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# QUANTITATIVE MODELLING OF LONG-TERM MINERAL RESOURCE AVAILABILITY AND ENVIRONMENTAL IMPACT BASED ON THE TOTAL MATERIAL REQUIREMENT

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*This thesis is dedicated to my parents,*

*Sennye and Mary.*

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And God, who guards my heart and knows all things.

*For we know in part, and we prophesy in part. But when that which is*
*perfect has come, then that which is in part shall be done away.*

*1 Corinthians 13:9-10*

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# ABSTRACT

Historically, mineral resources have been vital in engineering the modern society. However, over the last few decades, the surge in demand of these resources for their specific usage changing the market landscape, has raised concern of their future availability. As the demand for metals rise, the metal prices simultaneously rise, further increasing the anxiety in physical scarcity and quality of these metals. In addition, the absolute decoupling of the environment from resource activity is a necessity to ensure that economic development progresses without harming the environment.

To sustainably plan for our future resource requirements, creating a supply model for these metals is critical to understand how much resources will be economically accessible at a given grade, which is a measure of the metal quality. If there is a shortage, how much recycling production quantities are needed to meet the increasing demand of these exhaustible metals. Vulnerability to the environment caused by these anthropogenic activities is a confronting issue in the society that also requires attention through modelling their sustainable projections based on future metal production patterns.

There remain few studies that examine long term trends in mining production and linking them to environmental sustainability based on factors such as ultimate recoverable resources, increasing production quantities, declining ore grade, and mine waste (overburden and mine muck) and ultimately how recycling promotion will ameliorate the shortage of primary metal supply to satisfy metal demand. Therefore, the study investigates the future resources and their grade qualities by geographic location, their supply and demand long term trends, and the degree of vulnerability on the environment created by these metals during metal mining activities. The analysis period of this study ranges between 1990-2070.

The long term future availability of resources proposes a quasi-dynamic approach that measures economically extractable reserves to determine the physical scarcity of resources. The limit of future reserves is determined by ultimate recoverable reserves at a given cut off grade. The deteriorating metal ore grade creates a concern of future resource quality and ultimately how this inherent nature harms the environment. The environmental impact is tracked based on the total material requirement indicator. This indicator is dependent on changes of strip ratio and ore grade during metal mining production. A comparative analysis of six metals namely copper, gold, iron, lead, nickel and zinc whose importance to the basic applications of modern use in society has risen is evaluated to identify the resource lifetime, quantity and quality by geographic location is applied. The study identifies that physical scarcity is unlikely to occur in this century, but the physical peak of some resources will occur earlier than others as the mining industries become fully matured. Gold for example, has an early Hubbert’s peak contributed by the long historical mining history, resource size and occurrence. The total material requirement depicts that gold attributes to the largest environmental harm compared to copper, nickel, lead, zinc and iron ore with the least impact. This is because larger material volumes of gold are removed to access the low ore grades and thin veins of gold ore deposits. For copper, the Latin American region experiences high potential negative environmental impacts compared to other regions mainly because of the high global extractions in the top copper producer country, Chile, where similar high ore TMR trend patterns are experienced. Nickel, lead and zinc have similar trend patterns to copper due to their close association in occurrence. For iron, even though it has the least impact on the environment, positively spiking anomalies in the ore TMR trends in Australia synonymously with the Asian Pacific region due to historical large scale increase in production for iron from Australia for exports to consuming countries. The dynamically varying ore TMR trends therefore outlines the importance of investigating ore TMR trends with unique individuality to tackle these potential concerns on the environment.

With regards to the promotion of recycling, system dynamics modelling using STELLA software is carried out on copper, gold and iron to investigate the future total supply trends to satisfy the metal demand by application. By investigating additional supply, factors such as the recycling rate, recycling efficiency, recyclability potential and the environmental implication on the total system boundary are applied. Primary production will remain the largest contributor of copper supply to 2070 while production ratio of primary and secondary supply is almost equivalent over the same period. Finally, we observe the resource outlook based on the United Nations Environmental Programme-International Resource Panel scenarios ideal to achieve the Total Sustainability and Recycling Efficiency scenarios. By achieving these scenarios, a 25% and 17% reduction, respectively, in global extraction are proposed. The study outlines these adjustments relative to increasing consumption as primary production declines whilst maintaining the same current demand levels. The appreciation of these to manage our future resource would ultimately reduce the outcome of future ore TMR patterns during metal mining production.

From a sustainability perspective this study demonstrates that the trends of primary production will increase the environmental footprint in the future as the total economic and non-economic material flows increase and the associated metal ore grades decline. However, the promotion of secondary metal sources will provide an alternative supply source should availability of primary resources be constrained. Therefore, tracking of both economic and non-economic material flows is crucial for effectively decoupling resource activity from the environment.

Mineral resources are a fundamental component to the global society and economic growth. Although the combination of forecast trends on mineral production based on the URR values and promotion of recycling as a secondary metal supply source outline that a supply risk is not eminent to 2070, this study did not include other factors of uncertainty such as economic, technological and social factors in which future systems modelling could be improved. However, the study provided and important basis towards the total material flow of resources to establish material efficiency in the quantities and quality of resource use. Further, accountability of resources through material flow tracking is discussed, providing a basis for quantitative assessment on environmental implications.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The 21st century has witnessed exponential resource exploitation, which aligns with the economic growth of nations to increase productivity within the modern civilization. The extraction for resources has risen steadily driven by the increasing global metal demand consumed at an average growth rate of approximately 3.2% (Van Vuuren et al., 1999; Krausmann et al., 2018). For example, copper has high demand because of its applications in both electrical and electronic applications due to the rapid industrial growth in China. The contribution of gold was the highest in the industrial sectors, such as in jewellery (52%), investment and banks (39%), and technology (9%), thereby creating an increasing stable market (World Gold Council, 2021). Figure 1-1 illustrates the forecast trends of potential increasing material output of renewable and non-renewable materials to 2050 to sustainably supply resources to nations for their specific usage. With focus to the non-renewable resources, the rising scales of production in metal mining for material consumption are a concern to resource stakeholders as these minerals typically exhibit a “limit to growth” with “peaking metals”. Furthermore, mining is an unsustainable practice due to its intrinsic nature (Meadows et al., 1972, 2004; Mudd et al., 2013; Northey et al., 2014; Pagani and Bardi, 2016; Meinert et al., 2016). Since mineral reserves are finite, they will become physically scarcer by accessibility and quality with progress in mineral production. In addition, the upward increases in commodity prices especially since the early 2000 displayed in Figure 1-2, exacerbates this agenda as metal miners exploit these resources to take advantage of the resource windfalls within the volatile commodity market.

The limit of the ultimate recoverable resources (URR), which is the total amount of metal recovered throughout its extraction history and potential extraction of a mine project, is influenced by the degree of exploration, rate of discovery, and technological advancement to reach the predetermined cut-off grade (COG). With the advancement of mineral extraction from high-grade ores that are economical to low-grade sub-economic ores, huge volumes of used and unused extractives composed of overburden and gangue are left over from the economic business. Over time, corrosion of ore grades occurs within the mine sites as larger volumes of these accumulated surface overburden, mine waste and other gangue materials increase against the unit of ore extracted. Open pit mines generally exhibit higher strip ratios than underground mines due to their inherent nature. Figure 1-3a and Figure 1-3b display the trends in ore grade and strip ratio of various metals over time in a given region. This has been evidently observed in Australia (Mudd, 2009; Mudd, 2010). Furthermore, this is observed at the global-scale (Crowson, 2011; Calvo et al., 2016, Rötzer and Schmidt, 2018), for copper (Mudd and Weng, 2012; Mudd et al., 2013; Northey et al., 2014), Ni (Mudd and Jowitt, 2014; Henkens and Worrell, 2020), Pb-Zn (Mudd et al., 2017), and Au (Mudd, 2007; Friedrich-W and Scholz, 2017).

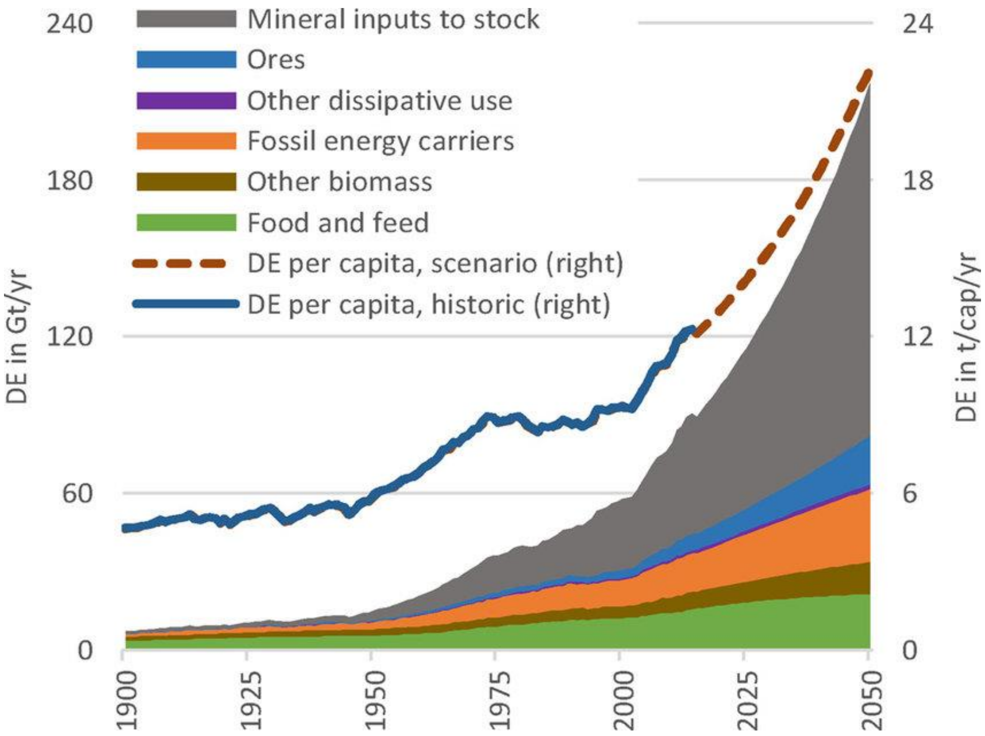

Figure 1-1 Global material extraction by material group (Krausmann et al., 2018)

Future mineral availability regarding until when could producer countries and/or regions supply these metals to consumers for various applications is a growing concern. Additionally, whether these practices will remain sustainable under constant supplies is another impending question.

This requires dematerialization and increasing the economic output while reducing negative environmental impacts as Figure 1-4 depicts through resource decoupling (IRP, 2011). Increasing metal demand for its varied applications in modern society, fulfilled through increased metal production is associated with potential environmentally degrading impacts at regional and/or global scales. Furthermore, high material consumption rates are linked to low ore grades and high strip ratios, thus, raising questions regarding physical or economic sustainability, especially in developing countries with poor legislative infrastructure that is insufficient to monitor and regulate environmental vulnerability. Various studies have revealed that hidden flows created by resources can be accounted through the ore grade and strip ratio from "used" and "unused" material along their lifecycle (Bringezu et al., 2004; Fischer-Kowalski et al., 2011; Wuppertal Institute, 2014; Tokimatsu et al., 2017, 2019; Nakajima et al., 2019; Watari et al., 2019). By distinction, used materials are defined as the amount of extracted resources entering the economic system for further processing or consumption (Fischer-Kowalski et al., 2011). Unused materials are comprised of overburden and other extraction waste from mining activities. Direct flows refer to the actual mass of material or product and thus do not consider accumulative material requirements along production chains. Indirect material flows indicate all materials required along a production chain to manufacture a product. Indirect flows are also known as hidden flows and may comprise both used and unused materials (Fischer-Kowalski et al., 2011). As such, during metal mining of economically valuable ore material, commercially valueless material comprising gangue, and "unused" extracted material, such as overburden, are moreover produced. These material

Figure 1-2 Commodity Price Index [food, non-food agricultural raw materials, metals, energy] (Dobbs et al., 2013)

remnants thus, “degrade” into the environment especially that the latter is not properly accounted for in terms of storage, disposal and or alternative usage.

Total material requirement (TMR) is an indicator used to measure the environmental vulnerability caused by metal production. It was originally developed for economy-based material flow that reflects the physical material flow, including export and import volumes, and “hidden” and non-economic materials, such as overburden, within and outside the boundaries of an economy as depicted in Figure 1-5 (European Environmental Agency, 2000; OECD, 2008). The physical material flows included in TMR evaluations account for in situ earth movements during mining. In addition, metal mining activities cause the highest environmental damage in upstream areas. The degree of mineral exploitation through mining largely depends on the ore grade and strip ratio (Norgate and Hanque, 2010, Northey et al., 2014, Kosai and Yamasue, 2019). Thus, TMR includes these mining factors during assessments. Over time, TMR increases as more gangue and overburden is produced and as the ore depletes.

TMR has recently been recognized to have ability in accounting the environmental impact in secondary production (Yamasue et al., 2009, 2013). However, studies in the extent of TMR in recycling are still limited and further research needs to be conducted especially in recyclability processes of metals.

## 1.2 Problem Statement

The need to shift to a more sustainable framework with emphasis to ease pressure to the environment is largely dependent on the issues augmented:

- Availability of economic and recoverable resources
- Increasing the scales of mining in which significant volumes of waste rock and surface overburden are produced
- Declining ore grade

Thus, to address these issues, at a global, regional and country context, the intrinsic linkage of metal mining associated with environmental impacts provide the basis of investigation based on the following hypothesis:

- Ore grades are progressively declining
- The scale of economic mine production is rising

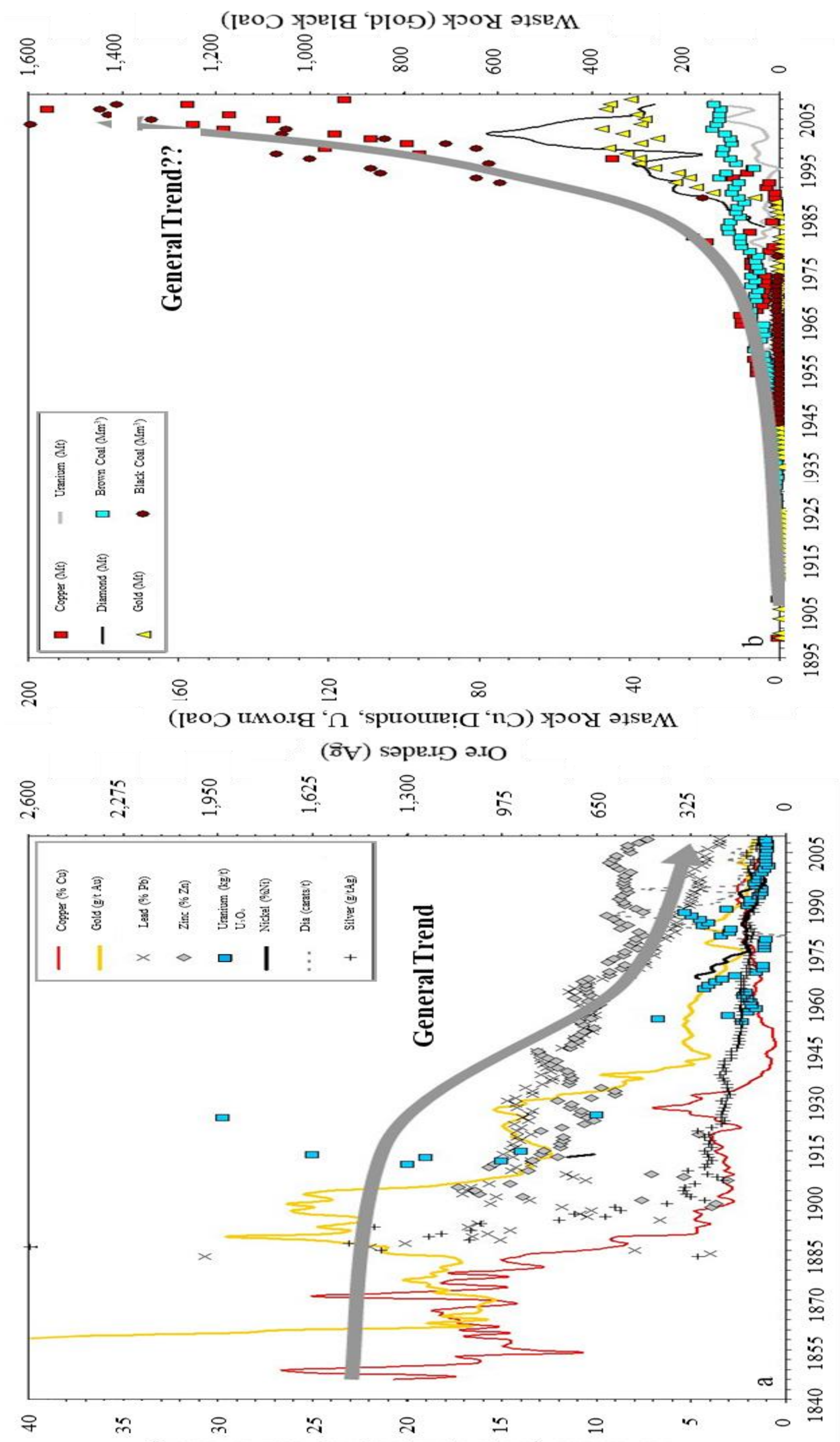

Figure 1-3  a. Declining trends in ore grades b. increasing strip ratios for various common metals (Mudd, 2007)

- The mine waste overburden is increasing per unit output of metal produced (strip ratio)

These are quantified by the following questions:

- Will resources be available in the future?
- How does the metal availability vary by geographical location and for how long?
- Is the environmental burden increasing?
- What impact do the long term trends have on the environment?
- To what extent does promotion of recycling offset the pressure on the environment?

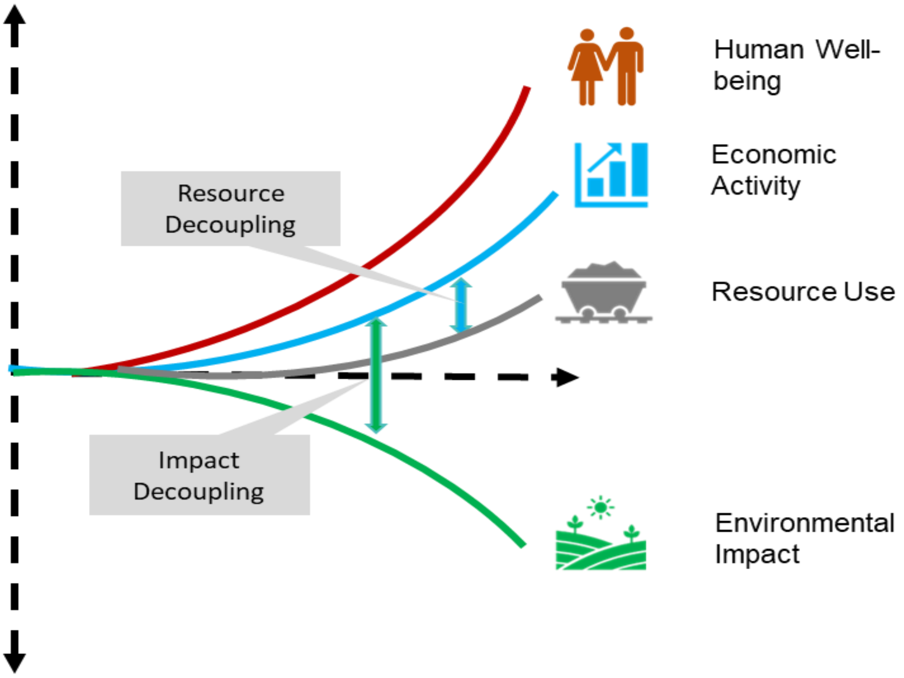

Figure 1-4 Schematic representation of Resource decoupling and Impact decoupling (IRP, 2019)

## 1.3 Purpose of the Study

In order to predict the future sustainability of metal mining to preserve the environment, it is therefore paramount to examine the ore grade trends, strip ratios and environmental burden created by the material volumes extracted. Metal depletion requires an understanding of the regional resource conditions, such as “how much metal is being produced?,” “where to explore?,” and “what is the temporal grade variation?” These questions provide a better understanding of the rate of technological improvement and can further highlight the need for metal substitution. Therefore, understanding the long-term trends of metals regarding the URR, ore grade, and the associated environmental impacts is important.

We examine the future supply trends to 2070. Ultimate recoverable resources are measured using regression trends on grade-tonnage curves. The peak of production is estimated at a cut-off grade to account for economic resources in the model. The world consumption is divided with respect to the consuming sectors using linear regression method at a constant gross domestic product per population therefore quantifying the intensity of use of these sectors. The intensity of use reflects the consumption of mineral commodity divided by the gross domestic product (Tilton, 2003). In addition, recognizing the importance of recycling as an alternative source of material supply for resource consumption. Accordingly, the research framework developed is expected to compare the potential environmental vulnerability against the declining ore grade during mining activity caused by copper (Cu), gold (Au), iron ore (Fe), lead (Pb), nickel (Ni) and zinc (Zn). In this way, the environmental indicator applied guides to correspond to sustainable management through responsible mining and consumption for the protection of the environment.

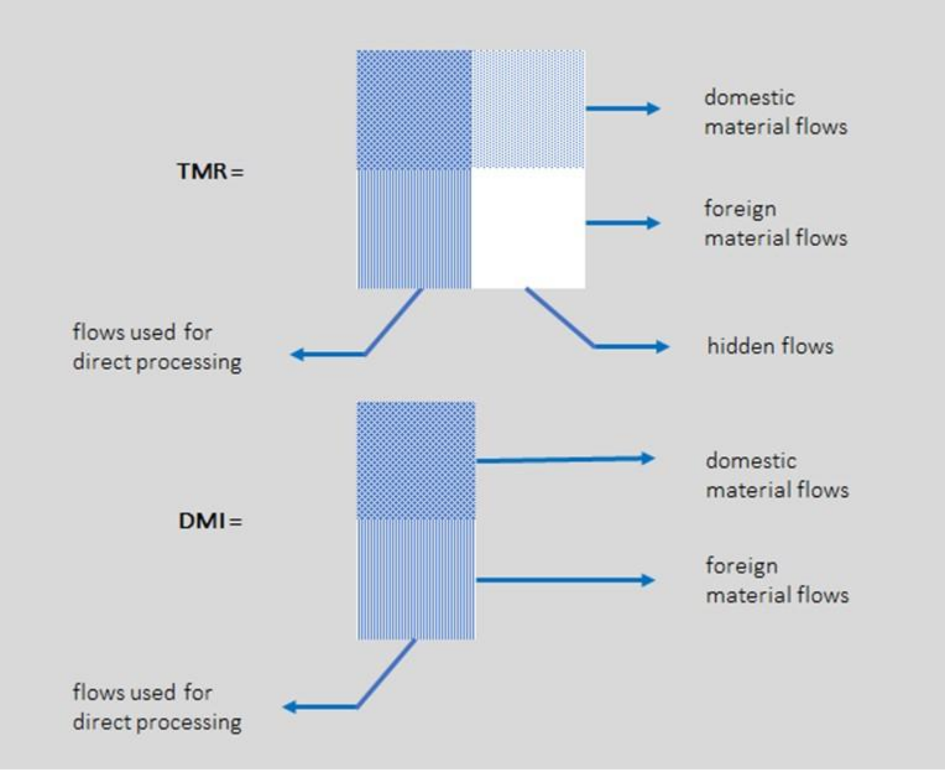

Figure 1-5 Environmental Indicator: Total Material Requirement (European Environmental Agency, 2000)

This study proposes the following:

1. Most previous studies assumed that a constant ore grade is mined for each region which ‘underestimates’ the ultimate recoverable resources which is the total amount of a metal recovered throughout extraction history and potential extraction (Crowson, 2011; Northey et al., 2014).

In reality, a broad distribution of ore grade is being mined at any given time. Therefore, introducing ‘delay time effect’ with metal production.

2. Some studies tend to neglect the functionality to model recycling to provide insight into the effect of secondary metal production (Northey et al., 2014; Calvo et al., 2018; Rötzer & Schmidt, 2018).

Our study aims to contribute to the relative economics of recycling versus mine production as it changes significantly with declining ore grade and intensity of use for the promotion of metal sustainability.

3. The intrinsic relationship between environmental impacts and declining ore grade indicates that there are hidden flows of the material output within the system interaction (Tokimatsu et al., 2017).

We propose to measure trend of vulnerability of the environment by use of total metal requirement of selected metals to delineate the impact mining has on the environment.

4. Most preceding studies evaluate ore-TMR on a single time period.

Our study is the first, to our knowledge, to measure long term ore-TMR trends.

## 1.4 Outline of the study

The fundamental structure of this dissertation is organized in the following descriptions:

Chapter one focuses on the introduction and background of the study. Herewith, the status quo between metals supply and demand and the environment are discussed. The problem statement of the study, research purpose which governs the motivation and objective of the study are introduced in this section.

Chapter two outlines the literature review relevant to the study. It focusses on identifying the gaps and achievement of previous studies and the current study related to metal resources, their production and consumption trends, and how they intrinsically impact the environment.

Chapter three investigates the tri-linkage between proven reserves, resource availability and the environment. It applies resource estimates to measure the lifetime and change in ore grade to quantify the future available resources. In addition to this, the available reserves are evaluated to delineate the impact on the environment using the total material requirement environmental indicator. Six metals: Au, Cu, Fe, Ni, Pb and Zn are evaluated, and a comparative analysis is made based on the TMR.

Chapter four succeeds the analysis presented in chapter 3 to derive the parameters estimated in computing the main analysis of this thesis. Herewith, time series analysis based on the system dynamics conceptual framework, is modelled on STELLA software to gain a basic comprehension of the interaction among the subsystems. The simulation models of Au, Cu and Fe are built on the systems model. The results of each metal model are comprehensively analysed to determine the long term trends of metal supply.

Finally, chapter five provides a comprehensive discussion and conclusion based on the analysis of the study. Further, recommendations of future work related to the study area are presented.

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# CHAPTER 2

# LITERATURE REVIEW

The physical constraint to the metal supply problem appears to draw attention as the metal production growth rises to accommodate an increasing metal consumption demanded by sectorial consumers. With the diminishing metal ore grade quality accelerating simultaneously with increasing metal production, resource stakeholders are prudent of the rising physical scarcity by geographical location and accessibility. The purpose of undertaking long term future conditions of metals including copper, gold, iron, lead, nickel and zinc is to access their future quantities at recoverable economic conditions. In addition, the consumption forecast is a substantial input to optimize and build a representative model of resource availability with the aspect of impact on the environment at the forefront.

In this chapter, the literature review of the material flows of metals is unravelled. The system dynamics framework is presented between the supply and demand interactions within this system. Lastly, the framework on the impact on the environment and sustainability scenarios are realized.

## 2.1 System Dynamics

Material Flow Analysis (MFA) has a defined system in focus e.g., a geographical region or industrial process such as mining, and tries to track and quantify the material flows both within and between the system boundary and the environment (Bringezu and Moriguchi, 2002; Spatari et al., 2005; Glöser et al., 2013a, 2013b). The system boundary is a boundary between the socio-economic system i.e., at national, regional, or global context, and the natural environment from which materials are extracted and waste is discarded (Fischer-Kowalski et al., 2011). The MFA approach is carried out as a system dynamics model that offers a contribution to material flows and anthropogenic stocks transparent through accounting and tracking the material flow during their lifetime from cradle-to-grave (van der Voet et al., 2000; European Communities, 2001; Glöser et al., 2013a, 2013b). Through systems dynamics, we improve the model inclusive of metal resources, their extraction, recycling, and supply dynamics and extend it to investigate the material flows on the impact on the environment. For example, such dynamic systems can identify spatial reservoirs of material in use should that material become scarce in future. The dynamic system operates on physical flows dependent on data acquired from individual mines of ferrous and non-ferrous metals. In addition, the MFA approach, quantifies the metal lifecycle by identifying how much ore material is produced during mining, the amount of secondary metal produced from recycling processes, and the waste flows are related to these processes (Glöser et al., 2013a, 2013b).

The spatial distribution of mineral resources required for input data can geographically be identified by their regional characteristics. This way researchers have been successful in characterising the resource constraints by geographical location over the long term trends of supply of these resources.

Several earlier attempts have been used to model metal production trends. The Hubbert function comprising the ultimate recoverable resources (URR) has been used to assess copper, zinc and lead mining rates, and other metals, to estimate when production will peak (Roper, 2009). Van Vuuren et al. (2009) outlined the principles for global metal cycles, in the case of copper, by using system dynamics modelling to simulate mineral resource consumption up to 2100 in relation to impacts of ore-grade decline, capital, energy requirements and waste flows. Mineral resources were characterized as abundant or scarce. The production cost was expressed as a function of the energy consumption whereas the demand was expressed in terms of intensity of use.

Adachi et al. (2001) developed a global copper supply and demand model using system dynamics from 1970-2120. In their study, they allocated 12 regions as copper primary producers and the final demand was measured at a level corresponding to recycling rate and product lifetime. This study had strong assumptions based on geological constraints in their analysis, where the results indicated that a strong promotion in recycling is required to satisfy the copper demand.

Ayers et al. (2003) applied time series supply and demand of copper lifecycle up to 2100 at a global level and for United States. Their model was based on the material balancing in the IPCC-SRES-B” in order to conduct simulations focused on a growing demand and functional and non-functional recycling levels to estimate the existing stocks.

Tokimatsu et al., (2004) forecasted the timing of global copper shortages and depletion based on the metal’s demand estimates. By this, they could quantitatively evaluate the sustainable supply of copper (Tokimatsu et al., 2004, 2017a).

Northey et al. (2014) use the concept of ‘peak mineral’ by using a geological model to measure future copper mining supply trend by considering the following aspects: ore grade, URR, and other constraints either economic or technological. Glöser et al. (2013a, 2013b) applied a mass flow analysis that underestimated the resource URR. This underestimation caused the model to define peak reserves with a smaller lifetime. Laherrère (2009) apply estimated the peak gold; it is expected to reach 250kt. Tokimatsu et al. (2017a) developed a sustainability model for supply of copper, lead and zinc that quantified demand and supply including scrap supply by examining the lifecycle of these metals at a global scale. Sverdrup et al. (2019) couple metal extractions which are accounted for in economic systems that also considers secondary extraction interactions for copper, aluminium, iron, lithium and platinum group metals.

Iron material flow analysis conducted at a global level and have applied a 70% end-of-life recycling rate based on the historical trends (Neelis and Patel, 2006; Oda et al., 2013). Neelis and Patel (2006) project the crude steel demand for 26 TIMER regions using the intensity of use approach and estimate 0.65% per year of future material efficiency. Oda et al. (2013) indicates that the future availability of scrap has a growing importance to the total scrap to alleviate the future primary steel which are dependent on the end-of -life recycling rate, discarded steel and the in-use stock. The stock and flow patterns of iron have accessed future long term emission reduction of carbon dioxide by increasing secondary steel production (Müller et al., 2011; Cullen et al., 2012).

## 2.2 Metal Supply

The amount of reserves, ore grade, mining and recycling are factors that affect the supply of a metal. When modelling the production of these metals, the aim is to forecast the future production to quantify their long term future availability for a sustainable use.

### 2.2.1 Theoretical Framework of Resources

The distinct parameters between resources and reserves are determined by the degree of certainty of the geological or physical occurrence of deposits and its profitability. Resources are geological occurrences exhibiting an inferred certainty of their existence, whereas reserves are resources with a measured and probable certainty of occurrence (USGS, 2012). In addition, reserves are economically extractable. The extraction nature of these metals is limited to exploration, technology, and profitability factors, which control the extent of the URR growth. In other words, metal reserves may increase as resources are identified and measured (Norgate and Rankin, 2002). Along the modified McKelvey resource classification diagram in Figure 2-1, the cumulative production, proven reserves and ultimate recoverable resources can be mined profitably with certainty, confidence and reduced production costs. Herewith, the ultimate recoverable resources are the limit of physical availability of economic resources which are defined as the total amount of metal recovered throughout its extraction history and potential economic extraction of an ore deposit.

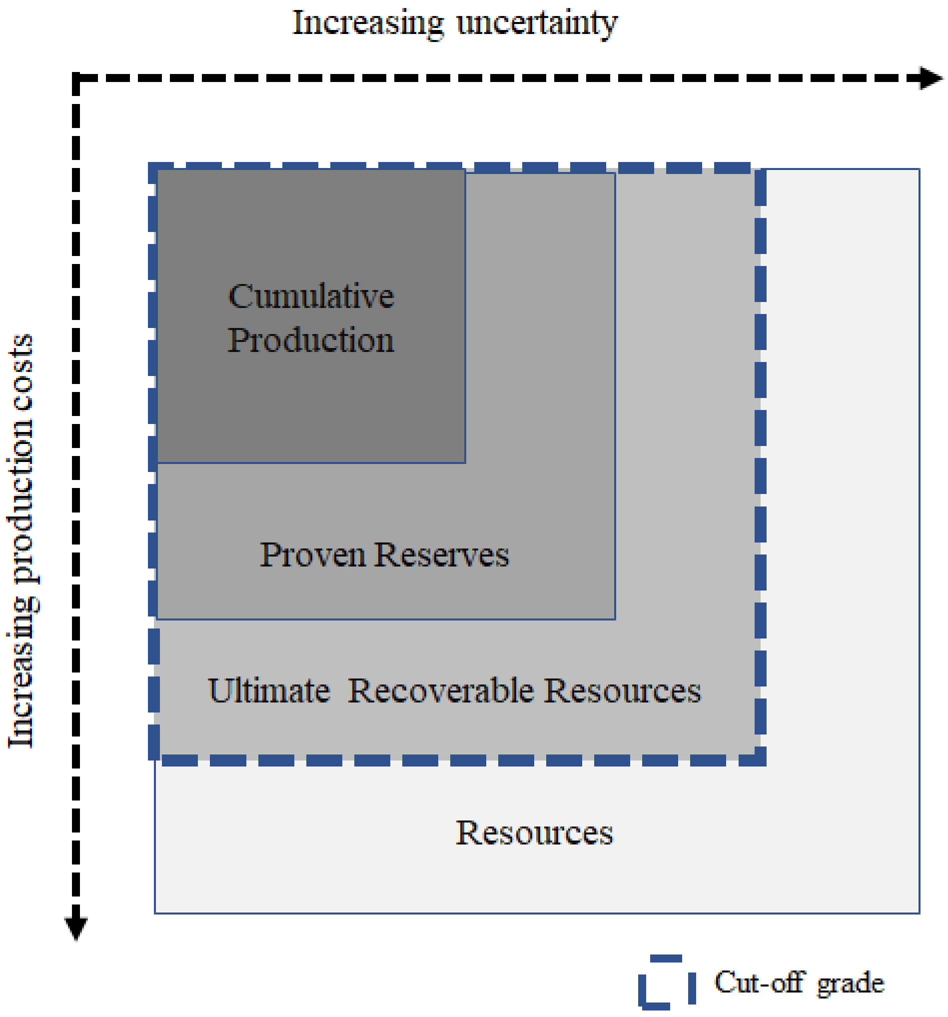

Figure 2-1 Modified McKelvey resource classification diagram (USGS, 1995)

### 2.2.2 Forecasting of Primary Production

Metal production is modelled using the logistic growth curve method. The popularity of this method was applied by Hubbert (1956) to forecast the US oil production. In Hubbert's theory of URR, this model is applicable to non-renewable resources including copper, gold, iron, etc (Pagani and Bardi, 2016; Sverdrup et al., 2014, 2017, 2019). The production curve of the 'peak oil' assumes a bell shape on the basis that production will commence and halt at zero level. However, Patzek (2010) states that the trend along Hubbert's symmetric bell shaped curve will alter with new discoveries, mine expansions and new technology but later declines with reduction in grade and tonnage or increased strip ratios during ore extraction. Whilst critics of the Hubbert theory acknowledge the contribution of scarcity and costs of production to peaking of the exhaustible resources, accounting physical and market factors as rather desolate (Graedel et al., 2014; Meinert et al., 2016). These factors among with many others assume that their influence on the progressive depletion of resources would adjust the commodity peak. In addition, Li et al. (2018) states that when the rigidity of mining supply is high due to the extended long mine life of a project and the dependency of metal use is high, the supply of metals like copper become less elastic to market demands.

Although, production forecast is commonly applied, critics of the growth curve are presented. The first is related to the URR where is a determinant of forecasting. The accuracy to estimate the URR forecasts and ultimately peak production depends on the accuracy of the data. Northey et al. (2014) highlight an inherent limitation of using URR and grade that these average ore grades are likely to be overestimated in the early years and underestimated in the latter years when using the GeReSMo which is strongly related to the peak year and production quantity. The accuracy of the R-squared is modelled is determined to reduce noise from the data set. Secondly, the historical data of metal production is likely to be smoothened by the growth curve before extrapolation to a fitted curve. The fitted curve will automatically generate an equation function depending on the historical data. However, using historical matching to fit the data provides a probable true reflection of the production trends historically and how they are likely to continue. The Root Mean Square Errors (RMSE) of the historically matched data, as a significance test in which a dataset has a low RMSE the model framework is stable and therefore could be used to perform analytical evaluations.

### 2.2.3 Forecasting Secondary Production

Secondary production inclusive primarily of recycling is a source of commodity supply. Over the past few decades, it has gained attention especially in resource poor countries that are presently recovering metals from metal products such as electronics, household appliances etc. This term is synonymously known as urban ore mining. The promotion of recycling processes the affects quantity of primary metal production by influencing the demand rather than the supply of that commodity (Radetzki and van Duyne, 1985; Tilton, 2003). In recent years, recycling technology for many metals has improved the recycling efficiencies and recycling rates of metals. In addition, this process is slowly becoming cost effective to the manufacturer. However, the recycling rate of a particular metal will vary by usage and the lifetime of that metal product (IRP, 2011).

The Weibull distribution is widely used as a model to measure the reliability for time to failure of a product. In other words, it creates lifetime simulations generalised by the exponential model to include the lifetime rate function. The Weibull model takes several forms based on various parametrizations inclusive of the scale factor, shape factor and location factor which affect the probability distribution function curve (Martz, 2003). When the location factor is 0 the Weibull reduces from a three-parameter distribution to become a two-parameter distribution. The application of the Weibull provides the functionality to the intensity of use of demanding sectors and how long will recyclates be availed from the recycling process. However, not all consumed products are recyclable, some material will take a non-functionality route to their end of life into disposal landfill sites (IRP, 2011, 2016).

Both conventional mining and urban ore mining will continue to play a sufficient role in acquiring resources. The sustainable mining as highlighted in the Sustainable Development Goals (SDG) 12 requires resource stakeholders to efficiently cooperate to practise sustainable resource production ethics.

## 2.3 Metal Consumption

Trend analysis is a simple approach to quantifying metal consumption. Herewith, the future metal demand is expected to remain constant, which is intrinsically related to the electricity demand. The intensity of metal use (IU) quantifies the volume of metal consumed by each geographical orientation to measure the future availability of metal resources.

In many developed and developing countries the level of metal required for consumption varies by their intensity of use dependant on the economic growth of those nations. In addition, the rising economic wealth of nations reflected in the gross domestic product per population continues to drive up material consumptions into the future. The GDP will grow at a steady average rate of 3% for at least 50 years (PWC, 2013; World Bank, 2021). The growth rate of population shows a deceleration change measured every 5 years ranging between 0.98% to 0.27% until 2070 (UN, 2019). The conventional theory of intensity of use depicts that a countries material or resource consumption will increase as the country’s economic wealth increases as it becomes industrialized (Van Vuuren et al., 1999; Tilton, 2003). Over time, the IU will peak or shift with the economic satisfaction derived from economic sufficiency, including services and human development are achieved and changes in mineral commodity are made. For example, resource saving technologies have shifted the IU curve downward. Construction of buildings and bridges use lesser steel than 50 years ago as steel manufacturing with greater strength and durability have been increased. The linkage between energy and metal consumption is described linearly trending (Tilton, 2003). Finally, the IU will consequently decline as lesser materials are required to maintain the efficiency of that economy. The IU of developing countries have a generally higher IU which is fast growing whilst developed countries IU are low.

Tilton (2003) highlight that the faster the demand for a commodity grows, the smaller the proportion of total consumption secondary production is likely to provide. While the convention of this is likely probable, resource stakeholders have considered the importance of recycling as a way not only to provide an alternative material source but also to have regard for the environment.

## 2.4 Modelling the Environment

Mining and processing activities have been interlinked with about 90% of land and water stresses causing detrimental impact to the environment. Resource stakeholders indicate that decoupling resource use and environmental degradation requires sustainable sourcing and management of resources over the whole lifecycle of the mineral in use (IRP, 2019). The SDG 12 encompass this principle of sustainable and responsible production and consumption. While mass flows are useful in understanding the environmental pressure from material consumption, understanding the environmental impacts caused by mineral production for their specific usage is also needed to support policymaking for the sustainable use of resources (van der Voet et al., 2005; IRP, 2019).

Life cycle assessment studies have been used to measure the environmental impacts using copper ore grade declines as production progresses and energy consumed during upstream production (Norgate and Haque, 2010; Northey et al., 2014). In addition, resource flows to account for known flows and hidden flows using linear programming with an extension to life cycle assessment has been applied in power generation and transport technologies following the International Energy Agency’s scenarios up to 2050 aiming to decarbonize these sectors, at the 2°C target (Tokimatsu et al., 2017a, 2017b; Watari et al., 2019). Nakajima et al. (2019) applied a global link input-output model (GLIO) for the total used and unused extraction of copper, nickel and iron mining induced by final demand in Japan. Product design for recoverability to reduce material losses have been done through investigation of these hidden flows (Ciacci et al., 2015; Elshkaki et al., 2018).

Relevant environmental impacts assessed related to this study based on resource extraction show that the extractive volumes inclusive of ore, waste surface overburden and other hidden materials, ore grade and strip ratios, are major factors used as indicators to measure the environmental vulnerability. To account for direct, indirect and hidden flows, the TMR indicator is applied for the assessment of environmental impact. It originates from economy-based material flow assessments reflecting the physical material volumes that occur within and beyond the trade boundaries of an economy as an index of material intensity (OECD, 2008; Wuppertal Institute, 2014). TMR valuations has two aspects: natural ore-TMR and urban ore-TMR. The natural ore-TMR refers to TMR related to the natural ore recovered during mine extraction. Urban ore-TMR is the TMR related to metal recoverability through recycling processes from metal products.

The physical material flows included in natural ore-TMR evaluations account for in situ earth movements during mining. In addition, metal mining activities cause the highest environmental damage in the upstream sectors (mine sites). The degree of mineral exploitation through mining largely depends on the ore grade and strip ratio (Norgate and Hanque 2010; Northey et al., 2014; Kosai and Yamasue, 2019). An ore TMR coefficient deduced based on these factors can be related with the mine production to account for the temporal ore TMR per time to delineate the environmental vulnerability created by mining over time. Thus, TMR includes these mining factors during assessments. Over time, TMR increases as more gangue and overburden are produced and as the ore depletes.

For the urban ore-TMR related to recycling processes, it is inappropriate to evaluate the impact on the environment using the elemental composition of the metal by its grade. This is because urban ore metals are metal products usually complex with an aggregated modified nature such as steel, alloys etc (Yamasue et al., 2009). However, to evaluate the urban ore-TMR (UO-TMR) on a scale comparable to the natural ore-TMR, Yamasue et al. (2009) created a framework that represents differences from urban ore TMR and natural ore TMR based on a logarithmic equation, where it is assumed that the elemental concentration in the natural ore is 100% and natural ore TMR (NO-TMR or metal ore grade) would be equal to 1 (Halada et al., 2001; Yamasue et al., 2009). In their results, they show that there is linearity between NO-TMR and UO-TMR. In addition, the “Elemental Concentration of Natural Ore Equivalent” (ECNOE) can be an induced index from the UO-TMR in understanding the environmental impact that takes place in the recycling processes (Yamasue et al., 2009). The potentiality in recyclability of the metal is deduced by comparing the natural ore and the urban ore grade. The larger the difference in these grades depicts the higher recyclability probability in a metal.

## 2.5 Summary

There are many critics governing the issue of “finite” resources. The concept of peak can only give predictions as to when metal supply would start becoming scarcer. However, models are focusing on sustainability patterns of these resources both on the production and consumption side. Understanding these patterns in terms of production rates, declining ore grades, recycling rates, etc, all can give better scenarios in the trajectory of future metal quantities and quality.

In addition, protection of the environment by responsibly tracing the material flows of these resources to account for used and unused, direct, indirect and hidden materials through accountability should be at the forefront. The total material requirement concept provides the opportunity to be able to measure the potential harm created during material production.

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# CHAPTER 3

# FUTURE AVAILABILTY OF MINERAL RESOURCES: ULTIMATE RESERVES AND TOTAL MATERIAL REQUIREMENT

## 3.1 Introduction

Mineral resources are essential for our modern society's technology, infrastructure, and human development. It is commonly held that these mineral resources are "finite", and that mining is therefore an unsustainable practice (Mudd, 2010; Mudd et al., 2013). The paradox, however, is that although the global metal production continues to grow at a bullish pace to concur to the increasing metal demand, the resources continue to grow and often in most producing regions will thrive for at least a few decades or more. Throughout the centuries, this pattern of metal peaking has been of concern to "when these resources will eventually peak" as the market dynamics operate with uncertainty due to growing demand, technological advancement, exploration finance, discovery rate and environmental protection, etc.

The "peak" concept which was initially introduced in the early 1950s by M. King. Hubbert to model the oil production. In this theory, as oil resources are discovered and developed, which are non renewable in their inherent nature, a steady rise in production will occur preceding an inevitable decline in production until production level ceases (Hubbert, 1956). The direction of this production creates a bell shape. Although Hubbert's peak theory is well recognized and has had substantial debate (Sorrell et al., 2009; Smith, 2012), the concept of "peak metals" is limited (Prior et al., 2011; Northey et al., 2012). While the fundamental basis that "peak oil" concept expresses the rapid depletion of resources that are finite before or alternatively moving to new metallogenic provinces or typically lower grade deposits in lesser accessible and subeconomic regions, minerals or metals typically take years before production can commence. This is because in the mining industry, cost minimization by delineating the ore deposit to convert it into an identified and measured resource and ultimately reserve is a common practice to ensure the viability and lifetime of the resource which should potentially remain profitable amidst uncertain market fluctuations.

The McKelvey classification system for mineral deposits outlines that a reserve includes recoverable amounts of a metal from a given location that is under development for profitability. Resources on the other hand include these reserves and other unidentified and non-/sub- economic potential with low geological confidence. The extraction nature of these metals is limited to exploration, technology, and profitability factors, which control the extent of URR growth. In other words, metal reserves may increase as resources are identified (Norgate and Rankin, 2002).

It is crucial to have an understanding of the long term trends of metals with respect to their "peak supply" or availability by their geographical location. This way potential metal mining will know where the potential production sites are located and their potential quality in terms of metal ore grade. By this, important aspects to delineate these trends are ore grade, ultimate recoverable reserves and environmental constraints, but not limited hereto.

When modelling the environmental impacts against metal mining through its life cycle impact assessment, there tends to be an inverse relationship between the ore grade and environmental impacts per tonne of metal produced (Norgate and Jahanshahi et al., 2010; Halada et al., 2011; Nakajima et al., 2019). In understanding the links between current and future environmental impacts and ore grade declines, coagulating policy makers, mining companies and the communities should be in synergy in these discussions. Limited studies (Northey et al., 2014) to model future metal grades at a regional and country level are limited based on the resource database. Herewith, we provide an assessment of the degree of decline for copper, gold, iron ore, lead, nickel and zinc into the future. The implication of the long future metal trends and their availability are applied to delineate future environmental impacts caused by metal mining of these six (6) metals. The outcome of the environmental impacts can assist resource stakeholders in the direction of research for sustainability in metal mining.

