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Stocks and flows of copper in the U.S.: Analysis of circularity 1970–2015 and potential for increased recovery

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ABSTRACT

An analysis of the copper life cycle in the U.S. was performed to investigate the circularity of copper from 1970 to 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.

1. 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, 2013a,b). 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, 2011). 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.

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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, 2013a,b). 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, 2013a,b) and up to 65% for water (Gunson et al., 2012; Reuter, 2013a,b). Additionally, whereas an average of more than 120 tons[1] 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 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, 2013a,b; 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; Mosbergen, 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.

2. Research methodology

2.1. 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 Fig. 1. The relevant key operations are shown geographically in Fig. 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 Fig. 1 (manufacturing, use, end-of-life, and waste disposal) are distributed throughout the U.S. and therefore not indicated on the map in Fig. 2.

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. Fig. 3 presents the framework

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

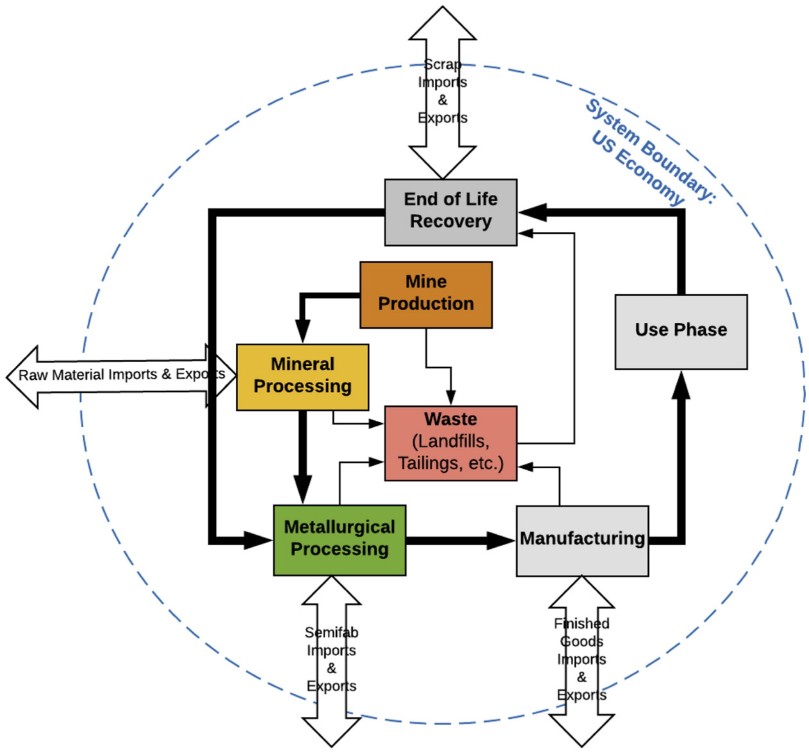

Fig. 1. Complete life cycle stocks and flows of metals in the U.S.

