An Assessment of Environmental Sustainability of Non-Fuel Mining and Mined Materials in the U.S.

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ABSTRACT

The concept of "sustainable mining" has been examined and acted upon by the industry since the 1990s, with focus on reducing the environmental footprint of mining in terms of energy consumption, water consumption, waste production, and other metrics. Despite these efforts, mined materials continue to have an ever-increasing environmental footprint, as the amount of material mined has increased with population and economic growth; waste production has increased with the transition to open pit mining from underground mining; and energy, water, and reagent use have increased as ore grades continue to decline, resulting in more greenhouse gas emissions and both water and soil pollution. This work investigated approaches for meeting current and future demand for non-fuel minerals – specifically using copper as a case study – in a more sustainable manner. Specific objectives of the research were to: establish a framework for sustainable mining that incorporates circular economy concepts; develop a model to represent stocks and flows of a mined material – copper - in the U.S.; identify and model future scenarios and assess their circularity; and finally to evaluate environmental sustainability for scenarios in the sustainable mining framework, accomplished in three chapters. These specific objectives all relate to the broader question of how much raw extractive mining is necessary to meet demand.

Several original contributions were accomplished in this research. The first is the completion of a review of existing works and initiatives in the area of sustainability and mining, including identification of an emerging field integrating circular economy concepts (circularity) and resource efficiency. This shift from environmental footprint metrics to considerations of circularity is necessary for future reduction of the major environmental impacts associated with increasing mining rates, inputs, land disruption, outputs, and closure, and also to also extend the lifetime of existing minerals reserves and resources. A framework for sustainable mining is proposed synthesizing metrics of circularity and environmental sustainability. Secondly, primary end-of-life management data were collected for copper in the U.S., providing a basis for evaluation of other datasets currently used in material flow analyses that do not use primary data or a bottom-up approach. A material flow analysis was performed for U.S. copper from 1970-2015 using these primary data and revealed a major accumulation of copper in the use phase – of which 20-40% is estimated as a potential hibernating stock for recovery and reuse going forward. Buildings and construction materials as well as electric utility equipment were identified as the largest and most readily available sources or recoverable copper of the four use phases considered. Thirdly, relationships between key drivers and major copper material flows via regression analysis were identified. These relationships were used to provide a long-term forecast for the copper life cycle in the U.S. Also, the identified relationships were employed in analysis of scenarios to assess qualitatively the circularity of the copper life cycle as it is modified by changing drivers. Finally, both circularity and environmental sustainability metrics were applied to assess quantitatively the copper life cycle and development of baseline indicators for comparisons. Results from evaluation of the scenarios demonstrate that a shift in copper demand driver growth in either direction, positive or negative, would result by 2030 in dramatic changes within the material flow system boundary, and that population dynamics appears to be the most significant driver affecting the complete life cycle of copper in the U.S.

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Chapter 1 : Introduction

1.1 Sustainability and Extractable Resources

Materials consumption in developed countries, including the U.S., exceeds by orders of magnitude that of developing nations and follows different trends and growth over time (Kesler, 2007). The U.N. Statistics Division (UNSD) has collected data for several of the Sustainable Development Goal (SDG) Indicators, one of which is Domestic Materials Consumption (UN Statistics Division, 2019), which is the total quantity of raw material purchases made in a country, and some of the immense variability in materials consumption is captured in these measurements. Table 1-1 presents the per capita data for several countries in different regions with varying levels of economic development. These data are the sum of all categories of measurement collected by the UNSD including metal ores, wood, plastics, etc. divided by population. Domestic materials consumption data specifically for metal ores, also from the SDG Indicators, are shown in Table 1-2. The associated environmental impacts with extraction, production, and disposal of these materials are of significant concern, especially because increasing population, affluence, and technological need have led to decreasing ore grades and increased environmental impacts (Krausmann et al., 2009; Steinberger et al., 2010).

Table 1-1: Per Capita Domestic Materials Consumption for Selected Countries, UN Statistics Division, (2019)

Domestic Materials Consumption (Tons) Per Capita				
Country	**2000**	**2005**	**2010**	**2015**
Qatar	96.4	204.2	147.1	143.3
Australia	120.7	120.1	109.0	102.3
Canada	93.9	88.2	82.9	83.6
China	27.6	39.0	58.5	71.0
USA	86.8	87.7	65.8	58.0
Germany	48.9	42.7	44.8	45.3
Iran	29.9	36.8	38.4	42.3
Brazil	26.6	27.5	35.7	36.3
Japan	37.7	34.6	30.1	28.5
UK	37.6	36.6	27.7	25.4
Egypt	17.9	18.9	23.5	22.6
Mexico	23.1	25.0	23.6	22.0
India	11.1	11.7	14.1	16.1
Philippines	11.3	11.2	12.2	11.7
Kenya	7.9	9.6	10.6	9.6
Bangladesh	5.8	6.4	7.1	7.7
Haiti	3.3	3.5	3.6	3.8

Table 1-2: Per Capita Consumption of Metals for Selected Countries, UN Statistics Division, (2019)

Consumption of Metallic Extracted Ores (Tons) Per Capita				
Country	**2000**	**2005**	**2010**	**2015**
Australia	17.4	16.1	14.4	13.6
Canada	6.44	4.79	4.08	5.05
Qatar	1.21	1.54	2.66	2.82
Mexico	1.38	1.35	1.75	2.42
China	0.37	0.73	1.58	2.30
USA	2.99	2.20	1.86	2.00
Iran	0.74	0.88	1.12	1.18
Japan	0.93	0.84	0.78	0.81
Germany	0.54	0.45	0.47	0.51
Brazil	0.47	0.50	0.67	0.46
Egypt	0.07	0.07	0.36	0.36
UK	0.28	0.26	0.12	0.15
India	0.07	0.08	0.10	0.13
Philippines	0.18	0.12	0.20	0.07
Kenya	0.02	0.02	0.03	0.04
Bangladesh	0.02	0.01	0.02	0.02
Haiti	N/A	N/A	N/A	N/A

Sustainability[1], the ability to meet present needs without compromising demands of future generations (Borowy, 2014), is often considered to be irreconcilable with the extractive industries which unavoidably involve depletion of finite resources and large-scale impacts on the environment (Anderson, et al., 2002; Parameswaran, 2016; Whitmore, 2006). However, the ability to reuse and recycle metals and other non-fuel minerals decreases the need for virgin extraction and makes the concept of sustainability more applicable to mining (Reuter, 2013). Further, extraction and processing of mined materials enables technological advancements and related societal benefits including economic growth, higher quality of life, and others that are important for sustainable communities and societies. The reconciliation of sustainability and mining is not a question of how to stop mining, but how to truly maximize the benefits associated with the finite resources we do have and adopt the sustainable mining concept. This is accomplished through the minimization of negative environmental, social, and economic impacts associated with mining and processing activities while limiting extraction to rates that do not exceed capabilities to establish new sources, substitutes, or recycle any particular material so as to not compromise potential demands of future generations (Allan, 1995).

Some environmental issues at the forefront of non-fuels mineral use include energy consumption and associated greenhouse gas emissions, water consumption and pollution of local watersheds and streams, land disruption including potential seismic effects, and the use and disposal of environmentally damaging chemical reagents for processing (Anderson, et al., 2002; AEMA, 1998; IIED and WBCSD, 2002; Miranda et al, 2005). Perhaps the most important environmental issue is that mining and consumption requires extraction from the finite source of

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[1] A glossary of terms which defines this and several other frequently used terms is included in Appendix A

that element that is economically accessible in the lithosphere (Allan, 1995; IISD, 2002; Buxton, 2012; Laurence, 2010). These concerns about not only resource availability, but also the various environmental impacts of mining, are the driving force of this research, especially as these concerns become continually more acute as the global population continues to increase, and per capita consumption of goods increases (Kesler, 2007; Krausmann et al., 2009; Nassar et al, 2012).

With a look at mined materials in the U.S., this research is focused on the intersection of sustainability and mined resources. Existing works in the area of sustainable mining typically follow the triple-bottom-line framework considering environmental, economic, and social issues (Anderson et al, 2002; IIED and WBCSD, 2002; EITI, 2003; Miranda et al, 2005; KIN, 2012). The focus of this work however is in the assessment of the environmental sustainability of mining, though the effects of the economic and social spheres on this assessment are significant. Policy and legislative action, which fall into the social sphere, as well as fluctuating prices drive recycling, recovery, and import and export trends. These factors all have significant effects on the circularity and therefore environmental sustainability of mined materials consumption and are therefore incorporated as upstream effects on environmental sustainability in this analysis.

The focus on environmental sustainability was used because (1) social and economic aspects are equally as complex and variable as environmental sustainability and would require their own body of work to assess without the risk of oversimplification, and (2) multiple definitions of sustainability exist and though most use the "triple bottom line" framework, some (such as eco-efficiency) do not incorporate all three of these aspects, so to consider sustainability completely, the reconciliation of these different definitions would be necessary. All definitions, however, include environmental sustainability, so this work focuses on the assessment of mining and mined materials consumption in the context only of environmental sustainability, though undeniably social and economic aspects affect these impacts. Within the environmental sphere, previous work primarily has explored efficiencies of mining operations in four key areas: reduction of inputs, outputs, land disruption, and proper closure and reclamation (Allan, 1995; Anderon et al., 2002; Azapagic, 2004; Basu and Van Zyl, 2006; Hendrix, 2006; Hilson and Murck, 2000; Miranda et al., 2005; Northey et al., 2013; Parameswaran, 2016). However, some previous studies have considered the integration of a materials flow viewpoint to sustainable mining, which has led to an area of research that includes consideration of a material's entire life cycle, not just front end extraction and processing (Chen and Graedel, 2012; Kesler, 2007; Rogich and Matos, 2008; Steinberger et al., 2010; Sverdup, 2017).

1.2 Material Life Cycle and Circularity

Physical resource limits and the life cycle of mined materials are a growing concern in the assessment of the environmental sustainability of a material or process. These topics need to be examined for a broader analysis of the sustainability of mineral extraction. Some motivation for improving the circularity of a material – the degree to which a material adheres to circular economy concepts of reuse, reduction, and minimization of losses – include the fact that significant resource savings can be associated with processing recycled materials, instead of raw materials, including measurable differences in energy and water consumption as well as a reduction in land disruption due to reduced extraction demand (Norgate and Haque, 2010; Northey et al., 2013; Gunson et al., 2012; Reuter, 2013). The water and energy savings from processing recycled materials, not raw materials, have been measured numerous times for various processes, metals, and locations, and can vary, but are typically between 75% to 95% for energy (Norgate and Haque, 2010; Reuter,

2013) and up to 65% for water (Gunson et al., 2012, Reuter, 2013). These resource savings would also necessarily reduce smelting and other processing operational costs for mining companies, improving economic sustainability, reduce negative impacts to nearby communities, and improve social sustainability.

For these reasons, a stocks and flows material flow analysis was developed to examine the circularity of extractible non-fuel mineral resources in the U.S. A stocks and flows analysis is a type of material flow analysis in which the quantity of a material is identified for each phase and any accumulation or depletion in each phase is calculated using mass balance formulae. The complete stocks and flows analysis can be assessed by comparing the relative size of flows from extraction, consumption, collection, recycling as well as inputs and losses from outside the system boundary (the U.S. economy) such as imports and exports as well as unrecoverable losses like dissipation and landfilling. Circularity can also be assessed through a number of metrics. Approximately 80 measurable circular economy metrics and elements have been identified (Parchomenko et al., 2019) and though not all of these are applicable to all materials or systems, there are several that can be used to qualitatively assess the circularity of different materials and scenarios.

1.3 Research Objectives

The research encompassed an assessment of environmental sustainability of mining and mined materials, focusing on a life cycle view of non-fuel mineral consumption in the U.S., and driven by the question "how much extraction do we really need to be doing to meet demand?" This was accomplished by examining the circular economy of a specific material, copper, and identifying opportunities to optimize circularity in addition to decreasing environmental impacts.

The selection of copper as the element to model was based on several factors: copper has a relatively high recycling rate; it has diverse uses (in contrast to a metal like lead) and therefore has more opportunities for identifying potential sources of recovery from hibernating stocks and waste streams; it is the highest-value metal mined in the U.S. and, linked to that, is not a completely import-dependent material, which means that domestic findings could have significant impact downstream (Reuter, 2013; USGS, 2017; Chen and Graedel, 2012). The framework established and the model of stocks and flows developed in this research, however, will be useful to assess the lifecycle of other materials.

These goals were accomplished through four major objectives:

1. Establish a framework for "sustainable mining" that incorporates circularity

2. Develop a model to represent stocks and flows of copper in the U.S.

3. Identify and model future scenarios for copper extraction and use and assess their circularity

4. Evaluate environmental sustainability for scenarios in the sustainable mining framework.

The first objective, the establishment of a framework for sustainable mining that incorporates circularity, was based upon a review both existing literature as well as industry and legislative actions and a critical analysis of any gaps in these frameworks. The second objective, to develop a model to represent stocks and flows of copper in the U.S, included development of primary of end-of-life data for use in the model, represents a new contribution to the field as similar studies have employed lifetime-based estimate to approximate these flows. The model is useful to identify limiting factors to the sustainability of the resource. The third objective was to identify and model future scenarios for copper extraction and use and assess their circularity. This involved development of new and unique relationships between typical demand drivers and consumption and collection flows in the U.S., a more limited system boundary than other studies, but one necessary to more accurately capture the specific dynamics of a material economy. As illustrated in Table 1-1, developing nations continue to see increasing per capita materials consumption, but many developed nations have reached a plateau and despite increasing population and affluence, per capita consumption of material stagnates, or even decreases, referred to as "dematerializing" (Fischer-Kowalski and Amann, 2001; Steinberger et al., 2010; Reuter, 2013). The final objective was to evaluate sustainability for scenarios using the metrics identified in the sustainable mining framework in Objective 1.

The emphasis of this analysis was in the area of environmental sustainability, but the intersection of how the other aspects of sustainability (economic and social) affect environmental sustainability are unavoidable and were also considered. Though primarily environmental sustainability metrics were used to assess sustainability, the role of such variables as price, international trade, policy and safety affect the environmental sustainability of mined materials consumption, and were not only be included in the analysis, but also had a significant role in the development of the scenarios under Objective 3. The incorporation of the outlined environmental sustainability metrics in addition to assessing the circularity helped to provide a more complete picture of the impacts of mined material consumption in the U.S., including consumption of resources like energy and water necessary to process copper as well as associated land disruption. The copper case study used provided valuable insight into non-fuel mined materials in general and facilitated response to the key motivating question about how much mining is necessary to meet demand.

1.4 Dissertation Structure

This dissertation consists of five chapters, with three central chapters that either have been or will be submitted for publication in peer-reviewed journals. Chapter 2 of the dissertation aligns with the first research objective, and contains a literature review of sustainability and mining, as well as a case study of best practices in the extractive industries. The analysis makes clear that a transition is underway in the thinking about sustainability in extractive industries, from the environmental impacts associated with the life cycle of the mine to the impacts throughout the complete life cycle of the mineral. The emergence of resource efficiency and the circular economy and their importance to long-term sustainability are made evident here. Chapter 3 aligns with the second research objective, expanding upon this by performing a circularity analysis of copper in the U.S. from 1970-2015 through a stocks and flows model. The analysis examines key use phases and end-of-life management specifically to develop a dataset of primary information that does not exist elsewhere. The model is then used to identify key limitations to material circularity in terms of losses to the system or stock accumulations. Chapter 4 addresses the third research objective by building upon the stocks and flows analysis and performing forecasts for future scenarios of the copper life cycle in the U.S. to year 2030. This is accomplished through identification of material flow drivers and analysis of the relationships between these drivers and the collected material flow data used in Chapter 3. Research objective four is also addressed in Chapter 4, which includes a sustainability assessment in the sustainability framework developed in Chapter 2. Circularity metrics as well as impact metrics for the extraction and processing phase are identified and calculated. The final chapter summarizes the findings of the studies, discusses the implications and limitations of the results, and provides recommendations regarding potential follow-up research.

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Chapter 2 : A Review of Sustainable Mining and Resource Management: Transitioning from the Life Cycle of the Mine to the Life Cycle of the Mineral

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2.1 Abstract

Application of sustainability principles to mining is inherently challenging, as mining is the act of removing and consuming a limited resource. However, consideration of sustainability – meeting present needs without compromising needs of future generations – is increasingly being incorporated into mine development and operation as demand for minerals and products of mining such as metals and fuel and non-fuel minerals and the environmental impacts associated with minerals extraction activities continue to increase. This paper provides a review of existing research literature and thought on sustainability in mining of non-fuel minerals.

A common sustainable mining framework is focused on reducing environmental impacts of mining. Strategies for assessing the sustainability of mining operations include measuring, monitoring, and working to improve various environmental performance metrics, and these are used to determine whether a mining operation is sustainable. The key metrics for environmental sustainability in mining relate to efficiencies in resource consumption, minimizing land disturbance, pollution reduction, as well as closure and reclamation of exhausted mine lands.

Another sustainable mining framework transitions from the emphasis on the environmental footprint of mining operations to responsible management of non-fuel mineral resources throughout their entire life cycle, including use phase and end of life, with attendant implications for reducing the quantity of mined material and preserving reserves for future generations. This paper examines the transition to a broader context that includes the entire mineral life cycle. We propose that assessment of sustainability in mining should encompass a systems view of mined materials in society, emphasizing existing environmental sustainability metrics from mining

operations as well as including “circularity” or “life cycle” metrics to assess the sustainability of production and extraction for the long term.

2.2 Introduction

Materials consumption, including non-fuel minerals consumption, in developed countries such as the U.S. exceeds by orders of magnitude that of developing nations (Kesler, 2007). Because the scale of non-fuel minerals consumption in developed nations is so large, the associated environmental impacts are also large. Globally, increased demand for non-fuel minerals driven by increasing population, affluence, and technological need have led to decreasing ore grades and increased environmental impacts, but these changes are even more acute in developed nations (Behrens et al., 2007, Krausmann et al., 2009; Steinberger et al., 2010). Additionally, mined materials continue to have an ever-increasing environmental footprint, as the amount of demand for material mined has increased with population and economic growth; additionally, waste production has increased with the transition from underground mining to open pit mining; and energy, water, and reagent use have increased as ore grades continue to decline, resulting in more air and greenhouse gas emissions and both water and soil pollution (Steinberger et al., 2010; Bloodworth and Gunn, 2012). For these reasons, interest in the environmental sustainability of mining and minerals consumption has been steadily increasing.

In a brief history of the sustainability and mining, Anderson et al. (2002) largely attribute the concept and definition of sustainability and sustainable development – the ability to meeting present needs without compromising the needs of future generations – to the 1987 Brundtland Commission. They also identify the 1992 Rio Earth Summit as the seminal global meeting that addressed environmental and socioeconomic issues of sustainable development by putting forward several legally binding agreements and establishing the United Nations Commission on Sustainable Development. This set the stage for the development and adoption of sustainable development goals by specific industries, including mining and metals industries. Sustainability is often considered to be irreconcilable with the extractive industries, which involve depletion of finite resources and large-scale impacts on the environment (Parameswaran, 2016; Whitmore, 2006). However, the ability to reuse and recycle metals and other non-fuel minerals decreases the need for virgin extraction, therefore prolonging reserves for the extraction and use of future generations and makes the concept of sustainability seem more applicable to mining (Reuter, 2013). Further, extraction and processing of mined materials enables technological advancements and related societal benefits including economic growth, higher quality of life, and others that are important for sustainable communities and societies. The reconciliation of sustainability and mining is not a questions of how to stop mining, but how to truly maximize the finite resources we do have and adopt the sustainable mining concept: where sustainable mining is the minimization of negative environmental, social, and economic impacts associated with mining and processing activities while limiting extraction to rates that do not exceed capabilities to establish new sources, substitutes, or recycle any particular material so as to not compromise potential needs of future generations (Allan, 1995).

Here we address the question "What is Sustainable Mining and how can the sustainability of mining be evaluated?" in several parts. We begin with an examination of how sustainability and sustainable development goals have been adopted by the mining industry over time. Two major themes emerge from review of the literature. The first, and dominant theme, focuses on improvement of the sustainability of mine operations. The second theme that emerges is a shift in focus from the life cycle of the mine to the life cycle of the mined material. Integration of this holistic view of the impacts of the life cycle of minerals in combination with the mine operations focus leads to the proposal of a framework for sustainable mining that addresses the limitations of the current frameworks.

This work contributes a compilation and synthesis of existing thought on the sustainable mining concept in a way unique from other works. We consider two separate foundational themes for the concept of sustainable mining: operational efficiency to reduce environmental impacts, and the consideration of materials extraction rates and total life cycle of a mined material. This synthesis of sustainable mining thoughts and metrics can be used to help inform sustainability assessments of specific non-fuel minerals.

2.3 Research Methodology

A systematic literature review was performed, the first step of which involved selecting databases of published peer-reviewed journals and searching for keywords such as "sustainable mining", "sustainable development AND mining", "sustainability and mining", as well as more generally "sustainab* AND mining". Only papers in English were considered. To narrow the body of works further, papers were only included that specifically discuss a sustainability or sustainable development context for mining, and papers with environmental sustainability focus were emphasized. For example, a publication about a specific mining technology that may mention a particular sustainability outcome was not included in the body of work, as this paper attempts to examine sustainable mining holistically.

Additionally, because the development of the sustainable mining concept is industry driven, searches were performed for published standards and legislation in areas beyond peer-reviewed publications. Of these industry or governmental initiatives, North-American-focused as well as global results were included. To be included in the body of compiled work the documents outside the peer-reviewed literature had to suggest specific actions for improving the sustainability of mining, not just a general discussion of the topic.

Once a body of work was established according to these requirements, an evaluation of the thematic areas in these works was performed. The works, according to this evaluation, can largely be separated into two groups.

A synthesis of the key findings of both groups of work was performed to develop a framework for sustainable mining that reconciles the differences between the driving concepts in sustainable mining. This synthesized framework for sustainable mining was analyzed and opportunities for future works were identified.

2.4 Results and Discussion

Two major thematic areas that drive frameworks for sustainable mining emerge from a review of the literature. The first, predominant framework for sustainable mining focuses on improvement of the sustainability of mining operations from extraction through processing. It is based on a set of core environmental concepts, guiding principles, and specific sustainability metrics that have been adopted by mining companies, industry organizations, and governing bodies with interests in improving the sustainability of the mineral extraction industry. The second thematic area that emerges as a focus for sustainable mining frameworks is a shift in focus to the life cycle of the mined material and its circularity, i.e., the degree to which a material is returned from end of life to the use phase to reenter the circular economy. These return flows in the context of a complete mineral's life cycle can be seen in Figure 2-1.

The two sustainable mining frameworks are presented and analyzed here. Strengths and limitations of each framework are examined, and research and technology development needs are identified.

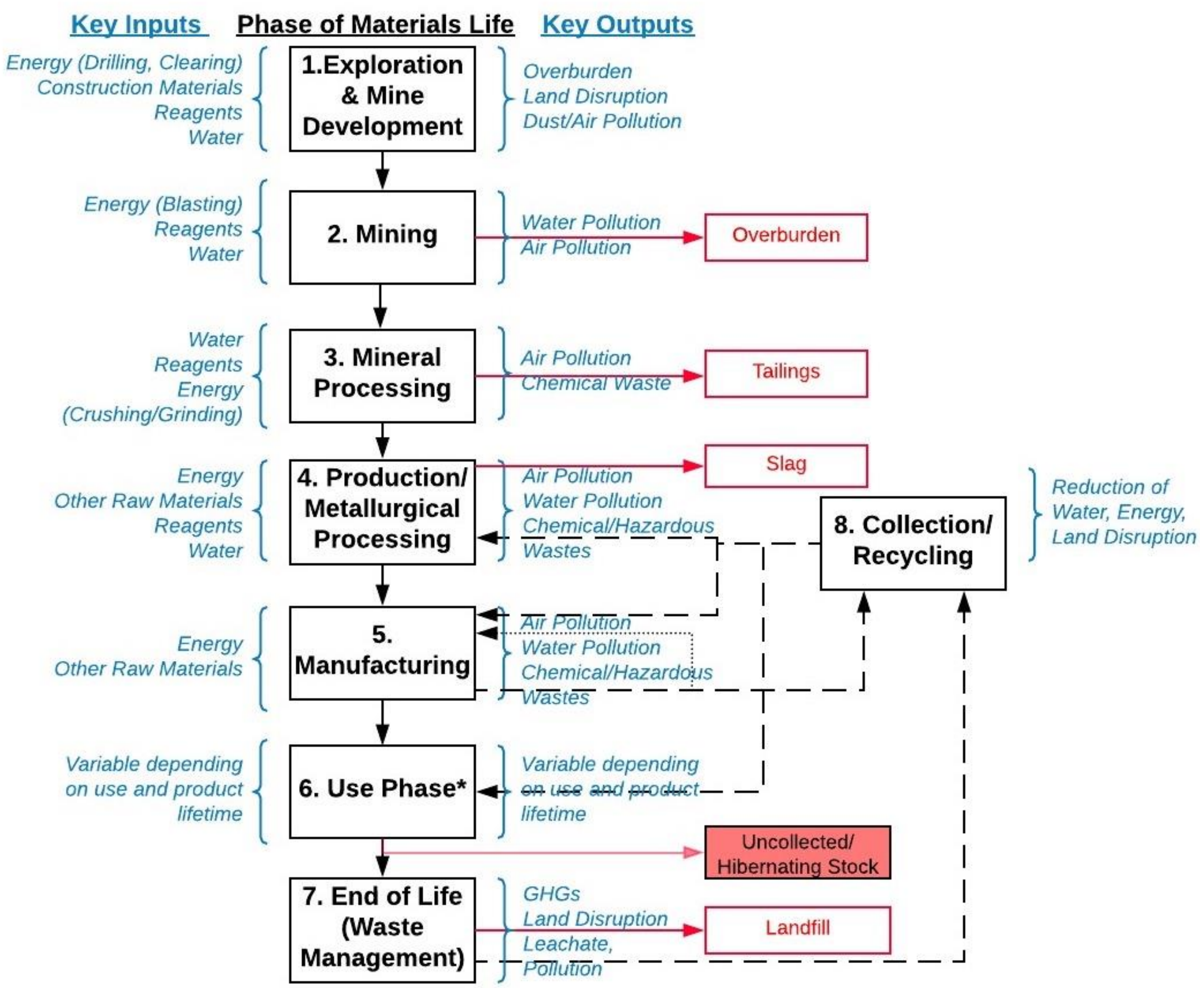

Figure 2-1: Life Cycle and Associated Environmental Impacts for a Mined Material

2.4.1 Historical context for the mining-operations-focused sustainable mining framework

Since the general concepts of sustainability and sustainable development were established and became well known after the 1987 Brundtland Commission report (Borowy, 2014) and 1992 Rio Summit (UN, 1993), there has been an adoption of these concepts in specific contexts, including mining. (The phrase “responsible mining” has been used by some as interchangeable with, or in preference to “sustainable mining” (Miranda et al., 2005).) In one of the earliest attempts to define sustainable mining, Allan (1995) suggested that sustainable mining be defined by a rate of mineral consumption and proposed that this rate should not surpass current capabilities to establish new sources of that mineral, substitutes for that material, or recycling capacity. However, the focus of efforts to quantify sustainability in mining through metrics has not been on the rate of consumption or of discovery of sources, but primarily on the environmental impacts of mine operations, even in the Allan (1995) paper that proposed this concept. Allan (1995) additionally examined the implicit contradictory nature of encouraging remediation of abandoned mine lands, noting that the abandonment of a mine is not necessarily because of exhaustion, but rather often occurs because of economic conditions. This means that reclamation and remediation of these abandoned mines may actually impede complete exhaustion of the site, or extraction efficiency, and lead to a net increase in negative impacts either due to the reopening of the same mine in the future at potentially high economic and environmental cost, or the land disruption associated with opening a new mine site to meet future demands that the existing location could have met (Allan, 1995).

The establishment of Global Mining Initiative, since renamed the International Council on Minerals and Mining (Anderson, et al., 2002) created the Mining, Minerals and Sustainable

Development report (MMSD), one of the first attempts to assess comprehensively the sustainability of mining and to identify steps for mining to become more sustainable (IIED and WBCSD, 2002). The multi-year research project involved more than 5000 organizations and culminated in a report intended to raise awareness of challenges to sustainable development issues presented at the 2002 Earth Summit. The report includes an assessment of the main challenges to sustainable development in the mining and minerals sector, an agenda for change, and key steps for improvements that support sustainable development (IIED and WBCSD, 2002). One of the key recommendations for improvement was the establishment of local best practices, which led to the development of regional MMSDs for Australia, South America, North America and Southern Africa, i.e., the key mining regions of the world (IIED and WBSCD, 2002). The MMSD North America project (MMSDNA) report included:

- a profile of the North American mining sector;
- development of four future scenarios for the mining industry in the region;
- "Seven Questions to Sustainability" (7QS): a framework for assessing the sustainability of an operation and identifying opportunities for improvement;
- "Towards Change," a final report with ten specific goals for the improvement of sustainable development in mining in North America in the areas of legacy issues, improving practices, enhancing capacity, and follow up (IISD, 2002).

Arguably the most influential of the four outcomes of MMSDNA was 7QS: a framework that by means of asking questions and then developing structured "ideal answers" (in the seven areas of engagement, people, environment, economy, traditional and non-market activities, institutional arrangements, and integrated assessment and continuous learning) can assess and improve the sustainability of a project at any stage (IISD, 2002). This 7QS framework has been used beyond the North American region and remains a common format for assessing sustainability of not only mines but any project.

In addition to the MMSDNA regional report, another regional comprehensive evaluation of sustainable mining was completed by the U.S. Bureau of Land Management in combination with the U.S. Forest Service (Anderson et al., 2002). Similar to MMSD, this report highlighted the importance of incorporating the triple bottom line into mining operations, but also emphasized recycling and reuse as a central issue to enhancing sustainability (Anderson et al, 2002). Concurrently during the international development of MMSD, several investigations explored effective environmental management of mines and proactively minimizing the negative impacts of mining activities, in contrast to passive or reactive environmental management (Hilson and Murck, 2000). The goals of these proactive strategies to be adopted by companies would include improved planning, waste management, cleaner technologies, addressing of needs of communities and stakeholders, training, as well as sustainability partnerships (Hilson and Murck, 2000; Hilson and Basu, 2003). The environmental improvements and solutions proposed still were primarily improvements to the efficiency of operations (Hilson and Basu, 2003). Azapagic (2004) suggested several sustainability indicators in economic, social, and environmental categories that could be used for performance assessment and improvement in line with the MMSD goals. A 2006 critical assessment of the social sustainability of mining from the nonprofit organization Mines and Communities used several of these concepts and social indicators and concluded that conditions were little improved since the release of the MMSD report and its Agenda for Change (Whitmore, 2006).

Following MMSD, several other regional and international initiatives to enhance the sustainability of the mining industry were introduced. The Extractive Industries Transparency Initiative (EITI) was launched in 2003 to encourage accountability of industries and governments to the public (EITI, 2003). This type of open communication encouraging debate and input from communities as well as economic transparency are issues outlined in the social and economic spheres of MMSD, fitting into place with the established triple bottom line framework for sustainability in the mining sector. The EITI Standards developed as part of the initiative have since been adopted in over 40 countries, including the U.S. in 2012, though the international board that monitors the progress of participating countries have not completed assessment and validation of all committed member countries. Following the 2003 EITI, Miranda et al. (2005) released the Framework for Responsible Mining (FFRM), and unlike EITI is specific to non-fuel minerals mining. They highlighted environmental and social issues associated with non-fuel minerals mining and provided recommended approaches for governments, social groups, industry organizations, and financial institutions. It emphasized the environmental and social sectors of the triple bottom line, and introduced the concept of "no-go zones", areas in which the environmental or social cost outweigh the economic benefits of mine. These may manifest in different ways, but a recent example is the controversial Alaska Pebble Mine, which has an estimated $500 billion of resources, but a 2013 EPA assessment indicated the watershed damage would be too extensive, so at that time development was delayed for additional study (Kittle, 2013).

In 2010, the World Economic Forum (WEF) published the first Responsible Mineral Development Initiative (RMDI) which established a six-step framework for responsible mineral development emphasizing knowledge-sharing and transparency, stakeholder engagement and dispute management as well as monitoring and enforcement of commitments (WEF, 2010). Further research and reports in this area include practical solutions to existing problems, mineral value management, and analysis of specific countries and companies in their performance in economic sustainability (WEF, 2013). The 2010 Natural Resources Charter (NRC) is a framework established by the Natural Resource Governance Institute emphasizing the economic and environmental responsibility of extractive industries for future generations (NRGI, 2010).

Preventing premature closure, as supported by Allan (1995), was identified as a key aspect of sustainable mining, achievable by mining lower grades, and mining full seam thickness despite immediate economic concerns (Laurence, 2011). Additionally, the practice of premature closure adds an aspect of unsustainable practice economically, as closure is paid for by the mining company, and is yet another cost it must incur (Azapagic, 2004). Other specific and actionable environmental solutions were identified primarily in the areas of water use, energy use, land management, and remediation.

When considering water use and water resource protection, a combination of evaporation reduction strategies, improved tailings disposal, ore pre-sorting, and water reuse led to a reduction of water use in Canadian mines from 0.76 to 0.2 m^3 water/ ton of copper ore, or 74% (Gunson et al., 2012; Parameswaran, 2016). For protection of water resources, mine waste should not be released directly to rivers or other surface water, acid-generating waste should be isolated, and mine dewatering should be prevented (Miranda et al., 2005; Parameswaran, 2016).

A 21% net reduction of energy use can be achieved by use of best practices, such as blast optimization, energy efficient grinding such has high pressure rolls, waste heat recovery, and cutting-edge smelting technology, and a further 40% reduction is theoretically possible based on practical minimum estimates (Norgate and Haque, 2010; Parameswaran 2016). Additionally, a life cycle view of mine operations has revealed other potential energy reduction opportunities: in-pit crushing that would reduce loading and hauling requirements and adoption of new sensor technology that could reduce exploratory digging and drilling (Norgate and Haque, 2010). Adoption of renewable energy on mine sites is also a major opportunity for reduction of fossil fuel energy use and greenhouse gas emissions (Parameswaran, 2016).

In the FFRM, Miranda et al. (2005) introduce possible opportunities for more sustainable land management, including public access to information about exploration, environmental impact analysis, and responsible waste management. They identify several approaches for improved waste management, such as lined tailings impoundments and waste rock dumps. Additionally, restoration and stabilization of disturbed areas have long been recognized as important to environmental and social stewardship of mine lands (Allan, 1995; Buxton, 2012; IIED and WBCSD, 2002; Laurence, 2011; Miranda et al., 2005). Approaches for restoration include replacement of topsoil, revegetation and backfilling, as well as financial guarantees of companies of ability to remediate as well as monitor exhausted mine lands (Allan, 1995; IIED and WBCSD, 2002; Miranda, 2005).

