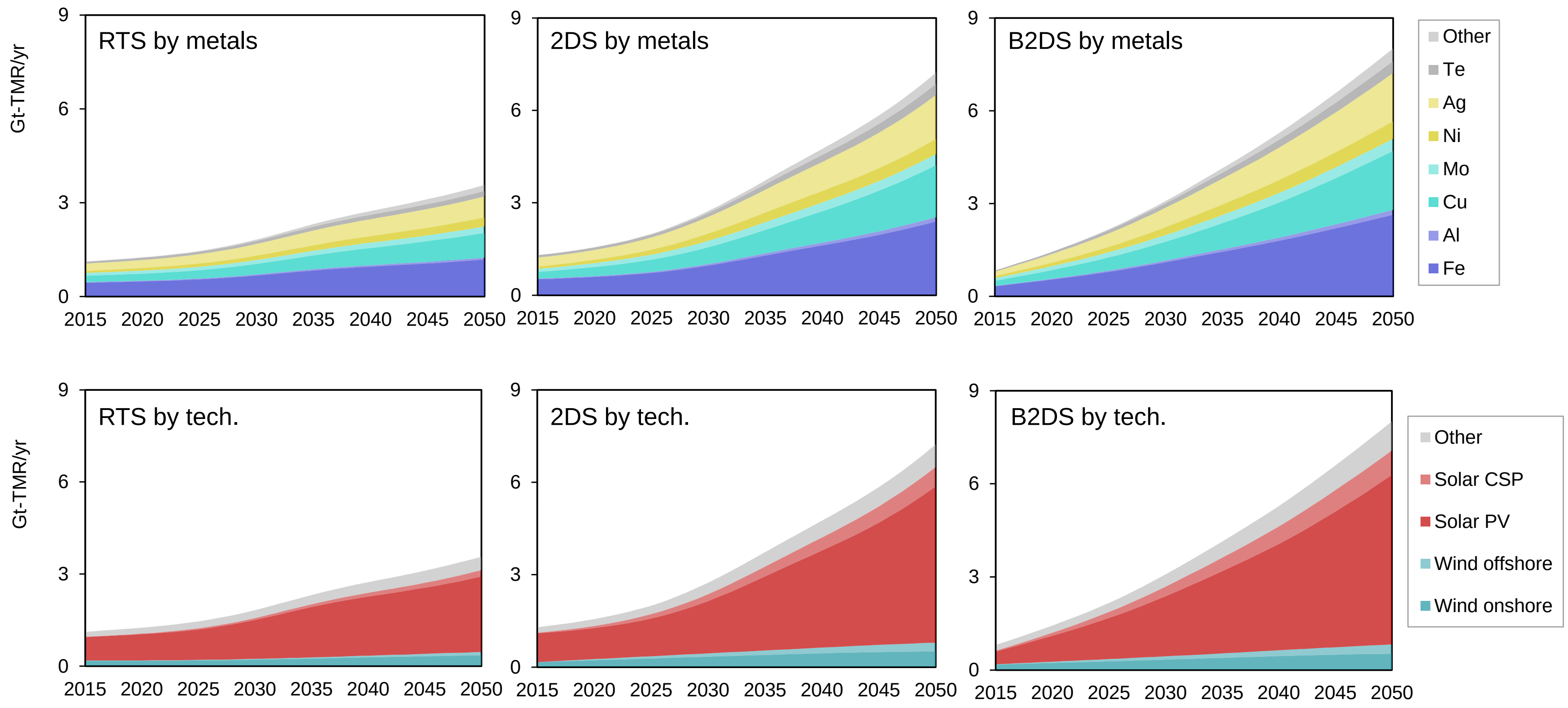

Figure 3- 6 Total material requirements associated with metal production in the electricity sector up to 2050 at the global level.

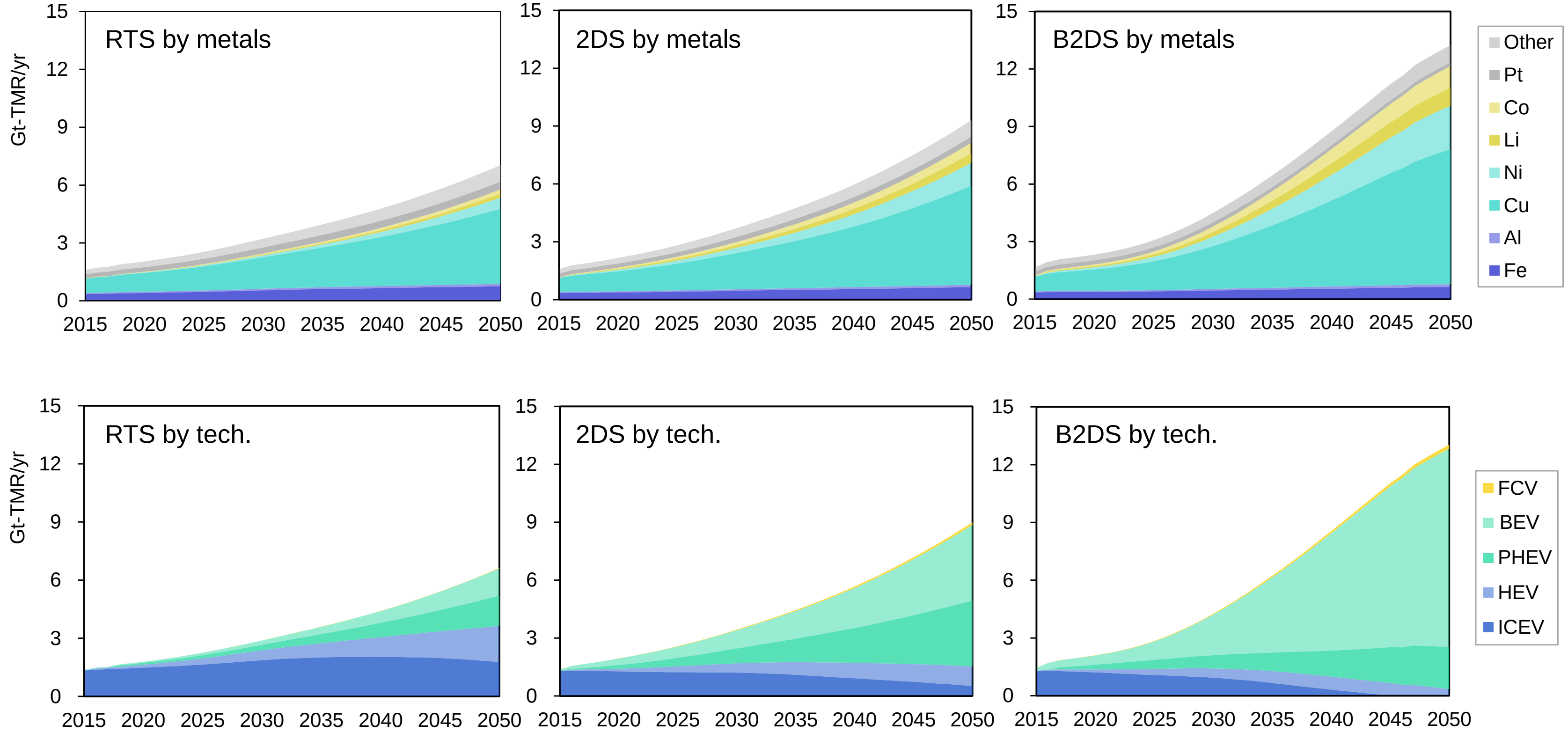

Figure 3- 7 Total material requirements associated with metal production in the transport sector up to 2050 at the global level.

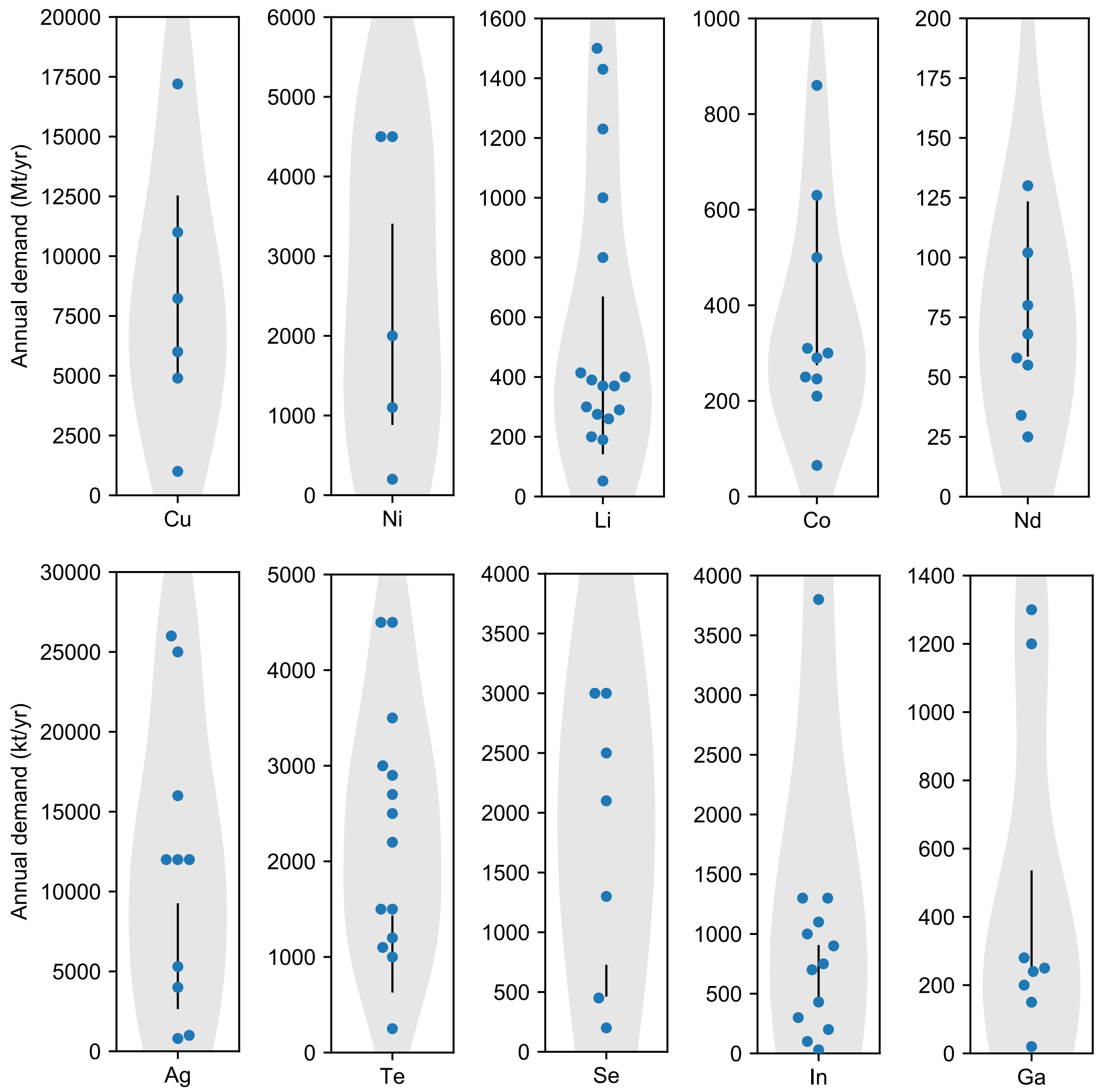

Figure 3- 8 Comparison of estimated ore demand in 2050 with estimates from existing studies reviewed in Chapter 2.

Such an increasing trend is heavily dependent on several critical parameters, including material intensity, TMR factor, and average lifetime of the product. Figure 3-9 shows that the sensitivity of the model to the standard deviation and the probability distribution is limited compared to the average lifetime, material intensity, and TMR factor. Thus, the Monte Carlo simulation was conducted by randomly setting the average lifetime, material intensity, and TMR factor based on the probability distribution.

Figure 3- 10 suggests that the upward trend in material extraction associated with metal production through 2050 is relatively robust, even after accounting for the uncertainty inherent in the multiple parameters. Obviously, there is still a great deal of uncertainty about the actual level of extraction. Still, the analysis in this domain confirms an inverse relationship between carbon emissions and material extraction associated with metal production.

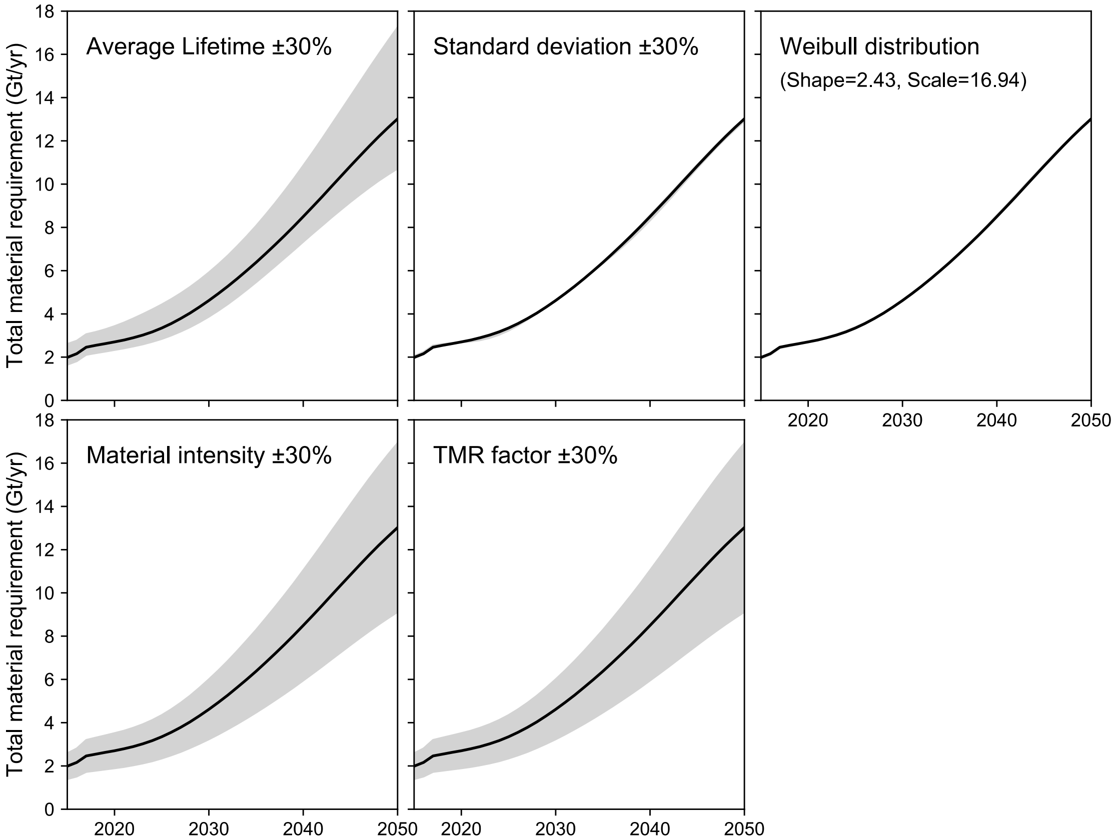

Figure 3- 9 Sensitivity of the model to various parameters expressed by estimated total material requirements associated with metal production in the transport sector in B2DS, 2015-2050. The lines represent the mean value, and the shaded regions indicate the range for parameter variations of ±30%. The Weibull distribution has a shape parameter of 2.43 and a scale parameter of 16.94 (Fishman et al., 2018).

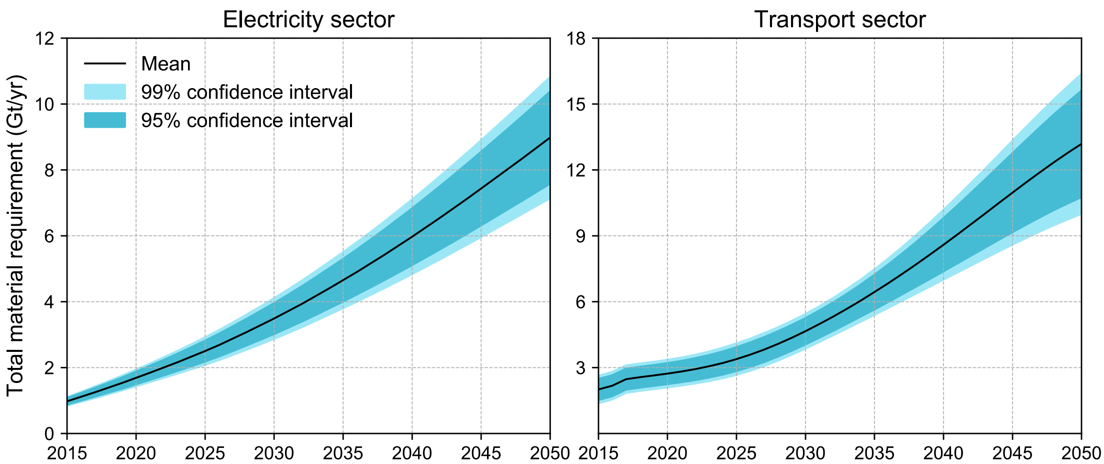

Figure 3- 10 Uncertainty in the results obtained for total material requirements associated with metal production in B2DS, 2015-2050. The 95% and 99% confidence intervals are derived from Monte Carlo simulations with a sample size of 1000.

3.4 Discussion

This study showed that decarbonizing the electricity and road transport systems could reduce fossil fuel production while rapidly increasing material extraction associated with metal production. Specifically, material extraction associated with metal production could rise sharply in both sectors, increasing by a factor of more than 7 from 2015 to 2050. This substantial increase is primarily due to increases in the extraction of iron, copper, nickel, silver, tellurium, cobalt, and lithium used for the production of solar PV and EVs. More specifically, around 70-95% of material extraction in 2050 is attributed to these metals and technologies.

The analysis in this study highlights the scale of material flows and the metals that are likely to lead to the greatest material extraction by expanding mining activities. However, it is also important to consider qualitative data on the potential consequences of mining activities to understand the specific risks and trade-offs which are not captured through quantitative analysis of material flows. It is also crucial to consider the locations where mining typically occurs for these minerals and where it is likely to expand to mitigate new adverse impacts that may arise due to the energy transition.

If not managed appropriately, significant environmental and social impacts are associated with the mining and processing of metals for decarbonization technologies in the electricity and transport sector. However, because of the complex nature of many supply chains, it isn't easy to directly link specific mining impacts to end-uses, particularly if these metals are used in many applications. For certain metals where decarbonization technologies are responsible for a high share of consumption and the metals are mined in only a few locations, such as rare earths or tellurium, it is easier to draw a link between mining impacts to specific technologies (Redlinger et al., 2015; Xiaoyue and Graedel, 2011). This becomes more difficult for metals such as iron and copper, which are used in a wide range of technologies, as well as mined in various locations around the world. For particular metals, including cobalt, lithium, and nickel, new or expanded mining operations are under development specifically because of increased demand for these metals from decarbonization technologies (Ali et al., 2018).

The most discussed impacts from mining activities associated with decarbonization technologies are the mining of cobalt from Democratic Republic of the Congo (DR Congo). Mining has led to heavy mineral contamination of air, water and soil, with severe health impacts for miners and surrounding communities (Banza Lubaba Nkulu et al., 2018). Cobalt used for lithium-ion battery manufacture is generally produced as a co-product of copper mining; the exception to this is the 15-20% of cobalt from DRC, which is produced from artisanal and small-scale mines (ASM) (BGR, 2017). Artisanal miners work in dangerous conditions in hand-dug mines that are at risk of cave-ins or landslides, and are at most risk for heavy mineral contamination (Tsurukawa et al., 2011). There is extensive child labor, with an estimated 40,000 children under 15 years working in artisanal cobalt mines (Amnesty International, 2016). New cobalt mines are proposed in DR Congo, as well as in Australia, Canada, Indonesia, the US, Panama and Vietnam.

Other metals for which significant impacts have been observed include mining of copper and nickel and rare earths. Copper mining can lead to long-lasting heavy mineral contamination of soils and water, as seen in Chile, the largest copper producer, as well as China, India and Brazil (Stowhas et al., 2018). Health impacts that have been observed include pulmonary tuberculosis (PTB) among underground miners exposed to silica in Zambia (Ngosa and Naidoo, 2016) and exposure to arsenic for smelter workers in China (Sun et al., 2015). High purity Class 1 Nickel, which usually comes from sulfide mines, is most suitable for lithium-ion battery manufacturing. Nickel sulphide mining has had historical environmental impacts in Canada and Russia, including damaging lakes and wetlands (Mudd, 2010a).

Rare earths processing is complex and requires large amounts of chemicals, which are harmful to human health if not managed appropriately, and produces large volumes of solid waste, gas and wastewater (McLellan et al., 2013). In China, where around 80% of the world's rare earths are produced, wastewater from tailings dams has polluted groundwater, which has led to crop failures and the displacement of farming communities (Bontron, 2012). There have also been social conflicts over the Lynas Advanced Materials Plant (LAMP) in Kuantan, Malaysia, which processes concentrate from Western Australia (Ali, 2014). New mines are proposed for Canada, Greenland, Malawi, South Africa and Uganda.

Although lithium mining is generally considered less risky than many other metals, 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). For some metals, such as specialty metals used in PV, little is known about environmental or social impacts, particularly as they are often mined as by-products. Indium, gallium, selenium, cadmium and tellurium are known to be hazardous to human health, and there are reports of lung disease from exposure to indium in manufacturing processes (White and Shine, 2016).

Although the production of metals increases in the energy transition, the production of fossil fuels decreases in the same scenario, this would lead to a reduction in the impacts associated with fossil fuel extraction, particularly coal mining, which can lead to lung damage from exposure to coal dust and kidney disease from the contamination of groundwater (Castleden et al., 2011). Across all mining associated with energy, responsible operations are necessary to avoid negative environmental health impacts for workers and local communities, ensure the respect of human rights and a sustainable energy transition.

An essential point in interpreting the results using TMR as an indicator is that the weight itself may represent pressure, but it does not directly describe the impact. (Stefan et al., 2008). For example, the importance and difficulty of managing the exact weight of extracted material will vary greatly depending on whether or not it contains toxic materials such as radioactive waste. In addition, since TMR captures only soil and rocks, it does not represent in detail other substances to be managed, such as acid mine drainage in mining activities. Therefore, the trend of increased material extraction shown in this study using TMR as an indicator should always be interpreted with these points in mind. In this context, an important contribution of this study is the identification of the scale of material flows and the metals that are likely to lead to the greatest material extraction through increased mining activities, on a global scale and from a long-term perspective. Such information is helpful in raising awareness of the importance of proper management of extracted materials and identifying metals and technologies to focus on when considering interventions from the material consumption side. Chapter 4 delves deeper into this issue by examining the role of mining countries and a circular economy.

3.5 Appendix to Chapter 3

Table 3- 5 Market share of each technology type of solar PV (Wade et al., 2016) [Unit: %].

Technologies	2000	2010	2020	2030	2040	2050
c-Si	100	96	90	89	87	86
CIGS	0	1	5	6	8	9
CdTe	0	3	5	5	5	5

Table 3- 6 Material intensity in Oil, Coal and Natural gas [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminium	500	(Vidal et al., 2013)
Copper	90	
Steel	52500	

Table 3- 7 Material intensity in Carbon Capture and Storage [Unit: t/GW].

Material	Material Intensity	Ref.
Chromium	326	(Moss et al., 2011; R.L. Moss et al., 2013)
Cobalt	8	
Copper	692	
Manganese	3,761	
Molybdenum	8	
Nickel	1,145	
Niobium	100	
Vanadium	100	

Table 3- 8 Material intensity in Nuclear [Unit: t/GW].

Material	Material Intensity	Ref.
Cadmium	1	(Moss et al., 2011)
Chromium	427	
Copper	60	
Hafnium	1	
Indium	2	
Lead	4	
Molybdenum	71	
Nickel	256	
Niobium	2	
Silver	8	
Steel	468,600	
Tin	5	
Tungsten	5	
Vanadium	1	
Yttrium	1	
Zirconium	31	

Table 3- 9 Material intensity in Biomass and Waste [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminium	3,900	(Ashby, 2012)
Chromium	2	
Cobalt	2	
Copper	2,270	
Lead	104	
Nickel	20	
Steel	138,000	
Zinc	160	

Table 3- 10 Material intensity in Hydro [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminium	3,400	(Ashby, 2012)
Chromium	1,500	
Copper	1,050	
Lead	300	
Magnesium	100	
Manganese	200	
Molybdenum	250	
Steel	175,000	
Zinc	400	

Table 3- 11 Material intensity in Geothermal [Unit: t/GW].

Material	Material Intensity	Ref.
Chromium	64,405	(Ashby, 2012; Moss et al., 2011; R. L. Moss et al., 2013)
Copper	2,335	
Manganese	4,325	
Molybdenum	7,209	
Nickel	120,155	
Niobium	128	
Steel	818,000	
Tantalum	64	

Table 3- 12 Material intensity in on shore wind [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminum	1,370	(Ashby, 2012; Bodeker et al., 2010; Falconer, 2009; Fizaine and Court, 2015; García-Olivares et al., 2012; Guezuraga et al., 2012; Habib et al., 2016; Habib and Wenzel, 2016, 2014; Hoenderdaal et al., 2013; Kleijn and Van Der Voet, 2010; Lacal-Arantegui, 2015; Martínez et al., 2009; McLellan et al., 2016; R. L. Moss et al., 2013; Roelich et al., 2014; Teske et al., 2016; U.S. Department of Energy, 2011; VESTAS, 2006; Wilburn, 2011; World Bank Group, 2017; Zimmermann, 2013)
Boron	1	
Chromium	680	
Copper	2,500	
Manganese	57	
Molybdenum	335	
Nickel	430	
Niobium	38	
Praseodymium	3	
Steel	120,000	
Terbium	1	
Tin	90	
Vanadium	90	
Zinc	5150	

Table 3- 13 Material intensity in offshore wind [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminum	2,100	(Ashby, 2012; Bodeker et al., 2010; Falconer, 2009; Fizaine and Court, 2015; García-Olivares et al., 2012; Guezuraga et al., 2012; Habib et al., 2016; Habib and Wenzel, 2016, 2014; Hoenderdaal et al., 2013; Kleijn and Van Der Voet, 2010; Lacal-Arantegui, 2015; Martínez et al., 2009; McLellan et al., 2016; R. L. Moss et al., 2013; Roelich et al., 2014; Teske et al., 2016; U.S. Department of Energy, 2011; VESTAS, 2006; Wilburn, 2011; World Bank Group, 2017; Zimmermann, 2013)
Boron	7	
Chromium	370	
Copper	9,370	
Dysprosium	16	
Manganese	57	
Molybdenum	335	
Neodymium	148	
Nickel	430	
Niobium	38	
Praseodymium	33	
Steel	333,500	
Terbium	7	
Tin	90	
Vanadium	700	
Zinc	5450	

Table 3- 14 Material intensity in Solar PV (c-Si) [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminum	34,500	(Andersson and Jacobsson, 2000; Ashby, 2012; Berry, 2012; Bleiwas, 2010; Bodeker et al., 2010; Elshkaki and Graedel, 2013; Fizaine and Court, 2015; Fthenakis, 2012; Kavlak et al., 2015b; McLellan et al., 2016; R. L. Moss et al., 2013; Stamp et al., 2014; Teske et al., 2016; The Warren Centre, 2016; U.S. Department of Energy, 2011; Valero et al., 2018a; Woodhouse et al., 2013; World Bank Group, 2017)
Chromium	1880	
Copper	4200	
Lead	39	
Molybdenum	200	
Nickel	1	
Steel	1,200,000	
Silicon	6,400	
Silver	30	
Tin	330	
Vanadium	2	
Zinc	1,460	

Table 3- 15 Material intensity in Solar PV (CSIG) [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminum	34,500	(Andersson and Jacobsson, 2000; Ashby, 2012; Berry, 2012; Bleiwas, 2010; Bodeker et al., 2010; Elshkaki and Graedel, 2013; Fizaine and Court, 2015; Fthenakis, 2012; Kavlak et al., 2015b; McLellan et al., 2016; R. L. Moss et al., 2013; Stamp et al., 2014; Teske et al., 2016; The Warren Centre, 2016; U.S. Department of Energy, 2011; Valero et al., 2018a; Woodhouse et al., 2013; World Bank Group, 2017)
Chromium	1880	
Copper	4200	
Gallium	20	
Indium	30	
Molybdenum	200	
Nickel	1	
Selenium	60	
Steel	1,200,000	
Tin	330	
Vanadium	2	
Zinc	1,460	

Table 3- 16 Material intensity in Solar PV (CSIG) [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminum	34,500	(Andersson and Jacobsson, 2000; Ashby, 2012; Berry, 2012; Bleiwas, 2010; Bodeker et al., 2010; Elshkaki and Graedel, 2013; Fizaine and Court, 2015; Fthenakis, 2012; Kavlak et al., 2015b; McLellan et al., 2016; R. L. Moss et al., 2013; Stamp et al., 2014; Teske et al., 2016; The Warren Centre, 2016; U.S. Department of Energy, 2011; Valero et al., 2018a; Woodhouse et al., 2013; World Bank Group, 2017)
Cadmium	87	
Chromium	1880	
Copper	4200	
Lead	8	
Molybdenum	300	
Nickel	1	
Steel	1,200,000	
Tellurium	90	
Tin	330	
Vanadium	2	
Zinc	1,460	

Table 3- 17 Material intensity in Solar CSP [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminum	73,000	(Ashby, 2012; Bodeker et al., 2010; Moss et al., 2011; Pihl et al., 2012; Teske et al., 2016; World Bank Group, 2017)
Chromium	8,400	
Copper	4,500	
Magnesium	4,000	
Manganese	6,400	
Molybdenum	260	
Nickel	2,200	
Niobium	140	
Silver	20	
Steel	970,000	
Titanium	25	
Vanadium	4	
Zinc	2,050	

Table 3- 18 Material intensity in Ocean [Unit: t/GW].

Material	Material Intensity	Ref.
Aluminum	27,500	(Ashby, 2012)
Copper	15,000	
Steel	410,000	

Table 3- 19 Material intensity in vehicles [Unit: g/vehicle].

Material	ICEV	HEV	PHEV	BEV	FCV	Ref.
Lithium	-	132	2,694	6,768	187	(Fishman et al., 2018; R.L. Moss et al., 2013; Rutherford, 2011; U.S. Department of Energy, 2011; Valero et al., 2018a; World Bank Group, 2017)
Magnesium	200	200	200	200	200	
Aluminum	71,300	94,750	110,658	127,302	32,888	
Chromium	-	560	12,789	11,850	-	
Manganese	11,200	4,970	13,399	36,050	3,739	
Steel	921,900	1,056,200	1,185,900	909,500	909,500	
Cobalt	-	753	3,775	13,460	501	
Nickel	-	5,368	11,689	34,589	794	
Copper	22,300	36,300	71,900	92,500	31,500	
Zinc	100	100	100	100	100	
Lanthanum	-	540	-	-	-	
Cerium	-	866	-	-	-	
Praseodymium	-	74	1	1	1	
Neodymium	-	683	876	969	500	
Gadolinium	-	5	-	-	-	
Terbium	-	0	-	-	-	
Dysprosium	-	181	125	279	34	
Erbium	-	0	-	-	-	
Platinum	2	2	2	-	20	
Lead	300	310	320	310	310	

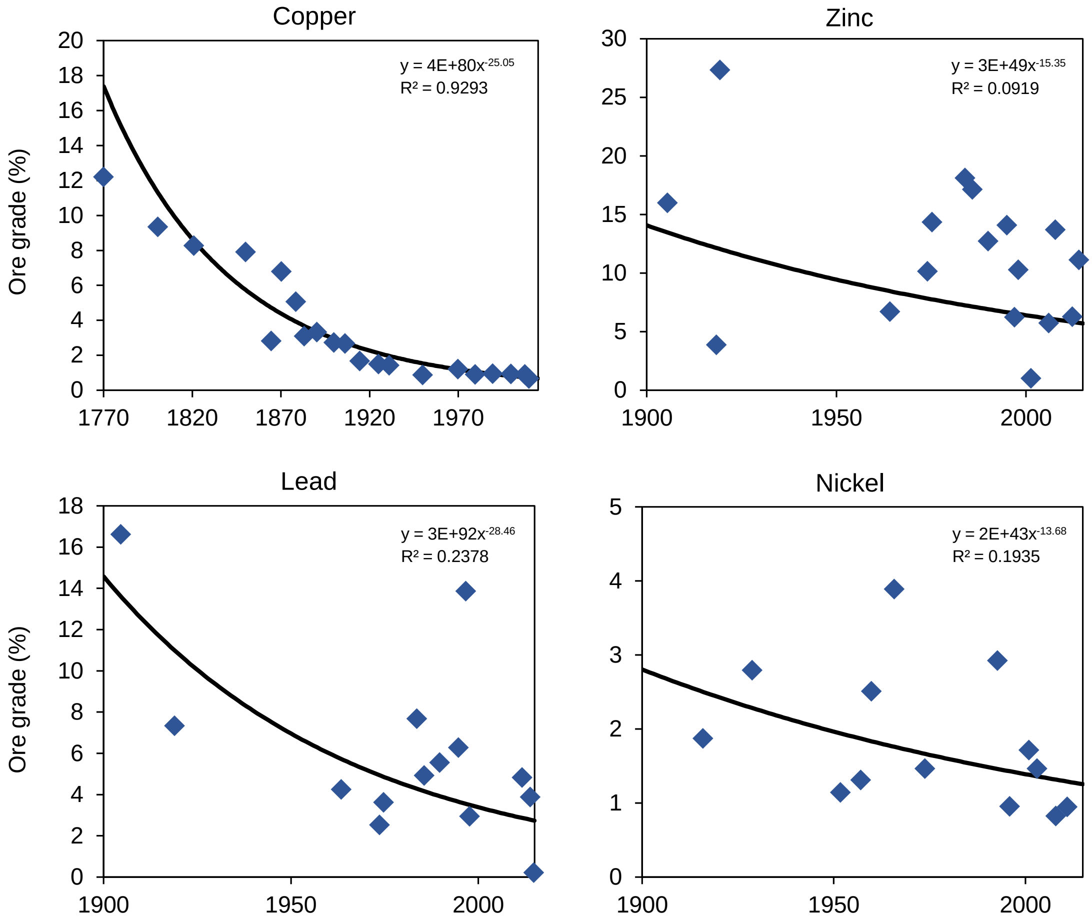

Figure 3- 11 Ore grade decline over time for four metals. Data is adapted from Van der Voet et al. (2019).