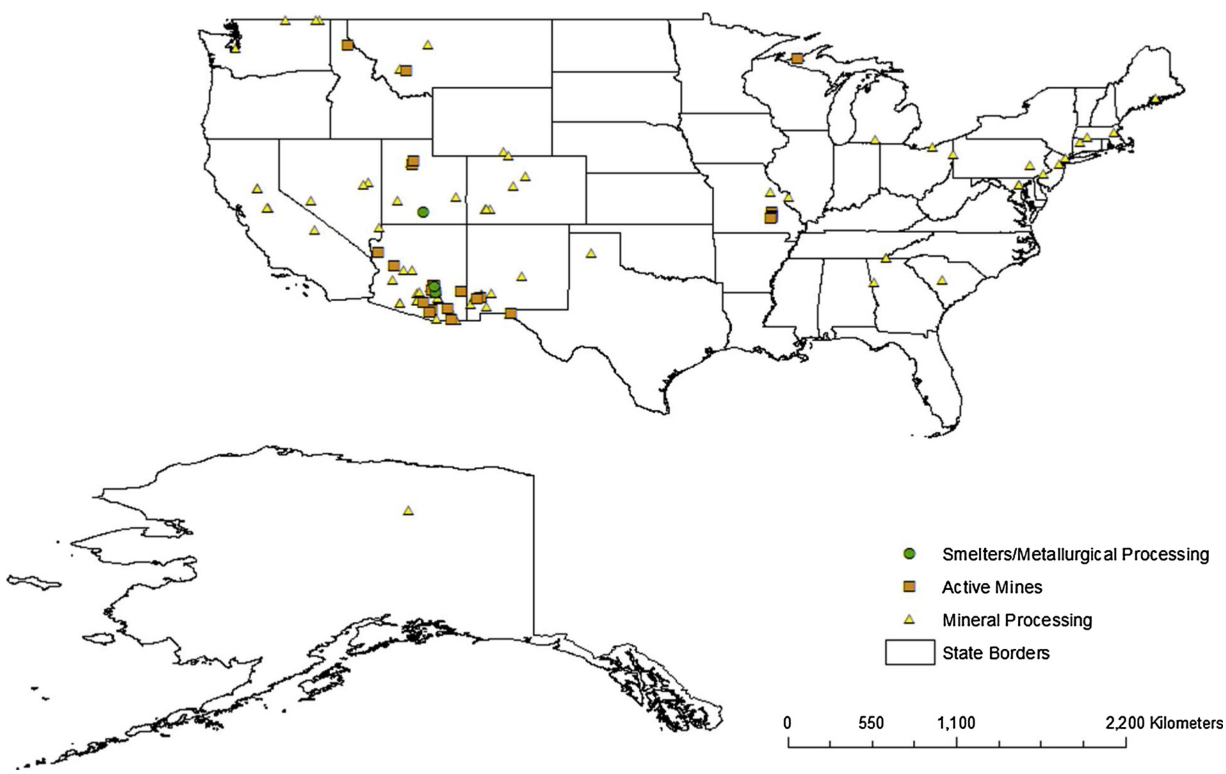

Fig. 2. Locations of key copper operations in the United States (2017).

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. Fig. 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.

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

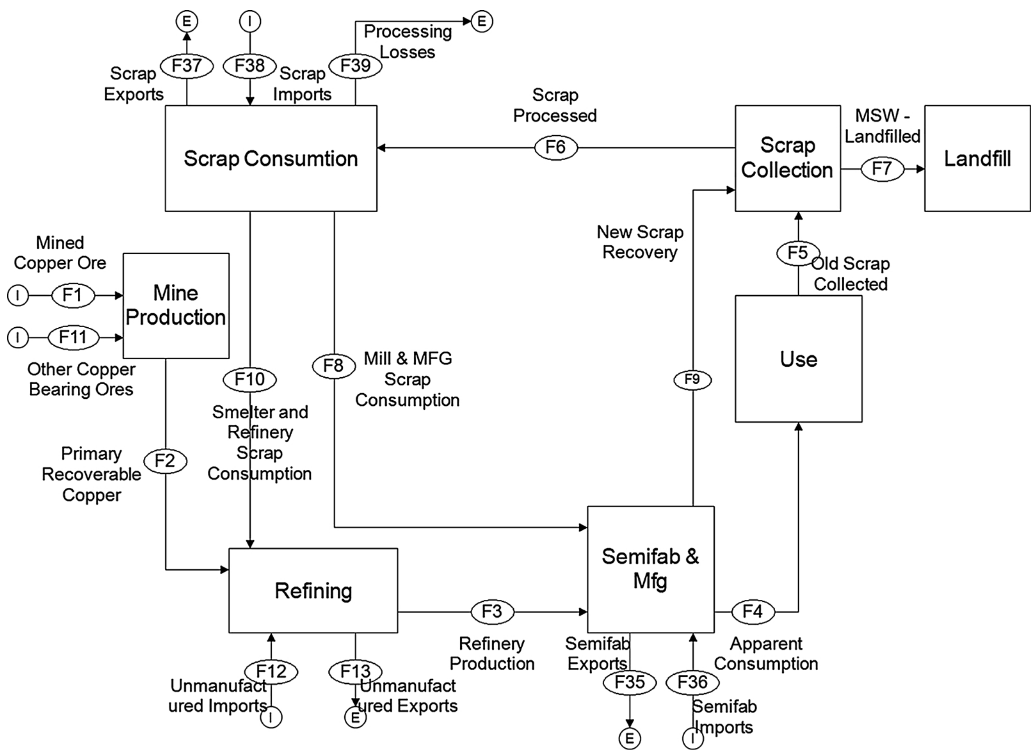

Fig. 3. Framework for copper flows in the U.S. Flows labeled F1–F36 are uniquely numbered flows that indicate mass exchanges between life cycle phases or stocks (shown as the boxes). Flows with I or E at the end indicate Imports and Exports, respectively, into or out of the U.S. system boundary that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