## 3.2 Methodology

### 3.2.1 Ultimate Recoverable Resources

Metal URR determines the present and future metal supply, and includes the identified resources and potential future reserves that could be converted from un-/sub-economic to economic reserves. Historical metal production data were used to predict the ultimate reserves. Annual data from the S&P Global database provided data on the metal production, ore grade, strip ratio, waste, and amount of ore mined from individual metal projects for 1991–2019 and forecasted to 2070. The model forecasts by regression the cumulative production to 2070, was estimated for selected countries and regions based on Equation 3-1:

$$P_{i,t} = Q_{i(t)} - Q_{i(t-1)}$$

Which can be rewritten as

$$P_{i,t}=\frac{dQ_i}{dt} \tag{3-1}$$

Here, $P_{i(t)}$ is the production of either a region or country $i$ in year $t$, with cumulative metal production $Q_i$ over the project lifetime in each region or country. The annual growth rate of production was assumed to be constant over time; therefore, the trends of future production ($P_i$) were derived linearly using Equation 3-2 as a function of time $t$, with $m$ and $c$ as constants.

$$P_i = mt + c \tag{3-2}$$

URR was modelled using cumulative grade-tonnage curves with an assumption that a preferential order of high-grade ores were mined before their transition to low-grade deposits. The ore grades for individual countries were used by the geological resource supply-demand model (Mudd and Weng, 2012; Northey et al., 2014) for analysis. Northey et al. (2014) explained that this approach is inherently limited by overestimating the global average grade in the early years of mining and underestimating it in the latter years; however, in reality, ore grades are determined only by profitability. To address this difference, they applied modified cumulative ore grade-tonnage curves to ensure that each data point represented an average of multiple deposits. In addition, the estimated URR is the major source of uncertainty, therefore an important issue to address is the appropriate use of reserve and resource estimates when modelling future production or resource scarcity (Northey et al., 2014).

In our study, we applied the head grades over resource grades as they provided the actual (“truest”) grade that was mined by considering market (or economic) factors. The head grade describes the metal content of the mined ore that is determined at the concentrator, while the resource grade describes the metal grade of the orebody. This approach was acceptable since resource grades ultimately converge to head grades over time. The head grade in our study are thus referred to as ore grades. URR is the maximum limit of metal resources that can be extracted and exploited; therefore, metal production can never exceed URR, i.e., URR $\geq Q_{i(t)}$. An ultimate COG (gc), such as 0.2% for Cu, Pb, and Ni; 0.2 g/t for Au; and 20% for Fe limits the future production and availability of that metal.

The general rule of thumb is that many geological data are log-normally distributed (Limpert et al., 2001). For the approximation of many metals grade (G)-tonnage(Q) relationships, the Lasky’s rule is applied. According to Lasky’s rule, an exponential grade decline precedes the cumulative tonnage of the ore (DeYoung, 1981; Limpert et al., 2001). However, in some cases, some metals may “fail to fit” into the log normal distribution, and therefore a change in grade would have a non-linear affect the cumulative production of that metal (Singer, 2013; Wellmer and Scholz, 2017). During our analysis, not all metals produced a “best fit" line according to the Lasky law. The grade (G)-tonnage (Q) relationships for Au, Fe, Pb, and Zn were measured linearly using Equation 3-3, whereas those for Cu and Ni were measured nonlinearly using Equation 3-4 and are both represented in Figure 3-1a and Figure 3-1b. Further, URR was extrapolated arbitrarily at the given metal COG using Equation 3-5 for Au, Fe, Pb, and Zn and Equation 3-6 for Cu and Ni. In these equations, a and b represented constants. As mining progressed, the reserves of the remaining fractions (RF) depleted, and were calculated according to Equation 3-7:

$$G_i = aQ_i + b \tag{3-3}$$

$$G_i = ae^{Q_i b} \tag{3-4}$$

$$Q_{URR,i} = \frac{G_i - a}{b} \tag{3-5}$$

$$Q_{URR,i} = \frac{\ln G_i - \ln a}{b} \tag{3-6}$$

$$RF_i = \frac{URR_i}{Q_i} \tag{3-7}$$

The lifetime of a metallogenic province in a given location *i*, is delineated by measuring the ore resource to the metal mining production (RbyP) by Equation 3-8:

$$RbyP_i = \frac{R_{p,t}}{P_{i,t}} \tag{3-8}$$

The accuracy of the modelled metal grade decline to cumulative production curves was determined using R-squared (coefficient of determination) value.

### 3.2.2 Total Material Requirement

TMR considers the significance of the environmental burden caused by mining. Mining focuses on metal ore production and the underlying profitability of these metals. However, the adverse environmental damages caused by ore refining waste, including surface soil, generated during mining is often neglected, and could have an adverse impact on the environment. Scheel et al. (2020) demonstrated that “conventional decoupling” along the linear production chain evidently causes material flows since large amounts of both economic product and waste are generated. Since the environmental impacts of mining hinder sustainable development, specifically the sustainable development goal 12, using TMR for accountability through database inventory would assist environmentalists and other relevant stakeholders to evaluate and manage these resources.

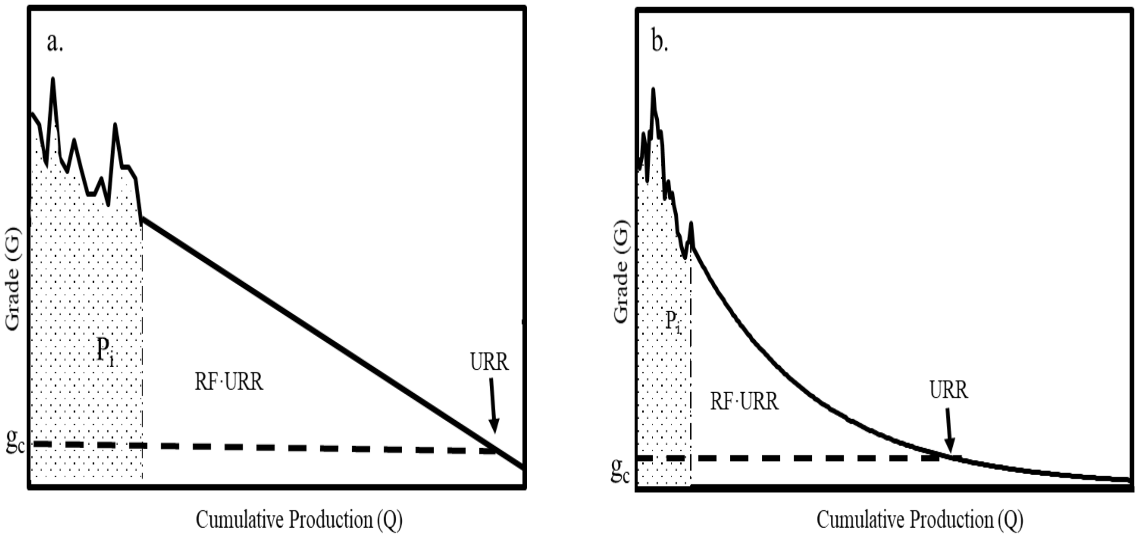

Figure 3-1 Grade-tonnage curves: **a** linear trend **b** non-linear trend

In this study, TMR represents the total amount of materials moved or extracted in situ to produce one tonne of ore during mineral production; therefore, it is an index of resource consumption (resource depletion). It was adapted by Halada et al. (2001), who represented TMR as the ore-TMR coefficient (Halada et al., 2001; Kosai and Yamasue, 2019). However, Halada et al. (2001) calculated the ore-TMR coefficient for only a single year. In this study, we conducted a quasi-dynamic analysis through linear regression of mine production over time to compute the future trends using Equation 3-2. Computation of the ore-TMR coefficient utilizes the strip ratio and ore grade of the metal. We derived the ore-TMR coefficient, which is the ratio of the total material production (x) to the metal production at a given head grade (G). The strip ratio (SR) acts as a multiplier effect on the ore-TMR coefficient. Therefore,

$$\frac{x(1-G)+xSR}{xG} \tag{3-9}$$

Where, x(1-G) refers to the total amount of tailings and xSR represents the amount of waste rock. The summation x(1-G)+xSR represents the total waste produced at the mine site. Since xG is the total metal production in Equation 3-9 represents how much waste is generated per unit metal production. G is large enough to assume in the equation:

If 1-G ≈ 1

Then

$$\frac{x+xSR}{xG}$$

Reduces to the ore-TMR coefficient

$$\text{Ore-TMR Coefficient}=\frac{1+SR}{G} \tag{3-10}$$

Later, we computed the annual ore-TMR which is the ratio of the metal production ($P_i$) to the TMR coefficient for a given country or region using Equation 3-11.

$$Annual\ Ore-TMR = ore-TMR\ Coefficient \times P_i \tag{3-11}$$

The annual ore-TMR increases with the increase in the ore-TMR coefficient. A high ore-TMR coefficient indicates that the material input required to achieve one ton of ore exhibits low degree of environmental impacts. In contrast, low TMR coefficient indicates a high degree of environmental impact.

## 3.3 Results and Discussion

### 3.3.1 Metal Ore Grades

A key hypothesis to this study was to investigate whether ore grades decline in the long term, and if so, what quantify their probable trajectory routes and rates for this decline. Figure Table 3-1 shows the ore grade trend equations for Au, Cu, Fe, Pb, Ni and Zn at a global level and corresponding regression estimates. These trends are a representative of the average ore grade patterns occurring at a regional level or country level. The constraint here was the cut of grade of each metal was given at the ultimate grade where the latter was either greater than or equivalent to the cut off. In other words, the cut-off grade is achieved the physical scarcity of ultimate resources are depleted.

Based on the ultimate economic reserves, these grades have an invariable decline at varying rates compared to their past trends. Even with increasing exploration success through improved technology and research and development, the high grades metallogenic provinces in these locations are increasingly becoming scarcer. It is unlikely that future prospects will discover higher grade deposits of an economic level at 0.2% COG Cu-Ni-Pb-Zn, 0.2g/t Au and 20% Fe.

Table 3-1 Statistics of average Ore grades of selected metals from 2000-2070

| | Equation | R squared |
|---|---|---|
| Copper | $G=1.228^{Q1.363*10^{-9}}$ | 0.935 |
| Gold | $G=5.373Q-2.074*10^{8}$ | 0.823 |
| Iron Ore | $G=44.683Q-2.046*10^{5}$ | 0.134 |
| Lead | $G=3.359Q-4.334*10^{5}$ | 0.905 |
| Nickel | $G=1.883^{Q3.999*10^{-11}}$ | 0.876 |
| Zinc | $G=7.114Q-2.268*10^{8}$ | 0.925 |

Copper

Table 3-2 presents the total resources and reserves, number of projects, and reserves by production (RbyP) ratio, which defines the reserve lifetime, for 2018 for different regions and countries of the selected metals. The resource (reserve) size for Latin America was 514 802 kt (249 965 kt). The production capacity of Cu mines was 6452 kt. The Asia-Pacific region reported 2857 kt (2018) with a resource (reserve) size of 88312 t (143 409 kt) and an RbyP of 81 years. More than 40% of African Cu was supplied by Zambia. Zambian Cu resources (reserves) accounted for 25802 kt (12304 kt) from four selected Cu mine projects. The 2018 production capacity was 533 kt with an RbyP of 72 years. Compared with Mudd et al. (2012), they reported 690 kt Cu (2010) with an RbyP of 67.7 years. Chile, the largest global Cu producer, exhibited a production capacity of 4086 kt with an RbyP of 156 years. The resource (reserve) size was 485 193 kt (150 039 kt). Mudd et al. (2012) reported 5418.9 kt in 2010 with an RbyP of 121.5 years using data collected from 51 projects. Our results were consistent with those of Mudd et al. (2012). The Chinese Cu mine data did not adequately present the Chinese results and exhibited a substantial level of bias. However, we considered this bias in our results. Tiejun and Weidong (2018) estimated approximately 101.1 Mt and 106.1 Mt Cu resources in 2016 and 2017, respectively. In addition, the authors noted that Cu resources exhibited a potential growth rate of 4.9%. Our study on 10 Chinese mine projects indicated a production of 436 kt (2018) with a resource (reserve) size of 6897 kt (10 478 kt) and an RbyP of 39.8 years.

Table 3-3 shows the grade-tonnage equations calculated based on Equations 3-3 and 3-4 applied for each location. Figures 3-3 and Figure 3-4 indicate the declining trend of Cu grades with cumulative production for selected localities. Grade-tonnage curves were predicted at 0.2% for Cu, Ni, Pb, and Zn; 0.2 g/t for Au; and 20% COG for Fe. Our results indicated that global Cu reserves will last beyond 2070 with 1.3 Bt. This value was significantly lower than the United States Geological Survey (USGS) estimates, which indicated 870 Mt of current global Cu reserves (USGS, 2020). However, Europe exhibited limited reserves of Cu (>0.5%) and by 2034, it will demonstrate 97.8 Mt of ultimate Cu reserves at a COG of 0.2%. Asia Pacific is expected to recover high-grade ores greater than 0.5% of Cu with ultimate reserves of 169.1 Mt by 2057. The ultimate reserves of Africa and Latin America at 0.2% of Cu were 59 Mt and 455 Mt, respectively. Further, 272.5 Mt of Chilean Cu reserves were accessible at 0.5% of Cu. In addition, Chilean copper will recover 304 Mt of reserves by 2070 at 0.46% of Cu. Cu recoverability in Chile serves as a potential sustainable supplier beyond 2070. Further, Latin American regions will continue to be hot spots for Cu exploration after 2070, while Europe, the USA, and Zambia will face exploration challenges, thus, highlighting the need to improve research and development by adopting advanced technology to recover low Cu grades.

Gold

Ninety-six Au mine projects were considered from the S&P Global Database (Table 1). The world Au resource (reserves) were 14390 t (12731 t) in 2018. The African region exhibited the largest resources (reserves) with 6626 t (3897 t), followed by the Asia-Pacific region with 3877 t (4946 t). The RbyP of Au availability in Africa and North America was 50 years and 19 years, respectively. In addition, South Africa estimated that its Au reserves (1862 t) will last for 103 years more with a production of 55 t in 2018. The production of Ghana was 45 t in 2018 with a lifetime of 61 years. The USA exhibited the least lifetime (18 years) with a resource/reserve size of 1001 t/1620 t. However, the African continent did not exhibit any potential for research and development through mineral exploration compared with the North American continent. Historically, African gold output was conveyed by small-scale artisanal mining, which lacks adequate infrastructure for efficient production within the informal sector where it largely operates. Thus, commercialization of the Au sector in Africa would improve Au production since it would promote business confidence and investment.

Table 3-2 Resource to Production ratio in 2018 by location for ferrous, non-ferrous and precious metals

| Location | No. of projects | Resources | Reserves | Production | R/P (Years) |
|---|---|---|---|---|---|
| *Copper* | | (kt) | (kt) | (kt) | |
| Africa | 10 | 70,277 | 25,750 | 1,153 | 83 |
| Asia Pacific | 33 | 143,409 | 88,312 | 2,857 | 81 |
| Europe | 5 | 27,184 | 21,118 | 651 | 74 |
| Latin America | 29 | 514,802 | 249,965 | 6,452 | 119 |
| North America | 14 | 23,294 | 46,401 | 1,444 | 48 |
| Australia | 9 | 76,523 | 14,578 | 688 | 132 |
| Chile | 16 | 485,193 | 150,039 | 4,086 | 155 |
| China | 10 | 6,897 | 104,784 | 436 | 40 |
| Indonesia | 2 | 19,357 | 21,689 | 557 | 74 |
| USA | 10 | 18,583 | 43,179 | 1,161 | 53 |
| Zambia | 4 | 25,802 | 12,304 | 533 | 72 |
| World | 91 | 777,774 | 431,546 | 12,556 | 96 |
| *Gold* | | (t) | (t) | (t) | |
| Africa | 28 | 6,626 | 3,897 | 211 | 50 |
| Asia Pacific | 36 | 3,877 | 4,946 | 362 | 24 |
| Europe | 3 | 403 | 261 | 16 | 42 |
| Latin America | 11 | 1,293 | 1,166 | 105 | 23 |
| North America | 18 | 2,180 | 2,461 | 240 | 19 |
| Australia | 11 | 1,068 | 1,151 | 113 | 20 |
| Canada | 9 | 699 | 531 | 67 | 18 |
| China | 10 | 756 | 240 | 28 | 35 |
| Ghana | 7 | 1,612 | 1,111 | 45 | 61 |
| Peru | 8 | 338 | 279 | 26 | 24 |
| Russia | 3 | 938 | 1,268 | 90 | 25 |
| South Africa | 9 | 3,791 | 1,862 | 55 | 103 |
| USA | 11 | 1,001 | 1,620 | 146 | 18 |
| Zambia | 4 | 14 | 13 | 1 | 29 |
| World | 96 | 14,380 | 12,731 | 935 | 29 |

| | | | | | |
|---|---|---|---|---|---|
| *Iron Ore* | | (Mt) | (Mt) | (Mt) | |
| Australia | 10 | 34,415 | 7,054 | 1,365 | 30 |
| Brazil | 10 | 9,541 | 10,173 | 204 | 97 |
| China | 11 | 6 | 24 | 20 | |
| Russia | 6 | | 19,603 | 47 | |
| South Africa | 5 | 871 | 1,223 | 64 | 33 |
| USA | 7 | 841 | 3,054 | 49 | 79 |
| World | 63 | 62,914 | 52,017 | 1,930 | 60 |
| *Lead* | | (kt) | (kt) | (kt) | |
| Africa | 2 | 2,572 | 329 | 49 | 59 |
| Asia & Pacific | 25 | 51,472 | 20,930 | 815 | 89 |
| Europe | 10 | 4,451 | 3,835 | 115 | 72 |
| Latin America | 34 | 6,053 | 6,126 | 406 | 30 |
| North America | 7 | 2,707 | 5,215 | 327 | 24 |
| Australia | 10 | 43,860 | 14,736 | 379 | 155 |
| China | 9 | 1,601 | 2,775 | 125 | 35 |
| Peru | 15 | 3,278 | 1,602 | 154 | 32 |
| Mexico | 16 | 2,303 | 4,331 | 158 | 42 |
| USA | 6 | 2,610 | 5,215 | 317 | 25 |
| World | 78 | 67,254 | 36,434 | 1,712 | 61 |
| *Nickel* | | (kt) | (kt) | (kt) | |
| Australia | 5 | 1,707 | 1,067 | 108 | 26 |
| Canada | 5 | 1,230 | 2,157 | 196 | 17 |
| China | 2 | 48 | 5,622 | 87 | 65 |
| Indonesia | 2 | 6,181 | 6,167 | 100 | 124 |
| Philippines | 2 | 326 | 1,908 | 22 | 101 |
| South Africa | 3 | 573 | 54 | 13 | 47 |
| Zimbabwe | 3 | 874 | 226 | 8 | 146 |
| World | 26 | 16,684 | 18,788 | 631 | 56 |
| *Zinc* | | (kt) | (kt) | (kt) | |
| Africa | 3 | 1,256 | 1,301 | 127 | 20 |
| Asia Pacific | 23 | 81,762 | 38,989 | 2,275 | 53 |
| Europe | 9 | 8,795 | 17,280 | 800 | 33 |

| | | | | | |
|---|---|---|---|---|---|
| Latin America | 26 | 34,301 | 24,092 | 1,281 | 46 |
| North America | 8 | 7,680 | 7,745 | 853 | 18 |
| Australia | 8 | 49,520 | 19,482 | 724 | 95 |
| China | 8 | 8,332 | 6,939 | 514 | 30 |
| India | 4 | 16,890 | 8,558 | 678 | 38 |
| Mexico | 9 | 2,411 | 13,714 | 234 | 69 |
| Namibia | 2 | 1,134 | 842 | 127 | 16 |
| Peru | 14 | 30,133 | 8,570 | 690 | 56 |
| USA | 3 | 5,754 | 6,837 | 718 | 18 |
| World | 69 | 133,793 | 89,407 | 5,335 | 42 |

Table 3-3 indicates that North America and Asia Pacific contribute largely to the global URR at 29403 t and 22896 t of Au, respectively, with a COG of 0.2 g/t. The modern era of cryptocurrency wherein digital coins is developed for investment trading can suppress Au production in the investment sector by replacing public coins. However, the digital currency would not replace Au as a secure investment. In addition, this represents only a minor fraction of the total Au demand compared with jewellery (52%) and technology (9%) applications. Au peak can occur because of economic factors rather than physical factors (Wellmer and Scholz 2017); therefore, the physical availability of Au is unlikely to disrupt supply.

Table 3-3 Grade-Tonnage estimates and URR for ferrous, nonferrous and precious metals

| | Equation | R-squared | URR |
|---|---|---|---|
| *Copper* | | | *URR @ 0.2% Cu [Mt]* |
| Africa | $G=-3.86*10^{-8}e^{1.91Q}$ | 0.76 | 59 |
| Asia Pacific | $G=-5.76*10^{-9}e^{1.31Q}$ | 0.95 | 329 |
| Europe | $G=-8.15*10^{-9}e^{0.47Q}$ | 0.61 | 98 |
| Latin America | $G=-4.02*10^{-9}e^{1.23Q}$ | 0.95 | 455 |
| North America | $G=-7.81*10^{-9}e^{0.94Q}$ | 0.77 | 200 |
| Australia | $G=-2.55*10^{-8}e^{2.10Q}$ | 0.78 | 93 |
| Chile | $G=-2.70*10^{-9}e^{1.04Q}$ | 0.68 | 616 |
| China | $G=-2.37*10^{-8}e^{0.88Q}$ | 0.45 | 64 |
| Indonesia | $G=-2.55*10^{-8}e^{1.07Q}$ | 0.81 | 66 |
| USA | $G=-2.50*10^{-8}e^{1.61Q}$ | 0.96 | 84 |
| Zambia | $G=-6.03*10^{-8}e^{2.19Q}$ | 0.79 | 40 |
| World | $G=-1.36*10^{-9}e^{1.22Q}$ | 0.93 | 1,344 |
| *Nickel* | | | *URR @ 0.2% Ni [Mt]* |
| Australia | $G=-4.71*10^{-10}e^{2.72Q}$ | 0.70 | 5,596 |
| Canada | $G=-6.39*10^{-11}e^{2.23Q}$ | 0.49 | 37,964 |
| China | $G=-1.34*10^{-10}e^{1.01Q}$ | 0.45 | 12,185 |
| Indonesia | $G=-8.73*10^{-11}e^{2.14Q}$ | 0.33 | 27,312 |
| South Africa | $G=-2.96*10^{-9}e^{1.17Q}$ | 0.49 | 596 |
| Zimbabwe | $G=-4.44*10^{-9}e^{1.74Q}$ | 0.81 | 492 |
| World | $G=-3.99*10^{-11}e^{1.88Q}$ | 0.88 | 56,380 |
| *Gold* | | | *URR @ 0.2g/t Au [t]* |
| Africa | $G=-1.19*10^{-8}Q+8.17$ | 0.74 | 18,912 |
| Asia Pacific | $G=-6.14*10^{-9}Q+5.16$ | 0.64 | 22,896 |
| Europe | $G=-1.19*10^{-7}Q+3.65$ | 0.38 | 819 |
| Latin America | $G=-4.25*10^{-8}Q+7.82$ | 0.91 | 5,111 |
| North America | $G=-5.64*10^{-9}Q+6.10$ | 0.20 | 29,403 |
| Australia | $G=-2.53*10^{-8}Q+6.88$ | 0.84 | 7,509 |
| Canada | $G=-3.03*10^{-8}Q+6.58$ | 0.39 | 6,018 |
| China | $G=-1.54*10^{-7}Q+5.75$ | 0.88 | 1,026 |
| Ghana | $G=-1.86*10^{-8}Q+5.74$ | 0.30 | 8,441 |

| | | | |
|---|---|---|---|
| Peru | $G=-2.07*10^{-8}Q+3.98$ | 0.89 | 5,132 |
| South Africa | $G=-5.96*10^{-8}Q+13.41$ | 0.84 | 6,294 |
| USA | $G=-2.24*10^{-8}Q+7.09$ | 0.54 | 8,759 |
| World | $G=-2.07*10^{-8}Q+5.37$ | 0.82 | 77,141 |
| *Lead* | | | *URR @ 0.2% Pb [Mt]* |
| Africa | $G=-1.67*10^{-3}Q+4.91$ | 0.86 | 3 |
| Asia & Pacific | $G=-1.01*10^{-4}Q+3.99$ | 0.82 | 38 |
| Europe | $G=-1.16*10^{-3}Q+5.01$ | 0.88 | 4 |
| Latin America | $G=-1.26*10^{-4}Q+1.97$ | 0.66 | 15 |
| North America | $G=-2.82*10^{-4}Q+5.83$ | 0.74 | 20 |
| Australia | $G=-1.84*10^{-4}Q+5.66$ | 0.84 | 30 |
| China | $G=-1.32*10^{-3}Q+3.41$ | 0.80 | 3 |
| Mexico | $G=-1.70*10^{-4}Q+1.40$ | 0.28 | 7 |
| Peru | $G=-3.79*10^{-4}Q+2.4$ | 0.77 | 6 |
| USA | $G=-4.19*10^{-4}Q+7.04$ | 0.75 | 17 |
| World | $G=-4.33*10^{-5}Q+3.36$ | 0.90 | 73 |
| *Zinc*[†] | | | *URR @ 0.2% Zn [Mt]* |
| Asia Pacific | $G=-2.36*10^{-8}Q+7.27$ | 0.55 | 300 |
| Europe | $G=-1.07*10^{-7}Q+5.25$ | 0.74 | 47 |
| Latin America | $G=-1.61*10^{-7}Q+7.38$ | 0.95 | 44 |
| North America | $G=-9.24*10^{-8}Q+7.45$ | 0.85 | 78 |
| Australia | $G=-1.92*10^{-7}Q+9.79$ | 0.74 | 50 |
| China | $G=-9.54*10^{-8}Q+6.08$ | 0.42 | 61 |
| India | $G=-1.23*10^{-7}Q+6.86$ | 0.69 | 54 |
| Mexico | $G=-4.76*10^{-7}Q+5.06$ | 0.93 | 10 |
| Peru | $G=-3.41*10^{-7}Q+8.17$ | 0.95 | 23 |
| Namibia | $G=-1.24*10^{-6}Q+12.79$ | 0.66 | 10 |
| USA | $G=-1.12*10^{-7}Q+7.84$ | 0.83 | 68 |
| World | $G=-2.27*10^{-8}Q+7.11$ | 0.92 | 303 |
| *Iron Ore* | | | *URR @ 20-39%Fe [Mt]* |
| Australia | $G=-3.29*10^{-5}Q+59.74$ | 0.65 | 56,231[‡] |
| Brazil | $G=-1.04*10^{-3}Q+57.12$ | 0.93 | 17,065 |
| China | $G=-7.43*10^{-3}Q+33.42$ | 0.62 | 1,804 |

| | | | |
|---|---|---|---|
| Russia | $G=-0.99*10^{-3}Q+27.41$ | 0.34 | 4,791 |
| South Africa | $G=-2.80*10^{-4}Q+62.97$ | 0.06 | 6,109§ |
| USA | $G=-2.76*10^{-4}Q+23.99$ | 0.40 | 4,698 |
| World | $G=-2.05*10^{-5}Q+44.68$ | 0.13 | 107,147‡ |

† Africa Zinc not included in interpretation due to limited data.

‡ Australia and World estimates URR@>40-59%Fe cut-off grade

§ South Africa estimates URR @ >60%Fe cut-off grade

Iron Ore

Table 3-2 indicates that the global Fe ore resources (reserves) are 62914 Mt (52016 Mt). The Fe resources (reserves) in the Asia-Pacific region were 38397 Mt (30271 Mt), while those in Latin America were the second largest with 10405 Mt (912 187 Mt). The RbyP of Fe ore supply for North America, Europe, Latin America, Brazil, and the USA was 168, 146, 99, 97, and 79 years, respectively. Due to its high abundance in the Earth's crust, Fe ore availability is less threatened by physical, political, or economic factors.

Table 3-3 shows the linear trend estimates of Fe URR. Figures 3-5 and 3-6 present the trends in the Fe grades with cumulative production. Fe ore would be currently available for an average of 155 years. The South African high-grade ore (>60% Fe, 6109 Mt) will be available till 2070. Australia and Brazil are both medium-high grade Fe ore suppliers with ultimate reserves of 56231 Mt and 17065 Mt, respectively. China and Russia produce low-grade ores with 1804 Mt and 4791 Mt cumulative production, respectively, in 2070.

Nickel

Ni is the 5th most common element on Earth. In addition, 80% of Ni has been historically extracted, and Ni resources are gradually increasing (Nickel Institute, 2021). Global Ni resources are expected to be available for at least 56 years (Table 3-3). The Asia-Pacific region is the largest producer with countries, such as Australia and Indonesia exhibiting production capacities over 100 000 t. Although the Ni production capacities of the Philippines (22kt) and Zimbabwe (8 kt) are low, their RbyP exceeds 100 years owing to the large resource/ reserve. Figure 3-4 displays the grade-tonnage trends of Ni for Australia and Indonesia. Table 3-3 indicate that Australia, Canada, China and Indonesia accounts for more than 30% of the global Ni resources, with ultimate reserves ranging from 1000 to 5000Mt at 0.2% COG of Ni.

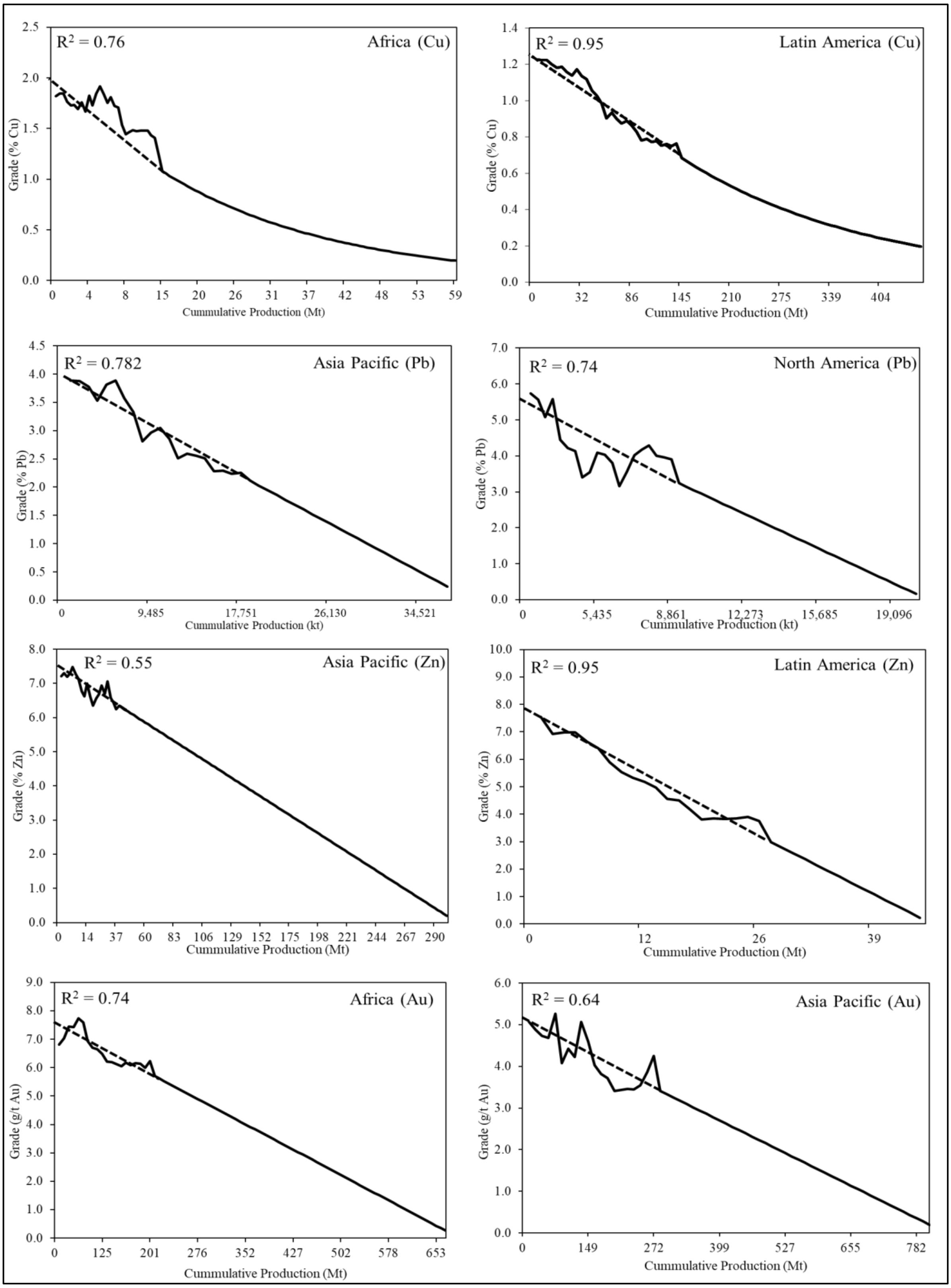

Figure 3-2 Grade tonnage plots by regions

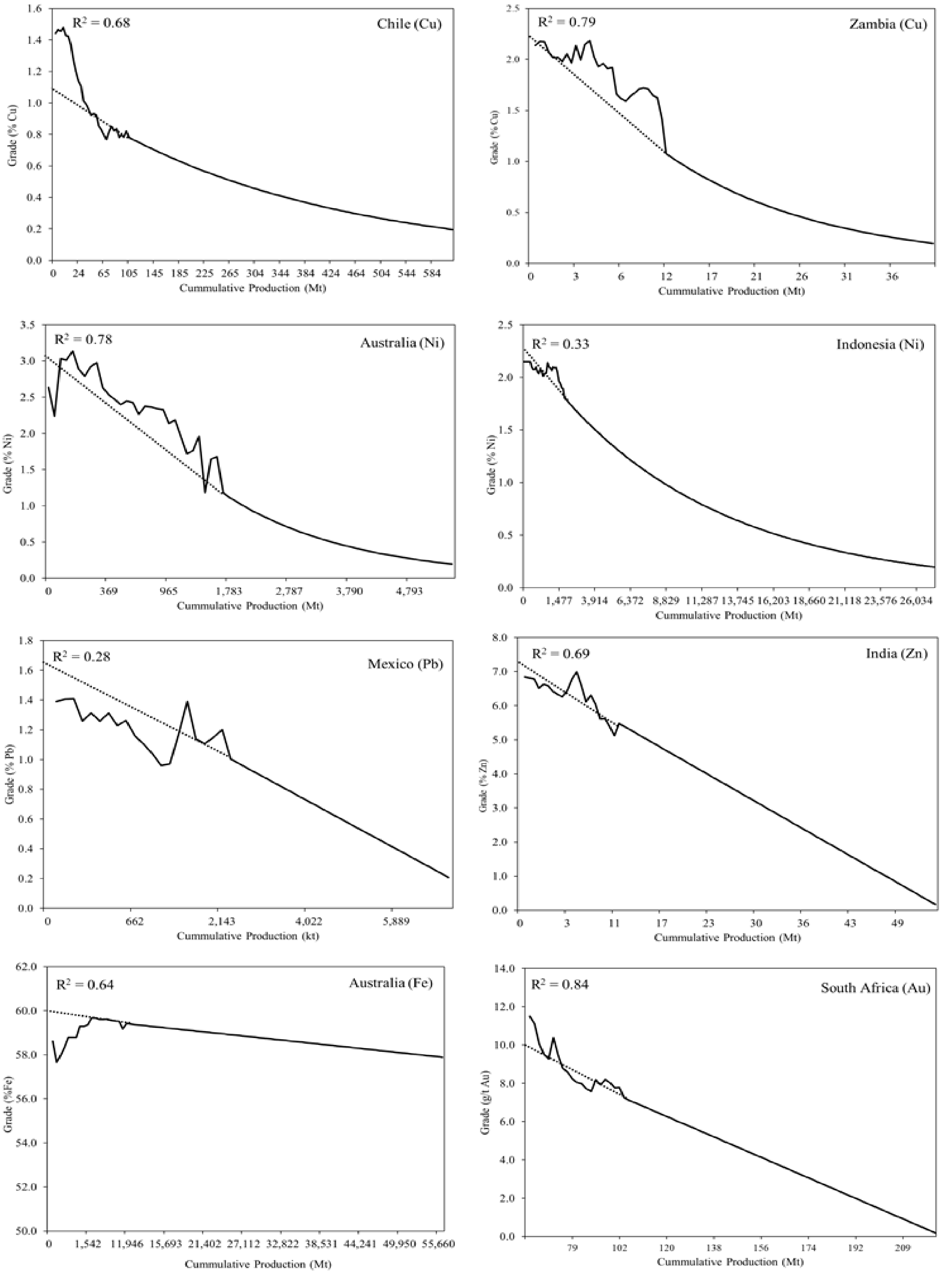

Figure 3-3 Grade tonnage plots of the selected countries

Table 3-4 Production estimates for selected metals

| | Equation (tonnes) | R-squared |
|---|---|---|
| *Copper* | | |
| Africa | $P=3.86*10^4t-7.67*10^7$ | 0.73 |
| Asia Pacific | $P=7.24*10^4t-1.43*10^8$ | 0.78 |
| Europe | $P=7.12*10^3t-1.37*10^7$ | 0.58 |
| Latin America | $P=1.43*10^5t-2.83*10^8$ | 0.80 |
| North America | $P=2.90*10^3t-4.42*10^6$ | 0.35 |
| Australia | $P=1.94*10^4t-3.84*10^7$ | 0.83 |
| Chile | $P=8.67*10^4t-1.70*10^8$ | 0.58 |
| China | $P=1.63*10^4t-3.25*10^7$ | 0.92 |
| Indonesia | $P=-1.17*10^3t+2.99*10^6$ | 0.39 |
| USA | $P=1.21*10^3t-1.33*10^6$ | 0.21 |
| Zambia | $P=1.66*10^4t-3.29*10^7$ | 0.71 |
| World | $P=2.64*10^5t-5.20*10^8$ | 0.90 |
| *Nickel* | | |
| Australia | $P=2.51*10^6t-4.96*10^9$ | 0.75 |
| Canada | $P=4.01*10^6t-7.87*10^9$ | 0.35 |
| China | $P=2.97*10^6t-5.90*10^9$ | 0.81 |
| Philippines | $P=1.13*10^6t-2.24*10^9$ | 0.54 |
| South Africa | $P=2.51*10^5t-4.87*10^8$ | 0.37 |
| Zimbabwe | $P=2.82*10^5t-5.63*10^8$ | 0.65 |
| World | $P=1.42*10^7t-2.80*10^{10}$ | 0.80 |
| *Gold* | | |
| Africa | $P=2.51t-4.82*10^3$ | 0.64 |
| Asia Pacific | $P=9.25t-1.83*10^4$ | 0.92 |
| Europe | $P=0.94t-1.88*10^3$ | 0.84 |
| Latin America | $P=4.32t-8.57*10^3$ | 0.53 |
| North America | $P=6.39t-1.26*10^4$ | 0.67 |
| Australia | $P=2.11t-4.15*10^3$ | 0.76 |
| Canada | $P=3.30t-6.55*10^3$ | 0.67 |
| China | $P=1.53t-3.05*10^3$ | 0.69 |
| Ghana | $P=1.00t-1.97*10^3$ | 0.43 |

| | | |
|---|---|---|
| Peru | $P=-0.56t+1.12*10^{3}$ | 0.24 |
| Russia | $P=3.07t-6.10*10^{3}$ | 0.92 |
| South Africa | $P=0.53t-1.01*10^{3}$ | 0.78 |
| USA | $P=1.97t-3.81*10^{3}$ | 0.21 |
| World | $P=23.2t-4.58*10^{4}$ | 0.82 |
| *Lead* | | |
| Africa | $P=3.92*10^{3}t-7.86*10^{6}$ | 0.97 |
| Asia & Pacific | $P=2.67*10^{4}t-5.30*10^{7}$ | 0.88 |
| Europe | $P=3.09*10^{3}t-6.10*10^{6}$ | 0.85 |
| Latin America | $P=1.56*10^{4}t-3.10*10^{7}$ | 0.97 |
| North America | $P=8.32*10^{4}t-1.64*10^{7}$ | 0.31 |
| Australia | $P=1.02*10^{4}t-2.00*10^{7}$ | 0.32 |
| China | $P=6.99*10^{3}t-1.40*10^{7}$ | 0.67 |
| USA | $P=8.03*10^{3}t-1.58*10^{7}$ | 0.30 |
| Peru | $P=3.69*10^{3}t-7.28*10^{6}$ | 0.55 |
| Mexico | $P=6.68*10^{3}t-1.33*10^{7}$ | 0.86 |
| World | $P=5.27*10^{4}t-1.04*10^{8}$ | 0.76 |
| *Zinc*[†] | | |
| Asia Pacific | $P=7.52*10^{4}t-1.49*10^{8}$ | 0.86 |
| Europe | $P=1.72*10^{4}t-3.39*10^{7}$ | 0.57 |
| Latin America | $P=6.45*10^{3}t-1.17*10^{7}$ | 0.16 |
| North America | $P=-2.20*10^{3}t+5.26*10^{6}$ | 0.29 |
| China | $P=2.58*10^{4}t-5.15*10^{7}$ | 0.93 |
| Australia | $P=1.27*10^{4}t-2.48*10^{7}$ | 0.44 |
| China | $P=2.58*10^{4}t-5.15*10^{7}$ | 0.93 |
| India | $P=3.17*10^{4}t-6.32*10^{7}$ | 0.71 |
| Mexico | $P=8.31*10^{3}t-1.65*10^{7}$ | 0.86 |
| Namibia | $P=6.77*10^{3}t-1.34*10^{7}$ | 0.30 |
| Peru | $P=1.54*10^{4}t-3.01*10^{7}$ | 0.44 |
| USA | $P=3.52*10^{3}t-6.41*10^{6}$ | 0.26 |
| World | $P=9.20*10^{4}t-1.80*10^{8}$ | 0.79 |
| *Iron Ore* | | |
| Australia | $P=9.10*10^{7}t-1.82*10^{11}$ | 0.79 |

| | | |
|---|---|---|
| Brazil | $P=4.87*10^6t-9.61*10^9$ | 0.71 |
| China | $P=5.16*10^5t-1.02*10^9$ | 0.82 |
| Russia | $P=4.30*10^5t-8.22*10^8$ | 0.62 |
| South Africa | $P=5.95*10^6t-1.01*10^{10}$ | 0.80 |
| USA | $P=-2.04*10^5t+4.56*10^8$ | 0.27 |
| World | $P=1.02*10^8t-2.03*10^{11}$ | 0.82 |

† Africa Zinc not included in analysis due to limited data

Lead-Zinc

In the next 50 years, the supply of Pb-Zn resources is expected to decline with the Asia-Pacific region representing the last remaining centre for these resources for an additional 10–20 years. Australia, which is the leading Pb-Zn producer, exhibits an RbyP of approximately 100 years, with in situ Pb-Zn resources (reserves) in a range of 40–50 Mt (10–20 Mt). The physical availability of these materials is critical (Table 3-2) since these metals cannot disrupt the value chain in major industries due to their easy substitution by other metals. The decline in the Pb supply is mainly due to the transition towards green technology, which replaces Pb by metals, such as lithium and cobalt, which are important components in in electric vehicle batteries. Zn is majorly used in iron plating because of its non-corrosive properties. However, high costs of Zn processing have resulted in its replacement by low-cost metals, such as aluminium.

Table 3-3 shows that the recoverable reserves for Zn are higher than those for Pb. The global ultimate reserves for Zn and Pb were approximately half the resource size estimated by Mudd et al. (2017). Figure 3-3 and Figure 3-4 depict the grade tonnage trends for Pb and Zn. Asia Pacific exhibited 299.6 Mt of Zn and 37.9 Mt of Pb in recoverable reserves at 0.2% COG. In Africa, Namibia is a major source of Zn resources, with ultimate reserves at 10 Mt (0.2% of Zn). However, Latin American regions, such as Peru, would witness a major decline in the Pb-Zn supply by 2040.

## 3.4 Production and environmental sustainability: Ore-TMR

Sensitivity analysis indicated that amplifying metal production would increase the ore-TMR coefficients magnitude by more than two orders. Such high coefficients would rapidly increase the environmental vulnerability. Therefore, future trends of the ore TMR coefficients were evaluated linearly.

The future trends in target metal productions are presented in Figure 3-5 and Figure 3-6 and Table 3-4 (Appendix 3-1). The results were used to assess the future trends of annual ore-TMR metals (Figure 3-7 and Figure 3-8) based on Equation 3-8 and Equation 3-9 by countries or regions. Higher the ore-TMR coefficient, higher was the expected annual ore-TMR. Consequently, the ore-TMR coefficient was estimated to be 2070. The assumed COG for metal production was 0.2% for Cu, Ni, Pb, and Zn; 0.2 g/t for Au; and 20% for Fe. Similar to the metal grade, the strip ratio varied over time during metal production of the production history between 1991 and 2019. The range of strip ratios for Cu, Ni, Pb, and Zn was 0.5–3, whereas that for Fe and Au was 0.3–2.6 and 0.8–6, respectively. The future trends of the strip ratio increased by an order from 1 to 3 depending on the metal. Thus, different trend trajectories were observed within these metals.

Copper

According to the future trends, the annual ore-TMR (ore-TMR coefficient) of Cu for Asia Pacific increased rapidly over time from 336 Mt-TMR/year (156 t/metal-t) in 2000, 585 Mt/year (205 t/metal-t) in 2018 to 2 317 Mt/year (338 t/metal-t) in 2070. During this period, Asia experienced a proliferation in the mineral sector, including Cu production. The material intensity in Asia is rapidly growing due to increased production to boost economic development, especially in China and India. The results were consistent with those of Australia from 47 Mt/year (87 t/metal-t) in 2000 and 69 Mt/year (100 t/metal-t) in 2018 to 418 Mt/year (230 t/metal-t) in 2070. The global annual ore-TMR increased from 2 127 Mt/year (228 t/metal-t) in 2000 and 4 758 Mt/year (379 t/metal-t) in 2018 to 40 430 Mt/year (2 462 t/metal-t) in 2070. Our results were consistent with the global Cu estimates of Halada et al. (2001) for 2000, with 300 t/metal-t and annual ore–TMR of 3 870 Mt/year. In addition, Nakajima et al. (2019) estimated 2683 Tg (2 683 Mt) and 5477 Tg (5 477 Mt) of globally used and unused Cu extractions in 1990 and 2013, respectively.

Gold

Halada et al. (2001) recorded the annual ore-TMR for Au at 4401 Mt/year (1 800 000 t/metal-t) in 2000. The magnitude as estimated by us at 694.6 Mt/year (931 541.7 t/metal-t) was significantly lower than these estimates during the same period. In 2018, the global annual ore TMR was 1 157 Mt/year (985 163 t/metal-t) and 9944 Mt/year (3 313 580 t/metal-t). The trend of annual ore-TMR (ore-TMR coefficient) in Africa is estimated to change from 226.3 Mt/year (1 033 965 t/metal-t) in 2000 and 354.6 Mt/year (1 676 806 t/metal-t) in 2018 to 1 554 Mt/year (4 306 083 t/metal-t) in 2070. This trend during the same period will change from 55.3

Mt/year (1 171 875 t/metal-t) and 120.6 Mt/year (2 686 269 t/metal-t) to 491 Mt/year (4 426 821 t/metal-t). The exponential increase in future annual ore-TMR indicated a potential environmental severity by Au; therefore, environmental sustainability by finding Au substitutes, or implementing sustainable mining practices should be adopted quickly.