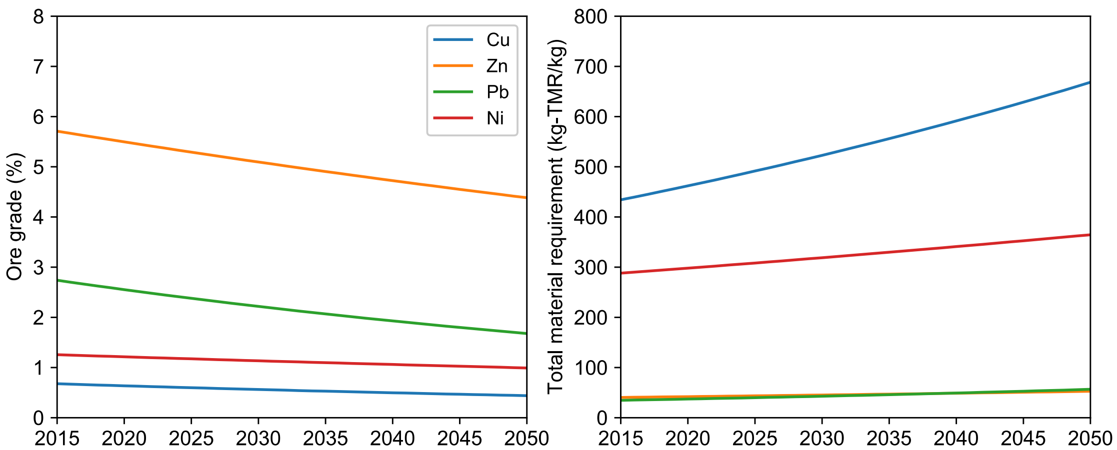

Figure 3- 12 Ore grade and TMR factor for four metals up to 2050. Data is adapted from Van der Voet et al. (2019).

Chapter 4

Role of mining and a circular economy in sustainable energy transition

4.1 Introduction

Chapter 3 showed that the decarbonization of both the electricity and transport sectors could curtail fossil fuel production while increasing material extraction associated with metal production by a factor of more than 7 by 2050 relative to 2015 levels. This observation highlights the inverse relationship between carbon emissions and material extraction. However, the analysis conducted in Chapter 3 lacks the geographical resolution to identify which countries will support the energy transition by their material extraction. Without this information, it is challenging to discuss areas of concern where policy interventions will be most needed (Lèbre et al., 2020). Furthermore, the expectations of many studies regarding the circular economy strategies required for sustainable resource supply are very high (Stahel, 2016); however, despite the potential of the circular economy, empirical analyses of its effect are heavily biased toward end-of-life (EoL) recycling. Consequently, a full range of other possibilities, such as lifetime extension and servitization, are overlooked, as discussed in Chapter 2. The omission of these other possibilities prevents decision makers from understanding the true potential and/or limitations of such strategies.

This chapter, therefore, addresses these research gaps by using material demand-supply models on a country-by-country basis. This chapter also links circular economy strategies (i.e., lifetime extension, servitization, and EoL recycling) to the models to obtain a quantitative understanding of the potential roles of such strategies in the sustainable energy transition.

4.2 Methodology

The basis for the approach employed here is based on Chapter 3. The extracted materials for the global energy transition calculated in Chapter 3 are allocated to each mining country, and the role of circular economy strategies is explored through scenario analysis. Graphical representation of the calculation steps is shown in Figure 4- 1. The scenarios in this chapter are based on the B2DS, which assumes that the rise in global temperatures will remain below 1.75°C to 2100 compared to preindustrial levels (IEA, 2017).

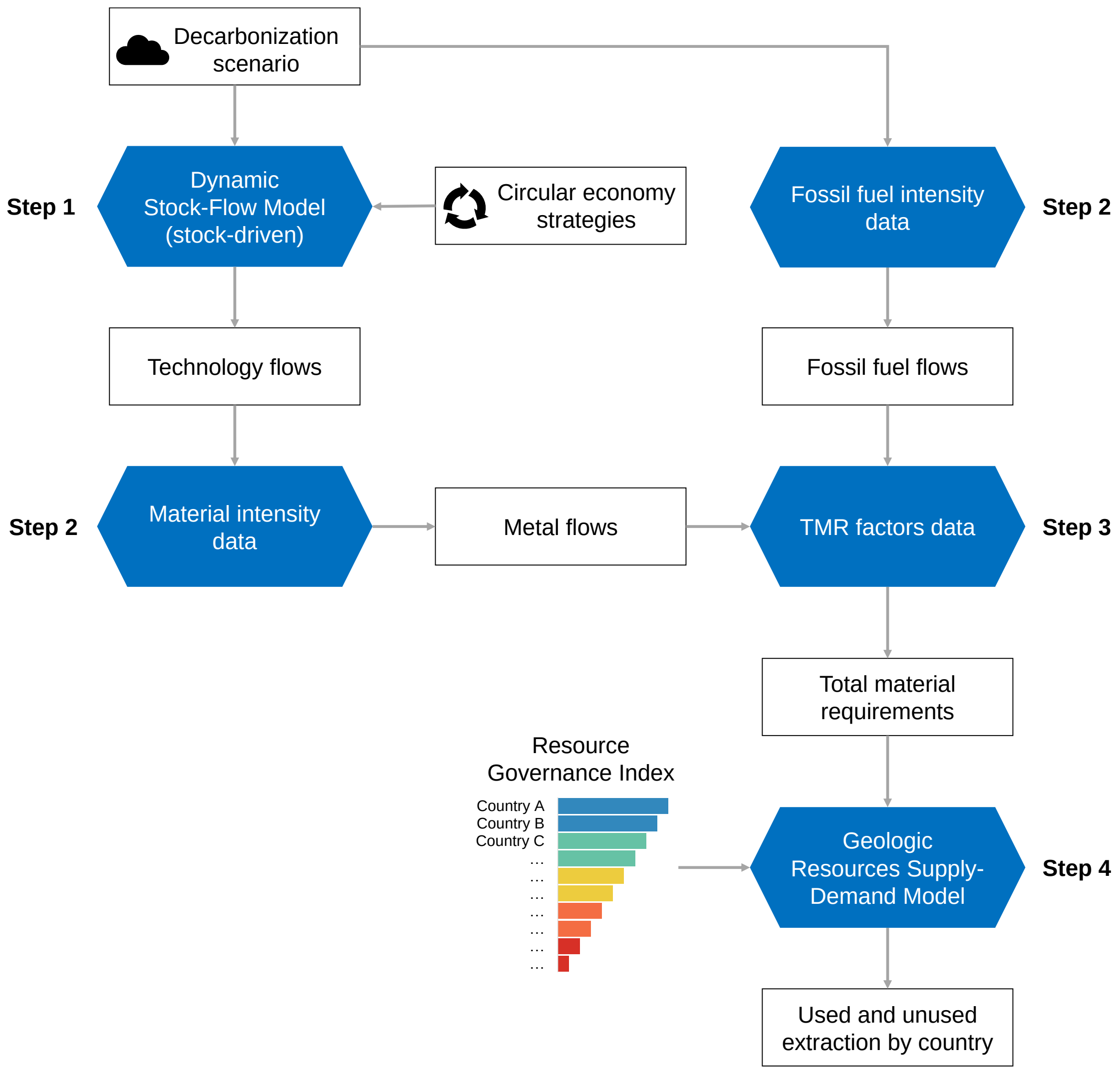

Figure 4- 1 Graphical representation of the calculation steps.

4.2.1 Allocating used and unused material extraction to each mining country

Estimates for material extraction were allocated to each mining country using mine production data on a country-by-country basis. Several approaches, including Hubbard peak theory, system dynamics, and linear programming, have been used to model future mine development. Their effectiveness has been demonstrated in several studies, as shown in Chapter 2. However, most of those models do not have the capability to estimate future mine development on a country-by-country basis for multiple metals. Among the studies reviewed, the Geologic Resources Supply-Demand Model (GeRS-DeMo) is the only model that satisfies two essential factors in this study: it can be applied to multiple metals used in decarbonization technology, and it can estimate future mine development on a country-by-country basis. Thus, future mine production data was obtained by the GeRS-DeMo, which determines when to bring idealized mines online using detailed data on exploitable Ultimate Recoverable Resource. Full details of the model are described by Mohr (2010).

From multiple references, this study obtained data on future production of iron (Mohr et al., 2015), copper (Northey et al., 2014), zinc (Mohr et al., 2018), lead (Mohr et al., 2018), and lithium (Mohr et al., 2012). The other elements for which such data were not available were supplemented by assuming the 2015 production share to be constant over the scenario period (BGS Minerals UK, 2018; U.S. Geological Survey, 2020). Obviously, as different countries have mines that differ in quality and technological capacity, accurate allocation of material extraction to each mining country requires more sophisticated data, including the operational data for each mine (Mudd, 2010b; Northey et al., 2013). Furthermore, given the pressure on the mining industry to protect the environment, mine closure due to environmental constraints may well occur in the future (Lèbre et al., 2019). However, the model simply assumes that the currently identified resources can be used up without facing any environmental constraints other than physical depletion. Thus, the analysis provided here should be regarded as one illustrative scenario rather than a realistic forecast.

The validity of the model was evaluated by comparing the model estimates with the actual values for major metals since 2010. Figure 4- 2 and Figure 4- 3 show that the estimated and actual values are generally in agreement, but there is a certain amount of variation. This can be attributed to the fact that multiple factors such as new mine development and price fluctuations are not considered. Therefore, it should be noted that the results presented in this study are not intended to capture a precise representation of short-term volatility in mine development but rather an overview of long-term trends.

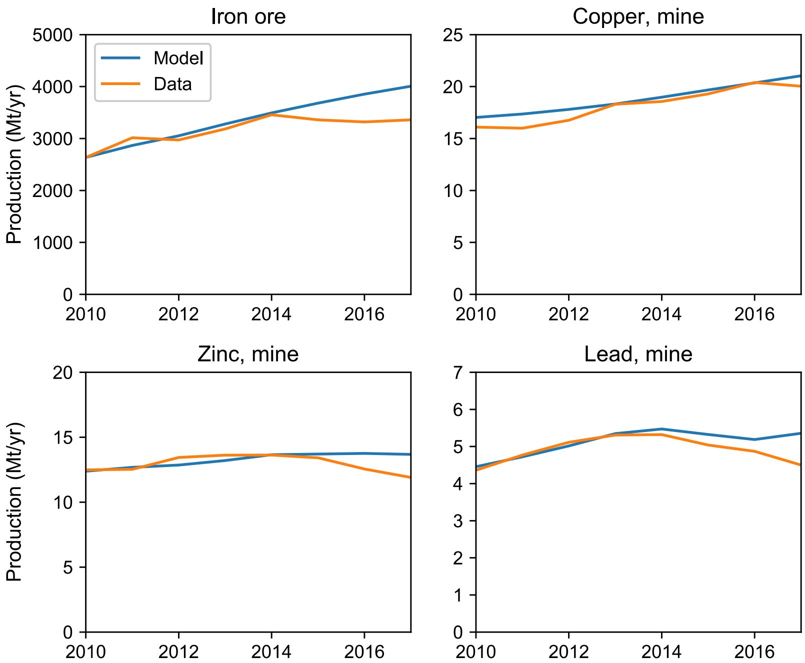

Figure 4- 2 Comparison of estimated and actual mine production of major metals. The actual values were obtained from BGS Minerals UK (2018).

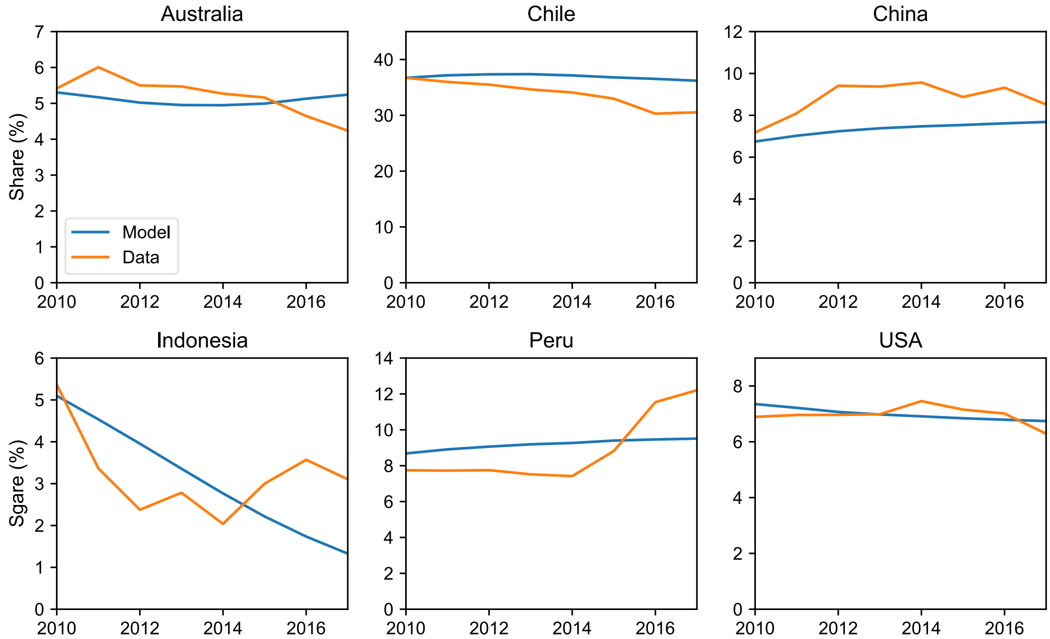

Figure 4- 3 Comparison of estimated and actual copper mine production in major countries. The actual values were obtained from BGS Minerals UK (2018).

This study characterized each mining country by the quality of resource governance using the Resource Governance Index (Natural Resource Governance Institute, 2017), which quantifies the quality of governance of the mining sector in 81 countries. The quality of governance was evaluated as being good, satisfactory, weak, poor, or failing, with each category assigned based on value realization, revenue management, and enabling environment. Insufficient resource governance means that the increase in mining demand is associated with a high risk of improper management due to activities such as unclear licensing practices.

4.2.2 Circular economy scenarios

This study examined the role of circular economy strategies related to solar PV and EVs (PHEVs and BEVs) and their important role in energy transition, in light of the particularly large impacts identified in Chapter 3. With reference to several studies (Dominish et al., 2018; Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017), this study summarized the following main circular economy strategies associated with the two abovementioned technologies (i.e., PHEVs and BEVs) as they relate to reuse, repair, refurbish, remanufacturing, recycling, durable design and servitization. These strategies are reflected in the model parameters of average lifetime, EoL recycling rate, and car ownership.

Lifetime extension (reuse, repair, refurbish, remanufacturing, and durable design)

The lifetime of a product can be extended by durable design or replacement of defective parts. In the case of PV panels, the average lifetime is estimated to be approximately 20 years due to economic reasons, such as the duration of feed-in tariffs, rather than due to degradation (IRENA and IEA-PVPS, 2016). Technically, a PV panel can be reused at a price that is approximately 70% of its original value after a quality check and/or refurbishment (IRENA and IEA-PVPS, 2016). Therefore, this study assumes that the average lifetime can be doubled linearly to 2050 by implementing policies that incentivize progress in the PV panel reuse business. For EVs, the International Resource Panel indicates that a design that allows for easy replacement of parts that wear faster than structural parts can increase product lifetime by 20% (IRP, 2020). This study therefore assumes that extended use can be achieved by 2050, as with PV panels.

Servitization (carsharing and ridesharing)

Focusing on "service provision" rather than "ownership" of products can reduce the need for product ownership while meeting human needs. Sharing cars or journeys is a typical example, and multiple business models have already emerged in this area. In terms of its effects, Martin et al. (2010) showed that per-capita car ownership of car-sharing subscriber households was decreased by half, based on online surveys in North America. Other scientific evidence indicates that ridesharing can reduce vehicle occupancy by 25-75% (Yin et al., 2018). This study assumes that car ownership can be reduced by 25% with the penetration of carsharing and ridesharing which accounts for up to approximately 30% of mileage demand by 2050 (IRP, 2020).

End-of-Life recycling

End-of-life recycling has been intensively studied in the scientific literature and in policy analyses, as shown in Chapter 2. However, little statistical data has been published to date on the current EoL recycling rate of solar PV or EVs. Several studies (Dominish et al., 2019; Giurco et al., 2019; Ziemann et al., 2018) have shown that approximately 80% of the metals used in solar PV and EVs could potentially be recovered. This study therefore assumes that the current recycling rate is 0% and that this can be increased linearly to 80% by 2050. This recycling rate implies a high level of efficiency in the entire recycling chain, consisting of collecting, dismantling, sorting and concentrating of PV and EV components.

4.3 Results

4.3.1 Countries with poor resource governance will underpin the energy transition

Figure 4- 4 shows that a substantial amount of material extraction will occur in countries with weak, poor, and failing resource governance. From 2015 to 2050, around 32% of material extraction associated with metal production in the electricity sector will take place in countries with weak, poor, and failing governance. The situation is worse in the transport sector, where extraction in countries with weak, poor, and failing resource governance accounts for around 40% of the total.

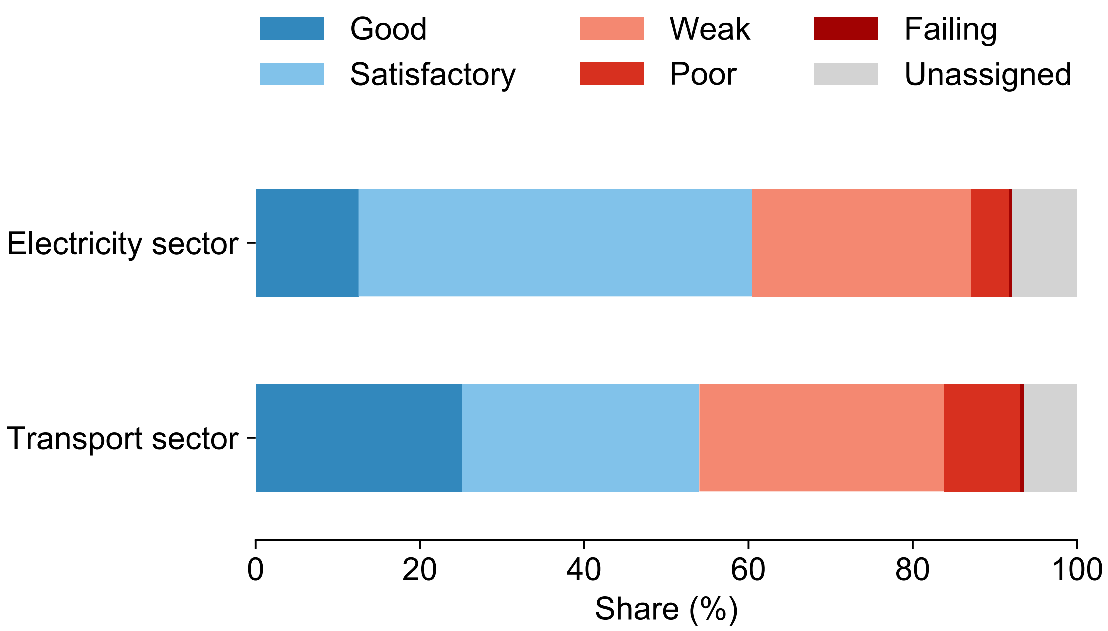

Figure 4- 4 Share of cumulative total material requirements associated with metal production from 2015 to 2050 in regions with different levels of resource governance. The quality of resource governance is evaluated as good, satisfactory, weak, poor, or failing, which are determined by value realization, revenue management, and enabling environment (Natural Resource Governance Institute, 2017).

A closer look at the country-level breakdown shows that while Chile and Australia, which have good and satisfactory resource governance, respectively, are the dominant players in resource extraction, countries with weak and poor resource governance are also high on the list (Figure 4- 5).

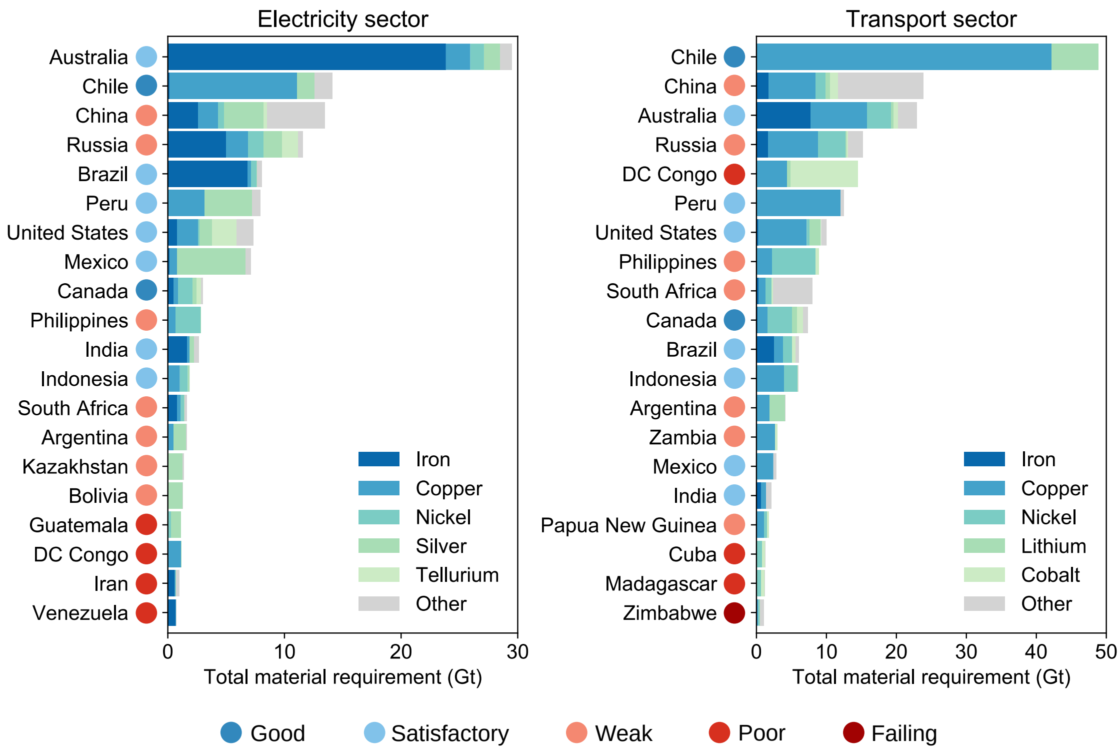

Figure 4- 5 Cumulative total material requirements associated with metal production from 2015 to 2050 in different countries. The top 20 countries with the largest cumulative extraction volume in each sector have been selected. The color of the circle to the right of the country name reflects the quality of resource governance.

The relative change reflects a more problematic picture (Figure 4- 6). Decarbonization of both the electricity and transport sectors will lead to the largest increase in material extraction in countries with poor governance, increasing by factors of 13 and 17, respectively, from 2015 to 2050. This category includes DR Congo, a major producer of cobalt and copper; Madagascar and Cuba, which are nickel-rich countries;

and Guatemala, which is rich in silver. This suggests that, if current trends continue, the rapid increase in mining activities that the energy transition will induce will likely have negative consequences, such as environmental degradation, rather than benefiting local communities.

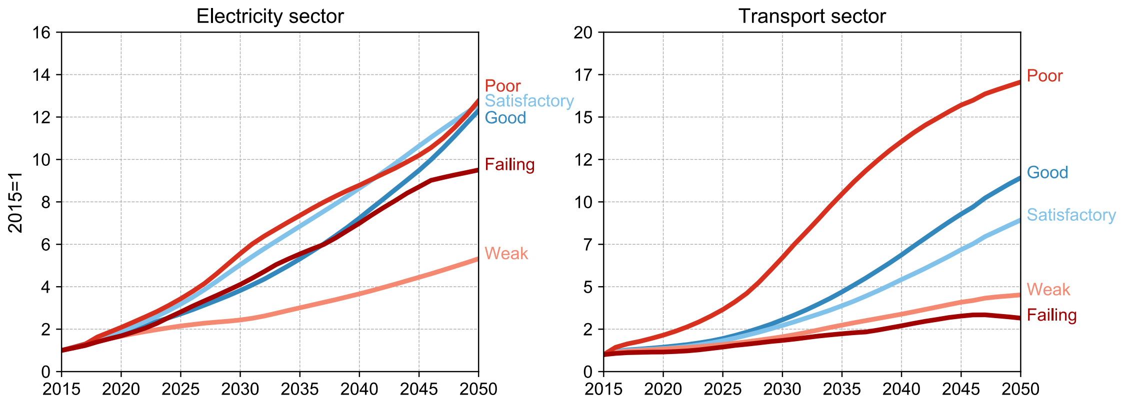

Figure 4- 6 Relative changes in total material requirements associated with metal production in each region with different levels of resource governance, 2015-2050.

4.3.2 Circular economy strategies may not fully offset material extraction growth

The analysis described above indicates that the energy transition will induce a sharp increase in material extraction in countries with insufficient resource governance. An emerging question is to what extent the circular economy strategy can complement the growth of material extraction. Figure 4- 7 shows that a suite of circular economy strategies can reduce material extraction associated with metal production in the electricity sector by 23% in 2050, compared to the case where no such strategies are implemented. Specifically, a 13% reduction could come from lifetime extension and the other 10% reduction from recycling. Looking at the transport sector, a 60% reduction can be achieved by 2050, reflecting the more diverse strategies considered. Closer examination of the effects of each strategy reveals that lifetime extension, through measures such as reuse and repair, could decrease material extraction by 8% in 2050. Combining car- and ride-sharing activities could provide an additional 27% reduction. Further, the addition of EoL recycling could achieve a 25% reduction, resulting in a total reduction of 60%. This finding clearly underscores the importance of implementing circular economy strategies along with the energy transition.

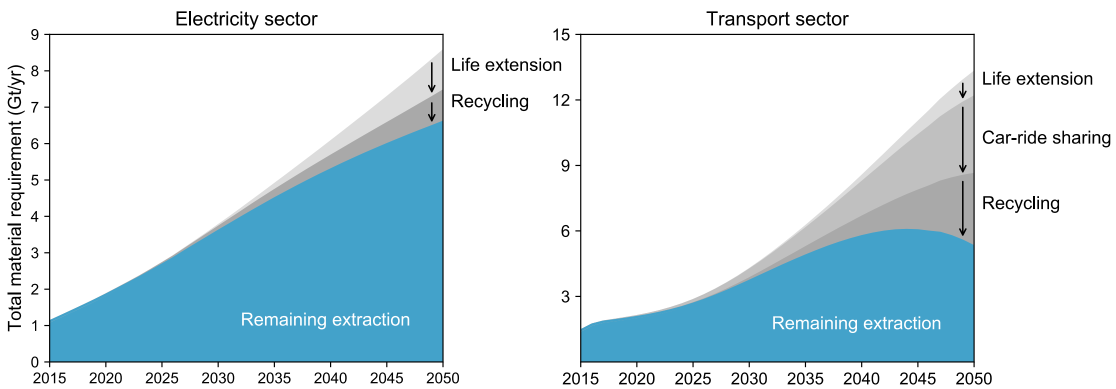

Figure 4- 7 Effects of circular economy strategies on total material requirements associated with metal production, 2015-2050. The circular economy strategies include lifetime extension, servitization (car and ride sharing), and end-of-life recycling.

However, another key perspective in this domain is that the series of the circular economy strategies considered in this paper may not completely offset the increase in material extraction. Namely, at least a seven-fold increase in material extraction is inevitable in countries with poor resource governance, even if circular economy strategies are fully implemented (Figure 4- 8). This simply means that the set of circular economy strategies alone may not completely eliminate the paradox in which energy transition leads to a substantial increase in material extraction in countries with insufficient resource governance. A truly sustainable energy transition will require the implementation of complementary measures to enhance resource governance.

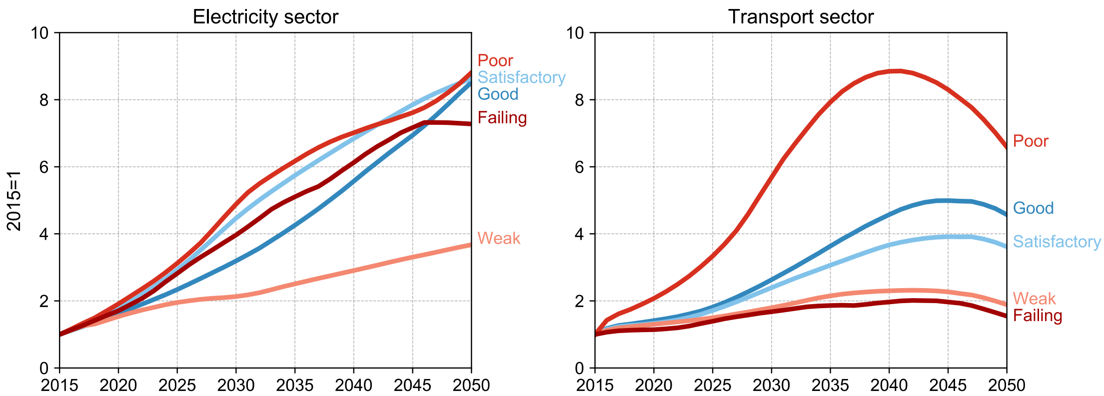

Figure 4- 8 Relative changes in total material requirements associated with metal production in regions with different levels of resource governance under the circular economy scenario.

4.4 Discussion

This study showed that the increased extraction of materials associated with the energy transition could be heavily concentrated in countries with weak, poor, and failing resource governance. This means that the impending mining boom driven by the energy transition could result in severe socio-environmental damage rather than benefitting local communities due to improper management of the extracted materials. Such outcomes should be carefully considered by energy policymakers, particularly with detailed knowledge of local contexts and using deliberative approaches, to navigate potentially deleterious trade-offs in this complex area. Accordingly, in the absence of effective mitigation measures, the energy transition may present policymakers and shareholders with an ethical conundrum in which a reduction in global carbon emissions is associated with a variety of socio-environmental risks at the local mining site. This can ultimately lead to a worsening of the spatial disparities between "material-consuming" and "material-producing" countries (Prior et al., 2013).

The analysis highlights the considerable potential of circular economy strategies regarding such issues. In particular, a set of strategies comprising lifetime extension, sharing and recycling of EVs can reduce material extraction by more than half compared to not implementing these strategies by 2050. In this context, while previous studies have indicated that EoL recycling has the greatest potential for reducing the primary demand for metals (Dominish et al., 2019; Watari et al., 2018), this study adds another perspective that needs to be considered. That is, other strategies, including lifetime extension and sharing practices, have the same or even greater potential to reduce material extraction as EoL recycling. This clearly emphasizes the importance of exploring a cross-cutting strategy that spans the entire life-cycle of decarbonization technologies, not just the waste management stage.

In this regard, another important perspective obtained from this study is that a suite of circular economy strategies alone will not entirely offset the concomitant increase in material extraction in countries with weak, poor, and failing resource governance. Responsible sourcing will be required where supply cannot be met by circular resource flows. In this context, initiatives related to responsible sourcing or ethical minerals schemes, such as the IRMA Standard for Responsible Mining, CERA (certification of raw materials), and the Responsible Cobalt Initiative could play a significant role (Ali et al., 2017; Brink et al., 2021). Given the characteristics of decarbonization technologies that utilize a diversity of metals, and which have a high reliance on mining countries with weak, poor, and failing governance, these initiatives need to be adapted widely and immediately to achieve truly sustainable energy transition. Clearly, improving resource governance is not a trivial task, and improvements will require a variety of approaches, not just certification schemes (Ali et al., 2017). This study does not directly identify the best way in which resource governance can be improved, but it does identify the main areas of concern, including technologies, metals, and countries, that require attention.