2.4.2 A summary of mining-operations-focused sustainable mining framework

A general synthesis of the collective works discussed above leads to the following general definition: sustainable mining involves the adoption of practices in the mining operations phase that result in environmental and social improvements over traditional resource development methods, so as to reduce negative impacts, while maintaining health and safety of mine workers and the interests of stakeholders and affected communities. The environmental impacts of mining have received the most attention in development of the current framework for sustainable mining. For improved sustainability of mining operations, environmental performance characteristics can be categorized primarily into four distinct elements: reduction of inputs, minimization of land disruption, reduction of outputs, and responsible reclamation and rehabilitation of mine lands (Calas, 2017; Dubiński, 2013; UN, 2010; Miranda et al., 2005; MAC, 2004; U.S. EPA, 2016). Specific aspects for the assessment of environmental sustainability in mining are summarized in Table 2-1. The frameworks and standards included in the table include groups considering only extraction (Bureau of Land Management, American Exploration and Mining Association, Extractive Industries Transparency Initiative), extraction and processing (Mining Minerals and Sustainable Development, 10 Principles for Change, 7 Questions to Sustainability, Framework for Responsible Mining), as well as complete life cycle (Natural Resource Charter, MMSD10+).

Table 2-1: Key Environmental Sustainability Parameters Related to Mining, and Corresponding Multi-Party Initiatives

Concepts	Legislation and Industry Adopted Initiatives for Sustainability[*]								
	BLM	MA	MMSD	10PC	7QS	EITI	FFRM	NRC	MMSD+10
Inputs									
Water Use (Reduction & Recycling)			x	x	x		x		x
Energy (Reduction & Renewables)	x	x		x	x		x		
Reagents (Reduction & Substitutes)		x			x		x		
Land Disruption									
Biodiversity	x		x	x	x		x		x
Soil Disruption (Erosion)	x				x		x		
Study and Prevention of Seismic Effects					x		x		
Critical Areas	x	x	x	x	x		x	x	x
Outputs									
Greenhouse gasses/Climate Change			x		x		x		x
Mine Waste (AMD)	x	x	x	x	x		x		x
Pollution (Air, Water, Soil)	x		x	x	x		x		x
Closure									
Remediation & Reclamation	x		x	x	x	x	x	x	x
Monitoring	x	x	x	x	x	x	x	x	

[*]Abbreviations in the Table are as follows: BLM: Bureau of Land Management Sustainable Development and its influence on mining operations; MA: American Exploration and Mining Association Statement of Environmental Principles; MMSD: Mining, Minerals and Sustainable Development; 10PC: ICMM 10 Principles for Change; 7QS: IISD Seven Questions to Sustainability; EITI: Extraction Industries Transparency Initiative; FFRM: Framework for Responsible Mining; NRC: NRGI Natural Resource Charter; MMSD10+: Reflecting on a decade of mining and sustainable development.

Within the four elements of environmental sustainability, which are the focus of the current framework, some key metrics are used to assess sustainability of mining and opportunities for improvement. These metrics, shown in Table 2-2, are organized by phase of mine life, as sustainable mining assessments to date have focused predominantly on the life cycle of the mine.

Mine life is typically considered in four stages: exploration, construction, operations, and closure (Miranda et al., 2005; WEF, 2013; IIED and WBCSD, 2002; KIN, 2012). The impacts associated with exploration and construction are largely interchangeable and, in some cases, difficult to differentiate, so these are considered a single phase. The metrics in Table 2-2 are the primary means by which mineral extraction sustainability can be measured at present. When considering exploration and construction, the first part of a mine's life cycle, quantifiable assessments of sustainability can be made by determining the total land area required for the project and ultimately disturbed, as well as various pollutant levels. The smaller these negative impacts, the more sustainable a mining operation can be considered to be. Similarly, smaller volumes of waste generation, resource consumption such as energy and water, as well as emissions from machinery, among other metrics can provide quantifiable data for the assessment of environmental sustainability during mining operations. Finally, several metrics are also assessed post-closure to contribute to an evaluation of the sustainability of a mining operation, e.g. growth rates of certain species in the affected area, pH or contaminants in nearby water bodies and soils, whether the disturbed lands are returned to their pre-mine state or not, etc. (IIED and WBCSD, 2002; Miranda et al., 2005; Anderson, 2002). These types of metrics can be measured and assessed throughout the life cycle of a mine and are sufficiently straightforward to enable comparison to other mines or past projects, and are therefore critical to the assessment of mining sustainability within the current framework for sustainability that emphasizes efficiency of operations and minimizing environmental impact of the mine.

Table 2-2: Key Environmental Sustainability Metrics and the Relevant Phase of Mine Life

Exploration & Construction	Operations	Closure & Long-Term Monitoring
Land requirements for development	Volume of materials inputs (water, reagent, fuels, solvent use)	Population effects on indicator species / Biodiversity losses
Area of land permitted/owned & disturbed	Volume of waste generated (rock, chemicals, water)	Contaminant levels in water and soil
Dust emissions	Volume of materials recovery/recycling	Area of land stabilized and re-contoured / Pace of restoration
Noise pollution	Volume of hazardous & non-hazardous waste generated	Revegetation (number trees planted, etc)
Propensity for soil erosion/landslides	Rate of depletion of resource	Backfilling
Land area in sensitive areas	Emissions rates (pollutants, GHGs)	Number of environmental incidents
	Transport intensity (materials & employees)	Air emissions (dust, etc.)
	Total energy use and percentage from renewables	Post-closure water runoff

The current sustainable mining framework and related metrics clearly focus on the mining operations realm, despite much exploration in the literature of the life cycle of mined materials. For example, MMSD (IIED and WBCSD, 2002) dedicates an entire chapter to an integrated approach to mining which takes into account recycling, life cycle assessments, and downstream use of materials. However, the MMSD proposed approaches for improving the environmental sustainability of mining do not include mined material life cycle at all; no tangible metrics or recommendations are proposed in the "Agenda for Change" included in MMSD (IIED and WBCSD, 2002).

2.4.3 Historical context for mineral-life-cycle-focused sustainable mining framework

Though the primary focus of improvement of sustainability in mining continues to be in the context of mine operations and reduction of environmental impacts (water and energy consumption, remediation of mine lands, the effects on local communities, etc.), a more holistic view of mined materials has been emerging with key questions being "how long can metals extraction rates be sustained?" and "how can we reduce mined material recovery losses and dissipation?" (Gordon et al., 2006; Hendrix, 2006). The concept of circularity and rates of extraction are often mentioned in the mining-operations-focused frameworks, but specific actions are seldom recommended (IIED and WBCSD, 2002; IISD, 2002; Allan, 1995; Rogich and Matos, 2008; KIN, 2012; Krausmann et al., 2009; Hendrix, 2006; Buxton, 2012). Extraction efficiency as well as rates of consumption and recovery of mined materials are recognized by many as priority topics in regard to the sustainability of mineral extraction (Allan, 1995; Laurence, 2011; Parameswaran, 2015, Wall et al., 2017). However, the rates of extraction and recovery are largely unconsidered in the current framework for environmentally sustainable mining. The concepts of closed-loop material use and circular economy are acknowledged and often referenced in industry initiatives as well as external studies (IIED and WBCSD, 2002; Allan, 1995; IISD, 2002; Buxton, 2012), yet no metrics for the assessment of status or progress on actionable solutions have yet been suggested.

The shift from looking at the life cycle of a mine to the life cycle of the material is a trend that is expanding. Quantification of stocks and flows of various materials, with estimations of unrecoverable resources has been conducted (Behrens et al., 2007; Bloodworth and Gunn, 2012; Gordon et al., 2006; Kesler, 2007; Steinberger et al., 2010). Key goals and challenges outlined for the mining industry are expanding beyond operational efficiency, and include the development of reclamation technology, incorporation of recycling, as well as finding uses for wastes and ponded tailings (Hendrix, 2006; Basu and Van Zyl, 2006). As an example of recent advances in closed-loop thinking, Garcia-Herrero et al. (2018) used a Life Cycle Assessment to determine whether mine waste is a sustainable feedstock option for chemical production. The emerging material life cycle approach to assessing the sustainability of mining and minerals use is mirrored in a growing interest in materials flow analyses, in which a society's consumption of materials is analyzed to assess resource scarcity, environmental impact, and the effects of these on sustainable development (Krausmann et al., 2009; Steinberger et al., 2010; Bloodworth and Gunn, 2012; Rogich and Matos, 2008; Sverdrup et al., 2014; Henckens et al., 2014; Hawkins et al., 2007). A quantification of the global materials flow analysis for the 20th century showed that the extraction and consumption of mineral goods increased substantially from 1900 to 2005, more than the rates of increase for use of biomass or even fuel minerals (Krausmann et al., 2009; Steinberger et al., 2010; Henckens et al., 2014).

A major benefit of looking at cycles and flows of minerals in the various phases of material life cycle is highlighting the importance of recovery and reuse, because without improvements in these areas the dissipation and losses of materials are very large (Chen and Graedel, 2012; Sverdrup et al., 2014). Additionally, identifying flows and cycles allows for the assessment of materials supply security, increasing the use-phase lifespan, and identifying potential urban hibernating stock for collection and use (Graedel, 2011; Chen and Graedel, 2012; Henckens et al., 2014). These types of frameworks can also be used in combination with future growth scenarios to identify opportunities to improve supply security and to increase public awareness of the finite nature of mined materials as well as which materials are consumed at higher rates (Dubiński, 2013; Chen and Graedel, 2012; Sverdrup et al., 2014; Wall et al., 2017; Henckens et al., 2014).

The holistic view of a material's life cycle beyond the mine provided by material flow analysis leads to an emphasis of the importance of recovery and recycling. The weight of this shift can be seen in a UNEP (Reuter, 2013) analysis of the state of metal recycling globally, culminating in the identification of key limitations and opportunities, including an emphasis on "product-centric" vs. "materials-centric" recycling, design for recovery, landfill mining, and the improvement of processing e-waste (Burlakovs et al., 2017; Reuter, 2013). These strategies are echoed in much other research on the improvement of metals recycling (Charles et al., 2016; Chen and Graedel, 2012; Gordon et al., 2006; Gunson et al., 2012). Increase in recycling rates and use of recycled materials not only improves the circularity and therefore supply security of metals, but also results in a significant reduction in the environmental damages for the same amount of material processed (Reuter, 2013).

In 2012, ICMM published MMSD + 10 (Buxton, 2012), a look at MMSD in the decade since initiation of the effort, identifying achievements, ongoing challenges, and new developments in the mining industry not foreseen in the 2002 report. Importantly, MMSD + 10 identified that a key challenge to sustainable development in mining is that extraction efficiency and closed-loop thinking are not yet widespread considerations of the industry (Buxton, 2012). This was reflected in the 2015 Kellogg Innovation Network review of mining, which emphasized that an important path forward for mining is a shift "from an extractive industry, to a development industry" (KIN, 2012). Key concepts and metrics for assessing and improving sustainability of mineral extraction and use, based on this body of work, indicate the need to focus not only on mine life, but to consider extraction efficiency, rate of resource depletion, recovery rates, losses and dissipation, co-mining, and recycling rates, among others. Materials flow analysis will have a significant role in determining key opportunities for improvement in the circularity of a mined materials life cycle (Chen and Graedel, 2012; Reuter, 2013; Henckens et al., 2014).

2.4.4 A summary of mineral-life-cycle-focused Sustainable Mining Framework

The material life cycle focus of recent explorations of sustainable mining indicates that a new framework for sustainable mining is emerging. Life-cycle-focused analysis of sustainable mining is not yet widely adopted by industry organizations and governing bodies, nor emphasized in peer reviewed publications. A summary of the works that discuss the mineral life cycle and its impact on sustainability of mining and minerals consumption is presented in Table 2-3. The figure shows that the topic is dominant in third party analyses of the mining sector and is less integrated into discussions of sustainability by industry groups or governing bodies. Additionally, a trend that can be seen is the inclusion of specific action or measurable metrics to assess sustainability in the context of a minerals life cycle and extraction rate over time. A look at the works in sustainable mining show that resource management and mineral life cycle concepts largely have been examined in an abstract way since the beginning of exploration of this area. However, tangible solutions and a deeper inspection of the relevance and benefits of the incorporation of a holistic look at an extracted resource's entire life cycle in the context of responsible use and the circular economy did not emerge until over a decade after the first explorations in the early 1990s of sustainable mining concepts and definitions.

Table 2-3: Summary of Work on Optimization of Mineral Life Cycle, Categorized by Focus

Category of Work	Author	Year	Introduction of Topic	Suggested/Prescribed Solutions
Peer Reviewed Publications by Independent Groups	Allan	1995	x	
	Basu and Van Zyl	2006	x	
	Gordon et. al	2006	x	
	Hendrix	2006	x	
	Behrens et al.	2007		x
	Krausmann et al	2009	x	
	Burlakovs et al.	2010		x
	Laurence	2010		x
	Steinberger et al.	2010		x
	Bloodworth and Gunn	2012		x
	Chen and Graedel	2012		x
	Gunson et al	2012		x
	Parameswaran	2012		x
	Dubinski	2013	x	
	Henckens et al	2014		x
	Sverdup et al.	2014		x
	Charles et al	2016		x
	Wall et al.	2017		x
Reports by Industry or Government Groups	IIED and WBCSD	2002	x	
	IISD	2002	x	
	Kesler (USGS)	2007		x
	Rogich and Matos	2008	x	
	Buxton	2012	x	
	KIN (UChicago + Industry)	2012	x	
	Reuter (UN)	2013		x

The life-cycle-focused sustainable mining framework can be summarized in the following way: the sustainability of mining and minerals consumption depends upon responsible rates of extraction and consumption of a mineral throughout its life cycle as well as the preservation of reserves and minimization of any losses. The life-cycle-focused framework does not emphasize specific metrics, as the operations-focused framework does, such as energy or water consumed, volume of waste, etc. It is important to note that this life-cycle-focused framework has potential benefits for society to help meet demand for extractible resources through recycling and responsible sourcing, and also potential benefits for the extractive industries, which should encourage adoption of this framework into their sustainability goals and commitments. Extraction efficiency is one of the life-cycle-focused sustainability concepts that can most readily be seen to have industry benefits: more complete recovery of mineral deposits during extraction leads to a production company with more supply to sell, as well as less waste to dispose. This may include co-mining of non-primary minerals which could provide an additional income stream. Moreover, improved end-of-life recovery and recycling is also beneficial to primary production industries, as processing and manufacturing from recycled goods is typically less expensive and less energy intensive than manufacturing from virgin materials (Reuter, 2013; Parameswaran, 2015). This advantage of a lower cost material to supplement processing and manufacturing directly benefits many mining companies with processing plants comprising smelters and refineries.

2.4.5 Limitations of the existing sustainable mining framework

A limitation of the current sustainable mining framework is the significant focus of the majority of works on mining operations. Extraction efficiency as well as rates of consumption and recovery of mined materials are recognized by many as priority topics in regard to the sustainability of mineral extraction (Allan, 1995; Laurence, 2011; Parameswaran, 2015). However, the rates of extraction and recovery are largely unconsidered in the current framework for environmentally sustainable mining. The concepts of closed-loop material use and circular economy are acknowledged and often referenced in industry initiatives as well as external studies (IIED and WBCSD, 2002; Allan, 1995; IISD, 2002; Buxton, 2012), where the circular economy is a method to enhance both economic prosperity and environmental quality (Kirchherr et al., 2017) yet no metrics for the assessment of status or progress or even actionable solutions are suggested. With the exception of some complete life cycle models developed for specific metals (Chen and Graedel, 2012), the circularity of non-fuel mineral consumption remains largely unexplored. Even these developed models simply identify flows and often fail to propose solutions.

A second important limitation is the lack of connection between work on reduction of the environmental footprint of mining operations, and work on improving reuse of non-fuel minerals. Though there is a minority research interest in life cycle sustainability of minerals, there is little overlap between the parties interested in one framework for sustainable mining vs. the other, and both points of view bring valuable methods for assessing environmental sustainability of mining and mineral consumption.

2.4.6 An expanded framework for sustainable mining and associated research needs

An expanded framework for sustainable mining is emerging, one that not only focuses on mine operations but that also includes material life cycle. The relevant system boundaries of mining-operations-focused frameworks and mineral life-cycle-focused frameworks can be seen in Figure 2-2. While the life-cycle-focused framework includes the entirety of a mineral's life through end of life and then re-entering the circular economy through recycling or reuse, the mining-operations-focused frameworks only consider extraction and processing; though not all mineral operations necessarily include processing, many of the considered works in this area do, so the system boundary includes this step. Where mine operations focused frameworks can include higher resolution tangible sustainability metrics (shown in Figure 2-2 as inputs and outputs), mineral life cycle frameworks include more variables because they include more phases of life that also affect sustainability. A sustainable mining framework should include the key environmental impact metrics associated with the life cycle of a mine (in the areas of land disruption, use of inputs, production of outputs, and closure) and also metrics to assess circularity of the complete life cycle of related products including life cycle phases manufacturing of goods, rate of consumption in the use phase, and finally collection and reuse of the mined material. The use of all of these metrics to assess sustainability in the future will provide a more holistic view of mineral consumption in societies without sacrificing the actionable metrics currently used by industry organizations and legislating bodies.

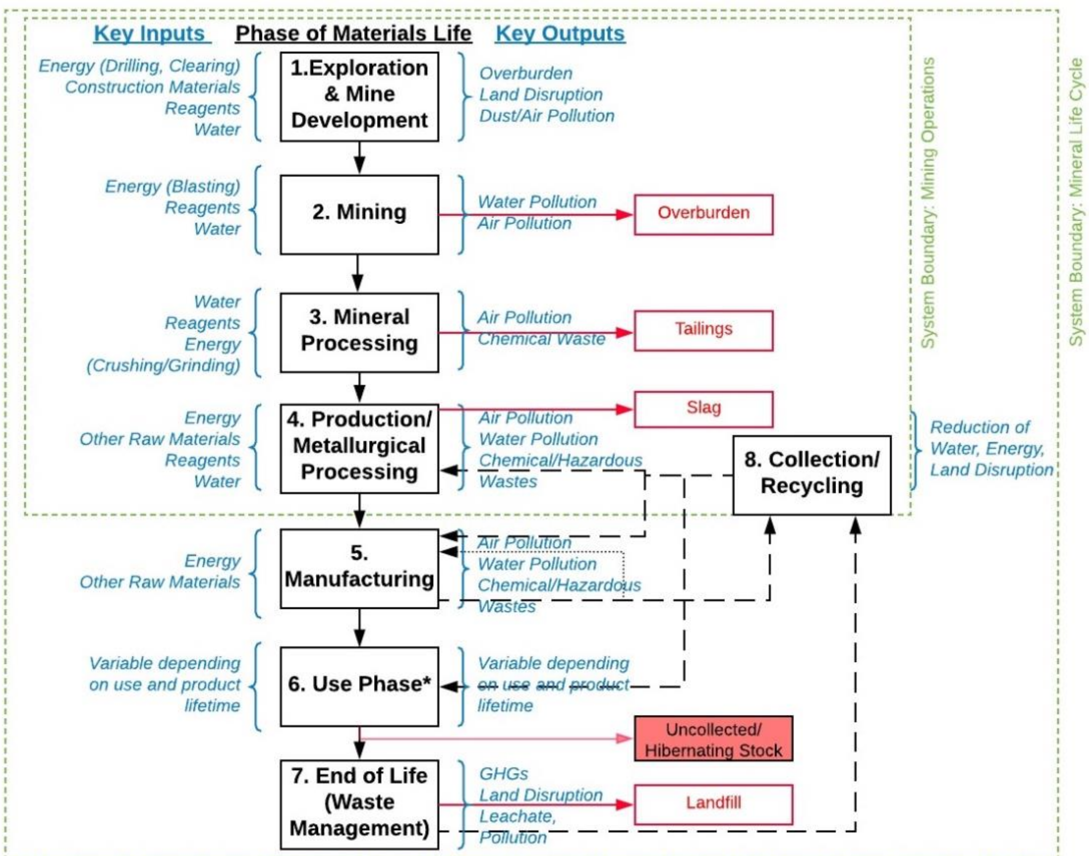

Figure 2-2: Life Cycle Framework and System Boundaries for Sustainable Mining

Moving beyond a mine operations-focused framework, to a materials-flow and life-cycle-focused framework will be facilitated by research and technology advances. The mining-operations-focused framework's emphasis on efficiency supports developments such as the implementation of more efficient grinding technologies, water recycling, or incorporation of renewable energy, solutions that exist and can be adopted by most mining companies. However, an improvement of the circularity of mined materials relies on system-scale developments that are more challenging. Product-centric recycling is a potential means to increase the recycling of complex e-waste, for example, but recycling infrastructure and markets are not currently set up to implement this at scale (Reuter, 2013). Similarly, design for recovery is a solution that is widely discussed (Reuter, 2011, 2013; Ilgin and Gupta, 2010), but will require many manufacturers to redesign existing goods in ways that need significant research and development: for example, a case study of various vacuum cleaners showed even the best model only allowed for half of total material recovery at end of life (Parajuly et al., 2016). Van Schaik and Reuter (2010) modeled various design characteristics of electronic goods and their relationships to recyclability and examined how design can be used to improve design for recovery. Hendrickson et al (2010) and Dzombak et al. (2017) performed similar analyses for solid-state lighting products. Identification and recovery of hibernating stock is yet another example of a potential solution for which there currently are not cost-effective methods for adoption (Goonan, 2009; Reuter, 2013).

Policies that provide economic and other incentives for material recovery are also critical (Hendrickson et al., 2006; Graedel, 2011; Matthews et al., 2015). Policy and societal motivations are unpredictable obstacles, however, to the adoption of sustainability solutions for a life-cycle-focused framework for non-fuel mineral use. For example, extended producer responsibility is theorized as a method to improve collection of goods at end-of-life, largely the limiting factor to increasing recycling. However, some countries have seen significant results with policies that require or incentivize extended producer responsibility, whereas others have not (Mayers, 2008; Gupt and Sahay, 2015; Turner and Nugent, 2016). In the U.S., some extended producer responsibility programs have been implemented, but have tended to be unsuccessful either due to consumers not taking advantage due to the largely voluntary structure of these programs or because of the distributed or prescriptive nature of such programs. There are few centralized collection organizations, as in Canada (Nash and Bosso, 2013; Hickle, 2013). Policies and programs generally vary state by state, sometimes in connection with national networks. For example, a mandatory battery takeback law implemented in Minnesota and New Jersey led to voluntary nationwide collection sites and other states prescribing laws, however the initial goal of 70% collection was never met and eventually removed from discussion (Nash and Bosso, 2013).

Though technology and research needs exist as barriers to the implementation of a life-cycle-focused framework for sustainable mining, the transition to consideration of a complete materials life cycle is important to ensure the supply of mined materials for future generations. As previously established, there exist both static and dynamic models of materials flows (Chen and Graedel, 2012), which provide a foundation for implementing a life-cycle-focused framework. The use of existing materials flow models and the development of new and improved ones for mined materials is key to determining limitations and opportunities to improving the circularity of these materials. A materials flow model for a particular metal may be able to identify particular processes and flows from each phase of a material's life cycle where there are major losses, in addition to identifying where recovery is maximized and whether these practices can be implemented in other phases or in production and use phases of other materials. The development of comprehensive models that incorporate historical data and trends will be important to identifying where research and technology development should be focused for any specific material.

2.5 Case study: sustainability best practices in metal mining operations.

To illustrate the ways in which sustainability is presently incorporated in mining and extractive industries, a case study of best practices in ASARCO LLC (American Smelting and Refining Company or Asarco)) operations is included. Asarco is an integrated producer of refined copper that operates mines, mills, and processing plants, and therefore encompasses all aspects of the Mining Operations system boundary in Figure 2-2.

The Asarco Ray Operations in Arizona consists of an open pit mine, a concentrator, and leach, solvent extraction, electrowinning facilities which produces electrowon cathode and copper concentrates. The copper concentrate from Ray Operations along with that from its Mission Complex is smelted at the Hayden smelter all in Arizona and the anode copper from the Hayden smelter is electrorefined at the Amarillo Copper Refinery in Amarillo Texas that produces refined copper products—cathodes, rod and cake (Parameswaran, 2017; Asarco, 2017). The primary copper production process is highly energy and water intensive and produces large quantities wastes, i.e., waste rock, tailings and smelter slag. In order to minimize the potentially significant environmental impacts, Asarco has implemented several initiatives and adopted strategies to make their operations more sustainable. One of their most significant strategies deals with water conservation. Approximately 80% of water used at its mines and mills is reclaimed and reused. In 2009 ASARCO renovated the pumping station at Hayden well field and added a booster station at Ray. The Hayden well field provides fresh water to the Ray operations.

The renovated pumping system has significantly improved control of the water system leading to increased use of reclaimed water at Ray. More importantly, the project resulted in a reduction in electricity usage estimated at 5,786,595 KWH annually at the time of installation and the benefits of lower electricity use has continued (Parameswaran, 2017). The fresh water pumps were replaced with more efficient variable-drive models, which led to significantly improved control of the water system and the increased use of reclaim water (Parameswaran, 2015). This project also resulted in a reduction of electricity consumption by 5.8 million kWh annually.

At the Asarco Hayden Smelter, hoods were installed in 2010 on anode furnaces to capture air emissions and meet revised air quality standards (Parameswaran, 2017; Asarco, 2017). This action led to an annual reduction between 88–92% in particulate matter emissions, from a maximum emission in 2010 of 76 tons/year to a minimum in 2013 of 6 tons/year, 6.6 tons in 2014, and 8.9 tons in 2015 (Parameswaran, 2017). Hazardous air pollutant emissions were also reduced up to 98% in the years following the introduction of these hoods (Parameswaran, 2017). It additionally improved the energy efficiency of the anode furnaces and caused a 12% reduction in natural gas consumption at the smelter (Parameswaran, 2017). Adoption of flash smelting and bath smelting techniques have also resulted in reduction of fossil fuel consumption and SO2 emissions (Parameswaran, 2017).

Beyond these operations-level changes, Asarco has also hosted the Avalon Solar Project, a 35 MW solar facility on disturbed agricultural lands near its Mission mine. The power from this project is sold to Tucson Electric Power under a 20-year power purchase agreement. (Parameswaran, 2015). This project created over 300 jobs during the construction (Parameswaran, 2015) and will provide renewable energy long term to the region, indicating that environmental sustainability goals can also have positive effects on social and economic sustainability. The result of this solar plant is a reduction in over 57,000 tons of CO2, while providing power to over 5700 homes (Parameswaran, 2015). The solar power plant has been expanded to 56 MW (Parameswaran, 2017).

In addition, Asarco has also implemented techniques for reclamation that promote waste reuse and other sustainability goals. Biosolids from municipal wastewater treatment plants are used to amend tailings to promote vegetation, which could not only provide a useful way to employ waste biosolids, but also where there is a shortage of topsoil (Parameswaran, 2015). In addition, Asarco has used livestock, instead of mechanical methods, to introduce organics into tailings (Parameswaran, 2015). Cows are used to trample manure into tailings which produces a soil-like medium that can support plant growth for the re-vegetation that is required by law during mine land remediation (Parameswaran, 2015).

These examples of actions developed with assistance of a sustainability framework by a major mining and production company illustrate the kinds of advancements being made in reducing the environmental impacts of mining and production operations. Incentives to consider the entire life cycle of the material, however, are still lacking. In Asarco's considerations of sustainability, it is acknowledged that "recycling can conserve energy since recycling processes are much less energy intensive than the primary metals production processes. Recycling also contributes to the conservation of natural resources by providing an above-ground 'virtual mine'" (Parameswaran, 2015). Methods for incorporation of this idea into mining operations are still in development. The concept of "above-ground mines" as resources that are continually mined and used is not new: Gordon et al. (2006) estimated that 70 Tg of copper have accumulated in the use phase in society and that 56 Tg of copper have accumulated in landfills globally. These stocks, in addition to copper in tailings and other processing wastes, are all theoretically recoverable and may act as above-ground mines in the future.

2.6 Summary and Conclusions

The original framework for sustainable mining developed in the 1990s focuses on improving efficiency of mine operations for reduction of environmental impacts. The framework also includes consideration of social and economic impacts, but the focus has been predominantly on modification of specific operational aspects to reduce environmental impacts and the environmental footprint of mining. The operations-focused framework has stimulated development and implementation of associated concepts and metrics that are specific, quantifiable, and actionable. This has enabled, with respect to non-fuel mining operations, environmental sustainability to be measured and improved in actionable ways by mining companies, with motivation to do so now fairly widespread in the industry and supported by consumers, communities, and stakeholders. The major limitation of the current framework is the focus on mining operations. The entire life cycle of a mined material must be considered to assess fully what rates of mining and processing are environmentally sustainable considering future demand driven by population and economic growth.

A new framework for sustainable mining is emerging that encompasses the entire life cycle of the mined material. This shift to a life-cycle-focused framework will not only allow for reduction of the major environmental impacts associated with increasing mining rates, inputs, land disruption, outputs, and closure, but also extend the lifetime of existing minerals reserves and resources. Some of the ways this shift to a material life cycle focus can be achieved are through the incorporation of materials flow analysis and concepts into both public and private sector planning and policies, as well as improving collection and recycling through design for recovery, product-centric recycling, and extended producer responsibility, among other approaches.

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Chapter 3 : Stocks and Flows of Copper in the U.S.: Analysis of Circularity 1970-2015 and Potential for Increased Recovery

This chapter, written by Miranda R. Gorman and co-authored by Dr. David A. Dzombak, has been submitted to the Journal of Resources, Conservation and Recycling.

3.1 Abstract

An analysis of the copper life cycle in the U.S. was performed to investigate the circularity of copper from 1970-2015. A stocks and flows model for copper was developed for the major life cycle phases by collecting extensive primary data from government and private sector sources, via available data and surveys and interviews with individuals within companies, government, and other organizations. The data were integrated into a stocks and flows model. Collection and inclusion of primary end-of-life data into the model represents a contribution of the material flow analysis presented and provides insight into specific limitations and opportunities for improving the circularity of copper. The analysis incorporates 45 years of data, providing historical context and insight into changing trends. A number of key findings emerged from of the stocks and flows analysis. First, end-of-life collection is a complicated ecosystem. The largest stock accumulation of copper is in the use phase - on the order of 72 million tons since 1970. Over half of this is in buildings and construction, an order of magnitude more than the total accumulation in any other part of the copper life cycle. The analysis also revealed that while there are losses of copper via process losses, degradation, and tailings generation, exports (much of which are unaccounted for as embedded flows) and hibernating stock are much more significant losses from the U.S. circular economy. Finally, building and construction and electric/electronic products are the two use phases where improved collection and recycling would yield the most impact to improving circularity of copper since they together comprise more than 80% of total accumulation.

3.2 Introduction

The concept of "sustainable mining" has been explored in the past two decades, with focus on reducing the environmental footprint of mining and processing activities (Allan 1995; Gorman and Dzombak, 2018). These environmental impacts can be measured and fall largely into four categories: inputs such as water, chemical, and energy consumption during mining, transportation, and processing; land disruption from mining activities including soil erosion, increased seismic activity, or biodiversity loss; outputs such as greenhouse gasses and other air pollutants, water contamination and waste rock; and closure effects requiring remediation and monitoring (Gorman and Dzombak, 2018). Despite industry and legislative efforts to advance the sustainability of mining through quantification and benchmarking of these impacts, extraction and processing of mined materials continue to have an ever-increasing environmental footprint due to the persistent increase in the amount of materials consumed globally and ever decreasing ore grades (Miranda et. al, 2005; Reuter, 2013). The expanding environmental impacts of mining are attributable primarily to developed countries, such as the U.S., where materials consumption exceeds by orders of magnitude that of developing nations, resulting in a higher total environmental impact per capita (Kesler, 2007). This demand, driven by increasing population, affluence, and technological need necessitates more mining to attain production goals and leads to the depletion of high-grade ore resources (Krausmann et al., 2009; Steinberger et al., 2010). Impacts associated with mining lower grade ores are greater than high grade ore mining and processing. Perhaps the most important environmental issue is that mining and consumption of mineral resources require extraction from the finite source of these elements that is economically accessible in the lithosphere (Allan, 1995; Laurence, 2010). Limited resource availability concerns and the various environmental impacts of mining and mineral processing, which will become more acute as both the global population and per capita consumption of goods increase (Kesler, 2007; Krausmann et al., 2009; Nassar et al, 2012), motivate this investigation of the circularity of copper.

Significant resource savings can be associated with processing recycled materials, instead of raw materials, including measurable differences in energy and water consumption as well as a reduction in land disruption due to reduced extraction demand (Norgate and Haque, 2010; Northey et al., 2013; Gunson et al., 2012; Reuter, 2013). The water and energy savings from processing recycled materials, not raw materials, have been measured numerous times for various processes, metals, and locations, and can vary, but are typically between 75% to 95% for energy (Norgate and Haque, 2010; Reuter, 2013) and up to 65% for water (Gunson et al., 2012, Reuter, 2013). Additionally, whereas an average of more than 120 tons[2] of copper ore are required to produce one ton of concentrated copper (Brininstool and Flanagan, 2017), end-of-life copper can be re-refined and recycled with minimal losses (Goonan, 2004), avoiding hundreds of tons of waste production. These resource savings would also necessarily reduce costs for mining companies, reduce negative impacts to nearby communities, thereby improve social, economic, and environmental sustainability, all aspects of the triple bottom line definition of sustainability, which has been embraced by extractive industries for the past two decades (Gorman and Dzombak, 2018). Environmental sustainability, however, dominates quantifiable sustainable mining metrics. Meeting a larger proportion of demand for materials with recycled as opposed to raw materials also extends the potential lifetime of reserves, making these resources available to future generations, another key aspect of sustainability, and a more recent consideration of extractive industries, as the concept of a circular economy - that where goods and resources are not produced, used and discarded linearly, but are reused and recycled to close the figurative loop - emerged

[2] "Tons" in this paper always means metric tons. All values are given in metric tons.

about a decade after the initiation of thinking about sustainable mining in the 2000s (Gorman and Dzombak, 2018).