### Iron ore

Our estimates of global annual ore-TMR of 3 148 Mt/year (6.6 t/metal-t) for Fe ore in 2000 ore significantly higher than 2912 Mt/year as estimated by Halada et al. (2001). Nakajima et al. (2019) estimated 2 754 Tg (2 754 Mt) and 6684 Tg (6 684 Mt) of globally used and unused extractions of Fe ore in 1990 and 2013, respectively. Australia and South Africa exhibited an annual ore-TMR (ore-TMR coefficient) of 531 Mt/year (5.24 t/metal-t) and 142 Mt/year (4.91 t/metal-t) for Fe ore and ranked among the top producer countries globally in 2000. The material intensity in global Fe ore production increased sharply around 2010. The annual ore-TMR (ore-TMR coefficient) of Australia in 2010 was 1967 Mt/year (6.81 t/metal-t) majorly because of a need to supply commodities to the Asian Pacific for consumption. During this period, Australia ramped up its Fe ore reserves for production in steel making for construction, especially in China. In addition, the environmental vulnerability for the Chinese Fe ore was 201 Mt/year (12.3 t/metal-t) of annual ore-TMR (ore-TMR coefficient) during this period since it was a net importer of the resource primarily from Australia. In 2070, the Chinese annual ore-TMR (ore-TMR coefficient) was estimated at 554.2 Mt/year (11.8 t/metal-t), while the global annual ore TMR was 46 433 Mt/year (20.04 t/metal-t) during the same period.

### Nickel

The global used and unused Ni extractions for 1990 and 2013 as estimated by Nakajima et al. (2019) were 195 Tg (195 Mt) and 600 Tg (600 Mt), respectively. Halada et al. (2001) measured the global annual ore-TMR (ore-TMR) at 246 ore-TMR/year (200 t/metal-t) for Ni. Our estimates indicated that the annual ore-TMR coefficient for China was 197 Mt/year (377 t/metal-t), whereas it was 205 Mt/year (169 t/metal-t) and 276 Mt/year (139 t/metal-t) for Canada and Zimbabwe, respectively, in 2000. These estimates were consistent with those of Halada et al. (2001) and Nakajima et al. (2019).

### Lead-Zinc

The global annual ore-TMR of Pb estimated by Halada et al. (2001) was 283.1 Mt/year (95 t/metal-t) in 2000, whereas we recorded the annual ore-TMR at 90 Mt/year (58.6 t/metal-t) for Latin America and 9 Mt/year (20.8 t/metal-t) for North America in 2000. Moreover, countrywise estimates indicated that the annual ore-TMR of China, Mexico, and Peru were 2 Mt/year (35.6 t/metal-t), 7 Mt/year (154 t/metal-t), and 23 Mt/year (154 t/metal-t), respectively. The future annual Pb ore-TMR in 2070 was 3634 Mt/year (767 t/metal-t). Halada et al. (2001) estimated the annual ore-TMR for Zn at 344 Mt/year (43.0 t/metal-t) in 2000, while we estimated 101 Mt/year (27.1 t/metal-t) in 2000 and predicted 1189 Mt/year (114.4 t/metal-t) in 2070. Further, the future annual ore-TMR for 2100 for Europe, Namibia, and India were predicted as 318 Mt/year (142.6 t/metal-t), 127 Mt/year (1 429.6 t/metal-t), and 794 Mt/year (233.5 t/metal-t), respectively.

The trends of Cu, Pb, and Zn according to the regions and the selected countries indicated a marginal exponential increase. However, Europe displayed a rapid exponential increase in the ore-TMR for Cu and Pb over time because of low grades and high strip ratios within the mature region, thus, causing a rapid increase in the annual ore-TMR over time. In addition, the strong association between these three metals resulted in a similar pattern of physical flow (co-movement).

Fe ore is a bulk commodity and is the 4th most abundant element in the Earth’s crust. On comparing the metals based on the order of magnitude, the ore-TMR coefficient did not change significantly. Over time, the annual ore-TMR is expected to remain constant for many Fe-producing countries despite movement of large Fe ore quantities from their in-situ localities. The demand for Ni material requirements will steadily increase in the future due to the increased consumption of electric vehicle batteries and utilization of renewable energy. In Cu bearing and platinum-group element (PGE)-bearing deposits, which are recovered as secondary by-products, the physical decline in the ore grade and the availability of these metals will increase their scarcity, and thereby importance of Ni.

The Au production capacity is less than 20 000 tons per annum. However, its annual ore-TMR is exponentially increasing worldwide because Au is not driven by physical factors but by economic factors, especially in the jewellery and monetary banking sectors. In addition, Au is found in auriferous porphyry, skarn, and vein deposits, which require heavy removal of gangue to access the ore. The impact of Au on the environment negatively deteriorates the mine sites, especially through informal mining, such as artisanal mining, thus, necessitating the requirement for sustainable practices.

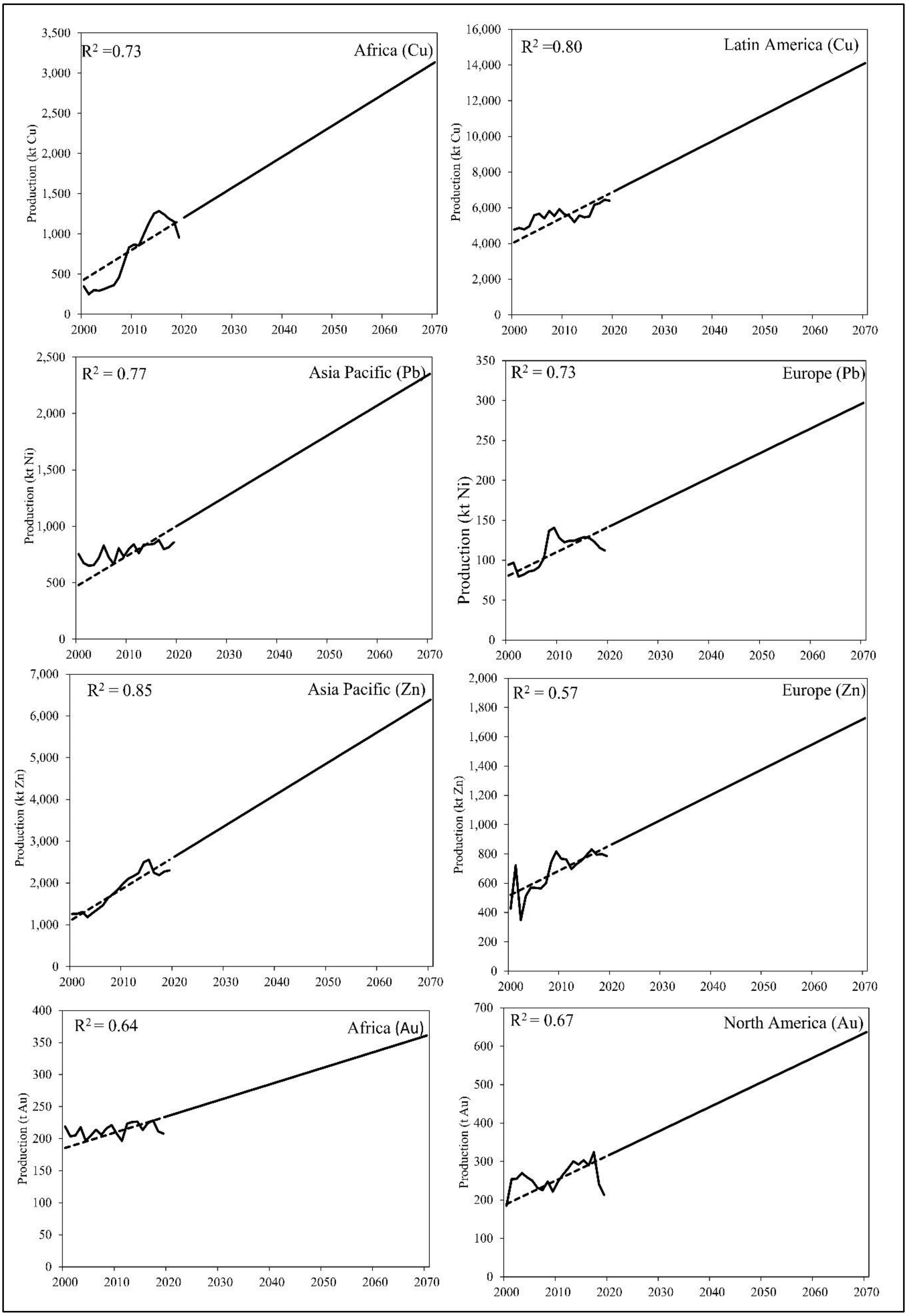

Figure 3-4 Metal production trends by region

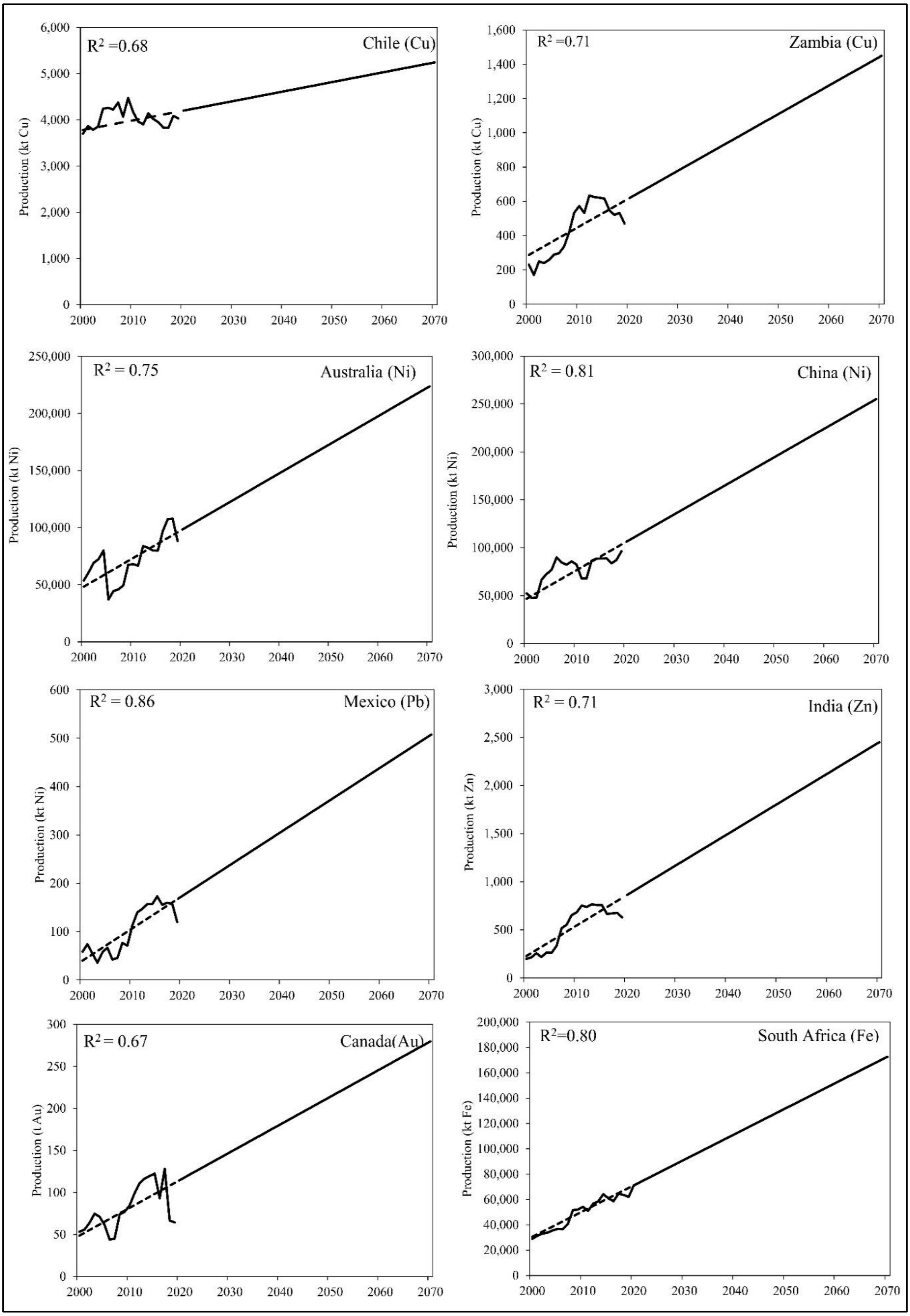

Figure 3-5 Metal production trends by country

Toxicity can influence supply of Pb which is used commonly in vehicle batteries has partially been replaced by new battery technologies e.g., cobalt-lithium batteries (Nassar et al., 2015). Over the past decade, lead production has been substantially decreasing as a measure to combat the environmental pollution caused by the metal. The decline in production could reduce the acceleration towards the impact on the environment. The adverse impact is that in as much as lead production is constrained, the resource stakeholders may ultimately require improved R&D to create a balance when mining lead-zinc deposits for zinc or find better alternatives to managing the toxicity of lead and its storage.

The rate of acceleration of the ore-TMR will continue to increase in the future. However, it will increase rapidly for some metals than others. In this study, we observed that Fe ore exhibits the least environmental impact, with the lowest ore-TMR coefficient trends. Base metals, including Cu, Ni, Pb, and Zn, exhibited a similar trend in the trajectory patterns of the ore-TMR since these metals are co-products that are recovered simultaneously. Au exhibited the highest ore-TMR, thus, demonstrating the highest impact on environmental vulnerability.

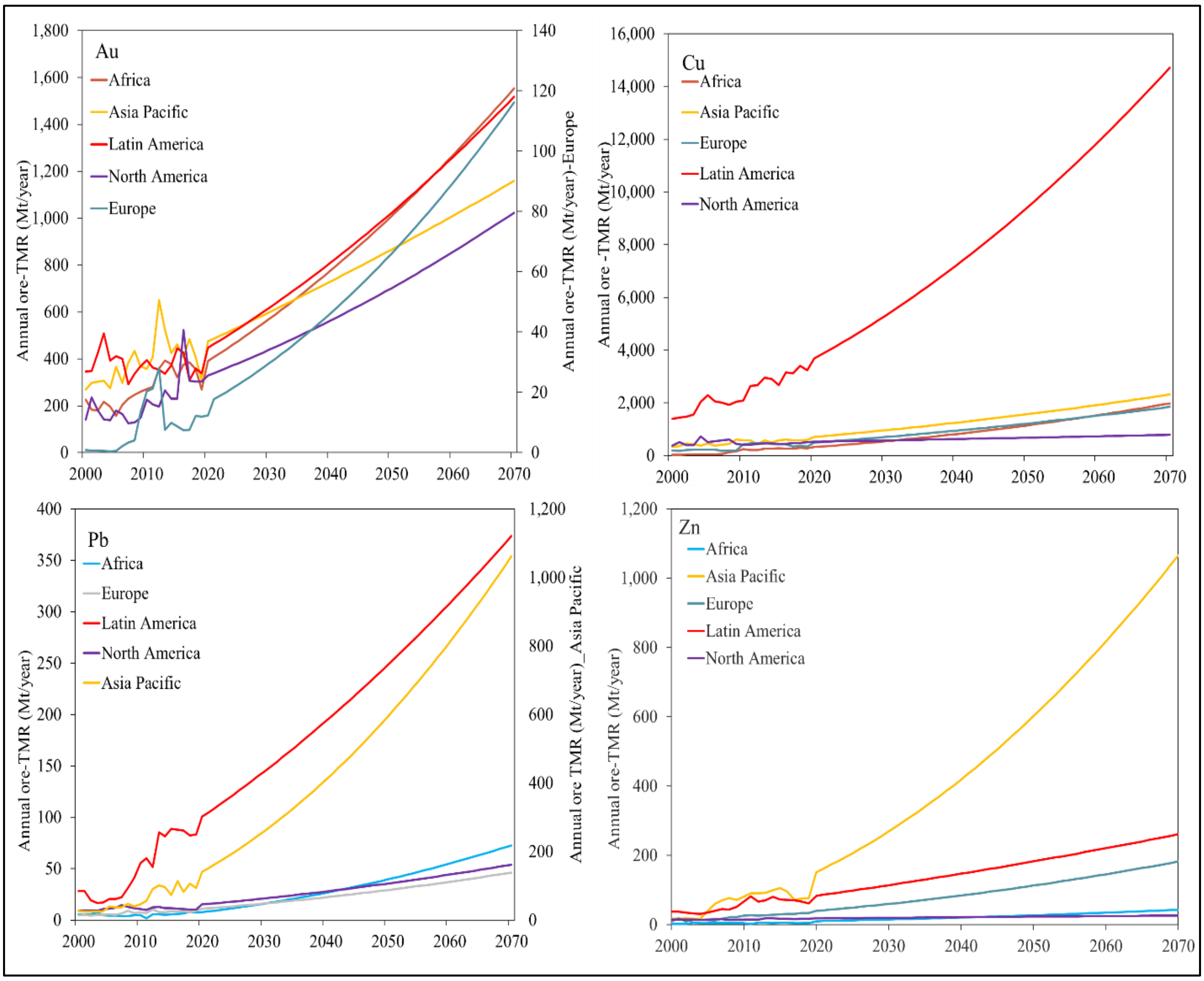

Figure 3-6 Future trends of annual ore-TMR by region

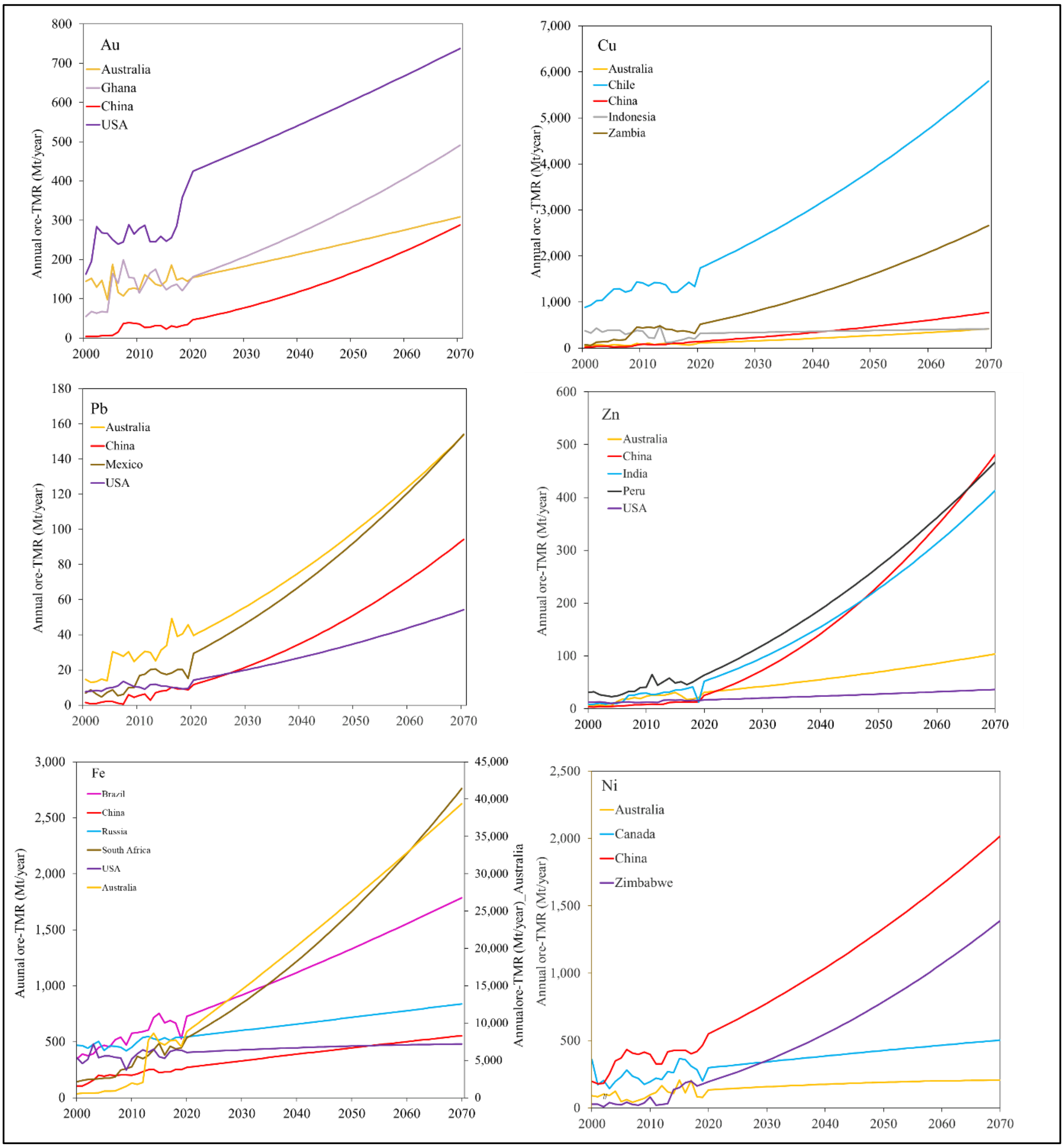

Figure 3-7 Future trends of annual ore-TMR by country

## 3.5 Summary

The system dynamics model was able to present a supply focused model by material flow analysis that provided unique insights on the future direction to meeting metal demand given the recent attention on the concept of urban mining or metal recycling for resource conservation. The study examined the ultimate recoverable reserves of Cu, Au, Fe, Ni, Pb, and Zn at the regional and national levels, and assessed the future changes in ore grade in 2070. The existing literature discussed the availability issue of these resources and the static environmental impact of their extractions, and we proposed to investigate the TMR trajectory of these metals since resources attained their limit of resource recoverability. The results showed that the ore grade steadily decreased with the increase in the cumulative production. A declining trend was observed for Cu, Au, Ni, Pb, and Zn. A marginal change in decline of the Fe ore grade was observed because it generally exhibits a "homogeneous" ore body with marginal changes in its ore quality. However, information on the ore grade data for non-operating mines or projects is not readily available or completely absent (Calvo et al. 2016). Provision of this vital information could assist in approximating the potential degree of impact of mining activities through TMR estimation forecasts on the environment. In addition, the general rule of thumb in metal mining is depleting high-grade ores prior to assigning operation of low-grade ores along the physical material flow that allows the mining company to recover its costs and maximize profits. Other production factors, including technical, social, economic, governmental, and technological also play a fundamental role to this "rule" and should thus, be considered. West (2011) asserts that when the demand continues to increase, average grades are expected to decrease regardless of whether high grades resources are depleted. While resources may maintain an average ore grade, it is quite likely that economics and technological improvement will continue to lead to a further decline in ore grades over time, as observed in our study and various studies before (Crowson, 2012; Mudd and Weng, 2012; Mudd et al., 2013; Northey et al., 2014; Wellmer and Scholz 2017).

The critical issue for primary production in the medium and long term for Au, Cu, Fe, Ni, Pb and Zn will not be the physical scarcity and their corresponding ore quality (ore grade) in most regions. Rather, the economic and environmental issues relating to environmental degradation play a greater role in metal production restrictions (Nasscar et al., 2015). Norgate and Haque (2010) state that the environmental impacts caused by primary production will generally increase along with the associated production costs. The down scale production of lead over the years due policy measures placed against the mineral to its toxicity towards human health will constrain the future its future availability of the resource.

The probability towards environmental vulnerability caused by these metals will continue to rise. Their rates of impact on the environmental will vary. Gold is expected to cause the largest damage to the environment as its global ore-TMR coefficient rises from 931 542 t/metal-t to 2 601 061 t/metal-t over the study period. The TMR patterns for base metals Cu, Ni, Pb and Zn simultaneously evolve based on their similar physical attributes. However, in 2070 the Cu annual ore TMR (ore-TMR coefficient) rose significantly to 40 430Mt/year (2 462 t/metal-t). This is indicative of current production rates that would likely cause environmental damage and as such, resource stakeholders should take action towards “the time value of production” by engaging in new alternative solutions that enhance sustainable sourcing and consumption of copper. Similarly, the global iron industry would suffer these consequential trends as copper should the annual ore-TMR (ore-TMR coefficient) rise significantly from 3 148 Mt/year (6.6 t/metal-t) to 45 213 Mt/year (20.04 t/metal-t) our result display.

Global resource demands have historically proven that metal mining is a critical source for satisfying the metal requirements in infrastructure, medicine, information technology, and other services that can boost economic development. Furthermore, metal exploration is not flexible to immediate production. Resource transformation from the early exploratory stages to production requires time, thus, reducing the actual availability rate of materials for consumption. As ore grades continue to decline, metal recycling and urban ore mining will be necessary to complement archaic mining to assure supplementation of current and future increasing global demand and consumption. In addition, comprehensive studies regarding material scarcity or availability and their environmental impact through exploration, research and development, and technological improvement are necessary for tracking (Bringezu et al., 2004; Nakajima et al., 2019; Watari et al., 2019) and accountability of material flow to improve resource management and adapt to global sustainability towards mining principles and practices for the present and future generations.

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# CHAPTER 4

# DYNAMIC MODELLING OF LONG TERM SUPPLY FOR COPPER, GOLD AND IRON

## 4.1 Introduction

The long term material supply availability consideration focuses on the bias distribution of supply prospects. The physical constraints linked to resources which are finite are an escalating factor to the supply risk. To measure the resource availability, we estimate the supply and demand for copper, gold, and iron ore. Further, the supply of mineral resources to drive economic progress and infrastructural development have adverse negative environmental impacts which need to be addressed to adhere to sustainable production and consumption. The case herewith presents the framework of material availability according to the concern of the environment.

Material decoupling results from a decline in resource use or pressure on the environment while the economic activity continues to grow (absolute decoupling) or grows slower than the activity causing it (relative decoupling) (IRP, 2011, 2019). According to the International Resource Panel (IRP), global material extraction has risen rapidly reaching 92 Gt in 2017 compared to 27 Gt in 1970 (IRP, 2019). The drivers of resource use are primarily the increasing demand for new infrastructure, energy intensive stages of production and other applications driving towards a greener efficient society. The IRP model outlines two scenarios: the Towards Sustainability scenario and Resource Efficiency scenario. Under these scenarios, a 25% and 17% respectively, result in slower growth patterns of global resource extraction compared to historical trends. As such, by 2060, the global resource extraction grows to 190 Gt under historical trends compared to 143 Gt and 158 Gt under the Towards Sustainability and Resource Efficiency scenarios, respectively (IRP, 2019).

According to the International Energy Agency (IEA), energy has been central to the economic development; and global energy use, the gross domestic product (GDP) and population have all risen sharply since the beginning of the 19th century (IEA, 2020). In as much, the global energy use is slowly regressing as the countries become more developed and wealthier. The pace of energy use reflects to be decelerating at a faster rate in advanced countries compared to emerging countries. Over the period 2000-2019, for every one percentage rise in global GDP, energy demand increased around 0.6%. In other words, the energy intensity-energy consumption per unit GDP has been declining steadily (IEA, 2020). Between 2019- 2070, the world primary energy demand increases modestly as the population and economies rise. In addition, the electricity share accounts to one fifth of the final energy consumption. This share is expected to increase from the current 20% to 24% by 2040 should countries remain on the Stated Policies scenario (STEPs) course outlined by the IEA (IEA, 2017; IEA, 2020). While the share of electricity in the final consumption is less than half that of oil today, in 2040 it overtakes oil in the Sustainable Development scenario (SDS) (IEA, 2017).

Buildings account for 38% of the total final energy consumption. The rate of growth in this sector is expected to grow at an average growth rate of 1.3% per year (IEA, 2008). Likewise, the transport sector is expected to grow at a rate of about 4% in 2015 driven by the renewable energy sector (IRENA, 2018). Ciacci et al. (2015) assigns the market share for iron ore by application are construction-48%, machinery-31%, transportation-13%, others-8%. For copper, the market share percentages for electrical, industrial, transportation and others are 26%, 19%, 13% and 42% respectively. For gold the market shares are jewelry-62%, investment- 23%, dental-2%, electronics and others-13% (Ciacci et al., 2015; GMFS, 2010, 2019).

In measuring the recyclability of metals from end use consumption (construction, jewellery, transport, investment, etc.), the system assigns a product lifetime on the basis that the metal product would potentially be recyclable with a ratio of that material having an end of life loss into the landfills. In our study, the recyclability of the products is calculated on the Weibull probability distribution function (Spatari et al., 2005; Murakami et al., 2010).

The growing concern regarding material extraction, consumption and their impact on the environment has potential to provide recommendation towards conservation and management of the environment (van der Voet et al., 2002). A common methodology to quantify the resource flows and their probability implications to the environment is the materials flow analysis (MFA). MFA is capable to quantify the material inflows and outflows within the societal boundaries. However, most MFA systems shortfall in addressing the hidden flows that occur within the systems boundaries. Mining activities have been identified as common culprits to deforming the landscape of a habitat through mine waste rock, mine liquids, and soil overburden (Prior et al., 2007; Guirco et al., 2010; Mudd, 2010; Mudd et al., 2012). The research on these hidden flows is very limited despite the strong correlation with the environmental burden (Halada et al., 2001; Halada, 2012; Kosai and Yamasue, 2019). By virtue, it is important to recognize that hidden flows negatively affect the habitat in which mining activity occurs, and therefore an objective to investigate the quantities of material flows including hidden flows.

Thus, in our study, we address this issue by quantifying the environment through the Total Material Requirement (TMR) indicator that provides environmental tracing and accountability during mining and recycling production. The TMR accounts for these hidden flows by considering the production volume, metal ore grade and strip ratio. This indicator was developed by the Wuppertal Institute to evaluate the total material flow by volume caused by economic activities such as mining, which includes direct and indirect flows including hidden flows (Brigenzu, 1993; Wuppertal Institute, 2011). Even though TMR does not directly indicate the environmental impact caused by these economic activities, it does however act to provide a preface of the potential impact from the total material volume induced during anthropogenic activities like mining (Bringezu, 2003; Kosai and Yamasue, 2019; Watari et al., 2019). Examples of the TMR concept on the scale of resource efficiencies for an economy include (Bringezu et al., 2004; Bringezu and Schültz, 2001; Moriguchi and Hashimoto, 2010), or the recyclability of products (Yamasue et al., 2009a, 2009b; Yamasue 2013a, 2013b; Kosai and Yamasue, 2019) or decarbonization scenarios using energy technologies (Nakajima et al., 2019; Watari et al., 2019). However, there have not been many studies in trying to quantify the resource flows including hidden flows under long term supply scenarios. Most studies quantify the long term trends of resource flows excluding hidden flows (Van Vuuren et al., 1999; Adachi et al., 2001; Ayres et al., 2003; Tokimatsu et al., 2004; Glöser et al., 2013; Northey et al., 2014; Sverdrup et al., 2019) and fail to effectively quantify the environment. A comparative analysis of the TMR indicator during these stages of metal production is thus carried out.

## 4.2 Theory and Methodology

Several earlier attempts have been used to model metal production trends involving system dynamics. Adachi et al. (2001) developed a long-term global copper supply and demand model using system dynamics to allocate 12 regions as copper primary producers and the final demand was measured with respect to recycling and metal substitution. This study had strong assumptions based on geological constraints in their analysis, where the results indicated that a strong promotion in recycling is required to satisfy the copper demand. In the base case simulation, primary copper production and secondary copper production increase to about 16 Mt and 5 Mt in 2070, respectively. The production share of Chile’s resources grows by 80%

over the study period. Van Vuuren et al. (2009) outlined the principles for global metal cycles, in the case of copper, by application of system dynamics to simulate mineral consumption up to 2100 considering ore-grade decline, capital, energy requirements and waste flows in their modelling. Mineral resources were characterized as abundant or scarce. The production cost is expressed as a function of the energy consumption to investigate the sustainability concern of metal resource use. Ayers et al. (2003) applied time series supply and demand of copper lifecycle up to 2100 at a global level and for United States. Their model involved material balancing in the IPCC-SRES-B" (IPCC, 2000) in order to conduct simulations focused on a growing demand and functional and non-functional recycling levels to estimate the existing stocks. In 2010, their demand scenarios ranged from 16.9Mt/year to 19.1Mt/year, and in 2050 from 42.4 Mt/year to 55.1 Mt/year. To meet these scenarios, would require approximately 3 000 Mt Cu compared to 1, 344 Mt Cu URR estimated in our study (Table 3-3). Kapur (2005) modelled four economic regions under economic growth and technological change scenarios with low population, that partially adopted the IPCC-SRES (IPCC, 2000). The intensity of use was measured for each scenario with the copper consumption ranges from 52 Mt/year to 107 Mt/year in 2050 and 33 Mt/year to 133Mt/year in 2100. However, the study shortfalls to elaborate how this demand might be met. Northey et al. (2014) explains that assuming ~50% of the demand in 2100 was met through recycling, then the range of mined copper would be of a similar magnitude to Ayres et al. (2003)'s scenarios. The peak in mine production in Ayres et al. (2003) and the overall copper consumption after Kapur (2005) can be depressed by the dematerialization of economies in the overall per capita GDP due to the intensity of use relationships indicating an increase in the overall scrap flows growing from the in-use stocks over time as secondary copper production rise significantly to offset the demand.

Northey et al. (2014) use the concept of 'peak mineral' by using a geological model to measure future metal mining supply trend by considering the following aspects: ore grade, ultimate recoverable resources (URR), and other constraints either economic or technological. Northey et al. (2014) measured the resource estimate as 1 780.9 Mt Cu. The URR, which is the limit of physical availability of economic resources defined as the total amount of metal recovered throughout its extraction history and potential economic extraction of an ore deposit, Glöser et al. (2013a, 2013b) applied a mass flow analysis that underestimated the resource URR. Laherrere (2010) used the Hubbert model for nonferrous metal analysis but underestimated the resource estimate. This underestimation caused the model to define peak reserves with a smaller lifetime. Tokimatsu et al. (2017) developed a sustainability model for supply of copper, lead and zinc that quantified demand and supply including scrap supply by examining the lifecycle of these metals at a global scale. In their study, the copper mine production peaks in 2040 followed by a decline, whereas the old scrap copper increases rapidly thereafter to compensate for the decreasing primary supply. The global average recovery rate of used products increases rapidly to reach 90% between 2040 and 2090.

Iron material flow analysis have also been conducted at a global level and applied a 70% end-of-life recycling rate based on the historical trends (Neelis and Patel, 2006; Oda et al., 2013). Neelis and Patel (2006) project the crude steel demand for 26 TIMER regions using the intensity of use approach where they estimate 0.65% per year of future material efficiency. The global consumption grows in 2004 is estimated at 1 058 Mt which peaks between 2050 and 2100. Neelis and Patel (2006) further suggest that the global share of secondary inputs to steel production is expected to increase from 40% to 60% to 2100. Oda et al. (2013) explores future steel scrap availability up to 2050. The total summation of iron in the direct reduced iron production (DRI) and electric arc furnace (EAF) is 332 Mt/year in 2000. It grows from 513 Mt/year to 518 Mt/year in 2000 to a range of 1 150 Mt/year to 1 321 Mt/year in 2070 depending on the scenario. Oda et al. (2013) assessment indicate that the future availability of scrap has a growing importance to the total scrap to alleviate the future primary steel which are dependent on the end-of -life recycling rate, discarded steel and the in-use stock. The stock and flow patterns of iron have accessed future long term emission reduction of carbon dioxide by increasing secondary steel production (Müller et al., 2011; Cullen et al., 2012). The iron stocks (reserves) are estimated at 79 Gt (global), 16 Gt (Brazil), Australia (9 Gt) and China (7 Gt) (Müller et al., 2011). Cullen et al. (2012) mentions that the global steel demand is about 1.4 Gt/year and is set to double by 2050. Cullen et al. (2012) estimate 1 001.5 Mt of global iron ore injected for steel production. The total scrap recovery yield was 568.6 Mt of recyclable material with 5.7 Mt scrap discarded into the landfill as non-recyclable steel. Tokimatsu et al. (2019) estimated the global apparent consumption level of 1.7Pg in 2010 increasing by a 2.1 factor more than in 1995. Between 1990 and 2013, the global distribution of used and unused extraction amounts increased from 2 754 Tg to 6 684 Tg with an increasing rate of 143% (Tokimatsu et al., 2019).

The constraint for analysing gold is the limited literature available for model comparison. However, according to the USGS, global gold reserve estimate is 50 000t in 2019. The global mine production increases from 2 445t in 2000 to 3 300t in 2019 (USGS, 2001, 2000). Laherrère (2009) apply Hubbert’s model to estimate the peak gold; world cumulative gold production is expected to reach 250 kt. Gold, as a “cash cow” commodity, is largely accounted by the jewellery and, investment and banks sectors (World Gold Council, 2021). Due its high commodity price, gold can still be mined at the current low grades. However, the recycling efficiency of gold which has a EOL recycling rate of about 90% allows the metal to be available in the gold market and to sustainably consume it (UNEP, 2011; World Gold Council, 2021). Future gold will largely be dependent on the recycling processes.

The physical constraint in metal supply problem appears to draw attention as the metal production growth rises to satisfy an increasing metal consumption demanded by sectorial consumers. With the diminishing metal ore grade quality accelerating simultaneously with production, resource stakeholders are prudent of the rising physical scarcity by geographical location and accessibility. The purpose of undertaking long term models on future conditions of copper, gold and iron ore is to access their future quantities at recoverable economic conditions. Simultaneously with recycling production, recyclates excluding the end-of-life metal waste flow in the supply stock market for stockpile as supply inflow to balance quantities the total supply system. In addition, the consumption forecast is a substantial input to optimize and build a representative model of resource availability with the aspect of impact on the environment at the fore front. The metal flow assumed in the model is presented in Figure 4-1 (Appendix 4-1) to quantify the simulation model required to answer the objectives of this study through identification of variable linkages to comprehend the justification of the study. Wherein the primary metal resource exists and flows in existence within the system boundaries of the model assumed either, directly, indirectly or hidden within its environment.

In this chapter, the methodological approach of production and consumption of copper, gold and iron ore are mentioned. The framework on the impact on the environment is also applied. Lastly, the results of these metals are independently discussed followed by a comparative summary at the end of the chapter. Table 4-1 displays the parameters and variables applied in the model.

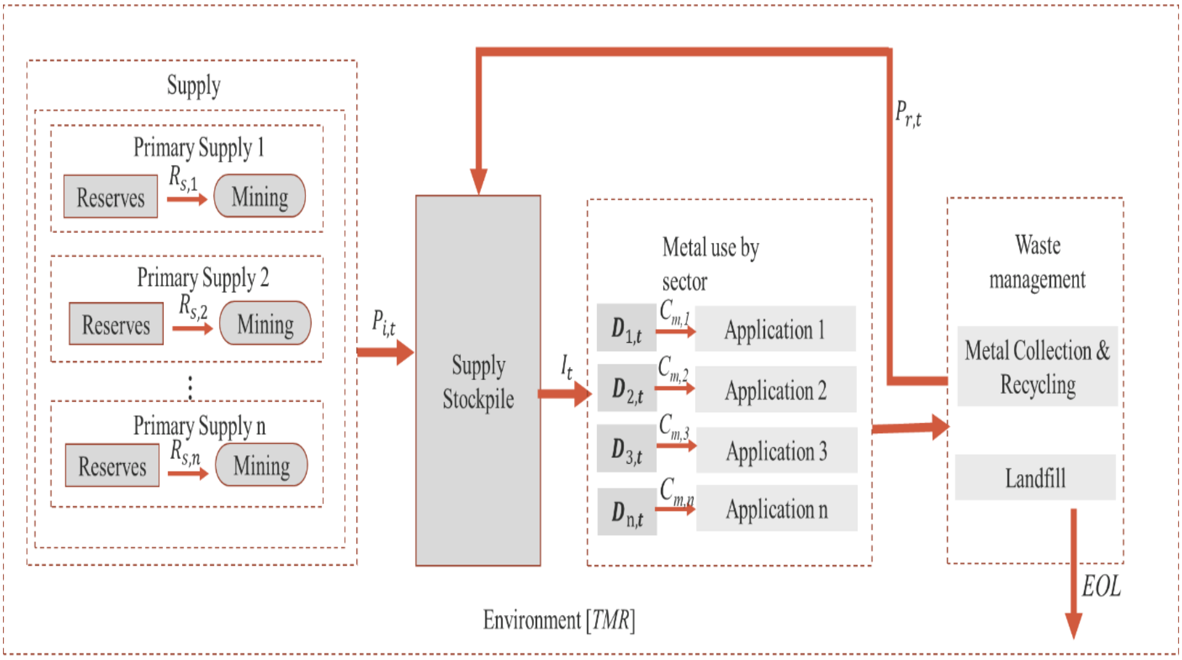

Figure 4-1 Simplified metal flow

### 4.2.1 Model Assumptions and Stability

Assumptions placed on to the modelling are necessary to pragmatically present the system dynamics approach within the model boundary. The general model assumptions are:

- Economic, technical and social factors are ignored. This is because the scope of the study aims to address the foundational framework of environmental modelling and sustainability through the physical material flow of mineral resources. As such, physical flows are exogenous and unaffected by these factors.
- Primary metal supply is dependent on the production rate, technology and exploration rates leading to discovery that have an influence on the proven resources to likely to be extracted over time and processed during metal mine production. Mine production is constrained by the resource quantity on earth at recoverable and economic rates.
- The recycling rate and recycling efficiency rate are the driving forces of secondary recycling production. The amount of recycling material recovered during scrap recovery at the disposal plant can never exceed the quantity of primary metals available.
- Metal consumption is endogenous to the metal demand which adjusts to the consumption rate. It depends on the feedstock inflow from the total metal supply inclusive of primary and secondary supply. The metal consumption can never exceed the total supply available in the metal stockpile.
- The metal product lifetime in each sector is assumed to match the current average.

Instability is a major concern with regards to implications to the environment and mineral sustainability. To stabilize the resource model, the model relies on feedback loop mechanisms to visualise the long term effects of the various material flows, both used and unused, propagating within the system's supply and demand environment. An unstable model would create and overflow or underflow at any point of the analysis as these resources are dependent on the 'Law of Mass Conservation'. As exogenous events occur within the resource model, their impact on the system is predicted using simulation with analysis made based on the stable model.

Table 4-1 Parameters and variables of model

| **Symbol** | **Brief Definition** | **Unit** |
|---|---|---|
| $\boldsymbol{URR_i}$ | Ultimate recoverable metal resources in location *i* | Metric ton |
| $\boldsymbol{R_s}$ | Proven reserves | Metric ton |
| $\boldsymbol{P_{i,t}}$ | Metal mining production per year *t* | Metric ton |
| $\boldsymbol{P_{r,t}}$ | Metal recycling production per year *t* | Metric ton |
| $\boldsymbol{Q_{m,t}}$ | Cumulative production at year *t* in location type *i* of metal *m* | Metric ton |
| $\boldsymbol{I_t}$ | Stock outflow per year *t* | Metric ton |
| $\boldsymbol{D_t}$ | Metal demand per year *t* | Metric ton |
| $\boldsymbol{D_{u,t}}$ | Metal demand for usage sector u.<br>If u=u-C, for Construction<br>If u=u-T, for Transport<br>If u=u-E, for Electronics<br>If u=u-O, Other sectors<br>Where n is an additional sector | Metric ton |
| $\boldsymbol{E_i}$ | Exploration in location *i* | % |
| $\boldsymbol{T_i}$ | Technology in location *i* | % |
| $\boldsymbol{p.d.f.}(\boldsymbol{\lambda})$ | Probability distribution of metal lifetime | |
| $\boldsymbol{\beta}$ | Maximum Lifetime of a metal product | Year |
| $\boldsymbol{y_m}$ | Electricity consumption per year *t* of metal *m* | GWh |
| $\boldsymbol{C_m}$ | Metal Consumption of metal *m* | Metric ton |
| $\boldsymbol{MS_m}$ | Market share of metal *m* by usage | % |
| $\boldsymbol{EOL\text{-}RR}$ | End-of-life recycling rate | % |
| $\boldsymbol{RE_m}$ | Metal recycling efficiency rate of metal *m* | % |

### 4.2.2 Mining Supply Modelling

#### Primary Supply

The metal primary production of Au, Cu, and Fe are simulated based on the system dynamics model computed on STELLA software by defining equations. The URR is estimated by authors (refer to Chapter 3), production is estimated from (S&P Global database, 2021; World Steel, 2000-2020) between 1991-2019 for copper and 2000-2019 for gold and iron are collected. The forecast period is over the long term period from 2020 to 2070.

The total extraction of metal mining at a given location (*i*), either global, regional or country, is the cumulative production volume of that locality in the current term (*t*) minus the previous term (*t-1*). Regional localities are divided into 5 locations: Africa, Asia Pacific, Europe, Latin America and North America. At country level, selected countries are analysed depending on the producing country of that metal.

$$Total\ Extraction_{m,i,t}=Total\ Extraction_{m,i,\ t\text{-}1}+\sum_{i=1}^{t=n} Supply_{m,i,\ t} \tag{4-1}$$

This extraction rate is affected by the growth rate of resources. An extraction factor has a multiplier effect on the extraction. A 0.9 extraction factor is applied to all mine sites (AusIMM, 2012).

Proven reserve ($R_s$) tonnage is determined by the difference between newly discovered reserves at a given time *t* of a producer location and previously discovered. These reserves are affected by the changing discovery rate (*DR*) over time.

$$R_{s,\ m,i,t}=R_{s,\ m,i,\ t\text{-}1}+\sum_{i=1}^{t=n}(DR_{m,i,\ t}-S_{m,i,\ t}) \tag{4-2}$$

*S* is the total metal supply. The discovery rate is inversely proportional to the remaining fraction. Technically, the quantity of proven reserves is equivalent to the cumulative production. However, unproven and undiscovered resources can essentially be converted to identified and proven reserves at any time and change the size of these reserves and ultimately be mined economically in future even at lower grades. In this model, the limit of ore grade modelling is assumed at a cut off grade of 0.2% Au, 0.2% Cu, and 20% Fe which is a determining factor in limiting future available resources. Lower ore grades than these pre-determined cut off grades are assumed that they could not be economically mined in future.

The ultimate reserves which essentially includes both cumulative production and proven resources is defined. However, to extract only economically, extractable and recoverable resources, ultimate reserves (*URR*) are defined by the cumulative production in metal ore mining along the production history and at a given economical cut off grade. These resources are defined by exploration (*E*) and technology (*T*) changes that occur during the lifetime of mining in a given location.

$$URR_{m,i,t} = URR_{m,i,\,t-1} + \sum_{i=1}^{t=n} (E_{m,i,\,t} + T_{m,i,\,t}) \tag{4-3}$$

The percentage change in exploration is represented as a function of time *t*. The rate of change in exploration is determined by the remaining fraction of reserves exploited with time. A constant 10% exploration factor is applied due to the difficulty in adjusting this factor.

$$Exploration\ Rate_{m,i,t} = 0.9\ (Exploration\ Rate_{m,i,\,t-1} * Remaining\ Fraction_{m,i,\,t-1}) \tag{4-4}$$

The technology rate changes by 0.8% annually (van Vuuren et al., 1999; Adachi et al., 2001). It accounts for all mining, smelting and recycling progress that occur over time. In our study, we apply this rate for all metal models. Even though this rate should be adjusted as a function of time, we keep it constant due its inelasticity and inertia to be changed. We calculate the technological rate as

$$T_{m,i,t} = e^{-rt} \tag{4-5}$$

The changing resource by production ratio (RbyP) which describes the lifetime of commodity *m* in a location *i* is obtained by the division of proven reserves by the annual production therefore delineating the resource potential over time *t*. The lifetimes of primary producing metal areas are shown in Table 3-2 of Chapter 3.

The remaining resources reduces over the production lifetime of the mine as the ore deposit reserves are depleted. It refers to the ultimate recoverable resources minus the cumulative primary mining production.

$$Remaining\ Resources_{m,i,t} = URR_{m,i,\,t-1} - Q_{m,i,\,t-1} \tag{4-6}$$

The supply capacity of the metal ore flow changes over time assuming that the smelting capacity and total mine capacity are kept constant with a carrying capacity index of 0.9 as the ore grade the capacity ore production tonnage flows into production at a given time. Production delay is also assumed as mine projects do not commence instantly due to their inherent nature. Herewith, a two-year time delay factor is applied to the model considering mine projects in the stages of development can take between 1 to 5 years to occur (AusIMM, 2012).

$$\text{Supply Capacity}_{m,i,t} = \text{Carrying Capacity Index} * \text{Capacity Metal Ore}_{m,i,\,t-1} * \text{Grade}_{m,i,\,t-1} \tag{4-7}$$

The mining supply is estimated to determine the cumulative trends of each metal. The logistic curve (Höök et al., 2012) modelled is used to forecast by regression the cumulative production to 2070, was estimated for selected countries and regions based on Equation 4-8:

$$P_{i,t} = Q_{i,t} - Q_{i,t-1}$$

Which can be rewritten as

$$P_{i,t} = \frac{dQ_i}{dt} \tag{4-8}$$

The annual growth rate of production was assumed to be constant over time; therefore, the trends of future production ($P_i$).