Overall, the message is clear. First, a set of circular economy strategies spanning the entire life-cycle of decarbonization technologies, not just EoL recycling, needs to be implemented to effectively mitigate the rapid increase in material extraction in countries with weak, poor, and failing resource governance. Second, there is a need for widespread adaptation of responsible sourcing frameworks, such as verified certification schemes, to compensate for supplies that cannot be met by circular material flows. If such instruments can be optimized, then increased mining demand could be an important source of economic growth, and adverse socio-environmental impacts could be avoided (IRP, 2019a; Sovacool et al., 2020). Energy transition with enhanced resource governance therefore presents important opportunities, not only for mitigating climate change, but also for achieving a broader set of sustainable development goals (United

Nations, 2015), such as SDGs1 (no poverty) and SDGs8 (decent work and economic growth).

4.5 Appendix to Chapter 4

Table 4- 1 The quality of resource governance by each country based on the Natural Resource Governance Index (Natural Resource Governance Institute, 2017).

Country	Score	Classification
Norway	86	Good
Chile	81	Good
United Kingdom	77	Good
Canada	75	Good
United States	74	Satisfactory
Brazil	71	Satisfactory
Colombia	71	Satisfactory
Australia	71	Satisfactory
India	70	Satisfactory
Colombia	69	Satisfactory
Indonesia	68	Satisfactory
Ghana	67	Satisfactory
Trinidad and Tobago	64	Satisfactory
Mongolia	64	Satisfactory
Peru	62	Satisfactory
Mexico	61	Satisfactory
Botswana	61	Satisfactory
Burkina Faso	59	Weak
Philippines	58	Weak
Argentina	57	Weak
South Africa	57	Weak
Ghana	56	Weak
Kazakhstan	56	Weak
Tunisia	56	Weak
Malaysia	56	Weak
Cote d'Ivoire	55	Weak
China	55	Weak
Cameroon	54	Weak
Niger	54	Weak
Ecuador	54	Weak
Kuwait	54	Weak
Bolivia	54	Weak
Mali	53	Weak
Tanzania	53	Weak
Morocco	52	Weak
Kyrgyz Republic	51	Weak
Oman	50	Weak
Zambia	50	Weak
Mozambique	50	Weak
Tanzania	49	Weak

Country	Score	Classification
Timor-Leste	49	Weak
Ukraine	49	Weak
Vietnam	48	Weak
Papua New Guinea	47	Weak
Azerbaijan	47	Weak
Tunisia	46	Weak
Sierra Leone	46	Weak
Russia	45	Weak
Uganda	44	Poor
Liberia	44	Poor
Qatar	43	Poor
United Arab Emirates	42	Poor
Nigeria	42	Poor
Guatemala	41	Poor
Ethiopia	40	Poor
Bahrain	39	Poor
Egypt	39	Poor
Iraq	38	Poor
Iran	38	Poor
Guinea	38	Poor
Lao PDR	38	Poor
Gabon	36	Poor
Cuba	36	Poor
Bangladesh	36	Poor
Madagascar	36	Poor
Saudi Arabia	36	Poor
Angola	35	Poor
Afghanistan	34	Poor
Chad	34	Poor
Algeria	33	Poor
Venezuela	33	Poor
Congo, Democratic Republic	33	Poor
South Sudan	32	Poor
Myanmar	31	Poor
Yemen	30	Poor
Cambodia	30	Poor
Uzbekistan	29	Failing
Zimbabwe	29	Failing
Mauritania	29	Failing
Myanmar	27	Failing
Equatorial Guinea	22	Failing
Sudan	21	Failing
Libya	18	Failing
Turkmenistan	11	Failing
Eritrea	10	Failing

Chapter 5

International inequality in in-use metal stocks

5.1 Introduction

Metals, in the form of in-use stocks, underpin many of the essential functions of modern society, such as housing, transportation, and communications (Pauliuk and Müller, 2014). However, the extraction and processing involved in creating and maintaining metal stocks is currently putting heavy pressure on the environment (IRP, 2019b). This includes land modification, water contamination, air pollution, and climate change—all of which have attracted significant attention in recent years, as shown in Chapter 2.

The climate change impacts associated with metal production are particularly serious. Despite significant efforts to improve energy efficiency in the metals industry (Wang et al., 2021), increased production has led to increased GHG emissions associated with metals production from 1.9 Gt-CO_2e in 1995 to 4.4 Gt-CO_2e in 2016 (Hertwich, 2021). A deep and rapid reduction in GHG emissions from metal production is clearly a critical condition for achieving climate goals. However, the literature review in Chapter 2 revealed a lack of quantitative understanding of the impact of time-series carbon constraints on long-term metal flows and stock dynamics. This gap prevents a better understanding of the relationship between carbon constraints and metal cycles, and makes it difficult to discuss interventions to reconcile climate change mitigation with sustainable metal use.

How in-use metal stocks have been distributed over time across the globe can provide context and direction to such discussions. Information in this area is sure to give useful insights into future demand growth, secondary resources potential and provide a basis for examining future scenarios of the global metal cycles under the carbon constraints in the production process. To date, however, data on the global distribution of in-use metal stocks have been highly fragmented among several case studies using slightly different analytical frameworks (Liu and Müller, 2013; Müller et al., 2011; Pauliuk et al., 2013b; Rauch, 2009). Moreover, such previous studies do not quantify the degree of international inequality in metal stocks, even though comparable data exist for various environmental indicators, including carbon emissions (Duro, 2016), water use (Zhan-Ming and Chen, 2013), land use (Teixidó-Figueras et al., 2016), and ecological footprint (Duro and Teixidó-Figueras, 2013). The absence of this type of metals-related information makes it difficult to discuss future metal stock evolution patterns from an equitable and just transition perspective. In two related studies targeting metals, Steinberger et al. (2010) and Schaffartzik et al. (2019) analyzed the international inequality of material flows. However, as material *flow* itself does not provide a service, the implications for human development are, at best, rather limited (Pauliuk et al., 2013a). In order to capture important characteristics of the services provided by metal use, it is necessary to understand the global distribution patterns of metal *stocks* rather than flows (Haberl et al., 2017).

Accordingly, this chapter aims to elucidate distribution patterns and inequality in global metal stocks over time. This is accomplished by constructing and applying a global metal cycle model that tracks overall metal flows and stock dynamics for 231 countries and regions over a 110-year period, from 1900 to 2010. The study covers six major metals—iron, aluminum, copper, zinc, lead, and nickel—which together account for more than 98% by mass of all metal production (U.S. Geological Survey, 2020) and are responsible for approximately 95% of the GHG emissions associated with metal production (Hertwich, 2021).

5.2 Methodology

5.2.1 Mass balance equations

This study built a global metal cycle model that tracks the entire metal flows and stock dynamics for 231 countries and regions from 1900 to 2010. The model covers all processes of the metal life cycle, which consists of ore extraction, processing, manufacturing, in-use stock, and waste management, along with the losses that occur in each stage. Figure 5- 1 represents the system definition of the anthropogenic major metal cycles consisting of a series of processes, from extracting natural resources from the lithosphere to waste management. The flow indicated by X is an economic flow; ℓ denotes the loss to the environment that occurs in each process.

To capture the metal flows associated with international trade, this study compiled trade volume data in monetary and physical units by using the BACI (Base pour l'Analyse du Commerce International) database (CEPII. BACI (Base pour l'Analyse du Commerce International), 2018), which is an improved version of the UN Comtrade database. The system boundaries and basic methods for selecting traded commodities are based on existing studies (Nakajima et al., 2018; Nansai et al., 2014). The number of commodities considered to contain each metal is 543 for steel, 264 for aluminum, 288 for copper, 272 for zinc, 254 for lead, and 303 for nickel. Data for the production of ore, concentrates, and refined metal were taken from World Bureau Metals Statistics (World Bureau Metal Statistics, 2015) and the U.S. Geological Survey database (U.S. Geological Survey, 2020). Other model input data such as market share and yield ratios were gathered based on existing studies involving material flow analysis for each metal. The basis of the model is the mass conservation law, and all metal flows are determined by the mass balance equations shown as equations (5-1)-(5-13) The in-use stock was estimated using the dynamic inflow-driven approach (Wiedenhofer et al., 2019), assuming the average lifetime of each product category. More specifically, this is a time-cohort-type approach that derives the in-use metal stocks from the sum of the metal inflows embedded in surviving products each year. Thus, the in-use stock of metal is defined as the apparent quantity of material in products that are in-use in any given year. A detailed explanation is below.

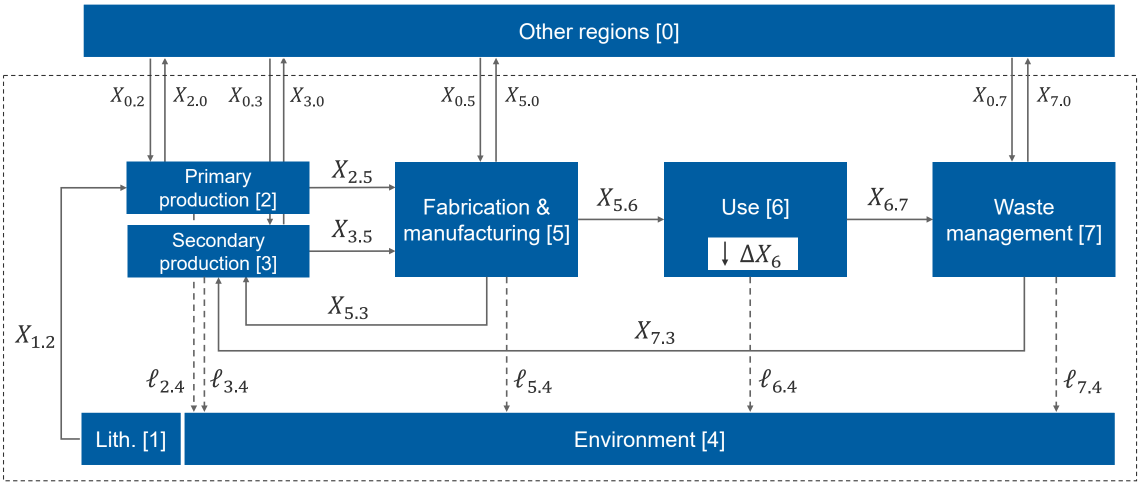

Figure 5- 1 System definition of the anthropogenic major metal cycles. The dashed line indicates the system boundary of the target country or region.

Table 5- 1 List of system variables.

Symbol	Description
$X_{1.2}$	Extracted ore
$X_{2.5}$	Primary production
$X_{3.5}$	Secondary production
$X_{5.3}$	New scrap
$X_{7.3}$	Old scrap
$X_{5.6}$	Final product
ΔX_6	Stock change
$X_{6.7}$	End-of-life product
$X_{a.0},\ a \in (2,3,5,7)$	Exports to other regions
$X_{0.a},\ a \in (2,3,5,7)$	Imports from other regions
$\ell_{a.4},\ a \in (2,3,5,7)$	Tailing, slag, scaling losses, and landfilled wastes
$\ell_{6.4}$	In-use dissipation

The output of each process is defined as follows:

Raw material production

$$X_{2.5} = \delta(X_{1.2} + X_{0.2} - X_{2.0}) \tag{5-1}$$

$$\ell_{2.4} = X_{1.2} + X_{0.2} - X_{2.0} - X_{2.5} \tag{5-2}$$

$$X_{3.5} = \theta(X_{5.3} + X_{7.3} + X_{0.3} - X_{3.0}) \tag{5-3}$$

$$\ell_{3.4} = X_{5.3} + X_{7.3} + X_{0.3} - X_{3.0} - X_{3.5} \tag{5-4}$$

where δ and θ are the primary and secondary production yields, respectively.

Product fabrication and manufacturing

$$X_{5.6} = \lambda(X_{2.5} + X_{3.5} + X_{0.5} - X_{5.0}) \tag{5-5}$$

$$X_{5.3} = \xi(1 - \lambda)(X_{2.5} + X_{3.5} + X_{0.5} - X_{5.0}) \tag{5-6}$$

$$\ell_{5.4} = X_{2.5} + X_{3.5} + X_{0.5} - X_{5.0} - X_{5.3} - X_{5.6} \tag{5-7}$$

Here, λ represents the manufacturing yield and ξ denotes the new scrap collection rate.

In-use stock

$$\Delta X_6 = X_{5.6} - X_{6.7} \tag{5-8}$$

$$\ell_{6.4} = \omega X_{5.6} \tag{5-9}$$

Here, ω denotes in-use dissipation loss rate.

Assuming that the flow into the in-use stock phase in year t is $X_{5.6}(t)$ and the lifetime distribution is ϕ, then outflows from the in-use stock phase in year t, $X_{6.7}(t)$, can be defined as follows:

$$X_{6.7}(t) = \sum_{t'=0}^{t}((1-\omega)X_{5.6}(t')\phi(t-t')) \quad (5\text{-}10)$$

Therefore, the in-use stock at time τ representing the end of the year t, $X_6(\tau)$, can be calculated by the simple mass balance:

$$X_6(\tau) = \sum_{t'=0}^{t}\big((1-\omega)X_{5.6}(t') - X_{6.7}(t')\big) \quad (5\text{-}11)$$

Waste management and recycling

$$X_{7.3} = \gamma(X_{6.7} + X_{0.7} - X_{7.0}) \quad (5\text{-}12)$$

$$\ell_{7.4} = X_{6.7} + X_{0.7} - X_{0.7} - X_{7.3} \quad (5\text{-}13)$$

Here, γ is the old scrap collection rate.

5.2.2 Measuring inequality in global metal stock

This study quantified the international inequality in metal stocks using the Gini coefficient (Gastwirth, 1972), which is derived from the Lorenz curve and is widely used to measure inequality (most commonly, in income) (Wiedenhofer et al., 2017). In this case, the Lorenz curve for metal stock was produced by arranging the global population in order of increasing metal stock per capita, then showing of the cumulative ratio (percentage) of the population on the horizontal axis and the cumulative ratio (percentage) of stock on the vertical axis. In the case of perfect equality, the Lorenz curve coincides with the 45-degree line. In all other cases, the greater the inequality, the more the curve bulges downward from the line. The Gini coefficient can be derived directly from the Lorenz curve. Defining the area between the Lorenz curve and the 45-degree line as X and the area under the Lorenz curve as Y, the Gini coefficient can be expressed as X/(X+Y). The value of the Gini coefficient ranges from 0 to 1, where 0 denotes perfect equality and 1 represents absolute inequality.

5.2.3 IPAT analysis

To better understand the history of the metal stock distribution, this study applied the standard IPAT identity to explore the key determinants of metal stock growth. The original IPAT identity explains impact (I) using three drivers: population (P), affluence (A) and technology (T) (Waggoner and Ausubel, 2002). This simple decomposition analysis has been widely applied in various studies analyzing drivers of material flows and stocks (Fishman et al., 2015; Schandl et al., 2018; Schandl and West, 2010). In these cases, affluence is often expressed as per capita GDP, and technology as material flow or stock per GDP. This study took a similar approach: $\mathrm{Stock} = \mathrm{POP} \times \frac{\mathrm{GDP}}{\mathrm{POP}} \times \frac{\mathrm{Stock}}{\mathrm{GDP}}$. As the interest of this study is in per capita stock growth, the population multiplier is removed. The logarithmic transformation thus yields the following equation for comparing different time periods:

$$\Delta \log\left(\frac{\mathrm{Stock}_r}{\mathrm{POP}_r}\right) = \Delta \log\left(\frac{\mathrm{GDP}_r}{\mathrm{POP}_r}\right) + \Delta\log\left(\frac{\mathrm{Stock}_r}{\mathrm{GDP}_r}\right) \tag{5-14}$$

Here, $\mathrm{Stock_r/POP_r}$ represents the metal stock per capita in region r, $\mathrm{GDP_r/POP_r}$ denotes gross domestic products per capita in region r, and $\mathrm{Stock_r/GDP_r}$ is the metal stock intensity of the economy in region r. This study applied equation (5-14) using intervals of 10 years for the years between 1970 and 2010 (i.e., 1970 to 1980, 1980 to 1990, 1990 to 2000, 2000 to 2010).

5.3 Results

5.3.1 Significant inequalities in international metal stocks

The six major metals were unevenly distributed across the globe (from Figure 5- 2 to Figure 5- 7). In 2010, the global average of per capita stock reached about 3,700 kg/cap for iron, 97 kg/cap for aluminum, 48 kg/cap for copper, 19 kg/cap for zinc, 7 kg/cap for lead, and 4 kg/cap for nickel. In-use stocks of metals are highly concentrated in regions such as North America, Western Europe, and developed Asia—areas where the per capita stocks are roughly 3 to 4 times the world average. In contrast, the level in most developing countries, such as those in Africa, is slightly less than 10% of the world average. To a great extent, this contrast reflects the uneven economic development and the consequent disparity in major metal use in products and infrastructure across the world.

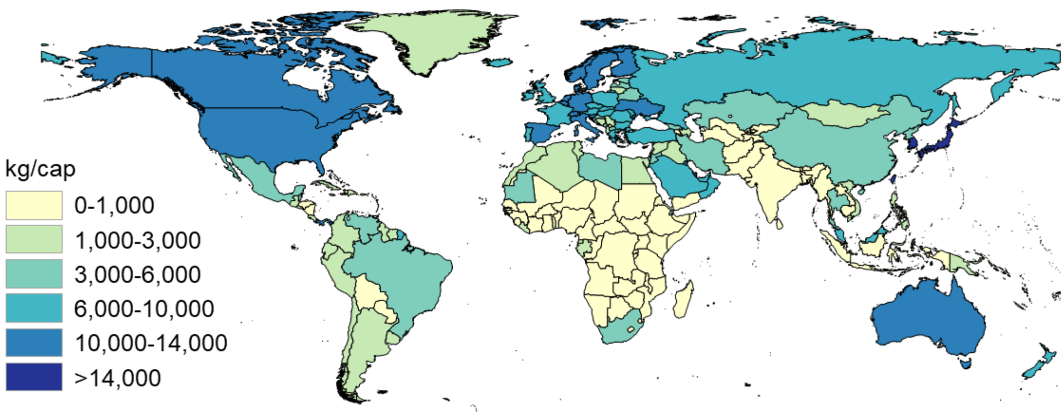

Figure 5- 2 Global distribution of per capita iron and steel stocks in 2010

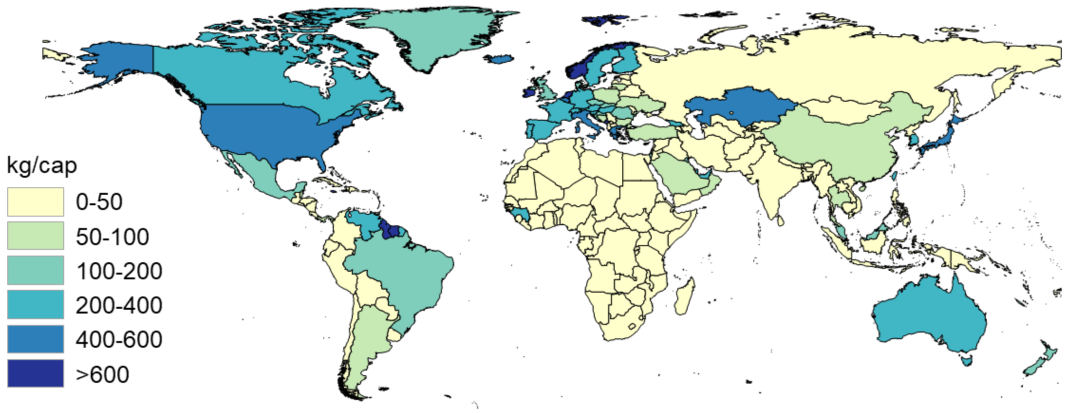

Figure 5- 3 Global distribution of per capita aluminum stocks in 2010

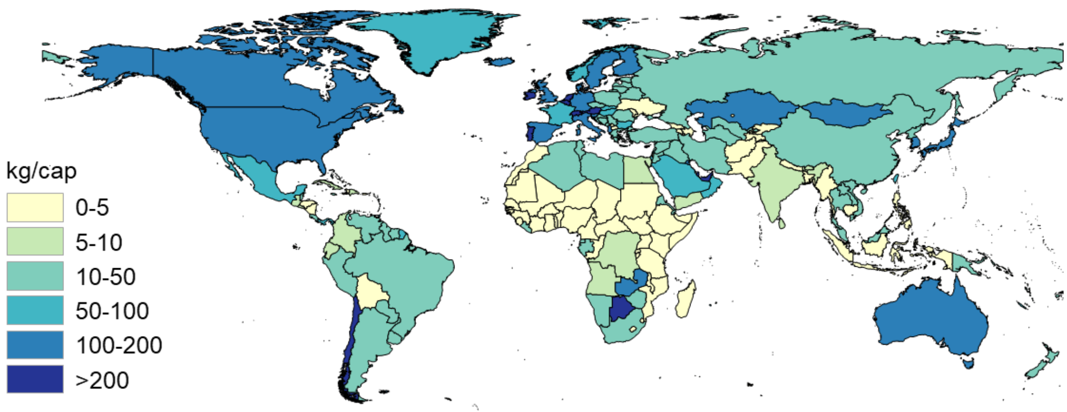

Figure 5- 4 Global distribution of per capita copper stocks in 2010

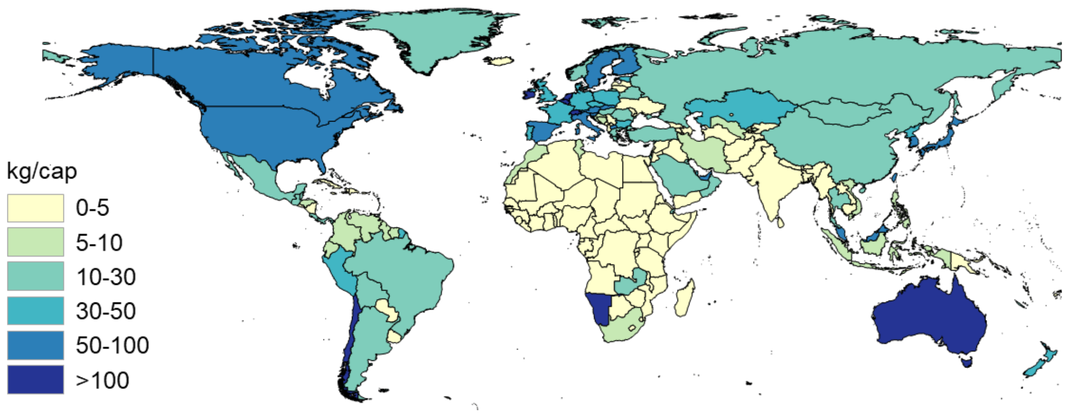

Figure 5- 5 Global distribution of per capita zinc stocks in 2010

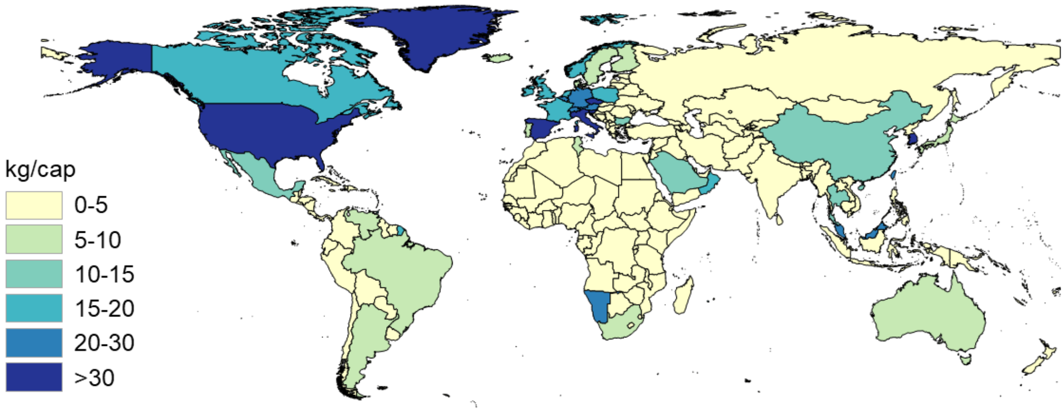

Figure 5- 6 Global distribution of per capita lead stocks in 2010

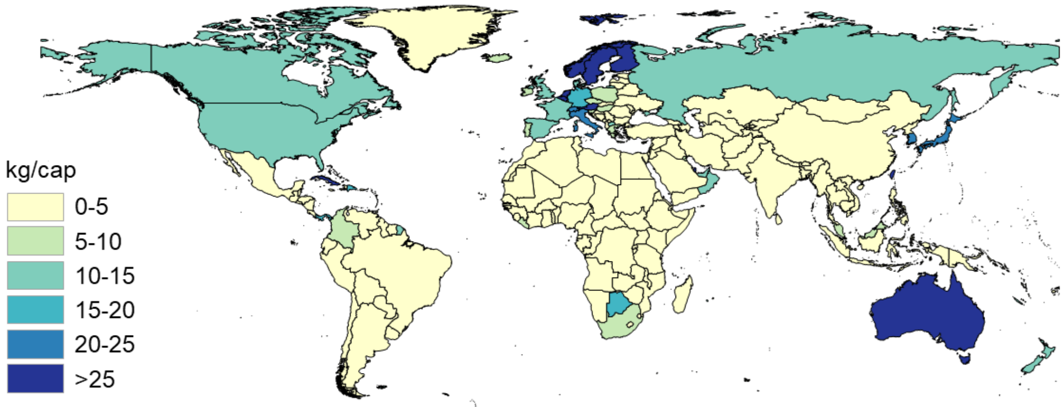

Figure 5- 7 Global distribution of per capita nickel stocks in 2010

Such global inequality can be expressed quantitatively by the Gini coefficient, where 0 denotes perfect equality and 1 represents absolute inequality. The estimated Gini coefficient of per capita metal stock ranges from 0.57 to 0.73 depending on the metal (Table 5- 2). A closer look at each of the six metals shows that iron is the most evenly distributed, followed by zinc, aluminum, copper, lead and nickel. This is perhaps because iron, zinc, and aluminum are more often used for basic infrastructure (e.g., bridges and roads) than the other metals, and are thus distributed more rapidly in the early stages of economic development. Surprisingly, the top 20% of the population (based on per capita stocks) accounts for roughly 60% of steel, 70% of aluminum, 62% of copper, 60% of zinc, 58% of lead, and 75% of nickel stocks, while the lowest 20% accounts for only about 1% of the total stock for all six metals (Figure 5- 8).

By way of comparison, the disparities indicated by these values exceeds global disparities in per capita energy consumption (0.55), carbon emissions (0.52), land-use intensity (0.42), and ecological footprint (0.38) (Table 5- 2), clearly indicating the substantial inequalities in international metal stocks. These observations underscore the undeniable fact that the use of these major metals, whose extraction and processing negatively impact the Earth's environment, but on which humanity depends, is unevenly distributed across countries according to income level.

Table 5- 2 Gini coefficient of metal stocks and other environmental indicators. The value of the Gini coefficient ranges from 0 to 1, where 0 denotes perfect equality and 1 represents absolute inequality (Gastwirth, 1972). All indicators are referred to in per-capita terms.

	Gini coefficient	Reference year	Ref.
Iron and steel stock	0.57	2010	This study
Aluminum stock	0.66	2010	This study
Copper stock	0.67	2010	This study
Zinc stock	0.61	2010	This study
Lead stock	0.73	2010	This study
Nickel stock	0.73	2010	This study
Energy consumption	0.55	2010	(Lawrence et al., 2013)
CO_2 emission	0.52	2010	(Lawrence et al., 2013)
Land use intensity	0.42	2000	(Teixidó-Figueras et al., 2016)
Ecological footprint	0.38	2007	(Teixidó-Figueras and Duro, 2015)

How have the unequal distribution patterns of global in-use metal stocks changed over time? Figure 5- 8 shows the Gini coefficients for each of the six metals from 1970 to 2010. As illustrated here, the international inequality in all the major metal stocks has been steadily decreasing over time. Depending on the metal, the Gini coefficients in 2010 were approximately 18-34% lower than they were in 1970. This is primarily because a number of upper-middle-income countries (mainly in developing Asia) are rapidly catching up with the stock levels of the high-income countries (Figure 5- 9). In particular, the per capita stock growth rate of the upper-middle-income countries between 1990 and 2010 was a robust 120-490%, while the growth rate in the high-income countries was only 26-63%, resulting in a substantial reduction in the Gini coefficients.

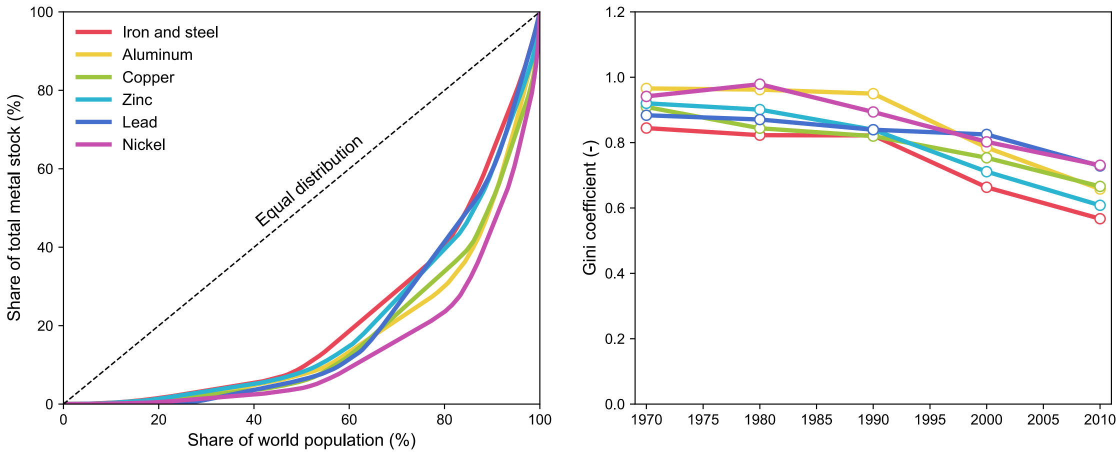

Figure 5- 8 Lorenz curves of international metal in-use stocks in 2010 and Gini coefficients from 1970 to 2010.

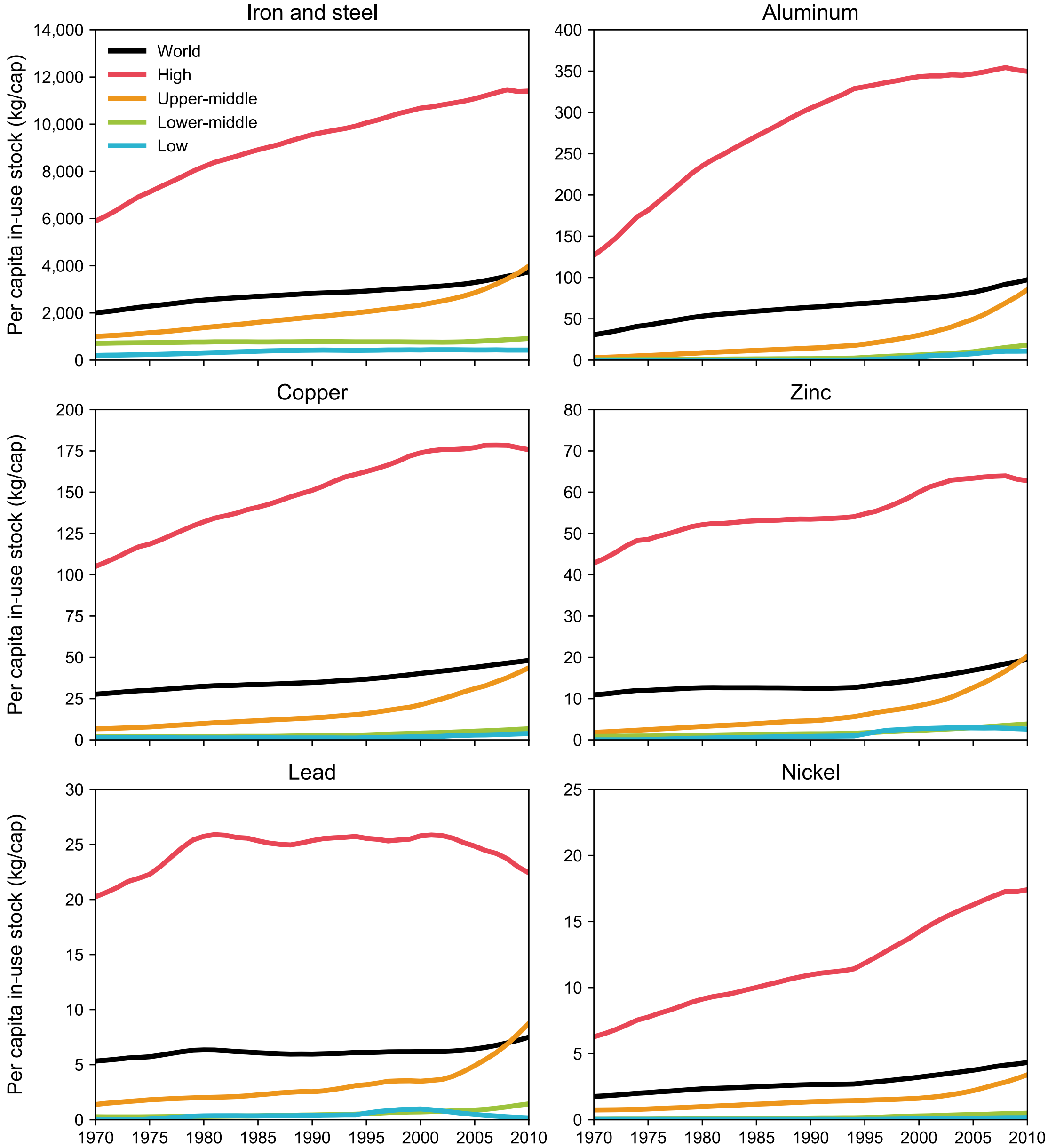

Figure 5- 9 Per capita metal stocks of different income groups, 1970-2010. Income-grouping is based on the World Bank classification; the 2010 classification is used throughout.