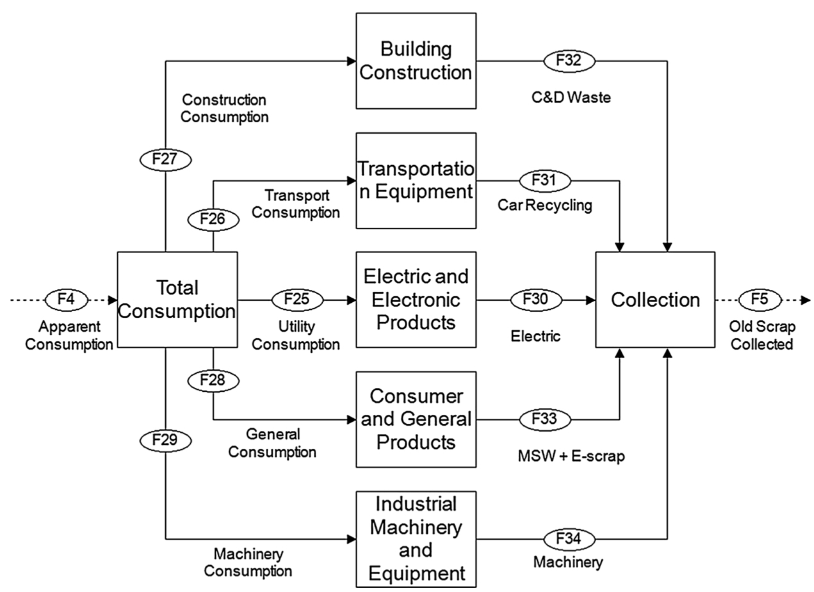

Fig. 4. Use-phase stocks and flows framework. Flows labeled F1–F36 are uniquely numbered flows that indicate mass exchanges between life cycle phases or stocks (shown as the boxes). Flows with I or E at the end indicate Imports and Exports, respectively, into or out of the U.S. system boundary that is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

phase sub-system which is relevant to this analysis are available in the Supplemental Information). F6, Scrap Processed, is a calculated flow based on scrap collection and recovery data as well as landfilling data:

$$F_6 = \Sigma F_{in} - \Sigma F_{out} = F_5 + F_9 - F_7 \tag{1}$$

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

$$\Delta Stock_{year} = \Sigma F_{in,year} - \Sigma F_{out,\,year} \tag{2}$$

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:

$$F_{39} = \Sigma F_{in} - \Sigma F_{out} = F_6 + F_{38} - F_{37} - F_8 - F_{10} \tag{3}$$

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.

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

Collection of data for most major flows in Fig. 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 Fig. 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 Fig. 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.

The framework of Fig. 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 Fig. 4) are necessary for detailed modeling. As is illustrated in Fig. 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.

2.3. 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 Fig. 6. The categories for use phase collection were determined using the USGS data series 140 categorization of copper use phases (USGS, 2005).

For each of the five categories shown in Fig. 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 the Supplemental Information: uncertainty ranges were calculated for each use phase, described in the following sections and reported in Table SI-5. Data reported in the Supplemental Information and used for calculations and results are averages within these ranges.

2.3.1. 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, 2019) 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 Fig. 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 et al. (2016) 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