Secondary Supply

Metal recycling from old scrap is a function of generation from old scrap and end-of-life recycling rate (EOL-RR). The metal scrap of these resources generates scrap depending on the product lifetime from consuming sectors. We estimate this by applying the Weibull distribution, specifically the probability distribution function (p.d.f.). The Weibull statistical distribution is adopted in this study to model the metal lifetime of products generally applied to many studies related to stock and obsolete simulations (Spatari et al., 2005; Murakami et al., 2010). The justification in using the Weibull probability distribution is that it has the ability to provide a better goodness of fit than the normal distribution as it allows retiring products to enter their end of life to be disposed into the landfills. These products are the varying applications for usage such as industry, transport, construction etc. The characteristics of the Weibull (two-parameter Weibull) random variable $x$ is characterized by a scale parameter $\lambda$, shape parameter $\beta$ and location parameter $\alpha$. Table 4-2 displays the Weibull distribution parameters of copper, gold and iron ore and the market share of metal usage by sector. The market share is estimated after Ciacci et al. (2015). The scale parameter is predefined on Solver. The shape parameter $\beta$ is the metal product lifetime. The location parameter in a two-parameter function distribution is insignificant, therefore set at 0. $P_r$ in the Weibull distribution represents the secondary recycling production over time $t$ is measured by:

$$P_{r,t} = \left\{ \sum_{t=1}^{t_n} D_{t-t_n} * \left[ \frac{\beta}{\lambda} \left( \frac{\beta}{\lambda} \right)^{\beta-1} e^{-\left(\frac{x}{\lambda}\right)^{\beta}} \right] \right\} * EOL\text{-}RR \tag{4-9}$$

The period of delay $t$-$t_n$ in the metal demand creates a periodic lag in the consumption of a metal in the sector. Therefore, the recycling of either copper, gold or iron is simulated as a function of their individual metal demands ($D_t$) consumed in each sector for usage with a recycling rate as the Weibull probability distribution (pdf: $x, \lambda, \beta$). The end-of-life recycling rate (EOL-RR) measures the recycling rate as a ratio in which the metal in a discarded product is separated to obtain recyclates that is returned to the production processes to the total discarded product inclusive of retired metal (UNEP, 2011). The recycling rate is assumed constant in this study.

The annual discard flow amounts were calculated for each consuming sector for copper, gold and iron ore. The retiring period was calculated in years as waste is generated at the peak lifetime.

The retired lifetime is part of Equation 4-9 as:

$$\frac{\beta}{\lambda} \left( \frac{\beta}{\lambda} \right)^{\beta-1} e^{-\left(\frac{x}{\lambda}\right)^{\beta}}$$

Figure 4-2 displays the recycling production on the Weibull distribution for the largest consuming sector in copper, gold and iron ore markets. Table 4-2 presents the estimated values for λ and β parameters used in the Weibull distribution used to determine the recycling flows of copper, gold and iron ore by their respective metal consuming sector estimated on Minitab. Furthermore, the residence times to end of life are assumed constant during the forecast period (2020-2070).

Because the annual data of each consuming sector was estimated based on market shares to allocate a percentile for each sector over the study period, the total consumption data of a metal was collected to provide these estimates. Furthermore, the market shares remain constant throughout the lifetime of the consuming sector of the metals in this study.

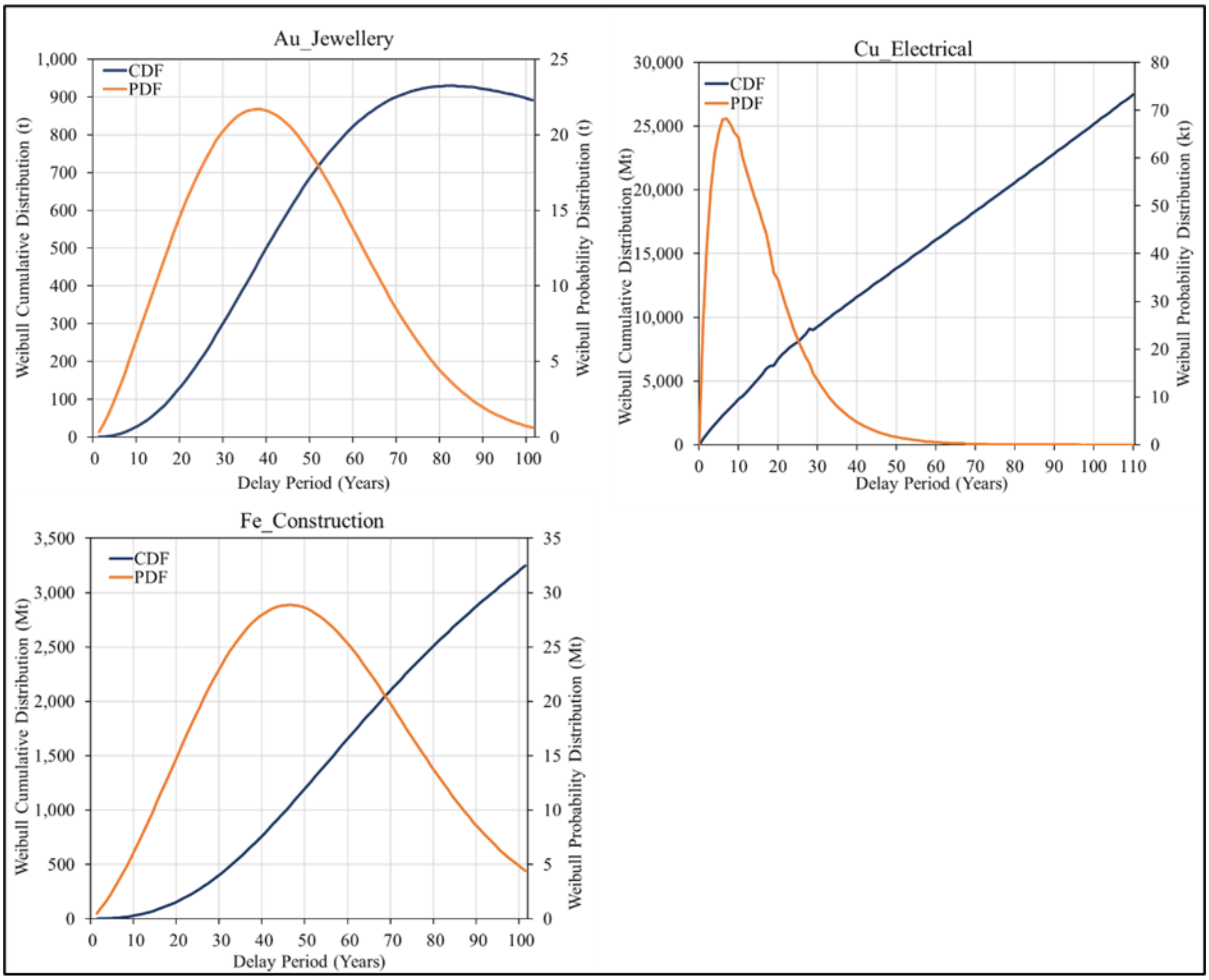

Figure 4-2 Weibull Distribution Product lifetime for copper, gold, and iron ore in selected sectors

### 4.2.3 Metal Demand

In the 1960s, economic growth was limited to a few countries that had about 20% of the world’s population, but the present rate of growth in the global population has mushroomed tremendously with the economic growth of those nations (Tilton, 2003). The current population has reacted to an explosive growth in metal consumption. In addition to this, the linkage between energy consumption and metal consumption presents a strong interrelationship (van Vuuren et al., 1999; Halada et al., 2008). Due to the large share of electricity in the final energy consumption, electricity consumption presents as a driver of metal consumption. In this section, we present the methodology of electricity consumption, metal consumption and the intensity of use in these consuming sectors of copper, gold and iron ore.

Table 4-2 Weibull Distribution Product lifetime for copper, gold, and iron ore

| | Market Share (%) | Lifetime max | Weibull Distribution Parameters | |
|---|---|---|---|---|
| | | | λ | β |
| Copper | | | | |
| Industry | 19 | 35 | 1 | 1.619 |
| Transport | 13 | 17 | 1 | 2.559 |
| Electrical | 26 | 8 | 1 | 1.598 |
| Other | 42 | 5 | 1 | 1.629 |
| Gold | | | | |
| Jewellery | 62 | 50 | 1 | 2.321 |
| Investment | 23 | 4 | 1 | 1.847 |
| Technology | 15 | 10 | 1 | 2.158 |
| Iron Ore | | | | |
| Infrastructure | 48 | 50 | 1 | 2.031 |
| Transport | 13 | 8 | 1 | 2.019 |
| Industry & Machinery | 31 | 35 | 1 | 2.031 |

Future population and GDP estimates have been assessed by many entities such as the United Nations. The global GDP will grow at an average growth rate of about 3% to at least 2050 (Adachi et al., 2001; PWC, 2013). In our study, this rate is kept constant until 2070. In addition, the global population statistic survey outline that the population growth rate will not be constant until 2070. In this path, the growth rate decelerates from 0.98% to 0.04% between 2020-2070 (UN, 2019). The predicted trends based on these growth rates of population and GDP are displayed on Figure 4-3.

The carry forward inventory is the remaining material tonnage left unused by consuming sectors from the previous year. As such the inventory is used as an adjustment to balance supply and demand of the systems model with changing time. The balanced model therefore cannot assume negative conditions. As such, to measure the demand, this carry forward inventory from the previous year is reduced from the summation of the consuming sectors ($C_{m,u,t}$) at the market share ($MS$).

$$World\ Demand_{m,i,t} = \sum_{i=1}^{t=n} \Big( Consuming\ Sectors_{u,m,i,\ t} - Carry\ Forward\ Inventory_{m,i,\ t} \Big) \tag{4-10}$$

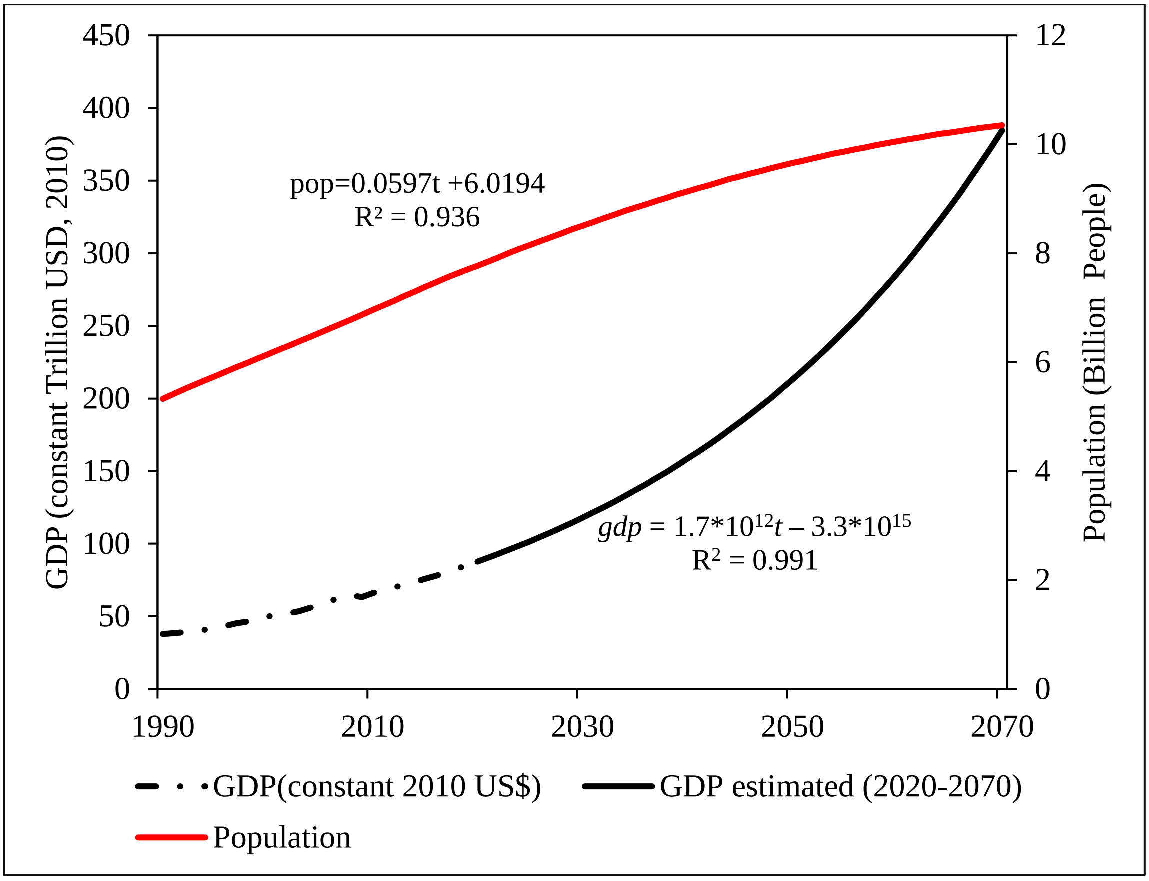

Figure 4-3 World GDP and Population predicted to 2070

Van Vuuren et al. (1999) expressed the metal demand as a function of the energy consumption. They outline that about 5-10% of the global primary energy is consumed by metal industries. The linkage between energy consumption and metal demand is viewed as having a positive linear relationship (Halada et al., 2008). Because of the large share of electricity consumption in the total energy demand, it is used as the basis of interrelationship with the metal consumption of the consuming sectors.

$$y_u = a_u t + c \qquad (4\text{-}11)$$

Here, $y$ shows the electricity consumption of a consuming sector $u$. The electricity consumption is measured as a function of time $t$ where $a$ and $c$ are constants.

The metal consumption of a consuming sector $u$ estimated based regression equations as a function of the electricity consumption in Equation 4-12. Herewith the metal consumption, $C_m$, expected to have a demand rate of 3 % is regressed linearly:

$$C_{m,u} = y_u t + c \qquad (4\text{-}12)$$

Then the metal consumption at the market share of a consuming sector is given by:

$$C_{m,u,MS} = y_{u,MS}t + c \quad (4\text{-}13)$$

The trend in intensity of use is given as a ratio of the metal consumption in sector $u$ by the per capita GDP in a given country or region $i$.

### 4.2.4 Historical Matching

In order to find relevance for the model, the model has been calibrated by comparative analysis of simulated results from actual historical data through historical matching for copper, historical matching ranges from 1991 to 2019 and from iron from 2000 to 2019 over mining production, secondary recycling production and consumption data. Historical matching is conducted by adjusting a set of model parameters to give the best possible outcome to stabilize the model before prediction commences. Though historical matching provides us with past trends, the objective is not to reproduce these trends but to provide a base line of assumption of future long term trends.

The mean square error (MSE) corresponds to the prediction error per square of the given sample population. Practically, a low MSE value means that the predicted values are close to the real values shown in Equation 4-14. Occasionally, the root mean square error (RMSE) is used which is the square root of the MSE (Ait-Amir et al., 2015) depicted in Equation 4-15. In other words, the RMSE is the square root of the variance of the residuals. This criterion depends on the order of magnitude of the observed values which indicates the absolute fit of the model to the data–how close the observed data points are to the model’s predicted values. Whereas R-squared is a relative measure of fit, RMSE is an absolute measure of fit. As the square root of a variance, RMSE can be interpreted as the standard deviation of the unexplained variance and has the useful property of being in the same units as the response variable (Ait-Amir et al., 2015). Lower values of RMSE indicate better fit. RMSE is a good measure of how accurately the model predicts the response, and it is the most important criterion for fit if the main purpose of the model is prediction.

$$MSE=\frac{1}{m}\sum_{i=1}^{n}\left(y_i-\bar{y}_i\right)^2 \quad (4\text{-}14)$$

$$RMSE=\sqrt{MSE} \quad (4\text{-}15)$$

R-squared has the useful property that its scale is intuitive: it ranges from zero to one, with zero indicating that the proposed model does not improve prediction over the mean model, and one indicating perfect prediction. Improvement in the regression model results in proportional increases in R-squared. The low R-squared shows that even noisy, high-variability data can have a significant trend. The trend indicates that the predictor variable still provides information about the response even though data points fall further from the regression line.

The MAE criterion is a similar measurement to the RMSE. Nevertheless, it is more robust since it is less sensitive to extreme values compared to the MSE represented in Equation 4-16. The MSE, RMSE and MAE together help quantify the accuracy of the approximated variable compared to the simulated data. The proximity of all these values to the real value assumes better accuracy to the model.

$$MAE=\frac{1}{m}\sum_{i=1}^{m}\left|y_i-\bar{y}_i\right| \tag{4-16}$$

The study conducted historical matching over the primary production, secondary consumption and consumption for the world, regional cases in all metal models on with the simulated values on Stella software. For example, Figure 4-4 and Table 4-3 presents historically matched data primary production, secondary consumption and consumption for copper, gold and iron ore at a global level are presented.

Table 4-3 R-Squared, MAE, MSE and RMSE statistics for Au, Cu and Fe world primary production, secondary consumption and consumption at global level

| | | R-Squared | MAE | MSE | RMSE |
|---|---|---|---|---|---|
| World Primary Production | Au | 0.571 | 3.068 | 1.544 | 1.243 |
| | Cu | 0.493 | 2.265 | 18.375 | 4.287 |
| | Fe | 0.251 | 1.73 | 1.06 | 1.03 |
| World Secondary Production | Au | 0.233 | 1.342 | 0.158 | 0.397 |
| | Cu | 0.276 | 0.168 | 5.778 | 2.404 |
| | Fe | 0.158 | 1.24 | 1.43 | 1.20 |
| World Consumption | Au | 0.251 | 3.23 | 0.17 | 0.413 |
| | Cu | 0.629 | 0.454 | 8.629 | 2.937 |
| | Fe | 0.564 | 0.343 | 0.127 | 0.357 |

### 4.2.5 Total Material Requirement

While the larger proportion on impact on the environment is caused by the downstream processes occurring during metal mining, the rising importance of secondary production through recycling requires further investigation on how these activities affect the environment.

Herewith, we introduce the ore-TMR of the urban ore and compare it with ore-TMR of the natural ore.

Ore-TMR in Primary Production

While the ore-TMR was investigated in the preceding Chapter 3, herewith, the ore-TMR coefficient represents a portion of the TMR. The discussion is extended by observing at how the effect of exploration, technology and production rate have an impact on the total supply and ultimately the environment.

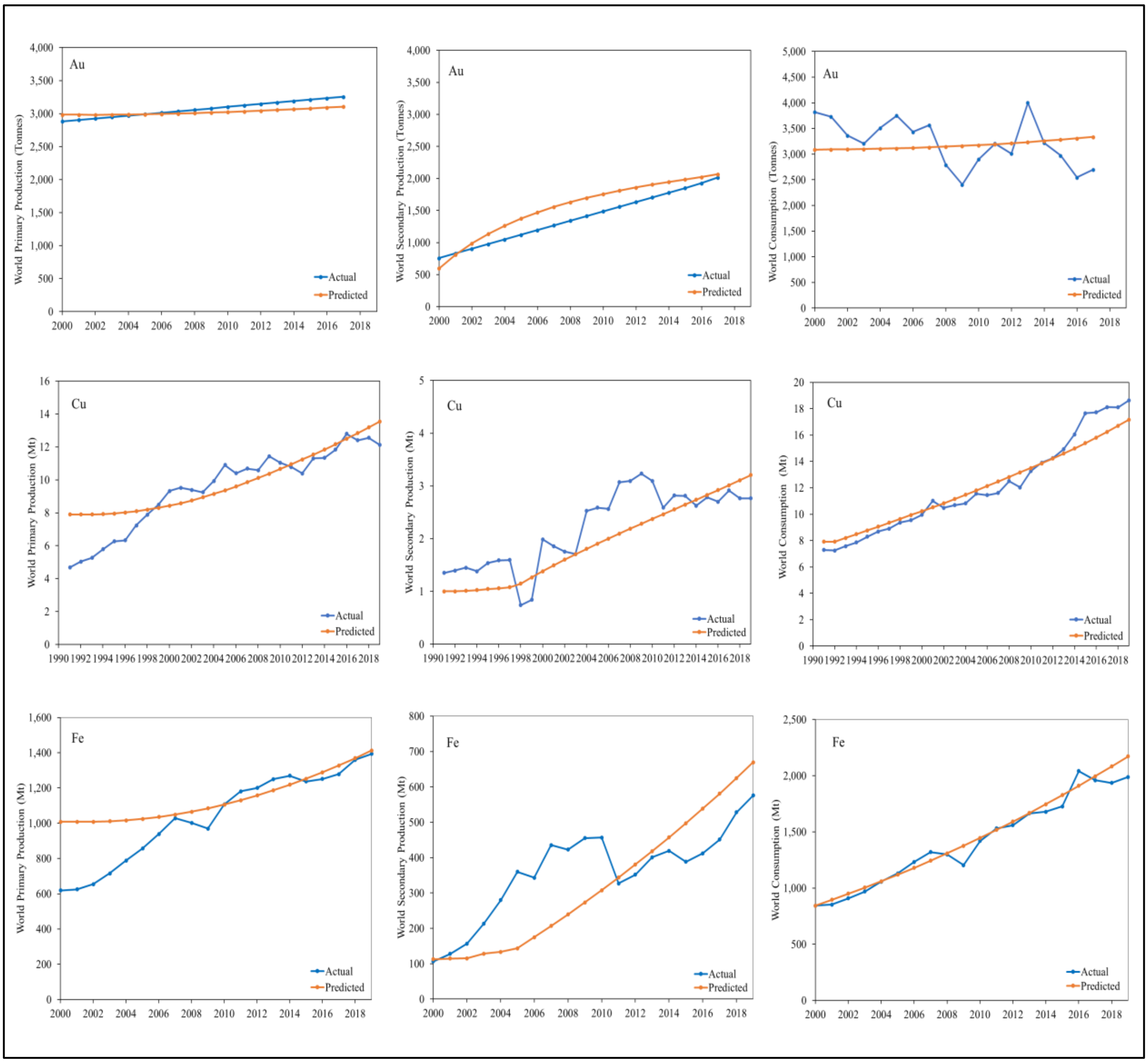

Figure 4-4 Historical matching Au, Cu and Fe world primary production, secondary consumption and consumption at global level

### Ore-TMR in Recycling Production

Even though promotion of recycling has received much attention over the past few years, understanding the impact in which recycling has on the environment remains limited. Few studies have applied the TMR approach for individual appliances and processes such as slag desulfurization and electronic and home appliances (Yamasue et al., 2009a, 2009b, 2013a). Here with, we apply the urban ore TMR approach after Yamasue et al. (2009a) and Yamasue et al. (2013a) to estimate the amount of urban ore TMR from the economic sectors of metals including, construction, transport, jewellery, investment, residential etc.

The generation precedes the commencement of waste recycling which is an input flow from end use consumption. The volume of direct, indirect and hidden flows is accounted in the modelling framework. According to Yamasue et al. (2009a) and Yamasue et al. (2013a), the natural ore-TMR (NO-TMR) and urban ore-TMR (UO-TMR) have a comparable linearity based on the logarithmic equation:

$$\log(NO - TMR) = -0.982 \log(\bar{x}) + 2 \qquad (4\text{-}17)$$

, where it is assumed that the elemental concentration in the natural ore is 100% and NO-TMR would be equal to 1 (Halada et al., 2001; Yamasue et al., 2009a). The UO-TMR is substituted for NO-TMR in Equation 4-17, and $\bar{x}$ is the reduced elemental concentration of the urban ore (elemental concentration of natural ore equivalent- ECNOE) (Yamasue et al., 2009a). A high elemental concentration indicates a higher degree of recyclability which is ultimately reduced the degree of impact to the environment.

## 4.3 Results and Discussion

Herewith, the structured simulation of the system dynamics model is utilized for copper, gold and iron. The sensitivity analysis of the model parameter values is examined on how the dependent variables are affected based on the input (independent) variables with the base simulation compared under various uncertainties. The analysis attempts to evaluate the TMR behaviour prompted by the production rate and technology in the global primary metal supply persistently growing faster than the physical availability of the resource. In addition, the effect of secondary metal production through recycling is observed which aims to delineate the sustainable resource production. The scenario analysis of TMR over the supply and demand of metals are investigated to address the following questions:

1. How does production rates affect reserves and mining production?

2. What is the effect of the recycling rate and recycling efficiency on secondary production and consumption?
3. How does TMR change over time affect metal supply?

### 4.3.1 Copper

In this section, the baseline behaviour of world copper supply and demand model is simulated under the conditions set in parameter values of Appendix 4-2. Figure 4-5 illustrates the trend behaviour of primary and secondary supply and the consumption of copper over the course of 79 years from 1991 to 2070. From this figure, historical supply marginally met the copper demand, with periodic events of excess supply. Total supply increases from 8.89 Mt in 1991 to 39.9 Mt in 2070. The primary copper production remains as the main source of copper into 2070 with production volumes of 26.8 Mt (2070) from 7.89 Mt (1991). Latin America presents as the main producer to avail copper as shown in Figure 4-6. The production volume doubles from 7.5 Mt (2020) to 16.4 Mt (2070). In as much, metal mining in the Asia Pacific region triples from 3.7 Mt (2020) to 11.1 Mt (2070) at a 1.4% growth rate. The scale of mining in the European region remains significantly small. By country, Chile continues to play a significant role in copper supply given the large Chilean scale in production with about 30% share in total supply (Figure 4-6). Further, we observe peaking in the primary production as the production rate decreases to stabilizes to around 2% from 2060.

Meanwhile, the accelerating growth rate of secondary copper production is expected to rise to surpass primary copper production in the long term should it maintain a growth rate of about 0.29% per annum beyond 2070. This trend is driven by the estimated consumption which grows from 7.9 Mt to 39.6 Mt between 1991 and 2070 at an average growth rate of 0.43% particularly electrical (E) applications followed by industrial (I), transport (T) and other (O) applications respectively. This scenario is consistent with Adachi et al. (2001) base model. In their analysis, the primary copper production begins peaks decelerates from 2090 and by 2110 the secondary copper production becomes the main supper of the metal. The historical growth rate of copper production since 1965 has increased at an average annual rate of 2.8% (USGS, 2017; Henkens and Worrell, 2020).

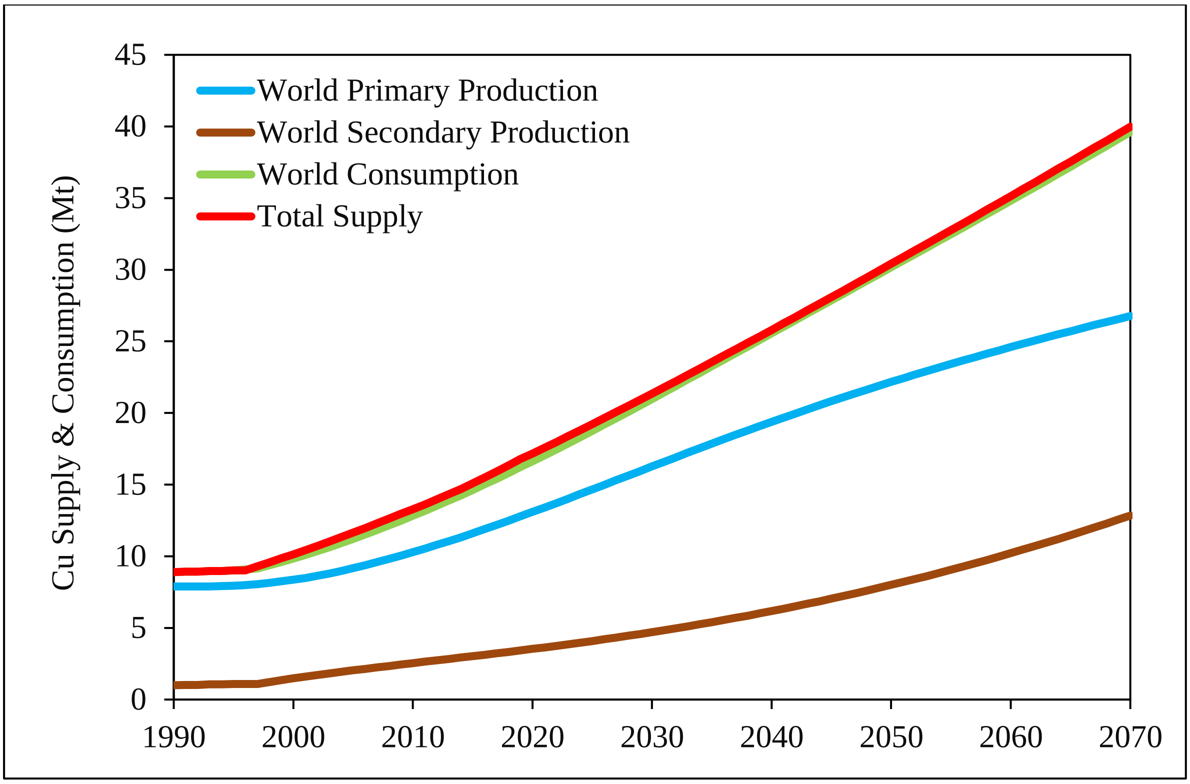

Figure 4-5 Copper supply and consumption simulation

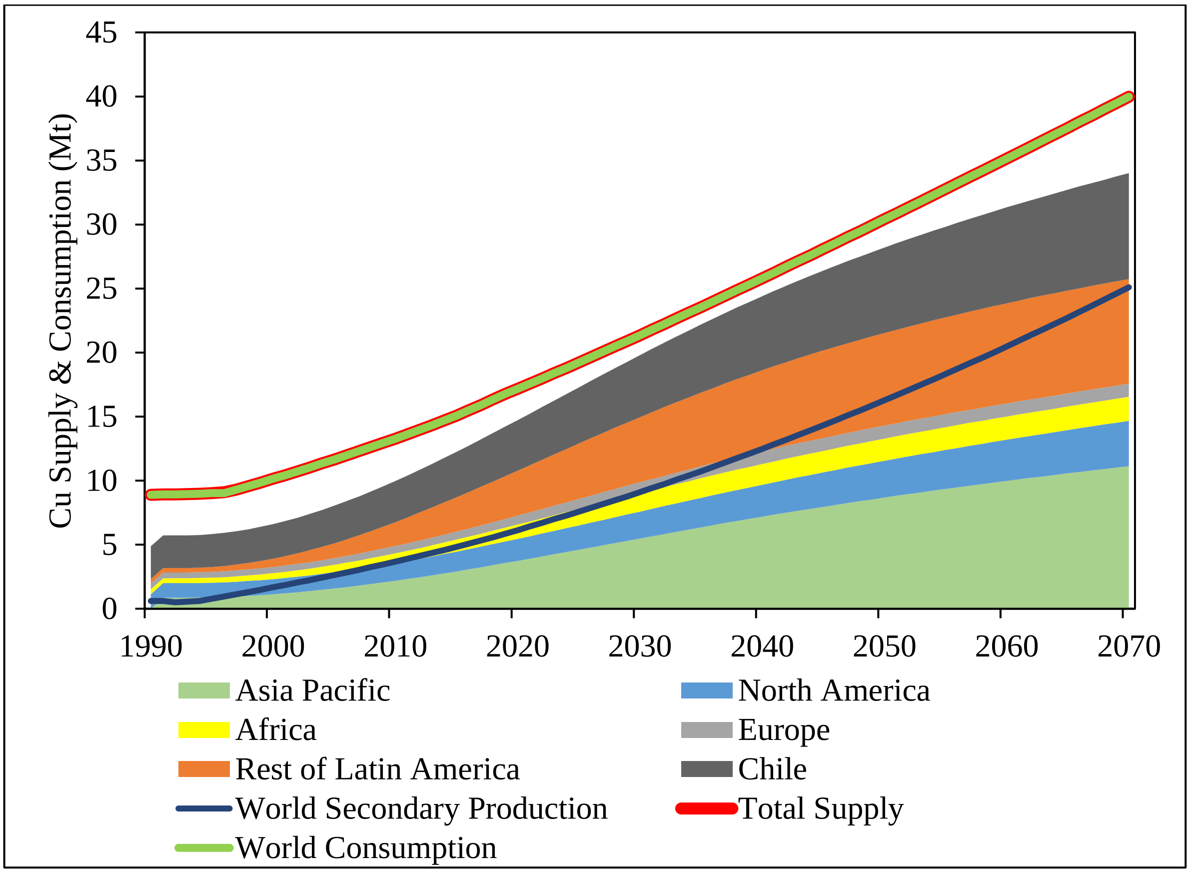

Figure 4-6 Copper regional primary supply, secondary production, and consumption simulation

The consumption trends, measured in million tonnes, of these applications are regressed below:

$$C_{Cu,E,MS}=0.222t-306{,}855 \qquad (R^2 = 0.958)$$

$$C_{Cu,I,MS}=0.239t-296{,}866 \qquad (R^2 = 0.958)$$

$$C_{Cu,T,MS}=7.686t-530{,}326 \qquad (R^2 = 0.912)$$

$$C_{Cu,O,MS}=4.926t+2{,}851{,}125 \qquad (R^2 = 0.948)$$

Figure 4-7 shows the copper sectorial demand trends of copper demonstrate a monotonic increase to 2070. The sectorial demand of the sectors accelerates at varying demand rates, with the total demand increasing almost five times in 2070 to 48.8 Mt/year compared to 1991. The increase is slightly lower compared to Ayres et al., (2003) and Tokimatsu et al., (2017) that range at 50-80 Mt/year in 2070 estimates that vary by analytical methodology. The electrical sector has the largest demand by market share increasing from 5.2 Mt/year to 20.4 Mt/year over the study period followed by the industrial sector then transport and to a less extent the agglomeration of minor shares.

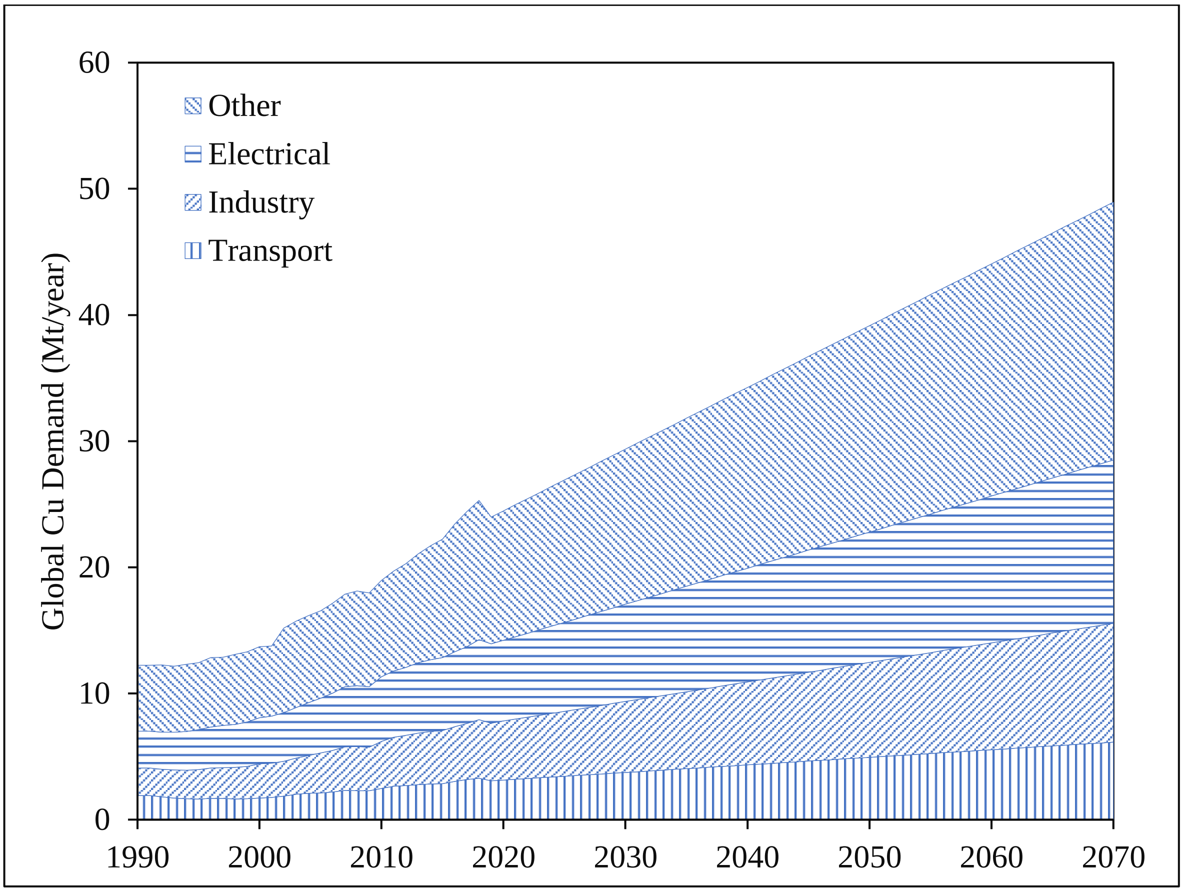

Figure 4-7 Copper demand by sector

The intensity of use in the transport, industry, electrical and other sectors which inherently reflect the future demand projections for copper shows monotonic increases over time shown in Appendix 4-3a. The major demand in copper is sourced from the other sector, which is a summation of various minor sectors, followed by electrical, industry and transport. The Asia Pacific trend displays a steeper intensity of use pattern in the electrical sector sectors which decelerates quick as material consumption reduces in the region but remains high in the comparative sectors. Figure 4-8 depicts the total intensity of use of copper by each region. Asia Pacific, Europe, Latin America, Africa and North America shows the order of increasing IU from highest to lowest. The trend in IU of Europe has been showing a fast decline from the beginning of the study period. By 2050, the IU of all regions will be on a decline as the copper sector achieves maturity through economic development.

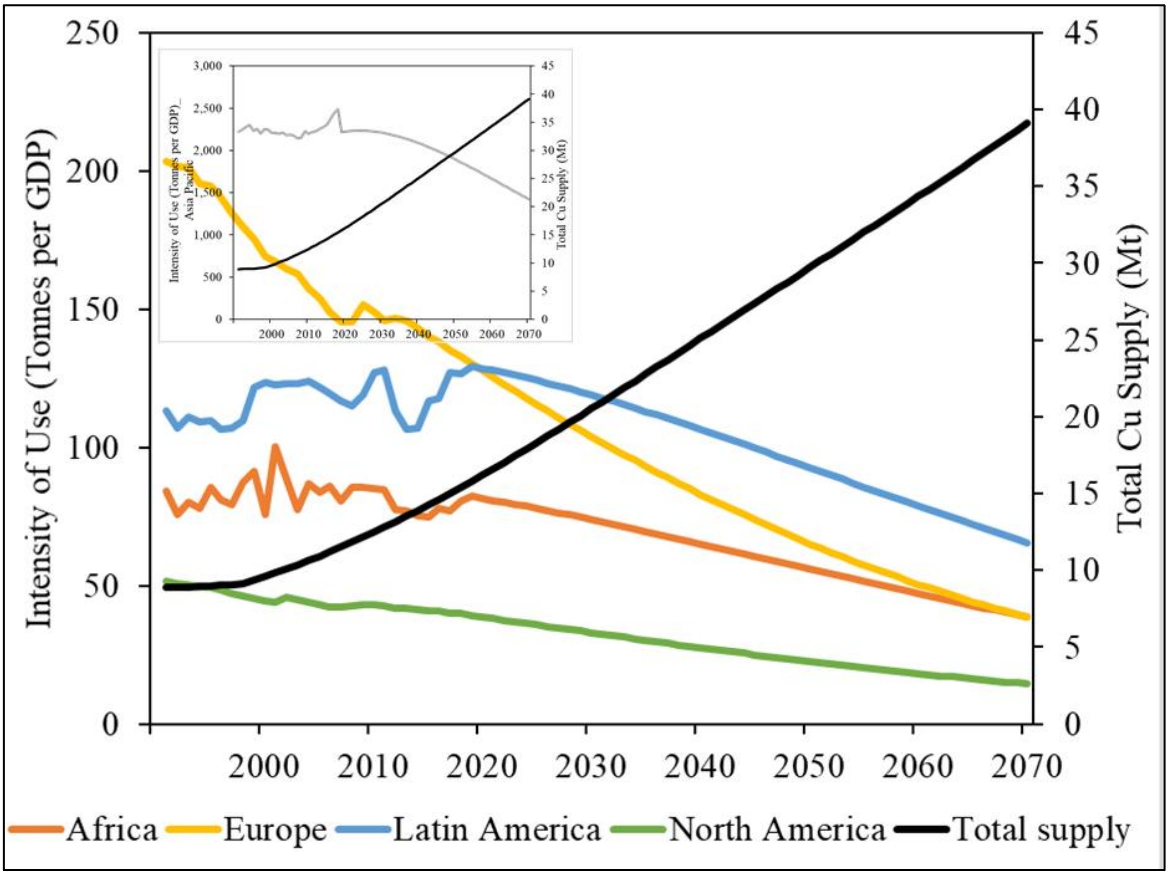

Figure 4-8 Copper intensity of use by region and total supply

By application share (Appendix 4-3a), Africa IU in the transport sector declines to 3.2 tonnes per GDP by 2070 and Latin America IU falls to 4.1 tonnes per GDP over the same period. In the industry sector, by 2070 the IU of use remains above 5 tonnes per GDP. Due to the rapid development of electrical applications in the Asia Pacific region, the resource IU fell, as it has been on an accelerating decline since early 2000s and falls below Latin America around 2020. North America has a relatively low material intensity in consumption in the electrical sector.

While the future of copper dependency in achieving economic development and greener renewable energy continues to grow, associated negative impacts to the environment will consequentially grow especially as the production rates rise, increasing strip ratios, and the metal ore grades deteriorate with the rising scales of physical factors related to mining. Therefore, increasing recycling efficiencies would decouple the impact of mining to the environment for resource use. The growth rate of recyclability of urban ore copper to the elemental ore in Figure 4-9 potentially increases by 39.4% between 2000 and 2070 with the probability of recycling in UO-TMR grade increasing over time. This large probability to recyclability is driven by the deteriorating copper ore grades over time. Additionally, the current level of recycling efficiency and recycling rate need to be increased to reduce the dependency of primary mining sources for copper in order to decrease the annual ore TMR of copper for sustainability into 2070.

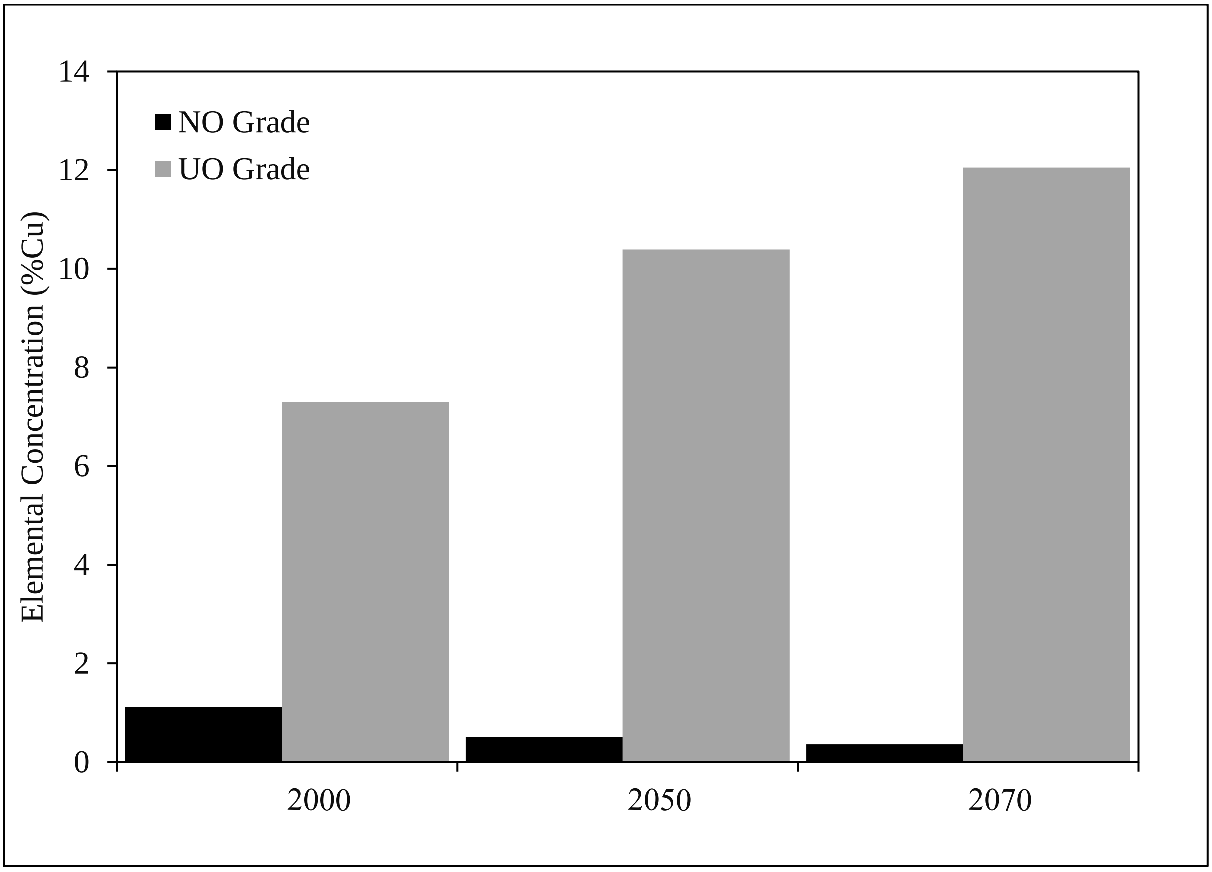

Figure 4-9 Copper natural ore and urban ore grade

Impact of the production rate on primary production and reserves of copper

Many studies assert that the production rate on mining activities is an important factor in metal extraction and production (Adachi et al., 2001; van Vuuren et al., 1999; Northey et al., 2014). The level of iron production allocated by a producer country, region or globally is vital to sustain the appetite of consuming sectors. Iron production is very sensitive to changes in the production rate. The proven reserves decline with an increase in production rate.

The primary production increases with the increasing production rate. The impact of the production rate on the influence of depletion of proven resources. This analysis attempts to evaluate the impact of production rate on primary production, where the parameter values of production are simulated from the baseline value of primary production. Figure 4-10a shows that an increase in the rate of primary production contributes to the increased probability of resource availability for the consuming sectors. The production rate becomes sensitive at >50% change in the production rate. At 25% sensitivity, the production rate slightly adjusts to the factor change. Conversely Figure 4-10b depicts the proven reserves decline as the production rate is raised in a mirror image of the sensitivity analysis.