To examine the current life cycle of copper in the U.S. system boundary and identify opportunities for improving circularity an evaluation was conducted of U.S. copper production, use, recovery, and disposal. The selection of copper as the focus of the analysis was based on several factors: it has a relatively high recycling rate, it has diverse uses, and therefore has more opportunities for identifying potential sources of recovery from hibernating stocks and waste streams (Brininstool and Flanagan, 2017). Also, copper is the second-highest-value metal mined in the U.S. after gold (Brininstool and Flanagan, 2017), and, is not a completely import-dependent material, which means that domestic findings could have significant impact downstream (Reuter, 2013; Brininstool and Flanagan, 2017; Chen and Graedel, 2012). Thus, when considering the domestic metal economy, copper is one of the most important commodities to quantify. Selection of the U.S. as the system boundary is due to the previously mentioned extreme imbalance in demand, with the U.S.'s consumption of copper exceeding that of any other developed nation both in total and per capita, but unlike many other developed nations, the U.S. still has significant extraction and processing of copper domestically, and is not completely import reliant (Kesler, 2007; Krausmann et al., 2009; Brininstool and Flanagan, 2017).

The development and inclusion of primary end-of-life data in this study is a new contribution to the field. Related studies have focused on material use-phase lifetimes to estimate the end-of-life flows. One example is a recent study by Chen et al (2016), a material flow analysis based on data which are primarily lifetime-based estimates and do not include primary data from industry and waste management sources. The quantities of scrap processed locally as estimated in this study via a bottom-up method emphasizing primary data collection differ significantly from USGS (U.S. Geological Survey), CDA (Copper Development Association) or ICSG (International Copper Study Group) estimates, which have low variability between them due to the fact that they all are highly cooperative organizations that engage in significant data sharing between them, according to conversations with people in all of these organizations.. Other approaches include econometric regressions to estimate scrap supply (Fu et al., 2017). While these are valuable for forecasting, the emphasis on collection of primary data in the present study, not calculated estimates, is valuable in providing a baseline for comparison to other methods. The present study additionally includes more years of data on both the front and back end of the time period, the most crucial being scrap data for years after 2012, when scrap exporting patterns were affected by China's "Green Fence" trade policies which started in the 2000's but became official in 2013 (Earley, 2013; Mosenberg, 2018), the impacts of which can be seen in the results. This trend of reduced scrap importing by China can be expected to continue for the foreseeable future, especially because predictive analyses show that China's domestic scrap generation will continue to greatly increase, and the environmental impacts of the scrap industry are of expanding interest (Wang et al., 2017). The analysis described herein also considers dissipative losses (Lifset et al., 2012) of copper from the refining and manufacturing phases by estimation of average process losses, as this has been shown to be a potential detriment to the circularity of a material, but several orders of magnitude less than total copper uses (Lifset et al., 2012). Also, higher resolution data are examined in the use phase to facilitate specific determination of what types of material uses are optimized for recovery or end up as major sinks of material, limiting circularity.

The objective of this study was to identify limitations to the optimization of the circularity of copper life cycle in the context of a sustainable mining framework that includes consideration of resource extraction efficiency, rate of extraction, end-of-life collection rate, and other circularity metrics (Gorman and Dzombak, 2018). This was accomplished by developing a representation of the stocks and flows of copper in the U.S. to provide a framework for data integration and analysis, and by the collection of current and past data for the flows of copper in the U.S. economy. The incorporation of multiple periods of data into the developed materials flow framework enabled analysis of long-term trends and accumulations or depletions over time. The stocks and flows model for copper also provides a framework for the future assessment of consumption of other mineral and non-renewable resources in the U.S., allows for insight into which stages of the life cycle of a material are not optimized, and how a material's collection can be optimized in the context of the circular economy.

3.3 Research Methodology

3.3.1 Development of the copper life cycle framework

Within the U.S. system boundary, a complete representation of the copper life cycle was developed, from extraction through processing, refining, consumption, and then end-of-life where some copper is collected for reuse and recycling and some is lost to landfills or remains uncollected. The major life cycle phases were identified using USGS Mineral Yearbooks and Mineral Commodity Summaries (USGS, 2019), as well as Copper Alliance Annual reports (ICA, 2017). Flows between the life cycle phases and outside of the system boundary via imports and exports were identified. An overview of the system boundary and major flows and processes of copper in the U.S. is illustrated in Figure 3-1. The relevant key operations are shown geographically in Figure 3-2, where the limited number of mining, mineral processing, and metallurgical processing operations are indicated on a U.S. map. The other key life cycle phases indicated in Figure 3-1 (manufacturing, use, end-of-life, and waste disposal) are distributed throughout the U.S. and therefore not indicated on the map in Figure 3-2.

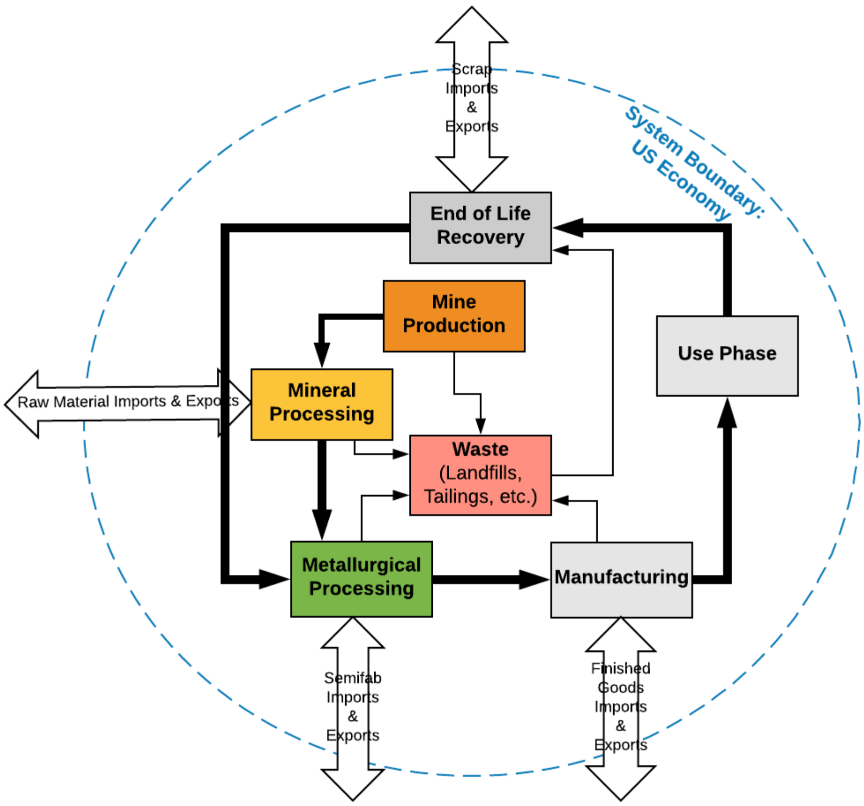

Figure 3-1: Complete life cycle stocks and flows of metals in the U.S.

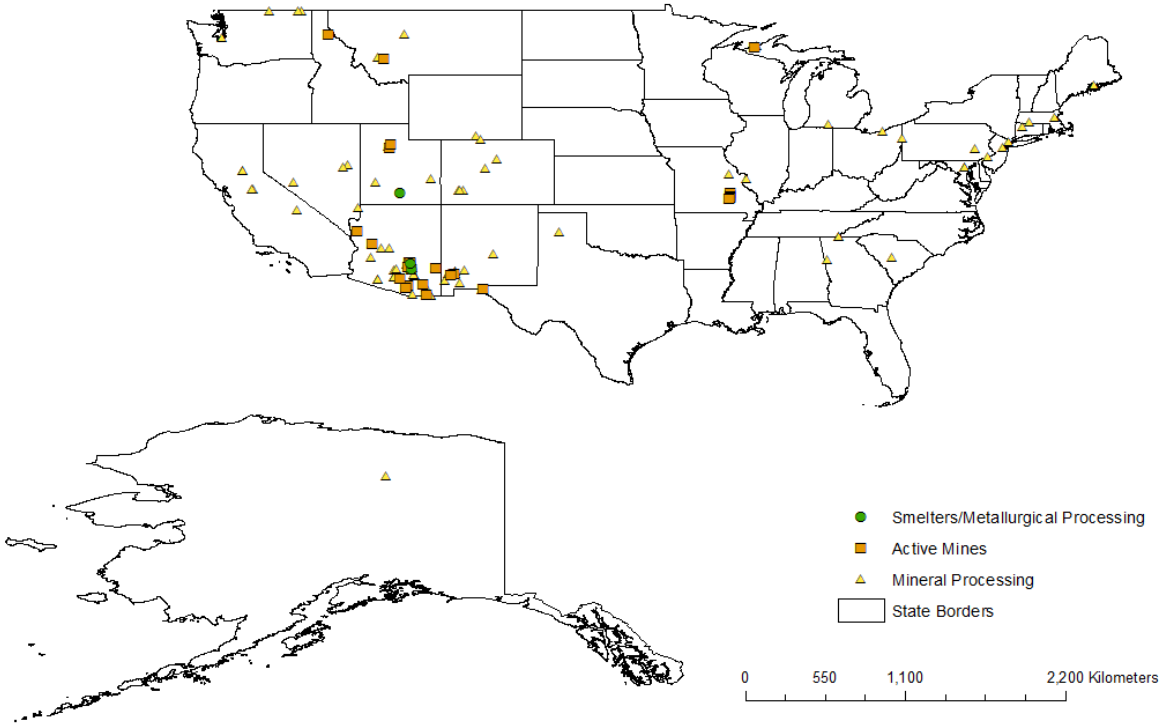

Figure 3-2: Location of Key Copper Operations in the United States (2017)

The STAN software, developed at the University of Vienna (Cencic and Rechberger, 2008), was used in this work to develop the materials flows diagrams and mass balances for copper in the U.S. in combination with calculations performed using Excel. Figure 3-3 presents the framework for stocks and flows for the entire life cycle of copper in the U.S. developed in the STAN software. Subsystems within some of the more complicated systems were also developed for a more detailed understanding. Figure 3-4 illustrates the use phase subsystem, which is the focus of this study's deeper look at primary data end-of-life collection and management. Subsystems for refining and manufacturing (F14-24) were also developed using USGS data, and a diagram for these flows can be found in the Supplemental Information, Appendix B.

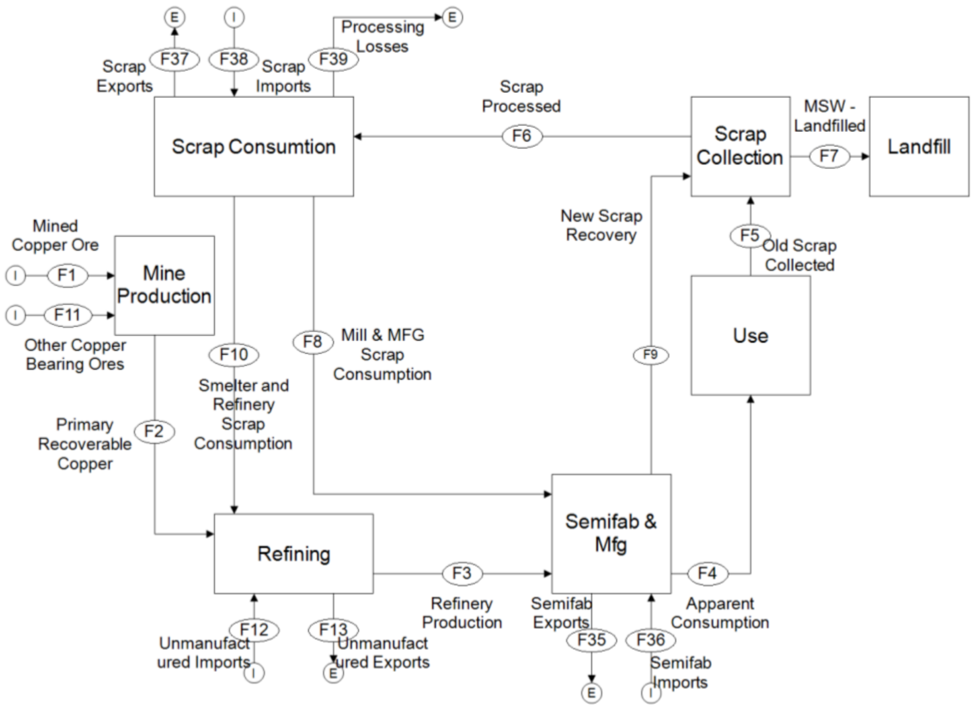

Figure 3-3: Framework for copper flows in the U.S. Flows labeled F1-F36 are uniquely numbered flows that indicate mass exchanges between life cycle phases or stocks (shown as the boxes). Flows with I or E at the end indicate Imports and Exports, respectively, in or out of the U.S. system boundary that is shown in Figure 3-1

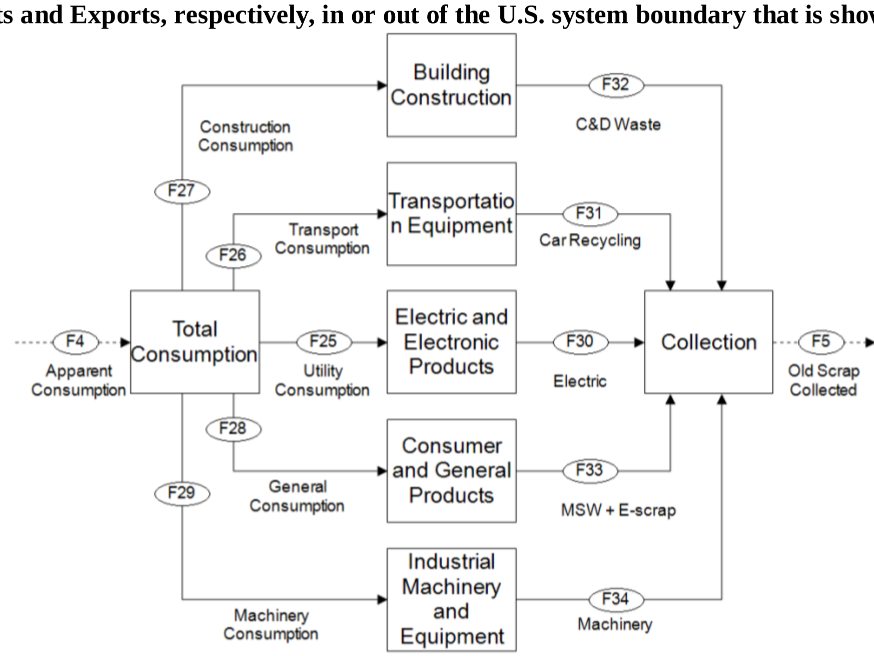

Figure 3-4: Use Phase Stocks and Flows Framework. Flows labeled F1-F36 are uniquely numbered flows that indicate mass exchanges between life cycle phases or stocks (shown as the boxes). Flows with I or E at the end indicate Imports and Exports, respectively, into or out of the U.S. system boundary that is shown in Figure 3-1

Mass balance formulae were used in combination with manual input of data for known flows to identify unknown flows as well as stocks accumulations and depletions. Flows F1 – F5 and F7 – F38 are input based on collected data (complete datasets for the total life cycle and the use phase sub-system which is relevant to this analysis are available in Appendix B: Supplemental Information). F6, Scrap Processed, is a calculated flow based on scrap collection and recovery data as well as landfilling data:

$$F_6 = \Sigma F_{in} - \Sigma F_{out} = F_5 + F_9 - F_7 \qquad \textbf{Eq. 3-1}$$

Stock changes for each life cycle phase are calculated over every calendar year as follows:

$$\Delta Stock_{year} = \Sigma F_{in,year} - \Sigma F_{out,year} \qquad \textbf{Eq. 3-2}$$

using standard mass balance formulae typical of stocks and flows analyses (Chen et al., 2016), and can also then be summed over multiple years for cumulative stock change estimates for multiple year periods. A process imbalance at end-of-life (F39) exists which is not based on collected data, but the uncertainty and differing sources of data, and is calculated as follows:

$$F_{39} = \Sigma F_{in} - \Sigma F_{out} = F_6 + F_{38} - F_{37} - F_8 - F_{10} \qquad \textbf{Eq. 3-3}$$

This flow represents and indicates the uncertainty associated with the hidden or informal flows described previously, voluntary reporting to USGS, ICSG, and author-conducted surveys. The synthesis of varying data sources leads to this imbalance in the Scrap Consumption phase where net export, and scrap consumption flows do not equal the newly collected primary data for scrap processed from different sources.

A potential source of inaccuracy and uncertainty in the materials flow accounting comes from incomplete accounting of trade and sales of materials. “Hidden” flows, for example, as described by Johnson and Graedel (2008), are flows of metals in finished goods or semi-manufactured products. For example, the copper in an electronic device or motor may not be accounted in trade as copper, but as finished products. Because “hidden flows” have been shown to be potentially significant (Johnson and Graedel, 2008), the bottom-up approach taken to data collection in the present study allows for consideration of these flows through inclusion of management of semi-manufactured and complete goods. Another potential source of data uncertainty are “informal” flows, as examined by Tran et al. (2016) in a case study in Vietnam, involve unregistered inflow of waste, particularly electronic waste. Extensive discussions and surveys with scrap dealers and particularly e-scrap dealers were performed in the present study to gauge the existence of an contribution of informal waste flows in the U.S., for example due to U.S. Environmental Protection Agency (USEPA) regulations as well as Institute of Scrap Recycling Industries and Basel Action Network e-waste incentives. From these investigations it was concluded that informal waste flows in the U.S. are much lower than in the described case study for Vietnam, especially in recent years. Thus, as much complete data as possible, including estimates of unreported flows, were included in the bottom-up calculations of the materials flows, but a complete assessment and separate quantification of informal flows was not performed, as they were considered not to be significant within the system boundary. Furthermore, uncertainty is introduced though material quality of flows. For this reason, alloyed scrap, consumption of materials by brass mills and manufacturers, and materials flows of all qualities are included in full, so that many cycles of use and inefficient refining of post-consumer material are captured in the model.

3.3.2 Collection of current and past data for flows in the U.S. copper life cycle

Collection of data for most major flows in Figure 3-3 was accomplished primarily from reports from the USGS, the International Copper Alliance (ICA), Institute of Scrap Recycling Industries (ISRI), and the Copper Development Group. Data for end-of-life collection, however, were not so readily available. Though organizations like USGS, ICA, and ISRI have data for annual amounts of scrap processed and exported, data from the specific use phases illustrated in Figure 3-4 are either not collected or not published by these organizations, but are critical to gain a better understanding of what types of uses serve as major sinks for copper as well as which use phases are leading candidates for recovery and reuse. For this reason, contact with individual companies as well as industry organizations was necessary to collect primary data for end-of-life material management. It was therefore critical to identify national organizations and representative agents in the scrap industry, to be able to follow end-of-life goods from their use phase to disposal or re-entry into the economy as a re-purposed or re-manufactured and recycled product.

A general framework for the ecosystem of the various roles of different agents in scrap copper recovery or disposal is presented in Figure 3-5. This ecosystem shows the various options at end-of-life for individual consumers as well as businesses with different types of scrap or larger-scale scrap volumes that cannot be handled in the same way. For either consumers or businesses, with end-of-life copper-bearing scrap, there are only a few options for management of the scrap at end-of-life: disposal to the municipal solid waste stream, transmittal to general or specialized scrap dealers, product returns through producer takeback initiatives, or specialty or regulated disposal. These threads all have their own downstream processes which culminate in scrap exports or disposal to landfills, after which the copper is unavailable to the circular economy within the established system boundary; or refurbishment, reuse, and recycling, which returns the copper to the circular economy, making the copper available in the U.S. again. The producer take-back stream is somewhat less defined, as copper-bearing goods may be dismantled for parts that are refurbished and reused and therefore re-enter the circular economy, or used on site for research and development, in which case producer take-back is a materials sink.

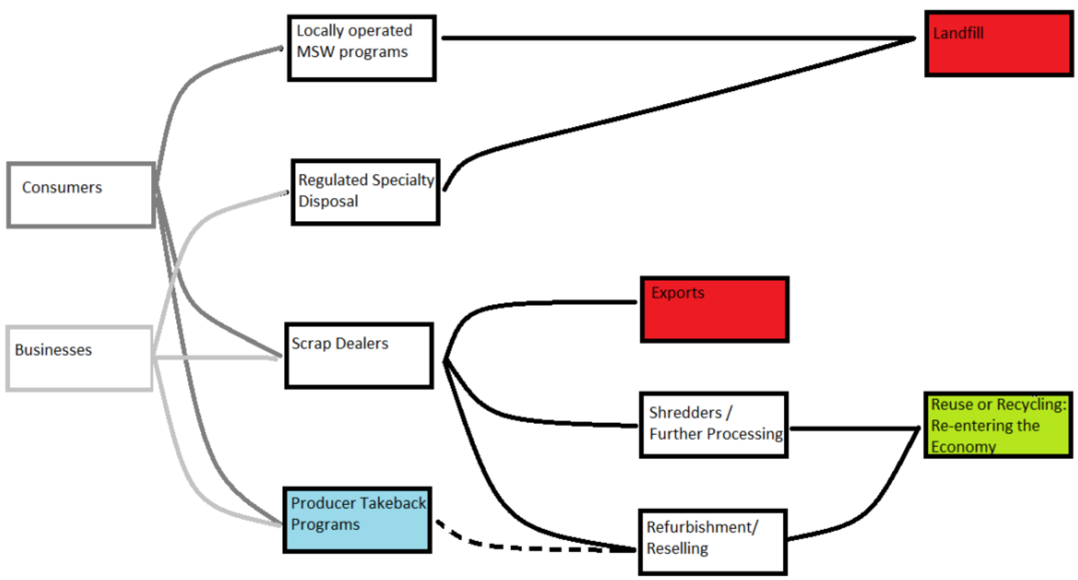

Figure 3-5: End-of-Life Ecosystem for Copper-Bearing Goods and Materials. Colored boxes represent fate of collected materials, with red showing losses to the U.S. circular economy, green being re-entry of materials to the U.S. circular economy, and blue being partial re-entry and partial continued processing.

The framework of Figure 3-5 provides insight into how copper-bearing goods and materials are processed in the U.S. at end-of-life, but higher resolution data for collection from the established use phases (shown in Figure 3-4) are necessary for detailed modeling. As is illustrated in Figure 3-5, the end-of-life ecosystem for copper scrap recovery and processing is varied and disparate, depending on the path a particular material takes. Therefore, these flows must be synthesized from discrete data points from various sources.

3.3.3 Calculation of end-of-life collection values for individual use phases

The discrete data points for copper collection were obtained from overseeing bodies like ISRI, SWANA, the USEPA as well as state environmental agencies, organizations that provide certifications and encourage sustainability and recycling like the Basel Action Network, Sustainable Electronics Recycling International, U.S. Green Building Council, as well as individual companies. The general framework for compiling these discrete data to align with the use phase framework in the copper stocks and flows model is provided in Figure 3-6. The categories for use phase collection were determined using the USGS data series 140 categorization of copper use phases (USGS, 2005).

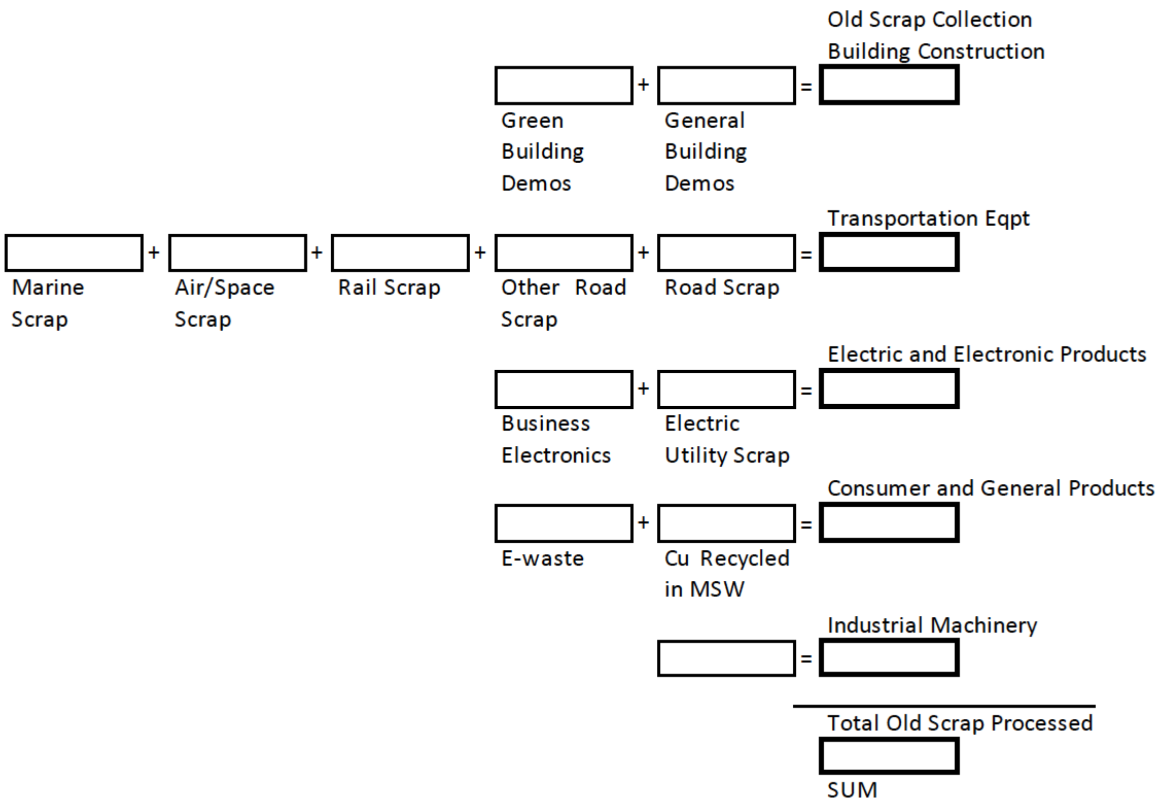

Figure 3-6: Synthesis of discrete data sources for end-of-life collection analysis for copper

For each of the five categories shown in Figure 3-6 – building construction, transportation equipment, electric and electronic products, consumer and general products, and industrial machinery – individual calculations from disparate data sources were performed. These are detailed with sources of data, where possible, and calculation methods in the following subsections. Some organizations specifically requested that their data be used confidentially, and that no link to their company be included in the results, so for that reason data from individual companies or organizations are withheld to protect the privacy of these parties. Any sources who provided permission for their name to be shared are included specifically. Complete data are available in Appendix B: Supplemental Information: uncertainty ranges were calculated for each use phase, described in the following sections and reported in Tables B-1-5. Data reported in the appendix and used for calculations and results are averages within these ranges.

3.3.3.1 End-of-life collection of copper from building construction

From USGS Data Series 140, "building construction includes electrical wire, plumbing and heating, air conditioning and commercial refrigeration, builders' hardware, and architecture uses" (USGS, 2005). EPA estimates of total construction and demolition (C&D) waste generated (EPA, 2015) can be multiplied by collection rates, as well as copper content and collection information to obtain total copper collected in the building construction category. Several specialty C&D landfill composition studies were considered to find these values – C&D landfills are one example of the regulated or specialty materials disposal shown in Figure 3-5, and therefore need to be considered in addition to C&D waste in MSW landfills. The Minnesota DEP found that 0.5% by weight of generated C&D waste was non-ferrous metals by weight, 90% of those nonferrous metals were recycled, and 10% were landfilled (Fisher, 2008; SWMCB, 2007). Another study in Wisconsin found that 0.4% of C&D waste is non-ferrous metal (MSW Consultants, 2010), in Massachusetts, 30% of total C&D waste is recovered, and it is on average about 1.2% non-ferrous by weight (DSM Environmental, 2017). Similar values were found in characterization studies by other states (Florida DEP, 2000; Pennsylvania DEP, 2015). Powell and Chertow (2018) conducted a complete bottom-up assessment of waste flows in the US and found that up to 24,000 tons of C&D waste are disposed in MSW landfills annually. This information combined with copper content of C&D waste was be used to estimate total amount of copper disposed in both C&D and MSW landfills, as well as high and low bounds based on the compositions of various studies.

3.3.3.2 End-of-life collection of copper from transportation equipment

Transportation equipment is defined as including “road (cars, trucks, and buses), rail, marine, and air and space vehicles” (USGS, 2005). The US Bureau of Transportation Statistics publishes the number of motor vehicles scrapped annually categorized by type (US BTS, 2016), which can be multiplied by the CDA’S estimate of copper content in different types of vehicles (CDA, 2018) to determine the total amount of copper scrapped in any given year from road vehicles. A linear increase in recoverable copper content is assumed from the introduction of hybrid vehicles in 2003 to the current 2% of the US fleet. Additionally, implementation of eddy-current shredder technology in the early 90s (Recycling Today, 2008) caused an increase in recovery of copper from 70% to 90%, according to discussions with recyclers: again, a linear increase is assumed since its implementation. Beyond road transportation, end-of-life materials from off-road construction/mining vehicles, and from air, rail, and marine transportation must be considered.

For air, rail, and marine transportation scrap, industry organizations were contacted to understand end-of-life management practices. Very little copper is recovered domestically from these uses, as essentially all ship-breaking occurs overseas, and has for decades (UNCTAD, 2017; Kuster, 1995), and air transportation equipment at end-of-life is also often exported for continued use or breaking in other countries (ICAO, 2016), or sometimes is stored for years or even decades (as hibernating stock) before end-of-life management even occurs according to discussions with both researchers and people in the shipping and transportation industries. These flows therefore are accounted for in scrap exports and not end-of-life collection. Rail transportation equipment as well as off-road construction/mining vehicles at end-of-life typically contains little copper, but any service or collection is typically performed by the manufacturer and acts more as in-house stock, and therefore does not re-enter the circular economy.

3.3.3.3 End-of-life collection of copper from electric and electronic products

From USGS Data Series 140 (USGS, 2005), electric and electronic products include "wire and equipment for the power and telecom utilities, business electronics, and lighting and wiring devices." Several electric utility companies were contacted to determine end-of-life management practices of wire and generation equipment. Some utilities shared their investment recovery data, and additional information on collection and waste diversion of copper was obtained from corporate sustainability reports. These data were scaled up by relative the fraction of US grid ownership for each company to extrapolate total copper recovery for the US. Business electronics and lighting, if not collected directly, would be found in construction and demolition waste or even e-waste and enter the waste stream with other electric and electronics scrap processing through scrap dealers.

3.3.3.4 End-of-life collection of copper from consumer and general products

"Consumer and general products includes appliances, cord sets, military ordnance and commercial ammunition, consumer electronics, fasteners and closures, coinage, utensils and cutlery, and miscellaneous products" (USGS, 2005). End-of-life collection from consumer and general products was estimated using the EPA Sustainable Materials Management Report (US EPA, 2015) which includes estimates obtained by Municipal Solid Waste (MSW) accounting. In the EPA analysis, all goods in MSW are assumed to be consumer and general goods, since all other use phases are specifically regulated and are disposed in non-MSW landfills and with non-MSW sorting methods. Further, the EPA methodology specifies that MSW is all non-hazardous wastes, and specifically excludes construction and demolition debris, automobile bodies, and industrial waste. Linear interpolation was used for missing years.

Several estimates of copper recycling as well as landfilling are performed for each year to calculate a range of values and take into account uncertainties. A minimum estimate was developed by assuming all e-waste is accounted for in the EPA publication, and that of the published "other non-ferrous" wastes, 20% of total weight is copper (based on an EPA figure stating that 68% of the "other non-ferrous" category is lead from lead acid batteries). A maximum estimate is based on the Powell and Chertow (2018) study which suggests that total MSW landfilling in the US is almost twice that published by the EPA. Reported values in the Supplemental Information (Appendix B) are average calculations.

Composition studies (US EPA, 2019.; Green Solutions, 2000; Midwest Assistance Program, 2000; Cascadia Consulting Group; 2015 & 2016; Oregon DEQ, 2007) show this landfilled material is on average 5.2% metal, less than the 10% metal estimate provided by the EPA, but that there is an additional 1.6% of the total 196 million tons of landfilled waste that is e-waste, which has some metals content as well. Overall, the sources indicate that average copper content in MSW is between 0.1% and 0.4% of total waste. Ore grades of copper in mines in the U.S. now are typically around 0.4% or 0.5% copper (Brininstool and Flanagan, 2017) which indicates that even if landfill mining as a potential source of copper and other metals is not economically viable at this point, as ore grade continues to fall the economic case for landfill mining will become increasingly stronger, since the copper content is already comparable.

3.3.3.5 End-of-life collection of copper from industrial machinery

The final category of use from USGS is industrial machinery, which includes a variety of equipment such as valves and fittings, off-highway vehicles, and heat exchangers. The types of materials that fit into this category are difficult to be distinguished from some of the other use phases when they are collected in the end-of-life ecosystem (Figure 3-5). Discussions with people at all stages at the end-of-life ecosystem indicated that there is no clear separate waste stream for industrial machinery. Heat exchangers for example, are likely to be grouped with collected end-of-life materials from electric utility generation. Off-highway vehicles are typically managed in the same way as transportation equipment, according to discussions with industry contacts. Other industrial machinery at end-of-life, like valves and fittings, would also be managed with other materials and be absorbed into the other categories, primarily construction and demolition waste during C&D projects that involve manufacturing facilities or buildings with old equipment and machinery in them. For this reason, the consumption of copper into industrial machinery is assumed to be divided among construction and demolition, transportation equipment, and electric and electronic products by distributing USGS consumption in this category according to the relative proportion of the others to the total – 54% in Building Construction, and 23% in both Electrical and Transportation (USGS, 2005). Accounting of end-of-life collection from industrial machinery therefore is also not separately included in the stocks and flows model, and the use phase frameworks were adjusted from Figure 3-4 to follow the structure shown in Figure 3-7.