5.3.2 Comparison of results with previous studies

The validity of the results was explored by comparing the results of this study with the global metal stock estimated by a previous analysis with different regional resolutions (Krausmann et al., 2017). This study estimated in-use metal stocks in 231 countries and regions around the world, while Krausmann et al. (2017) provided estimates based on three regions (industrial, China, and the rest of the world).

The difference between these two estimates for the last 20 years is generally less than ±8%; thus, the results in this study can be regarded as at least not extreme (from Figure 5- 10 to Figure 5- 12). While the lack of statistical data on metal stocks makes a perfect validation difficult, the general agreement between the two estimates using slightly different models confirms that the results of this study are plausible based on the previous study.

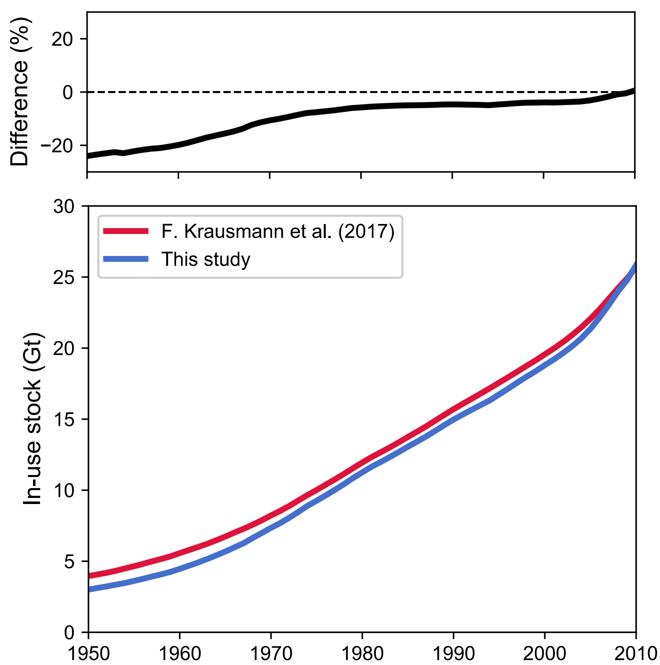

Figure 5- 10 Comparison of the estimated historical iron and steel stock in this study with Krausmann et al. (2017).

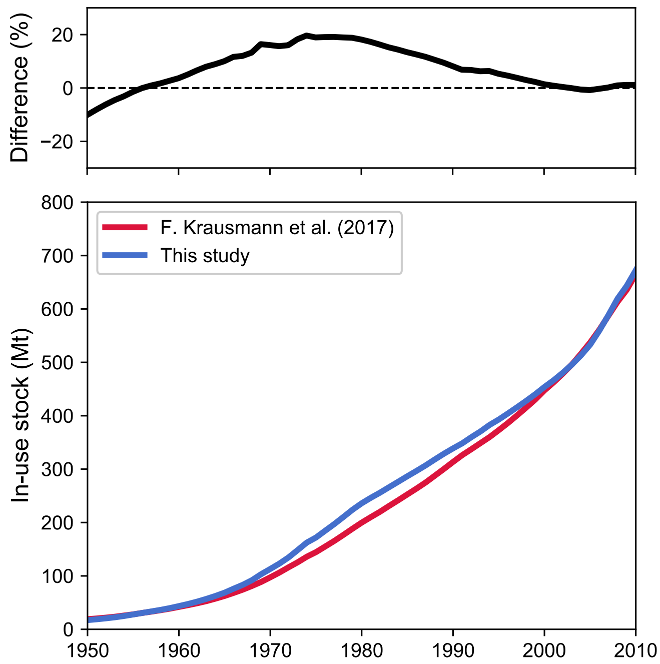

Figure 5- 11 Comparison of the estimated historical aluminum stock in this study with Krausmann et al. (2017).

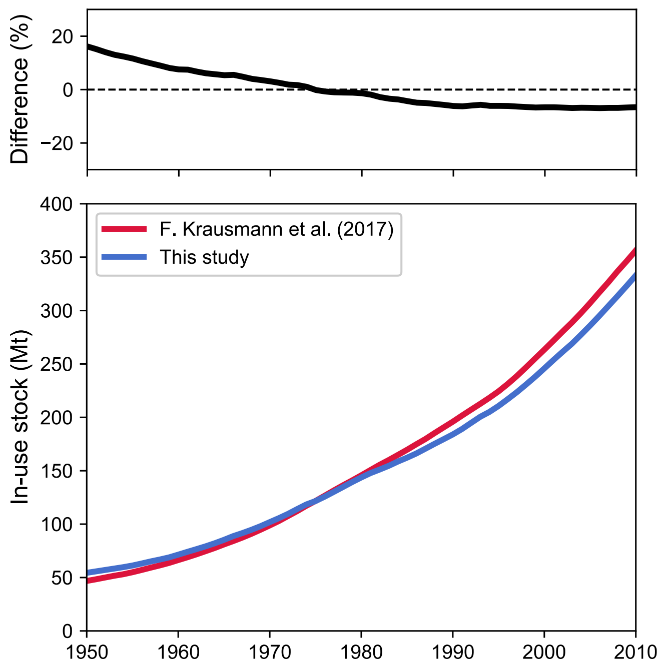

Figure 5- 12 Comparison of the estimated historical copper stock in this study with Krausmann et al. (2017).

5.3.3 Drivers of per capita metal stock changes

To better understand the drivers of historical metal stock changes, this study decomposed the factors of per capita stock change into affluence (GDP per capita) and stock intensity (metal stock per GDP) as a proxy for technology based on the standard IPAT identity. Population factors were not taken into account, as the focus here was on per capita stock change.

Table 5- 9 through Table 5- 14 show that, while the radical increase observed in per capita metal stock in upper-middle-income countries had been primarily driven by increasing affluence, it was also influenced by the increasing stock intensity of the economies. At the global level, what is interesting is the effect of stock intensity. Until 2000, the stock intensity had been a moderating factor in per capita stock growth; however, over the period from 2000 to 2010, it worked in the opposite manner, as global stock efficiency deteriorated. This phenomenon can be explained by the radical stock growth and continuous stock intensity increases in upper-middle-income countries. While affluence was the main driver, the stock intensity of the economy in these countries also played a significant role in increasing per capita stocks. As a consequence, the downward trend in world per capita stock growth, which persisted until 2000 and which was caused mainly by the reduced stock intensity in high-income countries, reversed after 2000. Another important observation here is that the mitigation of the per capita stock growth by reductions in stock intensity in high-income countries has been completely counteracted by increasing affluence. That is, historical stock efficiency improvements proved to be insufficient to stabilize per capita stock growth even in more-developed countries. While the simple IPAT analysis does not capture the details of the economic structural change, it clearly reveals that global economic and population growth may continue to drive the growth of global metal stocks.

5.3.4 Effects of metal stock inequality on future production activities

The historical trends raise a critical question regarding the future. If the unequal distribution of global metal stocks is resolved through the continued upward trend in metal use in developing countries, how will the global production activities change over the 21st century? To address this question, this study estimated the changes in primary (from natural ore) and secondary (from scrap) production for the six major metals out to 2100 based on the simple assumption that the world average per capita stock will catch up with the levels of current high-income countries by 2100.

The future demand $X_{5.6}\ (t)$ is calculated by the stock-driven approach as shown in equation (5-15).

$$X_{5.6}(t) = X_6(\tau) - X_6(\tau - 1) + \sum_{t'=0}^{t}((1-\omega)X_{5.6}(t')\phi(t-t')) \qquad \text{(5-15)}$$

In this case, in-use stock $X_6(\tau)$ is determined by an assumption that the per capita stocks $X_6'(\tau)$ follow the stock growth pattern of high-income countries by following the saturation curves shown in equation (6-16).

$$X_6'(\tau) = \frac{S_{\mathrm{high}}}{1 + \left(\frac{S_{\mathrm{high}}}{S_0} - 1\right)\exp\ (\alpha(1 - \exp\ (\beta(\tau - \tau_0))))} \qquad \text{(5-16)}$$

Here, S_{high} denotes the per capita stock levels in high-income countries in 2010 and S_0 represents global per capita stock in the beginning year τ_0 (2010). Additionally, α and β are shape parameters determining the growth patterns of the curve so that $X_6'(\tau)$ reaches 98% of the level of S_{high} in 2100.

According to this calculation, the total production (primary production + secondary production) in 2050 will increase by a factor of 3.2 for copper, 3.0 for nickel, 2.8 for zinc, 2.8 for lead, 2.7 for aluminum, and 2.0 for steel relative to 2010 (Figure 5- 13). After 2050, total production volume reaches a plateau and no longer increases. Such stabilized total production, together with the increasing availability of old scrap, increases the role of secondary production for all six metals continuously over the 21st century, while the peak of primary production occurs around 2040-2050. This observation does not change significantly even if we expect an immediate increase in the old scrap collection rate of 10% because of the limited scrap availability during the first half of the 21st century (Figure 5- 14).

The validity of the estimates was assessed by comparing them with the existing studies collected in Chapter 2. Figure 5- 15 confirms that the future scenario is generally consistent with the range of future demand (inflow) projections in existing studies.

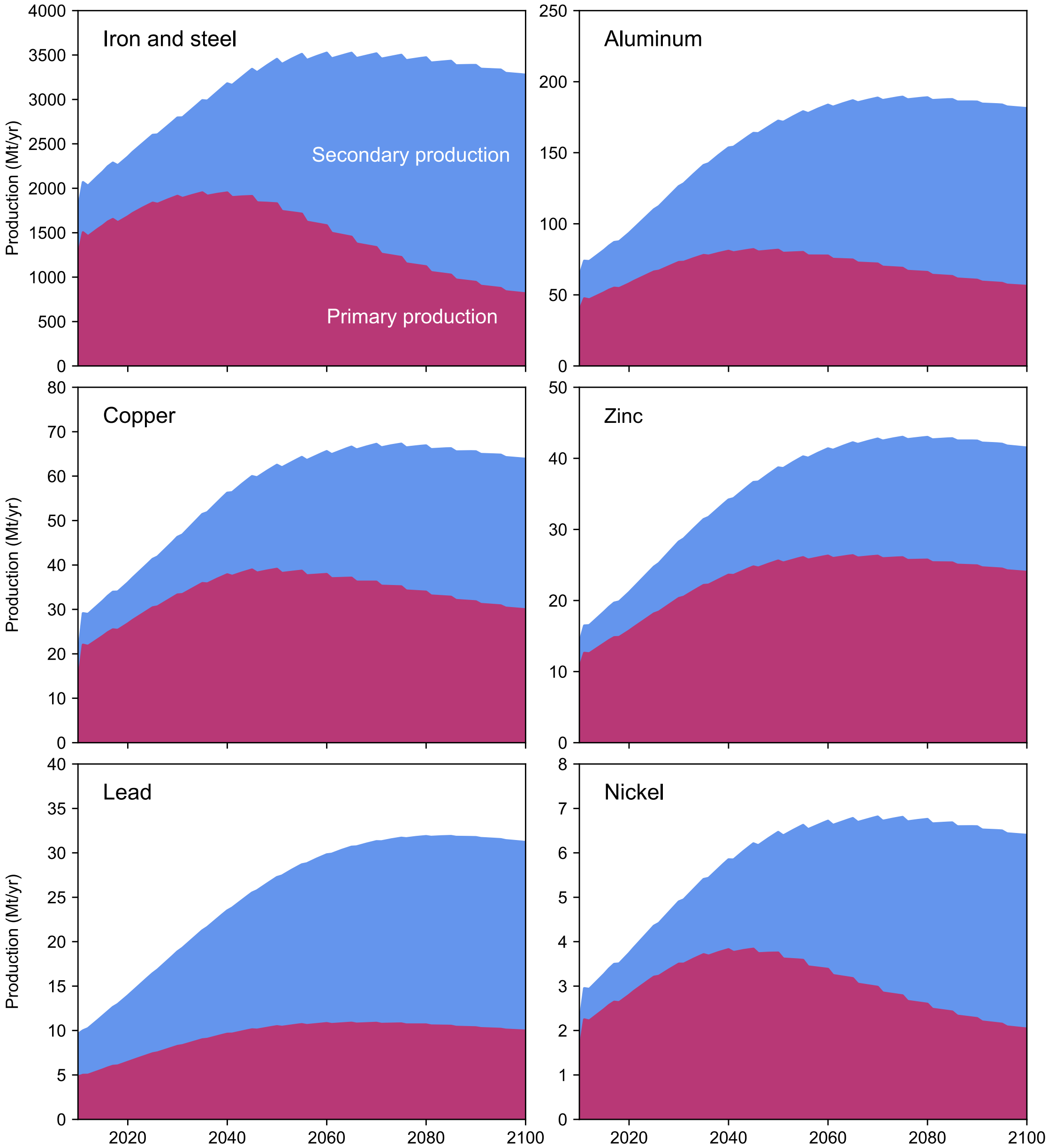

Figure 5- 13 Primary and secondary production for six major metals, 2010-2100. Secondary production includes both new and old scrap supply, assuming that the old scrap collection rate remains constant during the scenario period.

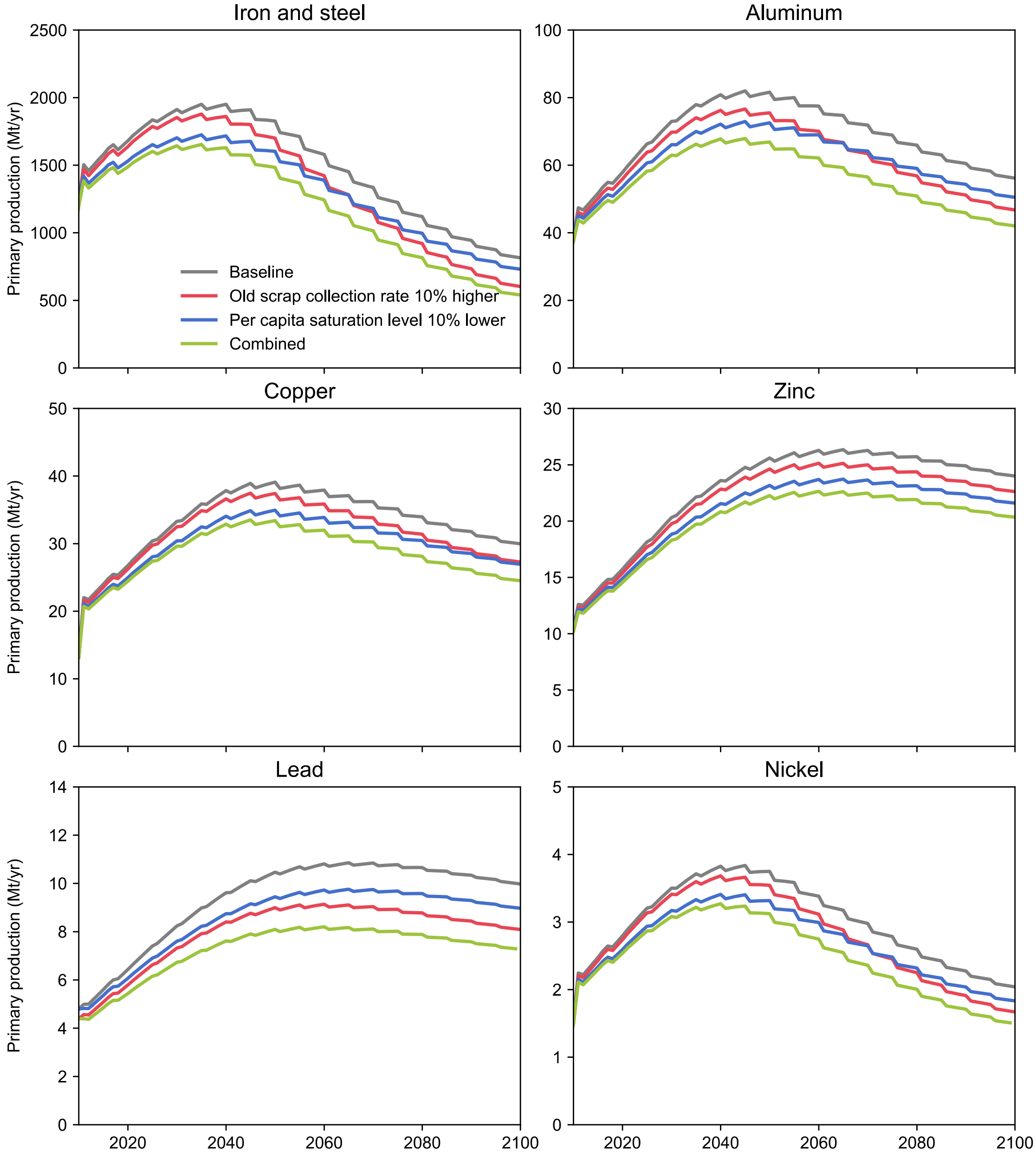

Figure 5- 14 Sensitivity analysis showing the impact of changes to old scrap collection rate and per capita stock saturation level on the primary production forecast, 2010-2100.

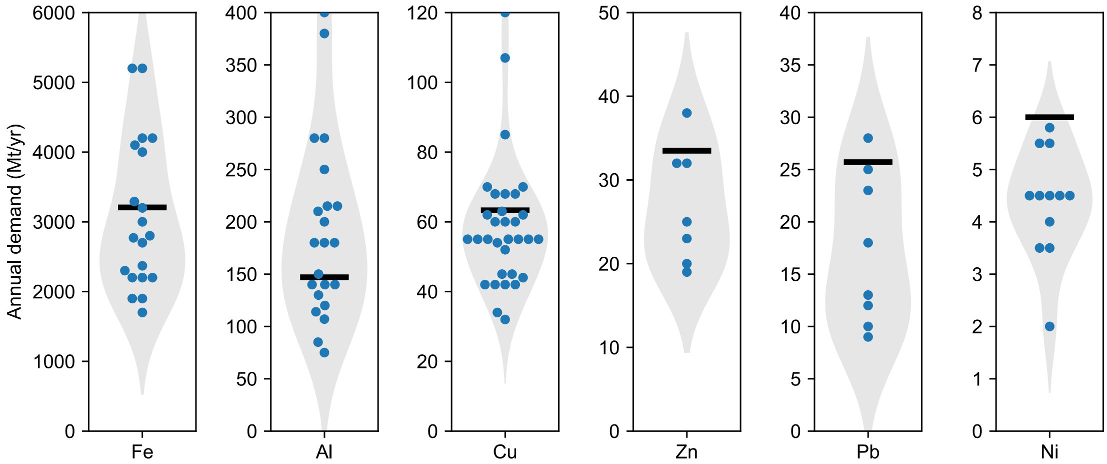

Figure 5- 15 Comparison of estimated demand (inflow) in 2050 with estimates from existing studies reviewed in Chapter 2.

5.4 Discussion

The analysis revealed that a substantial inequality exists in international metal stocks. Notably, the highest 20% of the population (ordered by per capita metal use) accounts for 60-75% of the world's total metal stock, while the lowest 20% accounts for only about 1%. Such numbers indicate that metal stocks are distributed more unevenly than other common indicators such as carbon emissions, ecological footprint and land use intensity.

It should be noted, however, that the international inequality in metal stocks identified in this study does not directly represent inequalities in the service level provided by these stocks. While there is certainly a level of metal stock that needs to be collocated with a population in order to provide essential services for a high quality of life (O'Neill et al., 2018), establishing just what this level should be is difficult, as it will very much depend on the local situation, including factors such as population density (Müller et al., 2013). Addressing the complex relationships between metal stocks and service level will require further research, perhaps extending beyond national level analyses. In this respect, the present study can be regarded as a useful steppingstone. What this study has clearly established is that metal-containing products and infrastructures are distributed very unevenly across the globe. Accordingly, the international inequality in metal stocks revealed here should be seriously considered in any discussion of a circular economy (Stahel, 2016) or science-based targets for material use (IRP, 2019c; World Economic Forum, 2019). Absent such consideration, the benefits of these materials, whose extraction and processing risk serious environmental degradation, are likely to be shared by only a limited portion of the world's population, as has been the case historically. In the context of sustainable development goals, such a situation must be avoided (United Nations, 2015).

An important lesson here is that relying on the continued progress of developing countries to resolve the unequal distribution of in-use metal stocks by reaching the metal use levels of developed countries could lead to an increase in metal production activities in the coming decades. Specifically, if today's developing countries catch up with the current stock levels of the world's developed countries over the course of the 21st century, major metal production can be expected to increase by a factor of 2-3 by 2050 relative to 2010. Such information provides a basis for exploring future scenarios of the metal flows and stocks under carbon constraints.

5.5 Appendix to Chapter 5

Executing the model requires a variety of datasets obtained from statistical databases and existing MFA studies. The required data and corresponding data sources are given below:

(a) *Historical metal production volume*: Time series data from 1900 to 2010 were extracted from the US Geological Surveys (USGS) (U.S. Geological Survey, 2020) and World Bureau of Metal Statistics (WBMS) (World Bureau Metal Statistics, 2015) databases.

(b) *Trade volume of semi-manufactured and finished products*: Time series data containing approximately 6,000 commodities from 1995 to 2010 were obtained from the Base pour l'Analyze du Commerce International (BACI) database (CEPII. BACI (Base pour l'Analyse du Commerce International), 2018), which improves the inconsistent trade data between countries in the UN Comtrade database.

(c) *Metal content of trade products*: Single year data were compiled based on a survey of the consulting firm (Mitsubishi UFJ Research and Consulting, 2019) and the Waste Input-Output MFA model (Nakamura et al., 2007), and were considered to be constant during the analysis period.

Table 5- 3 Parameter overview for iron and steel

	Construction	Transportation	Machinery	Products	Ref.
Market share	40%	25%	25%	10%	(Müller et al., 2011)
Lifetime	60 yr	13 yr	15 yr	25 yr	(Müller et al., 2011)
Primary production yield		87%			(Helbig et al., 2020)
Secondary production yield		94%			(Helbig et al., 2020)
Manufacturing yield		89%			(Helbig et al., 2020)
In-use dissipation rate		1%			(Helbig et al., 2020)
New scrap collection rate		100%			(Helbig et al., 2020)
Old scrap collection rate		74%			(Helbig et al., 2020)

Table 5- 4 Parameter overview for aluminum

	Construction	Transportation	Machinery	Electronics	Containers	Products	Other	Ref.
Market share	24%	28%	9%	11%	16%	6%	6%	(Elshkaki et al., 2018)
Lifetime	50 yr	13 yr	15 yr	20 yr	1 yr	8 yr	10 yr	(Liu et al., 2013)
Primary production yield				88%				(Helbig et al., 2020)
Secondary production yield				97%				(Helbig et al., 2020)
Manufacturing yield				83%				(Wang et al., 2018)
In-use dissipation rate				0%				(Helbig et al., 2020)
New scrap collection rate				95%				(Helbig et al., 2020)
Old scrap collection rate				83%				(Helbig et al., 2020)

Table 5- 5 Parameter overview for copper

	Construction	Infrastructure	Transportation	Machinery	Products	Ref.
Market share	38%	10%	15%	14%	23%	(Maung et al., 2017)
Lifetime	40 yr	30 yr	17 yr	18 yr	8 yr	(Maung et al., 2017)
Primary production yield			83%			(Helbig et al., 2020)
Secondary production yield			100%			(Helbig et al., 2020)
Manufacturing yield			97%			(Krausmann et al., 2017)
In-use dissipation rate			2%			(Helbig et al., 2020)
New scrap collection rate			92%			(Helbig et al., 2020)
Old scrap collection rate			47%			(Helbig et al., 2020)

Table 5- 6 Parameter overview for zinc

	Galvanizing	Zinc-based alloys	Brass and bronze	Other	Ref.
Market share	48%	16%	19%	17%	(Elshkaki et al., 2018)
Lifetime	17 yr	16 yr	19 yr	14 yr	(Elshkaki et al., 2018)
Primary production yield		84%			(Helbig et al., 2020)
Secondary production yield		64%			(Helbig et al., 2020)
Manufacturing yield		78%			(Helbig et al., 2020)
In-use dissipation rate		8%			(Helbig et al., 2020)
New scrap collection rate		91%			(Helbig et al., 2020)
Old scrap collection rate		65%			(Helbig et al., 2020)

Table 5- 7 Parameter overview for lead

	Batteries (transportation)	Batteries (industrial)	Cable sheathing	Alloys	Chemicals	Other	Ref.
Market share	50%	25%	1%	9%	9%	6%	(Elshkaki et al., 2018)
Lifetime	4 yr	12 yr	16 yr	10 yr	1 yr	12 yr	(Elshkaki et al., 2018)
Primary production yield			89%				(Helbig et al., 2020)
Secondary production yield			100%				(Helbig et al., 2020)
Manufacturing yield			94%				(Helbig et al., 2020)
In-use dissipation rate			5%				(Helbig et al., 2020)
New scrap collection rate			80%				(Helbig et al., 2020)
Old scrap collection rate			66%				(Helbig et al., 2020)

Table 5- 8 Parameter overview for nickel

	Construction	Transportation	Machinery	Electronics	Products	Ref.
Market share	17%	19%	31%	5%	28%	(Graedel et al., 2015)
Lifetime	50	18	25	15	15	(Graedel et al., 2015)
Primary production yield			79%			(Helbig et al., 2020)
Secondary production yield			100%			(Helbig et al., 2020)
Manufacturing yield			86%			(Helbig et al., 2020)
In-use dissipation rate			0%			(Helbig et al., 2020)
New scrap collection rate			84%			(Helbig et al., 2020)
Old scrap collection rate			63%			(Helbig et al., 2020)

Table 5- 9 Changes in per capita steel stocks and contributions of driving factors at four time periods, 1970-2010. I = metal stock per capita, A = GDP per capita, T = metal stock per GDP.

World	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	24%	18%	6%
1980-1990	11%	14%	-3%
1990-2000	8%	13%	-5%
2000-2010	19%	13%	6%
High-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	33%	26%	7%
1980-1990	15%	24%	-9%
1990-2000	11%	20%	-9%
2000-2010	7%	10%	-3%
Upper-middle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	31%	34%	-3%
1980-1990	28%	15%	13%
1990-2000	25%	20%	5%
2000-2010	53%	50%	4%
Lower-midle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	7%	8%	0%
1980-1990	2%	15%	-13%
1990-2000	-3%	14%	-16%
2000-2010	18%	44%	-26%
Low-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	43%	8%	34%
1980-1990	32%	-2%	34%
1990-2000	2%	-15%	17%
2000-2010	-1%	25%	-26%

Table 5- 10 Changes in per capita aluminum stocks and contributions of driving factors at four time periods, 1970-2010. I = metal stock per capita, A = GDP per capita, T = metal stock per GDP.

World	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	55%	18%	37%
1980-1990	18%	14%	5%
1990-2000	15%	13%	2%
2000-2010	27%	13%	14%
High-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	62%	26%	36%
1980-1990	26%	24%	2%
1990-2000	12%	20%	-8%
2000-2010	2%	10%	-8%
Upper-middle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	108%	34%	74%
1980-1990	49%	15%	35%
1990-2000	73%	20%	53%
2000-2010	104%	50%	55%
Lower-midle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	102%	8%	95%
1980-1990	46%	15%	31%
1990-2000	129%	14%	115%
2000-2010	108%	44%	64%
Low-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980			
1980-1990			
1990-2000			
2000-2010	93%	25%	69%

Table 5- 11 Changes in per capita copper stocks and contributions of driving factors at four time periods, 1970-2010. I = metal stock per capita, A = GDP per capita, T = metal stock per GDP.

World	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	16%	18%	-3%
1980-1990	7%	14%	-7%
1990-2000	14%	13%	1%
2000-2010	18%	13%	4%
High-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	23%	26%	-3%
1980-1990	13%	24%	-11%
1990-2000	14%	20%	-6%
2000-2010	1%	10%	-9%
Upper-middle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	40%	34%	5%
1980-1990	29%	15%	14%
1990-2000	47%	20%	27%
2000-2010	72%	50%	22%
Lower-midle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	-1%	8%	-8%
1980-1990	16%	15%	2%
1990-2000	51%	14%	37%
2000-2010	49%	44%	5%
Low-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	-7%	8%	-15%
1980-1990	-2%	-2%	0%
1990-2000	40%	-15%	55%
2000-2010	76%	25%	51%

Table 5- 12 Changes in per capita zinc stocks and contributions of driving factors at four time periods, 1970-2010. I = metal stock per capita, A = GDP per capita, T = metal stock per GDP.

World	%ΔI	%ΔA	%Δ T
1970-1980	15%	18%	-4%
1980-1990	-1%	14%	-15%
1990-2000	16%	13%	3%
2000-2010	28%	13%	15%
High-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	20%	26%	-6%
1980-1990	3%	24%	-21%
1990-2000	12%	20%	-9%
2000-2010	4%	10%	-5%
Upper-middle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	58%	34%	24%
1980-1990	35%	15%	21%
1990-2000	59%	20%	38%
2000-2010	89%	50%	40%
Lower-midle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	30%	8%	23%
1980-1990	26%	15%	11%
1990-2000	45%	14%	32%
2000-2010	51%	44%	7%
Low-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	0%	8%	0%
1980-1990	66%	-2%	68%
1990-2000	117%	-15%	132%
2000-2010	-4%	25%	-28%

Table 5- 13 Changes in per capita lead stocks and contributions of driving factors at four time periods, 1970-2010. I = metal stock per capita, A = GDP per capita, T = metal stock per GDP.

World	%ΔI	%ΔA	%Δ T
1970-1980	17%	18%	-1%
1980-1990	-6%	14%	-20%
1990-2000	4%	13%	-10%
2000-2010	19%	13%	6%
High-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	24%	26%	-2%
1980-1990	-2%	24%	-25%
1990-2000	2%	20%	-18%
2000-2010	-14%	10%	-24%
Upper-middle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	37%	34%	3%
1980-1990	23%	15%	8%
1990-2000	32%	20%	12%
2000-2010	92%	50%	42%
Lower-midle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	17%	8%	9%
1980-1990	32%	15%	18%
1990-2000	50%	14%	36%
2000-2010	70%	44%	26%
Low-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	520%	8%	512%
1980-1990	10%	-2%	11%
1990-2000	95%	-15%	110%
2000-2010	-180%	25%	-204%

Table 5- 14 Changes in per capita nickel stocks and contributions of driving factors at four time periods, 1970-2010. I = metal stock per capita, A = GDP per capita, T = metal stock per GDP.

World	%ΔI	%ΔA	%Δ T
1970-1980	28%	18%	10%
1980-1990	15%	14%	1%
1990-2000	20%	13%	7%
2000-2010	28%	13%	15%
High-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	38%	26%	12%
1980-1990	21%	24%	-3%
1990-2000	27%	20%	7%
2000-2010	20%	10%	10%
Upper-middle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	29%	34%	-6%
1980-1990	31%	15%	17%
1990-2000	20%	20%	0%
2000-2010	71%	50%	21%
Lower-midle-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	49%	8%	41%
1980-1990	64%	15%	50%
1990-2000	78%	14%	64%
2000-2010	56%	44%	11%
Low-income	**%ΔI**	**%ΔA**	**%Δ T**
1970-1980	-3%	8%	-12%
1980-1990	-6%	-2%	-4%
1990-2000	84%	-15%	99%
2000-2010	74%	25%	50%

Table 5- 15 Income-based country groupings. The classification is based on 2010 data and the World Bank (The World Bank, 2019) (High: per capita GNI above 12,275 US$; Upper-middle: per capita GNI between 3,976 and 12,275 US$; Lower-middle: per capita GNI between 1,006 and 3,975 US$; Low: per capita GNI less than or equal to 1,005 US$).