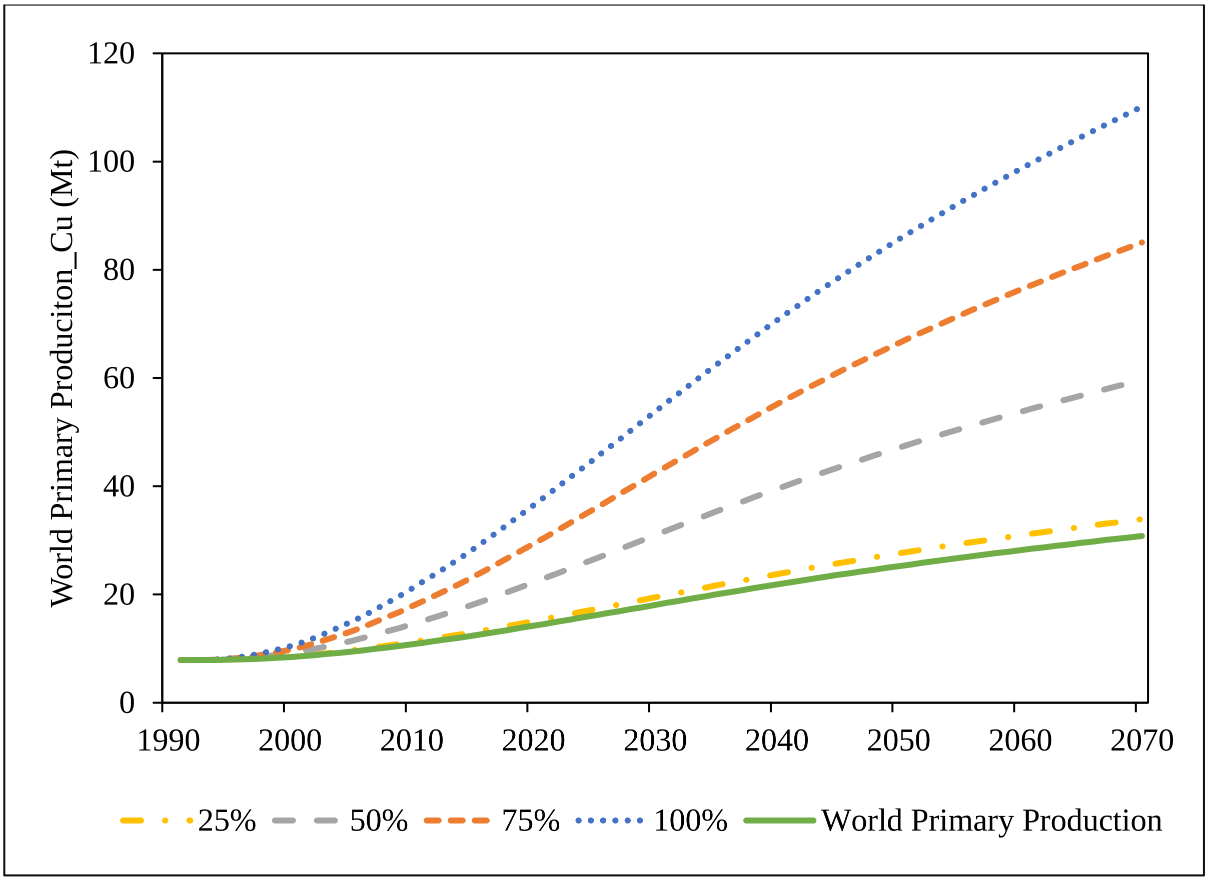

Figure 4-10 a Impact of production rate on world primary production of copper

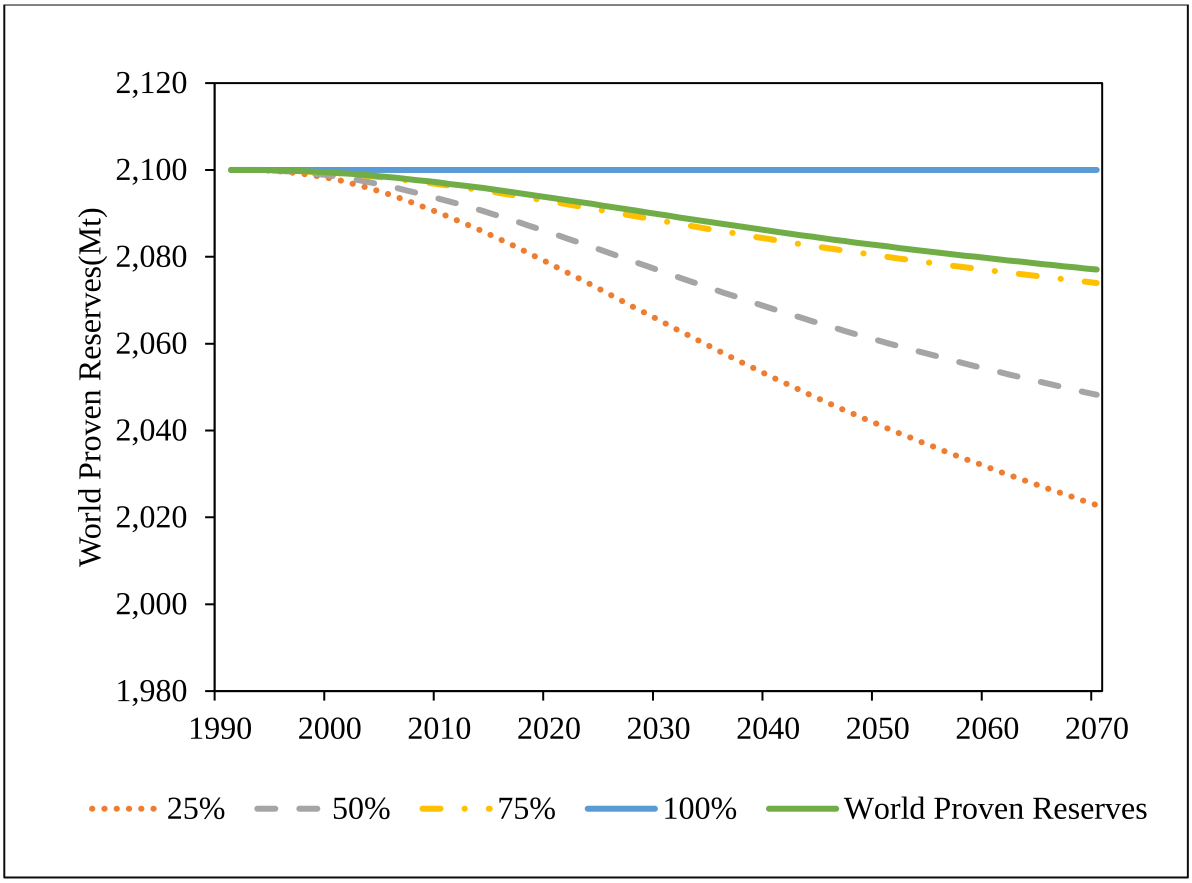

Figure 4-10 b Impact of production rate on world proven reserves of copper

Impact of exploration and technology on primary production and reserves of copper

The changes in exploration and technology are the main factors that increase the geological confidence of defined and measured resources/reserves available for copper mine production. Figure 4-11a and Figure 4-11b exemplify how the changes in exploration rate and technological advancement would alter the copper mine production as copper supply progresses. The exploration rate shows a strong elasticity to the mine production as the rate of exploration is adjusted compared to technology rate that is inelastic to changes in copper mine production. Consequently, technology requires large investment for changes in the copper industry to be visible especially in exploration and other stages of mine development e.g. metallurgical processing to upgrade the head grades.

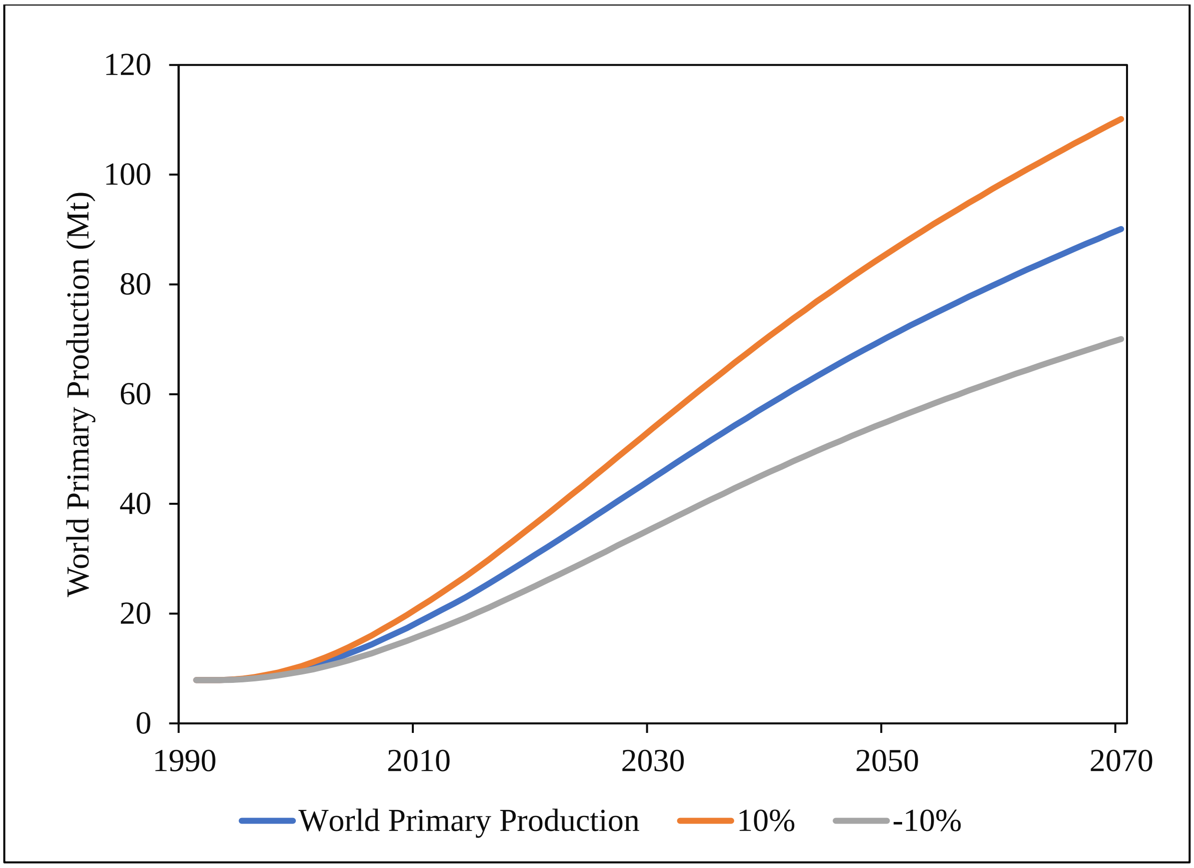

Figure 4-11 a Impact of exploration on world primary production of copper

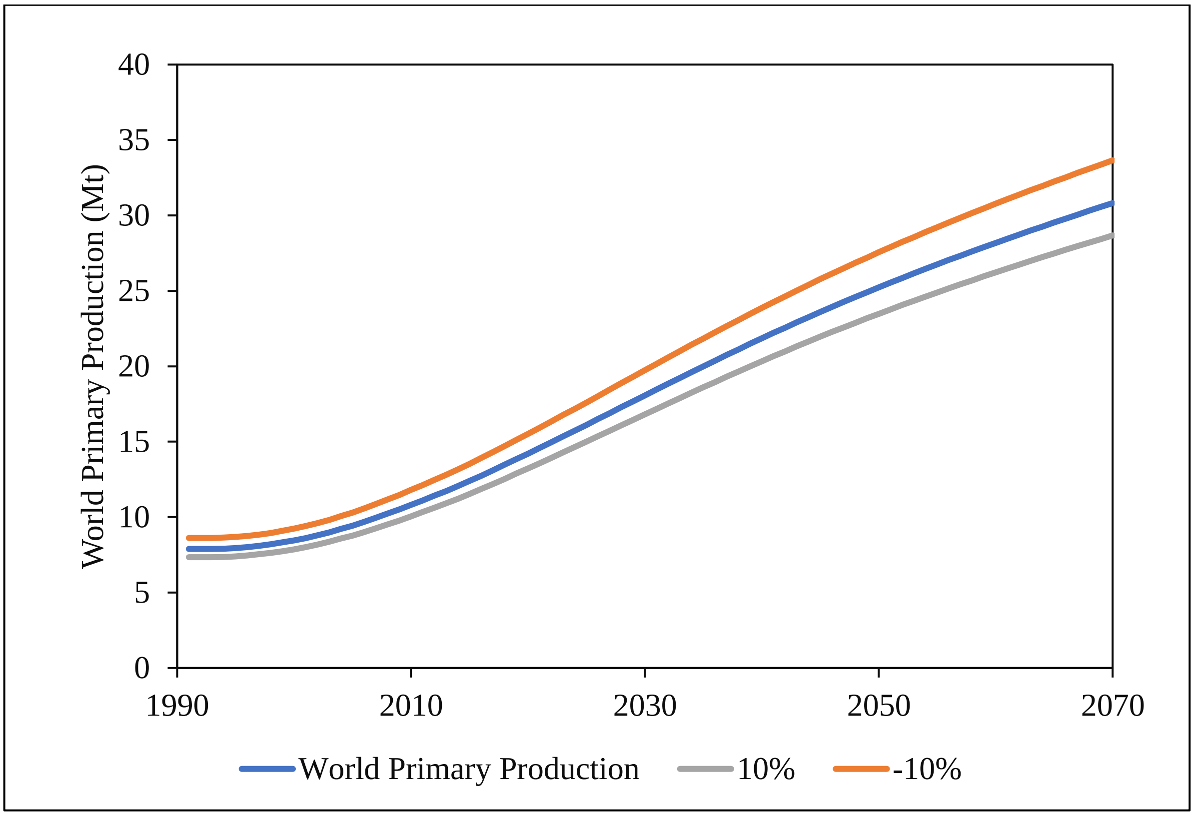

Figure 4-11 b Impact of technology on world primary production of copper

Impact of recycling on world copper consumption

The recycling rate and recycling efficiency on copper consumption in Figure 4-12a and Figure 4-12b depicts that raising the recycling efficiency between <25% sensitivity would result to ana lower material consumption. A 50% recycling efficiency is equivalent to the simulated level of consumption. A 75%-100% sensitivity on the recycling rate and recycling efficiency increases the world consumption to between 60 Mt- 90 Mt. Raising the recycling rate would optimize the material flow through secondary production processes and ultimately alleviating the negative impact on the environment caused by TMR flows.

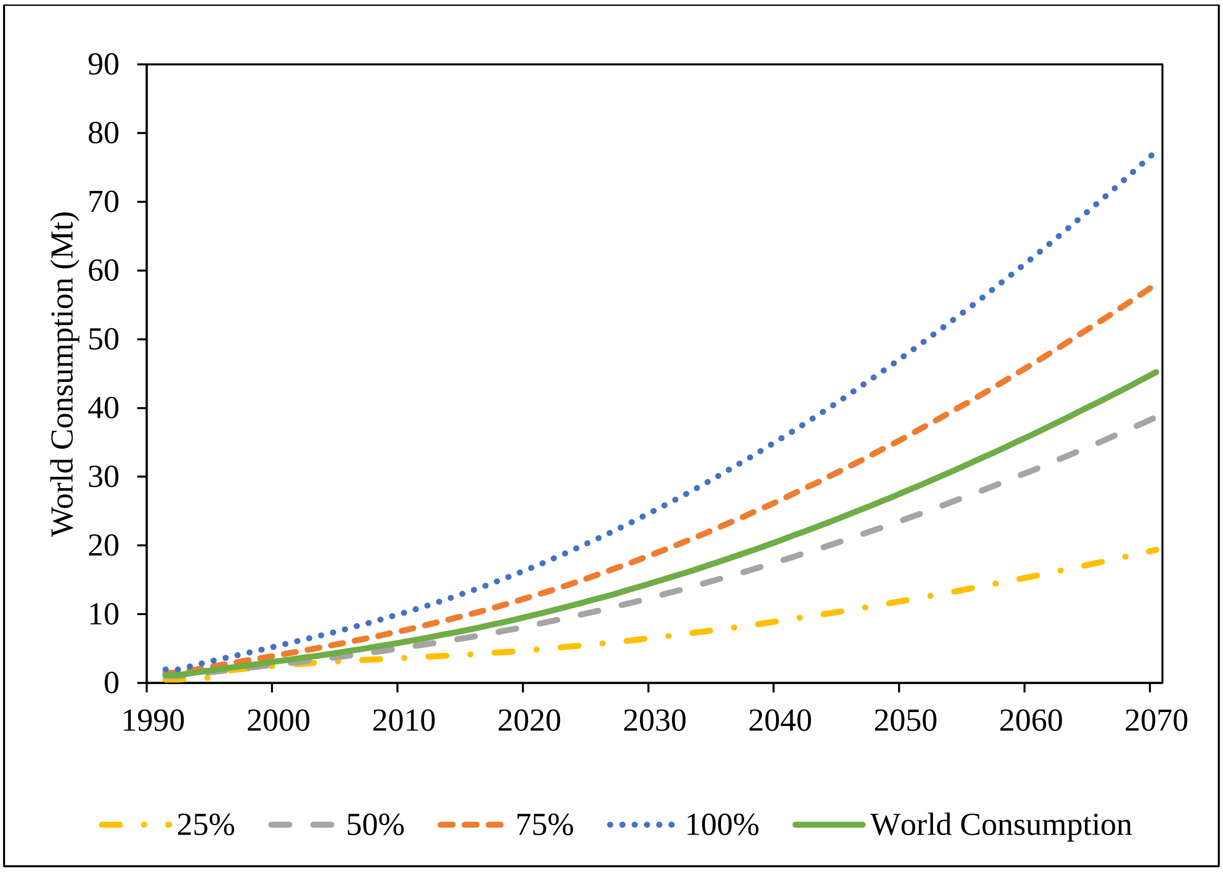

Figure 4-12 a Impact of recycling rate on world consumption of copper

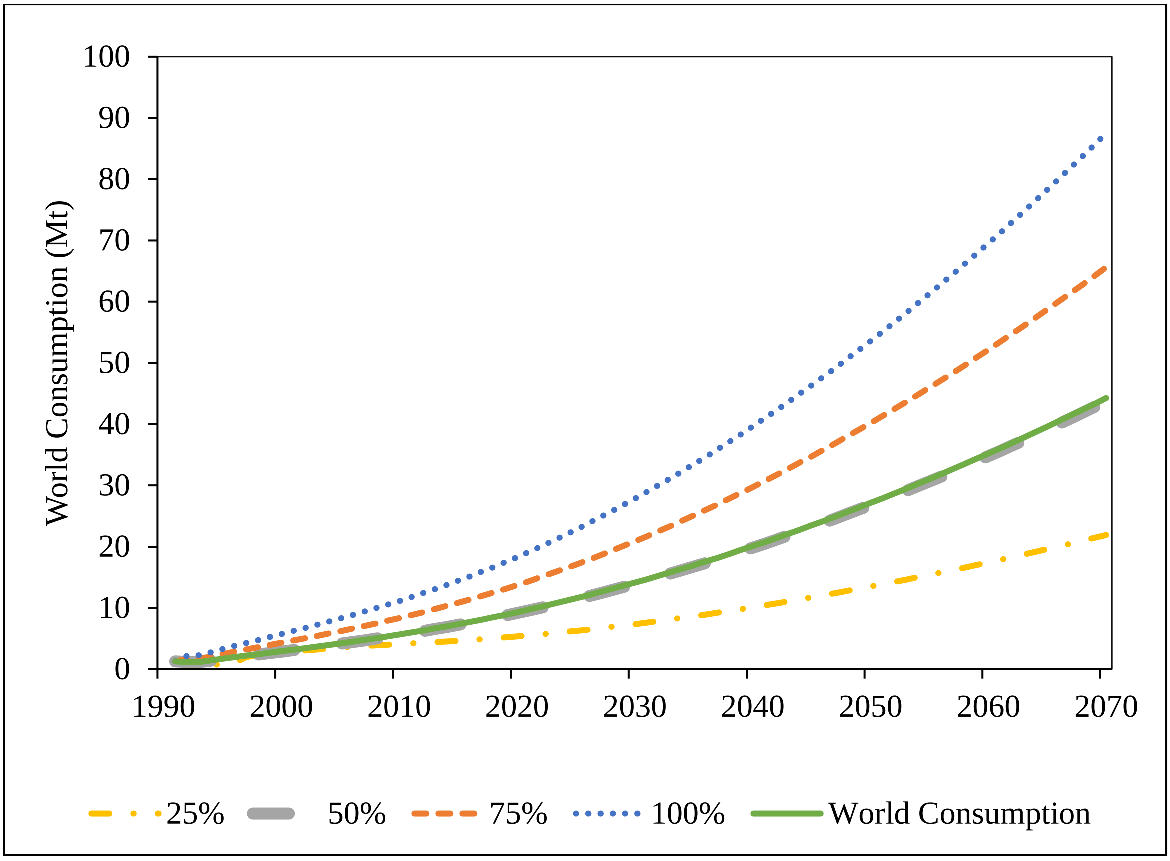

Figure 4-12 b Impact of recycling efficiency on world consumption of copper

Impact of recycling on secondary production

The parametric value of the recycling rate is 58.5%. Previous literature assumes the EOL-RR between 45-80% varying at global, regional or country level (UNEP, 2011; Spatari et al., 2005; Glöser, 2013; Soulier et al., 2018; Henkens and Worrell, 2020) [Appendix 4-4]. Assuming a 75% increase of EOL-RR as depicted in Figure 4-13a would improve the recycling rate in 2070 by 12 Mt (base case) to about 42 Mt, where recycling processes could become the main copper source of supply. Figure 4-13b shows that the recycling efficiency of copper is almost equivalent to 75% change in recycling efficiency displayed. These two factors show copper recycling could still be improved to increase recycling production and reduces the environmental consequence in copper TMR flows.

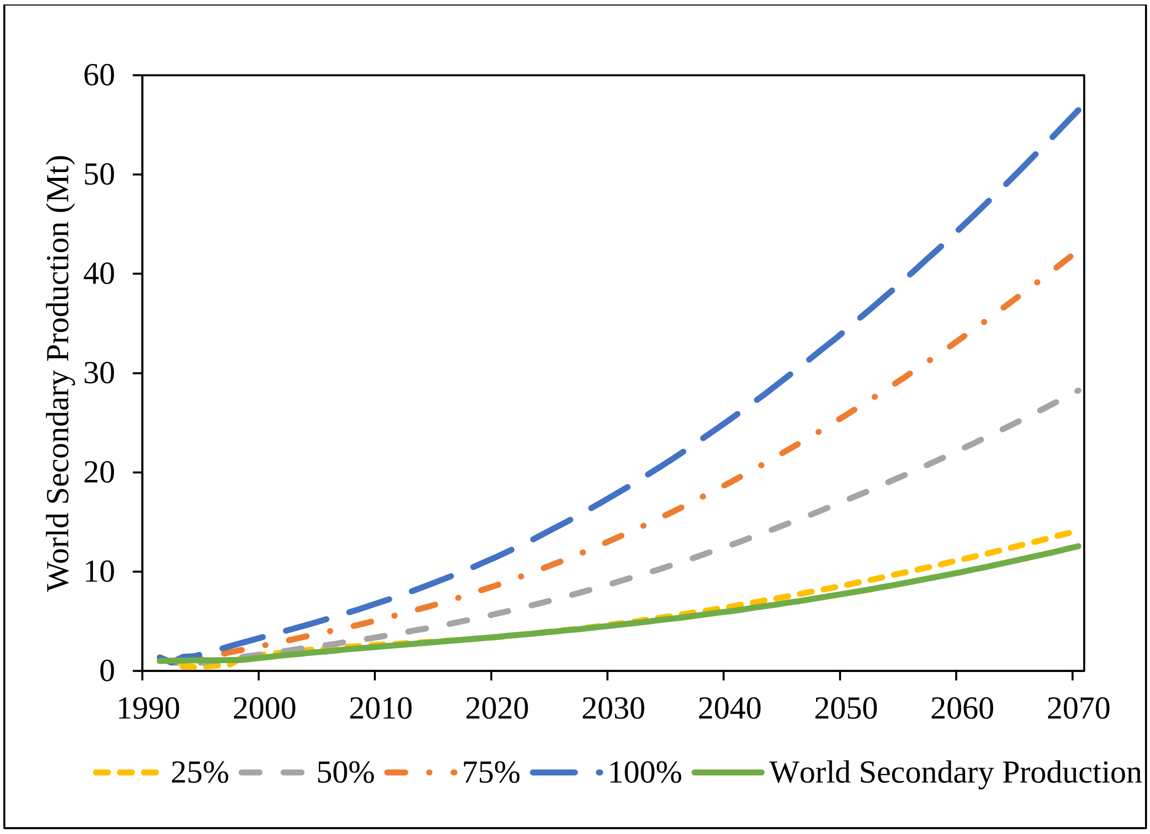

Figure 4-13 a Impact of recycling rate on world secondary production of copper

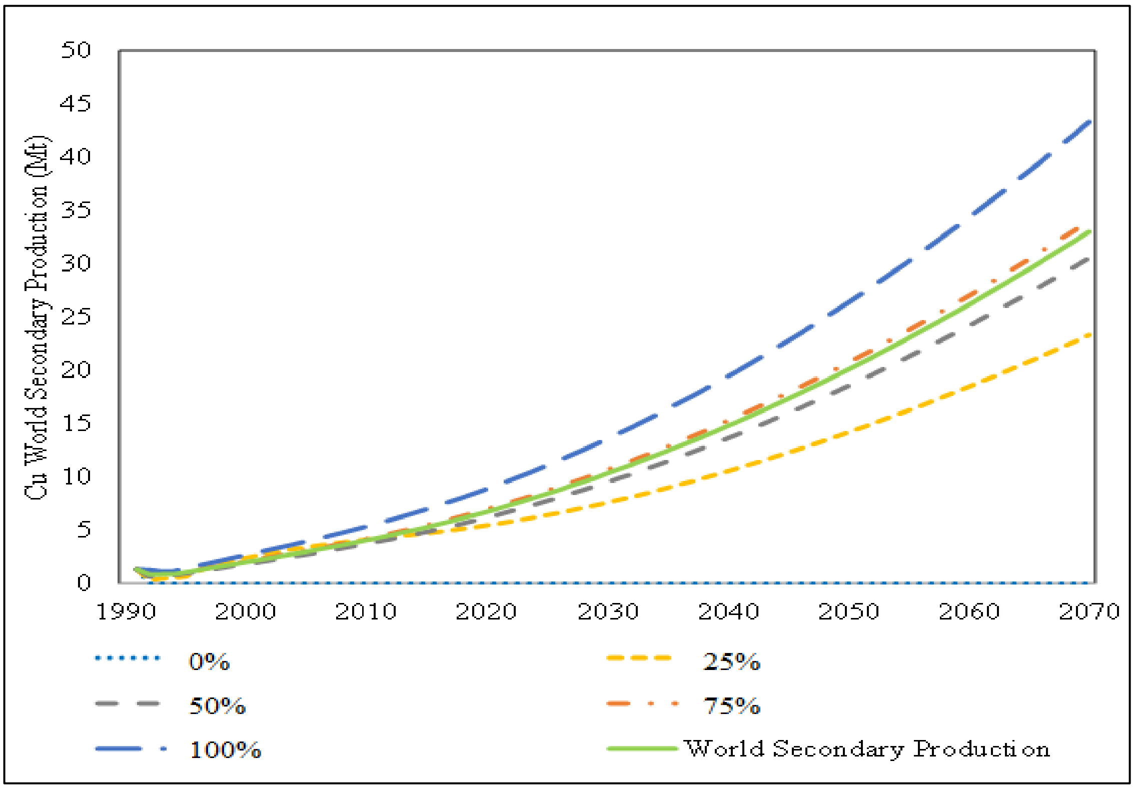

Figure 4-13 b Impact of recycling efficiency on world secondary production of copper

The Towards Sustainability and Resource Efficiency scenarios for copper are shown in Figure 4-14 and Figure 4-15. In 2020, primary copper production is 13.1 Mt. The resource outlook depicts that copper production will decline to 9.8 Mt and 10.9 Mt under the Towards Sustainability and Resource Efficiency Scenarios over the same period. By 2070, historical production trends in primary copper would reduce to 20.1 Mt and 22.2 Mt in Towards Sustainability and Resource Efficiency Scenarios respectively from 26.8Mt base trend. For Chile, material reduction from primary production processes could reduce from the original scenario of 8.3 Mt by 2070 to 6.2 Mt and 6.9 Mt in the Towards Sustainability and Resource Efficiency Scenarios. This reduction in copper production requires stimulation in secondary production processes where secondary copper rises to 15Mt and 16.1 Mt in Resource Efficiency and Towards Sustainability Scenarios from the 12.8 Mt in the Base trend by 2070.

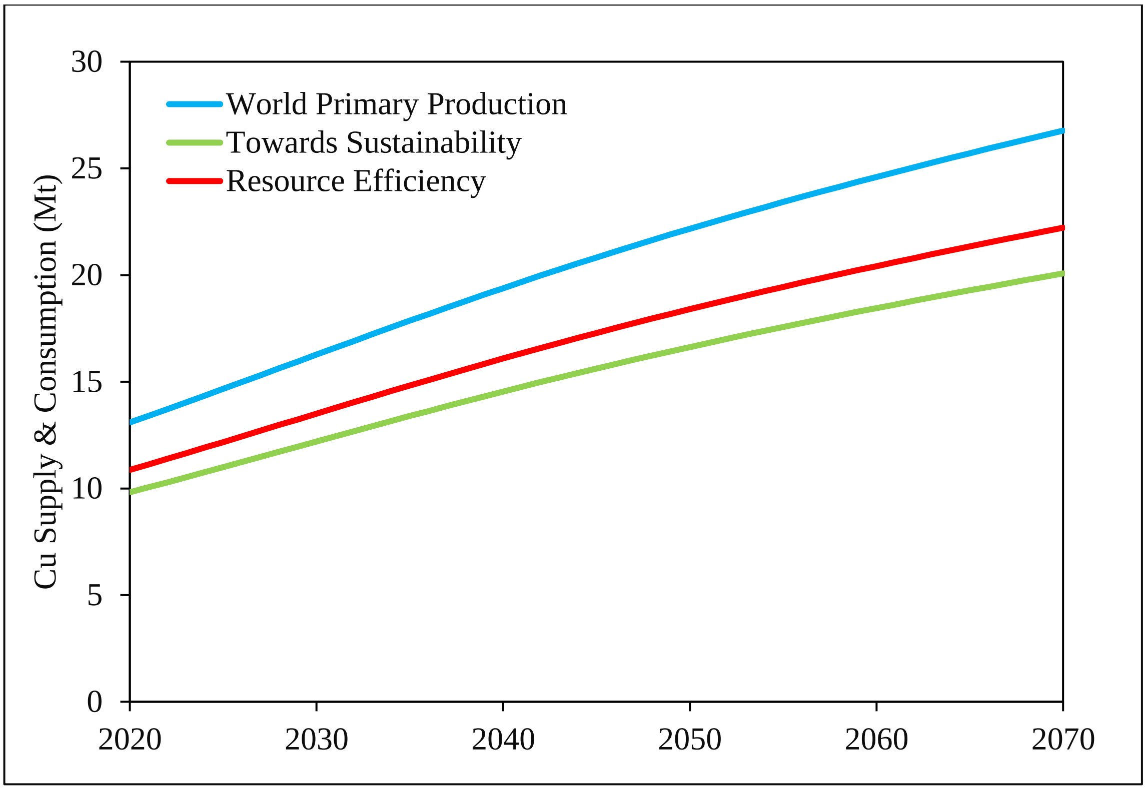

Figure 4-14 Towards Sustainability and Resource Efficiency Scenarios for copper primary production

TMR flows compared with the original scenario in Figure 4-16 would reduce to 63 870 Mt/year and 70 682 Mt/year on the Towards Sustainability and Resource Efficiency Scenarios from 85 160 Mt/year by 2070. This is a reduction of between 15 000-20 000Mt/ year on environmental pressure through global extraction during metal mining. In the case of Chile, ore TMR flows could reduce from 2 733 Mt/year to 2 050 Mt/year and 2 268 Mt/year along the Towards Sustainability and Resource Efficiency scenarios.

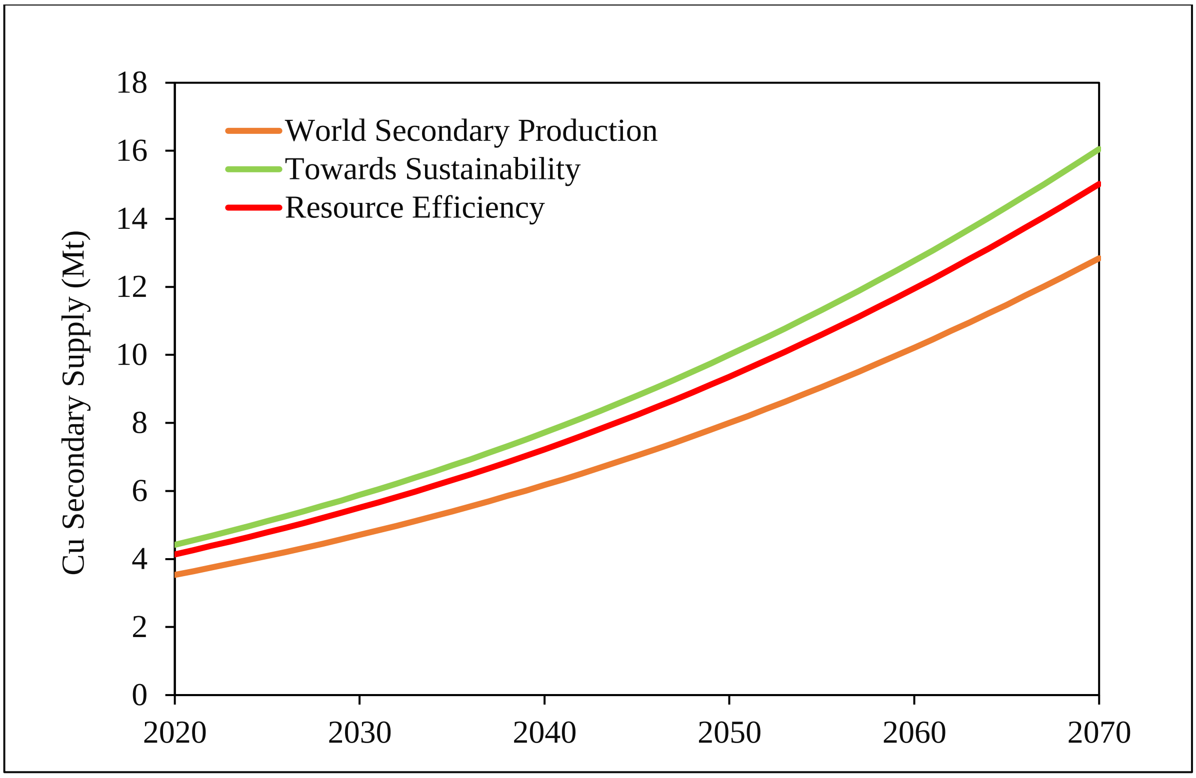

Figure 4-15 Towards Sustainability and Resource Efficiency Scenarios for copper secondary production

Copper Summary

Total supply increases from 8.89 Mt in 1991 to 39.9 Mt in 2070. Primary copper production is the main source of copper supply to 2070. Global production of copper is concentrated in the Latin American regions specifically Chile. This region has become a hotspot for copper production owing to the resource governance, ore grade, and the large copper reserves in the area. The ultimate resources with a maximum cut-off grade of 0.2% Cu are not a concern to the scarcity of the resource to 2070. The URR applied in our global model of 1780.9Mt Cu is similar to Northey et al. (2014) of 1 780.9 Mt Cu.

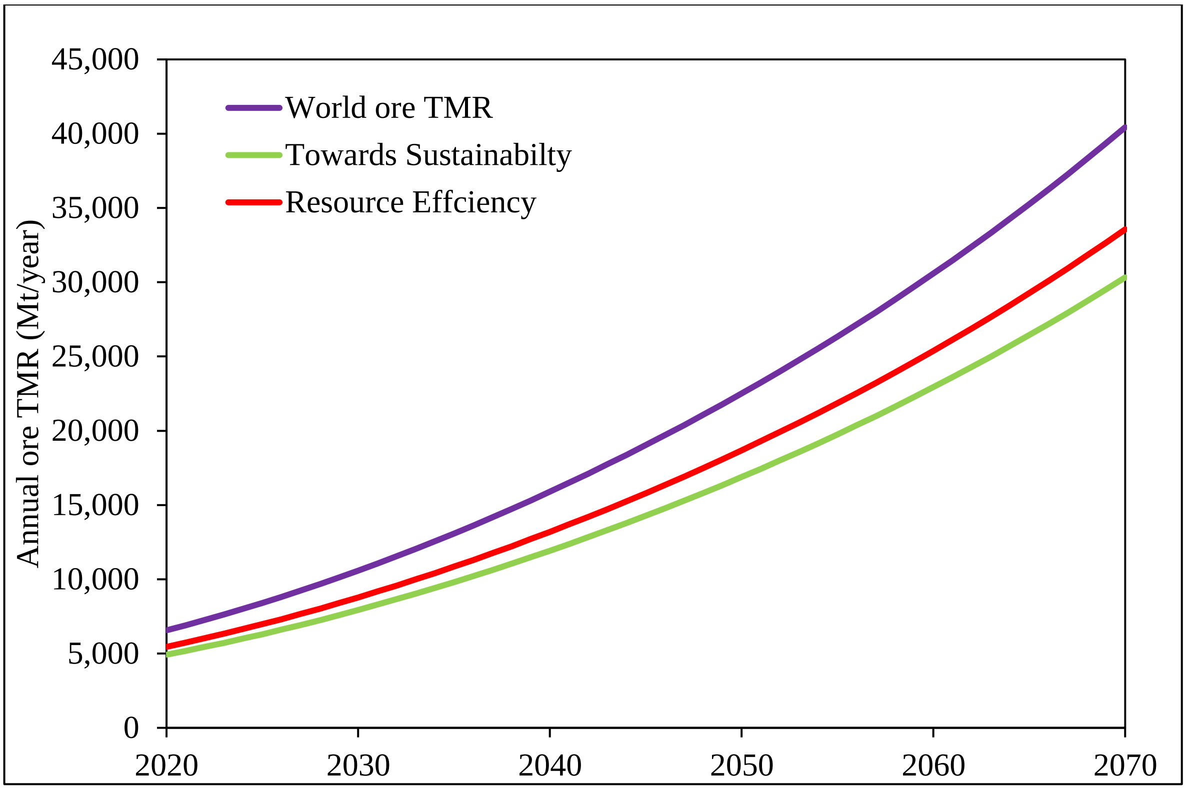

Figure 4-16 Towards Sustainability and Resource Efficiency Scenarios for copper TMR flow

The need to safeguard the resource conservation of copper for future generations will depend on the end-of-life recycling rate and recycling efficacy. At least 75% would be needed to achieve future copper sustainability.

While past studies estimate the current recycling efficiency at 84% (Glöser, 2013; Henkens and Worrell, 2020), we applied a 66% recycling efficiency. With the fast pace in decline on copper ore grade, recovery will become more difficult over time as cost of returns become higher hence adjusting these efficient for practical scenarios for copper use will provide a better understanding for resource stakeholders. Application of specific product lifetime of copper gave an improvement in the model in underpinning the copper rate of demand.

The sustainability scenarios provide pathways to reducing TMR material flows by 17% and 25%. By combining with the increased recycling rate, investment in higher grade ores in various regions may reduce the environmental consequence caused during copper mining.

### 4.3.2 Gold

Strong assumptions were placed under the gold simulation model. Gold supply is from primary mining production with the supply demand gap accounted by an efficient recycling system to achieve sustainability in the supply demand balance model. The secondary recycling is observed as a parallel to the model to measure the effect of recycling on the gold material flow. The secondary gold is kept as gold stocks at the warehouse only availed during a supply deficit. Adjustment factors applied to global and regional model do not “best fit” creating large errors. This is compensated by calculating the standard deviation between simulated gold consumption to allow for material flow gain or losses in the balanced model at regional and global levels. Parameters applied in the gold model are displayed in Appendix 4-2.

Figure 4-17 illustrates the gold supply and consumption trend to 2070. Total supply increases from 3 630t in 2000 to 4 653t in 2070. Mining production slightly increases from 2 698t in 2000 to 3 351t in 2050 then peaks to 3 513t in 2070. The total consumption changes from 3 630t in 2000 to 4 653t in 2070 resulting to no supply-demand gap in the model. In Figure 4-18 the regional mining supply trends are displayed. The Asian Pacific primary supply grows from 1 265t in 2000 to 1 662t in 2070. Africa’s regional supply grows from 600t to 721t over the same period. Europe primary gold supply eminently peaks owing to the depleted reserves and matured gold mining industry in the region. The supply deficit is accounted by secondary recycling which steadily grows from 932t in 2000 to 1 140t in 2070. By 2070, the mining production of gold remains the main source of gold supply.

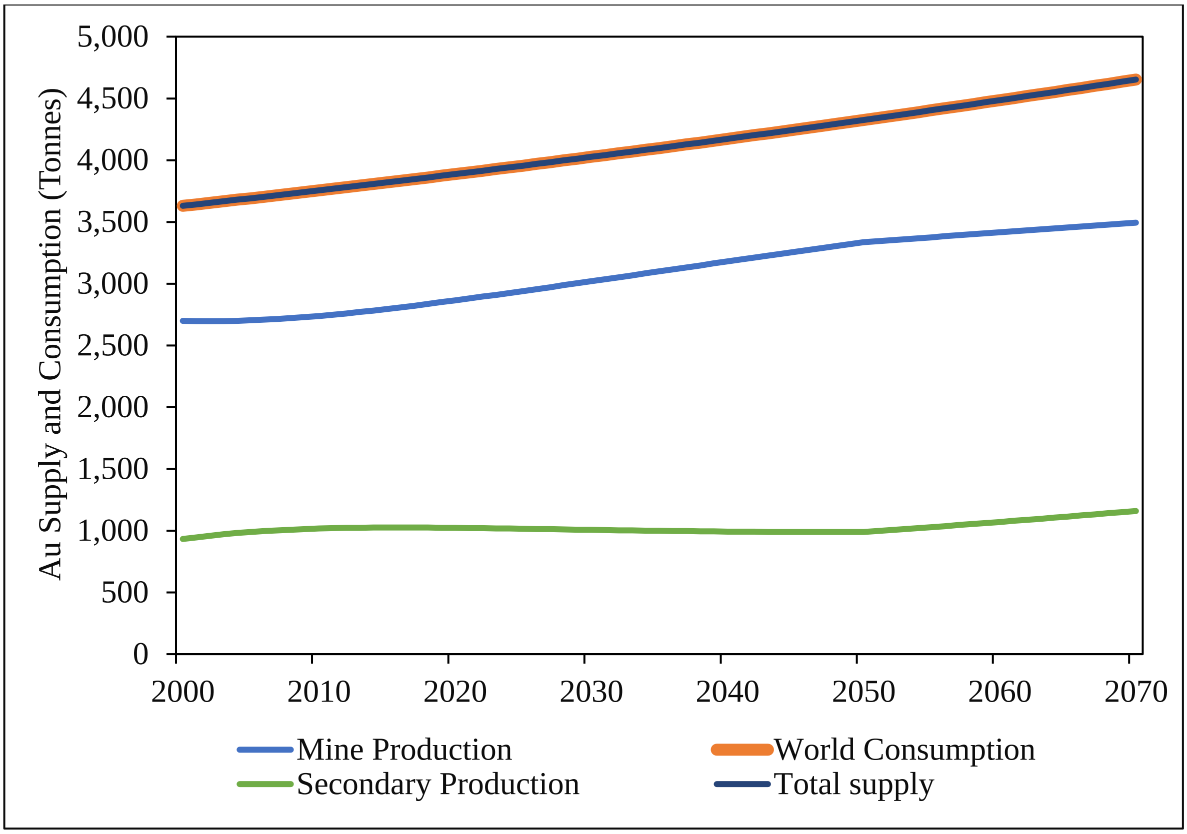

Figure 4-17 Gold supply and consumption simulation

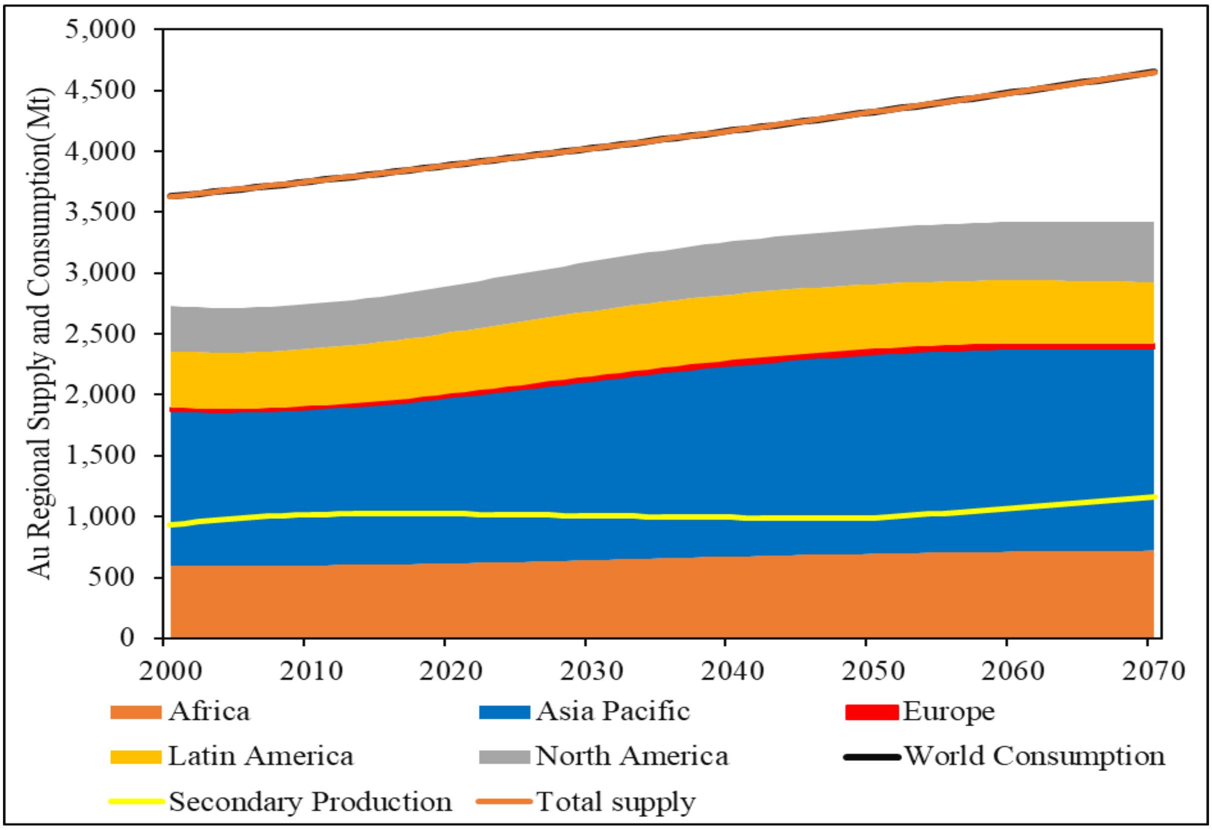

Figure 4-18 Gold regional primary supply, secondary production, and consumption simulation

The electricity demand required for gold consumption was not assumed in the gold model due to lack of data at both regional and global level. Therefore, the consumption equations were regressed as a function of time and market share. The consumer trends show monotonic increase to 2070 along with the supply. Demand steadily increases to 2070 for the jewellery (J) sector with a change from 2 214t in 2020 to 2 874t in 2070. The investment and banks (I), represented as investment sector grows from 1 798t (2020) to 1 872t (2070). The technology (T) sector inclusive of industrial, electronics and dental applications, demand changes from 524t in 2020 to 1 008t in 2070. The latter sectors will rise against increasing population, economic growth and the continued safe haven which gold portrays in the investment environment. Classification of the gold demand sectors are based on the past literature (Ciacci et al., 2015; Elshkaki et al., 2018). The percentage market shares for gold sector are jewellery 62%, investment and banks 23% and technology 15% (Ciacci et al., 2015; Elshkaki et al., 2018). The consumption trends, measured in tonnes, of these gold sectors are regressed below:

$$C_{Au,J,MS}=0.400t-1{,}317 \qquad (R^2 = 0.429)$$

$$C_{Au,I,MS}=1.493t-1{,}219 \qquad (R^2 = 0.408)$$

$$C_{Au,T,MS}=8.933t-17{,}502 \qquad (R^2 = 0.417)$$

Figure 4-19 outlines the gold demand trends from 2000 to 2070 by the sectorial market share. There is a slight incremental change in the jewellery sector over the study period rising from 1 950.8 tonnes/year to 2 874.2 tonnes/year. Investment and banks rapidly increase from 686.9 tonnes/year to 5 198.8 tonnes/year with an expected rise in future market share in the total gold consumption. The technology sector growth increase from 363.8 tonnes/year to 989.1 tonnes/year but remains significantly small in the total share of gold consumption.