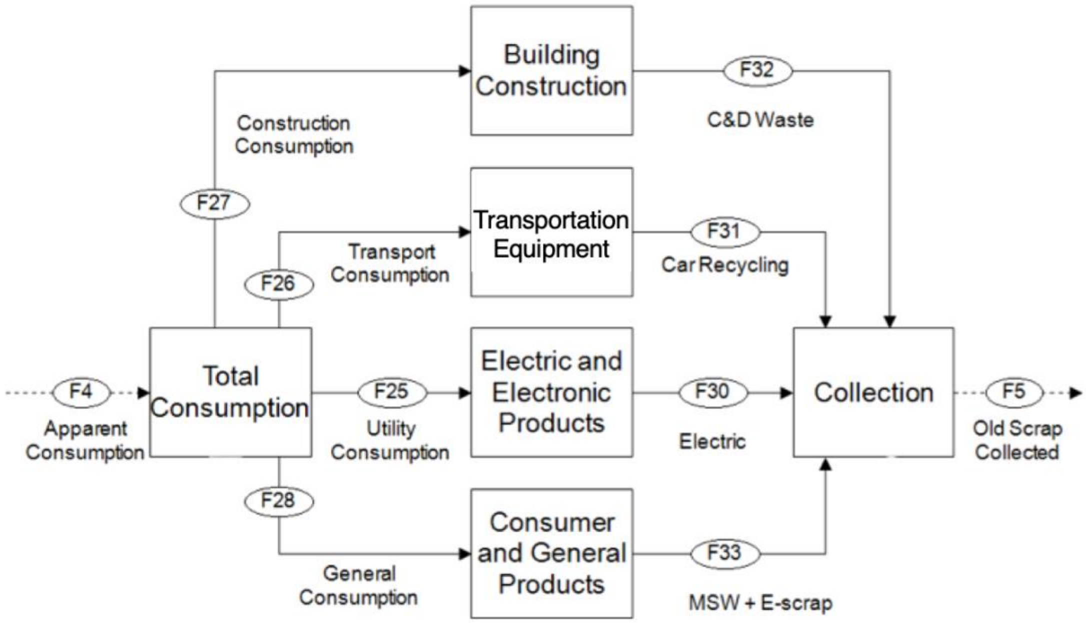

Figure 3-7: Use-phase stocks and flows framework, adjusted to show the distribution of industrial machinery between the other use phases.

3.3.4 Synthesis of data and framework of stocks and flows

Historical data beginning in 1970 were included for major flows and a multi-year mass balance was completed to assess total accumulation and depletion. The stocks and flows model enables identification of key material circularity challenges and opportunities from the life cycle of the copper and makes it possible to quantify which of these challenges and opportunities are most significant, based upon total amount of copper involved. A significant loss or limitation to circularity with no existing means of improvement, for example, may indicate a major technological or policy gap, whereas a lack of collection from a specific flow that could be rectified by improving current recycling incentives may prove easier to address. Some metrics have been established to assess circularity, including a development from the Ellen Macarthur Foundation, the Material Circularity Indicator, on which a material is ranked from 0-1, with 1 being the most circular material management (Ellen Macarthur Foundation, 2015). A variety of other metrics –

over 60 are identified in one study alone (Parchomenko et al., 2019) - to assess circularity and provide indication of sustainability within the circular economy (including recycling rate, recovery rate, material consumption, waste generation, recycled content, etc.) have been established and provide varying levels of clarity. For this reason, in the present study circularity is assessed holistically by examining in the life cycle framework where losses to the circular economy exist in the form of hibernating stock accumulations, or uncollected end-of-life material, and unrecoverable waste flows. Stock accumulation in the use phase is not necessarily a detriment to the circular economy, however, accumulation of materials that have reached their end-of-life, but are not collected to re-enter the circular economy, or hibernating stock, are sinks of recoverable material that should be minimized.

3.4 Results and Discussion

3.4.1 Copper production, use and recovery trends in the US 1970-2015

Collection of current and past data for major copper flows provides insight into trends in how the major flows have changed over the past decades. Complete data sets are available in Appendix B: Supplemental Information. Figure 3-8 shows primary – from virgin materials – and secondary – from recycled materials – production and consumption of copper in the U.S. from 1970-2015 (data from Table B-2). Secondary and primary production together are less than total U.S. consumption, showing a consistent import reliance that has grown in recent years. This may largely be attributed to the exponential increase in copper production and consumption in countries like China (Wang et al., 2017) that had been accepting scrap from the U.S. In 1970 the U.S. was a net exporter of copper, with net exports of 80,000 tons of refined copper (Table B-2) and 3,000 tons of net imports of unrefined copper (Table B-1). By 2015, however, refined copper imports exceeded exports by over 500,000 tons, and unrefined exports were 380,000 tons. This finding, that the U.S. has transitioned from a net exporter to a net importer of copper, has also been found in other material flow analysis studies (Chen et al., 2016; Wang et al., 2015). Both primary production and consumption of copper in the U.S. were growing until around 2000, when there was marked decrease in both production and demand for copper. These trends, seen in Figure 3-8, may be representative of dematerialization, a hypothesis posed by Matos and Wagner (1998) but the validity of this and the concept of dematerialization as a whole remain largely unexplored and controversial. More tangible reasons for decreasing consumption of copper in the U.S. may be explained by the closure of several smelters in past years and thus decreasing regional production capacity, as well as high volume materials substitutes such as PVC pipe for plumbing, fiber optics in telecommunications applications, and ACSR replacement of copper wiring for electricity transmission and distribution (Brininstool and Flanagan, 2017). Additionally, secondary production (or recycling) of copper in the U.S. has decreased, likely due to the availability of low-cost end-of-life processing in other nations, so an increasing proportion of secondary scrap is being exported and processed overseas. These conclusions are also supported by the findings of other substance flow analysis papers, which revealed similarly that U.S. production of copper has decreased over a similar time period, and that secondary production, specifically, has decreased even more steeply than total production (Chen et al, 2016; Wang et al., 2015).

Trends in processing of U.S. copper scrap are explored in Figure 3-9, which shows copper scrap imports to and exports from the U.S. (from Table B-4). There was a significant increase in net exports from only 76 thousand tons in 1998 to a maximum of 945 thousand tons in 2011, explaining the net decrease in U.S. production from secondary scrap. However, changes in import policies in China have decreased the amount of scrap that is sent to China by developed nations, so there is what appears to be a decreasing trend in U.S. net exports of scrap around and after 2010. This suggests that the U.S. will have to manage more metal scrap internally in the future and emphasizes the importance of locally optimizing the circular economy of copper and other commodity metals.

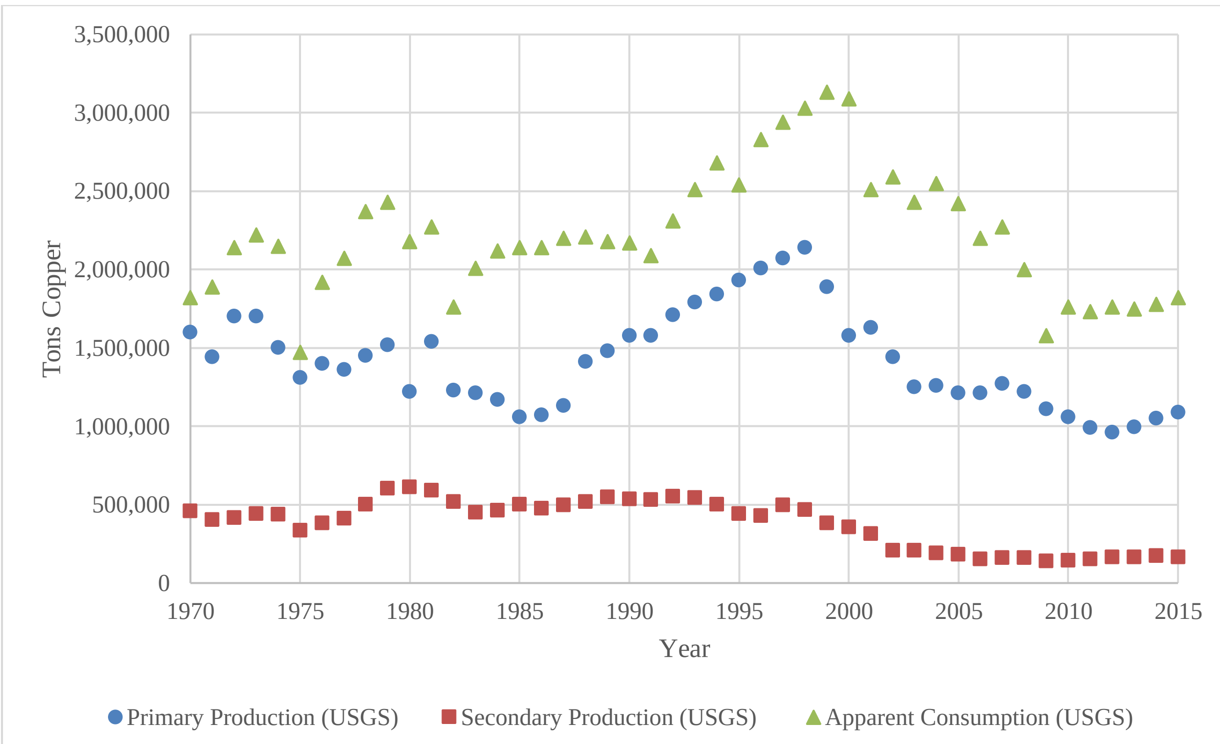

Figure 3-8: U.S. copper production and consumption trends, 1970-2015 (tons). Data from multiple sources; see Table B-2.

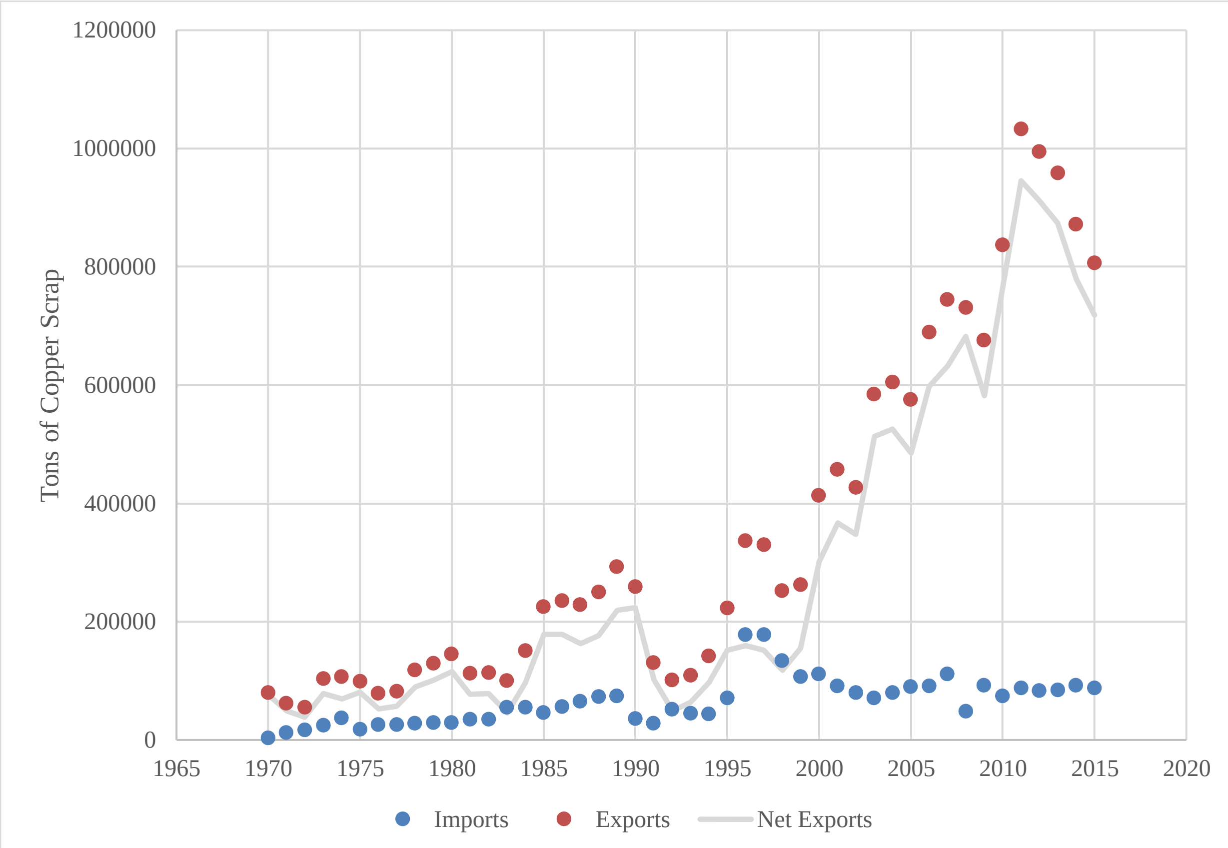

Figure 3-9: Copper scrap imports and exports from the U.S., 1970-2015 (tons). Data from multiple sources; see Table B-4.

The concept of "dematerialization" is a polarizing subject when considering consumption trends in different economies (Gorman and Dzombak, 2018). Looking forward, any attempts to meet demand for raw materials must consider different consumption patterns in growing, or developing countries, vs. developed countries, like the U.S. Figure 3-8 shows that consumption of a commodity material like copper can be highly volatile, and is dependent on a number of variables, such as global trade policies, and economic growth variables like recessions, population, and GDP (Kraussmann et al., 2009). As the U.S. per capita copper consumption trend in Figure 3-10 indicates, since 2000 there has been a decoupling of population growth from copper consumption. Whether or not this is considered to be dematerialization, the decoupling of per capita copper consumption from population growth in the U.S. suggests that developed economies do not necessarily follow global trends of increasing metal consumption.

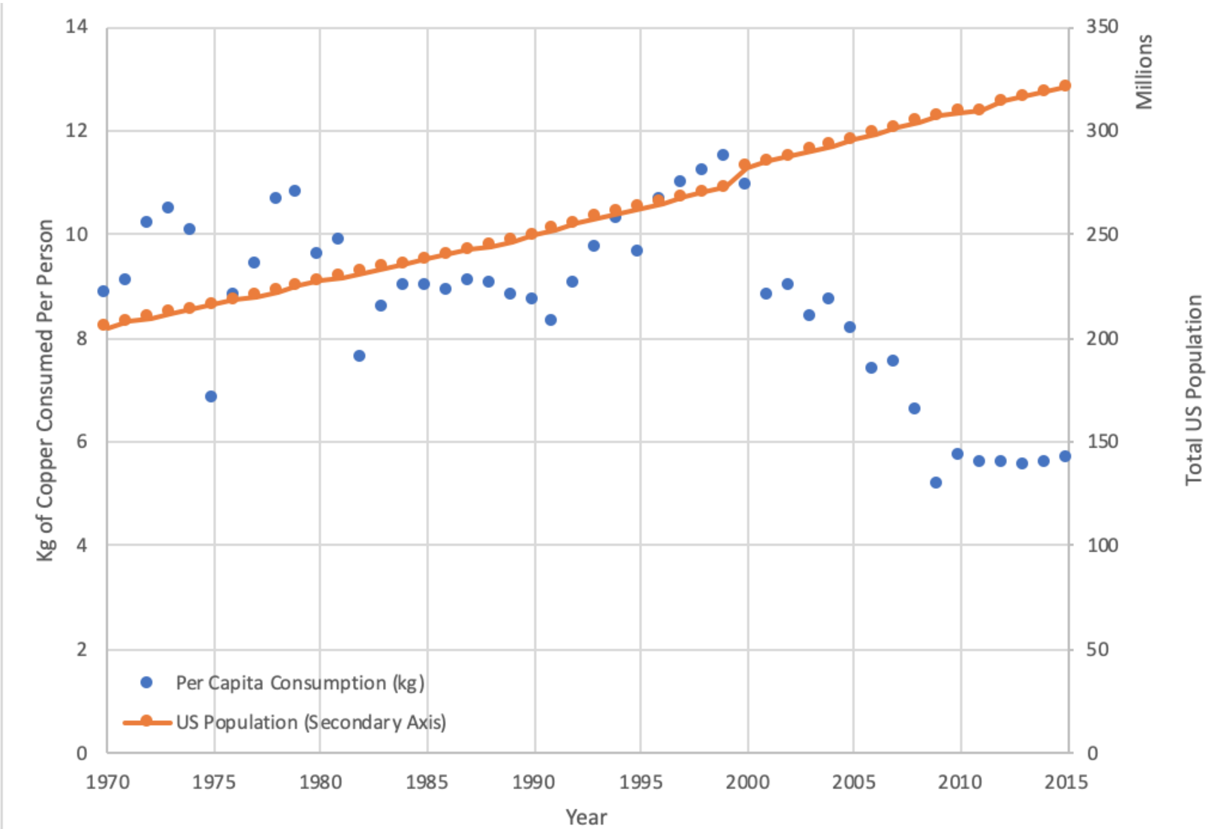

Figure 3-10: Per capita copper consumption in the U.S. 1970-2015 (kg) and Total U.S. Population. Data calculated from USGS Minerals Yearbooks (USGS, 2019) and US Census Bureau (USCB, 2018)

Mass balance accumulation calculations were performed to estimate stocks in the life cycle of copper in the U.S. using model outputs and the time series data collected (Tables B-1 to B-6). Based on processing loss rates of copper refining, approximately 7 million tons of copper accumulated in tailings from 1970-2015. Quantification of the stock of copper in tailings is important to evaluation of tailings mining as a source of non-fuel minerals such as copper. For comparison, 13 million tons of copper scrap have been exported out of the U.S. in the same time period (Table B-4). This scrap is not only higher quality than tailings, slag, and other processing byproducts, but it is also easier to process and therefore less costly and energy intensive (Reuter, 2013). This suggests that given the current state of the copper life cycle in the U.S., more effort should be spent trying to improve copper circularity by reprocessing scrap locally and exporting less material that could be reused instead of tailings mining. Finally, over ten times the amount of copper that has accumulated in tailings and landfill (both 7 million tons) has accumulated in the use phase since 1970, at 72 million tons.

A single-year snapshot of U.S. copper stocks and flows is shown in Figure 3-11. This shows the most recent year of collected data in this study (2015), which can be contrasted with Figure 3-12, which presents total cumulative, dynamic flows for all years of data 1970-2015. These results indicate that, similar to other non-single-use materials like steel (Nakamura et al, 2014), copper does not have the potential to be perfectly circular. There are processing dissipative losses, as well as complex uses that require varying levels of purity or quality. However, the current recycling rate for copper in the U.S. is still significantly below that of steel as well as aluminum (Chen and Graedel, 2011) indicating that opportunities for improvement of copper circularity exist.

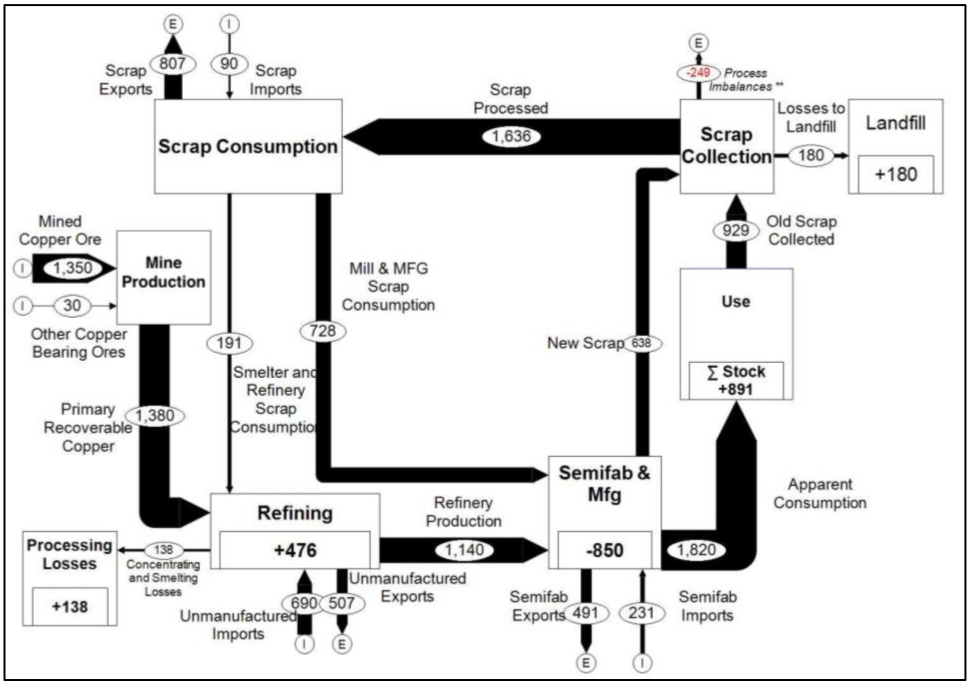

Figure 3-11: Stocks and flows of copper in the U.S. economy (in thousand metric tons) in year 2015. The total dynamic materials flow analysis is graphically represented in Figure 3-12, where the data for each year (1970-2015) of the data series for each flow have been summed. All flows shown are collected data; the only calculated values are stocks and process imbalances, marked**

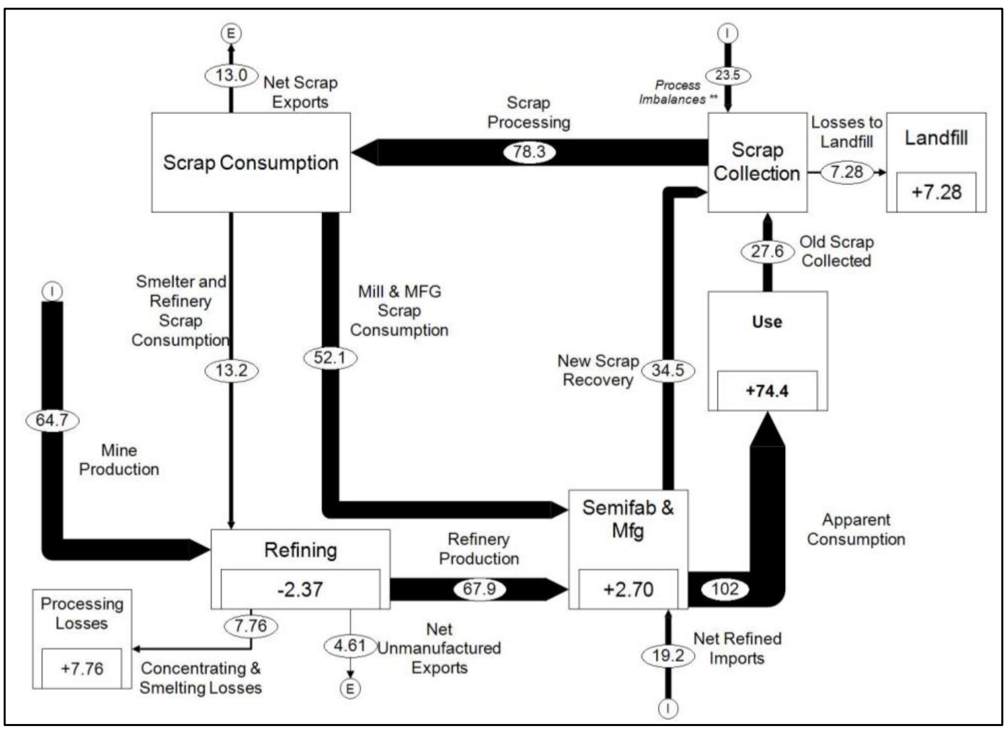

Figure 3-12: Total dynamic stocks and flows of copper in the U.S. economy (in million metric tons), from 1970-2015. All flows shown are collected data; the only calculated values are stocks and process imbalances, marked **

These stocks and flows diagrams, and the data used to produce them, available in Appendix B: Supplemental Information, can be used to assess the similarity or difference between the result of the primary data collection effort for end-of-life management and the lifetime-based estimation method. For example, Chen et al. (2016) found that for 2012 the material flowing from the use phase to waste management was over 20% more than the end-of-life collection calculated by this method (1.12 million metric tons), though the estimate for consumption in the same year is the same in both studies, since the same resources (USGS, ICSG, and CDA) were used to estimate consumption. The Chen et al. (2016) study provides six years of data from the 1975-2012 scope (1975, 1986, 1995, 2002, 2010, 2012), for which all years have notably different end-of-life collection estimates than those calculated here: in 1975 they find end-of-life collection to be only 3% more than in the present study, but in 1986 it is 30% more than the present study, in 1995 it is 21% more, and in 2002 it is 10% less (the only year in which the end-of-life collection estimate is lower), in 2010 it is 14% more and in 2012 it is 21% more than the present study. Another stocks and flows analysis found that in 1994 the copper flow from use phase to waste management was 1.26 million tons (Graedel et al., 2003), over double the calculated value in the present study, of 595 thousand tons.

Comparison of the findings of this U.S. stocks and flows analysis to studies for other countries provides additional insights. A look at the copper life cycle in China shows a different story from the U.S. – net import reliance is over 70% currently, and only 16% of all copper consumption from 1949 has transitioned to scrap, the remaining 84% is in use stocks (Wang et al. 2017). This is even more than the 71% of copper consumption that has accumulated in the use phase in the U.S. Furthermore, where secondary production of copper has decreased in the U.S. over this time period, secondary production in China has actually increased since 1975 (Zhang et al., 2014). Also, though U.S. consumption of copper has shown a stagnation and decrease in recent years, China's continues to grow significantly, and it is currently over 20 times what it was in 1975 (Zhang et al., 2014), and is expected to increase until 2045 (Zhang et al., 2015). These results show that it is helpful, when looking at materials consumption and life cycle trends, to consider a non-global system boundary, since different countries and regions show dramatically different trends.

3.4.2 Use phase results

A look at the subsystem comprising the use phases for copper is shown in Figure 3-13, where the consumption and collection trends for each of the four categories of use are shown as a single year (2015) data snapshot. The complete dataset, consisting of 45 years of primary data collected are available in Table B-5. This higher resolution examination at flows allows for more insight into potential opportunities for improving the circularity of copper. Of the 72 million metric tons of copper accumulated among the use phases from 1970-2015, over 38 million tons have accumulated in buildings and infrastructure. The second highest accumulation from 1970-2015 was 27 million tons in electric and electronic equipment, which again is not personal electronic devices, but electric utility infrastructure. 3.7 million tons accumulated in transportation equipment and 3.5 million tons have accumulated in consumer and general goods. Construction and demolition and electric and electronic product use phases are therefore the largest opportunities for copper recovery, as only half of the quantity of copper that enters the building construction sector in any given year is collected, and only ten percent of copper that enters the electric and electronic sector is collected, which represents close to forty percent of total consumption.

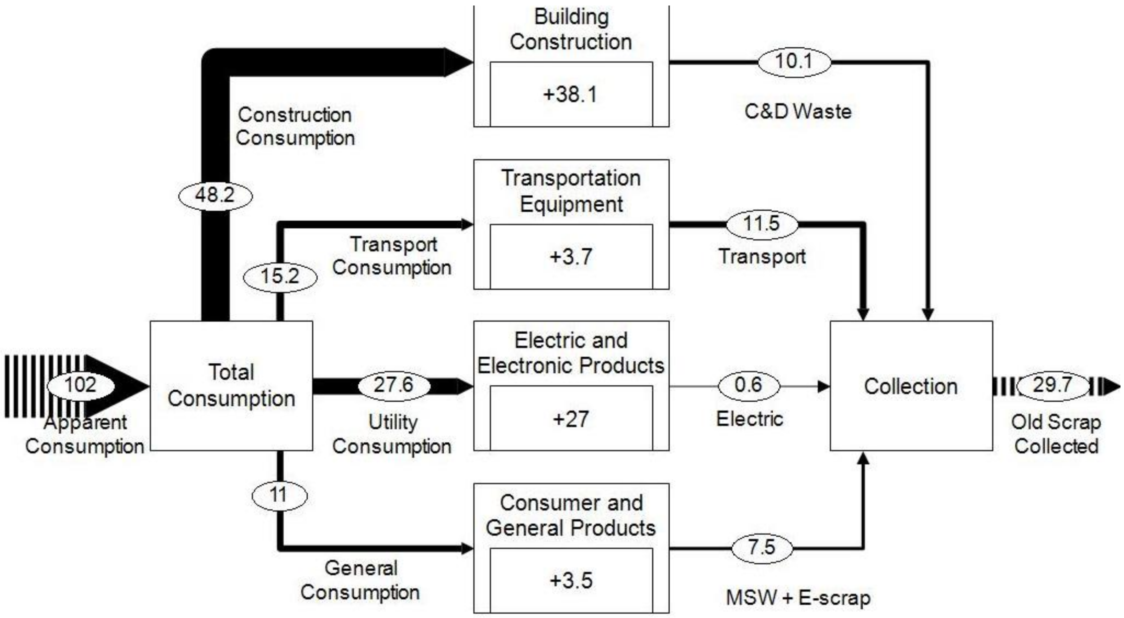

Figure 3-13: U.S. Cumulative se-phase subsystem stocks and flows (in thousand metric tons) in years 1970-2015 2015

The lifetime of materials in building construction and electric utilities is long, but as is shown in Figure 3-14, consumption of copper by both of these sectors has slowed significantly since 2000, which means that there should be a surplus of materials reaching end-of-life as development reliant on copper slows. Theoretically, as more copper reaches end-of-life than is consumed, there could be a larger collection flow than consumption flow, as is the case in consumer and general goods. However, there is still a significant lack of collection, which limits the amount of copper recycling that could exist in the U.S. Furthermore, copper scrap collected from infrastructure in buildings and electric utilities tends to be very high-quality copper in the form of wiring, busbar, pipes, etc., and isn't alloyed or integrated in the way that electronic products are in forms that are difficult to process (Reuter, 2013). Thus, improving collection from building infrastructure and electric utilities is likely to be the most profitable for secondary copper processors.

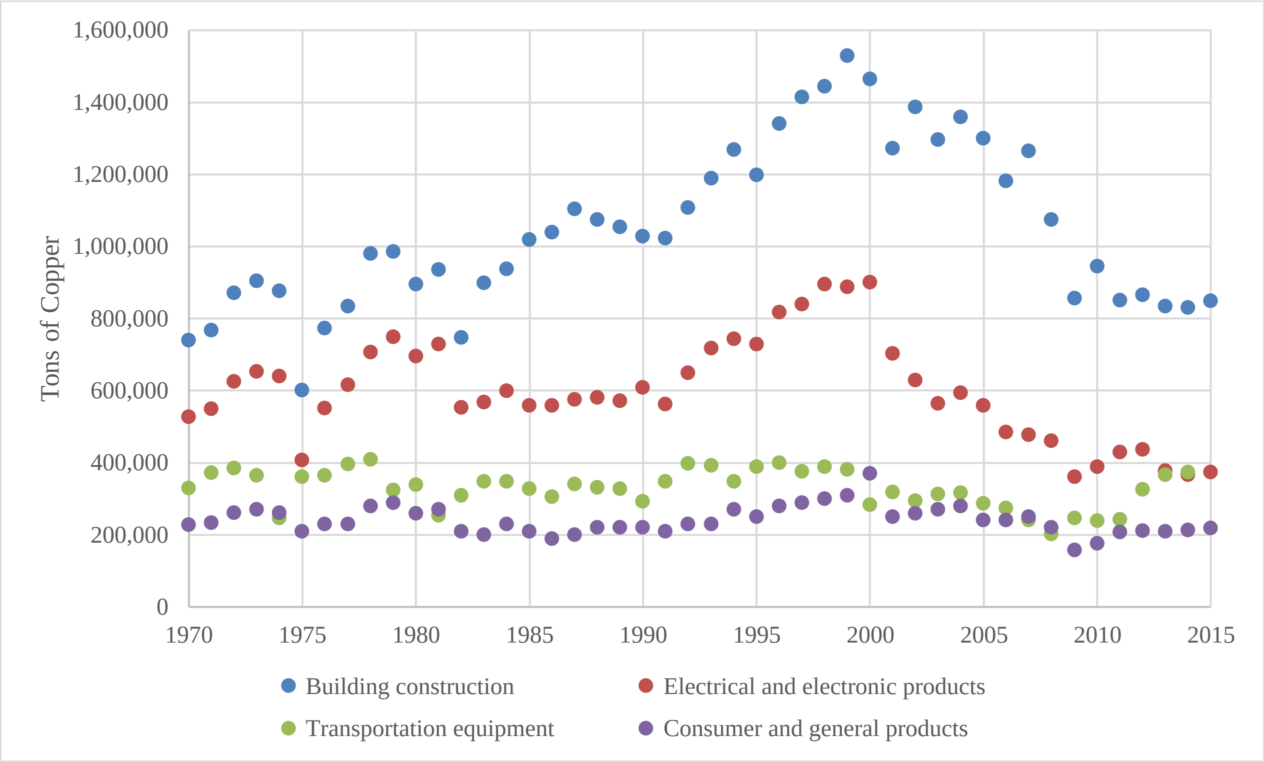

Figure 3-14: Historical trends in U.S. copper use-phase consumption by sector- building construction, electric utilities, transportation equipment, and consumer and general goods

Though end-of-life collection from consumer and general products seems to be significant, it is the largest quantity of scrap collection of the four use phases, shown in Figure 3-13, it is important to note that in 2015 of the 257 thousand tons of copper collected, 47% was landfilled (see Tables B-5 and B-6). This highlights that collection alone is not a sufficient solution to improving circularity, and that improvements in processing and residential recycling are necessary. Indeed, almost 4 million tons of copper are calculated to have accumulated in only municipal solid waste landfills from 1970-2015 (see Table B-6).

3.4.3 Implications for the U.S. Copper Circular Economy

The results of this work provide context and insight into the circularity and the copper circular economy in the U.S. One example is the implication of accumulating in-use stock, and how much of this accumulation is currently providing society utility versus how much is hibernating and could be reused. This work included a collection of primary data related to end-of-life collection, landfilling, and scrap processing for copper in the U.S., enabling calculation of in-use stock accumulations, found to be 72 million tons, or 71% of all consumed copper since 1970. As was discussed in Section 3.3.4, the accumulation of this in-use stock, alone, is not necessarily a negative factor with respect to material circularity. It is specifically the accumulation of hibernating stock, or end-of-life materials that are no longer in use and also have not been collected for reuse, that is a limitation to circularity.

Estimation of how much of the calculated 72 million tons of accumulated in-use copper stock is hibernating stock is complicated, but can be estimated as the difference in how much material has theoretically reached end of life and how much is actually collected based on the primary data evaluated here, or flow F5, end of life collection, found to be 29.7 million tons . Previous stocks and flows analyses have used estimation methods to predict theoretical end-of-life collection (Chen et al., 2016; Graedel et al., 2003, Spatari et al., 2005). Chen et al. (2016) developed such estimates for six particular years during the period 1975-2012; Spatari et al. (2005) developed an estimate for the cumulative time period 1900-1999, though individual years were not available; and Graedel et al. (2003) produced an estimate for 1994. These estimates of the theoretical amount of material that has reached end of life can be used in combination with the results of the present study to estimate the quantity of hibernating stock that is potentially recoverable for reuse and re-entry into the circular economy. Comparison of the end-of-life collection data in the present study to the six years of Chen et al. (2016) end-of-life collection estimates indicated that for individual years collection may be more up to 10% more than found in the present study or 30% less, with five of six years being less. Comparison to the Spatari et al. (2005) study indicated that 29% of accumulated in-use stock is theoretically hibernating, and comparison to the Graedel et al. (2003) study indicated even higher values of hibernating stock than the other two. These comparisons indicate that while the exact amount of in-use stock that is recoverable is still unknown, it is likely between 20-40% of the 72 million tons estimated in this study to have accumulated since 1970.