High	Upper-middle	Lower-middle	Low
Andorra	Albania	Angola	Afghanistan
Anguilla	Algeria	Armenia	Bangladesh
Antigua and Barbuda	American Samoa	Belize	Burkina Faso
Australia	Argentina	Benin	Burundi
Austria	Azerbaijan	Bhutan	Cambodia
The Bahamas	Belarus	Bolivia	Central African Republic
Bahrain	Bosnia and Herzegovina	Cabo Verde	Chad
Barbados	Botswana	Cameroon	Congo, Dem. Rep.
Belgium	Brazil	Comoros	Eritrea
Bermuda	Bulgaria	Congo, Rep.	Ethiopia
British Antarctic Territory	Chile	Cote d'Ivoire	The Gambia
British Indian Ocean Territory	China	Djibouti	Guinea
British Virgin Islands	Colombia	Egypt, Arab Rep.	Guinea-Bissau
Brunei Darussalam	Costa Rica	El Salvador	Haiti
Canada	Cuba	Fiji	Kenya
Canary Islands	Dominica	Georgia	Korea, Dem. People's Rep.
Cayman Islands	Dominican Republic	Ghana	Kyrgyz Republic
Ceuta and Melilla	Ecuador	Guatemala	Lao PDR
Commonwealth of the Northern Mariana Islands	Equatorial Guinea	Guyana	Liberia
Cook Islands	Gabon	Honduras	Madagascar
Croatia	Grenada	India	Malawi
Cyprus	Iran, Islamic Rep.	Indonesia	Mali
Czech Republic	Iraq	Jordan	Mozambique
Denmark	Jamaica	Kiribati	Myanmar
Estonia	Kazakhstan	Lesotho	Nepal
Falkland Islands and Dependencies	Lebanon	Marshall Islands	Niger
Finland	Macedonia	Mauritania	Rwanda
France	Malaysia	Micronesia, Fed. Sts.	Sierra Leone

High	Upper-middle	Lower-middle	Low
French Polynesia	Maldives	Moldova	Somalia
French West Indies	Mauritius	Mongolia	Syrian Arab Republic
Germany	Mexico	Morocco	Tajikistan
Gibraltar	Montenegro	Nicaragua	Tanzania
Greece	Namibia	Nigeria	Togo
Greenland	Palau	Pakistan	Uganda
Guiana	Panama	Papua New Guinea	Zimbabwe
Hong Kong SAR, China	Paraguay	Philippines	
Hungary	Peru	Samoa	
Iceland	Romania	Sao Tome and Principe	
Ireland	Russian Federation	Senegal	
Israel	Serbia	Solomon	
Italy	Seychelles	Sri Lanka	
Japan	South Africa	Sudan	
Korea, Rep.	Suriname	Swaziland	
Kuwait	Taiwan	Timor-Leste	
Latvia	Thailand	Tonga	
Libya	Tunisia	Ukraine	
Lithuania	Turkey	Uzbekistan	
Luxembourg	Turkmenistan	Vanuatu	
Macau	Tuvalu	Vietnam	
Malta	Uruguay	West Bank and Gaza	
Monaco	Venezuela, RB	Western Sahara	
Montserrat		Yemen, Rep.	
Netherlands		Zambia	
Netherlands Antilles			
New Caledonia			
New Zealand			
Niue Island			
Norway			
Oman			
Other Australian territories			
Pitcairn Islands			
Poland			
Portugal			
Puerto Rico			
Qatar			
Réunion			
Saint Christopher and Nevis			
Saint Lucia			
Saint Vincent and the Grenadines			
Saint-Pierre and Miquelon			
Saudi Arabia			

High	Upper-middle	Lower-middle	Low
Singapore			
Slovak Republic			
Slovenia			
Spain			
St. Helena Island and Dependencies			
Sweden			
Switzerland			
Territory of Guam			
The Azores			
Tokelau Islands			
Trinidad and Tobago			
Turks and Caicos Islands			
United Arab Emirates			
United Kingdom			
United States			
United States Virgin Islands			

Chapter 6

Impact of carbon constraints on the global metal cycle

6.1 Introduction

Chapter 5 revealed that a substantial inequality exists in international metal stocks, and the growth-led elimination of the inequality could increase global metal production by a factor of 2-3 by 2050 relative to 2010. However, mitigating climate change will require significant emission reductions by the first half of the 21st century in metal production activities, which account for more than 10% of total GHG emissions (Hertwich, 2021). The question thus arises as to how carbon constraints on production activities will affect global metal flows and stocks over the 21st century.

Technology-rich integrated assessment models are typically used to inform such areas by exploring possible technology mixes and their costs (Fujimori et al., 2019; IEA, 2017; IPCC, 2014). However, this approach typically does not reflect the physical interconnection in the series of metal cycles (Pauliuk et al., 2017) that includes material production, manufacturing, in-use stock, and waste management, resulting in a weak foundation for explaining future demand, scrap availability, and the relationship between metal stock and service provision (Müller et al., 2011).

Although two previous studies have demonstrated important steps by systematically linking metal cycles to carbon emissions based on the principle of dynamic material flow analysis (Liu et al., 2013; Milford et al., 2013), such studies do not take into account time-series carbon constraints. This limitation poses the risk that the scenarios do not guarantee strict alignment with the emission reduction requirements needed to meet climate goals.

Therefore, this chapter aims to fill these research gaps by developing global scenarios for metal flow, stock, and use intensity over the 21st century harmonized with the time-series carbon constraints. The analysis is accomplished by connecting the optimization routine to the global metal cycle model constructed in Chapter 5. The approach explicitly deals with the physical interconnections of the entire metal cycle based on mass balance principles and times-series carbon constraints, enabling the elucidation of the impacts of carbon constraints on long-term metal flows and stocks. As in Chapter 5, the approach is applied to the six major metals—iron, aluminum, copper, zinc, lead, and nickel.

6.2 Methodology

6.2.1 Model overview

Future metal flows and stock dynamics under the carbon constraints were explored using an optimization routine, with the global metal cycle model linked to emission intensities. The objective is to minimize the divergence between the baseline stock and the stock available under the carbon constraints within the scenario period, and the objective function is formulated as an intertemporal linear programming model. This framework enables us to derive long-term metal flows and stock dynamics consistent with the carbon constraints while ensuring that the laws of mass conservation, such as the availability of old scrap metals determined by stock dynamics, are respected.

In this case, the carbon constraint of each metal sector was determined based on annual emissions mitigation rates in the industrial sector to keep global temperature rise well below 2°C relative to pre-industrial levels by using data from representative concentration pathway 2.6 (Gidden et al., 2019). That is, the annual emissions constraint for each metal sector was estimated by multiplying the estimated GHG emissions in 2010 by the emissions mitigation rate in the industrial sector until 2100. This reflects the assumption that all metal sectors contribute to emissions mitigation pathways in proportion to the other industrial sectors. The reason this study uses data for the industrial sector rather than the overall emission reduction rate here is to reflect the fact that the material production is more difficult to decarbonize than the other sectors (Davis et al., 2018). The GHG emissions associated with metal production were estimated by multiplying primary production from natural ore and secondary production from scrap by their respective emission intensities. The emission intensity of each process was set based on the life cycle assessment database (Van der Voet et al., 2019) and was assumed to change over time due to decarbonization of the electricity system and declines in ore grade.

6.2.2 Equations

The optimization routine determines the annual metal production $(X_{2.5}(t) + X_{3.5}(t))$ while aiming to minimize the divergence between the baseline stock, $X_{6,\mathrm{base}}(\tau)$, and the stock available under the carbon constraints, $X_6(\tau)$, within the scenario period. The core equations of the model are shown below.

$$\text{minimize:} \quad \sum_{\tau}\left(1 - \frac{X_6(\tau)}{X_{6,\mathrm{base}}(\tau)}\right) \tag{6-1}$$

$$\text{subject to:} \quad X_6(\tau) \leq X_{6,\mathrm{base}}(\tau) \tag{6-2}$$

$$E_{\mathrm{pri}}(t)X_{2.5}(t) + E_{\mathrm{sec}}(t)X_{3.5}(t) \leq \mathrm{Cap}\ (t) \tag{6-3}$$

$$X_{3.5}(t) = \theta(t)(X_{5.3}(t) + X_{7.3}(t)) \tag{6-4}$$

$$X_{5.3}(t) \leq \xi(1-\lambda)X_{5.6}(t) \tag{6-5}$$

$$X_{7.3}(t) \leq \gamma(t)X_{6.7}(t) \tag{6-6}$$

$$\text{where:} \quad X_6(\tau) = \sum_{t'=0}^{t}\big((1-\omega)X_{5.6}(t') - X_{6.7}(t')\big) \tag{6-7}$$

$$X_{5.6}(t) = \frac{\lambda}{1-(1-\lambda)\xi\theta(t)}(X_{2.5}(t) + \theta(t)X_{7.3}(t)) \tag{6-8}$$

$$X_{6.7}(t) = \sum_{t'=0}^{t}((1-\omega)X_{5.6}(t')\phi(t-t')) \tag{6-9}$$

Table 6- 1 List of system variables.

Symbol	Description	Symbol	Description
$X_{2.5}$	Primary production	ξ	New scrap collection rate
$X_{3.5}$	Secondary production	γ	Old scrap collection rate
$X_{5.3}$	New scrap	ω	In-use dissipation loss rate
$X_{7.3}$	Old scrap	θ	Secondary production yield
$X_{5.6}$	Final product	ϕ	Lifetime distribution
$X_{6.7}$	End-of-life product	E_{pri}	Emission intensity in primary production
X_6	In-use stock	E_{sec}	Emission intensity in secondary production
λ	Manufacturing yield	Cap	Annual emission constraints

In this case, the baseline stock, $X_{6,\text{ base}}(\tau)$, is determined by the assumption that the global per capita stocks follow the stock growth pattern of high-income countries by following the saturation curves expressed in equation (6-10). This is the same procedure as the consideration of future scenarios in Chapter 5.

$$X_{6,\text{base}}(\tau) = \text{POP}(t)\frac{x_{\text{high}}}{1+\left(\frac{x_{\text{high}}}{x_k}-1\right)\exp\left(\alpha(1-\exp\left(\beta(\tau-\tau_k)\right))\right)} \qquad \text{(6-10)}$$

Here, x_{high} denotes the per capita stock saturation level and x_k represents per capita stock in the initial year τ_k (2010). Additionally, α and β are shape parameters that determine the growth pattern of the curve. In this case, we set x_{high} as the per capita stock of the current high-income countries in 2010 and the year in which the level is reached is assumed to be 2050 for the upper-middle-income countries, 2080 for the lower-middle-income countries, and 2100 for low-income countries, based on the literature (Milford et al., 2013; Pauliuk et al., 2013a). $\text{POP}(t)$ is population data obtained from the Shared Socioeconomic Pathways 2, which represents a middle-of-the-road scenario (Fricko et al., 2017).

It should be noted that the determination of the per capita stock saturation level and dates is much more complicated and requires deeper investigation. There is considerable variation in the per capita stock saturation level depending on the metal considered; for example, the analysis in Chapter 5 shows that per capita stocks of lead are decreasing in high-income countries, while nickel shows no tendency towards stabilization. Also, the saturation level is expected to vary widely from country to country (Liu and Müller, 2013; Pauliuk et al., 2013b). The lack of any in-depth investigation of this domain is clearly a limitation of this study and an important step for further research. In light of these limitations, the scenarios this study presents here should be interpreted in the context of 'what if' statements rather than being considered as precise projections.

Apart from this, the approach here has several inherent limitations. One of which is that this study did not consider material linkages, including co-extraction, in the mining process (e.g., lead and zinc), use as alloys (e.g., steel and nickel), and contamination in the recycling process (e.g., copper as a tramp element in steel recycling). The fact that these factors were not considered creates the risk that the model will generate unrealistic scenarios. Furthermore, the model does not consider the emissions mitigation effect during the utilization phase of metal products, such as the increased use of high-tensile steel, which contributes to improved fuel efficiency of automobiles (Bian et al., 2015). It should therefore be noted that the results presented in this study only focus on the achievement of GHG emissions mitigation targets in the metal production process. Incorporating these factors into the model would be an important step in future research and would build upon the current study.

6.2.3 Scenario

Metal cycle solution

This study explores two scenarios for metal cycles under carbon constraints: business as usual (BAU) and a circular economy (CE). The BAU scenario assumes that all model parameters regarding the metal cycle presented in Chapter 5 (Table 5- 3 through Table 5- 8) are constant during the analysis period. The CE scenario, on the other hand, expects that the end-of-life recycling rate (old scrap collection rate × secondary production yield) and product lifetime will rise to their maximum values, described in the existing literature, from 2010 to 2100 by following a gradual saturation curve (Table 6- 2 and Figure 6- 1). The rates and levels of implementation are meant to be ambitious but not unrealistic based on the scientific literature and technology roadmaps.

Table 6- 2 Description of circular economy scenario.

Scenario	Description
Near perfect recycling	The end-of-life recycling rate gradually reaching 90% by 2100 through improvements in old scrap collection rate and secondary production yield (Van der Voet et al., 2019).
Longer product lifetime	Average product lifetime rising gradually to reach theoretical maximum by 2100 through promoting durable design, reuse, repair, and remanufacturing activities (Cherry et al., 2018; Milford et al., 2013). Specifically, buildings, construction, and infrastructure are expected to increase by 90%, transportation by 20%, machinery by 10%, products by 300%, and others by 100% from current values.

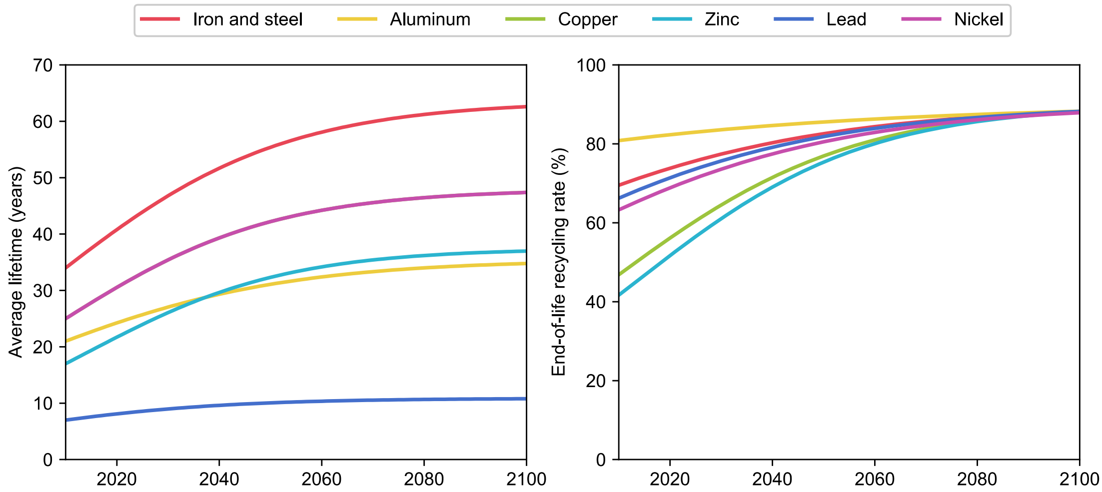

Figure 6- 1 Average lifetime (left) and end-of-life recycling rate (right) of six major metals under the circular economy scenario, 2010-2100.

Supply-side technology solution

This study examined the implications of supply-side technology developments such as best available technologies (BAT), carbon capture and storage (CCS), and hydrogen reduction, targeting iron and aluminum, for which a long-term roadmap (EUROFER, 2013; European Aluminium, 2019; JRC, 2012; The Japan Iron and Steel Federation, 2019) has already been well established. The detailed assumptions are as follows:

- BAT for steel and aluminum making: The International Energy Agency estimated that the global emission reduction potential of BAT implementation for primary steel and aluminum production is 21% and 10%, respectively (IEA, 2014). This study assumes these are achieved from 2010 to 2050 by following the saturation curve.
- CCS and hydrogen reduction for steel making: The emissions reduction target is set based on the long-term roadmap of the Japan Iron and Steel Federation for climate change mitigation (The Japan Iron and Steel Federation, 2019): Accordingly, the CCS reduction is 20% and the hydrogen reduction is 10%. As these technologies are

expected to be implemented after 2030, this study assumes that the above reduction targets for primary production are achieved gradually from 2030 to 2060 for CCS and from 2050 to 2080 for hydrogen reduction.

- Innovative technologies for steel making (e.g., top gas recycling, bath smelting, direct reduction, and electrolysis): The European Steel Association announced a more ambitious roadmap (EUROFER, 2013) that aims for a 90% reduction by 2050 in the European Union by combining a series of technologies such as HIsarna (smelting reduction) and ULCORED (direct reduction), both connected to CCS or CO_2 free hydrogen. This study assumes that a 90% reduction for primary steel production is accomplished by 2100 on a global scale after obtaining the reduction effects of all the BAT, CCS, and hydrogen reduction solutions mentioned above.
- CCS and inert anodes for aluminum making: European Aluminum created a scenario for lower carbon direct emissions reductions through CCS and inert anodes (European Aluminium, 2019) in the aluminum sector. The association projected that implementing these innovative technologies could reduce 23% of direct carbon emissions for primary aluminum production by 2050 in the European Union. This study thus assumes that a 23% reduction is achieved by 2100 on a global basis by following the saturation curve after 2030.

Note that the potential for further emission reductions by other possible strategies such as switching to renewable biofuels and charcoal instead of fossil fuels (McLellan et al., 2012) in thermal applications is not considered here due to the lack of a roadmap.

6.3 Results

6.3.1 In-use stock

Figure 6- 2 shows that under carbon constraints, the global average of per capita metal stock cannot follow the historical evolution patterns of high-income countries. More specifically, per capita stocks of all major metals in the world average will be saturated at levels 2-3 times lower than is currently the case in high-income countries: 6,500 kg/cap for iron, 230 kg/cap for aluminum, 58 kg/cap for copper, 34 kg/cap for zinc, 4 kg/cap for lead, and 8 kg/cap for nickel in 2100. If the circular economy transition fails along with supply-side technology solutions, these values can be expected to be 40-75% lower. The variation in per capita stock dynamics by each metal is primarily due to the difference in average lifetime and potential for improved end-of-life recycling rate and emission intensity. For example, as aluminum has more room to reduce emission intensity by decarbonizing electricity systems, its per capita stock dynamics under the carbon constraints are closer to the baseline than is the case for the other metals. Lead, in contrast, has a shorter average lifetime and has limited room for improving its end-of-life recycling rate and emission intensity, thus creating a downward trend rather than plateauing.

Overall, findings here indicate that metal cycle solutions limited to end-of-life recycling and product lifetime extension are unlikely to be sufficient for meeting the emission reduction requirements in the metal sector. Satisfying the metal service demand of 10 billion people within the carbon constraints will require a transformative system change to meet society’s needs with less metal in cases where there is little prospect of supply-side technology innovation. One benchmark can be stabilizing the growth of global major metal in-use stock at around 7 t/cap, which is approximately half the current level of high-income countries.

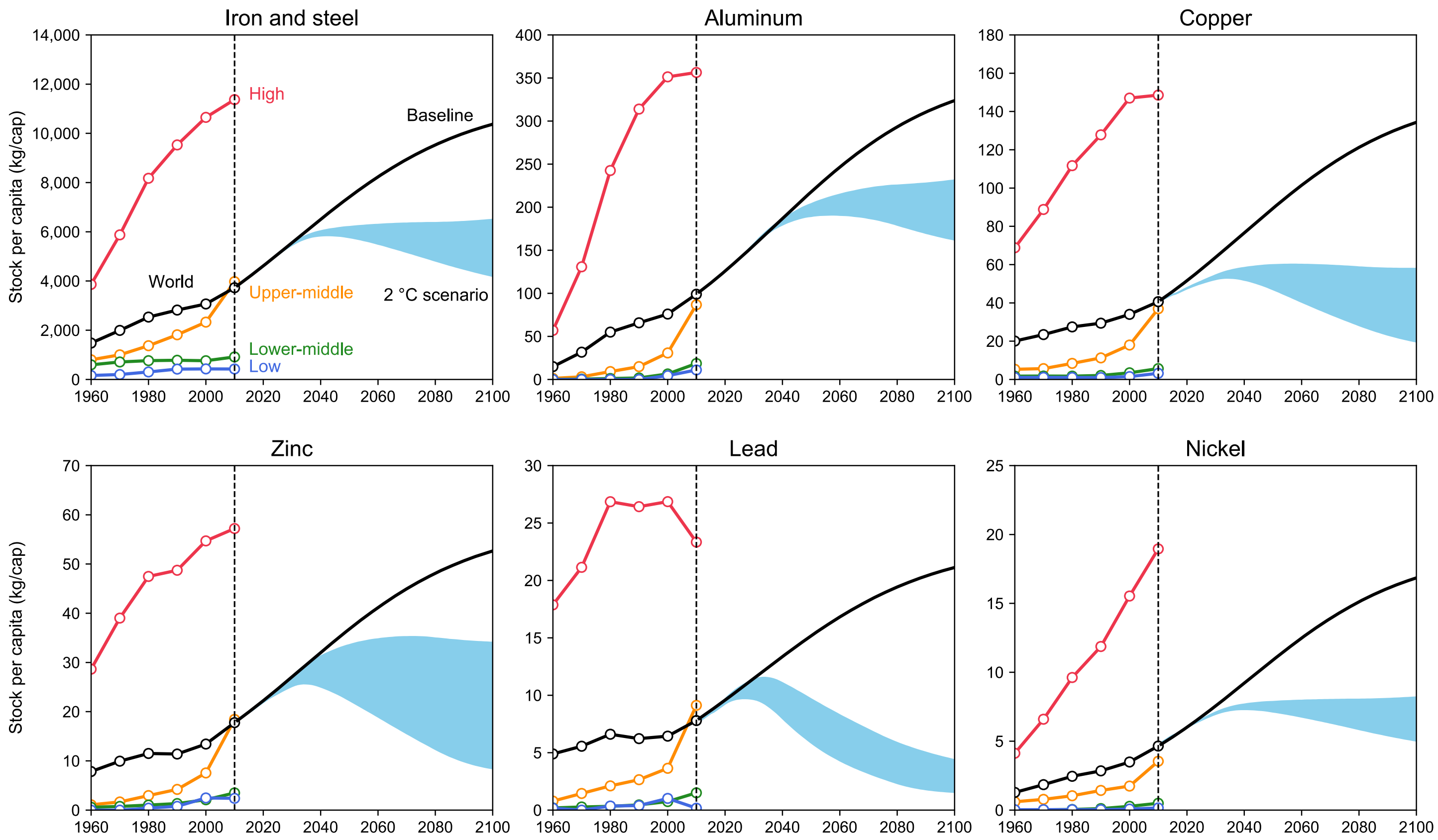

Figure 6- 2 Per capita in-use stock for six major metals, 1960-2100. The ranges in the 2 °C scenario are due to differences in assumptions regarding the end-of-life recycling rate and product lifetime. The upper limit of the range (circular economy scenario) assumes that the end-of-life recycling rate and product lifetime increase to the theoretical maximum by 2100 according to the saturation curve. The lower limit of the range (business as usual scenario) represents the assumption that all model parameters are constant throughout the scenario period.

6.3.2 Primary and secondary production

For the world average to follow stock growth patterns similar to those of high-income countries, production activities will need to be increased by a factor of 2-3 from 2010 to 2100, depending on the metal (Figure 6- 3). However, the carbon constraint in line with the climate goal significantly limits production activities. Figure 6- 3 clearly shows that production of all six major metals will peak by around 2030 due to the carbon constraints. That is, absolute decoupling of economic growth and metal production should be accomplished by no later than 2030 if we cannot rely on supply-side technology solutions. The role of secondary production (production from the scrap) is increasing over time, with approximately 54-87% of production coming from secondary production in 2050 and 84%-100% in 2100, with an increased end-of-life recycling rate. Primary production (production from ore), on the other hand, peaks around 2030 and continues to decline thereafter. These results suggest that metal demand will be substantially curtailed if the large-scale implementation of the supply-side technology solutions fails to scale. Realistically speaking, it is difficult to meet all of the demand with 100% secondary production due to quality issues (Nakamura et al., 2012) and thermodynamic reasons (Reuter et al., 2019). Thus, production activities will be more restricted if we fail to develop an advanced recycling technology that enhances the quality of secondary production or product design harmonized with scrap utilization.

Per capita production is stabilized at roughly 115.8 kg/cap for iron, 8.4 kg/cap for aluminum, 1.4 kg/cap for copper, 1.1 kg/cap for zinc, 0.3 kg/cap for lead, and 0.2 kg/cap for nickel until 2100 (Figure 6- 4). These values are 2-9 times lower than in current high-income countries, underscoring the urgent need to break the coupling of economic growth and metal demand (Zheng et al., 2018).

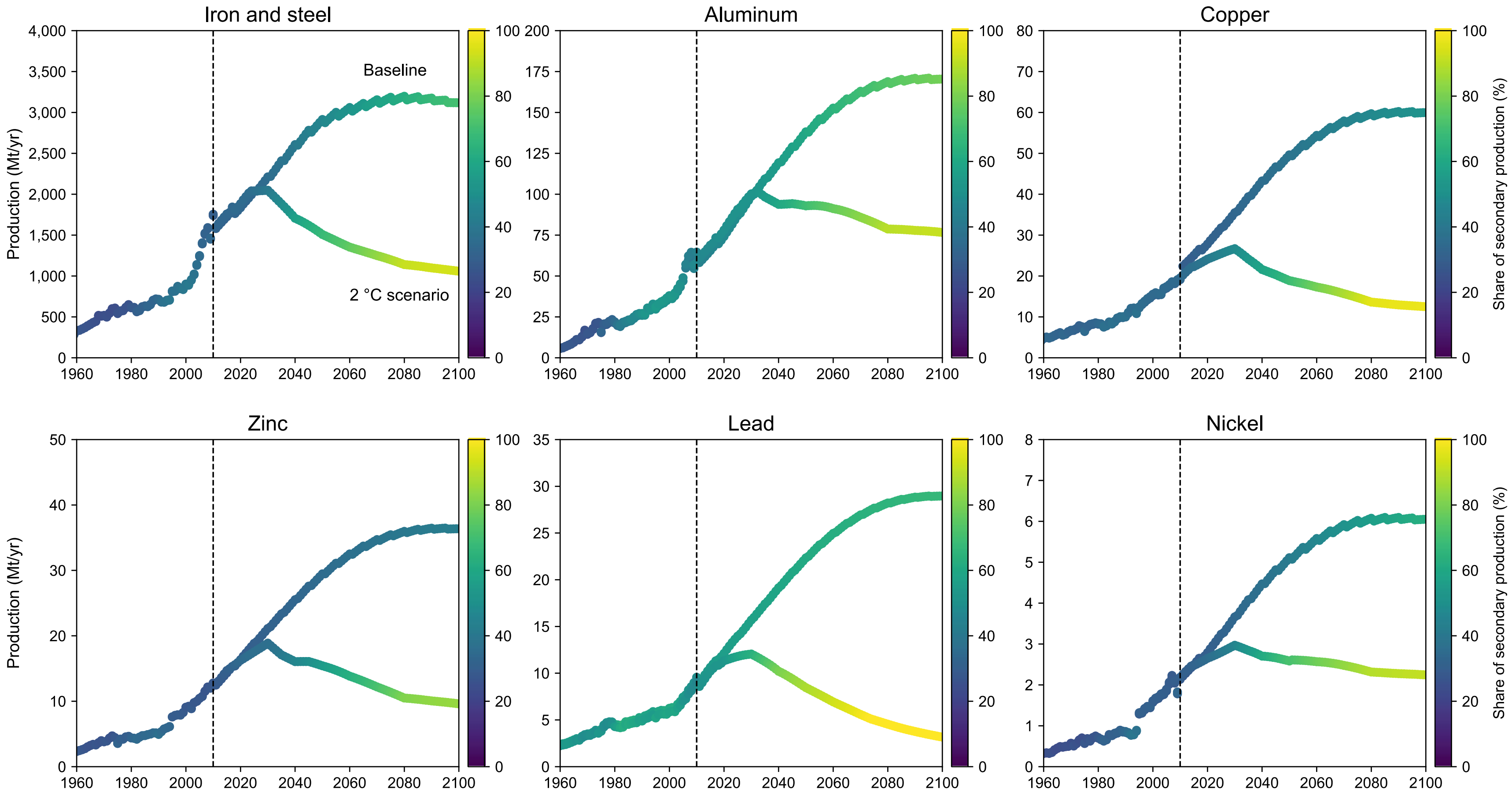

Figure 6- 3 Production activities for six major metals, 1960-2100. The shade of the line color represents the ratio of secondary production to total production. The 2 °C scenario shows a case assuming an increased end-of-life recycling rate and product lifetime (circular economy scenario).

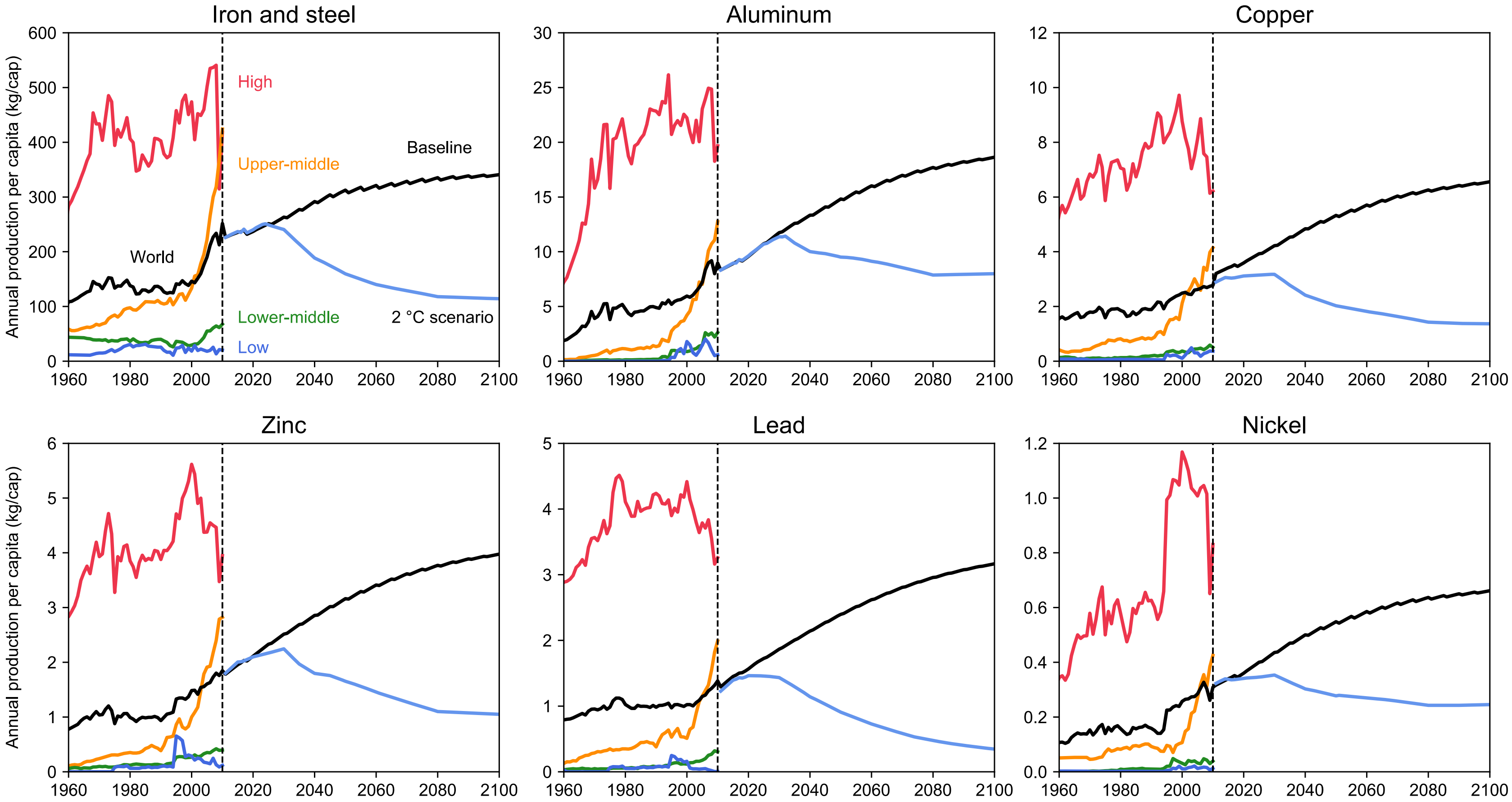

Figure 6- 4 Per capita annual production for six major metals, 1960-2100.