The global sectorial intensity of use is depicted on Figure 4-20. The intensity of use of gold investment increases steadily and ultimately decline around 2038 as the world economic growth increases as countries become more wealthier and move towards services from manufacturing industries. The jewellery sector intensity of use has a decelerating trend since 2000 primarily because of preference to other metal substitutes in the sector such as rubies, diamonds, and platinum. The IU for technology remains low compared to competing sectors into 2070.

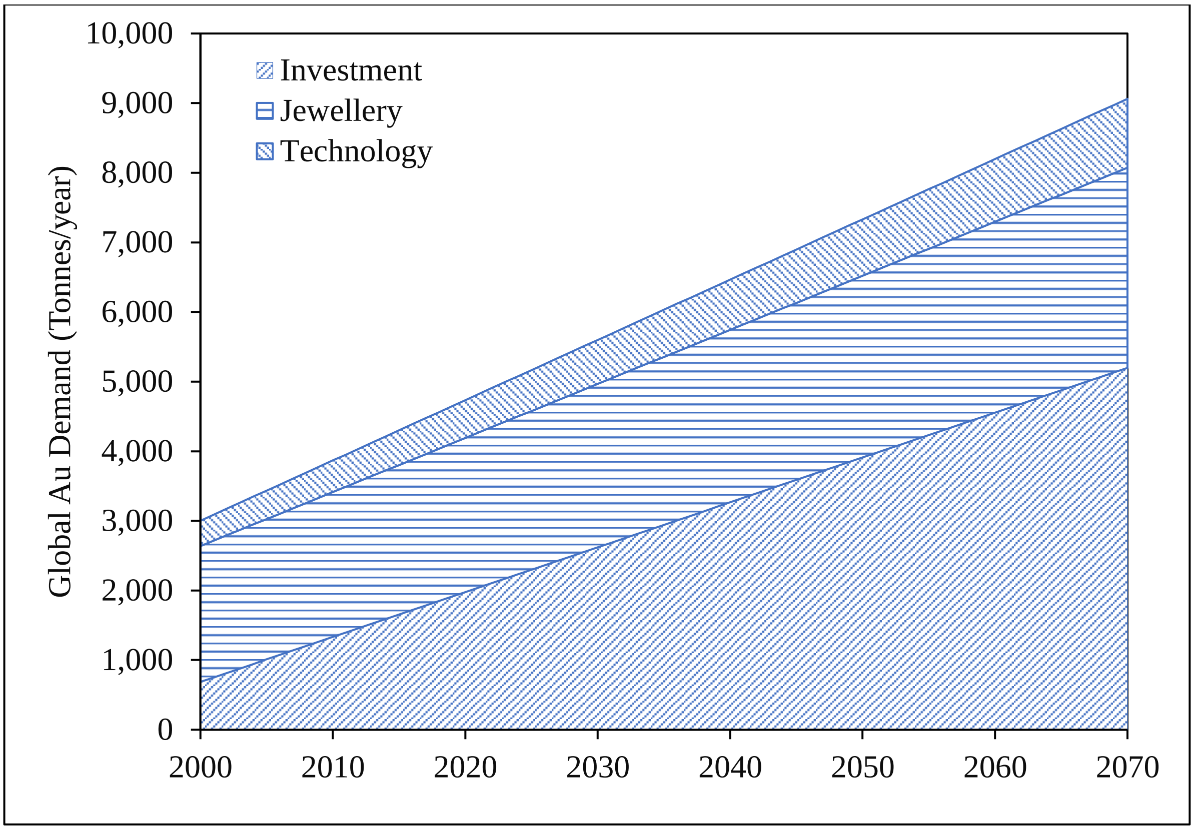

Figure 4-19 Gold demand by sector

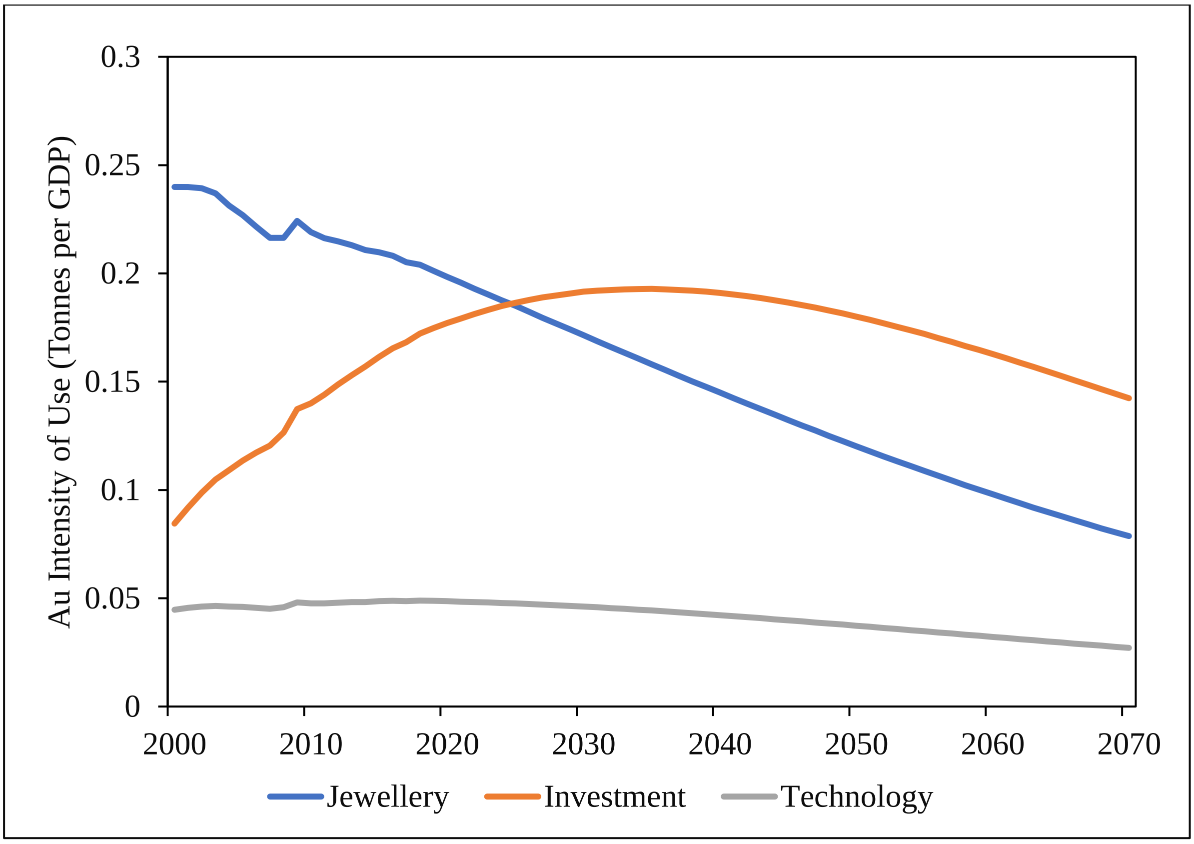

Figure 4-20 Gold intensity of use by region and total supply

The growth rate of gold recyclability probability is from 2000 to 2070 grows by 54%. As the natural ore grade continue to decline rapidly, owing to the matured mining industry, the probability of recyclability of urban ore grade grows from 6% to 13% Au displayed in Figure 4-21. This exemplifies the criticality of gold resources potential impact on the deterioration of the environment as discussed in Chapter 3. The prompt urgency of gold recyclability is eminent to decouple gold resource use from the environment. In addition, the long product lifetime of gold >80 years especially in the jewellery sector which is largest sector by market, due to cultural and individual preferences, slows down the material flow in potentially of availing the resources for secondary supply. However, this time lag avails acts as a "storage or incubator" for future material. However, by 2070, at current production and recycling rates gold supply suffice the demand.

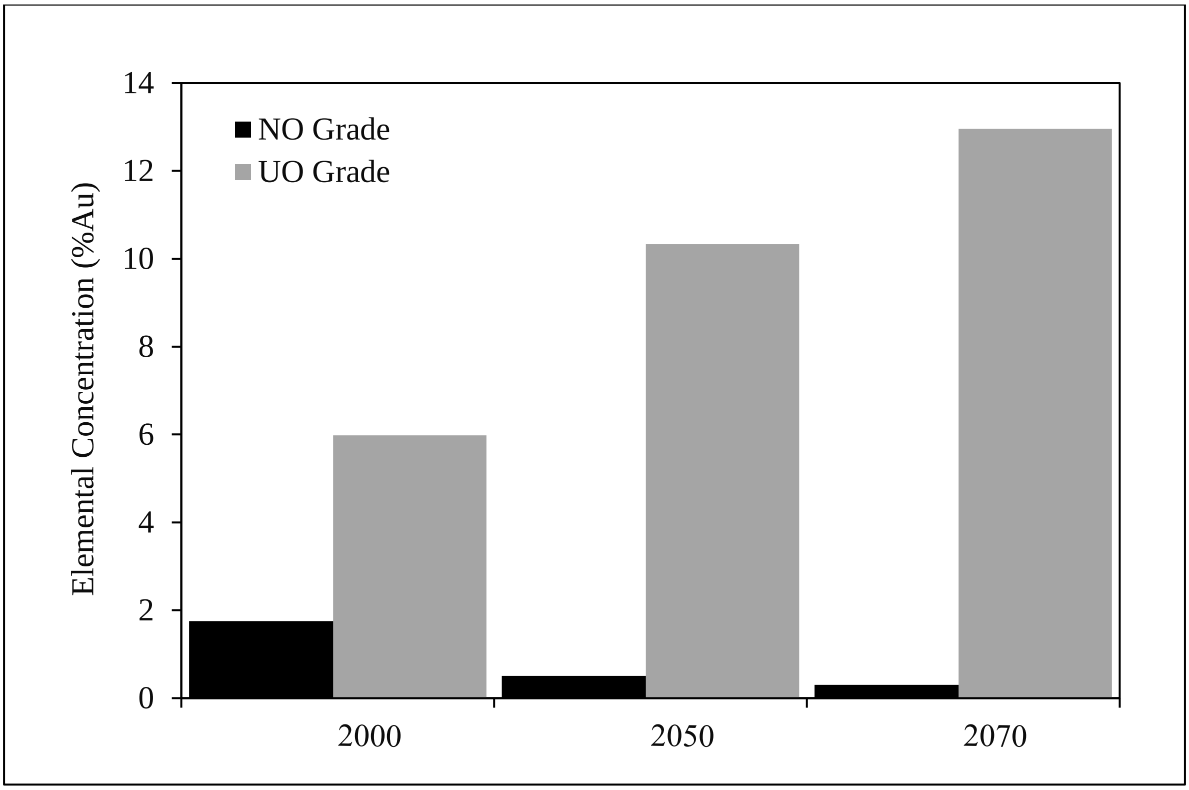

Figure 4-21 Gold natural ore and urban ore grade

Impact of the production rate on primary production and reserves of gold

Gold reserves have a constantly occurring sensitivity of the impact of production rate on the proven reserves. As the production rate increases, these proven reserves increase constantly up to 13 763 tonnes from the current level of 12 000tonnes in 2070. For every 25% adjustment, about 500 tonnes of gold reserves are availed for gold mine extraction as depicted in Figure 4-22.

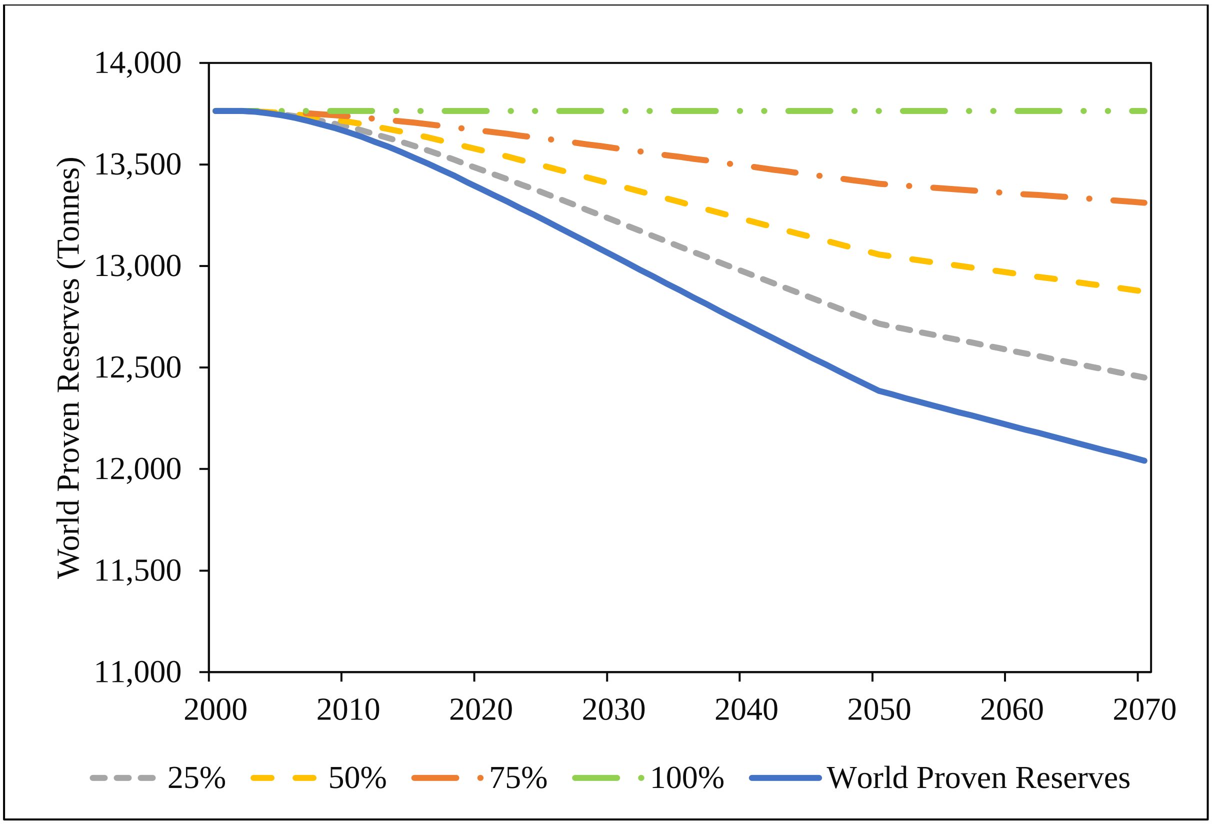

Figure 4-22 Impact of production rate on proven reserves of gold

Impact of exploration and technology on primary production of gold

According to the sensitivity analysis on the impact of exploration and technology (Figure 4-23a and Figure 4-23b) on gold mine production, both factors are equally important in potentially availing gold reserves for supply. The criticality of these factors is essential for both the discovery of new gold deposits and improvement of gold processing technology important to raise the gold head grades above the mine cut-off grade and essentially the market cut off grades competitive in the gold mine industry.

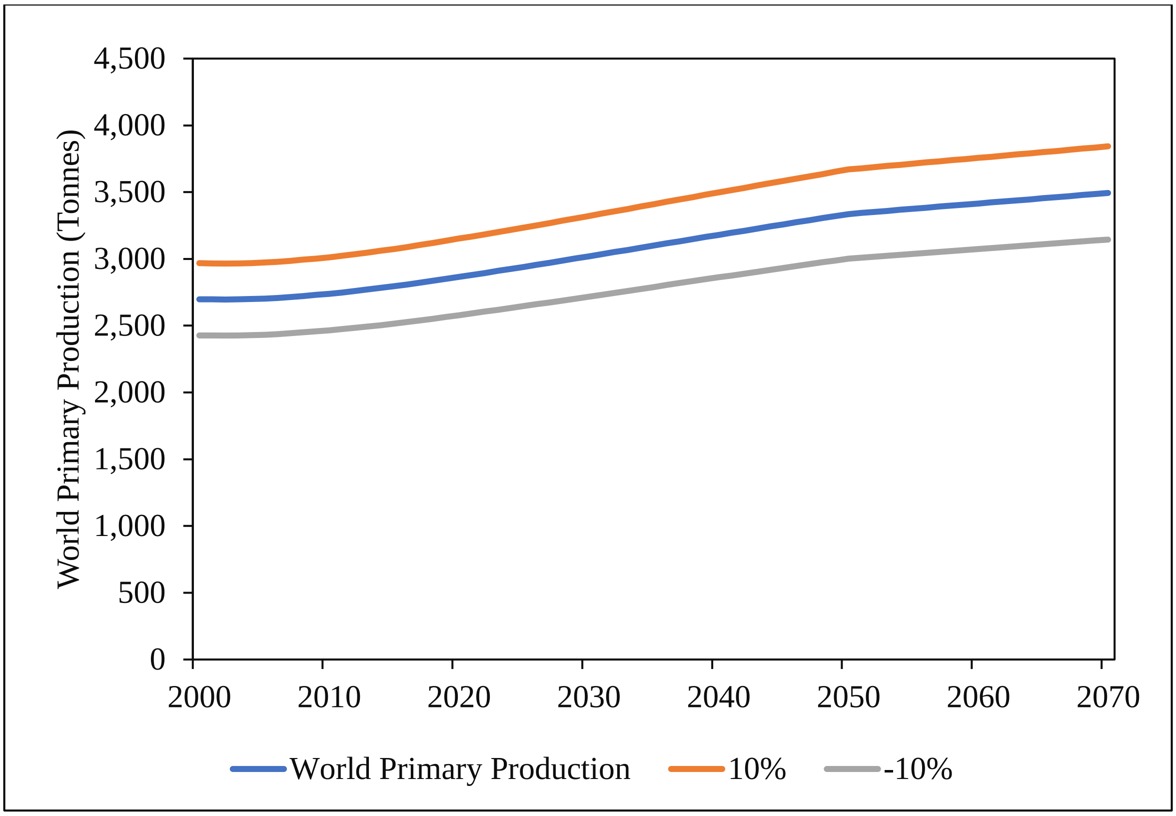

Figure 4-23 a Impact of exploration on world primary production of gold

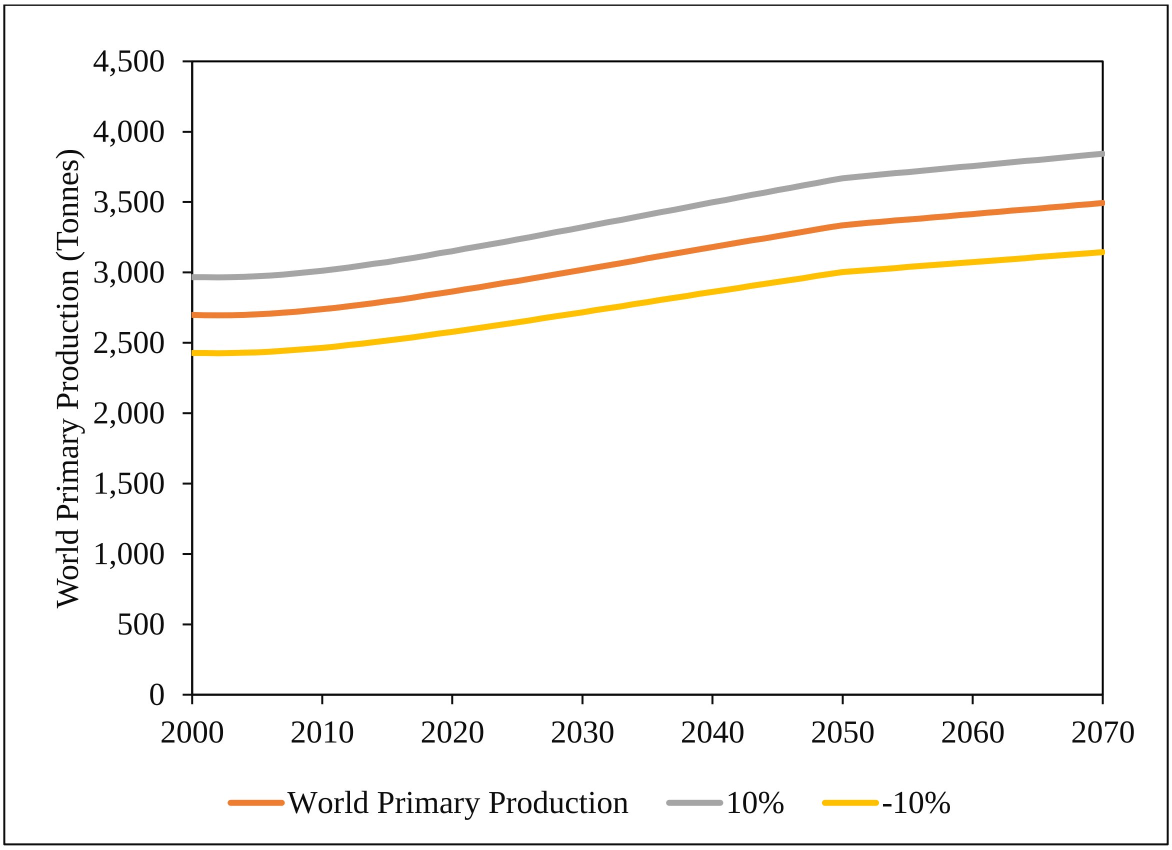

Figure 4-23 b Impact of technology on world primary production of gold

Impact of recycling on secondary production

The parametric recycling rate applied to this model is 53.9%. Past research work assumes EOL-RR between 15-96% (GFMS, 2009; IRP, 2011). The effect of recycling rate on secondary production is shown in Figure 4-24a. At approximately 50% gold recycling is assumed. Along the 75% sensitivity, could allow gold supply to wholly depend on secondary production. Figure 4-24b shows the effect of recycling efficiency on gold secondary production. The effective recycling efficiency assumed in this study is 60.1%. The recycling efficiency shows that a 100% efficiency would require primary resources to still be available. This is mainly because of the large time lag in the product lifetime of jewellery, greater than 80 years. Even though smaller quantities of recyclable material would be provided from other sectors, they would not achieve recycling with at least 3 000 t of gold in 2070 alone.

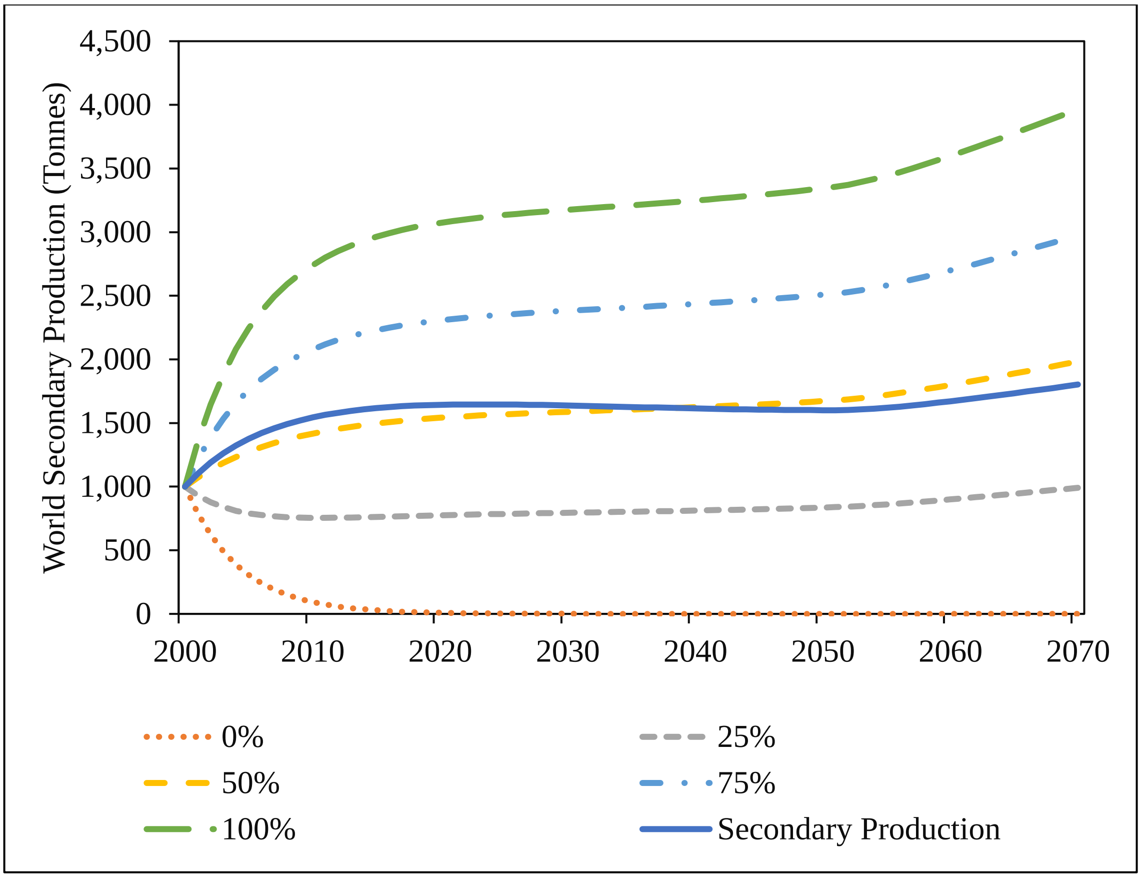

Figure 4-24 a Impact of recycling rate on secondary production of gold

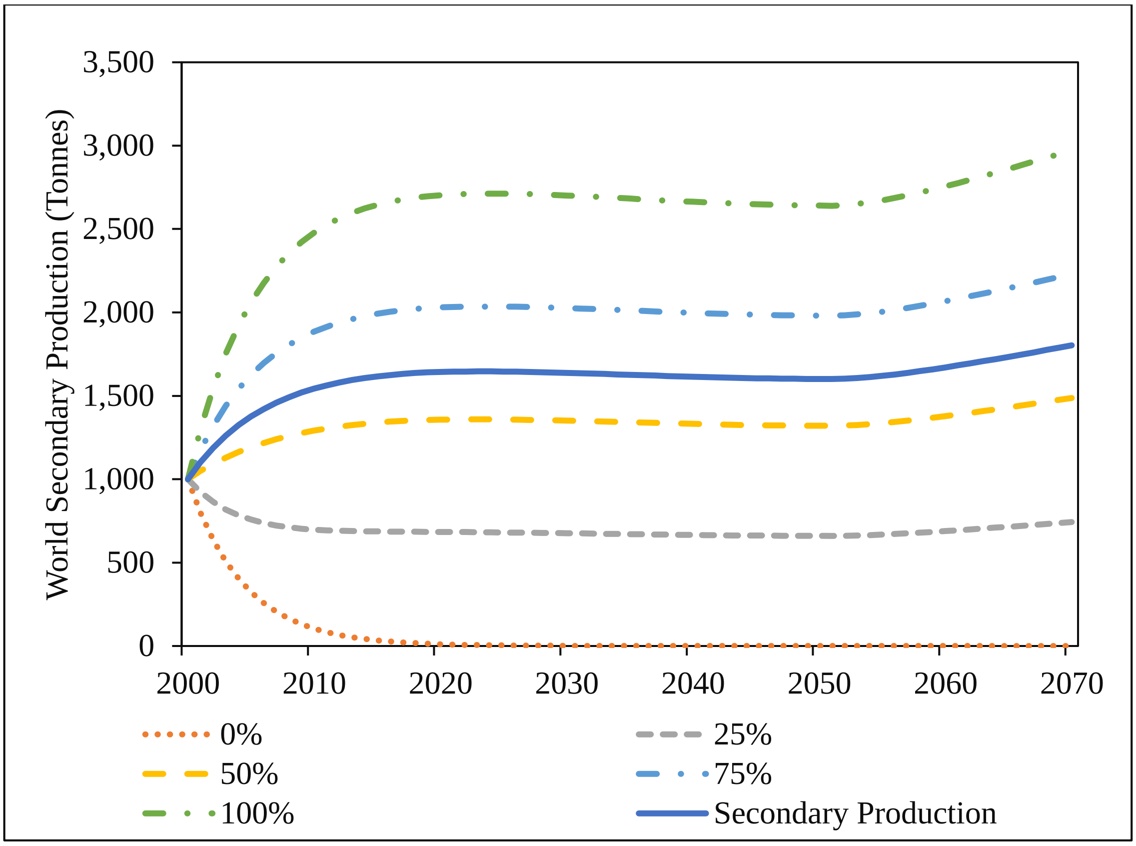

Figure 4-24 b Impact of recycling efficiency on secondary production of gold

Gold Resource Outlook

Decoupling gold resource use to reduce the future pervasive impact on the environment while maintaining the current and future consumption levels are outlined on the Towards Sustainability and Resource Efficiency scenarios depicted by Figure 4-25, Figure 4-26 and Figure 4-27. A 25% reduction on global gold extraction along the Towards Sustainability Scenario adjusts the mine production from 2 160t in 2020 to 2 620t in 2070. Along the Resource Efficiency scenario, mine production 2 390t (2020) to 2 900t (2070). Secondary Production under these scenarios decouples from the base case 1 645t (2020) and 1 803t (2070). The Towards sustainability and Resource Efficiency scenarios increase gold secondary production from 2 054t and 1 924t in 2020 to 2 253t and 2 093t in 2070, respectively.

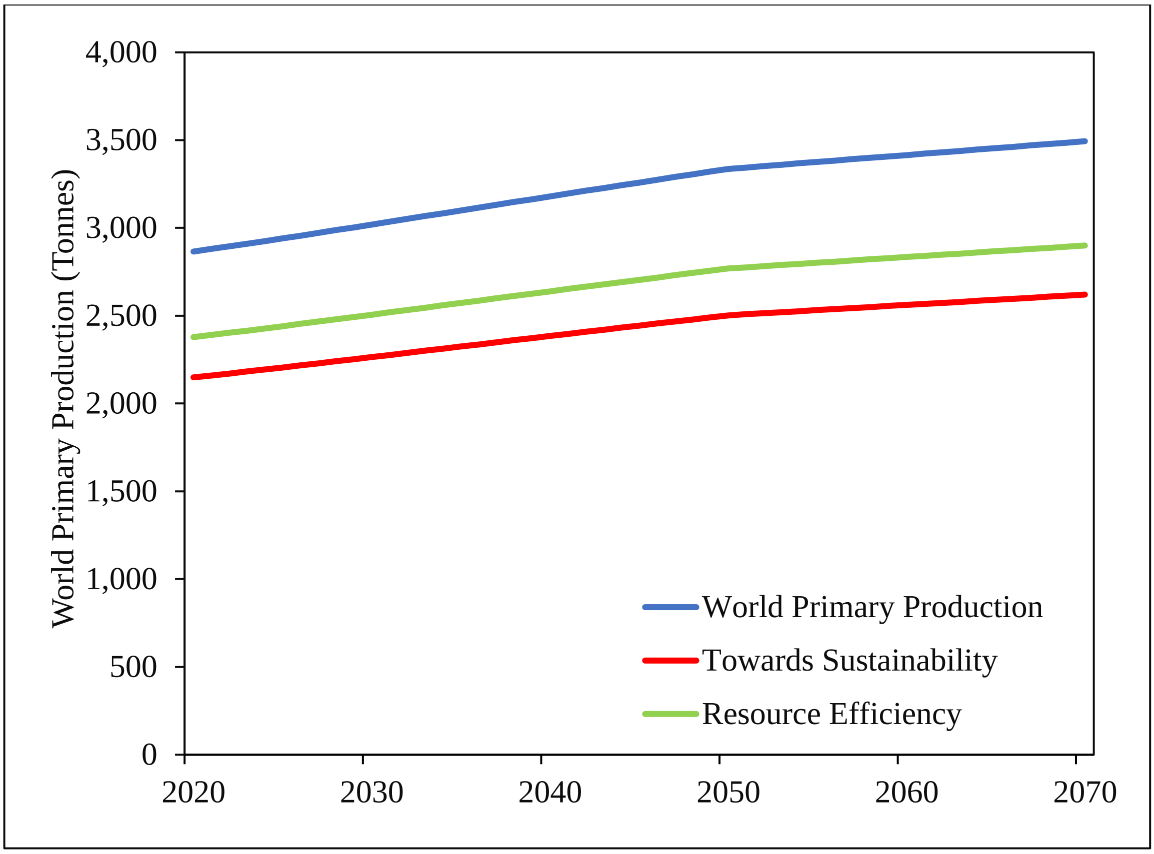

Figure 4-25 Towards Sustainability and Resource Efficiency Scenarios for gold primary production

The Towards Sustainability and Resource Efficiency Scenarios significantly reduces the material intensity of gold. Ore TMR reduces from 1 391t to 1 043t and 1 154t in 2020 and from 5 992t to 4 494t and 4 973t in 2070 respectively along these scenarios. In addition, increasing the EOL-RR and recycling efficiency, and reducing gold waste found in landfill would avail recyclates into the gold stocks.

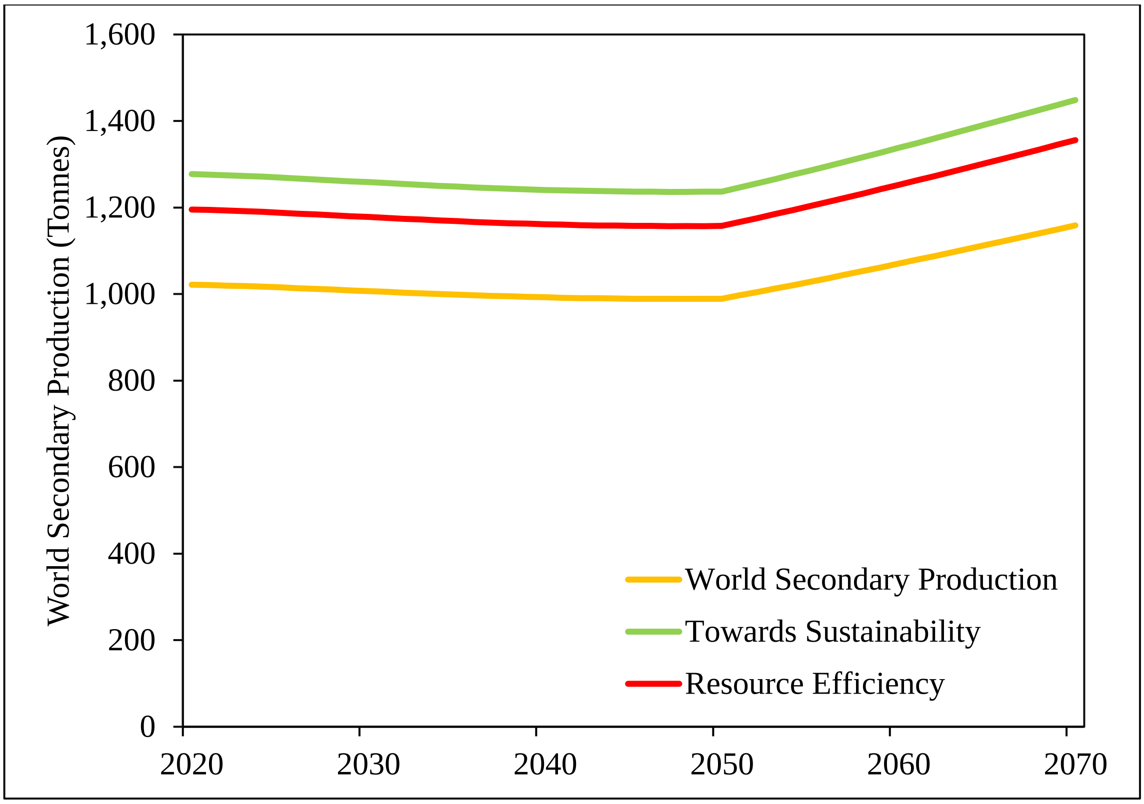

Figure 4-26 Towards Sustainability and Resource Efficiency Scenarios for gold secondary production

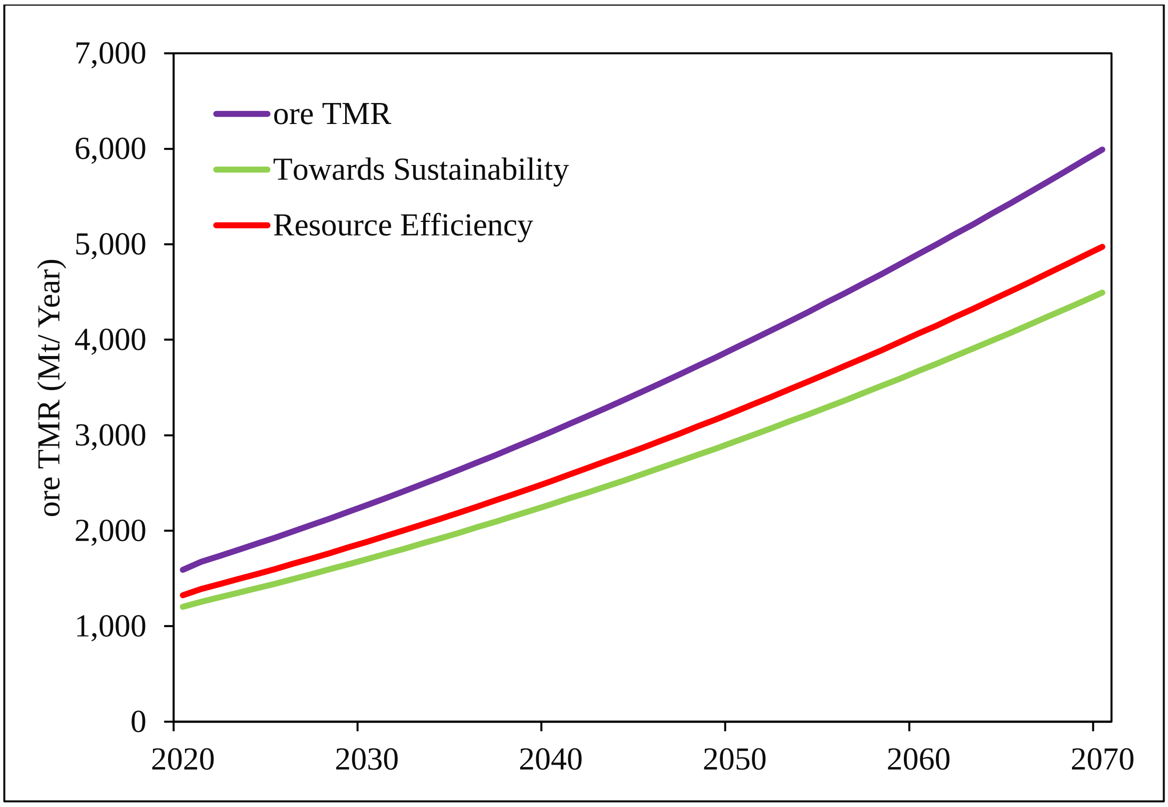

Figure 4-27 Towards Sustainability and Resource Efficiency Scenarios for gold ore-TMR

Gold Summary

While strong assumptions were placed under the gold model, the long term gold simulations show that gold mining will remain the main source of gold supply to 2070. Total gold supply increases from 3 630t in 1991 to 4 653t in 2070.Primary gold supply is the main contributor to the total supply increasing from 2 698t (2000) to 3 513t (2070). However, secondary production increases slightly as gold mining production stabilizes around 2050.

The lifetime of gold in consuming sectors has a large variability. This causes a "late" scrap recoverability where the material flows from secondary recycling increases in the third quadrant of the long term period of analysis applied in the study. However, EOL RR is high in the jewellery sector, ranging between 90-100%, which is the largest consumer by market share (IRP, 2011).

The criticality of gold in decoupling the metal from the environment has been discussed by other researchers (Nuss and Eckelman, 2014; Kosai and Yamasue, 2019; Watari et al., 2019). While these studies and our results are in agreement of the high impact of potential vulnerability that gold has on the environment, these studies do not address the critical importance of recycling to sustain the gold demand and the future long term changes of potential vulnerability and ultimately environmental conservation, in which we compel by applying gold TMR trends from Chapter 3 and through gold recyclability potential. We further observe the future outlook of gold along the Towards Sustainability and Resource Efficiency scenarios with aim to reduce the material flow of gold during primary production, which need to fall to 1 645t (2020) and 1 803t (2070), respectively, by 2070. In addition, under these scenarios secondary production would increase to provide the base case consumption to 2070.

To conserve the future sustainability of gold, producer countries need to improve their processing methods, recycling institutions and management, and further recommend formalizing the gold sector especially in developing countries. Further research on long term modelling studies based on the material flows of gold need to be improved. In addition, ethical sourcing of gold is also another major problem especially in developing countries. The materials flow accountability and tracking of gold in these countries requires synergy with the governing institutions to tackle social and environmental issues.

### 4.3.3 Iron Ore

The global model is iteratively calculated, with the adjustment parameters set to balance the model and minimize the error from the actual value by historical matching. Parameters applied in the iron model are displayed in Appendix 4-2. In our study, primary production refers to the summation of iron production from direct reduced iron (DRI) and electric arc furnace processes (EAF). This assumption is preferred as to reduce the complexity of material balance in modelling iron ore. In addition, the amount of iron ore sent into the DRI and EAF is equivalent to iron ore mining production. While the adjustment factors are treated as common parameters at a global level, they do not always fully fit the actual values at a regional or country level, where the error becomes large. To compensate for error at the regional level, the standard deviation between simulated world crude steel consumption at global and regional levels is measured to allow for any losses or gains in the material balance.

Figure 4-28 illustrates the base scenario trend behaviour between the total iron supply and consumption to 2070. The simulation scenario in the base case shows that iron supply is sufficient to meet consumption to 2070. Total iron supply will increase by 3-fold the current level from 1 220 Mt to 7 190 Mt. From this figure, the primary iron ore production is the main source of iron supply. Primary production is projected to increase from 1 420 Mt in 2020 to 2 555 Mt in 2070. However, by mid-2030 secondary production processes with quantities of 1 510Mt (in 2033) surpass conventional mining increasing its iron share proportion a 66% (in 2070) to sustain the demand of crude steel consumption to 2070 with 4 634Mt. World consumption increases from 1 019Mt in 2000 to 7 140Mt in 2070. In addition, between 2030 to 2070 there will be intermittent periods of excess supply.

The numerical crude steel consumption is relatively consistent with existing literature. The statistics of 2010 crude steel consumption are similar to our observed values at 1 458 Mt with 1 433 Mt (World Steel Association, 2000-2020) and 1 417 Mt (Oda et al., 2013). In 2050 the crude steel consumption is expected to reach 3 370 Mt. The rate of consumption grows from 0.3% in 2020 to 0.75% in 2070 as Figure 4-28 displays.

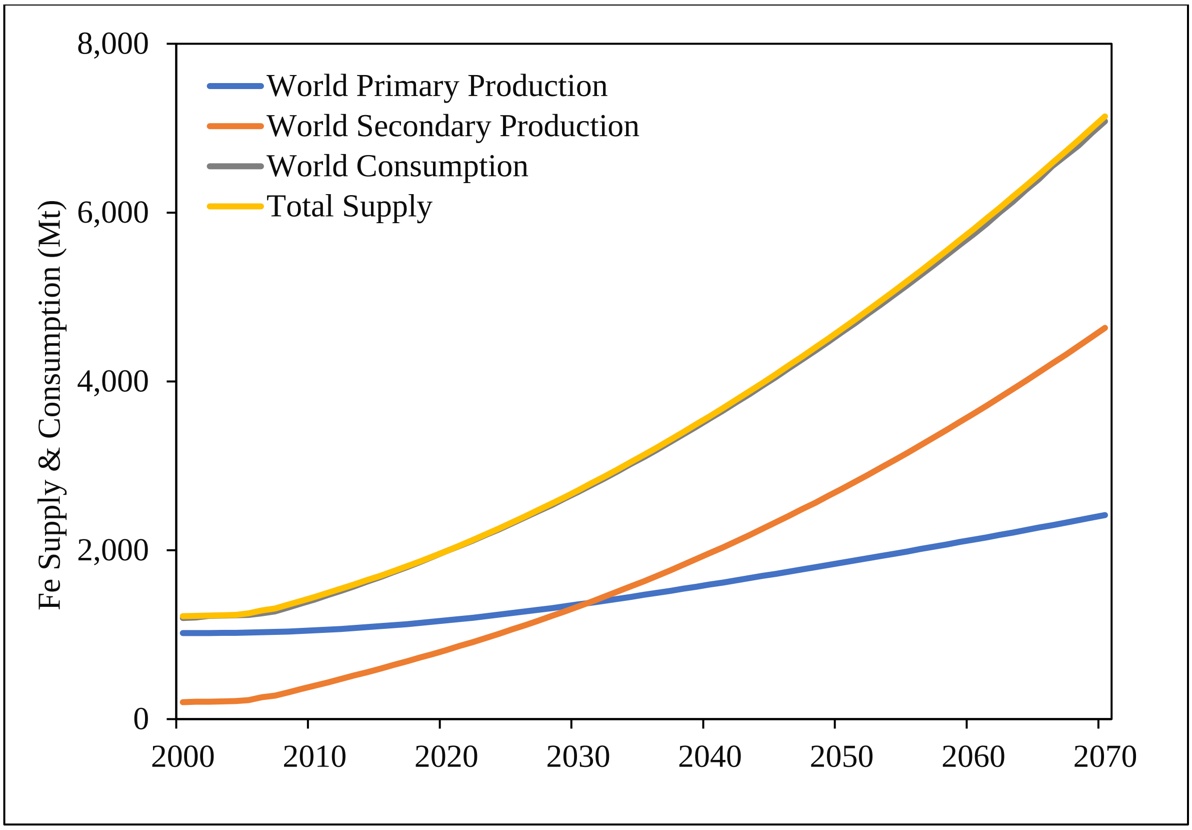

Figure 4-28 Iron supply and demand simulation

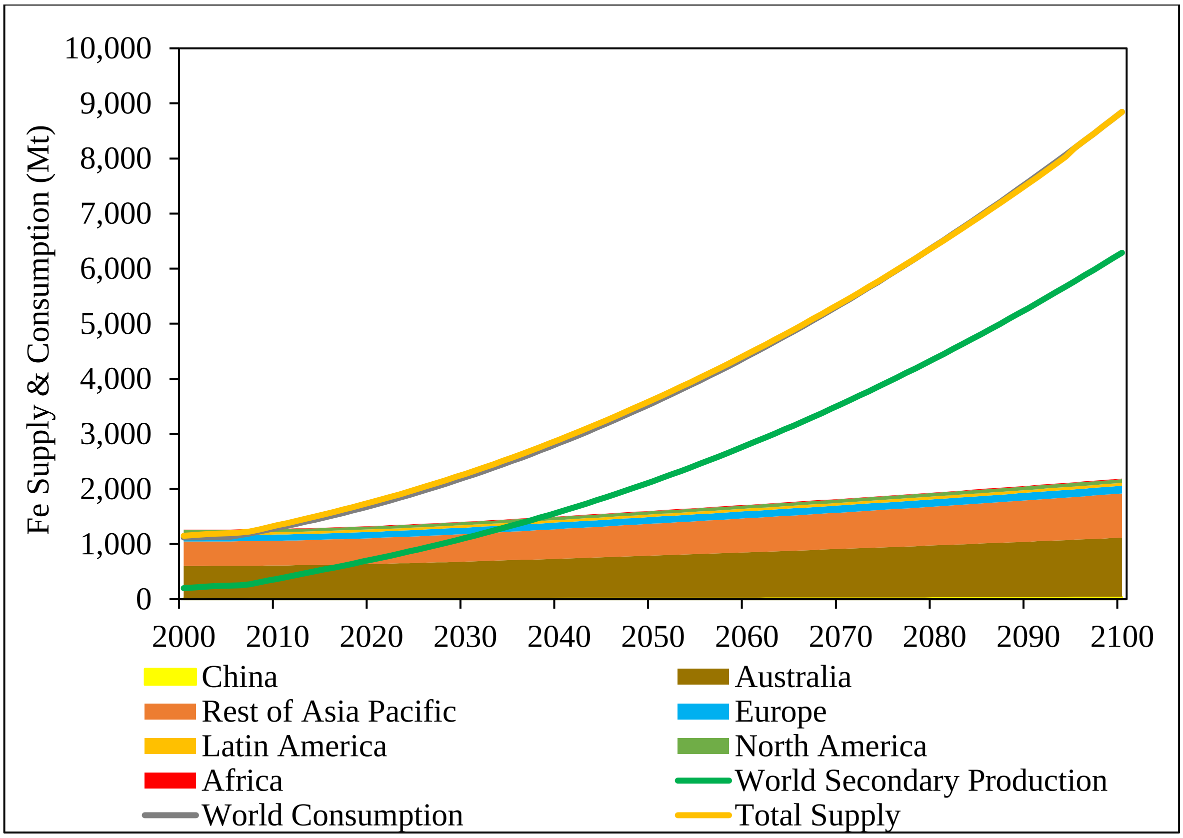

Figure 4-29 Iron regional primary supply, secondary supply and demand simulation

Figure 4-29 indicates the regional supply base model, where the Asia Pacific region has the largest cumulative share in iron ore supply of >80% that increases to 1 573Mt in 2070 from 1 047Mt in 2000. The top iron ore producer is Australia accounts to about 50% of the total share of production. The Australian production increased from 586Mt in 2000 to 881Mt in 2070. Around 2010, Australia experienced large scale iron ore production to cater for the increasing demand in China. The ore TMR of Australia increased rapidly by 5 folds and will continue putting pressure until the Asian Pacific market particularly China, reduces its material consumption per capita. Even though China is a large consumer iron for steel production its national production remains low, because of the low ore grades found in the country. The primary production changes from 146Mt to 161Mt over the study period. Old scrap supply could reduce up to 80% of iron ore required for steel making in China by 2050 (Oda et al., 2013; Pauliuk et al., 2013a, 2013b).