Another area to assess when considering the circular economy is resource efficiency, extraction rates, and long-term availability of materials. Contextualizing the extraction and consumption rates calculated in this study encourages a circular life cycle view of mineral resources (Gorman and Dzombak, 2018), which in turn leads to a consideration of mineral scarcity. A 2014 study of metal scarcity and sustainability estimates a global sustainable extraction rate of copper to ensure supply for 1000 years at around 800 g/person/year (Henckens et al., 2014). Consumption in the U.S. from 2008- present (shown in Figure 3-11) hovers around 6 kg/person/year but has been as high as 12 kg/person/year in 1999. This means that even if total per capita consumption of copper decreased by 50% in the future to 3 kg/person/year, the current share of consumption from old scrap, which is currently around 9%, would need to increase to 65% of consumption to meet demand. This can only be achieved by improving domestic collection and recycling programs, as well as reducing exports of scrap.

Additionally, the results of the several landfill composition studies considered in the calculations of end-of-life data for copper indicate that the relative presence of copper in landfills is not largely different than its naturally occurring ore grade. Though landfill mining is currently considered to be largely uneconomical, there is potential for economic feasibility, depending on available technology, regulation, population density, and other market variables (Van Passel et al., 2013). The similar weight percent of copper in landfills and ores suggests that as ore grades continue to decline, landfill mining may become an even more valuable and viable source of material, especially when considering that excavation would produce other valuable materials, as opposed to mostly waste rock and tailings that are produced during virgin extraction, with much less possible extraction of other valuable resources, even in co-mining operations. As organic matter decays in landfills with time, the durables like metals, which remain valuable, increase in relative abundance, meaning that older landfills that have lost the potential to produce landfill gas should be prioritized, and material recovery could become a new revenue stream. Complete recovery of landfill stocks of copper since 1970 would be sufficient to reduce by half the need for mine production for 10 years. Exports of scrap, however, are an even larger loss to U.S. circularity. Reduction by half of scrap exports would result in a 30% reduction in how much primary material is required to meet demand.

3.5 Summary and Conclusions

The objective of this study was to assess and identify limitations to the circularity of copper life cycle in the U.S., and to develop a framework for the future assessment of consumption of other mineral and non-renewable resources in the U.S. This research involved collection of new data to improve quantification of copper flows in the U.S. Results indicate that there are significant limitations to the circularity of copper in the U.S. The copper use phase sees the largest accumulation of copper – on the order of 72 million tons since 1970 – and thus merits focused attention despite the lack of data. Major improvements should be made in end-of-life collection from secondary scrap in the U.S., especially from building construction and electric utilities, as they make up 65 of the total 72 million tons of accumulation in addition to typically having a higher quality of copper scrap, shown in Figure 3-13. These results vary significantly from other materials: Aluminum, for example, is estimated to have only 48% of accumulation in in-use stock (Chen and Graedel, 2011).

Results from the data collection effort for copper can be verified in comparison to other materials flow analyses. Elshkaki et al (2016) found similar trends in decreasing scrap consumption as a percentage but predict an increase in supply to 2050. Also, the major trends in exports and imports identified in the present study are similar to Chen et al (2016).

Results of the study also suggest that improved collection infrastructure and processes themselves are not enough to improve copper recycling rates significantly. While there are losses of copper via process losses or tailings, exports (much of which are unaccounted for as embedded flows) and hibernating stock are much more significant losses to the circular economy for copper in the U.S. and should be prioritized for recovery. Exports of copper scrap since 1970 are twice the quantity of process losses (Figure 3-12), and use phase accumulation is more than five times exports. This means that though the emphasis in the extractive industries on process improvements and efficiencies is valuable, there are other impediments to the circularity of copper in the U.S. circularity that should be a focus of sustainability assessments and planning. Domestic recycling needs to be incentivized so scrap can be reused in the U.S. without being exported or ending up in a landfill. Though use-phase collection and mining hibernating stocks in buildings, out-of-service electric utilities, etc., are likely the most cost-effective and lowest impact ways to make significant improvements to the copper circular economy, the stocks and flows analysis conducted here also identified other accumulations of copper that, depending on future prices and processing technologies, may be useful to exploit for copper recovery in coming years. Tailings and mine waste hold significant stores of copper, as do landfills, not just municipal solid waste landfills, but construction and demolition landfills and other specialty or regulated disposal locations. Though the cost of landfill mining is currently preventative, as ore grades continue to decline, and with technological developments and the consideration of revenue from varied material collection not just copper, this may soon change.

The data collection process has highlighted a distinct lack of primary data from the waste and scrap industries, which would improve future studies, and continue to increase the accuracy of economy-scale stocks-and-flows analysis. Some industry groups or organizations that already perform surveys or collect data are already positioned to collect and manage this type of data, but do not pursue such data at present. The U.S. Green Building Council, for example, has a LEED credit called MR2, which is given to projects that perform materials recovery during construction and demolition projects. However, USGBC does not presently track total U.S. materials recovery from these credits and is unable to provide insight on total scale or even number of credits distributed. A focused shift on circular economies and recycling may incentivize similar groups and organizations to start doing some accounting of these types of flows, which would provide better datasets and more precise insights for copper and other materials.

This work provides a framework for similar analyses of other materials and highlights the importance of more widespread accounting of end-of-life material management. Because collection is not materials centric, but product centric (Reuter, 2013), improved accounting by industries would provide better data for materials beyond copper and make an assessment of primary end-of-life data more feasible for many materials. The compilation of 45 years of data for copper use and recovery in the U.S. also provides a basis for future work in trend analysis to extrapolate future scenarios of consumption, scrap collection, exports, etc., and to evaluate how different growth trajectories for these flows might affect the circularity and ultimately sustainability of copper. Such analyses could provide useful insights to industries about what long-term availability of primary and secondary materials would be and thus potential future costs, and is the subject of a subsequent work.

3.6 Acknowledgements

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Chapter 4 : An Assessment of the Environmental Sustainability and Circularity of Future Scenarios of the Copper Life Cycle in the U.S.

This chapter, written by Miranda R. Gorman and co-authored by Dr. David A. Dzombak, will be submitted for publication

4.1 Abstract

As consumption of finite extractable metals continues to be critical to economic development, assessments of availability of metal resources and the sustainability of consumption into the future are important for planning by producers, consumers, and governments. This work assesses current U.S. trends in the major life cycle phases of copper, one of the most valuable and critical of non-fuel minerals, by determining through regression modeling the relationship between drivers, including population, GDP, urbanization, manufacturing, dematerialization, price, and materials flows. These relationships are used to develop a base case scenario (FS1) for future U.S. production, consumption, collection of old scrap, new scrap recovery, scrap landfilling, and scrap exports of copper and to consider the related sustainability implications. Five additional future scenarios are also developed based on changing relationships between drivers as well as potential technological or economic changes. Two of these are high- and low-bound scenarios of likely ranges of activities (FS2 and FS3) and three of the other scenarios are more specifically focused: one on population migration changes (FS4) and two on changing economic landscape (FS5 and FS6). Results of the scenario analyses provide insights into the types of behaviors and trends that could be incentivized to allow for increased circularity of copper. Population dynamic variables are found to be particularly significant. Transitions that lead to slow population growth but high population density result in the largest improvement to circularity. A strong link between all end-of-life flows is also found that, if reduced, would also lead to improved circularity and more available scrap in the U.S. The base case results for system evolution to 2030 show a continued significant import reliance in the U.S. as well as very significant scrap export flow, both of which are limitations to circularity. The analysis of these six future scenarios indicates the clear importance of population and population dynamics to affect the overall circularity of copper, as

well as the importance of considering both environmental footprint metrics and circularity indicators when assessing the environmental sustainability of a system.

4.2 Introduction

Copper is among the most important metals in the U.S. due to its widespread use in the economy in large amounts in both commercial and residential sectors. The economic value of the copper metal is driven by its unique properties and wide range of applications. The growth in demand for copper globally, coupled with environmental impacts of extraction and processing speak to the need for assessment of the life cycle of the material and its circularity, so that reserves may be prolonged and the embedded energy and footprint of copper may be improved (Gorman and Dzombak, 2019). Several studies have attempted to assess the criticality of future demand for materials generally (Fishman et al, 2014; Schandl et al, 2016), metals (Gordon et al, 2006), and even specifically copper (Zeltner et al, 1999; Gerst, 2009; Elshkaki et al, 2016; Meinert et al, 2016), but these assessments have not taken into account the relevance of circularity and the circular economy, focusing mostly on the front-end of the material life cycle and not assessing end-of-life (EoL) and scrap flows which play a major role in meeting demand and material availability.

This study investigated prospects for circularity in the future (up to 2030) by forecasting material flows including production, use and recovery of copper in the U.S. An assessment of the environmental footprint associated with the forecast primary and secondary copper production was also performed. Material demand patterns generally have been studied since the 1950s, and socio-economic theories have predicted "dematerialization" or "decoupling" of material consumption from economic growth and development for several decades (Labys and Waddell, 1989; Wernick et al., 1996; Steinberger et al., 2010; Schandl et al., 2016), though the predicted absolute decrease in material consumption has not been observed at the scale of the national economy (Steger and Bleischwitz, 2011). However, starting around the year 2000, copper consumption - both absolute and per capita, and from both primary and secondary copper sources - in the U.S. has declined steadily following steady growth throughout the 20th century (USGS, 2017). In the development of material flow forecasts, therefore, inclusion of indicators that represent dematerialization or decoupling, which can be represented by material efficiency measurements (Zhang et al., 2018), was done and potential implications for the copper circular economy into the future were considered.

4.3 Methodology

4.3.1 Modeling Approach

Future (up to 2030) copper production, use and recovery were forecast using a regression model constructed with parameters that influence the copper life cycle. Primary data collected in a complete stocks and flow analysis for the copper life cycle in the U.S. (Gorman and Dzombak, 2019) from 1970 to 2015 were employed for determination of regression parameter values. The scale of data – annual data for just 45 years – lends itself to a regression analysis over methods that may be more applicable to larger data sets, such as learning algorithms. Multivariate regressions have been used to identify correlations between explanatory variables, referred to in this analysis as “drivers”, and materials flows in existing works globally for materials categories (Steinberger et al., 2009) as well as for individual commodities on the country scale (Bretschger, 2015) and regional scale (Steiger and Bleischwitz, 2011). This approach also has been demonstrated to be an effective method for predictive analysis for individual commodities

(Elshkaki et al., 2016; Zeltner et al., 1999). These studies include arguments for the use of linear modeling of copper specifically, as well as of commodities generally, based on global development variables in the absence of a definitive findings of specific non-linear relationships (Elshkaki et al, 2016).

Several of the material flows examined show abrupt changes in their historical trends, visible in Figure 4-1. Apparent consumption and primary production, for example, both show generally increasing trends for the first three decades and then a sharp decline. Net scrap exports follows a relatively flat, or very slowly increasing, trend in the same initial 30 year time period, and then a steep increase beginning around 2000. For this reason, piecewise regression analyses were performed for all flows for two time periods, 1970-2000 and 2000-2015, and material flow forecasts were developed based on the second, more recent time period since it is the most recent trends that are likely to continue. Piecewise linear regressions have been shown to be useful for time series data that show changing trends (Liu et al., 2010; Campra and Morales, 2016).

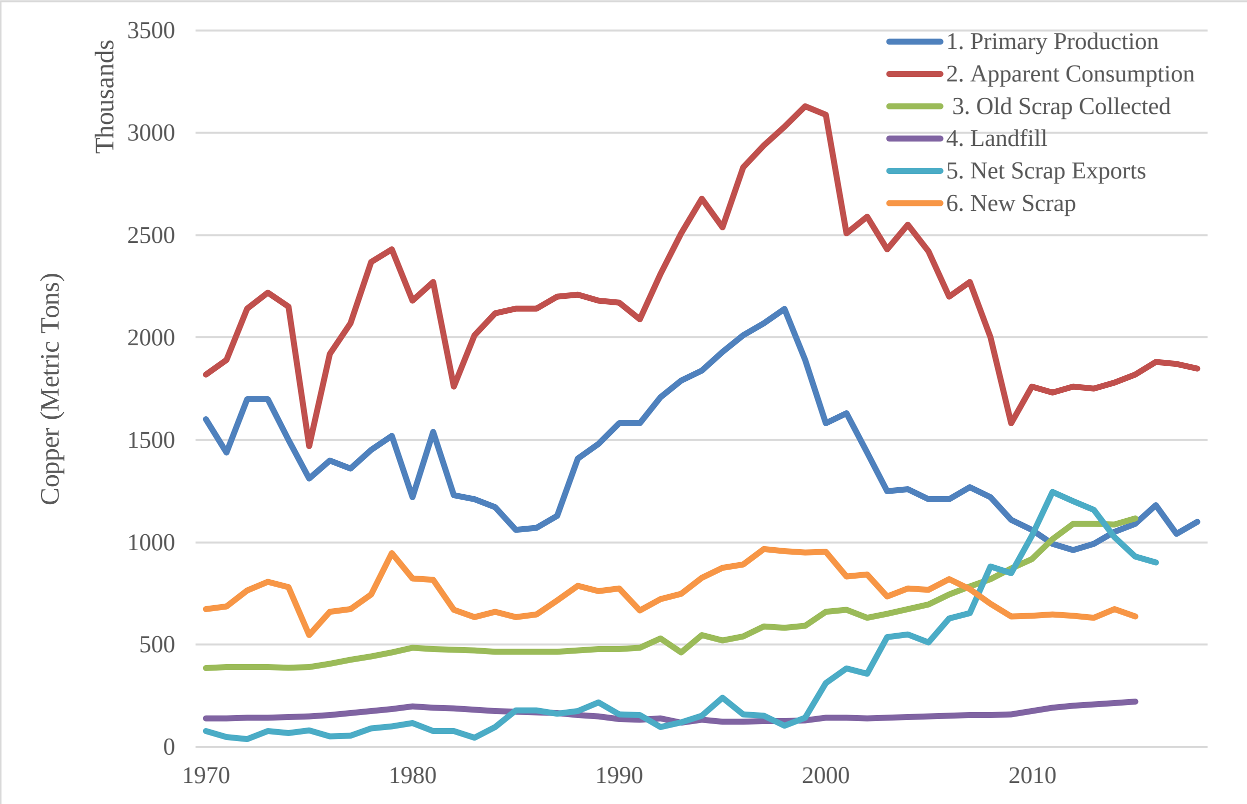

Figure 4-1: Major Flows of Copper in the U.S. 1970-2015. Data from Gorman and Dzombak (2019).

The piecewise linear regression was performed using several drivers of copper demand, which are shown in Table 4-1, with sources of the driver variables indicated. Data series for the same 1970-2015 timeframe of the materials flow data were collected for six drivers and time. Time is included to in the analysis to represent linearity in the regression, and to capture the linear trend of many of the material flows, as well as to represent trends over time that may not be easily represented by quantitative values, such as substitution or policy changes, similar to the approach of Elshkaki et al. (2016). Published projections available for some of these drivers to 2030 were also collected and are also shown in Table 4-1. If a published projection was unavailable, as was the case for the contribution of the manufacturing to total GDP (Mfg%) and for domestic materials consumption (DMC), a linear projection for the driver was calculated to 2030. Both Mfg% and

DMC show highly linear trends, as indicated in Figure 4-2, and were therefore able to be linearly projected to 2030. Socio-economic demand drivers were considered – gross domestic product (GDP), population, and urbanization – as well as material specific drivers – copper price – and finally materials use indicators to represent dematerialization and decoupling –DMC and Mfg%. Any potential derived variables, such as materials intensity (DMC/GDP) or GDP per capita, were not included as potential drivers in the analysis to avoid data redundancy in the model.

Table 4-1: Material flow drivers, units, and sources for data series used for regression analysis.

Material Flow Driver	**Unit**	**Source for Historical Data** **1970-2015 or most recently available**	**Source for Expected Projection 2015-2030**
Time	Year 1970-2030		
Population	10^6 People	U.S. Census Bureau (2012)	U.S. Census Bureau (2017)
Urbanization	% of pop	UN Population Division (2018)	UN Population Division (2018)
Copper Price	Cents/lb	USGS (2013); USGS (2017)	World Bank Commodity Markets (2019)
GDP	10^9 US2010 $	World Bank (2017)	USDA, (2018)
Manufacturing Contribution to GPD (Mfg%)	% GDP	World Bank DataBank (2019)	Linearly Projected*
Domestic Materials Consumption (DMC)	10^6 tonnes	UN Statistics Division (2019)	Linearly Projected*

* The linear trends that were used for the basis of these projections are shown in Figure 4-2

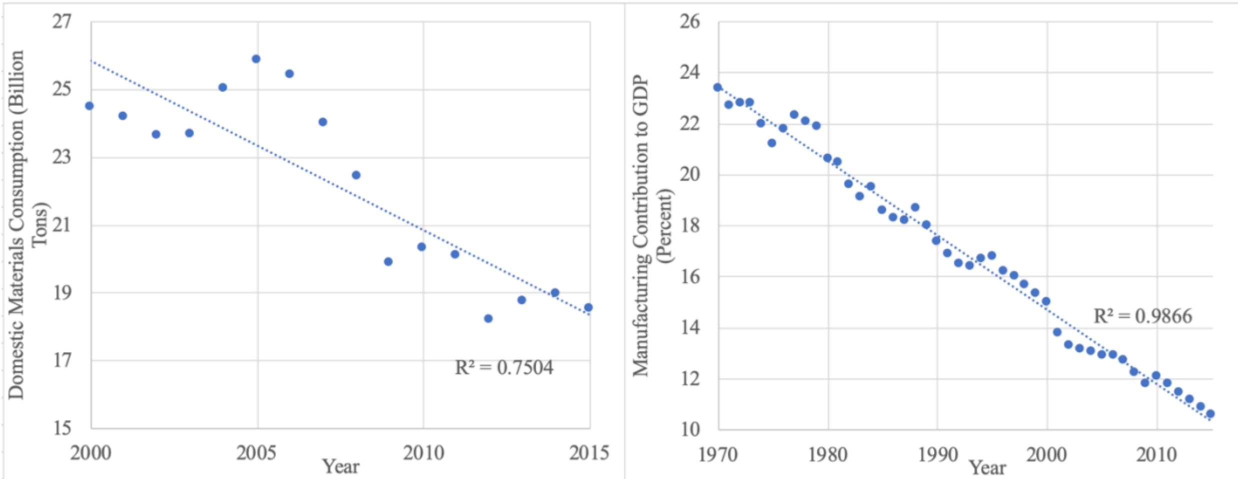

Figure 4-2: Linearity in primary data for drivers Manufacturing contribution to GDP and Domestic Materials Consumption

4.3.2 Base Case Scenario

A base case forecast, or Future Scenario 1 (FS1), was made for 2016-2030 based on the seven drivers and their projected values (from sources indicated in Table 4-1), for eight major materials flows labeled F1-F8 in the complete copper life cycle, shown in Figure 4-3. This forecast provides insight into the most likely trends in these major material flows – primary production, apparent consumption, end-of-life collection, landfilling, scrap exports, new scrap recovery, imports, and available scrap – to 2030. A range of other potential future scenarios was considered through the development of five additional forecasts (FS2-6); the development of these are described in Section 4.3.3.

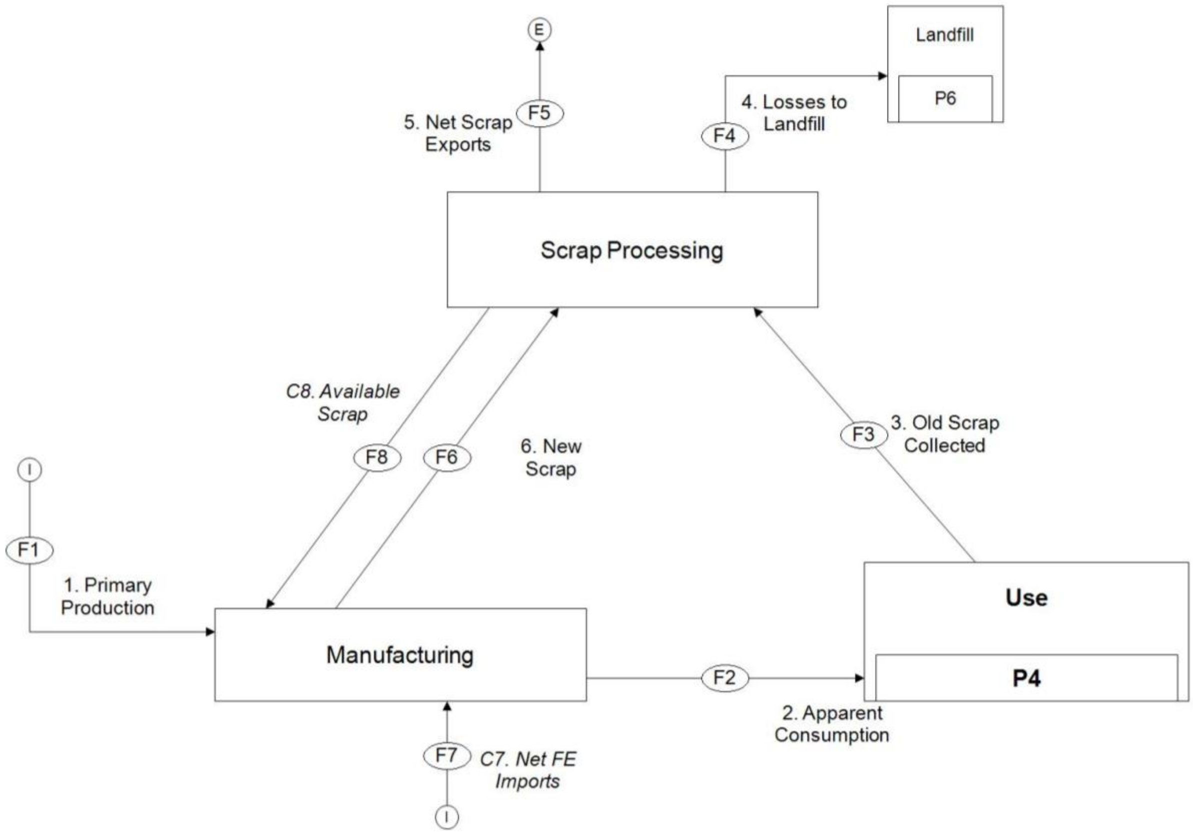

Figure 4-3: The U.S. copper circular economy: major life cycle flows. Flows 1-6 are forecast using a regression model and driver projections, and C7 and C8 are calculated flows based on stocks and flows mass balance formulae.

Regression analysis was performed on major life cycle flows F1-F6, shown in Figure 4-2, against the drivers listed in Table 4-1. In order to account for non-linear relationships between dependent (material flows) and independent (drivers) variables, all data were logarithmically transformed, and then quantile-quantile (Q-Q) plots, as introduced by Lorenz (1905) were used as one of the most established methods to check the assumption of multivariate normality (Wasserman and Vijit, 2003) . The results are presented in Appendix C: Supplemental Information (Figure C-1 and Table C-4). Piecewise linear regressions were then performed on these transformed data for an individual material flow against all seven drivers in an iterative manner to determine which drivers contributed in a meaningful way to the trends exhibited by the material flow. The p-value, which tests the null hypothesis, was used to assess driver influence. P-values above the standard rejection threshold of 0.05 indicate low correlation, or that changes in the driver are not meaningfully associated with changes in the dependent variable – material flow. Drivers with p-values higher than 0.05 were eliminated one by one until a relationship was established with all remaining drivers having a significant effect on the material flow. Material Flows 1-6 (Figure 4-2) - primary production, apparent consumption, end-of-life collection, scrap landfilled, scrap exported, and new scrap recovery - were forecast using the results of the second interval of the regression analysis based on the historical values (2000-2015). The general form of the resulting regression equation for each piece of the piecewise linear regression can be expressed as:

$$ln(Y_{1-6}) = \alpha + \sum_j \beta_j ln(X_j) \qquad \textbf{Eq. 4-1}$$

where X are drivers, Y are material flows, α and β are transformed coefficients, and j are the number of drivers with valid p-values. The overall quality of this regression can then be evaluated by the R^2 value, which indicates goodness-of-fit of the overall modeled result to the observed data. The results of these regressions and values of coefficients as well as R^2 values are reported in Table 4-4 in the Results (Section 4.4.1).

Material flows C7, Front End Imports, and C8, Available Scrap, are labeled as such in Figure 4-2 because they are not independently forecast, but are calculated flows using mass balance formula Eq. 4-2. The in-use stock accumulation is also calculated using a mass balance formula, Eq. 4-3.

$$C_{7,8} = \Sigma F_{in} - \Sigma F_{out} \qquad \textbf{Eq. 4-2}$$

$$\Delta Stock_{year} = \Sigma F_{in,year} - \Sigma F_{out,year} \qquad \textbf{Eq. 4-3}$$

Front end imports, here defined as net imports of unrefined, refined, and semi-manufactured copper, were calculated based on mass balance formulae instead of independently forecast because it is necessary to import (or export in the unlikely event of a surplus of primary production) enough copper to meet demand, represented by Flow 2 apparent consumption, that cannot be met by the primary production capacity of U.S. mining operations. Available scrap was also calculated instead of forecast because it is one potential representation of future circularity in that it is the predicted remaining scrap that is collected from end of life as well as new scrap recovered from manufacturers that is neither landfilled nor exported. This metric "available scrap" as such additionally does not have a representative data series currently, and therefore cannot be forecast from primary data, but must be calculated by mass balance.

The calculated stock and flows were synthesized with all forecasted flows in the framework shown in Figure 4-2 to represent the entire predicted life cycle of copper in the U.S. to the year 2030.

4.3.3 Scenario Analysis

In order to develop a range of forecasts beyond the base case a scenario analysis approach was used. The scenarios are summarized in Table 4-2. Two general future scenarios (FS) – slower driver change (FS2) and faster driver change (FS3) – were developed as bounding cases compared to the base case scenario (FS1). Three additional scenarios (FS4-6) were developed based on results of the base case scenario and used to explore more circular and sustainable future scenarios. All five of these future scenarios were developed using the base case regression equations employed for FS1 but using variability in projections of the drivers used to calculate material flows.

Table 4-2: Future scenarios (to 2030) for the life cycle of copper material flows, and the driver projections used in all six future scenario forecasts (sources in Table 4-3).

Forecast Scenario		**Description**	Population Increase Rate	GDP Increase Rate	Mfg % Decrease Rate	DMC Decrease Rate	Urbanization Increase Rate	Copper Price Increase Rate
FS1	**Base Case**	Expected outcome based on expected driver projections	Expected	Expected	Expected	Expected	Expected	Expected
FS2	**Slower driver change**	Outcome if drivers change more slowly than expected*	Low	Low	Low	Low	Low	Expected
FS3	**Faster driver change**	Outcome if drivers change more quickly than expected*	High	High	High	High	High	Expected
FS4	**Population Migration**	Slower population increase; faster pop. density increase	Low	Expected	Expected	Expected	High	Expected
FS5	**Economic transition**	Faster GDP growth;, slower decline in Mfg %	Expected	High	Low	Expected	Expected	Expected
FS6	**Economic stagnation**	Slower GDP growth; faster decline in Mfg %	Expected	Low	High	Expected	Expected	Expected

*Note that some drivers are increasing, where others are decreasing, so “change” refers to the rate of change, positive or negative: “slower” change indicates a smaller absolute value of the slope of the driver change with time, where “faster” change is a larger absolute value slope

Reported projections for these drivers were identified from available sources, listed in Table 4-3, when possible. For example, in the case of GDP the original U.S. Department of Agriculture projection (USDA, 2018) was used as a high-end value and an OECD (Organization for Economic Co-operation and Development) projection (OECD, 2019) that had a slightly slower growth rate was used as a low-end value. Population similarly has high and low rate-of-change projections developed by the UN Population Division (2019). For the drivers without published projections, manufacturing contribution to GDP (Mfg%), urbanization, and domestic materials consumption (DMC), the 95% confidence intervals of the linear regressions used for the expected projection were used as high and low values. Copper price was not varied in these scenarios because of a lack of alternate sources from the World Bank commodity forecast. Commodity prices can be highly volatile, so the development of another scenario would be primarily speculation.

Table 4-3: Sources for driver projections used in forecasts

Driver	Low rate-of-change projection	Expected Projection	High rate-of-change projection
Population	Zero migration scenario	U.S. Census Bureau (2017)	High variant scenario
	UN Population Division (2019)		UN Population Division (2019)
Urbanization	95% confidence interval linear fit	UN Population Division (2018)	95% confidence interval of linear fit
Copper Price	Expected projection was used in all scenarios World Bank Commodity Markets (2019)		
GDP	OECD (2019)	Expected projection used also for high rate-of-change USDA (2018)	
Mfg %	95% confidence interval of initial linear regression	Linear Projection	95% confidence interval of initial linear regression
DMC	95% confidence interval of initial linear regression	Linear Projection	95% confidence interval of initial linear regression

The first two scenarios considered outside of the base case forecast scenario (FS1) were the slower driver change (FS2) and faster driver change (FS3) forecasts, developed based on the estimated high- and low-range projections of drivers to identify high and low bounds for forecasted copper stocks and flows up to 2030. The development of these bounding scenarios is based on the general ebb and flow of the material and socioeconomic drivers. In the case that some externality spurs one driver to accelerate and change outside of the expected projection (in Table 4-1) the others would follow. Scenario FS2 is the slower driver change scenario in which population growth, population density, and total GDP all increase in a low-growth scenario, and the decreasing drivers Mfg% and DMC decrease more slowly than the expected projection. Scenario FS3 is the inverse, where population, population density, and GDP grow at their maximum projected rates, and Mfg% and DMC decline at the maximum rate.

Three additional scenarios (FS4-6) were also developed with different assumptions relative to the base case. These include a slow population growth but high migration scenario in which population changes more slowly than expected but population density changes faster than expected, referred to as FS4, or population migration. Additionally there is an economic transition scenario, FS5, where GDP grows faster than expected but the contribution of the manufacturing industry declines more slowly than expected. The inverse is considered in FS6, economic stagnation, where GDP grows more slowly but the contribution of manufacturing declines at a faster pace. All these future scenarios, including the base case, and the specific driver projections used to develop them are summarized in Table 4-2.

4.4 Results

4.4.1 Base Case (FS1) Scenario Results

Table 4-4 shows the results of the regression modeling for all six of the major material flows for copper in the U.S. for FS1, the base case forecast scenario. The intercept α as well as the coefficients β_j for each driver found to have a significant impact on flow are summarized and can be used in conjunction with Eq. 4-1 to reconstruct the complete equations for each flow. Primary production, in any year *t*, for example, would be as follows:

$$ln(Y_{1,t}) = 6730 + 221\, ln(Urbanization_t) - 1010\, ln(Year_t) \qquad \textbf{Eq. 4-4}$$

Drivers that exhibited negative correlations (β < 0) with flows are shown in red, whereas drivers with positive correlations (β > 0) are shown in green. The modeled material flow forecasts resulting from these relationships as well as observed historical data are presented in Figure 4-4. Data series for these results can be found in Appendix C: Supplemental Information (Table C-5). Forecasts are made for years 2015 – 2030, though there is observed data for years 1970-2015, the modeled data for 2015 serves as a check against observed data in that same year as well as a baseline for the other scenario analyses.

Table 4-4: Regression results, α, β coefficients (with p-values in italics) relating drivers to material flows and R^2 values associated with the resulting equations.

		Material Flows (Y_j)					
		1. Primary Production	**2. Consumption**	**3. EoL Collection**	**4. Landfilled Scrap**	**5. Scrap Exports**	**6. New Scrap**
Intercept (α)		6730	5155	-1333	-1896	202	-1486
β values for Drivers *(p-values)*	Year	-1010 *(0.002)*	-806 *(0.02)*	180 *(5e-8)*	28 *(2e-5)*		210 *(0.001)*
	Urbanization	221 *(0.004)*	223 *(0.006)*			-84.9 *(0.005)*	
	Population				-7.72 *(0.008)*	32.2 *(0.0002)*	-17.6 *(0.0002)*
	Cu Price		-0.239 *(0.008)*	0.21 *(0.0008)*	0.136 *(0.007)*		0.169 *(0.001)*
	GDP			-2.17 *(3e-5)*	-1.46 *(0.007)*		
	Mfg%		3.58 *(0.0007)*				
	DMC		0.861 *(0.009)*				
R^2		0.80	0.95	0.99	0.98	0.95	0.94

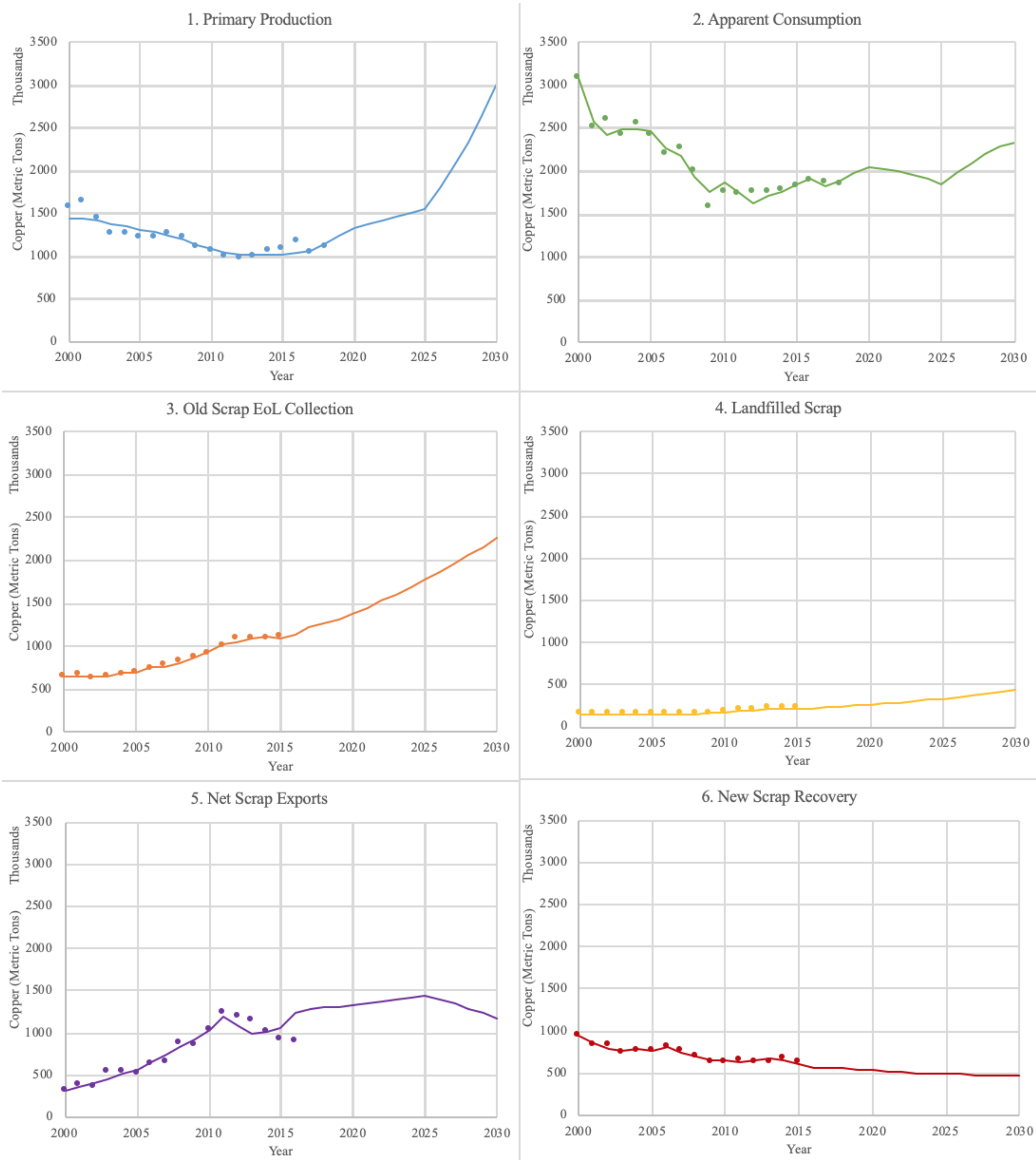

Figure 4-4: Materials flow forecasts for FS1 from regression analyses shown for years 2000-2030 with observed data

The regression modeling for base case scenario FS1 provided insight into the influence that each individual driver has on the overall life cycle of copper. Population dynamics, for example, was found to be a significant driver in five of the six material flows. The only aspect of the copper life cycle that either population or urbanization do not directly affect is end-of-life collection. Urbanization was found to be positively correlated with the front end of the life cycle – primary production and apparent consumption– and negatively correlated with the back-end activities scrap exports. Steady increase or even acceleration of urbanization in the U.S. would therefore likely have a positive influence on the circularity of copper by reducing scrap exports and by increasing both primary production and consumption effectively limiting import reliance.