6.3.3 Metal use intensity

To what extent should we promote decoupling in the coming decades? This question is addressed by linking the metal flows and stock dynamics identified above to the shared socioeconomic pathways (SSP) (Riahi et al., 2017). Here, this study defines the metal use intensity of the economy (g-metals/GDP)—that is, the physical metal flow or in-use stock per unit of economic activity—as an indicator of decoupling (Schandl et al., 2018).

Figure 6- 5 illustrates a significant decrease in the metal use intensity of the global economy over the 21st century, as well as the difficulty of achieving this decrease. The historical metal flow intensity of the global economy shows gradual improvements before 2000 but deteriorates after that period due to a drastic increase in upper-middle-income countries, mainly China. The metal use intensity in line with the carbon constraints calls for an immediate change in this situation. Figure 6- 5 shows that the metal flow intensity needs to be reduced by 36% by 2030, 70% by 2050, and 90% by 2100 relative to 2010, meaning a strong decoupling of global metal production from economic activities. This study also confirms the importance of improving metal stock intensity in parallel with flow intensity. Stock intensity provides better insights into the nexus of service provision and metal use, as metal services are delivered in the form of stock such as buildings and vehicles (Pauliuk and Müller, 2014). Historically, the metal stock intensity of the global economy has not improved significantly, remaining at roughly 400 g/US $. This observation is consistent with trends observed in previous studies involving comprehensive materials such as cement and biomass (Krausmann et al., 2017). This tight coupling, however, needs to be severely broken in the 21st century. The identified future values for metal stock intensity are to reduce it by 3-4% by 2030, 20-25% by 2050, and 60-75% by 2100 relative to 2010 levels, depending on whether this study assumes an increased end-of-life recycling rate and an extended product lifetime.

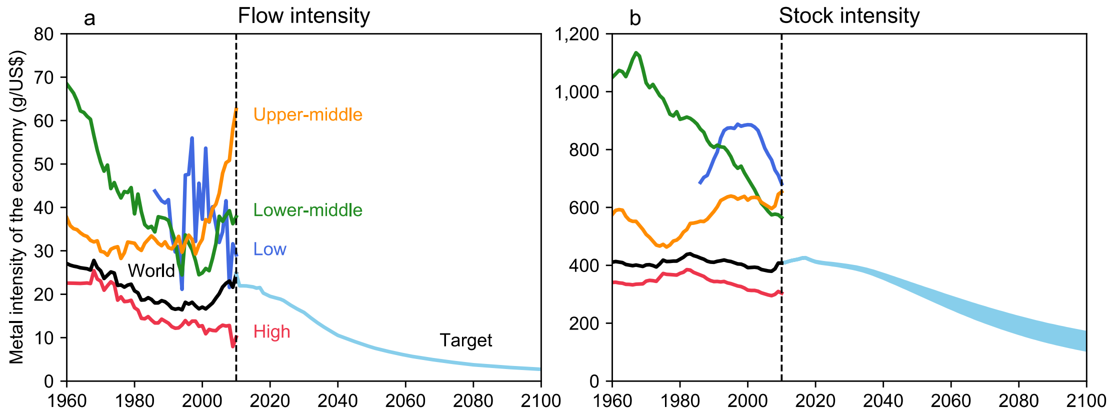

Figure 6- 5 Metal use intensity in the global economy, 2010-2100: (a) Metal flow intensity of the economy (metal inflows/GDP); (b) Metal stock intensity of the economy (metal stock/GDP). The ranges of the target are generated by the circular economy and business as usual scenarios. Future GDP is based on SSP2 (Fricko et al., 2017), which represents a middle-of-the-road scenario.

These scenarios intrinsically depend on the assumed socioeconomic futures and vary widely among SSP scenarios (Table 6- 3). However, even given significant uncertainties, the results consistently support the hypothesis that the carbon constraints require continuous and substantial decoupling during the 21st century (Figure 6- 6).

Table 6- 3 Socio-economic and technology development for each of the five Shared Socio-economic Pathway scenarios (Schipper et al., 2018).

Scenario	Economy and social equality	Technology
SSP1	High sustainable development with low inequalities. Fast technological innovation and change towards environmentally friendly and lower carbon-intensive industries and energy sources.	Fast technological innovation towards low carbon energy sources and industries.
SSP2	Intermediate between SSP 1 and 3.	
SSP3	Moderate economic growth and high inequalities.	A slow change in the energy sector, leading to high emissions.
SSP4	Heterogeneous development due to isolated economies. High social inequalities.	Heterogeneous technological development. Fast change towards low emitting technologies in key regions, but less development in lower emission regions.
SSP5	High economic growth and social equality.	Carbon-based fuel technologies, leading to high emissions.

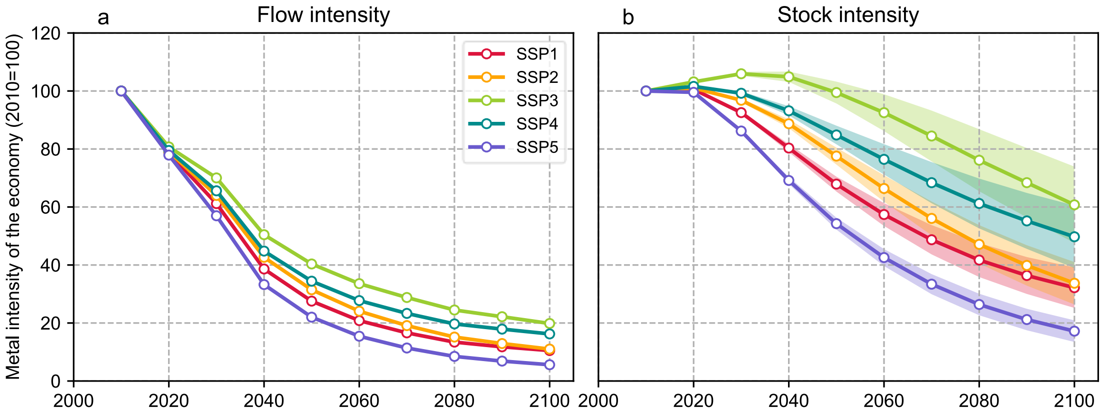

Figure 6- 6 Sensitivity of metal use intensity in the global economy under the five SSP scenarios, 2010-2100. (a) Metal inflow intensity of the economy (metal inflows/GDP); (b) Metal stock intensity of the economy (metal stock/GDP). The flow panel shows the ranges generated by the BAU and CE scenarios; the solid line represents the mean value. GDP data are extracted from the SSP database (Riahi et al., 2017). Note that the metal flows and stocks themselves are not directly linked to the SSP narratives. The ranges are simply due to the different future GDP growth assumed in each SSP.

6.3.4 Potential of supply-side technology solutions

Despite the considerable uncertainty, supply-side technology solutions such as BAT, CCS, and hydrogen reduction are currently considered central options for climate change mitigation (Pardo and Moya, 2013; Van Ruijven et al., 2016). Thus, it is worth investigating the potential impacts of these technologies on the future metal use scenario, specifically targeting iron and aluminum, for which a long-term roadmap (EUROFER, 2013; European Aluminium, 2019; JRC, 2012; The Japan Iron and Steel Federation, 2019) is already established. Figure 6- 7 shows that the various supply-side technologies are not likely to be sufficient to maintain the available amount of iron stock at the current level of high-income countries within the carbon constraints. The combination of BAT, CCS, and hydrogen reduction can contribute to raising the iron stock to 7,600 kg/cap in 2100. Implementing innovative technologies, which are currently only in the laboratory stage, such as CO_2-free hydrogen and electrolysis, has further promise of increasing the iron stock to 8,200 kg/cap. Still, none of these scenarios match the baseline scenario that follows a similar stock growth pattern as that of the high-income countries. Similarly, the implementation of BAT, CCS, and inert anodes in aluminum making has a limited effect on the stock available under carbon constraints (Figure 6- 8). This indicates that climate policy-making for the metal sector that focuses only on supply-side technology solutions may be highly problematic. The remaining gap needs to be filled by transitioning to a society in which the same services are delivered with less metal.

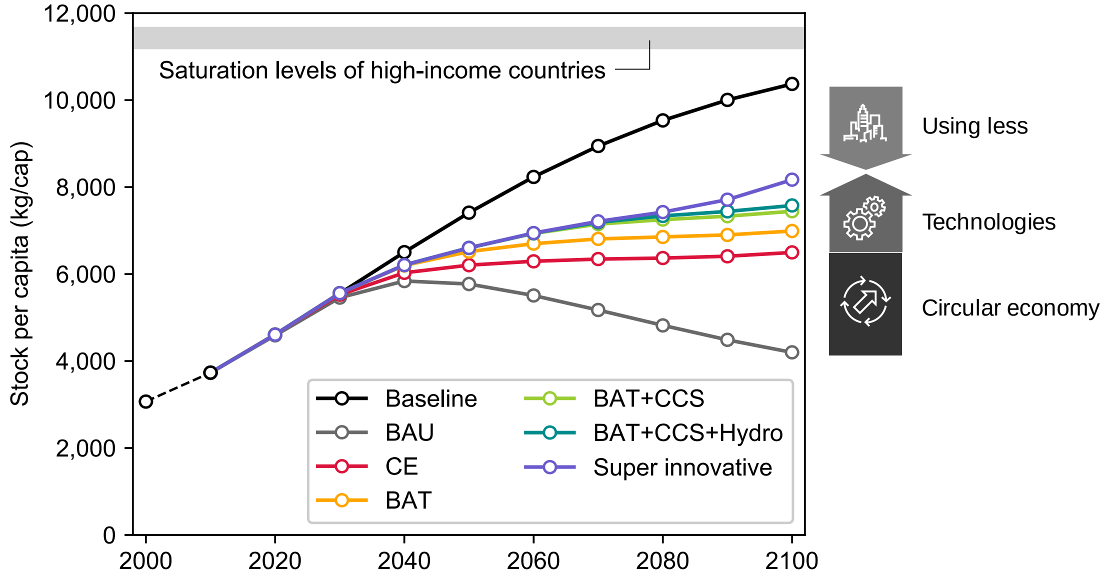

Figure 6- 7 Per capita in-use stock of iron and steel with the various supply-side technology solutions, 2000-2100. The horizontal grey area indicates the current saturation levels in high-income countries. The baseline represents the stock growth pattern without carbon constraints. Circular economy (CE) assumes increased end-of-life recycling rate and product lifetime, while business as usual (BAU) assumes the constant value of these parameters in the carbon constraints. Abbreviations for supply-side production technologies are as follows: best available technology (BAT), carbon capture and storage (CCS), and hydrogen reduction (Hydro). Super innovative includes, e.g., top gas recycling, bath smelting, direct reduction, and electrolysis.

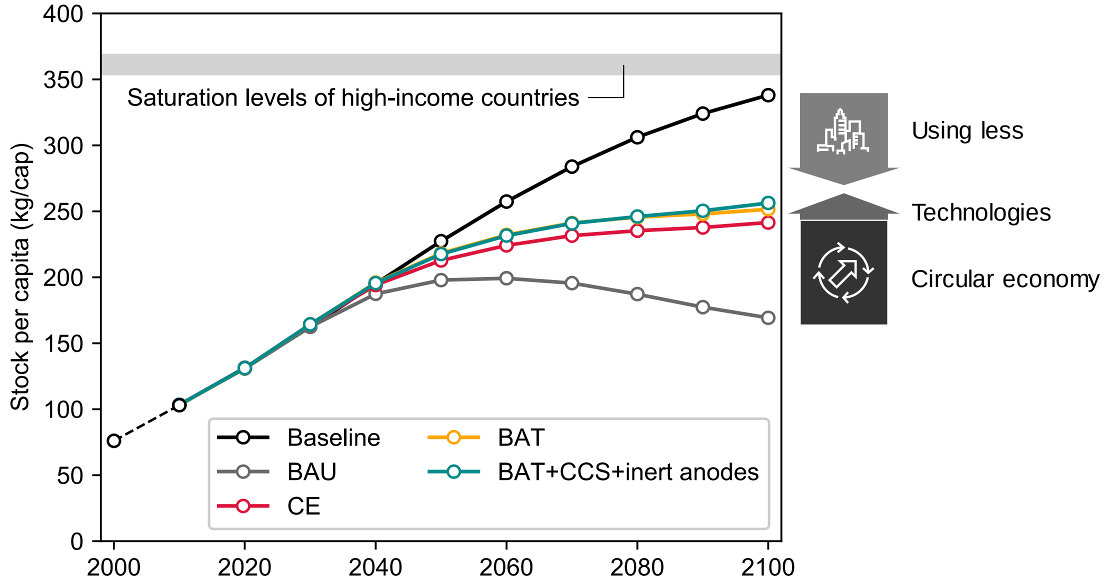

Figure 6- 8 Per capita in-use stock of aluminum with the various supply-side technology solutions, 2000-2100. The baseline represents the stock growth pattern without carbon constraints. Circular economy (CE) assumes an increased end-of-life recycling rate and product lifetime, while business as usual (BAU) assumes the constant value of these parameters in the 2 °C scenario. Abbreviations for innovative production technologies are as follows: best available technology (BAT), carbon capture and storage (CCS).

6.4 Discussion

What should we learn from these results? First, we can place the material-related indicators and their targets derived from this study into a national master plan to construct urban systems characterized by material-efficient goods and services. Most discussions about environmental degradation, including climate change, have hitherto rarely evaluated the material use perspective as a systemic cause of these impacts (World Economic Forum, 2019). Consequently, material-based indicators have not been widely implemented, and where such attempts have been made, their effectiveness appears to have been limited. As an example, while Japan has set national targets for three material flow indicators (resource productivity, cyclical use rate, and final disposal amount) (Ministry of the Environment, Government of Japan, 2020), the scientific basis for these targets remains fairly immature, and there is no scientific evidence that achieving the targets will lead to a sustainable pattern of materials use. As another example, in the context of a circular economy, European countries are proactively examining targets and roadmaps for material circularity (Morseletto, 2020). However, this study clearly demonstrates that as long as in-use metal stocks continue to increase over the 21st century, circularity improvements alone will not ensure sustainable use patterns. What is in fact required is decoupling, or material efficiency improvement, in order to achieve the same level of well-being with lower metal flows and fewer stocks (Allwood et al., 2011). In this regard, the level at which per capita metal stocks should converge in light of the carbon constraints identified in this study is considered a reasonable benchmark for the extent to which material efficiency needs to be improved.

Despite the key role of material efficiency in climate change mitigation, much about strategies to improve material efficiency (Hertwich et al., 2019) remains unknown or ill-defined, including their full potential, barriers to their implementation, and the trade-offs involved. Scientific knowledge regarding policy instruments and their costs also remains unclear. Indeed, the previous studies reviewed in section 2.2 of Chapter 2 largely lack a cross-cutting strategy across the life cycles. Figure 6- 9 illustrates the strong bias in the attention given to the end-of-life phase in material efficiency strategies. Of the various strategies spanning the metal life cycle (light-weighting, substitution, fabrication yield improvements, more intensive use, lifetime extension, reuse, remanufacturing, and recycling.), recycling is the most frequently examined strategy for all metals, with 52 of the 70 studies (74%) modeling its effect. On the other hand, few studies have examined other strategies; for example, only 13% investigated light-weighting, and 10% explored lifetime extension. Importantly, five strategies other than recycling and light-weighting have never been considered in analyses for zinc, lead, and nickel. These trends suggest a lack of life cycle perspectives in strategy considerations. Namely, most of the existing studies restrict potential strategies to only recycling at the analysis design stage, and little attention is given to assessing the full range of opportunities that span the entire life cycle. This oversight substantially weakens the potential policy implications of the analysis. A comprehensive and comparative assessment of a variety of potential strategies is needed to truly support environmental policy design.

Various case studies have already demonstrated the importance of the life-cycle perspective. For example, Carruth et al. (2011) showed that lightweight design could reduce steel and aluminum demand by up to 25-30% without compromising functionality. Chen et al. (2014) demonstrated that the lifetime of products can be extended by fabricating and using products more efficiently, and that such advances could reduce Chinese steel demand by around 20% in 2050. Further, Akashi et al. (2014) demonstrated that the combination of substitution with high-strength steel and more intensive use of steel stock could potentially reduce global steel demand by 40% in 2050. Moreover, Milford et al. (2013) showed that a full array of material efficiency strategies across the entire life cycle could reduce global steel demand by approximately 50% in 2050 compared to the no-action case. All of these case studies clearly demonstrate the importance of life cycle perspectives in strategy development. Given that the development of future scenarios that lack these perspectives could eventually lead to governments and companies to overlook important windows of opportunity, the amendment of current scenarios is crucial.

Reflecting the lack of attention, the latest International Resource Panel report (IRP, 2020) points out that commitments to material efficiency have been scarcely incorporated into the nationally determined contributions of the Paris Agreement. An important step would be to include material efficiency strategies in the list of climate change mitigation options, taking into account specific policy alternatives and their costs. Broadening the horizons of policy makers, business leaders, and consumers is an essential challenge if they are to see and understand the full range of opportunities across the entire life-cycle and value chain.

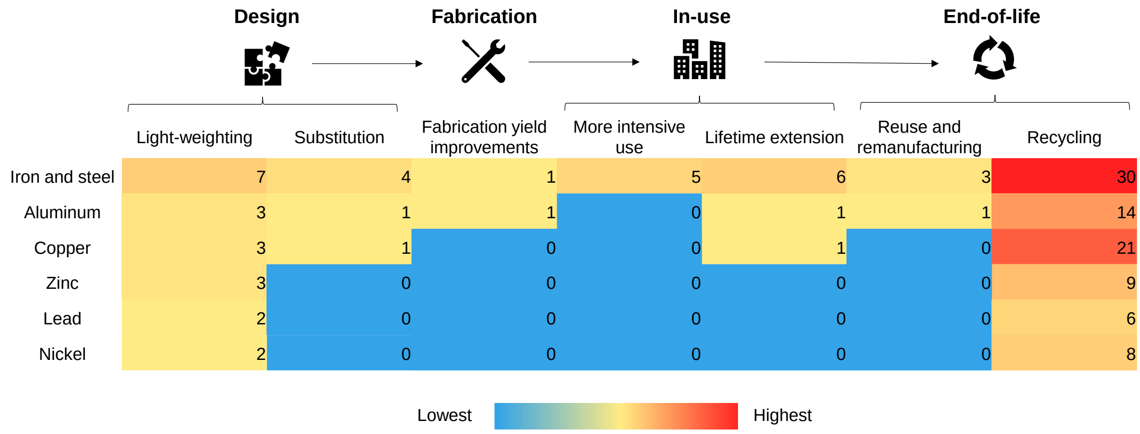

Figure 6- 9 Number of publications covering each material efficiency strategy at different life cycle phases. Seven strategies are considered here, including light-weighting, substitution, fabrication yield improvements, more intensive use, lifetime extension, reuse, remanufacturing, and recycling. The reviewed articles are based on section 2.2 in Chapter 2.

6.5 Appendix to Chapter 6

Table 6- 4 Estimated annual emission constraints for each metal sector, 2010-2100 [Unit: Mt-CO_2eq./yr]. Emissions mitigation rates are based on the industrial sector scenario to keep global temperature rise well below 2°C relative to pre-industrial levels (Gidden et al., 2019).

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	2,771	480	101	52	15	33
2020	3,113	539	114	58	17	37
2030	2,809	486	103	53	15	33
2040	1,834	317	67	34	10	22
2050	1,317	228	48	25	7	16
2060	969	168	35	18	5	12
2070	700	121	26	13	4	8
2080	457	79	17	9	2	5
2090	394	68	14	7	2	5
2100	355	61	13	7	2	4

Table 6- 5 Estimated cumulative emission constraints for each metal sector, 2010-2100 [Unit: Mt-CO_2eq.].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010-2100	134,275	23,238	4,909	2,513	729	1,598

Table 6- 6 Emission intensity of primary production [Unit: kg-CO_2eq./kg].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	2.1	13.3	6.3	3.9	2.3	22.0
2020	2.0	11.5	5.8	3.4	2.1	19.1
2030	1.9	8.5	4.8	2.4	1.7	14.0
2040	1.8	6.0	3.9	1.6	1.3	9.6
2050	1.8	5.1	3.7	1.4	1.2	8.2
2060	1.7	5.0	3.6	1.3	1.2	8.0
2070	1.7	5.0	3.6	1.3	1.2	7.9
2080	1.7	4.9	3.6	1.3	1.2	7.8
2090	1.7	4.9	3.5	1.3	1.2	7.8
2100	1.7	4.9	3.5	1.3	1.1	7.7

Table 6- 7 Emission intensity of secondary production [Unit: kg-CO_2eq./kg].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	0.3	0.7	1.6	2.2	0.7	0.5
2020	0.3	0.7	1.5	1.9	0.6	0.5
2030	0.3	0.6	1.2	1.2	0.5	0.4
2040	0.2	0.6	1.1	0.7	0.5	0.4
2050	0.2	0.5	1.0	0.5	0.5	0.4
2060	0.2	0.5	1.0	0.5	0.5	0.4
2070	0.2	0.5	1.0	0.5	0.5	0.4
2080	0.2	0.5	1.0	0.4	0.5	0.4
2090	0.2	0.5	1.0	0.4	0.5	0.4
2100	0.2	0.5	1.0	0.4	0.5	0.4

Chapter 7

Contraction and convergence of in-use metal stocks to meet climate goals

7.1 Introduction

While Chapter 6 quantified the impact of carbon constraints on global metal flows and stocks, the explored scenarios have only been clarified at a global level, making it difficult for governments and companies to incorporate them directly into future policies and activities. Furthermore, little consideration has been given to efforts to improve energy efficiency in the non-ferrous metals industry. In addition, Chapter 6 provides few suggestions regarding the physical depletion of resources, which has been a subject of debate for many years (Northey et al., 2018). If the currently identified resources are depleted before facing the carbon constraints, we may not have to worry about carbon constraints.

This chapter aims to fill these knowledge gaps by demonstrating a method that can be used to derive metal use scenarios for four country income groups (high-, upper-middle-, lower-middle-, and low-income countries) based on a principle of contraction and convergence (Böhringer and Welsch, 2004). As discussed in Chapter 6, the approach explicitly deals with the physical interconnection in the global metal cycles and the formulation of the time-series carbon constraints in line with prevailing climate goals. Here, the potential for future energy efficiency improvements in the production process of non-ferrous metals is taken into account, and the extracted natural ores available under the carbon constraints are compared with the currently identified resources. As in Chapters 5 and 6, the approach is applied to the six major metals—iron, aluminum, copper, zinc, lead, and nickel.

7.2 Methodology

7.2.1 Model overview

As discussed in Chapter 6, future metal flows and stock dynamics through to the year 2100 were explored using an optimization routine, with the global metal cycle model linked to GHG emission intensity and emission constraints data. The objective is to minimize the divergence between the baseline stock and the stock available under the carbon constraints within the scenario period, and the objective function is formulated as an intertemporal linear programming model. The optimization routine is used to derive global metal flows by considering the world as a single region, $X_{5.6}(t)$, and then multiplying the value by the metal flow allocation coefficient to assign a metal flow to each region. By introducing R for the aggregate of each income group r (high-, upper-middle-, lower-middle-, and low-income countries), the metal flows harmonized with the carbon constraints in each income group $X_{5.6,r}(t)$ are determined by using the metal flow allocation coefficient $k_r(t)$:

$$X_{5.6,r}(t) = k_r(t)X_{5.6}(t) \tag{7-1}$$

where $k(t)$ is estimated by:

$$k_r(t) = \frac{X_{5.6,r,\mathrm{base}}(t)}{\sum_{r\in R} X_{5.6,r,\mathrm{base}}(t)} \tag{7-2}$$

Here, $X_{5.6,r,\mathrm{base}}(t)$ represents the baseline demand, which is calculated using the baseline stock, $X_{6,\mathrm{base}}(\tau)$, estimated in Chapters 5 and 6 and the stock-driven approach shown in equation (7-3).

$$\begin{aligned} X_{5.6,r,\mathrm{base}}(t) &= X_{6,r,\mathrm{base}}(\tau) - X_{6,r,\mathrm{base}}(\tau-1) \\ &\quad + \sum_{t'=0}^{t}\left((1-\omega)X_{5.6,r,\mathrm{base}}(t')\phi(t-t')\right) \end{aligned} \tag{7-3}$$

where ω and ϕ denotes the in-use dissipation loss rate and the lifetime distribution, respectively.

This approach is based on the assumption that the availability of scrap is not limited to its region of origin and that it can be traded between countries, and on the widely established principle of contraction and convergence (Böhringer and Welsch, 2004), which is one of several equity principles (equal per capita allocation) (Höhne et al., 2014). This study, therefore, assumes a world in which the same level of per capita metal stocks becomes available to all income groups in the course of the 21st century. It should be noted that this principle, while simple, does not consider the complex relationship that exists between metal stock levels and the service levels provided by them. Although there is undoubtedly a level of per capita metal stock that needs to be collocated with a population, in order to provide essential services for a high quality of life (Pauliuk, 2018), establishing just what this level should be is difficult, as it is highly dependent upon the local situation and includes factors such as population density (Müller et al., 2013). This study should therefore be regarded as illustrating one possible effort-sharing scenario rather than providing a realistic forecast.

Finally, the estimated metal demand was decomposed to stock expansion demands and replacement demands using equations (7-4) and (7-5).

$$\mathrm{Expansion_r}(t) = \begin{cases} \Delta X_{6,r}(t), & \Delta X_{6,r}(t) > 0 \\ 0, & \Delta X_{6,r}(t) \leq 0 \end{cases} \tag{7-4}$$

$$\mathrm{Replacement_r}(t) = \begin{cases} X_{5.6,r}(t) - \Delta X_{6,r}(t), & \Delta X_{6,r}(t) > 0 \\ X_{5.6,r}(t), & \Delta X_{6,r}(t) \leq 0 \end{cases} \tag{7-5}$$

where $\Delta X_{6,r}(t)$ is the change in in-use stock in region r in year t.

7.2.2 Scenario developments

To consider uncertain trajectories in the progress of technological developments and the transition to a circular economy, this study envisions that the following five scenarios will be implemented individually and simultaneously.

- *No action*: All modeling parameters remain constant within the scenario period, except for the decarbonization of electricity generation according to the Reference Technology Scenario set out by the International Energy Agency (IEA, 2017).
- *Electricity decarbonization*: Electricity generation will be decarbonized through the increased adoption of renewable energy, becoming carbon neutral by approximately 2060 (IEA, 2017).
- *Energy efficiency improvements*: Energy efficiency improving gradually towards a theoretical maximum as the best technologies become more widespread (IEA, 2014; Wyns and Khandekar, 2020). More specifically, this study assumes that the emission intensity of primary iron and steel production will be reduced by 21% by 2050, and that the emission intensity of primary non-ferrous metal production will be reduced by 10% by 2050 and 21% by 2100 (IEA, 2014; Wyns and Khandekar, 2020). Specific options include smarter and integrated control systems, increased burner efficiency and increased heat recovery. Furthermore, for iron and steel production, additional emission reduction effects of 20% and 10% will be obtained by carbon capture and storage and hydrogen reduction, respectively, based on the COURSE50 roadmap (The Japan Iron and Steel Federation, 2019). These reduction rates will be reached gradually from 2030 to 2050.
- *Near-perfect recycling*: The end-of-life recycling rate will gradually rise to 90% by 2100 through improvements in the scrap collection rate and secondary production yields (Van der Voet et al., 2019).

- *Longer product lifetimes*: Average product lifetime will gradually increase and reach the theoretical maximum by 2100 by promoting durable design, reuse, repair, and remanufacturing activities (Cherry et al., 2018; Milford et al., 2013).

7.3 Results

7.3.1 Contraction and convergence of in-use metal stocks

Figure 7- 1 shows that the global per capita stock of all six major metals needs to converge to a much lower level than that currently enjoyed by today's high-income countries in order for the metal sector to contribute proportionally to industrial sector emissions mitigation targets. Specifically, the global per capita stock of the six metals combined needs to converge from the current level of around 3900 kg/capita to approximately 6500 kg/capita (with a range of 4400-9700 t/capita depending on advances in technology and the circular economy). In this case, high-income countries will need to contract their per capita stocks from the current level of around 12000 kg/capita to leave space for growth in middle- and low-income countries. Consequently, while middle- and low-income countries can increase their per capita stocks from the current levels, they need to converge to a level well below today's high-income countries.

Turning to each metal, the development path of such contraction and convergence scenarios varies depending on the metals. The global per capita stock in 2100 was estimated to be approximately 6200 kg/capita for iron and steel (with a range of 4250-9260, depending on advances in technological developments and the circular economy), 200 (130-270) kg/capita for aluminum, 40 (20-80) kg/capita for copper, 21 (6-49) kg/capita for zinc, 3 (2-4) kg/capita for lead, and 9 (4-14) kg/capita for nickel. Compared with today's high-income countries, these levels are around 55 (37-82)% for iron, 56 (36-77)% for aluminum, 23 (12-46)% for copper, 34 (9-80)% for zinc, 12 (7-20)% for lead, and 52 (25-82)% for nickel.

Overall, the findings here indicate that the decarbonization of electricity, improved energy efficiency, and circular economy practices are not silver bullets for reducing GHG emissions in the metals sector. Rather, what is needed, in tandem, is a systemic transition to a society that can satisfy basic human needs using considerably lower levels of metal stocks than those of today's high-income countries.

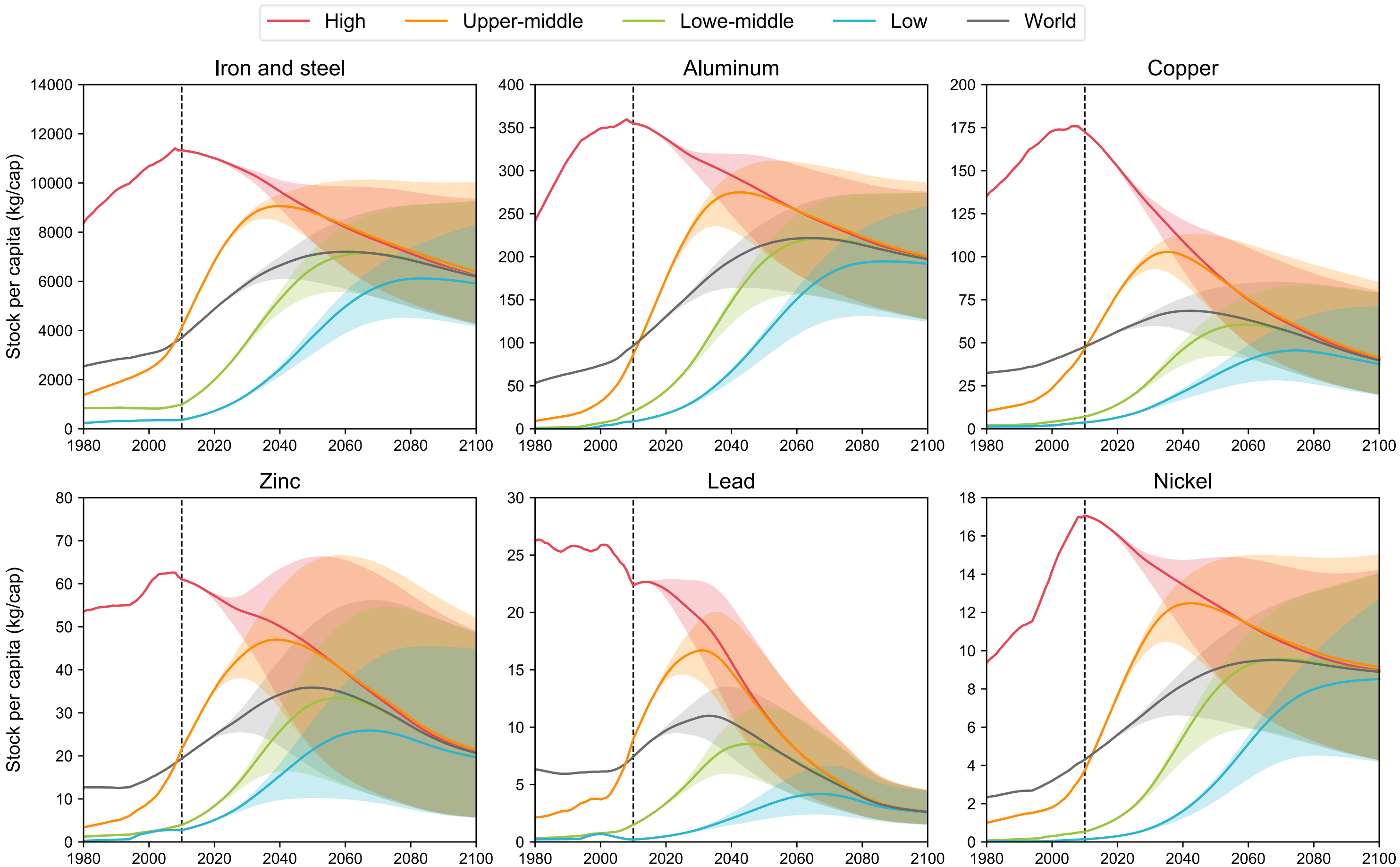

Figure 7- 1 Per capita in-use stocks of the six major metals under the carbon constraints, 1980-2100. The color band around each line reflects the uncertainties associated with advances in technology and the circular economy. The solid lines represent the means of scenarios. The vertical dashed lines mark the year in which the future projections begin (2010).