Classification of the iron manufacturing demand based on past work (Ciacci et al., 2015; Elshkaki et al., 2018). According to these sources, iron usage percentage share (MS) is 48% construction (C), 31% industry (I) and 13% in the automobile/transport (T) industries (Ciacci et al., 2015; Elshkaki et al., 2018) estimated on using Equation 4-13. The Others sector was not included in the analysis. The consumption trends of these applications are regressed, in million tonnes, below:

$$C_{Fe,C,MS}=6.235t+6.565*10^{8} \qquad (R^{2} = 0.620)$$

$$C_{Fe,I,MS}=0.30t-3.278*10^{7} \qquad (R^{2} = 1.000)$$

$$C_{Fe,T,MS}=828.08t-1.182*10^{7} \qquad (R^{2} = 0.634)$$

Figure 4-30 illustrates the iron demand trends to 2070 by the sectorial market share. The major iron demand is utilized in the construction sector followed by transport and industry. This large share in construction is largely accounted by the large scale consumption by China to support its national industrial growth for development which has been a leading potential market for iron since early 2000s.The total demand for iron steel grows to above 3Gt Fe by 2070. This trend is supported by available literature (Müller et al., 2011; Pauliuk et al., 2013a, 2013b; Morfeldt et al., 2015).

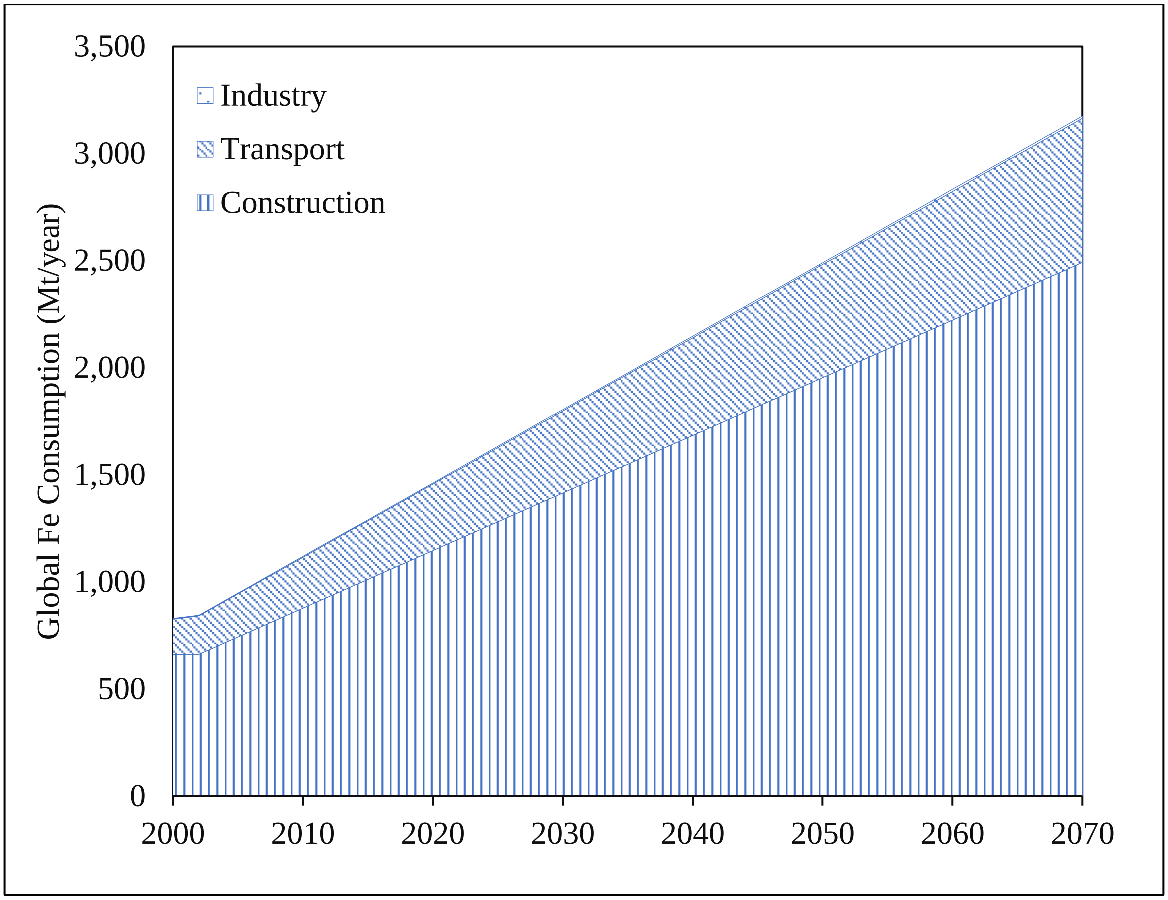

Figure 4-30 Iron demand by sector

The intensity of use by GDP is simulated on the basis of the demand trends (Appendix 4-3b) for each sector. Similar to copper, future intensity of use project monotonic increases over time before declining to 2070. However, the Asia Pacific region has a steeper deceleration in the industry sector. In the construction sector, the Asia Pacific and African regions have similar intensity of use future pattens with a small gap between the two trajectories as the Africa trend follows behind. In addition, Figure 4-31 depicts that the Asia Pacific region has the largest IU trajectory into the long term. The North American region which consists of advanced economies such as USA and Canada, require minimal resource consumption of about 2 500 tonnes per capita GDP as their economic focus has shifted to services. For Africa, its developing countries are expected to advance rapidly before peaking into before 2050 to become more advanced than Latin America.

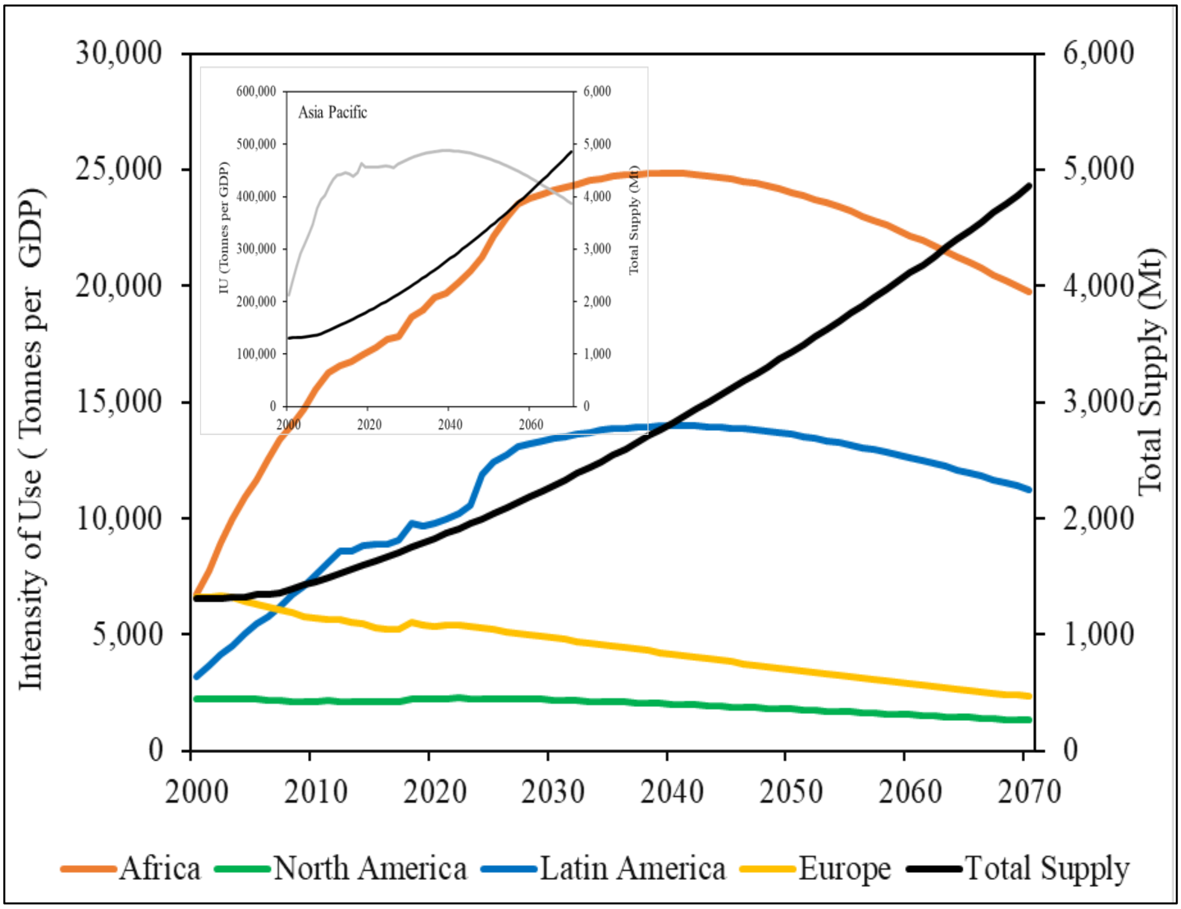

Figure 4-31 Iron total intensity of use by region

Like other metals, while iron has an integral part in transforming the economic development of a nation, it is also associated with potential degrading environmental impacts. In addition, though iron ore is a bulk commodity metal, the low iron ore-TMR coefficient measured in Chapter 3 exemplifies that iron has very little impact on the environment compared to other metals such as gold, copper, nickel, lead and zinc. The possibility of recycling in iron ore is at least twice as higher than the natural ore grade (Figure 4-32). The growth rate of recyclability increases by 0.89% between 2000 and 2070 with very little change in grade. This is because the iron ore grade and strip ratio changes negligibly over the study period. The recycling rate strongly influences the rising annual urban ore TMR compared to recycling efficiency. Additionally, the current level of recycling efficiency will ensure sustainability between production and environment to 2070.

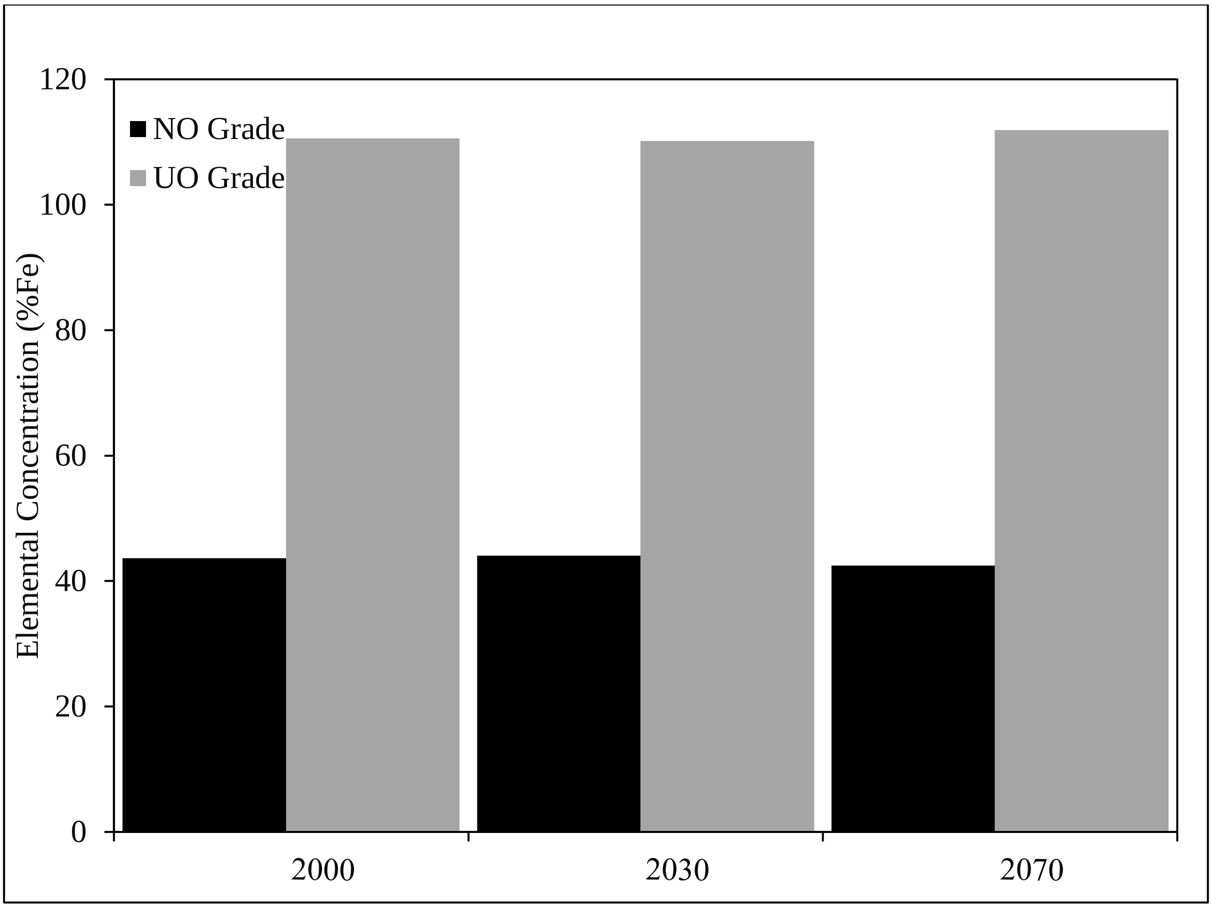

Figure 4-32 Iron ore natural ore and urban ore grade

Impact of exploration and technology on primary production of iron

Similar to copper production, exploration and technology are the main factors that increase the geological confidence of defined and measured resources/reserves available for iron ore mine production. Figure 4-33a and Figure 4-33b presents the sensitivity analysis of exploration rate and technology rate. In contrast to copper sensitivity analysis, changes in exploration rate have a less impact in change in tonnage of iron ore production while the technological advancement of iron is critical to the raw material availability. As such, technological advancement in the iron industry is important to continually purify the iron ore for steel production. Identifying iron ore deposits and continuity in exploration remains flexible due to the abundant resource in deposit size.

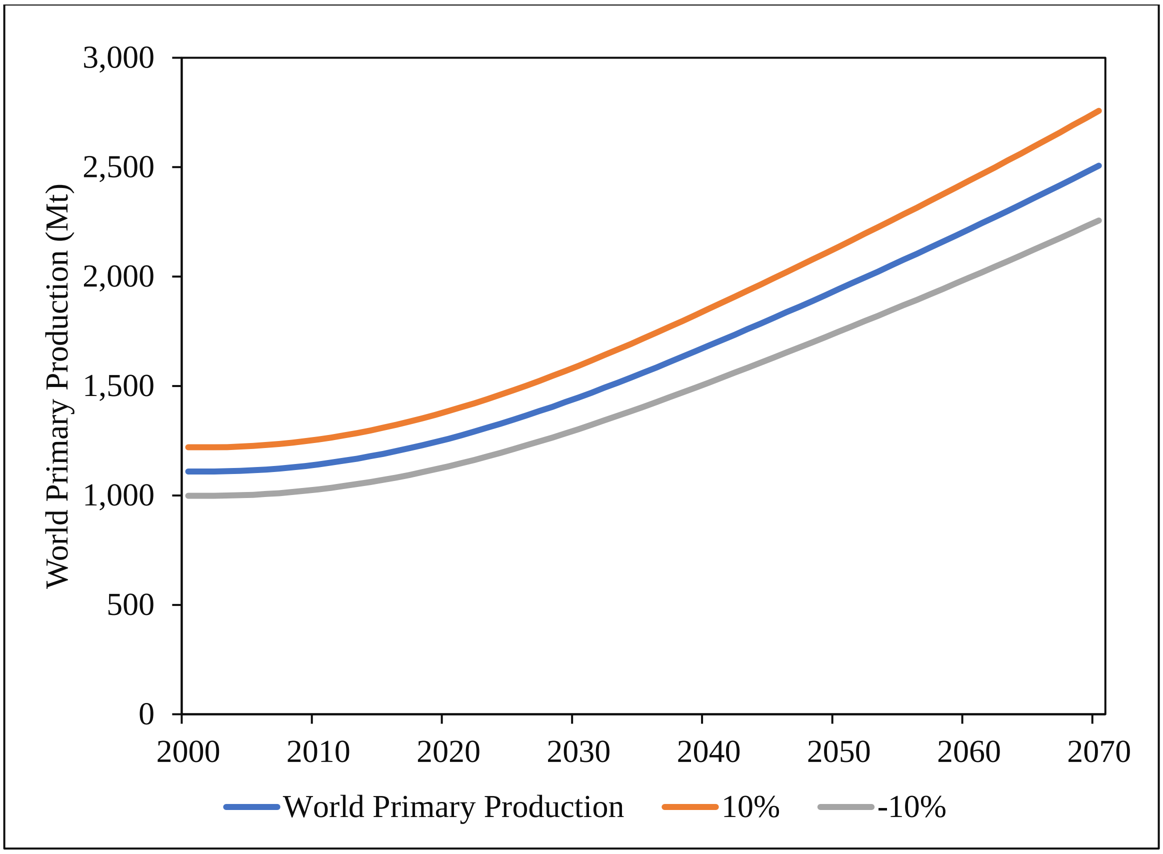

Figure 4-33 a Impact of exploration on world primary production of iron

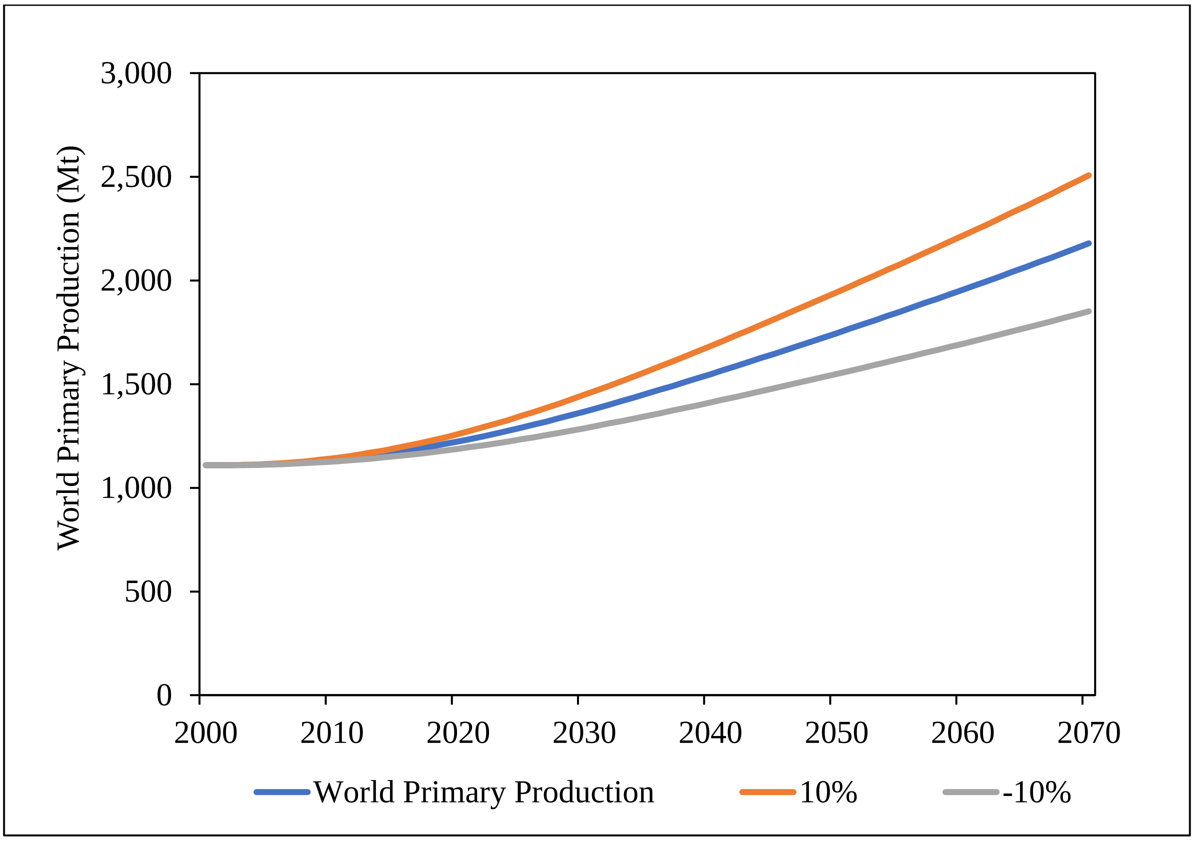

Figure 4-33 b Impact of technology on world primary production of iron

Impact of crude steel consumption on scrap recovery

The steel demand has a direct effect on scrap recovery. The rate of demand and consumption rate are almost equivalent in this study. Increasing in the annual consumption rate raises the recovery of scrap at a constant crude steel lifetime from the in-use stock of consuming sectors (Figure 4-34). A 25% and 75% increase in consumption can increase the probability of the recovery of scrap to 58 655Mt (25% sensitivity) and 168 613 Mt (75% sensitivity) by 2070. Oda et al. (2013) indicates that a circular economy can be achieved at a low-level demand reference case.

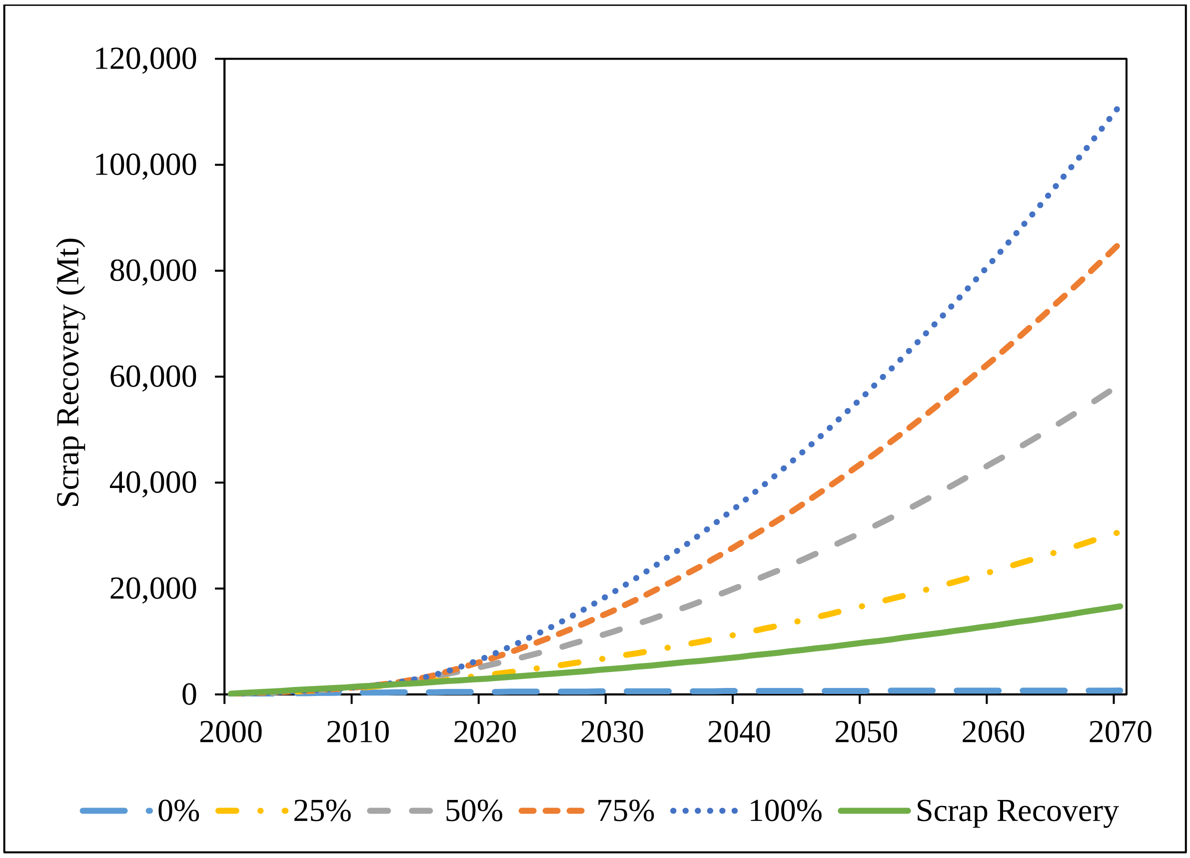

Figure 4-34 Impact of consumption rate on scrap recovery of iron

Impact of recycling on secondary production

On secondary consumption, two major factors are important to the future scrap availability: recycling efficiency and EOL-RR. The product lifetime, in-use stock from consuming sectors are intrinsically linked to the recycling rate. Recycling efficiency and EOL-RR are estimated at 43.7% and 33%, respectively. The recycling efficiency is consistent with various sources (UNEP, 2011). The model-based recycling rate is pessimistic compared to previous studies (Birat; 2001; Steel Institute; 2007; UNEP, 2011; Oda et al., 2013) as it is based on the assumed product lifetime duration function. Oda et al., 2013 notes that if a recycling rate of 85% is used, that could lead to an overestimate of future scrap availability. At a global scale a 70% EOL-RR is applied (Neelis and Patel, 2006; International Energy Agency, 2007; Oda et al., 2013). Recycling efficiency influences the degree of secondary production more significantly compared to the recycling rate. Raising or lowering the recycling efficiency have a decelerating effect, either positively or negatively, to the recovery of scrap. The current recycling rate at current levels is optimized (Figure 4-35 a) while the recycling efficiency is about 60% (Figure 4-357b). This is because every steel plant is also a recycling plant, and all the steel production consumes the scrap making the high level of recycling from iron to steel with very limited room for improvement (World Steel Association, 2021). To raise the recycling efficiency by 100%, the recycling rate would equate to the simulated secondary production level. Presently, the recycling efficiency ratio to recycling rate is 0.6. However, lowering the recycling efficiency to between 25-75% effect would result in a lower recycling rate in the system.

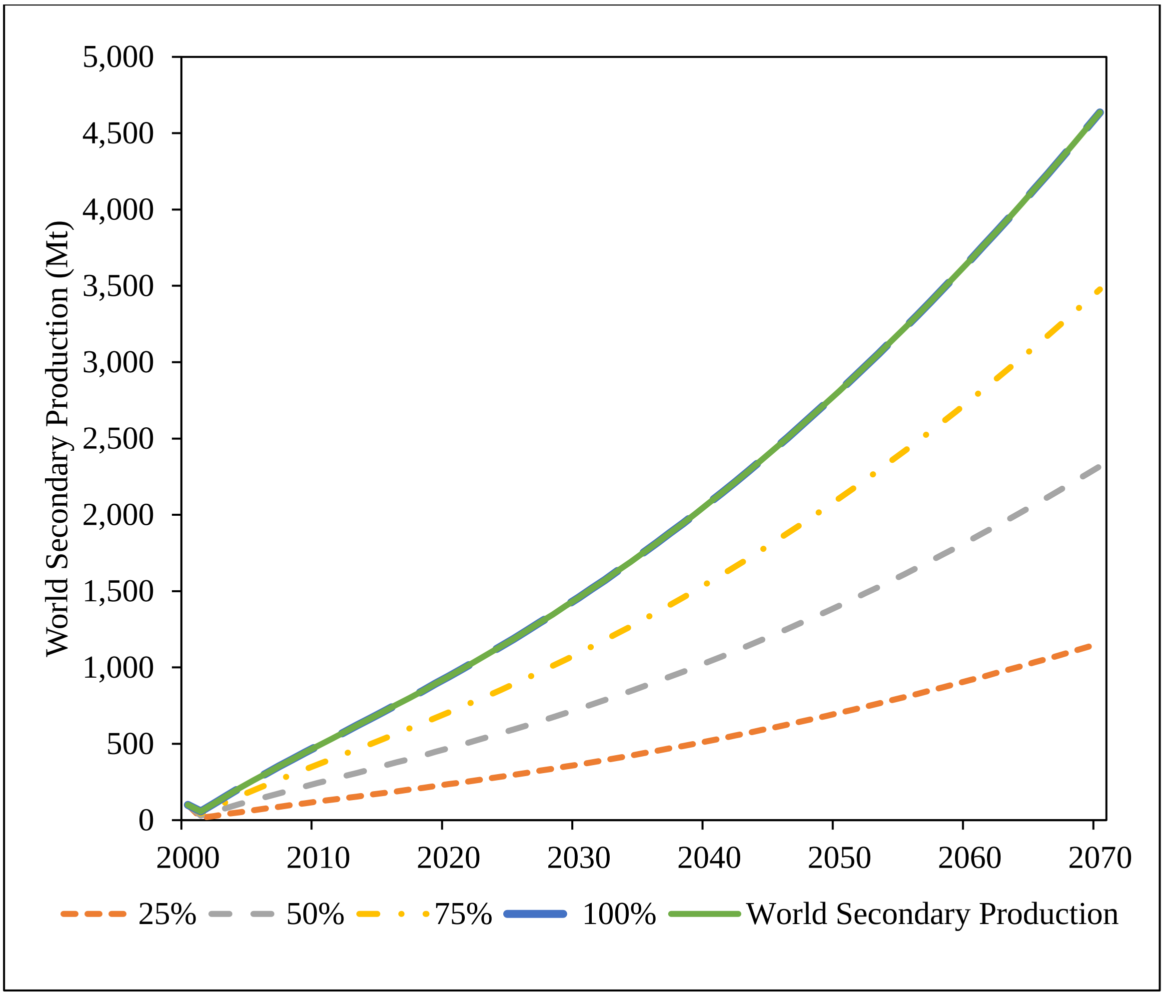

Figure 4-35 a Impact of EOL-RR on world secondary production of iron

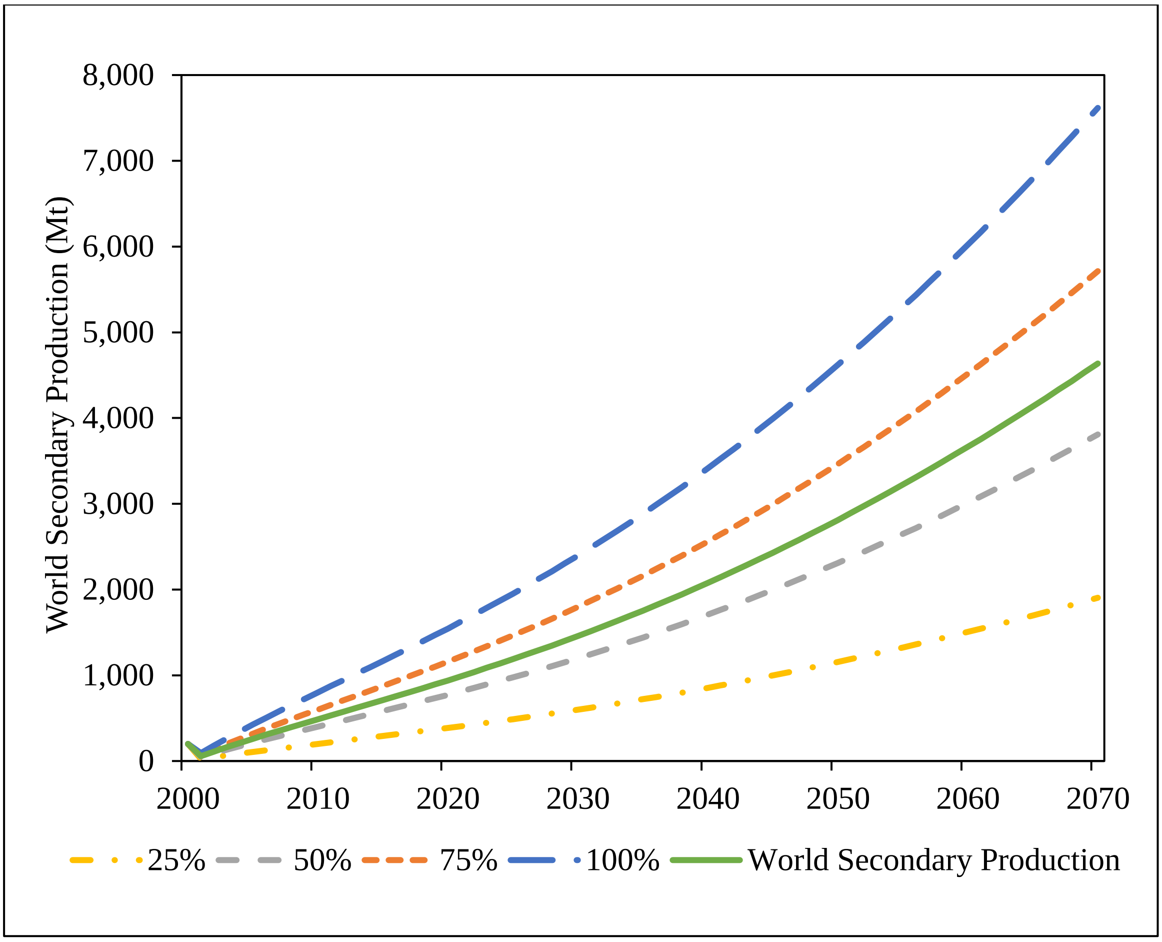

Figure 4-35 b Impact of recycling efficiency on world secondary production of iron

As the percentage change of EOL-RR increases the amount of inflow material into the landfills decreases as shown in Figure 4-36a from 25% to 100% sensitivity. This could possibly interpret to effective collection infrastructures of iron waste materials are becoming more efficient as displayed in Figure 4-36b. However, at 0% sensitivity of Figure 4-36 a with no influence in EOL-RR accumulate waste flows to about 2030 and quickly peaks to 2070, as the recycling efficiency takes a linear path at the same level in Figure 4-36b shows that a lot of material unaccountably diffuses in the system. Iron material flows accounted keeps the total material requirement of the resource as a higher proportion of iron is converted into recyclable material. Increasing the recycling rate of iron drastically reduces the inflow of waste material entering the landfills therefore nulling future waste flows.

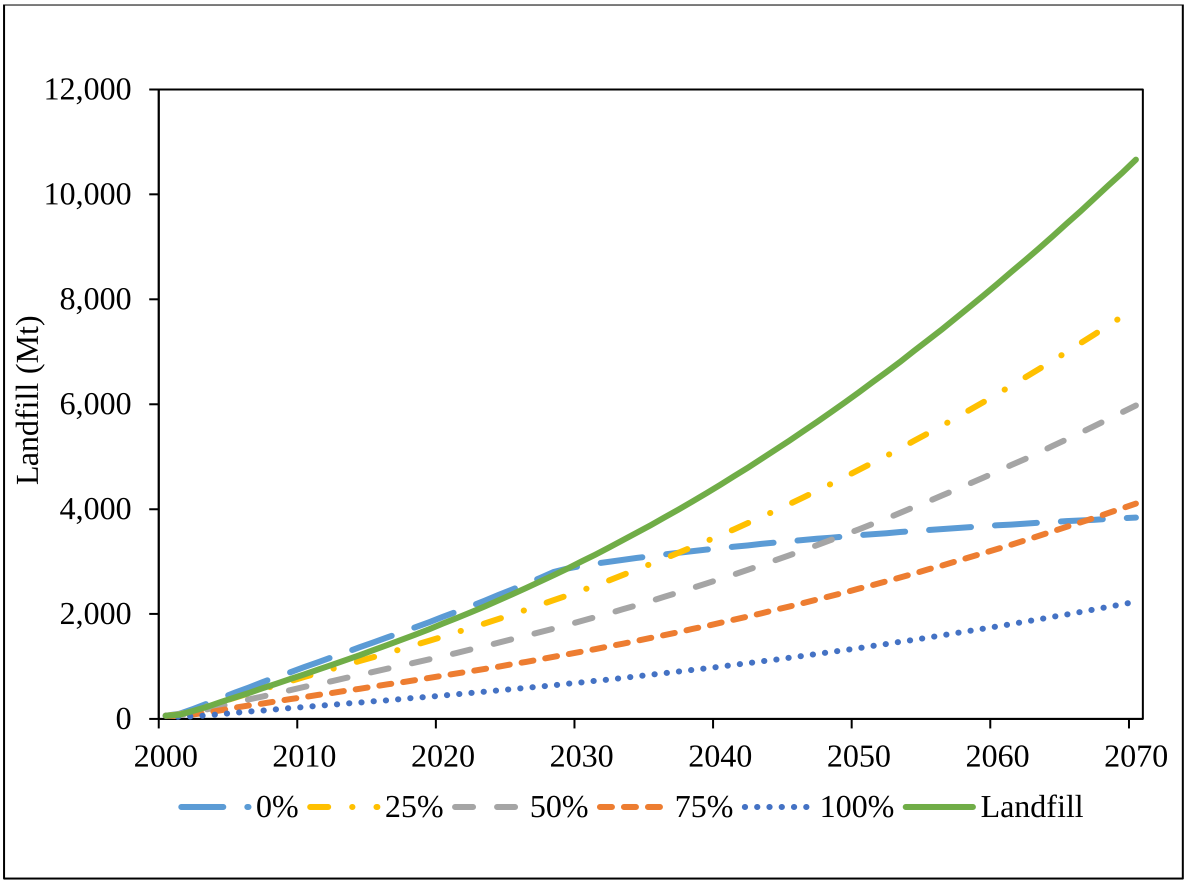

Figure 4-36 a Impact of recycling rate on landfill of iron

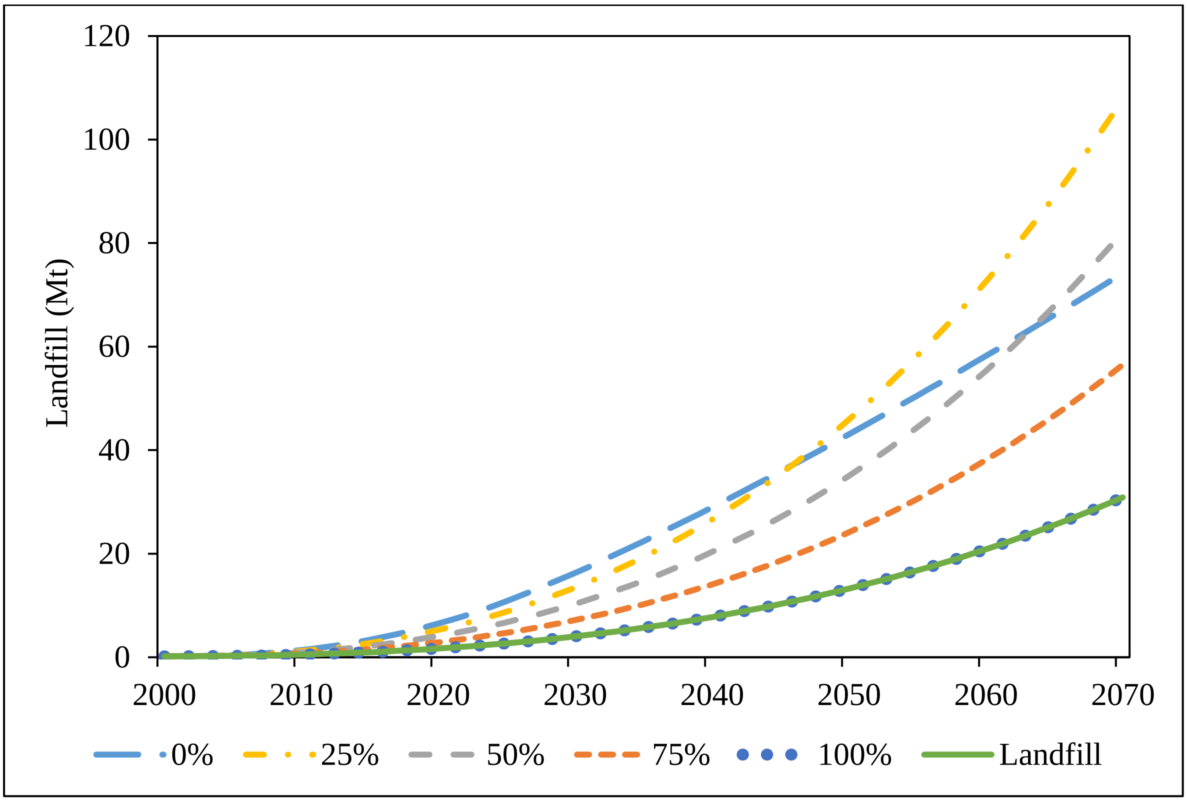

Figure 4-36 b Impact of recycling efficiency on landfill of iron

Iron Resource Outlook

The Towards Sustainability and Resource Efficiency scenarios for iron are shown in Figure 4-37, Figure 4-38 and Figure 4-39. Under the Towards Sustainability scenario, iron production falls by 25% would require the production levels to reduce from the base production level 2 417 Mt to 1 812 Mt in 2070. The Resource Efficiency scenario reduces iron production to 2 006 Mt in the same period. However, as global primary iron extraction falls, the iron consumption would require the EOL-RR and recycling efficiency to increase significantly to compensate for the resource supply gap. Secondary consumption under these scenarios, Towards Sustainability and Resource Efficiency, would increase from the base recycling production of 4 634 Mt to 5 207 Mt and 4 992 Mt respectively to 2070. Australian extraction against these scenarios could decline from 880 Mt by 2070 to 680 Mt and 744 Mt along the Towards Sustainability and Resource Efficiency scenarios, respectively.

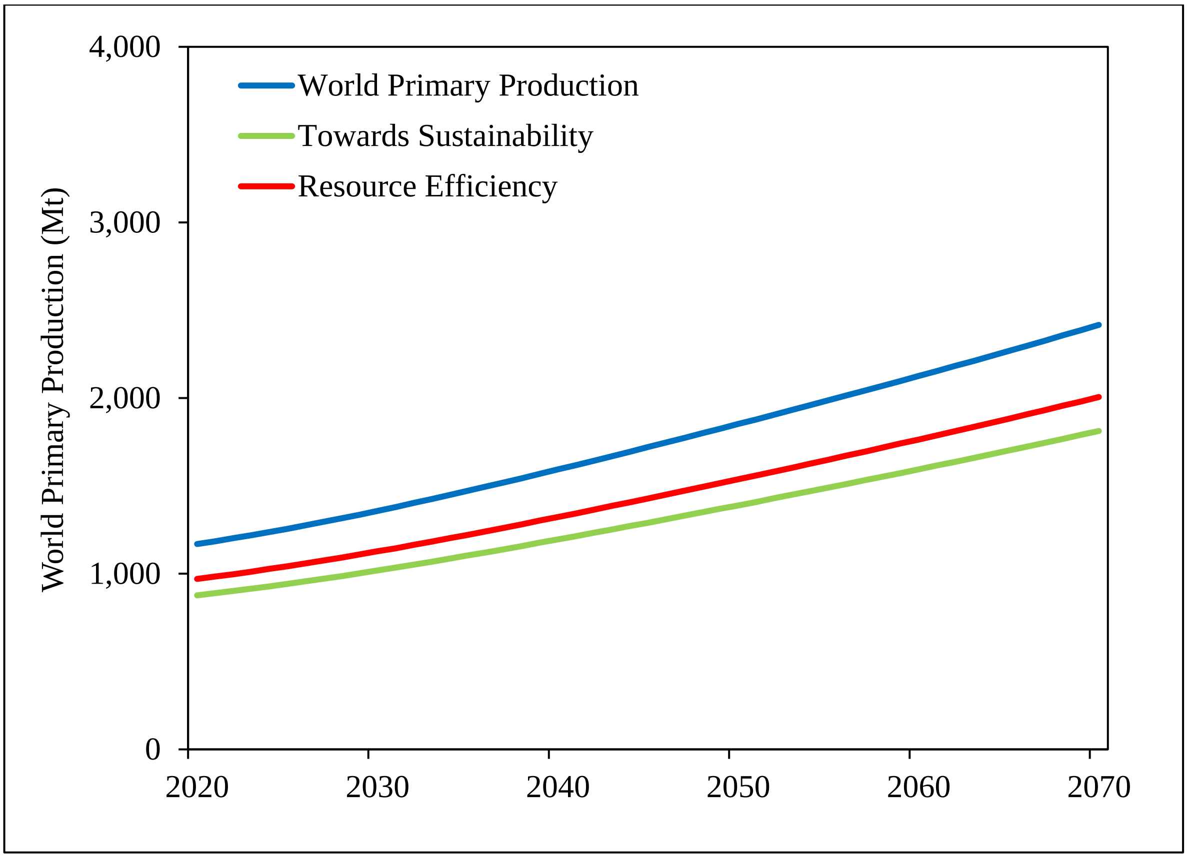

Figure 4-37 Towards Sustainability and Resource Efficiency Scenarios for iron primary production

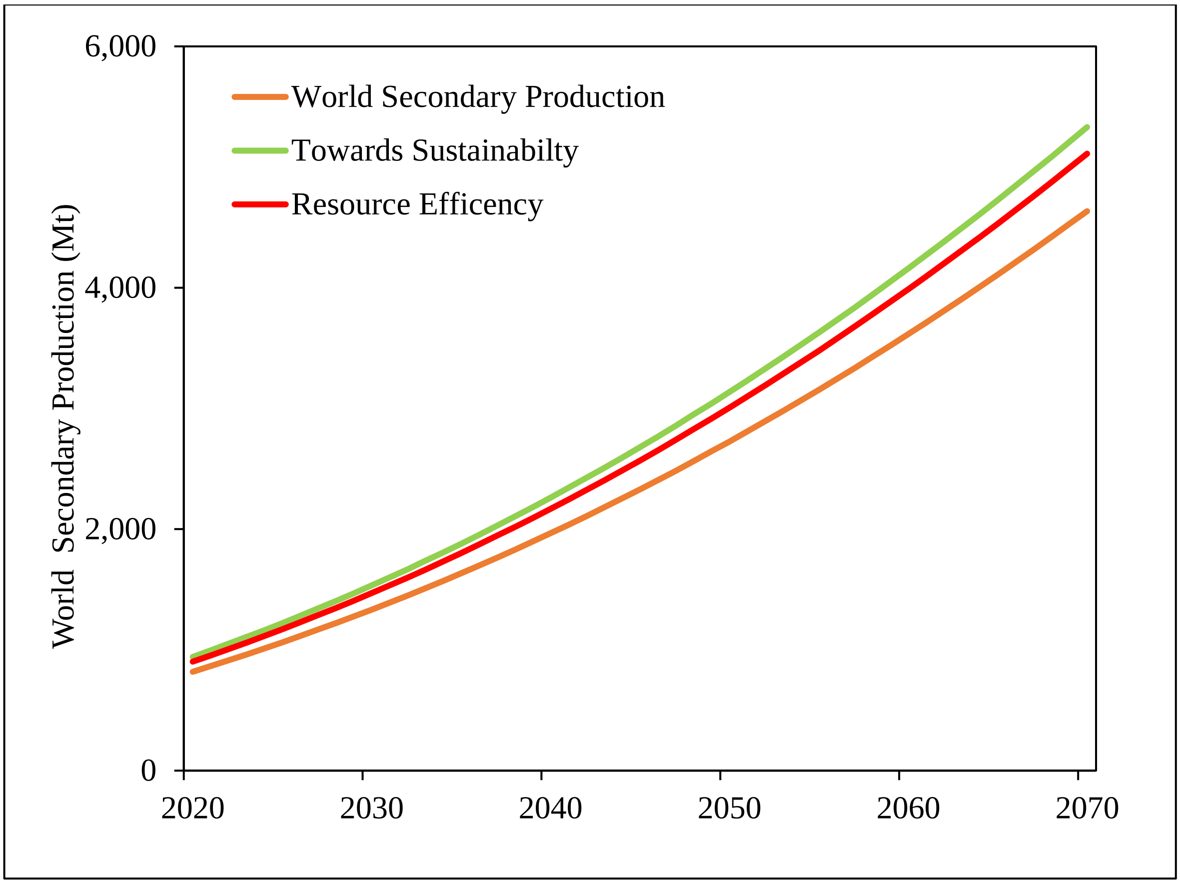

Figure 4-38 Towards Sustainability and Resource Efficiency Scenarios for iron secondary production

TMR flows compared with the original scenario in Figure 4-39 would reduce to 33 909 Mt/year and 37 526 Mt/year on the Towards Sustainability and Resource Efficiency Scenarios from 45 212 Mt/year by 2070. Even though the recycling rate in has limitations in future advancement, reduction on the production rate along the sustainability efficiency scenarios will reduce the global iron extraction by at least 10 000Mt/year in material flow in 2070. The ore TMR flows in Australia which is higher than the world iron TMR average, decrease to 29 551 Mt/year and 32 703 Mt/year at a 25% and 17% reduction by these scenarios from 39 401 Mt/year (base trend) by 2070, respectively. Improvement in the efficiency of collection of recyclates at the landfill sites could provide an efficient system in resource consumption thus reducing the environmental footprint.