Population and GDP are widely thought to be a driver of front-end activity similar to GDP (Fishman et al., 2014; Steger and Bleischwitz, 2011; Steinberger et al., 2010; Krausmann et al., 2009). A new insight revealed from this analysis, however, was that GDP is negatively correlated with end-of-life activities collection and landfilling. Population was also found to have decoupled from the primary U.S. copper market, and showed correlation with scrap exports, landfilling, and new scrap recovery. These relationships mean that slower population growth will likely cause a decline in copper exports but an acceleration in new scrap recovery, reiterating the importance of population dynamics.

U.S. copper price affects the consumption negatively, indicating the typical idea that as price increases consumption will decrease. As copper price increases, scrap activities are positively affected though, with higher copper values incentivizing end-of-life collection and new scrap recovery. There is no significant correlation between price and primary production. This result, that copper price affects the scrap market significantly more than the primary market, makes sense for a commodity where demand is primarily driven by necessity, and indicates that any unexpected increase in copper price may increase new scrap availability.

The variables Mfg% and DMC were included in this analysis as proxies for economic activities indicating dematerialization. The manufacturing industry has, for the entirety of the 1970-2015 data set, contributed continually less to total U.S. GDP, starting around 23% in 1970 and in 2015 only contributing to 11% of total economic activity. DMC, similarly, has decreased over 25% just since the year 2000. The regression analysis showed significant correlation between these dematerialization variables and consumption, but no other material flows. The results indicate that while trends in dematerialization variables might impact overall consumption, they may not yet have influence in the secondary market.

Looking at the materials flows individually instead of at the impacts of each driver also leads to some interesting conclusions. Landfilling and end-of-life collection are both driven by the linearity of time, copper price, and GDP, and have the same positive/negative correlations for each respective driver, the only difference being that population also affects landfilling, where it does not affect end-of-life collection. This is indicative of the relationship between landfilled scrap and collected scrap – an increase in collected material would necessarily lead to an increase in landfilled material, and decreases in total collected end-of-life material would result in less total material being landfilled. It is also a clear indicator that these two activities, if there is to be a significant change in the circular economy, must be unlinked in some way. To increase recovery of copper, landfilled scrap cannot simply follow the trend of total collected scrap, but it must decrease even as collection increases to allow for more material reuse and available scrap. Population dynamics, again, seem to be the most critical factor to accomplishing this, since population has the potential to affect landfilling without affecting total collection. The impact of GDP and price on collection is consistent with a hypothesis that a wealthier society would invest less in expensive and laborious disassembly, sorting, and recycling activities without very high economic incentive for collected materials from these efforts. In fact, A UNEP report found that the percentage of people likely to keep end-of-life goods "as a spare" was significantly higher in developed than developing nations (Reuter, 2013). The only drivers scrap exports are population and urbanization, indicating that a slowing in population growth may have positive impacts on the copper circular economy.

The relationship between consumption and collection of copper is also worth noting. The notable difference in factors affecting these flows is a significant indication that the U.S. economy is already starting to transition in a positive way for circularity – circumstances that decrease consumption will not actually result in decreased collection and therefore ultimately scrap availability – but will also result in increased end-of-life collection. For increased circularity of copper it is important therefore, to take steps to encourage decreasing consumption, knowing that it will not negatively impact end-of-life materials management.

The sums of all 15 years of forecast flows from 2015 to 2030 were calculated and put into the material flow framework in Figure 4-2. The results are shown in Figure 4-5, with Sankey-style arrows whose widths are directly related to quantity to aid in assessing circularity.

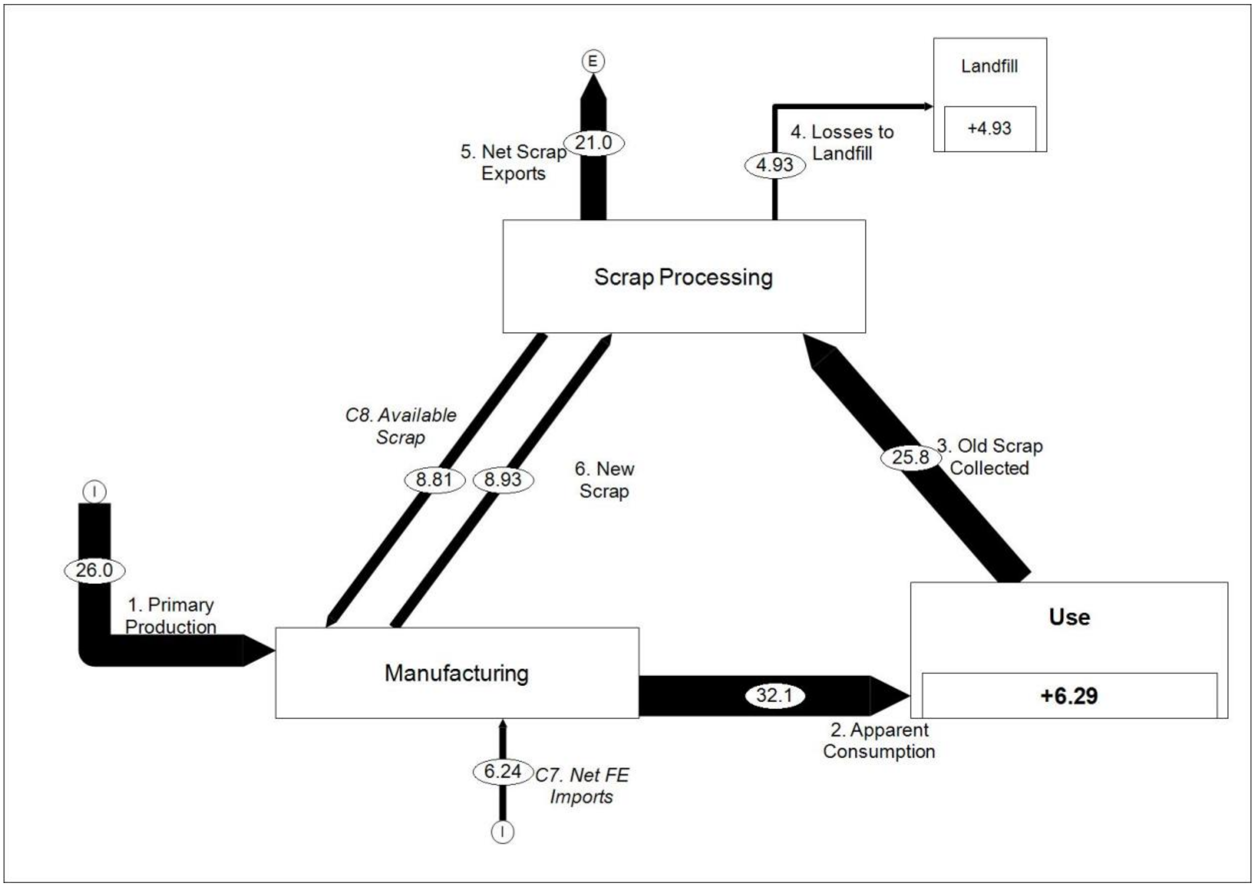

Figure 4-5: Cumulative copper life cycle forecast for Scenario FS1 for 2015-2030 in million metric tons

Results for the base case FS1 forecast for the U.S. copper life cycle from 2015 to 2030 in Figure 4-5 show that there is only available scrap (Flow C8) to meet 27% of demand (Flow 2), and almost 20% of the materials necessary to meet demand for copper must be imported (Flow C7). Almost as much scrap is exported out of the U.S. system boundary (Flow 5) over this time period than is collected from end-of-life (Flow 3).

4.4.2 Scenario Analysis Results (FS2-FS6)

Scenarios FS2 and FS3, as described in Table 4-2, were developed as bounding forecasts of changes in materials flows and the results of these forecasts shown in are presented in Figure 4-

6, overlaid with FS1 results and observed historical data. Complete data series for these forecast scenarios are available in the Supplemental Information (Appendix C) Tables C-6 and C-7. Scenario FS2, the slower driver change scenario, is shown in the life cycle framework in Figure 4-7. The result of a slowing in the drivers is a generally more circular scenario, with a smaller use-phase stock accumulation, more new scrap recovery, and less primary production, and even a complete reduction in necessary front-end imports to zero, with an excess of primary materials available, and therefore the U.S. transitioning to be again a net exporter of materials. Total consumption and landfilling rates, however, increase from the base case. Scenario FS3, the faster driver change scenario, shown in Figure 4-8, has very different results. Apparent consumption and primary production increase dramatically from the base case, without a corresponding increase in collection, leading to a significantly larger in-use stock accumulation. Scrap exports, additionally, increase about 50% from the base case, which, combined with the decrease in new scrap recovery results in a deficit of scrap availability. This net negative available scrap, meaning that there would not be enough available scrap to subsidize manufacturing demand for secondary materials. These drastically different results are due to the different relationships between individual flows and drivers. As discussed in Section 4.4.1, some drivers are highly positively correlated with some flows, but negatively correlated with others, so a slowing of one, population density, for example, leads to increasing consumption and primary production, and decreasing end-of-life collection and landfilling. Additionally, the low rate-of-change and high rate-of-change projections also apply to all drivers, even ones with decreasing trends, or negative slopes, so where all drivers follow a high rate-of-change (as in FS3) the result is a fast increase in some drivers, such as population, as well as a fast decrease in others, such as manufacturing contribution to GDP.

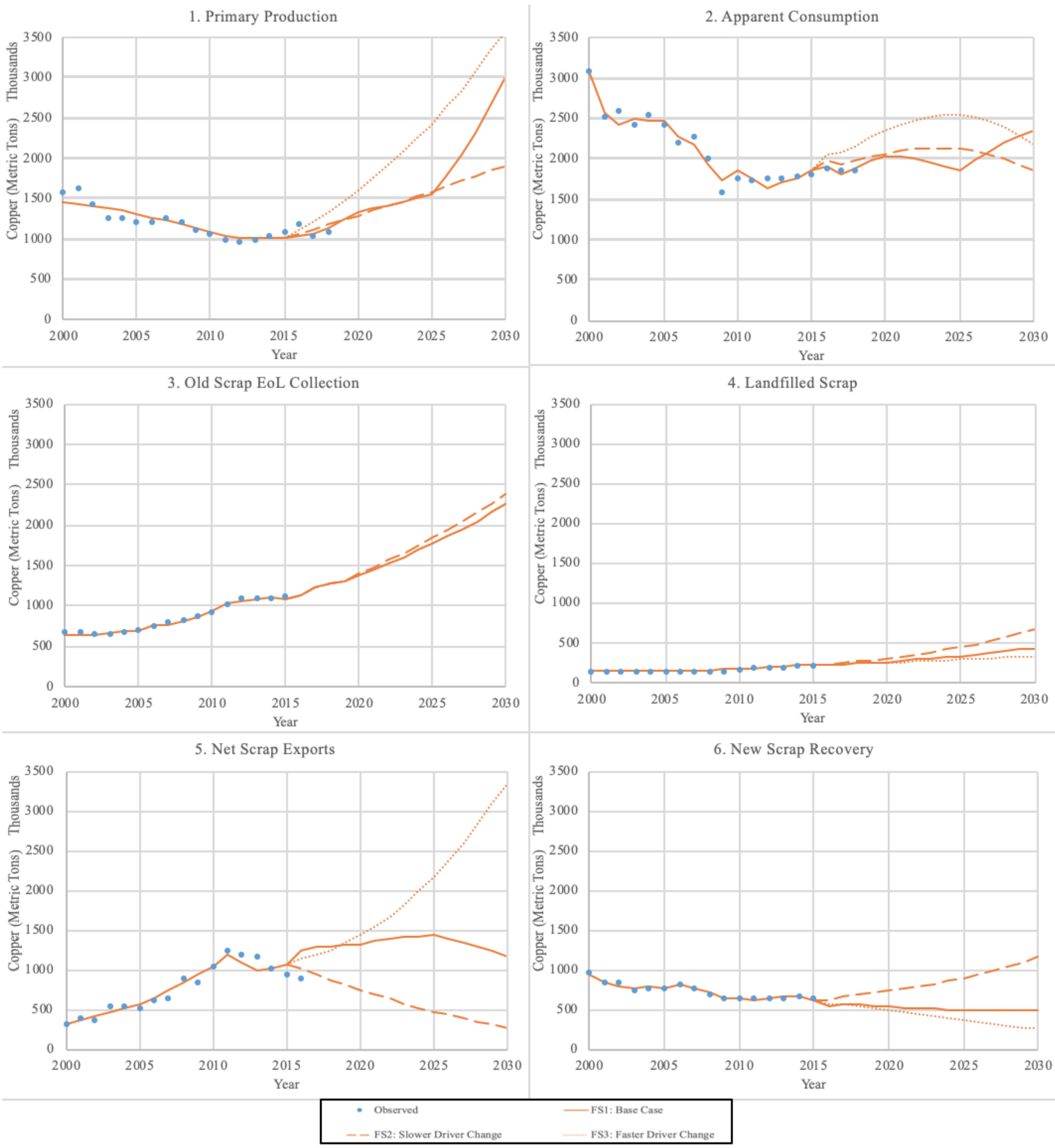

Figure 4-6: Copper flow forecasts for Scenarios FS1, FS2, and FS3 for 2015-2030 in thousand metric tons shown with observed historical data. FS1 is represented by the solid line, FS2 is the dashed line, and FS3 is the dotted line. Observed data are represented by circles.

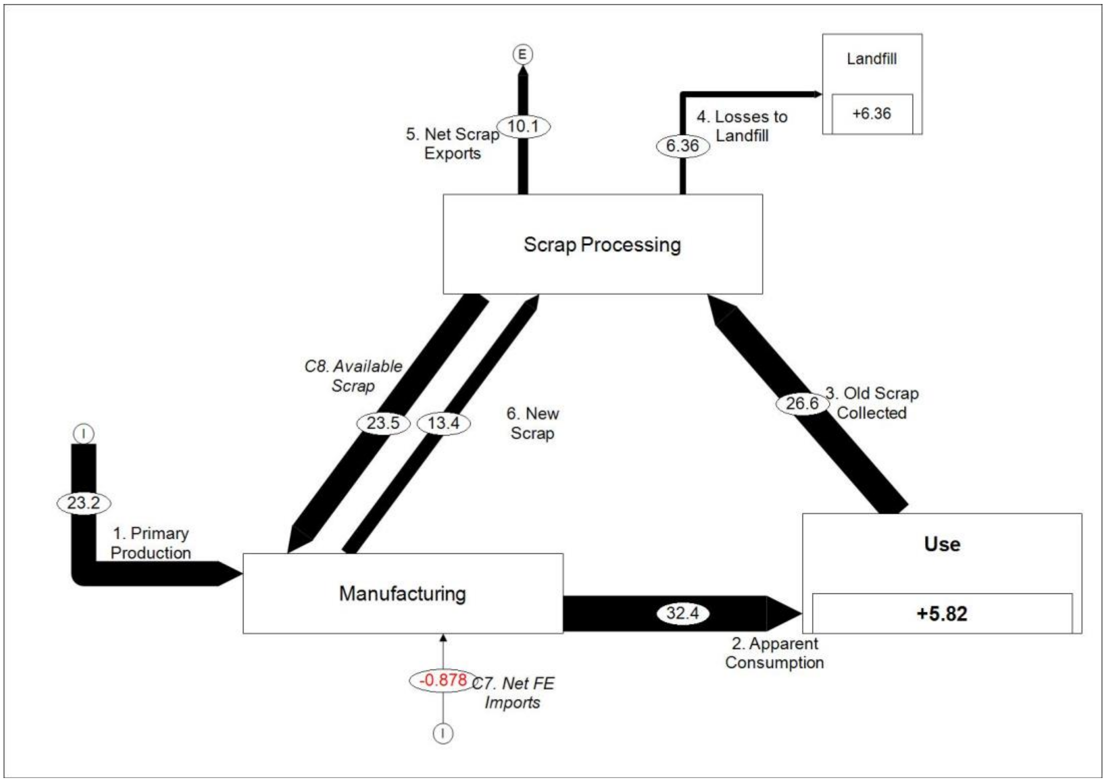

Figure 4-7: Cumulative copper life cycle flows for the slower driver change Scenario FS2 forecast for 2015-2030 in million metric tons

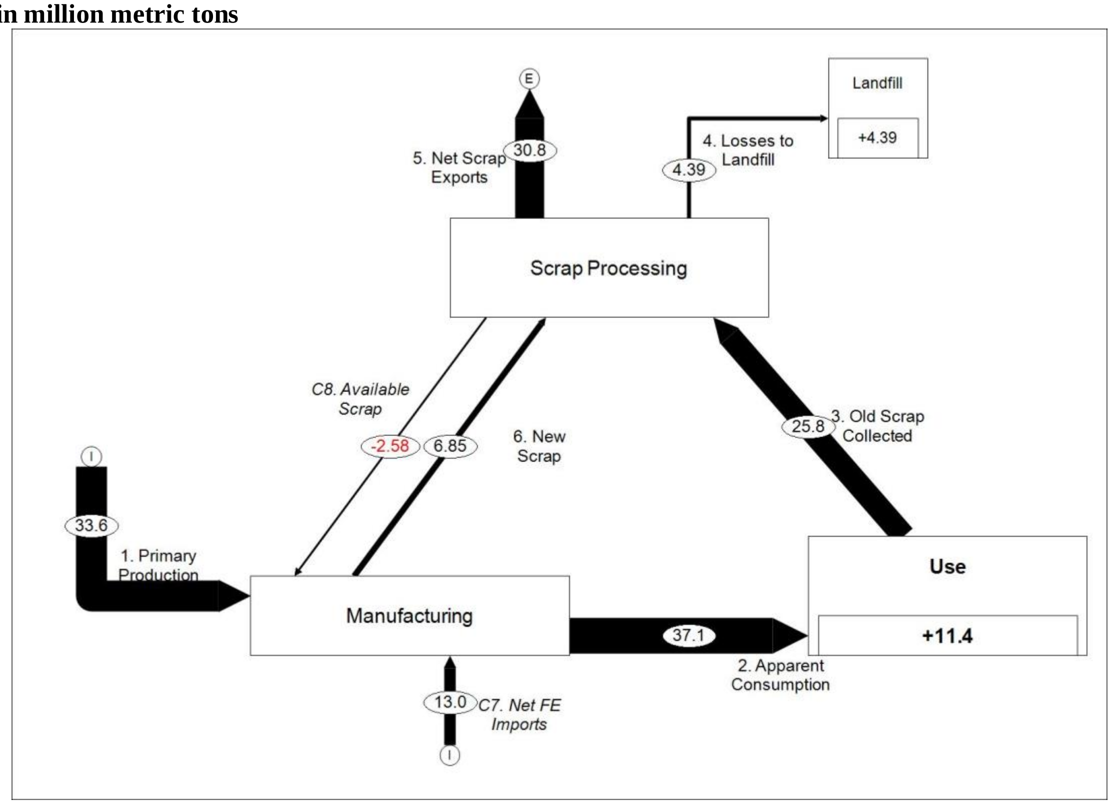

Figure 4-8: Cumulative copper life cycle flows for the faster driver change Scenario FS3 forecast for 2015-2030 in million metric tons

While Scenarios FS2 and FS3 were developed as bounding forecasts, Scenarios FS4-6 were developed based on the findings from the regression modeling for the base case scenario FS1. One key finding from the FS1 modeling, as described in Section 4.4.1, were the relationships between population dynamics population and urbanization with the material flows. These findings lead to the hypothesis that a high-migration scenario, in which total population grows slowly, but population density grows quickly, may lead to a more circular system, with decreased primary production, apparent consumption, and scrap exports but increased end-of-life collection. This hypothesis is tested through the development of the population migration Scenario FS4. Other results from the economic variables in Scenario FS1 led to the development of Scenarios FS5 and FS6, the economic transition and economic stagnation scenarios. Consumption, the largest volume flow, and in many ways the most important driver of the copper life cycle overall because demand for materials is ultimately what needs to be met, is positively correlated with Mfg%. GDP is correlated with end-of-life activities collection and landfilling. This leads to the postulated economic transition Scenario FS5 in which GDP grows quickly to theoretically reduce landfilling, but the manufacturing industry contribution to GDP changes slowly, and may therefore decrease consumption. The inverse of this, an economic stagnation scenario, was developed in which GDP grows slowly and Mfg% changes (declines) quickly, to identify which correlation, negative or positive, is stronger.

Resultant forecasts for Scenario FS4, the population migration scenario, are shown graphically in the life cycle framework in Figure 4-9, and the complete data series are available in the Supplemental Information Table C-7. Net scrap exports decreased over 56% from the base case, though landfilled scrap increased 35%. This, combined with a decrease in apparent consumption, resulted in a large quantity of available scrap, such that over 70% of demand could be met by recycled materials, and the U.S. actually becomes a net exporter of refined copper.

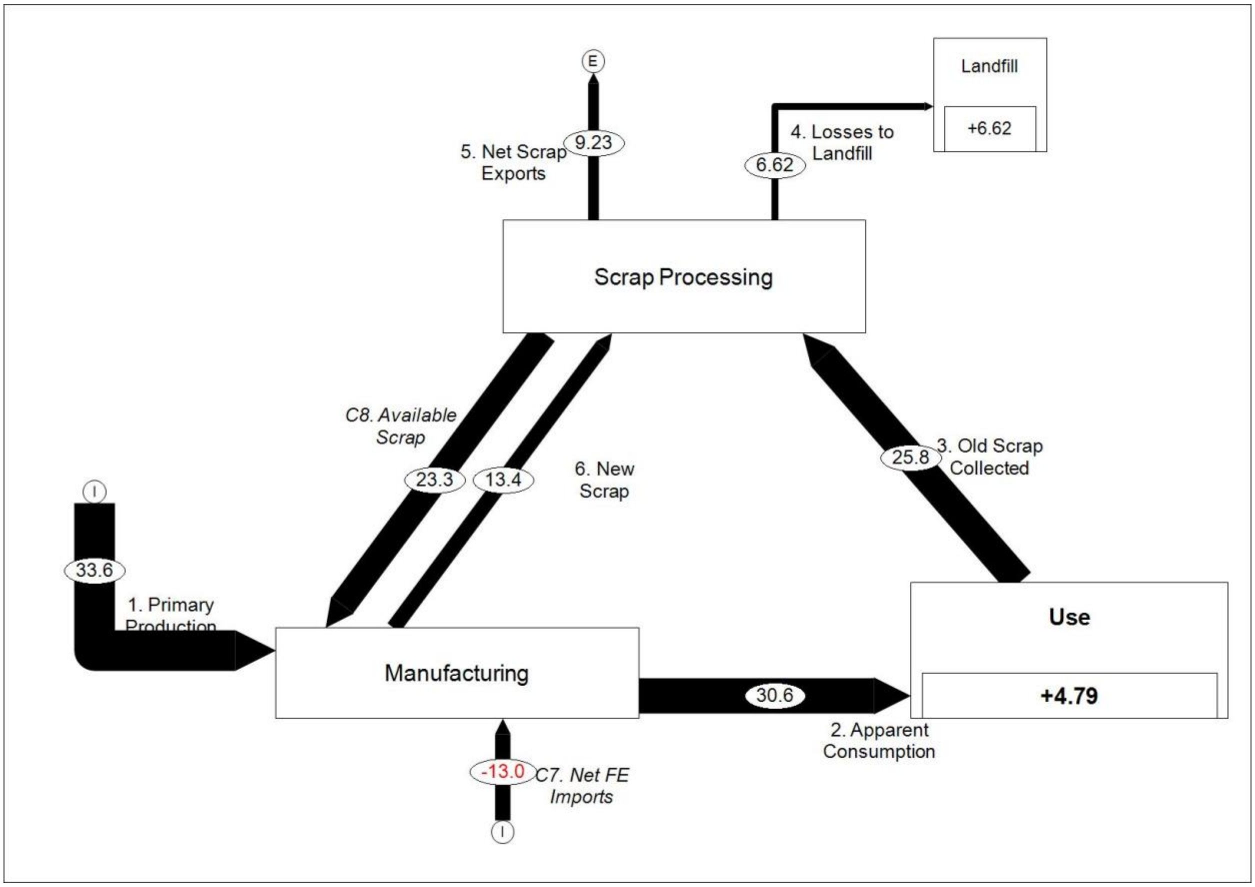

Figure 4-9: Cumulative copper life cycle flows for the population migration Scenario FS4 forecast for 2015-2030 in million metric tons

The economic scenarios, FS5 and FS6, shown in Figures 4-10 and 4-11 respectively, show less overall change to the copper life cycle than the population migration Scenario FS4. Complete data series for these forecasts are available in the Supplemental Information Tables C-8 and C-9. In fact, both economic transition and economic stagnation do not result in a net cumulative change in quantity for any flow greater than 5.5%, indicating that population dynamics are a more critical driver of trends in copper flows than economic drivers alone.

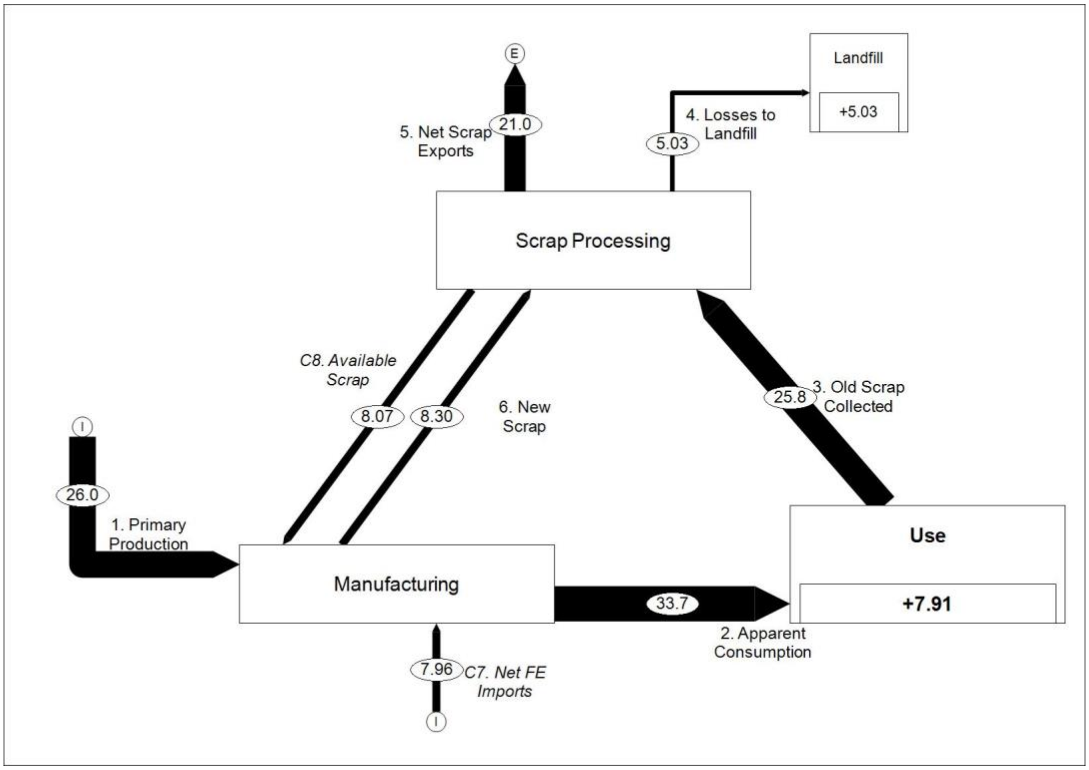

Figure 4-10: Cumulative copper life cycle flows for the economic transition Scenario FS5 forecast for 2015-2030 in million metric tons

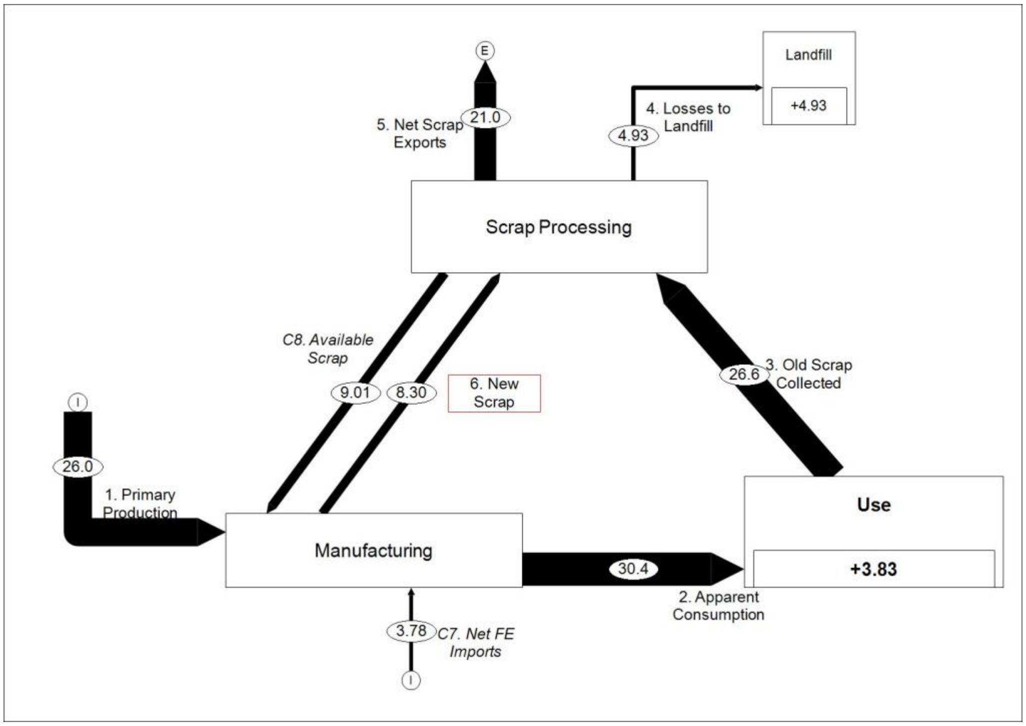

Figure 4-11: Cumulative copper life cycle flows for the economic stagnation Scenario FS6 forecast for 2015-2030 in million metric tons

4.4.3 Circularity Metrics for Evaluation of Scenario Analysis Results

Several dozen circular economy or circularity metrics exist that represent various aspects of the circular economy, including resource-efficiency, stocks and flows dynamics, and product-centric measures (Parchomenko, 2019). Many of these metrics are applicable only to specific processes or products, not complete materials economies with diverse uses. However, a few metrics can be used to quantify the circularity of the scenarios for the copper lifecycle, and were calculated for all future scenarios, based on the results of each forecast scenario (FS1-6). Circularity metric results are shown in Table 4-5. The first circular economy metric included is consumption from recycled material, which is the amount of apparent consumption that is met from the available scrap flow. The second is waste production, or total material to landfill, and the third is import reliance, which shows the percent of total apparent consumption that comes from imported materials, not domestically produced primary copper or scrap.

Table 4-5: Measures of Circular Economy Metrics for Scenarios FS1-6, 2015-2030

	Circular Economy Metrics		
Scenario	**Consumption from Recycled Material (% of demand met by available scrap)**	**Waste Production (thousand tons)**	**Import Reliance (% of Demand from Imports)**
FS1	25%	4926	19%
FS2	72%	6364	Net exporter (0.9 Mt)
FS3	N/A	4391	35%
FS4	77%	6221	Net exporter (13 Mt)
FS5	24%	5031	24%
FS6	30%	4921	125%

Scenario FS4, population migration, has the best circularity profile. Consumption from scrap is the highest by a significant margin, and import reliance is the lowest; this scenario results in the U.S producing more copper than necessary to meet demand. FS3 has lower landfilling rates, but would not be considered the most circular since it has a fairly high import reliance, and there is a negative scrap availability. This outcome confirms the previous findings that population dynamics are the most powerful drivers when it comes to circularity.

4.4.4 Environmental Sustainability Implications and Estimated Footprint

Circularity, a holistic look of resource efficiency in the context of the life cycle of a mineral is a key aspect of the environmental sustainability of mineral resources, but not the only one. Environmental sustainability of mining and mined resources has been a topic of study since the 1990s, and several metrics exist to evaluate environmental footprint (Gorman and Dzombak, 2018). Though there are dozens of potential indicators of environmental sustainability of mined materials, a few key metrics can be selected to provide insight. In this case, we consider fresh water consumption, solid waste production, PM production, and carbon footprint to evaluate beyond volume of material the associated environmental impact of copper in the future.