7.3.2 Supply constraints by emissions budget rather than resource depletion

In the contraction and convergence scenarios for in-use metal stocks described above, the dominant sources of supply will change significantly over the 21st century (Figure 7- 2). Primary production from natural ores is the main source of supply today, but primary production of all six major metals reaches a peak by 2030 and continues to decline thereafter. Secondary production from both new and old scrap, on the other hand, will play an increasing role, surpassing primary production at least by 2050 for all metals. Consequently, the cumulative ore requirements from 2020 to 2100 will remain lower than the currently identified resources of all six major metals (Figure 7- 3). This clearly implies that natural ore extraction will be limited by carbon constraints long before resource depletion is a reality.

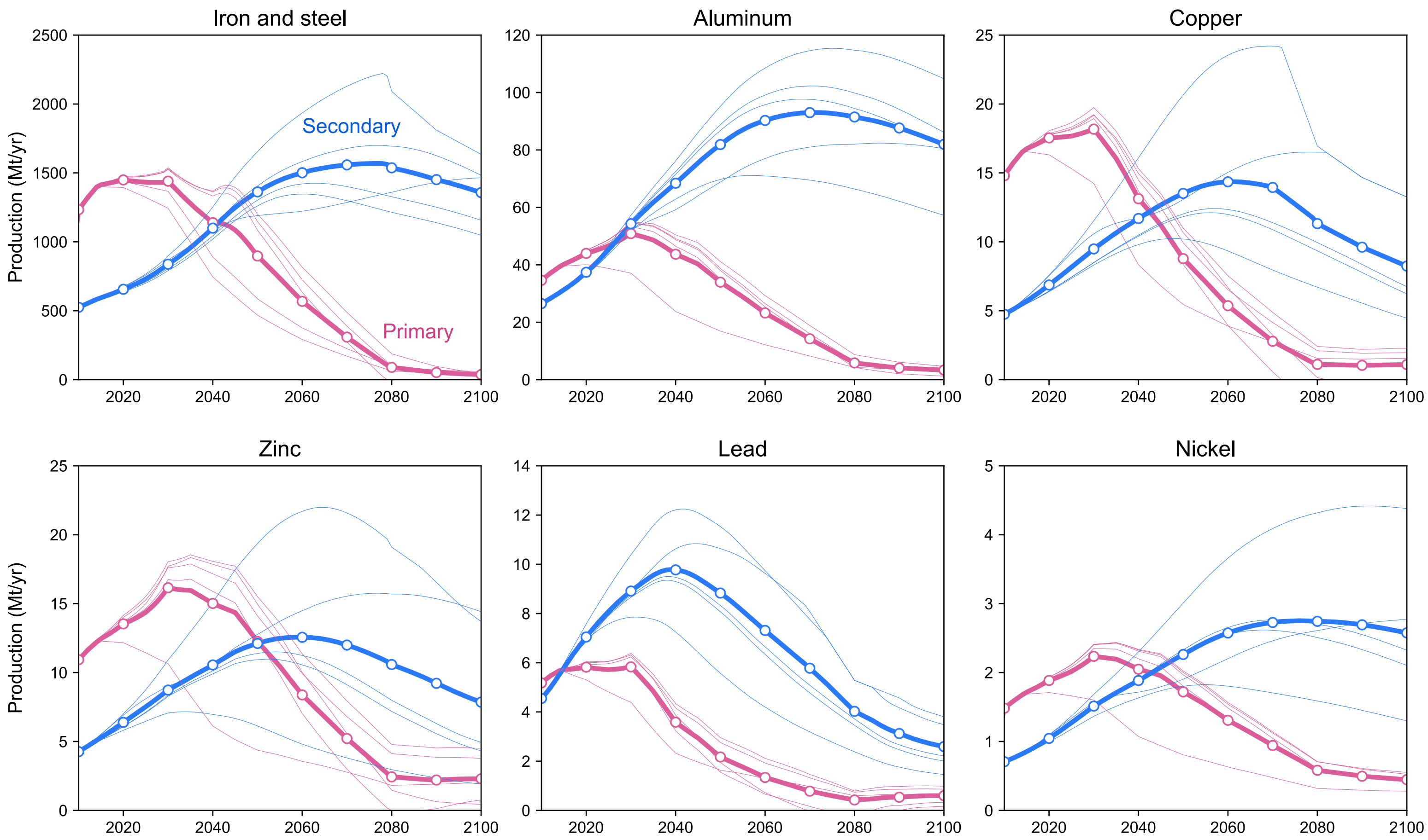

Figure 7- 2 Primary and secondary production of the six major metals under the carbon constraints, 2010-2100. The thin lines show the various scenarios with different advances in technology and circular economy, and the thick lines represent the means of the scenarios.

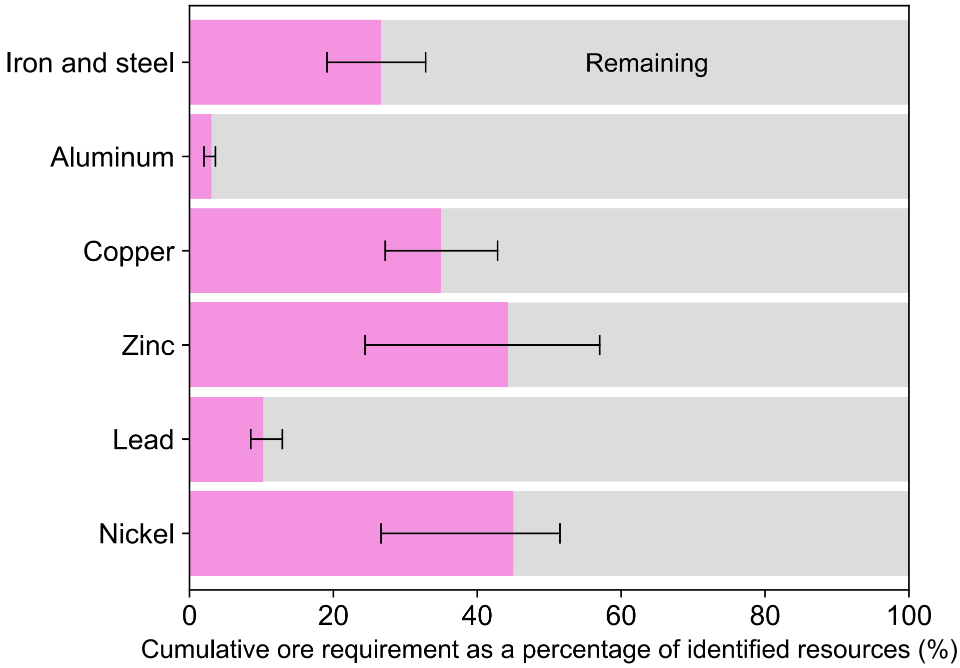

Figure 7- 3 Comparison of cumulative ore requirement under the carbon constraints from 2020 to 2100 with currently identified resources. The identified resource data are obtained the from USGS (USGS, 2020). The error bars represent the minimum and maximum values of the scenario.

7.3.3 Common but differentiated responsibilities

Realizing the metal stock contraction and convergence scenario clearly requires an international effort involving all countries, but specific responsibilities will vary according to income group (Figure 7- 4). In today's high-income countries, where the per capita stock is already trending towards saturation, and the prospects for population growth are modest, the mainstream metal demand in the 21st century will be to compensate for the retirement of the existing stock. It is therefore important to control such replacement demand. Conversely, today's middle- and low-income countries, especially in the first half of the 21st century, are in a phase of stock expansion to improve their living standards, and thus have the greatest opportunity to control the expansion demand. These observations imply that there is a need for prioritizing different strategies. Namely, today’s high-income countries can effectively reduce future metal demand by using the existing stock more intensively through sharing activities and by extending the lifetime of the existing stock through reuse, remanufacturing, and refurbishing practices. Today’s middle- and low-income countries, on the other hand, can build long-lasting and material-efficient infrastructure to curtail expansion demand in the first half of the 21st century. These findings provide new insights into the widely adopted principle of "common but differentiated responsibilities" (Stone, 2004) from a metal flow-stock perspective.

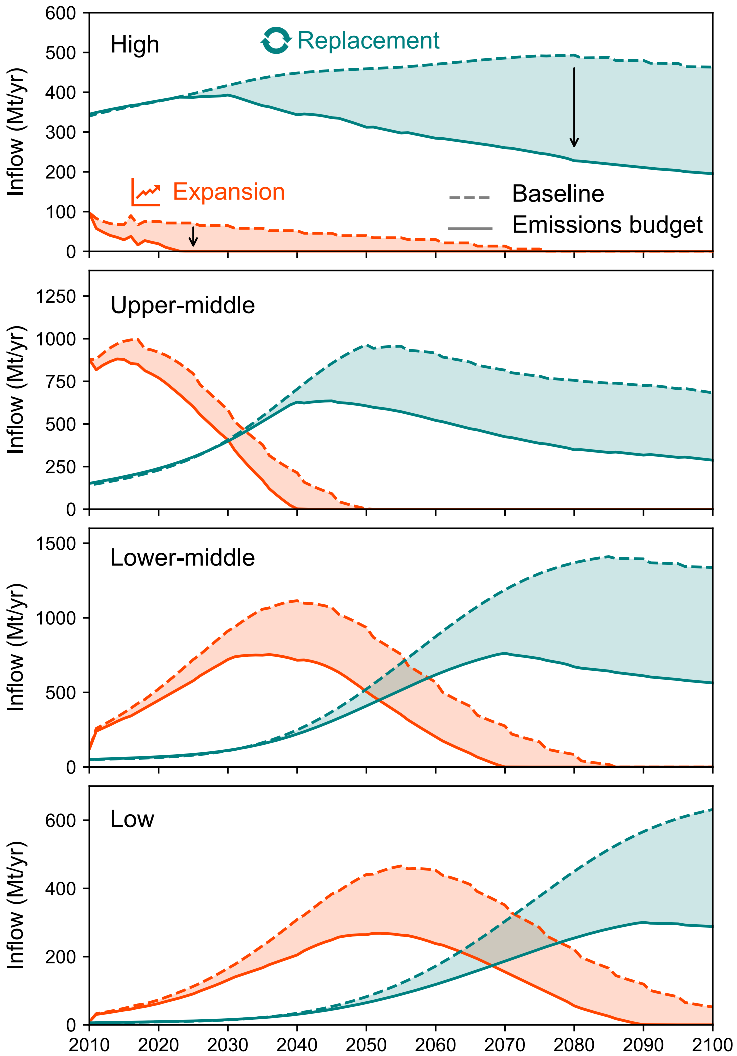

Figure 7- 4 Expansion and replacement demand for six major metals for each country income group under the carbon constraints and baseline scenario, 2010-2100. The baseline scenario is determined based on the assumption that the per capita stocks follow the stock growth pattern of current high-income countries by following the saturation curves. The demands under the emissions budget represent the means of the scenarios.

7.4 Discussion

This study highlighted that carbon constraints could significantly limit future metal flows and stocks. Specifically, primary production of all six metals will peak by 2030, and secondary production will surpass primary production by at least 2050. Consequently, cumulative ore requirements over the 21st century will remain below currently identified resources, implying that natural ore extraction will be limited by carbon constraints before existing resources can be depleted. In such a case, the global per capita metal stock would converge to about 7 t/capita in the scenario average, which is lower than the 12 t/capita currently used in high-income countries. These results again emphasize the importance of decoupling, or material efficiency improvement, in order to achieve the same level of well-being with lower metal flows and fewer stocks (Allwood et al., 2011).

While there are no existing studies with the same scope as this study, it would be helpful to compare benchmarks for per capita metal stock levels consistent with the carbon constraints identified in this study with existing studies. Table 7- 1 shows that the benchmarks identified in this study are in good agreement with existing studies. This fact reinforces the study's assertion that the global per capita metal stocks need to converge to a much level lower than the current level in high-income countries in order for the metals sector to contribute proportionally to industrial sector emission reduction targets. With this in mind, an important contribution of this study is the identification of specific levels and timing of such convergence for six major metals.

Table 7- 1 Comparison with existing studies on benchmarks for per capita metal stock levels consistent with carbon constraints [Unit: kg/capita].

Metals	Stabilization level of per capita stock under carbon constraints	Ref.
Iron and steel	6,200 (with a range of 4,250-9,260)	This study
	6,000	(Milford et al., 2013)
Aluminum	200 (with a range of 130-270)	This study
	200	(Liu et al., 2013)

The results of this study could also help to effectively address such challenges by highlighting strategies that should be prioritized. By decomposing the future metal demand into stock expansion and replacement demand, this study found that the window of opportunity varies by income group. Namely, wealthy countries will need to use existing infrastructure, buildings, machinery, and transportation systems more intensively and for longer periods to reduce the stock replacement demand. Poor countries, on the other hand, will need to establish long-lasting and material-efficient infrastructure to effectively curtail the stock expansion demand through such measures as careful urban design. These findings highlight the need, especially in high-income countries, to support business innovation related to sharing, reuse, and remanufacturing practices in parallel with government action, by raising consumer and investor awareness of the importance of sustainable material use. This will eventually open windows of opportunity for meeting emission reduction targets in a cost-effective and innovative manner.

7.5 Appendix to Chapter 7

7.5.1 Emission intensity

Table 7- 2 Emission intensity of primary production under no action scenario [Unit: kg-CO_2eq./kg].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	2.1	13.3	6.3	3.9	2.3	22.0
2020	2.1	12.8	6.4	3.8	2.3	21.4
2030	2.1	12.1	6.3	3.6	2.3	20.4
2040	2.0	11.6	6.3	3.5	2.4	19.6
2050	2.0	10.7	6.2	3.3	2.3	18.4
2060	2.0	10.0	5.9	3.0	2.2	17.1
2070	1.9	9.4	5.6	2.8	2.1	15.9
2080	1.9	8.8	5.3	2.6	1.9	14.9
2090	1.9	8.3	5.1	2.4	1.8	14.0
2100	1.9	7.9	4.9	2.3	1.8	13.2

Table 7- 3 Emission intensity of primary production under electricity decarbonization scenario [Unit: kg-CO_2eq./kg].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	2.1	13.3	6.3	3.9	2.3	22.0
2020	2.0	11.5	5.8	3.4	2.1	19.1
2030	1.9	8.5	4.8	2.4	1.7	14.0
2040	1.8	6.0	3.9	1.6	1.3	9.6
2050	1.8	5.1	3.7	1.4	1.2	8.2
2060	1.7	5.0	3.6	1.3	1.2	8.0
2070	1.7	5.0	3.6	1.3	1.2	7.9
2080	1.7	4.9	3.6	1.3	1.2	7.8
2090	1.7	4.9	3.5	1.3	1.2	7.8
2100	1.7	4.9	3.5	1.3	1.1	7.7

Table 7- 4 Emission intensity of primary production under electricity decarbonization + energy efficiency improvement scenario [Unit: kg-CO_2eq./kg].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	2.1	13.3	6.3	3.9	2.3	22.0
2020	2.0	11.4	5.8	3.3	2.1	18.9
2030	1.7	8.3	4.7	2.4	1.6	13.6
2040	1.2	5.6	3.7	1.5	1.2	9.1
2050	0.9	4.6	3.3	1.2	1.1	7.4
2060	0.9	4.3	3.1	1.1	1.0	6.8
2070	0.9	4.1	2.9	1.1	1.0	6.5
2080	0.9	4.0	2.9	1.0	0.9	6.3
2090	0.9	3.9	2.8	1.0	0.9	6.2
2100	0.9	3.8	2.8	1.0	0.9	6.1

Table 7- 5 Emission intensity of secondary production under no action scenario [Unit: kg-CO_2eq./kg].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	0.3	0.7	1.6	2.2	0.7	0.5
2020	0.3	0.7	1.5	2.1	0.6	0.5
2030	0.3	0.7	1.5	2.0	0.6	0.5
2040	0.3	0.7	1.5	1.9	0.6	0.5
2050	0.3	0.7	1.4	1.7	0.6	0.5
2060	0.3	0.7	1.3	1.5	0.6	0.5
2070	0.3	0.6	1.3	1.4	0.6	0.4
2080	0.3	0.6	1.3	1.3	0.6	0.4
2090	0.3	0.6	1.2	1.2	0.5	0.4
2100	0.3	0.6	1.2	1.1	0.5	0.4

Table 7- 6 Emission intensity of secondary production under electricity decarbonization scenario [Unit: kg-CO_2eq./kg].

Year	Iron and steel	Aluminum	Copper	Zinc	Lead	Nickel
2010	0.3	0.7	1.6	2.2	0.7	0.5
2020	0.3	0.7	1.5	1.9	0.6	0.5
2030	0.3	0.6	1.2	1.2	0.5	0.4
2040	0.2	0.6	1.1	0.7	0.5	0.4
2050	0.2	0.5	1.0	0.5	0.5	0.4
2060	0.2	0.5	1.0	0.5	0.5	0.4
2070	0.2	0.5	1.0	0.5	0.5	0.4
2080	0.2	0.5	1.0	0.4	0.5	0.4
2090	0.2	0.5	1.0	0.4	0.5	0.4
2100	0.2	0.5	1.0	0.4	0.5	0.4

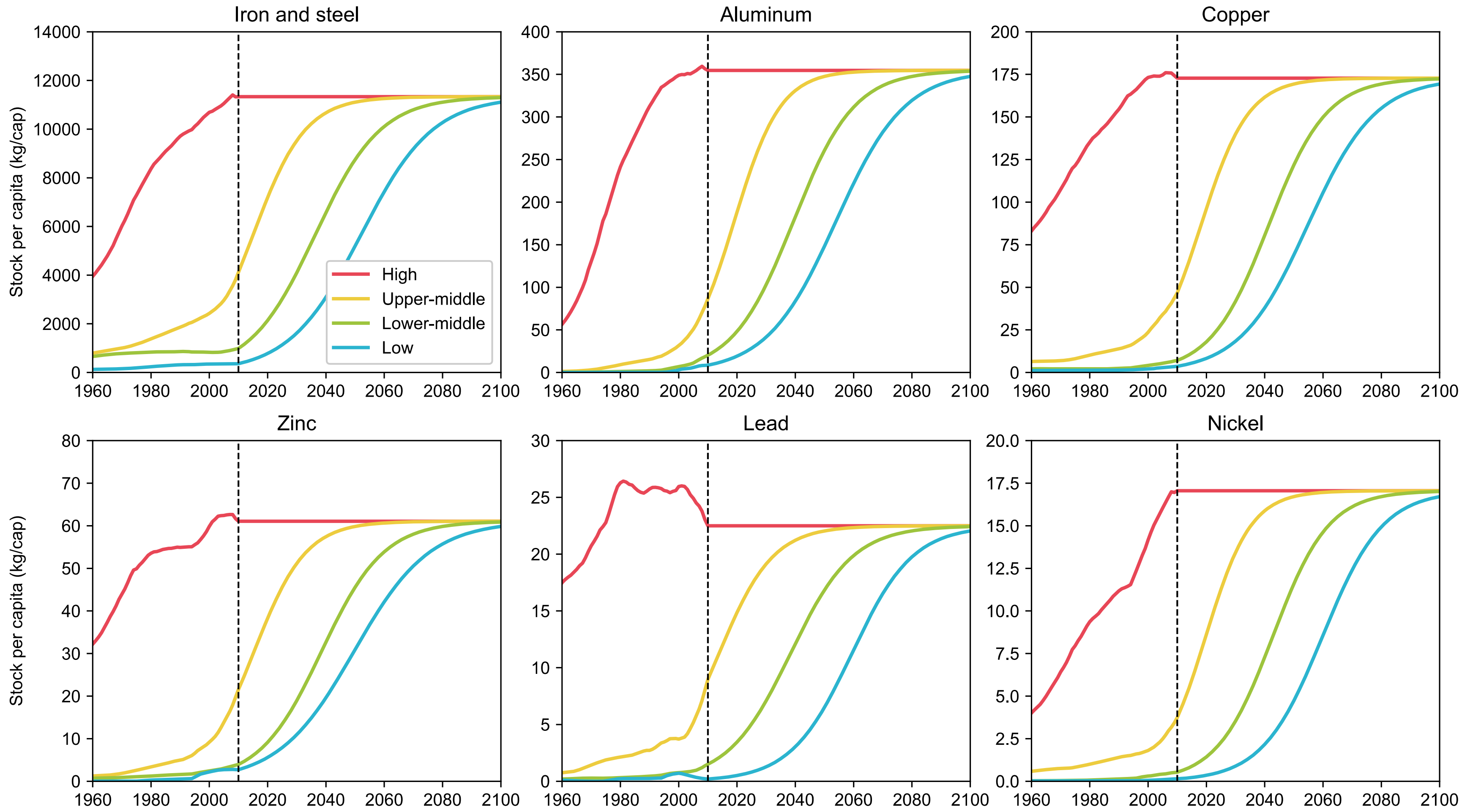

Figure 7- 5 Baseline levels of per capita in-use stock for six major metals, 1960-2100.

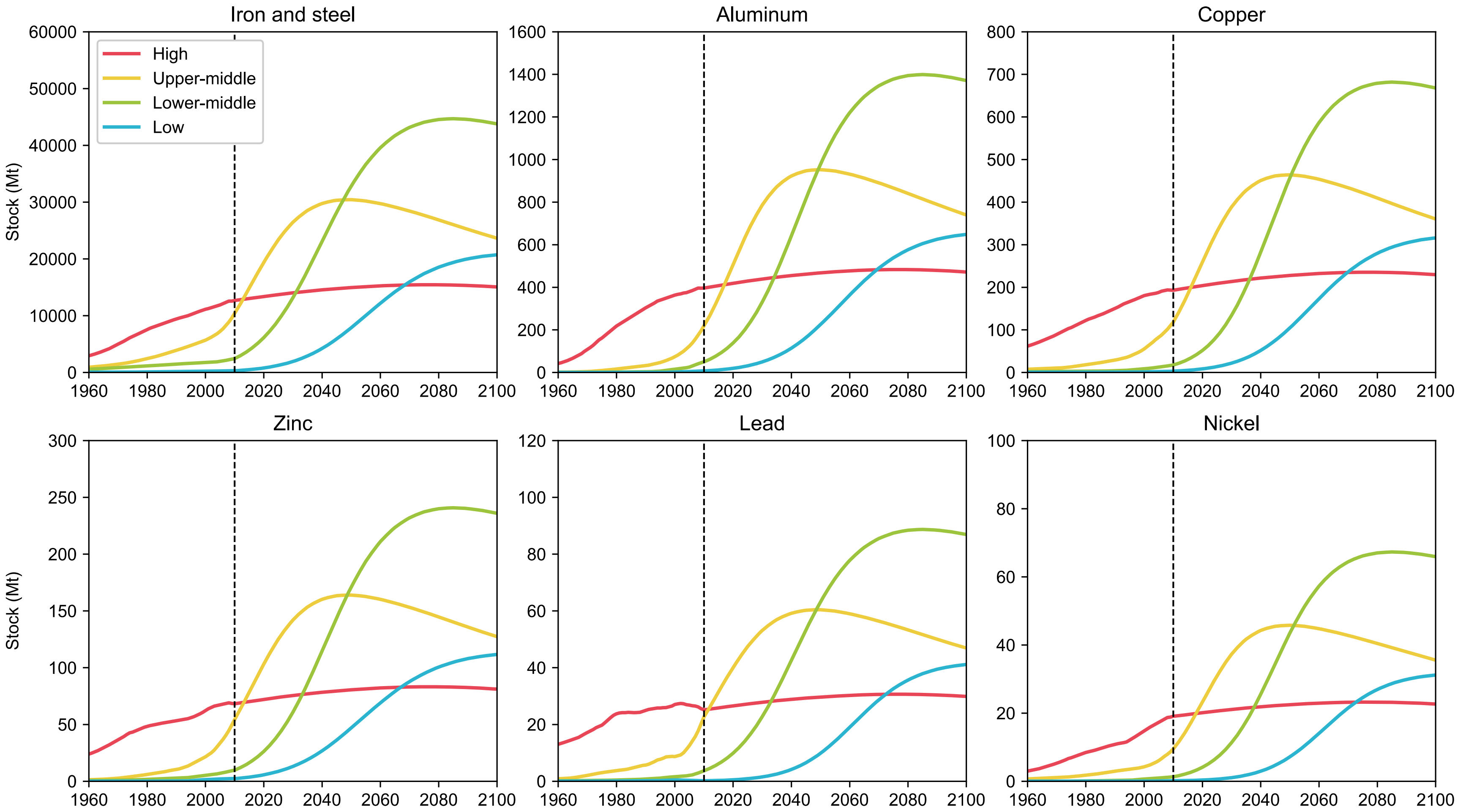

Figure 7- 6 Baseline levels of in-use stock for six major metals, 1960-2100.

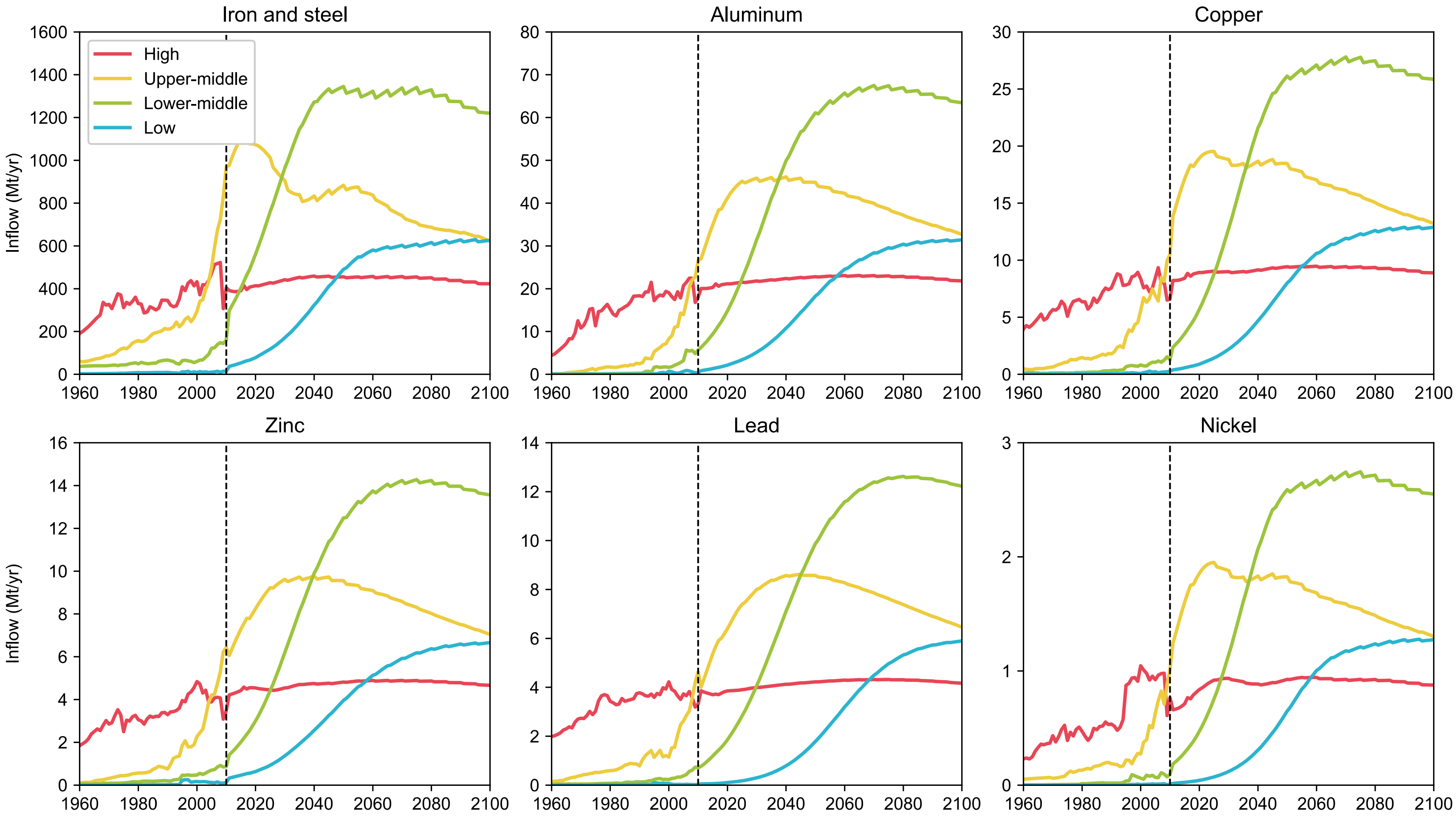

Figure 7- 7 Baseline inflows for six major metals, 1960-2100.

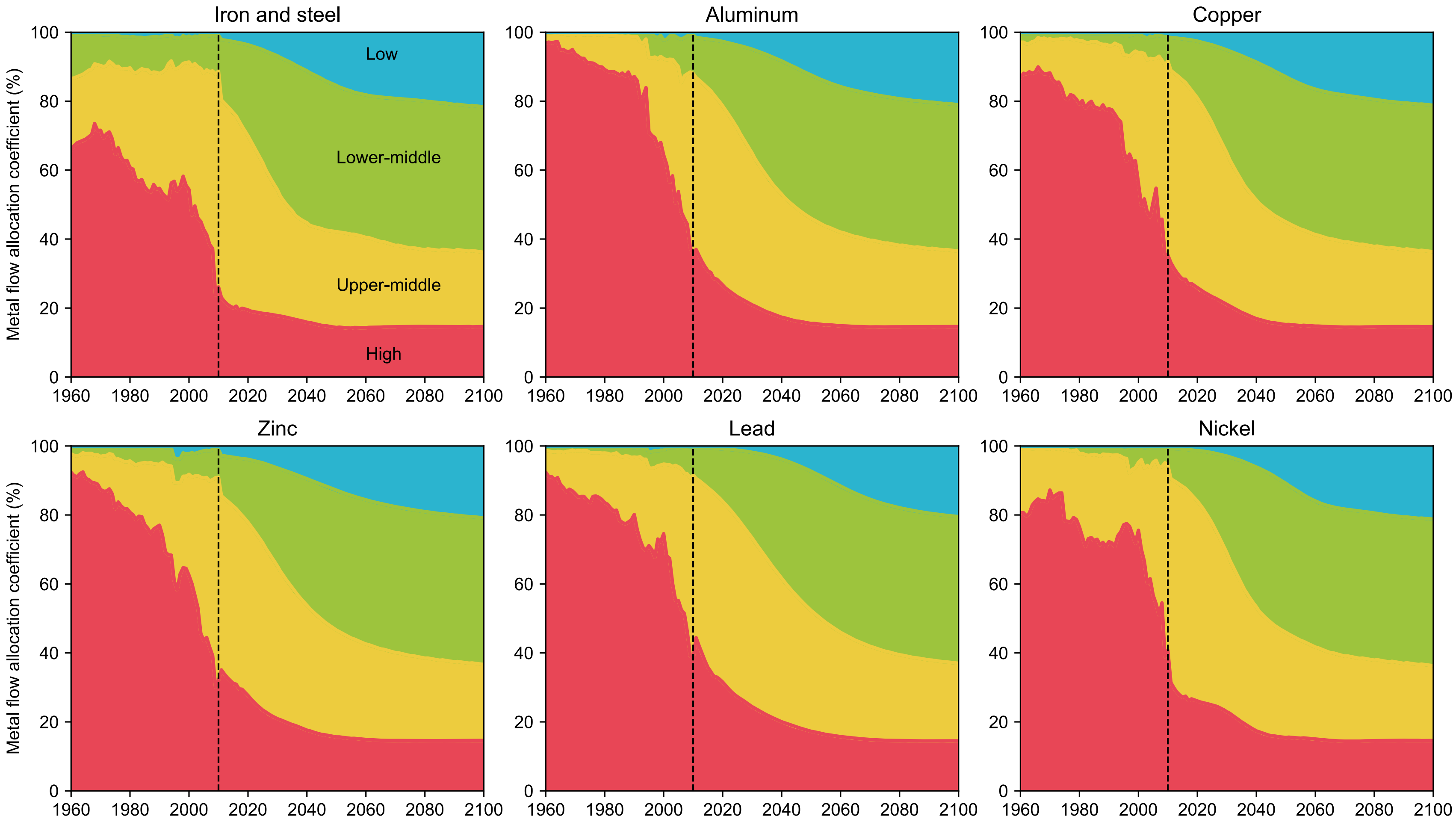

Figure 7- 8 Flow allocation coefficient for six major metals, 1960-2100.