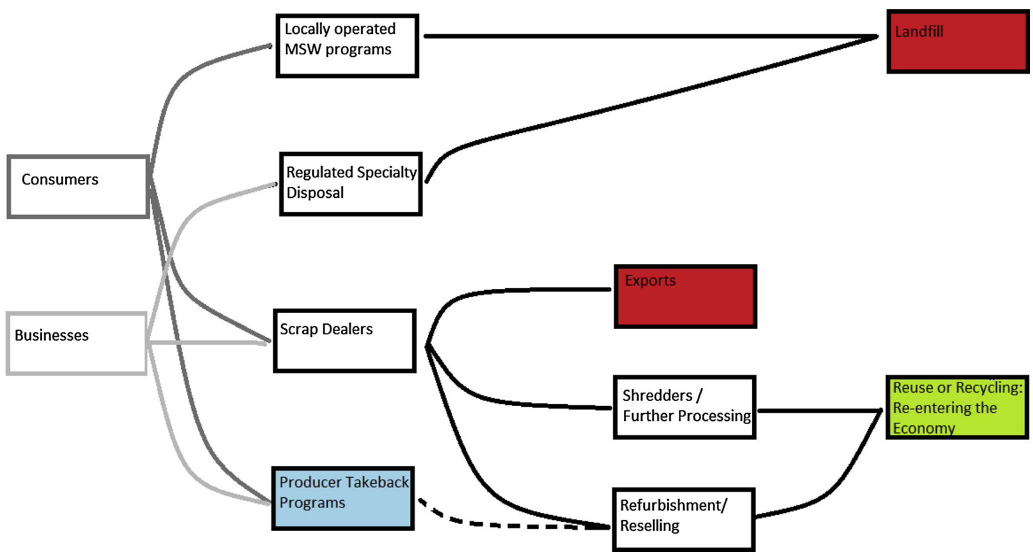

Fig. 5. End-of-Life Ecosystem for Copper-Bearing Goods and Materials. Colored boxes represent fate of collected materials, with red showing losses to the U.S. circular economy, green being re-entry of materials to the U.S. circular economy, and blue being partial re-entry and partial continued processing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

&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.

2.3.2. 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 90 s (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

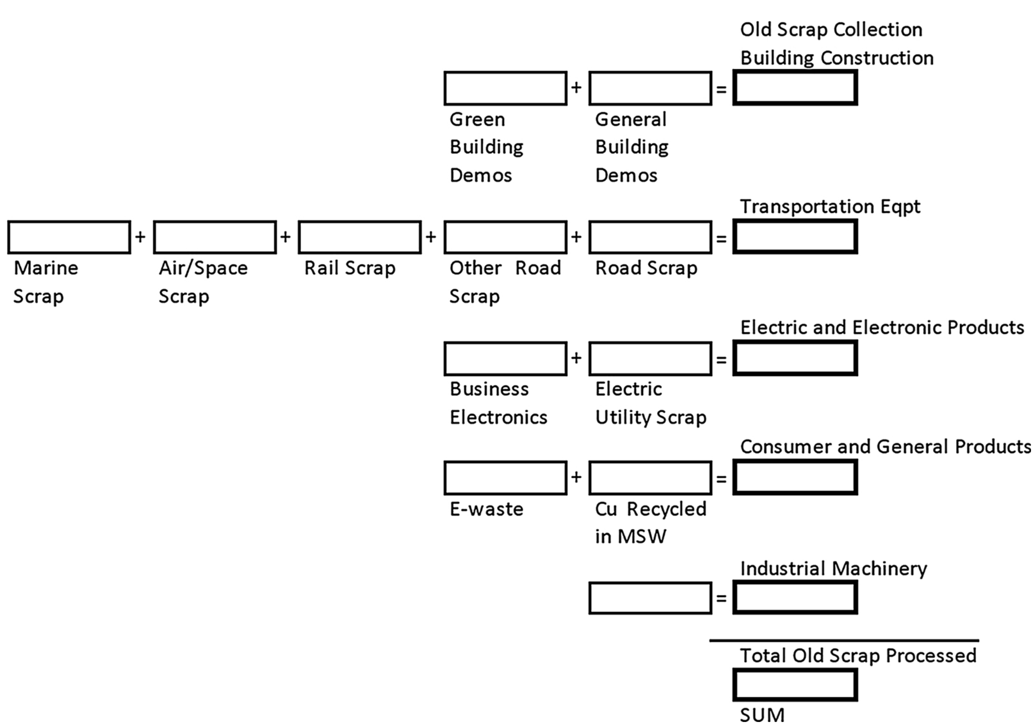

Fig. 6. Synthesis of discrete data sources for end-of-life collection analysis for copper.

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.

2.3.3. 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.