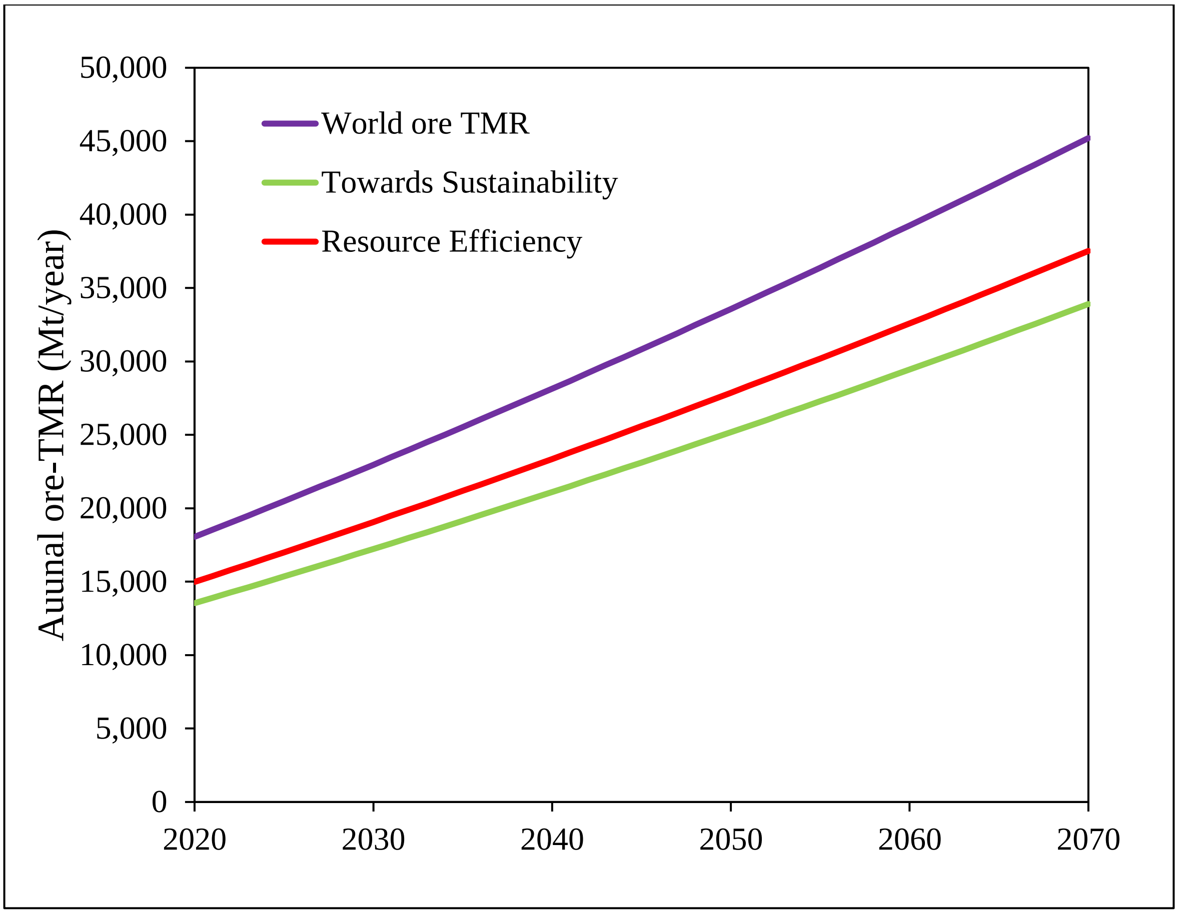

Figure 4-39 Towards Sustainability and Resource Efficiency Scenarios for iron TMR flow

Iron Summary

Iron ore primary production is surpassed by secondary recycling by mid 2030s to become the main source of resource supply to 2070. Even though iron ore resource/reserve size is abundant and requires ample exploration for new discoveries, the resource industry continues to improve the recycling industry for steel production (World Steel Association, 2020) and raising the recycling efficiency to recycling rate ratio. This industrial practise will ensure sustainability and future availability should demand rise at increasingly exponential rates.

Global iron mine production activities occur around the Asian Pacific Region with Australia being one of the top producer countries. For consumer countries, this provides a geographical advantage to accessibility to the iron markets especially fast increasing economies such as China and India.

With a relatively low vulnerability potential on the environment, resource stakeholders should continue to strive for pathways that create a “healthy” and sustainable in iron industry by focusing to achieve Towards Sustainability and Resource Efficiency trajectories to 2070.

## Summary

Global and regional simulations of copper, gold and iron were created with aim to comprehensively evaluate the sustainability of these metals over the long term period. The model focused on primary resources that determined the ultimate resource limit and ore quality. The ore quality is predetermined at a given cut off grade of 0.2% Cu,0.2g/t Au and 20% Fe. Secondly, the promotion of recycling becomes an important alternative in sustaining the total supply of these metals. The recycling rate and recycling efficiencies of the metals are considered.

On the demand side, consuming sectors of these metals as a function of the per capita GDP are the driving factors of the material flow in the systems. Their intensity of use is determined to delineate the material consumption share per sectorial use. Finally, the impact on the environment caused by these supply and demand dynamics are delineated.

From the study, the ultimate recoverable reserves of copper, gold and iron are unlikely to constraint the long term resource supply. However, the annual production rate and technological advancement of mining will influence the trajectory of resource supply.

The future demand and consumption of copper, gold and iron is expected to rise from their current levels by metal application. As the mining supply rises to support the consuming sectors, mining production will eventually peak. As metal mining peaks, secondary production would rise to support in availing the resources.

Primary copper production is expected to remain as the main source of copper supply into 2070. However, due to the accelerating deterioration in the metal ore grades, the recyclability probability requires to be increased at a growth rate of about 39%. The adverse negative impacts on the environment caused by copper production can be alleviated by advancement in technology including metallurgical and or metal substitution.

By 2070, the share of primary production and secondary production for iron supply is almost equivalent. This is owed primarily because the recycling rate of iron is optimized the system infrastructure of steel production and steel recycling are commonly on the same site creating insignificant material loss from the system (World Steel Association, 2021). Due to this the total material requirement of iron measured in both mining site and in urban ore of iron is unlikely to rise drastically in future. Apart from improving the recycling rate and recycling efficiency of these metals, an alternative in improving the product lifetime and durability would lead to a lower material consumption.

The iron secondary production grows twice the size of primary production in 2070. Our results are contrary to Oda et al., (2013) that state that the EAF steel making would increase 2.1 times in 2050 compared to 2010 but would not be sufficient to overtake the assumed steel production in that study and as such, primary steel making would remain the dominant source. However, they do not the importance of enhancement of the recycling rate for future resource conservation. Our study is similar to Neelis and Patel (2006) further suggest that the global share of secondary inputs to steel production is expected to increase from 40% to 60% to 2100. Gold recyclability potential grows by 54%. The adverse negative impacts related to gold mining will continue rising as gold deposits become matured brownfields. Gold recycling rate therefore needs to be raised further above to at least 75%, to improve scrap recovery. The range of recycling rate that ensures future sustainability is between 55% to 80% (Oda et al., 2013, Neelis and Patel, 2006; Paulick et al., 2017) similar to our estimate of 57.9% applied.

Further, the reduction of global metal extraction based on the Towards Sustainability and Resource Efficiency by 25% and 17% respectively provides a way forward for resource accountability in decoupling resource use from environment. As such, the total material requirement would ultimately reduce by these applied rates discussed therefore easing the negative pressure on the environment.

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# CHAPTER 5

# CONCLUSIONS

A sustainable future through sourcing and consumption of resources is at the forefront to comprehensively understanding the present value of these resources. The present trends in global resource extraction are steeply outward, with no significant sign of slowing down, leading to worries of the sustainability of resource supply in the future (van der Voet et al., 2005, 2018). No generally accepted global level quantitative resource scenarios exemplifying resource extraction and use exist at this moment, which can be considered as a huge gap in addressing the resource challenges (van der Voet et al., 2005, 2018).

Whether these resources are “finite”, or the impact of mining could have on the environment, it allows for a sustainability model. While existing literature denotes varying future projections of the future metal supply, they provide valuable hypothesis with regards to resource accountability and management. This study, therefore, aimed at comprehensively developing a systems framework in which metals could be quantitatively measured in the long term for the future resource availability, as a measure of supply risk. The critical issue of physical scarcity, ore quality and associated environmental implications relating to total material requirement are addressed.

The first chapter outlines the status quo in the relationship of mineral resources and anthropogenic activities linked to their extraction and consumption. The pertinent issue that highlights the concern of increasing environmental vulnerability caused by deteriorating ore grades and increasing strip ratios as a result of increased ore resource production therefore a threat to future resource availability. It further aims to investigate the potential of secondary recycling production as an alternative source for future metal sustainability and resource conservation. Chapter two gave a comprehensive outline of the literature review related to this study.

The third chapter aims to address ultimate reserves, declining ore grades and total material environment during mining production. The physical economies of scale of mining production depicted by the strip ratios will continue to increase. As such a larger material output will be moved to access a unit of ore production. Further, the gradual depletion of ore grades is characteristic for all mineral resources, the reserve uncertainty is unlikely to lead to a physical scarcity problem but by risks related to environmental, social and governance (ESG) that likely to cause supply disruptions (Henkens and Worrell, 2020; Jowitt et al., 2020). The rate of ore grade decline varies for these metals, with gold having an accelerating pace owing to the long historical mining background. The base metals copper, nickel, lead and zinc have similar decline patterns due to their co-occurrence nature and metallurgical processing patterns. Iron ore grade slightly declines over the study period to 2070 due to its large reserve size and crustal abundance. For the same reasons, the degree of vulnerability on the environment measured by the TMR, has high probability to rise due to metal mining activities is forecasted to be largest for gold, followed by the base metals and to a lesser extent iron. In addition, the quality and tonnage of these metals will vary by size. Latin America and Chile will continue being important contributors to the production share of copper at a 0.2% Cu cut-off grade. Asia Pacific and Australia will remain as significant players in the production of iron at 20% Fe cut-off grade. However, it is important to know that the future grades may decline lower than the assumed case following historical trends creating further negative adverse impacts to the environment as ore TMR rises.

In the fourth chapter, the study provided an account of recycling functionality. Improving the metal efficiency by adjusting the in-use metal stock to sufficient levels to meet metal demand for consuming sectors provides prospects in stabilizing the total metal supply (Northey et al, 2014). In our study, adjustment of the recycling rate and recycling efficiency provide the opportunity of a sustainable and consistent flow of metal resource in the dynamic system. As the primary metal production peaks secondary production sources rise to significant levels. For copper and gold, even though recycling processes increase, primary production remain the main source of metal supply by 2070. For iron, the relative share of secondary production to primary production in the total supply is almost equivalent by 2070. The TMR intensity which include hidden flows from economic and non-economic activities are high for gold followed by copper compared to iron owing to the lower ore grades.

In the copper sector, other sectors followed by electrical, industry and lastly transport sector have the highest material requirement leading to high ore TMR intensities. In addition, the Asia Pacific region has the highest copper intensity of use, which ultimately will lead to a higher material requirement as the countries consume more to progress into advanced economies. By 2070, the ore TMR trends will be high as discussed in Chapter 3. Measures to decouple resource use should be at the forefront of policy making towards reduction of the environmental footprint. The iron sector, however, has a generally equally distributed monotonic rate of material consumption thus the trend in intensity of use remains similar in decline trend. By sector, construction followed by industry and transport has the highest material use. Asia Pacific is the largest consumer of iron by region. Even though the ore TMR of iron remains low to 2070, policy makers should continue to support the industry and find alternatives in improving the materials flow of iron especially in the product lifetime to improve efficiency. Lastly in both these sectors, the transport sector remains the least metal consumer. As technology in electric automobiles transitions to cleaner energy the usage of these metals especially copper will spike the resource flow over time. As such, transition to the use of electric cars and greener technology should simultaneously design resource cycles that could provide a nexus approach to achieving sustainability in the sector (Watari et al., 2019). For gold, the intensity of use is largest in the jewellery sector owing to the large consumption by market share. However, the trend is on constant decline since 2000. The investment sector intensity of use rises before declining in late 2020s. the technology sector consumption doesn’t vary much over the study period.

The metallurgical processing of copper and other base metals requires further improvement to increase future secondary quantities. The EOL recycling process for iron operates at optimal conditions, owing to the efficiency of onsite steel plant and recycling plant that creates very limited material loss into the environment. Future technological development should emphasise on copper secondary efficiency to improve on material loss especially as the copper ore grades deteriorate to lower grades. Future iron productivity, in terms of extraction per capita GDP, should focus on future prospects by location as investors continue to search for economic deposits.

The application of the TMR indicator to understand the recyclability of metals provide future pathways for metals as an alternative to primary material reduction and ultimately reduction in the environmental cost provides insight towards material decoupling of resource use. Further the pathways for reduction in global material extraction are outlined to provide consideration of a more sustainable and efficient future.

The modelling framework presented herewith provides a foundational basis for a quantitative framework that could be extended to a multivariable study of environmental footprint such as carbon emissions and energy consumption (Watari et al., 2021). Further, an account of metal substitution and other factors either economic, social or economic in the systems framework would provide a detailed scenario of systems interaction which involves all these aspects towards policy planning for a sustainable environment.

Finally, the application of the mining histories of metals to convey understanding of material balance in metal supply continues to provide resource stakeholders with provisional forecast estimate of the future quantities. However, the underlying issue in linking material extraction and consumption to the environment continues to require extensive debate towards mining sustainability. As such these long term trends hope to create a balance in the resources we need today and those required in future.

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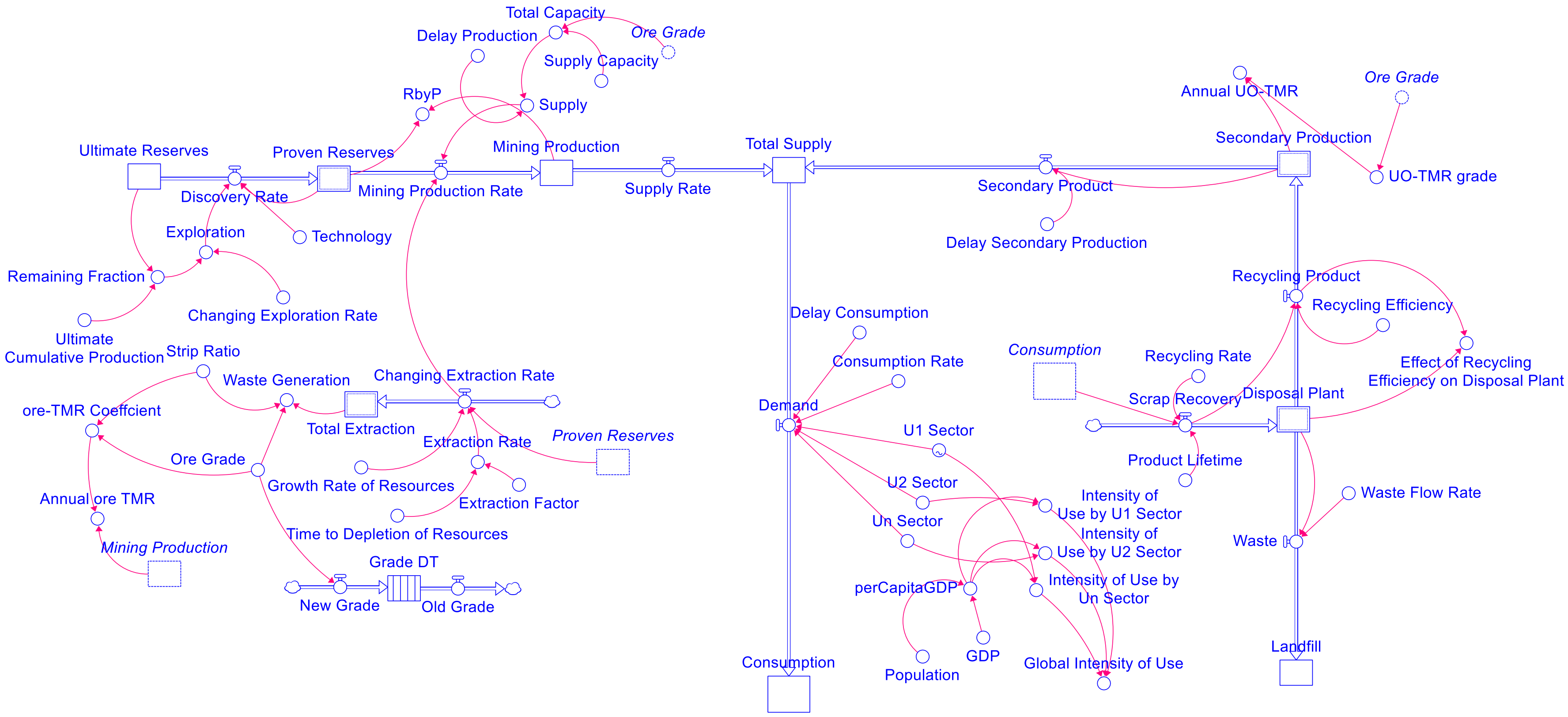
Appendix 3-1 Comparative table of ore-TMR coefficient with previous authors

| | Our Results | | | | Halada et al. (2001) | | Nakajima et al. (2019) | |
|---|---|---|---|---|---|---|---|---|
| | 2000 estimates | | 2070 estimates | | 2000 estimates | | 1990/2013 estimates | |
| | Annual ore-TMR (Mt/year) | ore-TMR Coefficient (t/metal-t) | Annual ore-TMR (Mt/year) | ore-TMR Coefficient (t/metal-t) | Annual ore-TMR (Mt/year) | ore-TMR Coefficient (t/metal-t) | Annual ore-TMR (Mt/year) | Ore-TMR Coefficient (t/metal-t) |
| Au | 694.6 | 931 541.7 | 5 992 | 2 601 061 | 4 401 | 1 800 000 | | |
| Cu | 2 127 | 228 | 23 018 | 862 | 3 870 | 300 | 2 683/<br>5 477 | |
| Ni | 664 | 139.3 | 3 378 | 242.3 | 246 | 200 | 195/<br>600 | |
| Pb | 101 | 27.1 | 766.1 | 3 634 | 283.1 | 95 | | |
| Zn | 101 | 27.1 | 1 189 | 114.4 | 344 | 43 | | |
| Fe | 3 148 | 6.6 | 45 213 | 20.4 | 2 912 | 5.1 | 2 754/<br>6 684 | |

# Appendix 4-1 Schematic framework of model

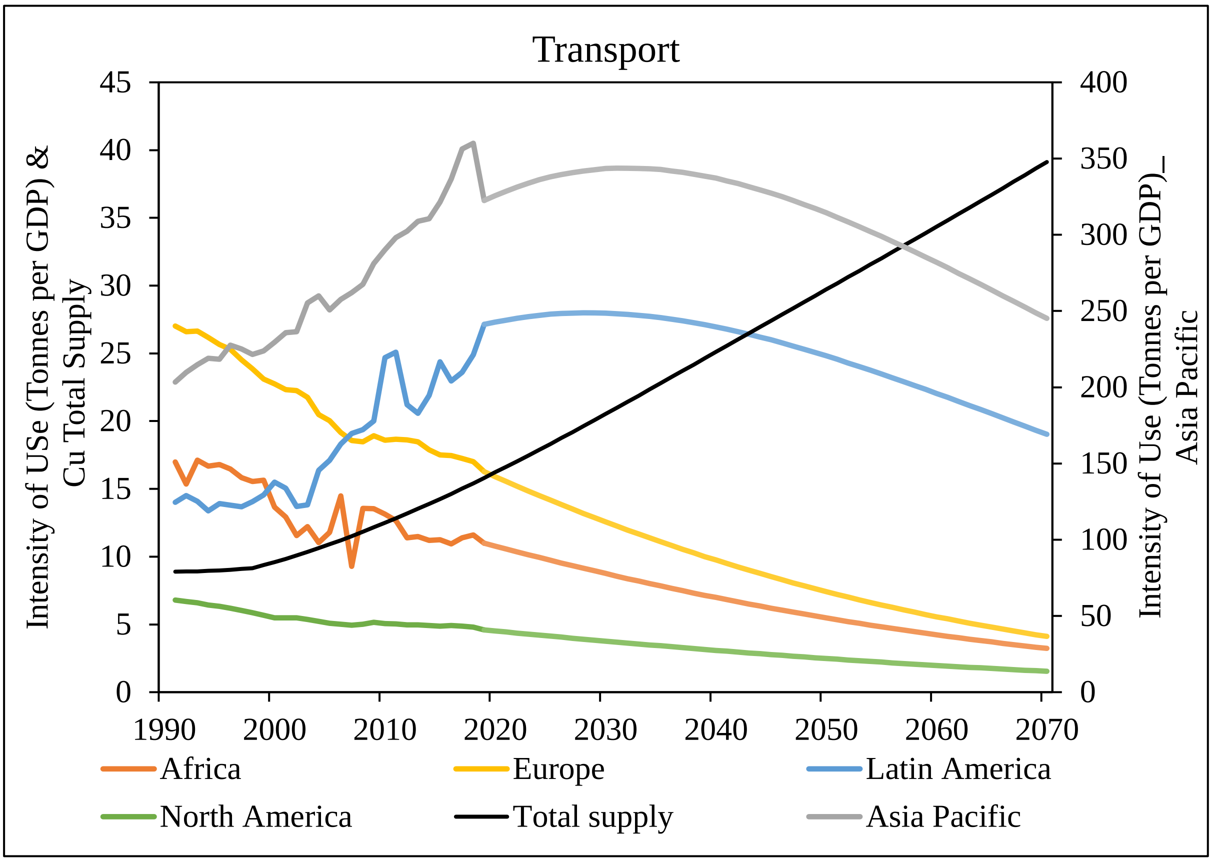


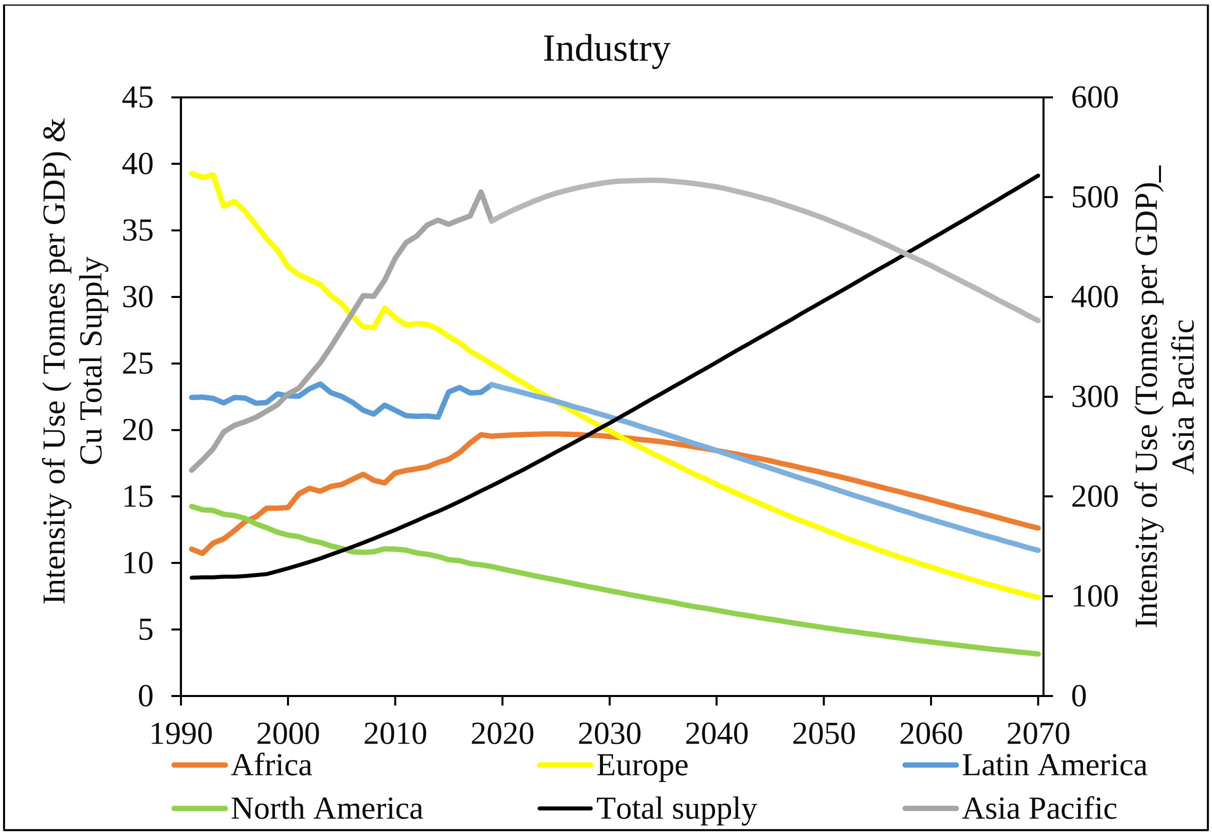
Appendix 4-2 Parameter values for copper, gold and iron.

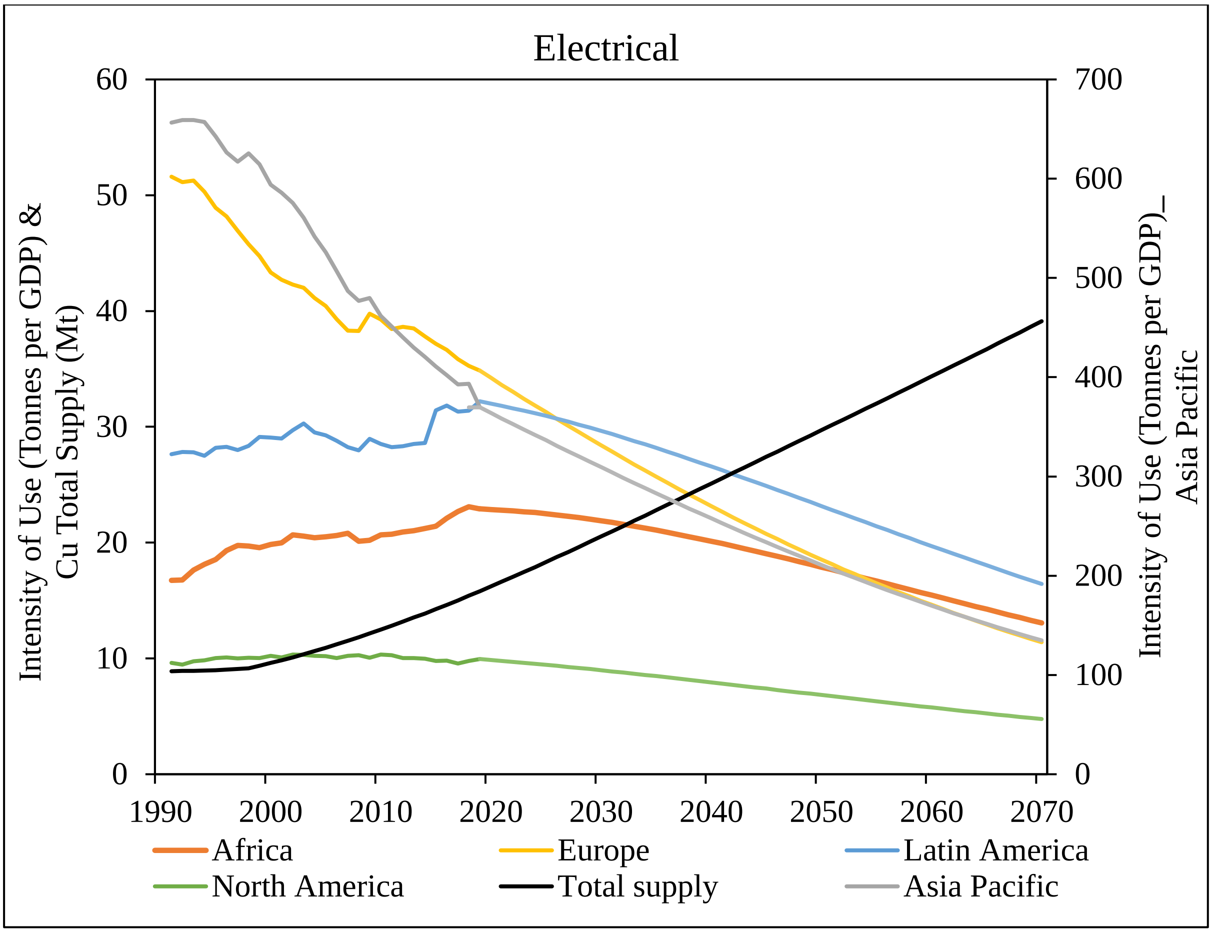
| Parameter Variable | Copper (Mt) | Iron (Mt) | Gold (t) |
|---|---|---|---|
| Initial Metal Production | 7.89 | 769.08 | 2698 |
| Initial World Consumption | 7.47 | 997.64 | 3630 |
| Initial Adjusted Consumption | 8.60 | - | - |
| Initial World Secondary Production | 1.34 | 200.36 | 1000 |
| World Ultimate Resources | 5368 | 287310 | 16861 |
| Initial Proven Reserves | 2003 | 34795 | 13763 |
| Initial Waste Disposal Plant | 1.29 | 89.86 | - |
| Initial Landfill | 0.42 | 17.58 | 60 |
| Production Rate (%) | 22.00 | 11.52 | 48.65 |
| Demand Rate (%) | 3.70 | 4.48 | 0.29 |
| Adjusted Consumption Rate (%) | 2.00 | - | - |
| Recycling Efficiency (%) | 65.99 | 64.78 | 60.62 |
| Recycling Rate (%) | 58.45 | 57.89 | 53.90 |

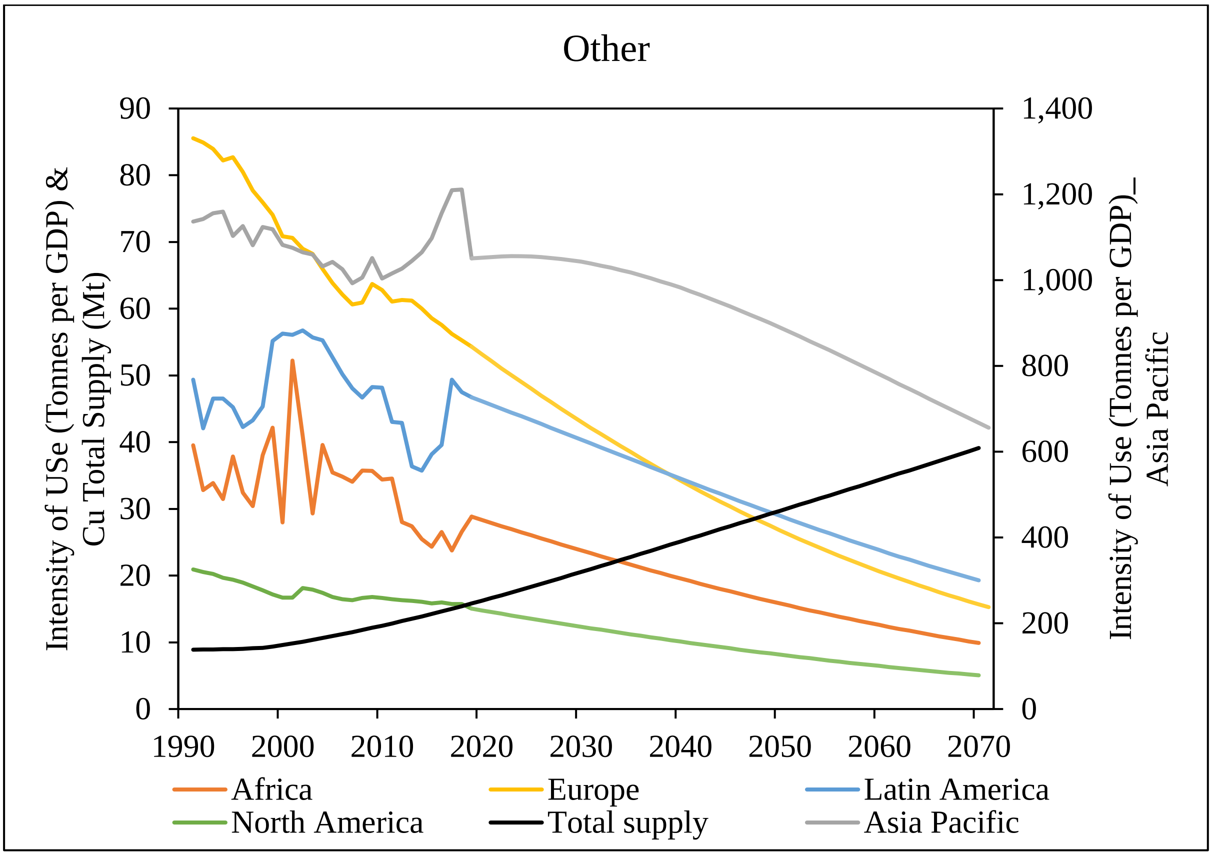
## Appendix 4-3 Metal Intensity of Use by sectorial share

### Appendix 4-3 a Copper Intensity of Use by sectorial share

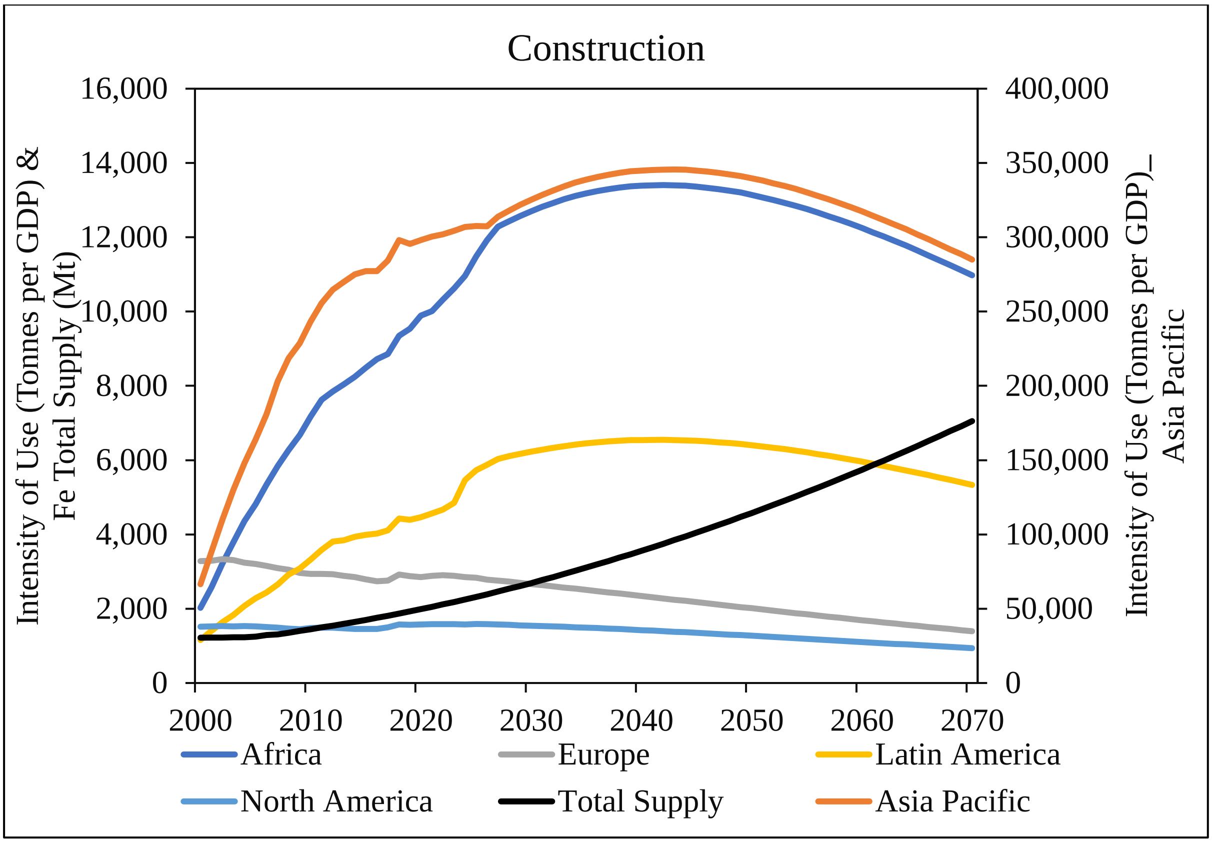


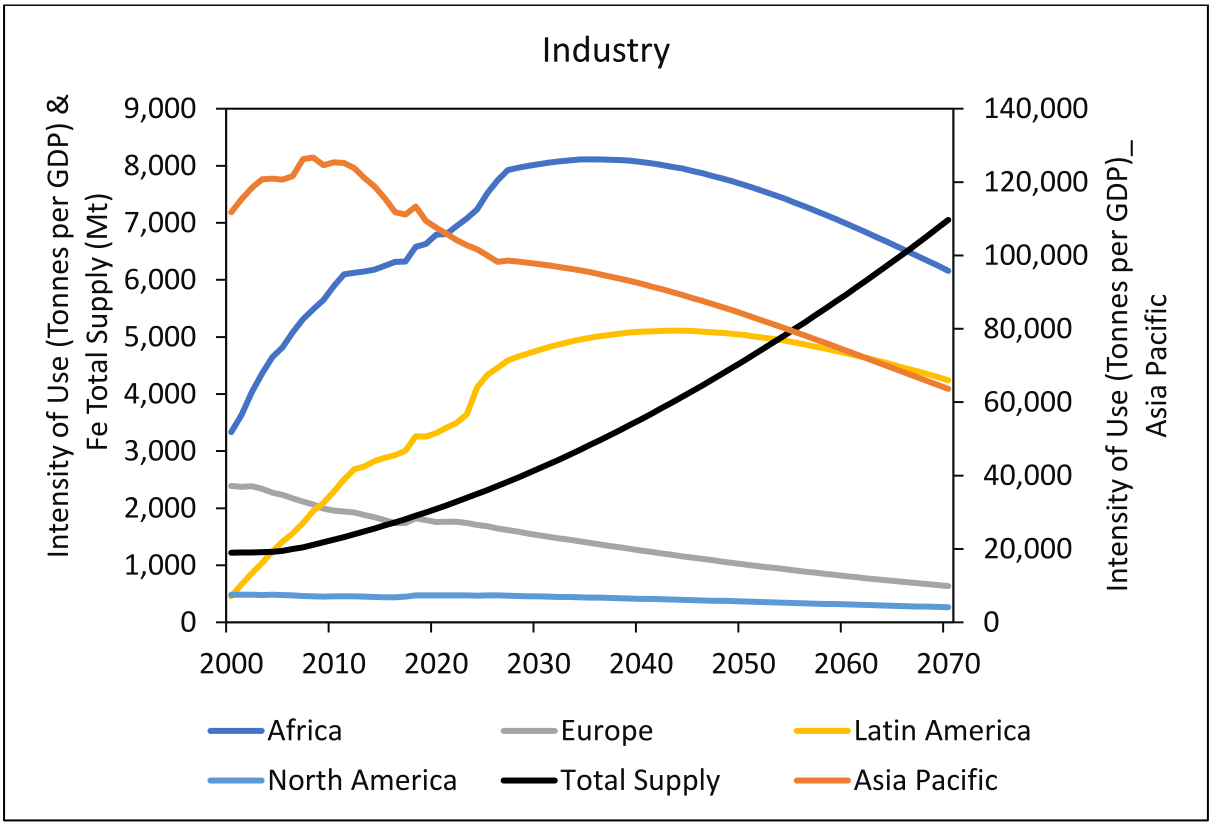


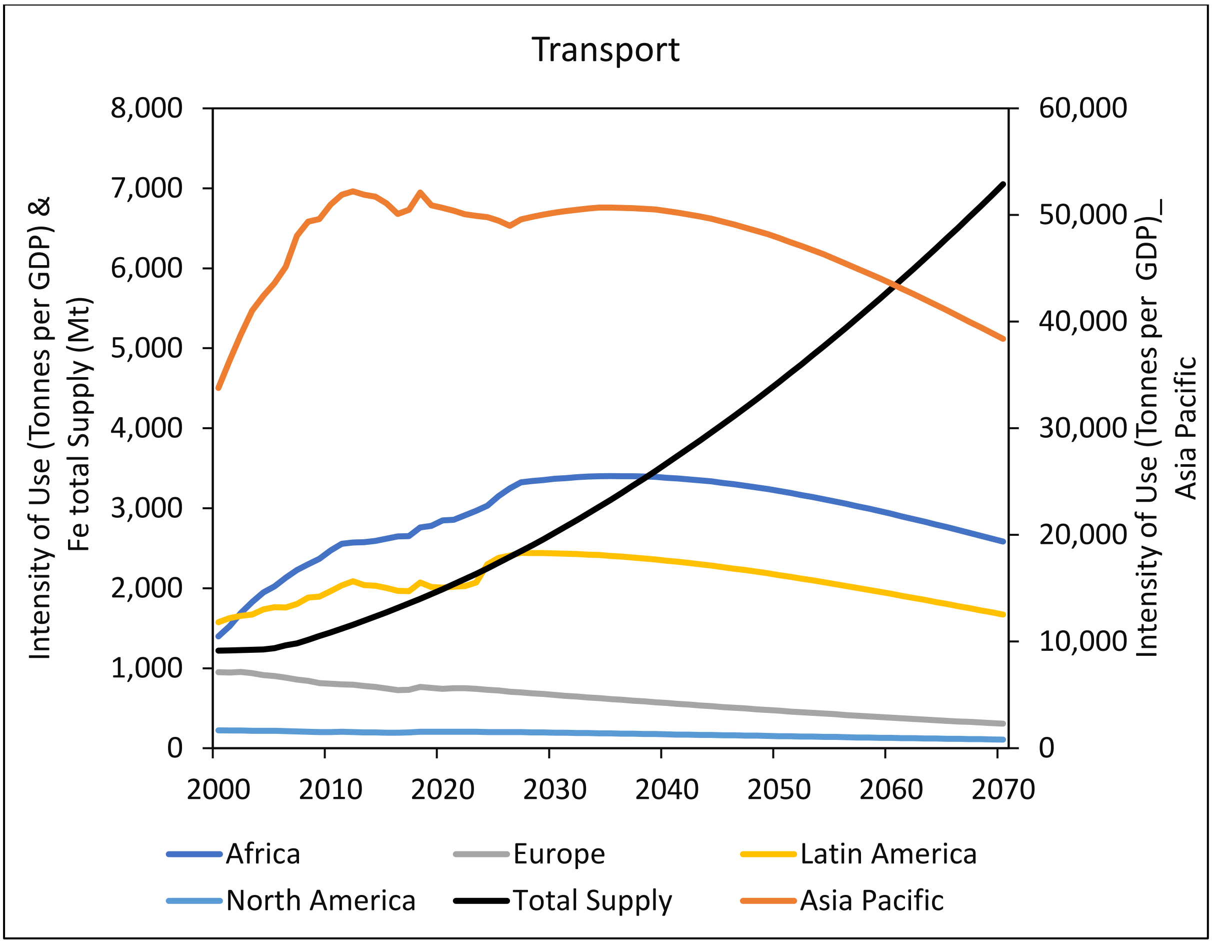

Electrical
Intensity of Use (Tonnes per GDP) &
Cu Total Supply (Mt)
Intensity of Use (Tonnes per GDP)_
Asia Pacific
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
1990
2000
2010
2020
2030
2040
2050
2060
2070
Africa
Europe
Latin America
North America
Total supply
Asia Pacific


Other
Intensity of USe (Tonnes per GDP) &
Cu Total Supply (Mt)
Intensity of Use (Tonnes per GDP)_
Asia Pacific
0
10
20
30
40
50
60
70
80
90
0
200
400
600
800
1,000
1,200
1,400
1990
2000
2010
2020
2030
2040
2050
2060
2070
Africa
Europe
Latin America
North America
Total supply
Asia Pacific

Appendix 4-3 b Iron Intensity of Use by sectorial share






Transport
Intensity of Use (Tonnes per GDP) & Fe total Supply (Mt)
Intensity of Use (Tonnes per GDP)_ Asia Pacific
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
60,000
50,000
40,000
30,000
20,000
10,000
0
2000
2010
2020
2030
2040
2050
2060
2070
Africa
Europe
Latin America
North America
Total Supply
Asia Pacific

Appendix 4-4 Metal Market Share, Lifetime and Recycling Rates

| Application | Market Share (%) | Source | Metal Lifetime (Years) | Source | RE (%) | EOL-RR (%) | Source |
|---|---|---|---|---|---|---|---|
| | *Copper* | | | | | | |
| Electrical | 26 | Ciacci et al., 2015; Elshkaki et al., 2018; Henkens et al., 2020 | 8 | Graedel, 2004; Ciacci et al., 2015; Elshkaki et al., 2018 | 20-37 | 43-53 | Graedel, 2004; UNEP, 2011 |
| Industrial | 19 | | 35 | | | | |
| Transportation | 13 | | 17 | | | | |
| Others | 42 | | 5 | | | | |
| | *Gold* | | | | | | |
| Jewelry | 62 | Ciacci et al., 2015; Elshkaki et al., 2018; Henkens et al., 2020; Refinitiv; GFMS, 2010; GFMS,2019 | 50 | Graedel, 2004; Ciacci et al., 2015; Elshkaki et al., 2018 | 29-31 | 15-96 | GFMS, 2009; UNEP, 2011 |
| Investment | 23 | | 4 | | | | |
| Industrial & Electronics | 10 | | 10 | | | | |
| Dental | 5 | | 10 | | | | |
| | *Iron Ore* | | | | | | |
| Infrastructure | 48 | Ciacci et al., 2015; Elshkaki et al., 2018; Henkens et al., 2020 | 50 | Graedel, 2004; Ciacci et al., 2015; Elshkaki et al., 2018 | 28-52 | 52-90 | World Steel, 2009; Steel Recycling Institute, 2007; UNEP, 2011 |
| Transport | 13 | | 8 | | | | |
| Industry and Machinery | 31 | | 35 | | | | |