Chen et al. (2019) performed a comparative life cycle assessment of primary and secondary copper production and identified the inputs and outputs necessary for 1,000 kg of copper production. Fresh water demand was identified as 29,600 kg for primary copper production, and only 1,400 kg for secondary copper production. Solid waste production was identified as 106,000 kg per 1,000 kg primary copper, and 1,330 kg for the same amount of secondary copper. Primary copper production resulted in 10.5 kg of PM release where secondary copper production resulted in 2.62. This study identified CO2 output as well, but the carbon footprint estimates used for this analysis were identified from Nilsson et al. (2017) in a study specifically identifying carbon footprint of copper production, not just CO2 emissions, which also looked at more operations overall, thus providing a slightly better metric. They identified the carbon footprint of primary copper production in the U.S. as 4,000 kg/1,000 kg Cu, and the average secondary copper production carbon footprint as 1,050 kg CO2,eq. Because the total amount of primary and secondary copper has been forecast in Scenarios FS1 and FS2, these values can be used to calculate the approximate impact of each scenario. The summarized results are provided in Table 4-6. The impacts associated in the forecast period 2015-2030 were calculated as well as the impacts observed in the period 2000-2015 for reference. The percent change for each future scenario from the historical data are provided in Table 4-7.

Table 4-6: Cumulative Environmental Footprint of Copper Production for 15-year time periods: 2015-2030 Forecast Scenarios FS1-FS6, and 2000-2015 Historical, Observed Data as a baseline.

	Fresh Water (million tons)	Solid Waste (billion tons)	PM (thousand tons)	Carbon Footprint (billion tons)
Future Scenarios:				
FS1	961	3.41	358	1.37
FS2	992	3.47	402	1.54
FS3	1,100	3.94	390	1.49
FS4	938	3.27	383	1.47
FS5	1,010	3.58	375	1.43
FS6	913	3.24	343	1.31
Observed Scenario:				
2000-2015	645	2.26	257	0.984

Table 4-7: Environmental Footprint Metrics Percent Change in 2015-2030 forecast from 2000-2015 Baseline.

Scenario	Fresh Water	Solid Waste	PM	Carbon Footprint
FS1	49%	51%	40%	39%
FS2	54%	53%	57%	57%
FS3	70%	74%	52%	51%
FS4	45%	45%	49%	49%
FS5	56%	58%	46%	46%
FS6	42%	43%	34%	33%

These results show that Scenario FS2, slower driver change, exhibited the most drastic increase over the historical baseline for PM and carbon footprint, and that Scenario FS3, faster driver change, had the largest footprint, for water consumption and solid waste production. FS6, economic stagnation, had the smallest environmental footprint in all categories, smaller even than Scenario FS4, population migration, which has the best circularity profile. This juxtaposition indicates how important it is, when considering sustainability, to assess multiple metrics, not to consider only circularity, and not only the impact through footprint. Additionally, this analysis shows that in a base case Scenario FS1, the environmental footprint of copper production is predicted to increase significantly over what it has been for 1970-2015. Though the footprint of one ton of Copper may potentially decline through technological advances or process efficiency improvements, it is unlikely that a 50% decrease in measured impacts would occur before 2030, emphasizing the importance of decreasing overall consumption to have a significant impact on improving sustainability.

4.5 Summary and Conclusions

This study has developed six future scenarios for the complete life cycle of copper flows in the U.S. A base case scenario, FS1, was developed based on the quantitative assessment of existing relationships between seven drivers of material flows and six major material flows. Projections of the drivers then allowed for the independent forecasting of these six material flows, and the use of mass balance formulae allowed for the forecasting of two calculated flows and in-use stocks. The fresh water use and solid waste footprints of this scenario are about 50% higher than the water use and solid waste footprints for production for the past 15 years, and PM production and carbon footprint are both about 40% higher. These measures indicate clearly that the environmental impact associated with copper production in the U.S. will continue to increase, even as consumption slows.

Additional scenarios were developed by considering variability in the projections of the drivers. Faster driver change and slower driver change projections were identified for five of the seven drivers. These were used, under varying assumptions, to develop five additional future scenarios in a scenario analysis.

Scenarios FS2 and FS3, slower and faster driver change, provided bounding scenarios for the base case in which the likely maximum and minimum changes in trends were determined. Results from the Scenario FS2 forecasts showed that when all the drivers slow from their current trajectory, consumption and import reliance for copper grow significantly relative to the base case scenario results, and dwarf all other flows, resulting in a high accumulation of copper in the use phase as well as an increased demand for primary materials, all of these things leading to a potential faster depletion of available resources. Results from Scenario FS3, when the rates of change for all drivers are accelerated, show that though dematerialization increases (consumption declines from the base case), circularity of copper is not improved, and there is a projected shortage of available scrap for manufacturers.

Scenarios FS4, FS5, and FS6 were developed based on results from the relationships identified for Scenario FS1. They were developed in order to evaluate specific driver changes that may improve the overall circularity of copper. Scenario FS4 is representative of a U.S. future in which the rate of population growth slows, but people live in denser and therefore more resource-efficient societies. This theoretical future resulted in the most improvement for copper circularity, with total consumption, import reliance, scrap exports and landfilling decreasing, and available scrap for recycling and reuse increasing significantly beyond the base case scenario.

Scenarios FS5 and FS6 were developed to explore potential economic transitions, in which only GDP and Mfg% were varied, and all other drivers followed base case trends. Scenario FS5, the economic transition, represents a scenario in which US GDP grows quickly, and the contribution of manufacturing to GDP declines more quickly – US industry transitions further away from manufacturing while experiencing net growth. Scenario FS6 is the opposite, in which GDP grows more slowly, and manufacturing remains a more significant contributor for longer. Both of these scenarios did not result in significant changes from the base case Scenario FS1.

A key finding of this study was that population change indicators are the most critical to the entire life cycle of copper. This finding suggests that policy changes to incentivize population density increases without increasing overall population may also be the most effective methods of increasing the circularity of copper in the U.S.

Another finding is that all end-of-life activities are necessarily linked. In all scenarios, collection, landfilling and scrap exports varied together. In any scenario where collection increased from the base case, such as Scenario FS3, faster driver change, and Scenario FS6, economic stagnation, so did scrap exports as well as landfilling. Where collection decreased from the base case, as in Scenario FS2, slower driver change, and Scenario FS4, population migration, scrap exporting and landfilled scrap also decreased. This means that an increase in collection of end-of-life scrap does not necessarily lead to an increase in scrap available for reuse in the U.S. This result is important in considering technological or policy changes that may possibly unlink these flows from their dependence on collection.

Finally, results indicated the importance, when considering sustainability, of assessing both the circularity as well as standard environmental impact metrics. Whereas Scenario FS4 yielded results with the highest level of copper circularity, Scenario FS6 yielded the smallest environmental footprint metrics, with percent increases over the 2000-2015 reference period not exceeding 22%. Despite an overall decrease in apparent consumption in FS4, the net increase in environmental impact over the reference period indicates a need to improve copper environmental footprint per unit. Improved efficiency of processing copper would reduce environmental footprint per unit, whereas increased circularity will reduce the overall demand for primary materials.

4.6 Acknowledgements

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Chapter 5 : Summary, Conclusions, and Recommendations for Future Work

5.1 Summary and Conclusions

This research had four objectives to meet the overall goal of examining the sustainability of mining and mineral resource consumption in the U.S.

1. Establish a framework for "sustainable mining" that incorporates circularity

2. Develop a model to represent stocks and flows of copper in the U.S.

3. Identify and model future scenarios and assess their circularity

4. Evaluate environmental sustainability for scenarios in the sustainable mining framework

Chapter 2 addressed the first objective through a complete assessment of existing frameworks for sustainable mining. The analysis in Chapter 2 identified a shift in focus of sustainability investigations from the life cycle of the mine to the life cycle of the mineral, with a focus on resource efficiency and the circular economy. This shift is necessary for future reduction of the major environmental impacts associated with increasing mining rates, inputs, land disruption, outputs, and closure, and also to also extend the lifetime of existing minerals reserves and resources. Some of the ways this can be achieved are through the incorporation of materials flow analysis as well as circularity concepts such as improving collection and recycling through design for recovery, product-centric recycling, and extended producer responsibility.

A stocks and flows model was developed in Chapter 3 to examine the sustainability of copper in the U.S. from 1970-2015, to address the second objective. Evaluation of the primary data identified in Chapter 2 showed that there has been a significant shift in consumption trends of copper over time as well as a major accumulation of copper in the use phase – of which 20-40% is estimated as a potential hibernating stock for recovery and reuse going forward. Buildings and construction materials as well as electric utility equipment were identified as the largest and most readily available sources of the four use phases considered. Other opportunities for improved circularity include recovery from landfills, where copper is present in amounts not dissimilar from existing U.S. mine ore grades which are typically less than 0.5% copper; reduction of dissipative and processing losses in the manufacturing phase; and reduction of scrap exports.

Objectives three and four are addressed in Chapter 4, which presents a forecast of the major copper life cycle flows to 2030 and an assessment of sustainability through quantitative assessment of both circularity and traditional environmental impact metrics. The analysis provided useful insight into how current trends and relationships between drivers and copper material flows will continue to affect copper material flow in the future. The analysis also enabled identification of which particular relationships may lead to improved circularity and overall environmental sustainability. Results from evaluation of the six scenarios demonstrate that a shift in copper demand driver growth in either direction, positive or negative, would result by 2030 in drastic changes to the copper material flow system, including in one case a shortage of scrap availability. Population dynamics appears to be the most significant driver affecting the complete life cycle of copper in the U.S.

5.2 Research Contributions and Implications

This research has provided several original contributions to the field of environmental engineering and sustainability of extractable resources. The contributions include:

1. Completion of a review of existing works and initiatives in the area of sustainability and mining, as well as identification of an emerging field integrating circular economy concepts circularity and resource efficiency. A framework for sustainable mining is proposed synthesizing metrics of circularity and environmental sustainability.
2. Collection of primary end-of-life management data for copper in the U.S., providing a basis for evaluation of other datasets currently used in material flow analyses that do not use primary data or a bottom up approach. A material flow analysis was performed for U.S. copper from 1970-2015 using these primary data.
3. Development of relationships between seven key independent drivers and major copper material flows via regression analysis. These relationships were used to provide a long-term forecast for the copper life cycle.
4. Use of scenario analysis with the identified relationships to assess qualitatively the circularity of the copper life cycle as it is modified by changing drivers.
5. Application of both circularity and environmental sustainability metrics to quantitatively assess the copper life cycle and development of baseline indicators for comparisons.

The research has provided information regarding how non-fuel mineral resources, through an in-depth look at copper, are used in the U.S. economy, as well as where there may be opportunities or limitations to the sustainable utilization of these resources. Additionally, the research has shown how mineral resources may fare in the U.S. over the next decade considering population growth, trends of population movement, and projected changes in other socioeconomic drivers. The components of the research provide a new avenue to assess mineral resources and identify limitations to sustainability in the complete life cycle before a risk of criticality emerges.

5.3 Recommendations for Future Work

This body of work advances the knowledge base of sustainability and mineral resources in the U.S. and identifies key elements that can be leveraged to improve long-term sustainability. This work provides a base for several potential areas of follow-up research.

One such area is the study of economic and social metrics that could be included in a sustainable mining framework. The focus of this work was environmental sustainability for reasons explained in Chapters 1 and 2, but social and economic dynamics are undeniably tied to sustainability and interlinked in many ways with environmental sustainability. The sustainable mining framework outlined in this work proposes inclusion of environmental impact metrics for the front end of a material life cycle- exploration, mining operations, processing, mine closure – as well as circularity metrics to assess entire life cycle through material flow studies and beyond. An exploration of the social, political, and economic dynamics that may also be quantitatively measured to assess both the sustainability of the life cycle of the mine and the life cycle of the mineral would be valuable additions, though they were outside the scope of this work.

The data used for Chapters 3 and 4 were collected from organizations willing to cooperate and voluntarily provide information. Several organizations exist with the capabilities to collect more complete and representative data for the use and end-of-life management phases of copper as well as other materials. Work to collect more complete data from construction and demolition products, utility asset management, non-road transportation equipment, etc. would provide valuable information to update the material flow analysis for this material, copper, and also for other materials including steel, aluminum, and other metals or even non-metal resources like plastics in piping, wood and concrete, etc. This would facilitate application to other resources of the methodology developed in this work. Beyond research applications, there would be industry benefits to the better collection and management of such data. This type of end-of-life management and asset recovery data, if published by industry groups, would provide insight for member organizations into quantitative sustainability measures that could be used in sustainability assessments, in which consumers have a growing interest, and it would also allow for organizations to acquire more easily LEED, BAN or other sustainability credits and accommodations if this type of data accounting was standard on all projects.

The application of the framework and methodology for assessing sustainability and circularity to other non-fuel mineral resources also is a valuable opportunity for future work. The relative sustainability of different materials in the U.S. could be assessed. Through such comparative analysis opportunities for optimization can be identified for potential application to multiple systems.

As mentioned in Chapter 4, many methods for predictive analysis exist. The method used in Chapter 4, a logistically transformed linear regression analysis, was identified to be the most applicable based on available data, and the approach employed in a number or related, existing studies. However, forecasts could also be made through learning algorithms, such as neural networks, decision trees, Bayesian networks, or more classical approaches such as resource reserve depletion calculations, "peak" resource identification, and other approaches. A comparative analysis, to compare the validity and findings of these different methodologies, would provide significant insight into how these predictions and forecasts should be made going forward.

Additionally, the work in Chapter 4 focused on forecasting material flows in a simplified material life cycle framework from the material framework identified in Chapter 3. An expansion of the forecasts to more specific use phases may provide interesting insight into the distribution of the growing consumption predicted. This might be accomplished by using more specific drivers in the analysis of relationship between driver and flow; for example the rate of electrification of vehicles may be a driver specifically for copper consumption in transportation equipment, or the market share of fiber optic internet may be a representative driver that affects copper consumption by utilities and buildings and construction.

More future scenarios are also always possible. Beyond shifting population and economic dynamics, there may be disruptors to the system in the future including the opening of a new mine, and therefore influx of primary material; further incentivization of electric vehicles; elimination of the penny; etc. Such disruption factors are not predictable and therefore not included in the original future scenarios, but may have significant implications on the copper life cycle, and may be worth assessing.

APPENDIX A Glossary of Terms

Circular Economy: A system in which economic growth is decoupled from consumption (and disposal) of finite resources. Material resources are not wasted or disposed, but restored into the economy, and inputs, waste, and leakage are all minimized. It is the antithesis to the "linear economy" currently embodied by most societies, in which products are made, used, and disposed.

Circularity: A measurement of how well a good, process, or material adheres to the circular economy concept. This may be measured by a variety of circularity indicators or metrics including but not limited to extraction rate, waste production, reuse, and recycling rate.

Extraction Rate: Also "resource extraction rate". The quantity of recoverable virgin material extracted in a given time period (usually one year, in this work) within a system boundary.

Life Cycle: A summary of the pathway followed and all activities performed on a material from "cradle to grave." In the context of non-fuel minerals, and specifically metals, this encompasses the major phases of extraction, processing, refining, semi-manufacturing, manufacturing, consumption, end-of-life collection, re-entry through recycling or reuse, imports and exports, as well as disposal, or landfilling.

Material Flow Analysis: Also "material flow accounting". A method for analyzing and characterizing the stocks and flows of a substance or good within a geographic boundary.

> **Stocks and Flows Analysis:** A method of material flow analysis in which solid materials are accounted for using data from life cycle phases. Flows of materials from extraction to production to fabrication to use to waste management are identified. Mass balance

equations that rely on conservation of mass in each life cycle phase allow for the calculation of stocks.

Stocks: Also "accumulating stocks" or "accumulated stocks". An accumulation or reservoir of a material within a life cycle phase.

In-use stocks: Stock that has accumulated in the "use" phase of a material life cycle, between the consumption flow and the end-of-life collection or waste management flow.

Hibernating stocks: A subset of in-use stocks that have reached the end of their useful life to the consumer but have not yet been collected. Some examples are: old wiring or plumbing in the walls of buildings that have not been removed; old phone, laptop, TV, or other electronic equipment that has been replaced with a newer model but is being kept by someone as a "backup"; out-of-use utilities or infrastructure, like old railroad tracks or transmission lines.

Sustainability: The ability to meet present needs without compromising the ability of future generations to meet their needs. Typically the concept is considered to encompass social, economic, and environmental resources and activities.

Environmental sustainability: Activities in which the quality of the natural environment is maintained or enhanced, not degraded, and natural resources are stewarded for future generations.

Sustainable mining: Mineral extraction and processing operations that adhere to the concept of sustainability.

APPENDIX B Supporting Information for Chapter 3- Stocks and Flows of Copper in the U.S.: Analysis of Circularity 1970-2015 and Potential for Increased Recovery

This appendix provides the supporting information for Chapter 3. Subsystems of the copper life cycle are included as well as the complete collected data for all life cycle flows in Tables B-1-6; with complete references as endnotes.

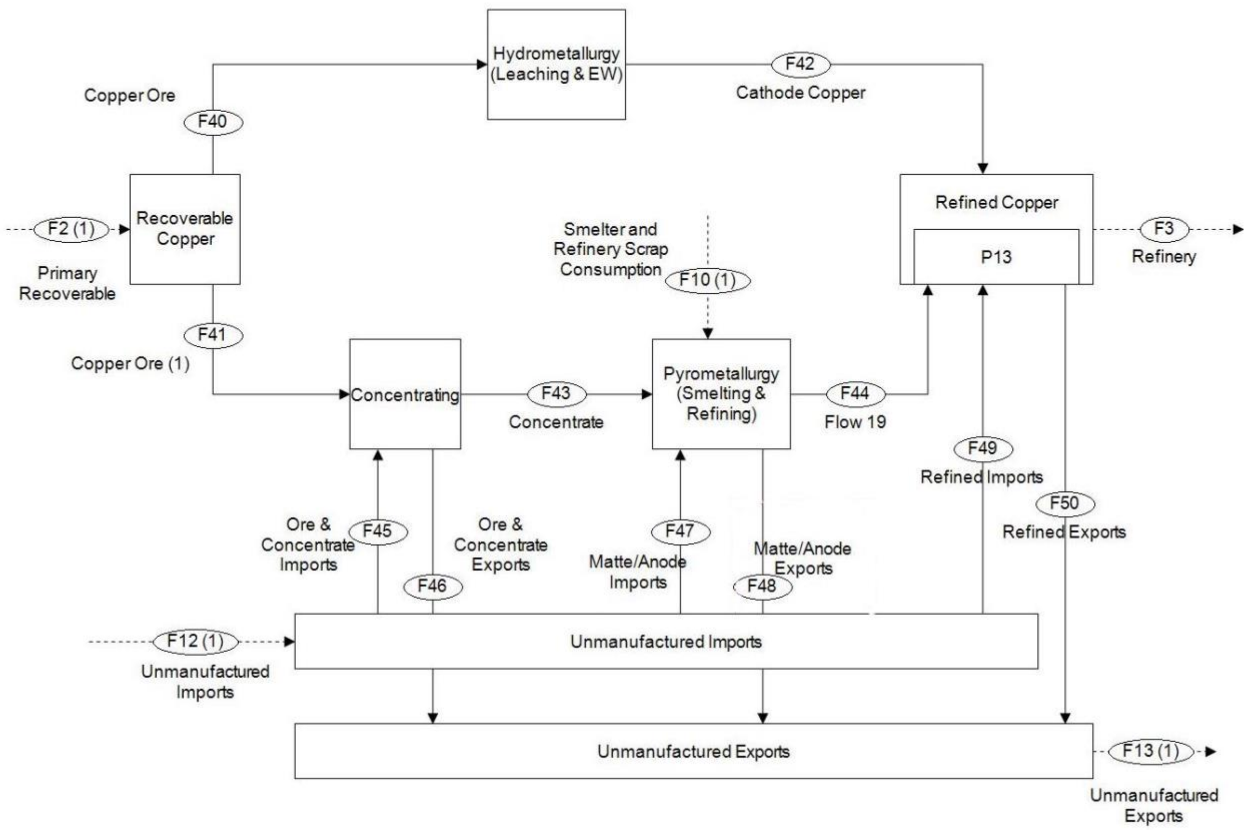

Figure B-1: Refining Subsystem – Complete Stocks and Flows within the Refining Phase of the Complete Copper Life Cycle

Table B-1: U.S. Copper Mining Life Cycle Data (Tons)

	F2 Mine Production (F1+F11) (USGS DS896[1] & Statistical Compendium (SC)[2])	**F12 Unrefined Imports** (USGS SC[2] & Minerals Yearbooks (MYB)[3])	**F13 Unrefined Exports** (USGS SC[2] & MYBs[3])	**Net Exports**
1970	1.60E+06	5.97E+04	5.58E+04	-3.86E+03
1971	1.44E+06	5.20E+03	7.37E+03	2.17E+03
1972	1.70E+06	7.52E+04	2.45E+04	-5.07E+04
1973	1.70E+06	2.20E+04	3.50E+04	1.30E+04
1974	1.50E+06	7.94E+04	2.50E+04	-5.43E+04
1975	1.31E+06	3.32E+04	1.35E+04	-1.97E+04
1976	1.46E+06	4.53E+04	1.81E+04	-2.72E+04
1977	1.36E+06	2.06E+04	2.28E+04	2.11E+03
1978	1.36E+06	3.09E+04	2.66E+04	-4.25E+03
1979	1.44E+06	3.09E+04	4.98E+04	1.88E+04
1980	1.18E+06	5.28E+04	1.14E+05	6.10E+04
1981	1.54E+06	4.21E+04	1.57E+05	1.15E+05
1982	1.15E+06	1.22E+05	1.98E+05	7.60E+04
1983	1.04E+06	9.39E+04	4.97E+04	-4.42E+04
1984	1.10E+06	1.32E+04	6.61E+04	5.30E+04
1985	1.11E+06	6.88E+03	1.28E+05	1.22E+05
1986	1.14E+06	4.93E+03	1.78E+05	1.73E+05
1987	1.22E+06	9.21E+03	1.31E+05	1.22E+05
1988	1.42E+06	8.26E+03	2.15E+05	2.07E+05
1989	1.50E+06	4.93E+04	2.74E+05	2.24E+05
1990	1.58E+06	9.95E+04	2.62E+05	1.62E+05
1991	1.63E+06	6.10E+04	2.53E+05	1.92E+05
1992	1.76E+06	1.02E+05	2.66E+05	1.64E+05
1993	1.80E+06	3.70E+04	2.27E+05	1.90E+05
1994	1.82E+06	8.20E+04	2.61E+05	1.79E+05
1995	1.85E+06	1.27E+05	2.39E+05	1.12E+05
1996	1.92E+06	7.20E+04	1.95E+05	1.23E+05
1997	1.94E+06	4.40E+04	1.27E+05	8.30E+04
1998	1.86E+06	2.17E+05	3.70E+04	-1.80E+05
1999	1.60E+06	1.43E+05	6.40E+04	-7.90E+04
2000	1.44E+06	0.00E+00	1.16E+05	1.16E+05
2001	1.34E+06	4.60E+04	4.50E+04	-1.00E+03
2002	1.14E+06	7.20E+04	2.30E+04	-4.90E+04
2003	1.12E+06	2.70E+04	9.00E+03	-1.80E+04
2004	1.16E+06	2.30E+04	2.40E+04	1.00E+03
2005	1.14E+06	0.00E+00	1.37E+05	1.37E+05
2006	1.20E+06	0.00E+00	1.08E+05	1.08E+05
2007	1.17E+06	1.00E+03	1.34E+05	1.33E+05
2008	1.31E+06	1.00E+03	3.01E+05	3.00E+05
2009	1.18E+06	0.00E+00	1.51E+05	1.51E+05
2010	1.11E+06	1.00E+03	1.37E+05	1.36E+05
2011	1.11E+06	1.50E+04	2.52E+05	2.37E+05
2012	1.17E+06	6.00E+03	3.01E+05	2.95E+05
2013	1.25E+06	3.00E+03	3.48E+05	3.45E+05
2014	1.36E+06	0.00E+00	4.10E+05	4.10E+05
2015	1.25E+06	0.00E+00	3.80E+05	3.80E+05

Table B-2: U.S. Copper Refining and Manufacturing Life Cycle Data (Tons)

	F10 Secondary Refinery Production (USGS DS140[4])	**F3 Refinery Production** (USGS DS140[4])	**F35 Refined Imports** (USGS SC[2] & MYBs[3])	**F36 Refined Exports** (SC[2] &MYBs[3])	**Net Imports**	**F4 Apparent Consumption** (USGS DS140[4])
1970	4.57E+05	1.52E+06	1.20E+05	2.01E+05	-8.08E+04	1.82E+06
1971	4.04E+05	1.41E+06	1.47E+05	1.71E+05	-2.35E+04	1.89E+06
1972	4.16E+05	1.68E+06	1.57E+05	1.65E+05	-8.32E+03	2.14E+06
1973	4.41E+05	1.70E+06	1.87E+05	2.22E+05	-3.53E+04	2.22E+06
1974	4.39E+05	1.42E+06	2.76E+05	2.07E+05	6.90E+04	2.15E+06
1975	3.35E+05	1.29E+06	1.29E+05	1.56E+05	-2.70E+04	1.47E+06
1976	3.80E+05	1.29E+06	3.46E+05	1.02E+05	2.44E+05	1.92E+06
1977	4.10E+05	1.28E+06	3.61E+05	4.20E+04	3.19E+05	2.07E+06
1978	5.02E+05	1.33E+06	4.03E+05	8.30E+04	3.20E+05	2.37E+06
1979	6.04E+05	1.41E+06	2.04E+05	7.40E+04	1.30E+05	2.43E+06
1980	6.13E+05	1.12E+06	4.27E+05	1.40E+04	4.13E+05	2.18E+06
1981	5.92E+05	1.42E+06	3.31E+05	2.40E+04	3.07E+05	2.27E+06
1982	5.18E+05	1.05E+06	2.58E+05	3.10E+04	2.27E+05	1.76E+06
1983	4.49E+05	1.03E+06	4.60E+05	8.10E+04	3.79E+05	2.01E+06
1984	4.61E+05	1.09E+06	4.45E+05	9.10E+04	3.54E+05	2.12E+06
1985	5.03E+05	1.00E+06	3.78E+05	3.80E+04	3.40E+05	2.14E+06
1986	4.77E+05	1.03E+06	5.02E+05	1.20E+04	4.90E+05	2.14E+06
1987	4.98E+05	1.13E+06	4.69E+05	9.00E+03	4.60E+05	2.20E+06
1988	5.18E+05	1.28E+06	3.33E+05	5.80E+04	2.75E+05	2.21E+06
1989	5.48E+05	1.35E+06	3.00E+05	1.30E+05	1.70E+05	2.18E+06
1990	5.36E+05	1.50E+06	2.62E+05	2.11E+05	5.10E+04	2.17E+06
1991	5.33E+05	2.00E+06	2.89E+05	2.71E+05	1.80E+04	2.09E+06
1992	5.44E+05	2.14E+06	2.89E+05	1.77E+05	1.12E+05	2.31E+06
1993	5.54E+05	2.25E+06	3.43E+05	2.17E+05	1.26E+05	2.51E+06
1994	5.00E+05	2.23E+06	4.70E+05	1.57E+05	3.13E+05	2.68E+06
1995	4.43E+05	2.28E+06	4.29E+05	2.17E+05	2.12E+05	2.54E+06
1996	4.28E+05	2.35E+06	5.43E+05	1.69E+05	3.74E+05	2.83E+06
1997	4.98E+05	2.47E+06	6.32E+05	9.29E+04	5.39E+05	2.94E+06
1998	4.66E+05	2.49E+06	7.25E+05	8.62E+04	6.39E+05	3.03E+06
1999	3.81E+05	2.12E+06	9.15E+05	2.52E+04	8.90E+05	3.13E+06
2000	3.58E+05	1.80E+06	1.02E+06	9.36E+04	9.26E+05	3.09E+06
2001	3.16E+05	1.80E+06	1.20E+06	2.25E+04	1.18E+06	2.51E+06
2002	2.08E+05	1.51E+06	1.06E+06	2.66E+04	1.03E+06	2.59E+06
2003	2.07E+05	1.31E+06	6.87E+05	9.33E+04	5.94E+05	2.43E+06
2004	1.91E+05	1.31E+06	7.04E+05	1.18E+05	5.86E+05	2.55E+06
2005	1.83E+05	1.26E+06	9.77E+05	3.95E+04	9.38E+05	2.42E+06
2006	1.51E+05	1.25E+06	1.07E+06	1.06E+05	9.64E+05	2.20E+06
2007	1.62E+05	1.32E+06	8.32E+05	5.11E+04	7.81E+05	2.27E+06
2008	1.59E+05	1.27E+06	7.21E+05	3.65E+04	6.85E+05	2.00E+06
2009	1.38E+05	1.16E+06	6.45E+05	8.08E+04	5.64E+05	1.58E+06
2010	1.43E+05	1.10E+06	5.83E+05	7.83E+04	5.05E+05	1.76E+06
2011	1.53E+05	1.03E+06	6.49E+05	4.04E+04	6.09E+05	1.73E+06
2012	1.64E+05	1.00E+06	6.28E+05	1.69E+05	4.59E+05	1.76E+06
2013	1.66E+05	1.04E+06	7.30E+05	1.11E+05	6.19E+05	1.75E+06
2014	1.73E+05	1.10E+06	6.14E+05	1.27E+05	4.87E+05	1.78E+06
2015	1.67E+05	1.05E+06	6.64E+05	8.65E+04	5.78E+05	1.82E+06

Table B-3: U.S. Copper Use Phase Life Cycle Data (Tons)

	F27 Building construction	F25 Electrical and electronic products	F26 Transportation equipment	F28 Consumer and general products	F4 Apparent consumption (USGS DS140[4])
1970	7.41E+05	5.28E+05	3.18E+05	2.28E+05	1.82E+06
1971	7.68E+05	5.50E+05	3.31E+05	2.33E+05	1.89E+06
1972	8.72E+05	6.25E+05	3.72E+05	2.62E+05	2.14E+06
1973	9.04E+05	6.54E+05	3.85E+05	2.71E+05	2.22E+06
1974	8.77E+05	6.41E+05	3.65E+05	2.62E+05	2.15E+06
1975	6.03E+05	4.08E+05	2.48E+05	2.10E+05	1.47E+06
1976	7.74E+05	5.51E+05	3.61E+05	2.30E+05	1.92E+06
1977	8.35E+05	6.16E+05	3.66E+05	2.30E+05	2.07E+06
1978	9.81E+05	7.07E+05	3.97E+05	2.80E+05	2.37E+06
1979	9.87E+05	7.50E+05	4.10E+05	2.90E+05	2.43E+06
1980	8.96E+05	6.95E+05	3.25E+05	2.60E+05	2.18E+06
1981	9.37E+05	7.30E+05	3.40E+05	2.70E+05	2.27E+06
1982	7.48E+05	5.54E+05	2.54E+05	2.10E+05	1.76E+06
1983	8.99E+05	5.69E+05	3.09E+05	2.00E+05	2.01E+06
1984	9.39E+05	5.99E+05	3.49E+05	2.30E+05	2.12E+06
1985	1.02E+06	5.59E+05	3.49E+05	2.10E+05	2.14E+06
1986	1.04E+06	5.59E+05	3.29E+05	1.90E+05	2.14E+06
1987	1.10E+06	5.77E+05	3.07E+05	2.00E+05	2.20E+06
1988	1.07E+06	5.81E+05	3.41E+05	2.20E+05	2.21E+06
1989	1.05E+06	5.71E+05	3.31E+05	2.20E+05	2.18E+06
1990	1.03E+06	6.09E+05	3.29E+05	2.20E+05	2.17E+06
1991	1.02E+06	5.62E+05	2.92E+05	2.10E+05	2.09E+06
1992	1.11E+06	6.49E+05	3.49E+05	2.30E+05	2.31E+06
1993	1.19E+06	7.19E+05	3.99E+05	2.30E+05	2.51E+06
1994	1.27E+06	7.44E+05	3.94E+05	2.70E+05	2.68E+06
1995	1.20E+06	7.29E+05	3.49E+05	2.50E+05	2.54E+06
1996	1.34E+06	8.18E+05	3.88E+05	2.80E+05	2.83E+06
1997	1.42E+06	8.41E+05	4.01E+05	2.90E+05	2.94E+06
1998	1.44E+06	8.96E+05	3.76E+05	3.00E+05	3.03E+06
1999	1.53E+06	8.88E+05	3.88E+05	3.10E+05	3.13E+06
2000	1.46E+06	9.01E+05	3.81E+05	3.70E+05	3.09E+06
2001	1.27E+06	7.03E+05	2.83E+05	2.50E+05	2.51E+06
2002	1.39E+06	6.30E+05	3.20E+05	2.60E+05	2.61E+06
2003	1.30E+06	5.65E+05	2.95E+05	2.70E+05	2.43E+06
2004	1.36E+06	5.94E+05	3.14E+05	2.81E+05	2.55E+06
2005	1.30E+06	5.58E+05	3.16E+05	2.42E+05	2.42E+06
2006	1.18E+06	4.86E+05	2.88E+05	2.42E+05	2.20E+06
2007	1.27E+06	4.78E+05	2.74E+05	2.50E+05	2.27E+06
2008	1.08E+06	4.61E+05	2.41E+05	2.20E+05	2.00E+06
2009	8.57E+05	3.61E+05	2.03E+05	1.58E+05	1.58E+06
2010	9.46E+05	3.88E+05	2.48E+05	1.76E+05	1.76E+06
2011	8.52E+05	4.30E+05	2.39E+05	2.08E+05	1.73E+06
2012	8.67E+05	4.37E+05	2.44E+05	2.11E+05	1.76E+06
2013	8.35E+05	3.78E+05	3.26E+05	2.10E+05	1.75E+06
2014	8.31E+05	3.67E+05	3.67E+05	2.14E+05	1.78E+06
2015	8.50E+05	3.75E+05	3.75E+05	2.18E+05	1.82E+06

Table B-4: U.S. Copper Scrap Data (Tons)

	F9 New Scrap (USGS DS140[4]**)**	**F8 Mill & Mfg Scrap (**SC & Recycling Yearbook (RYB)[5])	**F38 Scrap Imports** (SC[2] & RYB[5])	**F37 Scrap Exports** **(**SC[2] & RYB[5])	**Net Scrap Exports**
1970	6.75E+05	1.12E+06	3.65E+03	8.01E+04	7.65E+04
1971	6.85E+05	1.14E+06	1.25E+04	6.21E+04	4.95E+04
1972	7.65E+05	1.23E+06	1.70E+04	5.56E+04	3.86E+04
1973	8.08E+05	1.27E+06	2.47E+04	1.03E+05	7.88E+04
1974	7.81E+05	1.16E+06	3.77E+04	1.07E+05	6.95E+04
1975	5.47E+05	8.28E+05	1.84E+04	9.93E+04	8.10E+04
1976	6.59E+05	1.03E+06	2.67E+04	7.92E+04	5.26E+04
1977	6.75E+05	1.08E+06	2.62E+04	8.27E+04	5.66E+04
1978	7.46E+05	1.22E+06	2.86E+04	1.18E+05	8.98E+04
1979	9.48E+05	1.58E+06	2.96E+04	1.30E+05	1.00E+05
1980	8.24E+05	1.34E+06	2.98E+04	1.46E+05	1.16E+05
1981	8.16E+05	1.34E+06	3.52E+04	1.13E+05	7.74E+04
1982	6.70E+05	1.05E+06	3.53E+04	1.14E+05	7.87E+04
1983	6.34E+05	9.80E+05	5.49E+04	1.01E+05	4.56E+04
1984	6.59E+05	1.13E+06	5.50E+04	1.51E+05	9.62E+04
1985	6.36E+05	1.03E+06	4.65E+04	2.25E+05	1.79E+05
1986	6.49E+05	1.09E+06	5.61E+04	2.35E+05	1.79E+05
1987	7.16E+05	1.17E+06	6.60E+04	2.29E+05	1.63E+05
1988	7.89E+05	1.16E+06	7.33E+04	2.50E+05	1.76E+05
1989	7.61E+05	1.14E+06	7.41E+04	2.93E+05	2.19E+05
1990	7.75E+05	1.17E+06	1.01E+05	2.60E+05	1.59E+05
1991	6.67E+05	1.14E+06	1.05E+05	2.62E+05	1.57E+05
1992	7.22E+05	1.23E+06	1.30E+05	2.29E+05	9.86E+04
1993	7.48E+05	1.24E+06	1.21E+05	2.43E+05	1.22E+05
1994	8.27E+05	1.32E+06	1.23E+05	2.76E+05	1.53E+05
1995	8.74E+05	1.30E+06	1.41E+05	3.83E+05	2.42E+05
1996	8.91E+05	1.29E+06	1.78E+05	3.37E+05	1.59E+05
1997	9.67E+05	1.36E+06	1.78E+05	3.30E+05	1.52E+05
1998	9.56E+05	1.37E+06	1.35E+05	2.53E+05	1.18E+05
1999	9.49E+05	1.40E+06	1.08E+05	2.63E+05	1.55E+05
2000	9.55E+05	1.39E+06	1.12E+05	4.14E+05	3.02E+05
2001	8.33E+05	1.21E+06	9.11E+04	4.58E+05	3.67E+05
2002	8.42E+05	1.16E+06	8.03E+04	4.28E+05	3.47E+05
2003	7.37E+05	1.06E+06	7.11E+04	5.85E+05	5.13E+05
2004	7.74E+05	1.09E+06	7.98E+04	6.05E+05	5.25E+05
2005	7.69E+05	1.10E+06	9.03E+04	5.76E+05	4.85E+05
2006	8.19E+05	1.11E+06	9.16E+04	6.90E+05	5.98E+05
2007	7.72E+05	1.03E+06	1.12E+05	7.44E+05	6.32E+05
2008	7.00E+05	9.43E+05	4.91E+04	7.32E+05	6.83E+05
2009	6.39E+05	8.65E+05	9.30E+04	6.76E+05	5.83E+05
2010	6.42E+05	8.91E+05	7.50E+04	8.37E+05	7.62E+05
2011	6.49E+05	8.52E+05	8.76E+04	1.03E+06	9.45E+05
2012	6.42E+05	8.99E+05	8.38E+04	9.95E+05	9.11E+05
2013	6.30E+05	8.55E+05	8.47E+04	9.58E+05	8.74E+05
2014	6.72E+05	8.90E+05	9.26E+04	8.72E+05	7.79E+05
2015	6.38E+05	8.70E+05	8.83E+04	8.07E+05	7.19E+05

Table B-5: U.S. Copper End of Life Collection Data (Tons). Primary, calculated values.