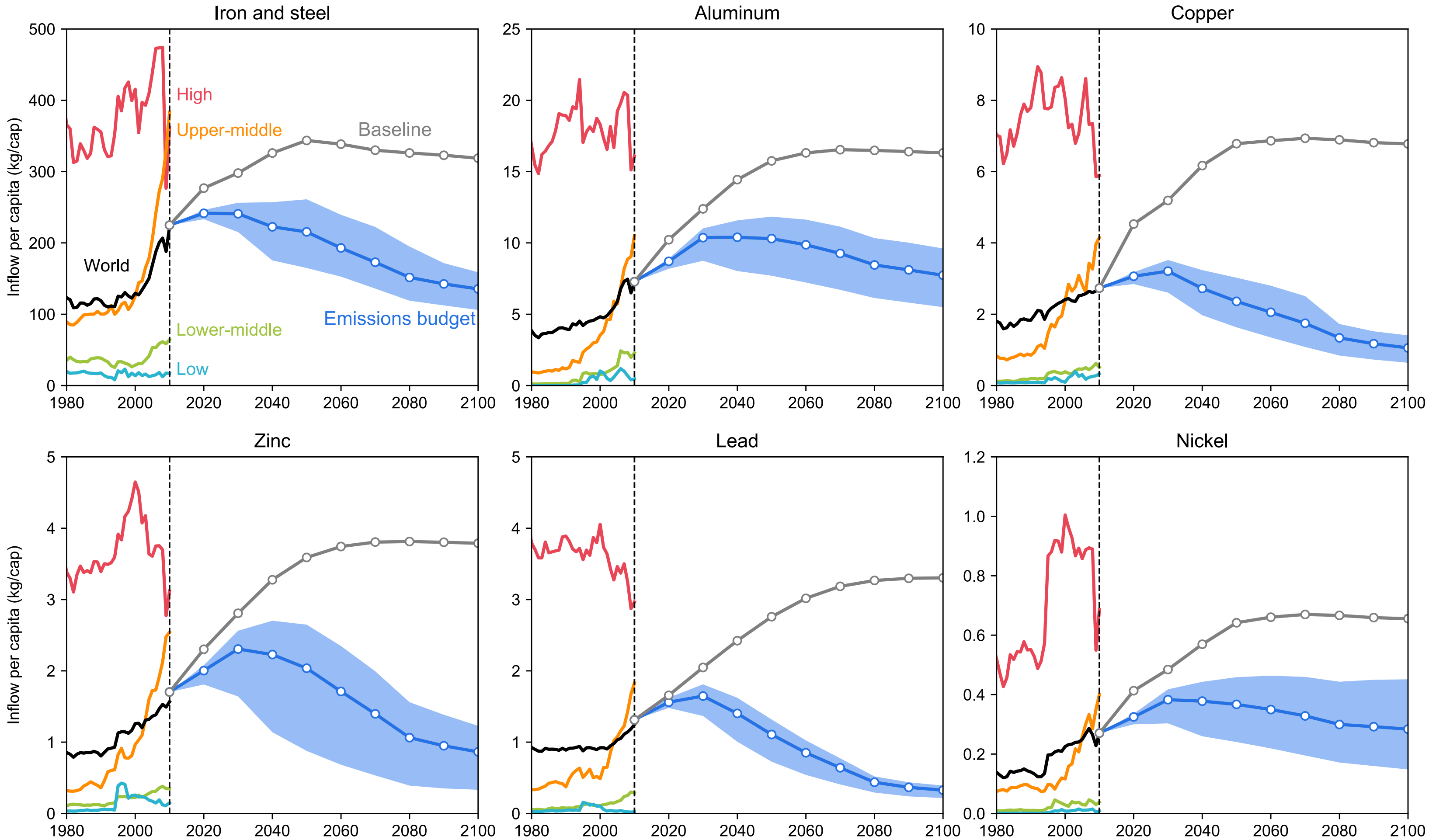

Figure 7- 9 Per capita flows for six major metals under the carbon constraints and baseline scenario, 1980-2100.

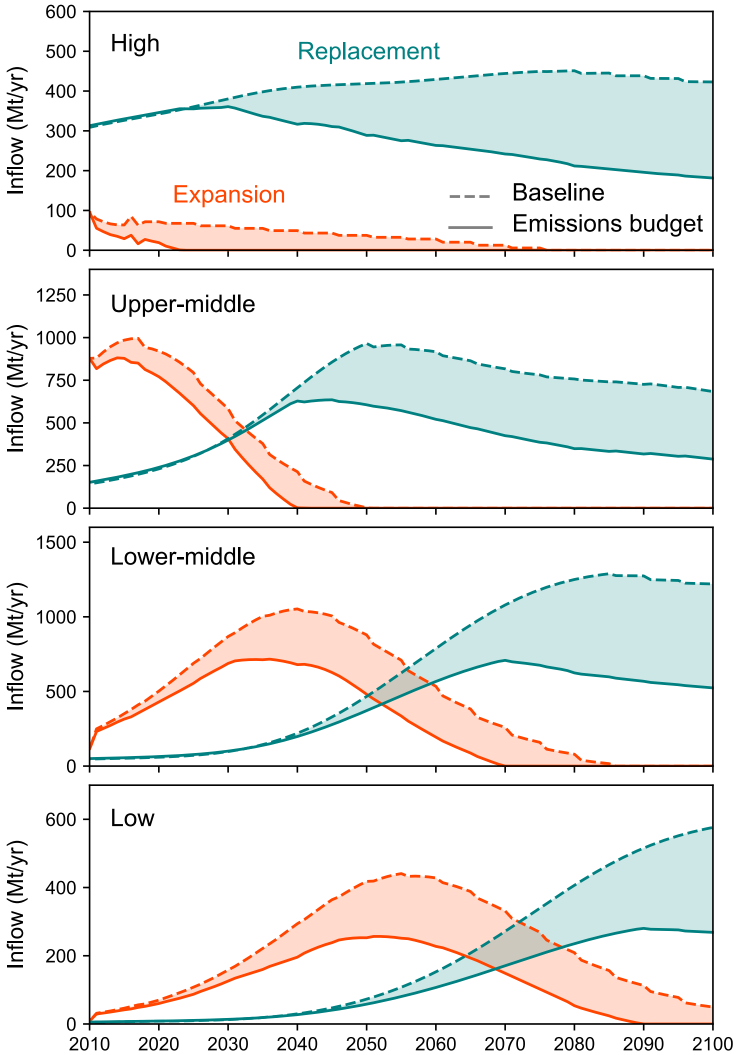

Figure 7- 10 Expansion and replacement demand for iron and steel for each country income group under the emissions budget and baseline scenario, 2010-2100.

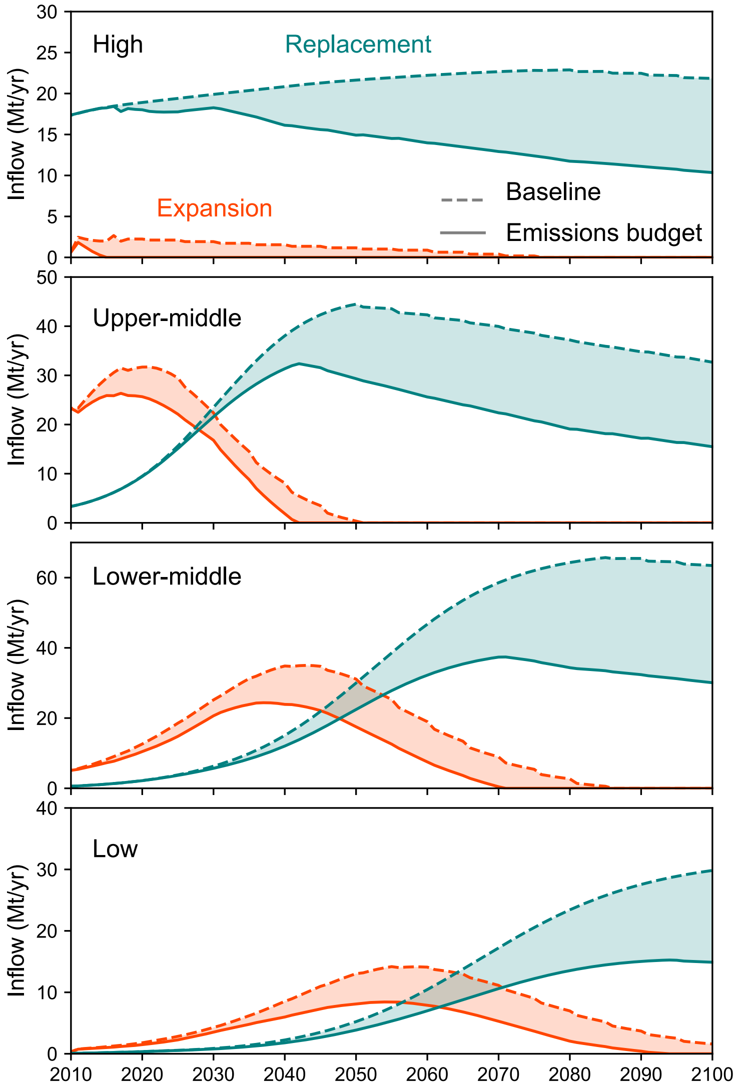

Figure 7- 11 Expansion and replacement demand for aluminum for each country income group under the carbon constraints and baseline scenario, 2010-2100.

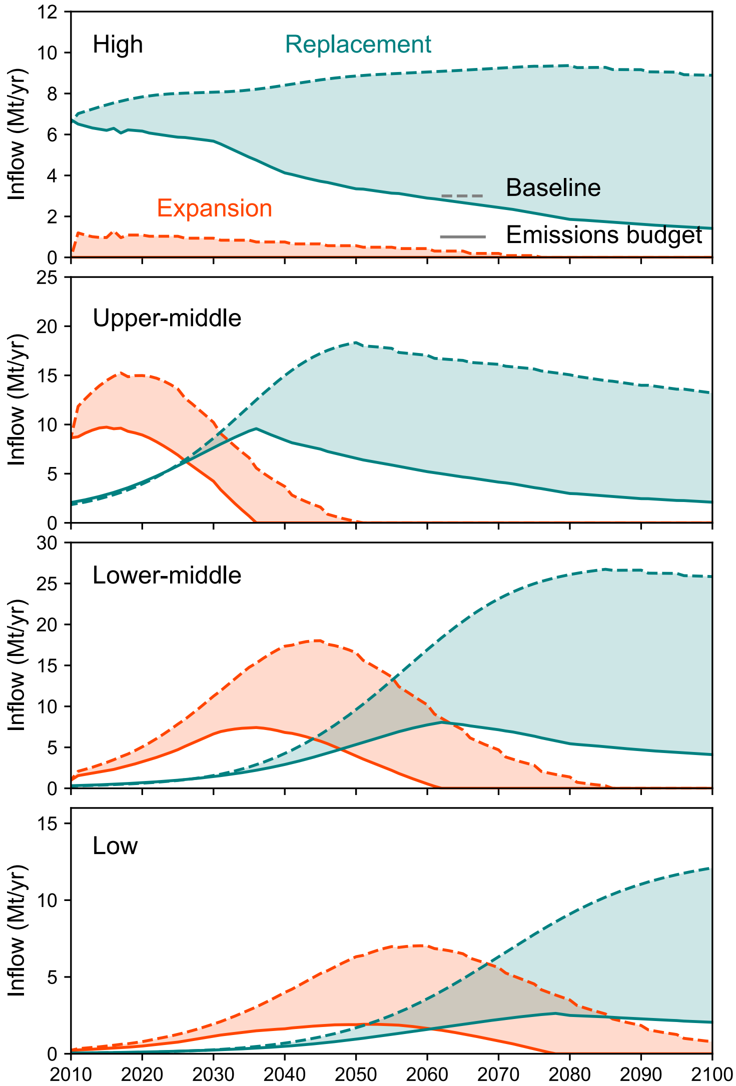

Figure 7- 12 Expansion and replacement demand for copper for each country income group under the carbon constraints and baseline scenario, 2010-2100.

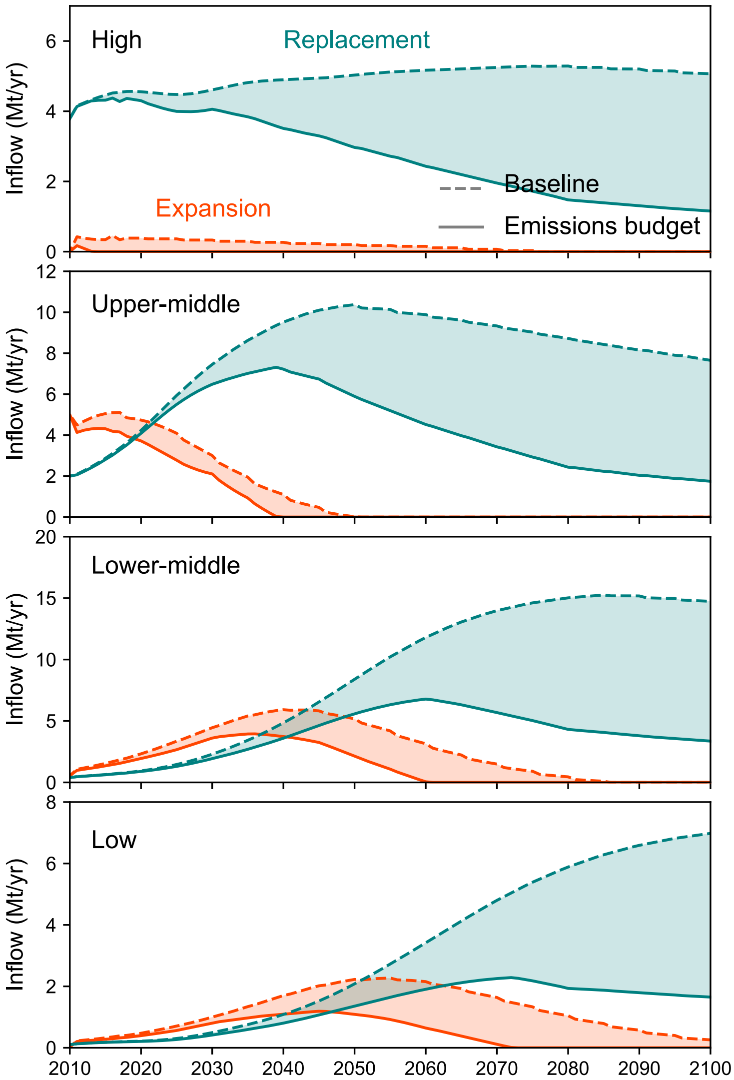

Figure 7- 13 Expansion and replacement demand for zinc for each country income group under the carbon constraints and baseline scenario, 2010-2100.

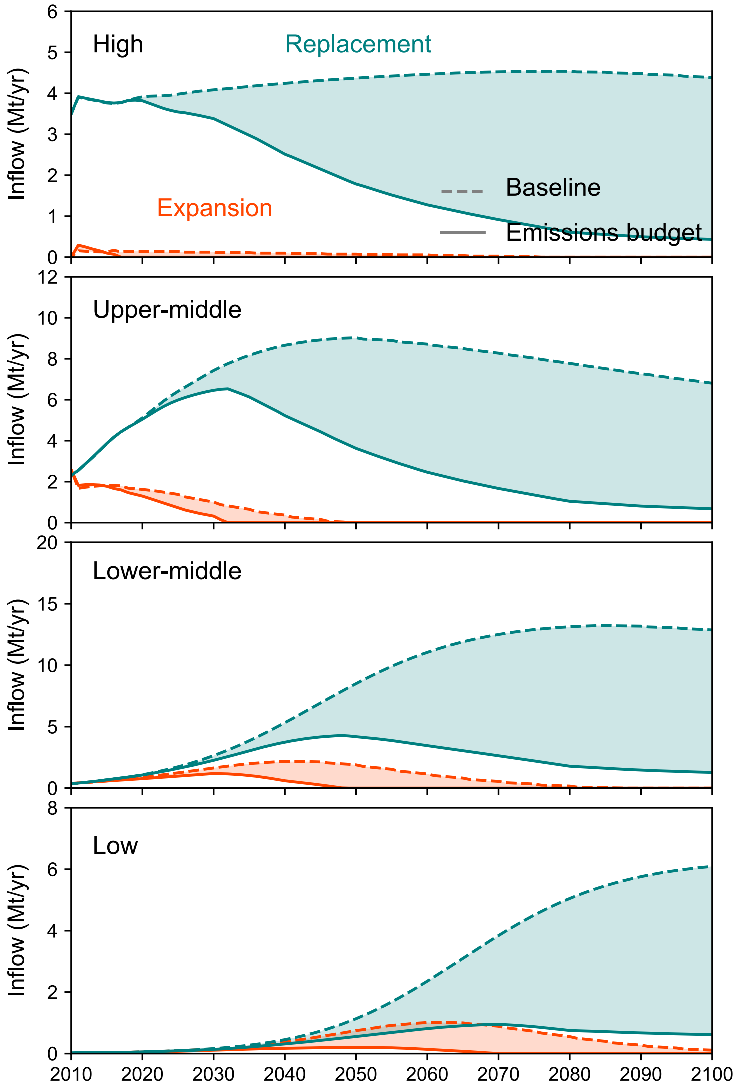

Figure 7- 14 Expansion and replacement demand for lead for each country income group under the carbon constraints and baseline scenario, 2010-2100.

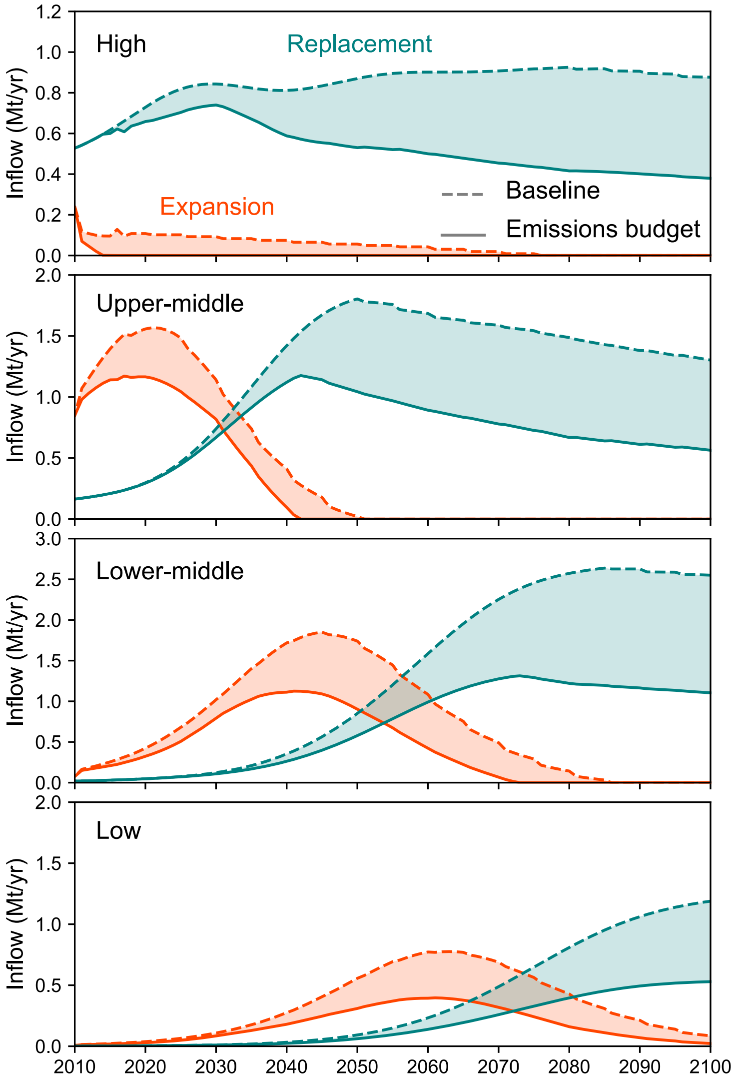

Figure 7- 15 Expansion and replacement demand for nickel for each country income group under the carbon constraints and baseline scenario, 2010-2100.

Chapter 8

Conclusions

8.1 Summary of findings

Climate change mitigation strategies could fundamentally alter future metal cycles through two drivers—implementation of decarbonization technologies and carbon constraints on production activities. The question thus arises as to how the global metal cycle will change in the future in a carbon-constrained world, and what interventions are needed to reconcile climate change mitigation with sustainable metal use. This thesis aimed to provide scientific support for discussions in such areas through a series of analyses. The main results and conclusions can be summarized as follows.

(1) **Decarbonization technology and metal cycles (Chapters 3 and 4)**

Chapters 3 and 4 aimed to identify the total extraction of materials, including mine waste, associated with the deployment of decarbonization technologies and the role of a circular economy in the energy transition. By linking global energy scenarios with material demand-supply models on a country-by-country basis, the analysis showed that the decarbonization of both the electricity and transport sectors could curtail fossil fuel production while paradoxically increasing material extraction associated with metal production by a factor of more than 7 by 2050 relative to 2015 levels. This substantial increase could be primarily due to the increase in the extraction of iron, copper, nickel, silver, tellurium, cobalt, and lithium used for the production of solar PV and EVs. Specifically, around 70-95% of material extraction in 2050 could be attributed to these metals and technologies. The analysis also highlighted that approximately 32–40% of the increase in material extraction could occur in countries with weak, poor, and failing resource governance, implying a high risk of improper management of the extracted materials. Countries with high levels of material extraction and insufficient governance include DR Congo, Guatemala, Iran, Venezuela, Cuba, Madagascar, and Zimbabwe. The analysis confirmed the considerable potential of circular economy strategies regarding such issues. However, implementing a suite of circular economy strategies, including lifetime extension, servitization, and recycling, could not entirely offset the concomitant increase in material extraction. Responsible sourcing will be required where supply cannot be met by circular resource flows. In the absence of such action from the consumption side, the decarbonization of the electricity and transport sectors may face an ethical conundrum in which global carbon emissions are reduced at the expense of an increase in socio-environmental risks at local mining sites. A series of analyses underscore the importance of proper management of extracted materials, which will increase rapidly along with the deployment of decarbonization technologies. This study also contributes to the identification of the main areas of concern, including technologies, metals, and countries, that require particular attention.

(2) **Carbon constraints and metal cycles (Chapters 5, 6, and 7)**

Chapters 5, 6, and 7 aimed to identify the scale and timing of the impact of carbon constraints on production activities on future metal flows and stocks. Chapter 5 first explored the historical flows and stock dynamics of six major metals (iron, aluminum, copper, zinc, lead and nickel) in 231 countries and regions over a 110-year period using a newly constructed dynamic metal cycle model. The analysis revealed that a substantial inequality exists in international metal stocks. Notably, in terms of per capita metal use, the top 20% of the population accounts for 60-75% of the world's total metal stock, while the bottom 20% accounts for only about 1%. International inequality in metal stocks has been decreasing over time due to the strong growth in developing countries, mainly those in Asia. However, the analysis showed that the continued reduction of metal stock inequality through this growth-led pathway could lead to an increase in global metal demand by a factor of 2 to 3 by the mid-21st century. Building upon these results, Chapters 6 and 7 explored the impacts of carbon constraints on global metal flows and stocks using an optimization routine coupled with a dynamic metal cycle model. The analysis showed that, under carbon constraints, primary production of all six metals could peak by 2030, and secondary production could surpass primary production by at least 2050. Consequently, cumulative ore requirements over the 21st century could remain below currently identified resources, implying that natural ore extraction could be limited by carbon constraints before existing resources can be depleted. In this case, the global in-use metal stocks could converge from the current level of about 4 t/capita to about 7 t/capita on average, which is lower than the 12 t/capita currently used in high-income countries. This implies the need for increased material efficiency to meet the same demand for goods and services with less metal use. Importantly, realizing such system changes will require urgent and concerted international efforts involving all countries, but specific responsibilities could will according to income level. Namely, wealthy countries will need to use existing metal stocks more intensively and for longer periods to reduce stock replacement demand, while poor countries will need to develop long-lasting and material-efficient infrastructure to curtail stock expansion demand in the first half of the 21st century.

The thesis highlighted the need for proper management of the extracted materialsalong with the deployment of decarbonization technologies and the need to improve material efficiency to meet basic needs using metals that can be produced and used under the existing carbon constraints. The approach presented here can be applied to any of a broad range of materials, including cement, biomass, and plastic, and thus can contribute to exploring future scenarios for a full array of materials.

8.2 Synthesis of findings

After observing the two trends independently—increasing demand due to the mass deployment of decarbonization technologies and limiting supply due to carbon constraints on production activities—the key question is: What implications can be obtained when these two perspectives are integrated? Here, the balance of annual supply and demand is examined using copper as a case study.

Figure 8- 1 illustrates the increasing role of electricity and vehicle technologies in total supply and demand over time. The share of these two technologies will increase from about 10% in 2015 to about 60% in 2050. This observation reinforces the importance of consumption-side interventions focused on decarbonization technologies, such as certification schemes, for responsible materials management. Namely, interventions that focus on these technologies can support efficient approaches to responsible materials management in an age where we are bombarded with countless metal-containing products.

Another important implication is that more significant material efficiency improvements may be required when the increased demand for decarbonization technologies is considered. Namely, we will face the fundamental challenge of providing the functions of both conventional and decarbonization technologies at a level of metal use available under carbon constraints. Existing climate change mitigation strategies largely miss this critical issue and necessary interventions.

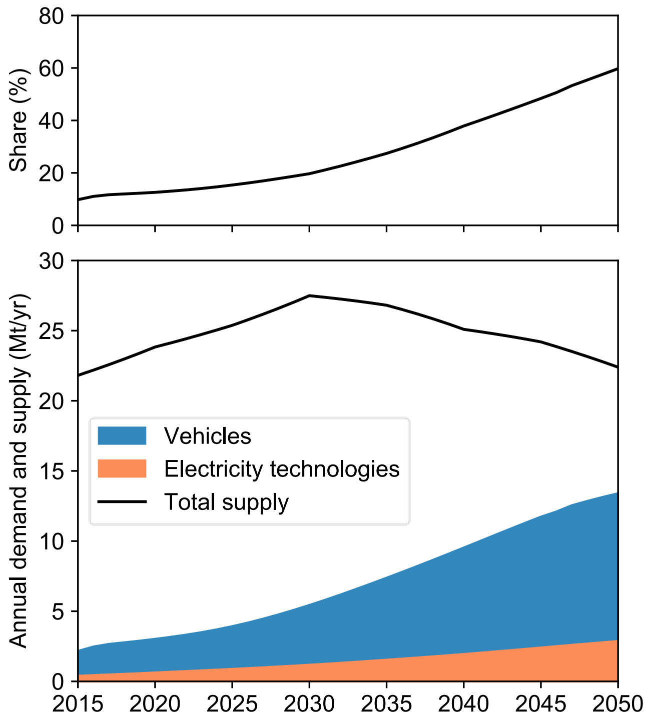

Figure 8- 1 Annual supply and demand of copper in a carbon-constrained world, 2015-2050. Electricity technologies include oil, coal, coal with carbon capture and storage (CCS), natural gas, natural gas with CCS, nuclear, biomass and waste, biomass and waste with CCS, hydro, geothermal, wind onshore, wind offshore, solar photovoltaics, concentrating solar thermal power, and ocean power. Vehicles include internal combustion engine vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, electric battery vehicles, and fuel cell vehicles. The future capacity of these technologies is based on the B2DS (IEA, 2017). Future supply was estimated in Chapters 7 under the assumption of electricity decarbonization and energy efficiency improvements (see Table 7- 4 and Table 7- 6). Circular economy strategies such as recycling and longer product lifetimes are not considered in either the supply or demand calculations. The carbon constraint is determined based on annual emissions mitigation rates in the industrial sector to keep global temperature rise well below 2°C relative to pre-industrial levels by using data from representative concentration pathway 2.6 (Gidden et al., 2019). Detailed assumptions can be found in Chapters 3-7.

This analysis also provides new insights into the long-standing debate on resource depletion. The potential for a surge in metal demand associated with the mass deployment of decarbonization technologies has led to much discussion of direct resource depletion (de Koning et al., 2018; Elshkaki et al., 2018; Schipper et al., 2018; Watari et al., 2018). However, the analysis here shows that long-term metal supply could be limited by carbon constraints rather than direct depletion, a risk that has been overlooked in many previous studies. Such a finding provides quantitative support for the assertions of recent studies suggesting that environmental, social, and governance factors are more likely to be the primary sources of risk in metals supply than direct depletion (Jowitt et al., 2020; Valenta et al., 2019).

The analysis here simply compares supply and demand, which are analyzed independently, thus not representing the dynamic interaction through price fluctuations in the actual market. Therefore, the results should always be interpreted as an illustrative scenario rather than a future forecast. Despite these limitations, the analysis provides an important sense for examining the essential conditions for reconciling climate change mitigation supported with sustainable metal use. The conditions implied in the analysis are proper management of extracted materials along with the decarbonization technology deployment and improved material efficiency to meet basic needs using metals that can be produced and used under carbon constraints. It is important to note here that each of these interventions is strongly interconnected. For example, failure to achieve the necessary material efficiency gains will lead to an overshoot in carbon emissions, which will result in demands for more decarbonization technology deployment. This will ultimately lead to an increase in the extracted materials to be managed. In the other direction, if extractives are improperly managed, short-term supply shortages through destructive social and environmental impacts may occur, limiting decarbonization technology deployment. Such an event can delay decarbonization in the metal production process, limiting the supply available under the carbon constraints. Consequently, more significant material efficiency improvements will be required. Thus, the failure of necessary interventions, on the one hand, makes sufficient interventions on the other more difficult. For avoiding such a feedback loop, both interventions need to be addressed simultaneously.

8.3 Outlook

The scenarios presented here are not intended to be a "preferred future vision". What this study has done is to hypothetically test the impact of climate change mitigation strategies on the future metal cycle and associated mining activities. Clearly, an important next step is to envision a preferred future for the metal cycle that can satisfy the basic needs of an expanding global population without compromising critical planetary boundaries. In this context, the importance of circular material use or increasing material efficiency, has been widely recognized (UNEP, 2016); however, the specific levels of circularity and material efficiency required for sustainable material use remains poorly understood. This deficiency in understanding is hampering the development of an international consensus on science-based targets as they relate to global material use, which in turn is impeding efforts to formulate national and international policies based on firmly established scientific knowledge (World Economic Forum, 2019). What is needed now is to define sustainable levels of global material use and to establish science-based targets for long-term material flows, stocks, and efficiency.

An important direction for addressing this challenge would be to clarify the functional value of the material use. Interestingly, previous studies have shown that increases in material stock over the past 50 years have not led to increases in well-being in the United Kingdom (Streeck et al., 2020). This observation, together with the findings of this study, raises the key question: What are the minimum levels of material stock required to meet basic human needs? Addressing this area is obviously not a trivial task as numerous functions serve in society. Such difficulties, however, must not hinder progress, but spark discussion and collaboration in science and societies around the globe. For example, it will be helpful to discuss this issue in conjunction with lifestyle changes that are frequently discussed as consumption-based solutions for climate change mitigation (Ivanova et al., 2020).

From a more technical point of view, various development possibilities can be suggested. One of them is to consider the scrap quality. The assumption that all scrap can be reused in lieu of primary production is highly simplified. There might be limits to the substitution of primary production because of material impurities (Daehn et al., 2017), the availability of sorting and recycling technology (Ohno et al., 2017) and the challenges associated with replacing primary production infrastructure with secondary production infrastructure (Reck and Graedel, 2012). Consideration of these factors will be essential to design a realistic metal recycling system. Another important direction is to consider the metal linkages. Metals can be broadly classified into those with large-scale, proactive flows (e.g., Fe, Al, Cu, Pb), those associated with proactive flows (e.g., Ni, Cr, Mo, Zn), and those with small-scale, proactive flows (e.g., In, Ga, Li, REE). In mining activities, there are host metals that have their mines and by-product metals that are co-extracted with the host metal (Nassar et al., 2015). Thus, tracing multiple elements simultaneously while taking such linkages into account will be required to depict realistic scenarios. Some of the work on these issues is already underway (Daigo et al., 2014; Nakamura et al., 2017; Tisserant and Pauliuk, 2016), but the further effort will be needed to place them in a broader context.

Notably, the main logic of scenario analysis in the field of material flow analysis so far has been something like "strategy X can increase/decrease subject Y by Z%”. This approach, however, cannot answer the critical question: How much of a gap exists between the ideal future and the scenario? Consequently, it gives little information about the specific scale and timing of the effort required to close the gap. To further increase the practical value of material flow analysis, an alternative research scheme that envisions a preferred future harmonized with the Earth's carrying capacity will be required. Such efforts will eventually enable material flow analysis to provide truly holistic support for environmental policy design and business innovation.

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