	F33 MSW	F32 C&D Waste	F31 Transportation	F30 Electric Utility	F5 Total EoL Collection
UNCERTAINTY	+/-30%	+/- 33%	+/-15%	+/- 26%	
1970	9.25E+04	1.49E+05	1.91E+05	1.06E+04	4.43E+05
1971	9.85E+04	1.49E+05	1.83E+05	1.24E+04	4.43E+05
1972	1.04E+05	1.49E+05	1.75E+05	1.46E+04	4.39E+05
1973	1.10E+05	1.49E+05	1.67E+05	1.29E+04	4.37E+05
1974	1.16E+05	1.49E+05	1.59E+05	1.42E+04	4.38E+05
1975	1.22E+05	1.49E+05	1.51E+05	1.34E+04	4.33E+05
1976	1.28E+05	1.49E+05	1.68E+05	1.51E+04	4.60E+05
1977	1.34E+05	1.49E+05	1.84E+05	1.41E+04	4.78E+05
1978	1.40E+05	1.50E+05	2.00E+05	1.32E+04	5.01E+05
1979	1.46E+05	1.50E+05	2.17E+05	1.20E+04	5.24E+05
1980	1.58E+05	1.50E+05	2.33E+05	1.18E+04	5.53E+05
1981	1.55E+05	1.50E+05	2.32E+05	1.42E+04	5.49E+05
1982	1.51E+05	1.50E+05	2.30E+05	1.39E+04	5.46E+05
1983	1.48E+05	1.50E+05	2.29E+05	1.08E+04	5.42E+05
1984	1.45E+05	1.50E+05	2.27E+05	1.23E+04	5.34E+05
1985	1.42E+05	1.50E+05	2.26E+05	1.07E+04	5.33E+05
1986	1.39E+05	1.50E+05	2.32E+05	1.12E+04	5.34E+05
1987	1.35E+05	1.50E+05	2.38E+05	1.17E+04	5.36E+05
1988	1.32E+05	1.50E+05	2.43E+05	1.23E+04	5.41E+05
1989	1.29E+05	1.50E+05	2.49E+05	1.17E+04	5.42E+05
1990	1.22E+05	1.51E+05	2.55E+05	1.13E+04	5.40E+05
1991	1.28E+05	1.51E+05	2.50E+05	1.23E+04	5.43E+05
1992	1.34E+05	1.51E+05	2.94E+05	1.24E+04	5.91E+05
1993	1.40E+05	1.51E+05	1.93E+05	1.34E+04	4.95E+05
1994	1.45E+05	1.51E+05	2.84E+05	1.23E+04	5.95E+05
1995	1.51E+05	1.51E+05	2.38E+05	1.30E+04	5.51E+05
1996	1.57E+05	1.51E+05	2.49E+05	1.48E+04	5.71E+05
1997	1.62E+05	1.55E+05	2.88E+05	1.16E+04	6.17E+05
1998	1.68E+05	1.60E+05	2.68E+05	1.32E+04	6.10E+05
1999	1.74E+05	1.64E+05	2.68E+05	1.47E+04	6.19E+05
2000	1.85E+05	1.68E+05	3.29E+05	1.47E+04	6.95E+05
2001	1.90E+05	1.72E+05	3.25E+05	1.26E+04	7.00E+05
2002	1.94E+05	1.76E+05	2.78E+05	1.37E+04	6.61E+05
2003	1.99E+05	1.80E+05	2.87E+05	1.21E+04	6.81E+05
2004	2.03E+05	1.85E+05	3.03E+05	1.24E+04	7.02E+05
2005	2.12E+05	1.89E+05	3.12E+05	1.31E+04	7.27E+05
2006	2.07E+05	2.39E+05	3.17E+05	1.39E+04	7.76E+05
2007	2.02E+05	2.89E+05	3.14E+05	1.41E+04	8.19E+05
2008	1.96E+05	3.39E+05	3.03E+05	1.52E+04	8.52E+05
2009	1.91E+05	3.89E+05	3.07E+05	1.19E+04	9.02E+05
2010	2.25E+05	4.39E+05	2.69E+05	1.21E+04	9.46E+05
2011	2.29E+05	4.89E+05	3.17E+05	1.16E+04	1.05E+06
2012	2.33E+05	5.39E+05	3.36E+05	1.18E+04	1.12E+06
2013	2.37E+05	5.89E+05	2.76E+05	1.14E+04	1.12E+06
2014	2.45E+05	5.93E+05	2.63E+05	1.09E+04	1.11E+06
2015	2.57E+05	6.09E+05	2.62E+05	1.52E+04	1.14E+06

Table B-6: U.S. Copper Landfilling Data (Tons). Primary, calculated values.

	Landfill (MSW)	Landfill (Transport)	Landfill (C&D)	F7 Total Landfilling
1970	6.35E+04	5.73E+04	1.85E+04	1.39E+05
1971	6.76E+04	5.49E+04	1.85E+04	1.41E+05
1972	7.17E+04	5.25E+04	1.86E+04	1.43E+05
1973	7.59E+04	5.01E+04	1.86E+04	1.45E+05
1974	8.00E+04	4.78E+04	1.86E+04	1.46E+05
1975	8.41E+04	4.54E+04	1.86E+04	1.48E+05
1976	8.82E+04	5.03E+04	1.86E+04	1.57E+05
1977	9.23E+04	5.52E+04	1.86E+04	1.66E+05
1978	9.65E+04	6.01E+04	1.86E+04	1.75E+05
1979	1.01E+05	6.50E+04	1.86E+04	1.84E+05
1980	1.09E+05	6.99E+04	1.86E+04	1.97E+05
1981	1.04E+05	6.95E+04	1.86E+04	1.92E+05
1982	9.93E+04	6.91E+04	1.87E+04	1.87E+05
1983	9.45E+04	6.87E+04	1.87E+04	1.82E+05
1984	8.97E+04	6.82E+04	1.87E+04	1.77E+05
1985	8.49E+04	6.78E+04	1.87E+04	1.71E+05
1986	8.01E+04	6.95E+04	1.87E+04	1.68E+05
1987	7.54E+04	7.13E+04	1.87E+04	1.65E+05
1988	7.06E+04	6.81E+04	1.87E+04	1.57E+05
1989	6.58E+04	6.47E+04	1.87E+04	1.49E+05
1990	5.62E+04	6.11E+04	1.87E+04	1.36E+05
1991	5.92E+04	5.49E+04	1.88E+04	1.33E+05
1992	6.22E+04	5.88E+04	1.88E+04	1.40E+05
1993	6.51E+04	3.48E+04	1.88E+04	1.19E+05
1994	6.81E+04	4.55E+04	1.88E+04	1.32E+05
1995	7.11E+04	3.33E+04	1.88E+04	1.23E+05
1996	7.40E+04	2.98E+04	1.88E+04	1.23E+05
1997	7.70E+04	2.88E+04	1.93E+04	1.25E+05
1998	8.00E+04	2.68E+04	1.99E+04	1.27E+05
1999	8.29E+04	2.68E+04	2.04E+04	1.30E+05
2000	8.89E+04	3.29E+04	2.09E+04	1.43E+05
2001	9.01E+04	3.25E+04	2.14E+04	1.44E+05
2002	9.13E+04	2.78E+04	2.19E+04	1.41E+05
2003	9.25E+04	2.87E+04	2.25E+04	1.44E+05
2004	9.37E+04	3.03E+04	2.30E+04	1.47E+05
2005	9.61E+04	3.13E+04	2.35E+04	1.51E+05
2006	9.19E+04	3.17E+04	2.97E+04	1.53E+05
2007	8.77E+04	3.14E+04	3.60E+04	1.55E+05
2008	8.34E+04	3.03E+04	4.22E+04	1.56E+05
2009	7.92E+04	3.07E+04	4.84E+04	1.58E+05
2010	9.43E+04	2.69E+04	5.46E+04	1.76E+05
2011	9.83E+04	3.17E+04	6.09E+04	1.91E+05
2012	1.02E+05	3.36E+04	6.71E+04	2.03E+05
2013	1.06E+05	2.76E+04	7.33E+04	2.07E+05
2014	1.14E+05	2.63E+04	7.39E+04	2.14E+05
2015	1.20E+05	2.62E+04	7.58E+04	2.22E+05

Reported values from the USGS in Tables B-1 to B-4 were validated against Copper Development Association Annual Data[6] and International Copper Study Group reports[7]

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APPENDIX C Supporting Information for Chapter 4- An Assessment of the Environmental Sustainability and Circularity of Future Scenarios of the Copper Life Cycle in the U.S.

This appendix provides the supporting information for Chapter 4. Historical data in Tables C-1 and C-2 have complete references at the end of this section. Driver projections and relevant calculation information are included in Table C-3, Figure C-1, and Table C-4. Complete calculated material flow forecast data are included in Tables C-5-10.

Table C-1: Historical Material Flow Driver Data and Sources, 1970-2015

	USCB (2012)	UNSD (2019)	USGS (2017)	USCB (2012)	World Bank (2019)	UNPD (2018)	World Bank (2017)
Year	**Population (10^6 people)**	**DMC (10^6 tonnes)**	**Copper Price (cents/lb)**	**Pop density (people/ mi^2)**	**Manufacturing (%GDP)**	**Urbanization (% of Pop)**	**GDP (Billion 2010 US$)**
1970	205.1	39,208	58.07	22.39	23.40	73.60	1,076
1971	207.7	38,717	52.09	22.67	22.70	73.61	1,168
1972	209.9	38,225	51.44	22.92	22.80	73.62	1,282
1973	211.9	37,734	59.49	23.14	22.80	73.63	1,429
1974	213.9	37,243	77.27	23.35	22.00	73.64	1,549
1975	216.0	36,751	64.16	23.58	21.20	73.65	1,689
1976	218.0	36,260	69.59	23.81	21.80	73.66	1,878
1977	220.2	35,769	66.77	24.05	22.30	73.67	2,086
1978	222.6	35,277	65.81	24.30	22.10	73.68	2,357
1979	225.1	34,786	92.19	24.57	21.90	73.69	2,632
1980	227.7	34,295	101.31	24.81	20.60	73.74	2,863
1981	230.0	33,803	84.21	25.05	20.50	73.89	3,211
1982	232.2	33,312	72.80	25.29	19.60	74.04	3,345
1983	234.3	32,821	76.53	25.53	19.10	74.19	3,638
1984	236.3	32,329	66.85	25.75	19.50	74.34	4,041
1985	238.5	31,838	66.97	25.98	18.60	74.49	4,347
1986	240.7	31,347	66.05	26.22	18.30	74.64	4,590
1987	242.8	30,855	82.50	26.45	18.20	74.79	4,870
1988	245.0	30,364	120.51	26.70	18.70	74.94	5,253
1989	247.3	29,873	130.95	26.95	18.00	75.09	5,658
1990	250.1	29,381	123.16	27.25	17.40	75.30	5,980
1991	253.5	28,890	109.33	27.62	16.90	75.70	6,174
1992	256.9	28,399	107.42	28.01	16.50	76.10	6,539
1993	260.3	27,908	91.56	28.38	16.40	76.49	6,879
1994	263.4	27,416	111.05	28.73	16.70	76.88	7,309
1995	266.6	26,925	138.33	29.07	16.80	77.26	7,664
1996	269.7	26,434	109.04	29.41	16.20	77.64	8,100
1997	272.9	25,942	106.92	29.77	16.02	78.01	8,609
1998	276.1	25,451	78.64	30.12	15.67	78.38	9,089
1999	279.3	24,960	75.91	30.47	15.35	78.74	9,661
2000	282.4	24,468	88.16	30.80	15.01	79.06	10,285
2001	285.3	24,204	76.85	31.10	13.81	79.23	10,622
2002	288.1	23,655	75.80	31.39	13.30	79.41	10,978
2003	290.8	23,668	85.01	31.66	13.19	79.58	11,511
2004	293.5	25,038	134.20	31.96	13.08	79.76	12,275
2005	296.2	25,879	173.57	32.25	12.91	79.93	13,094
2006	299.0	25,437	314.75	32.57	12.92	80.10	13,856
2007	302.0	24,009	328.00	32.88	12.71	80.27	14,478
2008	304.8	22,450	319.16	33.24	12.23	80.44	14,719
2009	307.4	19,878	241.38	33.54	11.82	80.61	14,419
2010	310.2	20,316	348.34	33.82	12.08	80.77	14,964
2011	313.2	20,099	405.90	34.07	11.79	80.94	15,204
2012	314.2	18,206	367.30	34.33	11.49	81.12	15,542
2013	315.1	18,758	339.90	34.57	11.19	81.30	15,803
2014	317.3	18,970	318.10	34.83	10.90	81.48	16,209
2015	319.7	18,548	256.20	35.10	10.60	81.67	16,673

Table C-2: Historical Copper Material Flow Data, 1970-2015 in metric tons
Data from Gorman and Dzombak (2019)

Year	1. Primary Production	2. Apparent Consumption	3. Old Scrap Collected	4. Landfill	5. Net Scrap Exports	6. New Scrap
1970	1,600,000	1,820,000	385,600	139,276	76,451	675,000
1971	1,440,000	1,890,000	389,319	141,033	49,541	685,000
1972	1,700,000	2,140,000	390,059	142,790	38,625	765,000
1973	1,700,000	2,220,000	389,567	144,547	78,755	808,000
1974	1,500,000	2,150,000	387,909	146,304	69,460	781,000
1975	1,310,000	1,470,000	391,239	148,062	80,976	547,000
1976	1,400,000	1,920,000	405,917	157,109	52,573	659,000
1977	1,360,000	2,070,000	426,098	166,157	56,564	675,000
1978	1,450,000	2,370,000	443,305	175,205	89,807	746,000
1979	1,520,000	2,430,000	460,475	184,253	100,490	948,000
1980	1,220,000	2,180,000	483,177	197,423	115,817	824,000
1981	1,540,000	2,270,000	479,677	192,227	77,397	816,000
1982	1,230,000	1,760,000	475,140	187,030	78,651	670,000
1983	1,210,000	2,010,000	471,448	181,833	45,649	634,000
1984	1,170,000	2,120,000	465,393	176,637	96,204	659,000
1985	1,060,000	2,140,000	463,796	171,440	178,930	636,000
1986	1,070,000	2,140,000	465,340	168,385	179,217	649,000
1987	1,130,000	2,200,000	464,341	165,331	162,975	716,000
1988	1,410,000	2,210,000	470,308	157,411	176,468	789,000
1989	1,480,000	2,180,000	478,671	149,263	218,928	761,000
1990	1,580,000	2,170,000	478,240	136,103	158,683	775,000
1991	1,580,000	2,090,000	485,246	132,860	156,899	667,000
1992	1,710,000	2,310,000	531,041	139,731	98,553	722,000
1993	1,790,000	2,510,000	462,150	118,748	121,689	748,000
1994	1,840,000	2,680,000	546,246	132,415	152,874	827,000
1995	1,930,000	2,540,000	520,519	123,145	242,267	874,000
1996	2,010,000	2,830,000	539,549	122,694	159,400	891,000
1997	2,070,000	2,940,000	587,992	125,117	152,180	967,000
1998	2,140,000	3,030,000	583,732	126,667	104,000	956,000
1999	1,890,000	3,130,000	592,439	130,155	142,000	949,000
2000	1,580,000	3,090,000	660,990	142,675	283,000	955,000
2001	1,630,000	2,510,000	668,957	144,000	347,900	833,000
2002	1,440,000	2,590,000	632,204	141,074	326,700	842,000
2003	1,250,000	2,430,000	650,786	143,684	487,300	737,000
2004	1,260,000	2,550,000	672,093	146,977	498,200	774,000
2005	1,210,000	2,420,000	696,274	150,906	465,700	769,000
2006	1,210,000	2,200,000	744,675	153,301	570,400	819,000
2007	1,270,000	2,270,000	785,718	155,024	592,000	772,000
2008	1,220,000	2,000,000	820,084	155,969	602,300	700,000
2009	1,110,000	1,580,000	870,879	158,340	576,700	639,000
2010	1,060,000	1,760,000	918,034	175,911	713,000	642,000
2011	992,000	1,730,000	1,015,049	190,871	896,500	649,000
2012	962,000	1,760,000	1,088,729	203,017	857,200	642,000
2013	993,000	1,750,000	1,089,288	207,258	823,300	630,000
2014	1,050,000	1,780,000	1,086,290	214,480	736,400	672,000
2015	1,090,000	1,820,000	1,116,774	221,746	681,600	638,000

Table C-3: Projected Material Flow Driver Data Ranges and Sources (2016-2030)

	Population (10^6 people)	DMC (10^6 tonnes)	Copper Price (cents/pound)	Mfg% (%GDP)	Urbanization (% of Pop)	GDP (Billion 2010 US$)
EXPECTED PROJECTION						
Source:	USCB(2017)	Linear	World Bank (2019)	Linear	UNPD (2018)	USDA (2018)
2016	323.1	18,094	225	10.30	81.86	16,920
2017	325.5	17,656	285	10.01	82.06	17,305
2018	327.9	17,165	300	9.71	82.27	17,832
2019	330.3	16,673	294	9.41	82.49	18,343
2020	332.6	16,182	303	9.12	82.70	18,701
2021	335.0	15,691	304	8.82	82.90	19,019
2022	337.3	15,199	306	8.52	83.10	19,342
2023	339.7	14,708	307	8.23	83.30	19,709
2024	342.0	14,217	308	7.93	83.50	20,084
2025	344.2	13,725	310	7.64	83.70	20,465
2026	346.5	13,234	311	7.34	83.94	20,854
2027	348.7	12,743	313	7.04	84.18	21,251
2028	350.9	12,251	314	6.75	84.42	21,654
2029	353.0	11,760	315	6.45	84.66	22,066
2030	355.1	11,269	318	6.15	84.90	22,485
LOW RATE-OF-CHANGE PROJECTION						
Source:	UNPD(2019)	95% CI	N/A	95% CI	N/A	OECD (2019)
2016	321.26	18,094		10.32		16,920
2017	322.61	17,656		10.03		17,304
2018	323.95	17,036		9.75		17,799
2019	325.29	16,416		9.46		18,293
2020	326.61	15,797		9.18		18,587
2021	327.91	15,177		8.90		18,850
2022	329.17	14,557		8.61		19,125
2023	330.40	13,937		8.33		19,422
2024	331.58	13,318		8.04		19,741
2025	332.72	12,698		7.76		20,076
2026	333.80	12,078		7.48		20,424
2027	334.83	11,458		7.19		20,784
2028	335.80	10,839		6.91		21,153
2029	336.70	10,219		6.62		21,531
2030	337.54	9,599		6.34		21,916
HIGH RATE-OF-CHANGE PROJECTION						
Source:	UNPD(2019)	95% CI		95% CI		OECD, 2019
2016	322.49	18,094	N/A	10.29	N/A	Same as Expected Projection
2017	325.22	17,656		9.98		
2018	328.09	17,293		9.67		
2019	331.08	16,930		9.36		
2020	334.15	16,567		9.05		
2021	337.29	16,204		8.75		
2022	340.50	15,841		8.44		
2023	343.77	15,479		8.13		
2024	347.09	15,116		7.82		
2025	350.47	14,753		7.51		
2026	353.90	14,390		7.20		
2027	357.35	14,027		6.89		
2028	360.81	13,664		6.58		
2029	364.24	13,301		6.27		
2030	367.63	12,938		5.96		

Figure C-1: Q-Q Plots -Logistically Transformed Material Flow Drivers and their Respective Inverse CDFs

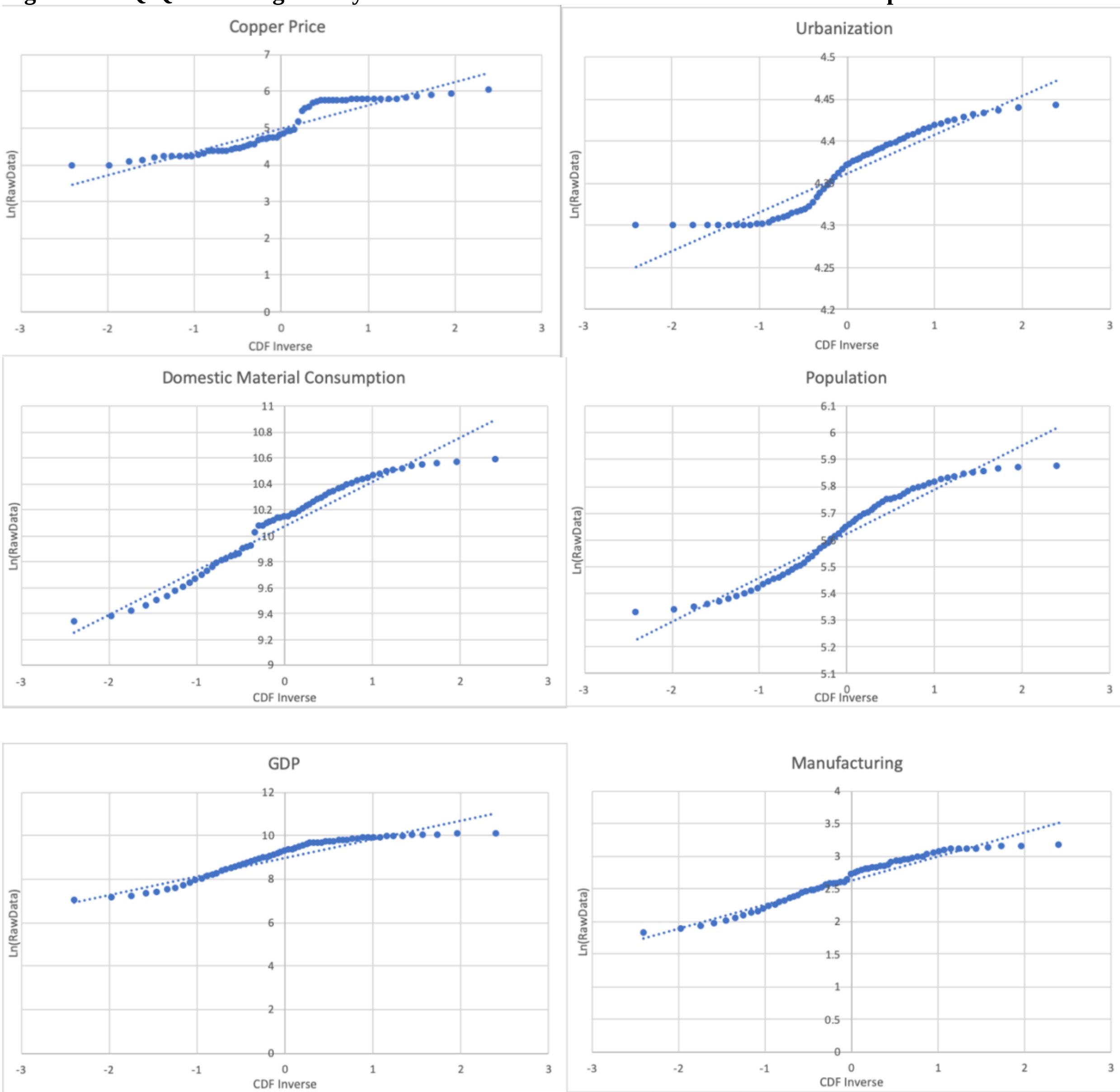

Table C-4: Logistically Transformed Material Flow Driver Correlation Coefficients. The threshold for rejection is $\alpha = 0.1$, or correlation coefficients < 0.9.

	Correlation Coefficient
Population Density	0.9746
Copper Price	0.9319
Domestic Material Consumption	0.9750
Population	0.9720
Manufacturing	0.9746
Urbanization	0.9537
GDP	0.9515

Table C-5: Scenario FS1 Forecasts of Material Flows (Values are in Thousand Metric Tons/Year)

Year	1. Primary Production	2. Apparent Consumption	3. EoL Collection	4. Landfilled Scrap	5. Scrap Exports	6. New Scrap	C7. Front End Imports	C8. Available Scrap
2015	1017	1849	1093	218	1072	615	1028	419
2016	1033	1904	1126	219	1240	554	1203	221
2017	1062	1812	1233	235	1282	563	1033	279
2018	1146	1880	1277	243	1299	554	1001	288
2019	1234	1973	1307	251	1315	540	997	282
2020	1327	2036	1379	263	1328	531	921	319
2021	1373	2022	1454	276	1358	521	829	341
2022	1420	1997	1534	290	1385	512	719	371
2023	1466	1960	1611	305	1408	504	595	402
2024	1513	1910	1691	320	1427	497	453	441
2025	1559	1848	1777	336	1441	492	290	490
2026	1784	1975	1865	354	1394	487	73	605
2027	2038	2092	1958	372	1342	483	-190	727
2028	2324	2195	2056	392	1288	481	-505	857
2029	2647	2281	2158	414	1230	480	-880	994
2030	3010	2343	2267	437	1170	480	-1327	1141

Table C-6: Scenario FS2 Forecasts of Material Flows (Values are in Thousand Metric Tons/Year)

Year	1. Primary Production	2. Apparent Consumption	3. EoL Collection	4. Landfilled Scrap	5. Scrap Exports	6. New Scrap	C7. Front End Imports	C8. Available Scrap
2015	1017	1849	1093	218	1072	615	1028	419
2016	1069	1979	1126	229	1015	613	1029	494
2017	1122	1932	1233	252	941	658	769	699
2018	1177	1971	1282	268	871	685	652	828
2019	1233	2035	1315	283	806	705	577	931
2020	1290	2068	1397	306	745	732	432	1079
2021	1348	2103	1483	330	687	759	289	1225
2022	1407	2127	1572	357	631	787	135	1372
2023	1468	2139	1663	385	578	819	-28	1519
2024	1529	2140	1756	416	527	854	-202	1667
2025	1591	2127	1852	450	478	893	-389	1818
2026	1654	2101	1951	486	432	937	-587	1970
2027	1717	2061	2055	526	388	985	-797	2126
2028	1781	2007	2163	570	347	1039	-1021	2286
2029	1846	1940	2276	618	308	1101	-1256	2451
2030	1911	1857	2397	672	272	1170	-1507	2623

Table C-7: Scenario FS3 Forecasts of Material Flows (Values are in Thousand Metric Tons/Year)

Year	1. Primary Production	2. Apparent Consumption	3. EoL Collection	4. Landfilled Scrap	5. Scrap Exports	6. New Scrap	C7. Front End Imports	C8. Available Scrap
2015	1017	1849	1093	218	1072	615	1028	419
2016	1117	2049	1126	222	1129	573	1159	348
2017	1224	2070	1233	237	1180	571	1030	388
2018	1339	2157	1277	242	1248	548	1031	335
2019	1464	2269	1307	246	1331	517	1075	247
2020	1598	2346	1379	254	1430	491	1053	185
2021	1743	2422	1454	262	1544	462	1031	110
2022	1897	2483	1534	270	1673	435	995	25
2023	2063	2525	1611	278	1819	408	948	-77
2024	2241	2548	1691	285	1983	383	884	-194
2025	2430	2547	1777	293	2167	359	801	-325
2026	2632	2524	1865	300	2373	336	700	-473
2027	2848	2475	1958	308	2600	314	576	-635
2028	3077	2400	2056	316	2842	295	425	-808
2029	3321	2300	2158	325	3092	277	238	-982
2030	3579	2173	2267	335	3342	261	3	-1148

Table C-8: Scenario FS4 Forecasts of Material Flows (Values are in Thousand Metric Tons/Year)

Year	1. Primary Production	2. Apparent Consumption	3. EoL Collection	4. Landfilled Scrap	5. Scrap Exports	6. New Scrap	C7. Front End Imports	C8. Available Scrap
2015	1017	1849	1093	218	1072	615	1028	419
2016	1117	1895	1126	229	999	613	881	511
2017	1224	1796	1233	252	910	658	501	730
2018	1339	1854	1277	267	829	685	335	865
2019	1464	1936	1307	282	755	705	201	976
2020	1598	1986	1379	303	686	732	-2	1122
2021	1743	1961	1454	326	622	759	-288	1265
2022	1897	1924	1534	351	563	787	-594	1408
2023	2063	1875	1611	377	507	819	-915	1546
2024	2241	1814	1691	406	455	854	-1257	1685
2025	2430	1741	1777	437	406	893	-1622	1826
2026	2632	1844	1865	471	361	937	-1821	1969
2027	2848	1935	1958	509	320	985	-2042	2115
2028	3077	2010	2056	550	281	1039	-2291	2264
2029	3321	2065	2158	596	246	1101	-2572	2417
2030	3579	2095	2267	647	214	1170	-2891	2577

Table C-9: Scenario FS5 Forecasts of Material Flows (Values are in Thousand Metric Tons/Year)

Year	1. Primary Production	2. Apparent Consumption	3. EoL Collection	4. Landfilled Scrap	5. Scrap Exports	6. New Scrap	C7. Front End Imports	C8. Available Scrap
2015	1017	1849	1093	218	1072	615	1028	419
2016	1033	1904	1126	219	1240	554	1203	221
2017	1062	1812	1233	235	1282	563	1033	279
2018	1146	1892	1277	244	1299	554	1013	287
2019	1234	1999	1307	252	1315	540	1024	281
2020	1327	2077	1379	265	1328	531	965	317
2021	1373	2079	1454	280	1358	521	889	338
2022	1420	2069	1534	295	1385	512	796	366
2023	1466	2048	1611	311	1408	504	690	395
2024	1513	2014	1691	328	1427	497	565	433
2025	1559	1967	1777	346	1441	492	418	481
2026	1784	2122	1865	365	1394	487	231	594
2027	2038	2272	1958	385	1342	483	3	715
2028	2324	2411	2056	406	1288	481	-275	843
2029	2647	2536	2158	429	1230	480	-610	979
2030	3010	2639	2267	454	1170	480	-1015	1124

Table C-10: Scenario FS6 Forecasts of Material Flows (Values are in Thousand Metric Tons/Year)

Year	1. Primary Production	2. Apparent Consumption	3. EoL Collection	4. Landfilled Scrap	5. Scrap Exports	6. New Scrap	C7. Front End Imports	C8. Available Scrap
2015	1017	1849	1093	218	1072	615	1028	419
2016	1033	1904	1126	219	1240	554	1203	221
2017	1062	1812	1233	235	1282	563	1033	279
2018	1146	1868	1282	243	1299	554	983	293
2019	1234	1947	1315	251	1315	540	963	290
2020	1327	1994	1397	263	1328	531	861	337
2021	1373	1965	1483	276	1358	521	743	370
2022	1420	1924	1572	290	1385	512	608	409
2023	1466	1871	1663	305	1408	504	455	454
2024	1513	1806	1756	320	1427	497	284	506
2025	1559	1729	1852	336	1441	492	95	566
2026	1784	1826	1951	354	1394	487	-163	691
2027	2038	1909	2055	372	1342	483	-469	824
2028	2324	1976	2163	392	1288	481	-832	964
2029	2647	2021	2276	414	1230	480	-1258	1112
2030	3010	2041	2397	437	1170	480	-1759	1270

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