2.3.4. 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 et al. (2016) study which suggests that total MSW landfilling in the US is almost twice that published by the EPA. Reported values in the Supplemental Information 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.

2.3.5. 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 (Fig. 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 Fig. 4 to follow the structure shown in Fig. 7.

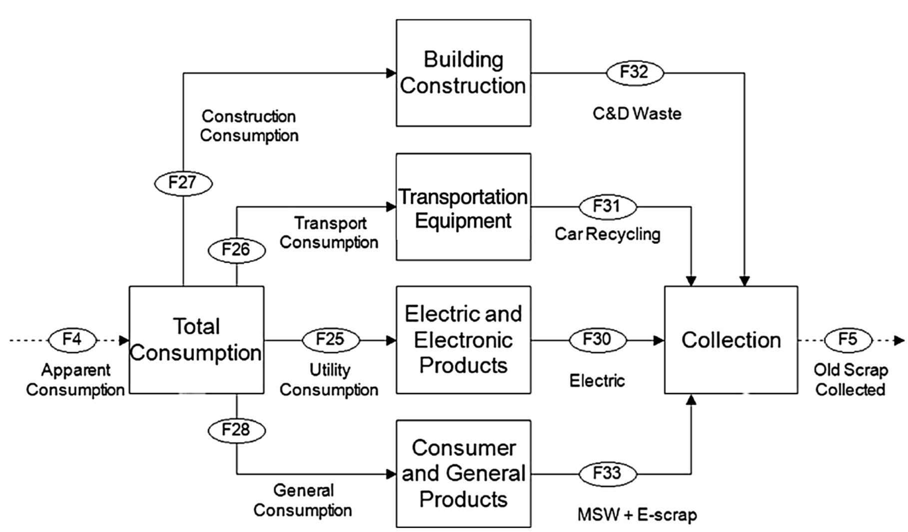

Fig. 7. Use-phase stocks and flows framework, adjusted to show the distribution of industrial machinery between the other use phases.

2.4. 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 to 1, with 1 being the most circular material management (Ellen Macarthur Foundation, Granta Design, 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. Results and discussion

3.1. 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 the Supplemental Information. Fig. 8 shows primary – from virgin materials – and secondary – from recycled materials – production and consumption of copper in the U.S. from 1970 to 2015 (data from Table SI-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 SI-2) and 3000 tons of net imports of unrefined copper (Table SI-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 Fig. 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 Fig. 9, which shows copper scrap imports to and exports from the U.S. (from Table SI-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

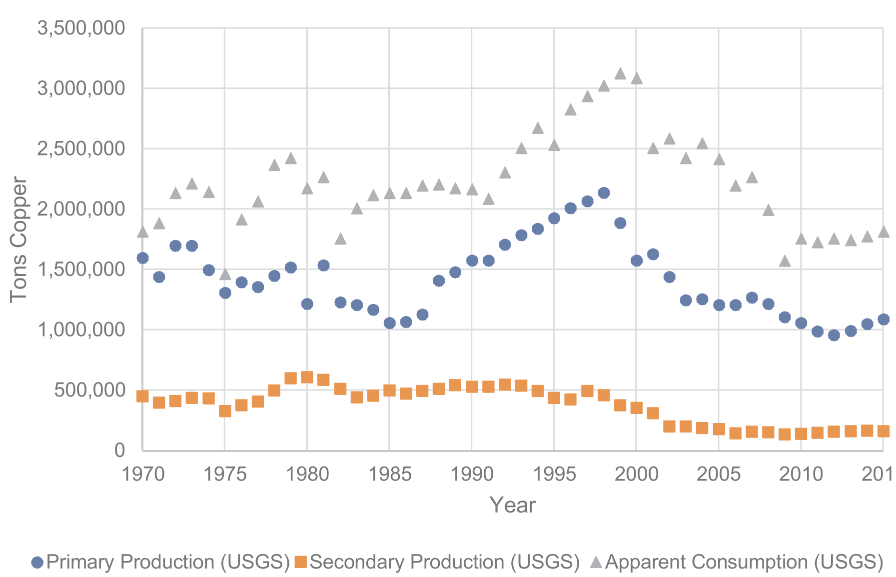

Fig. 8. U.S. copper production and consumption trends, 1970–2015 (tons). Data from multiple sources; see Table SI-2.

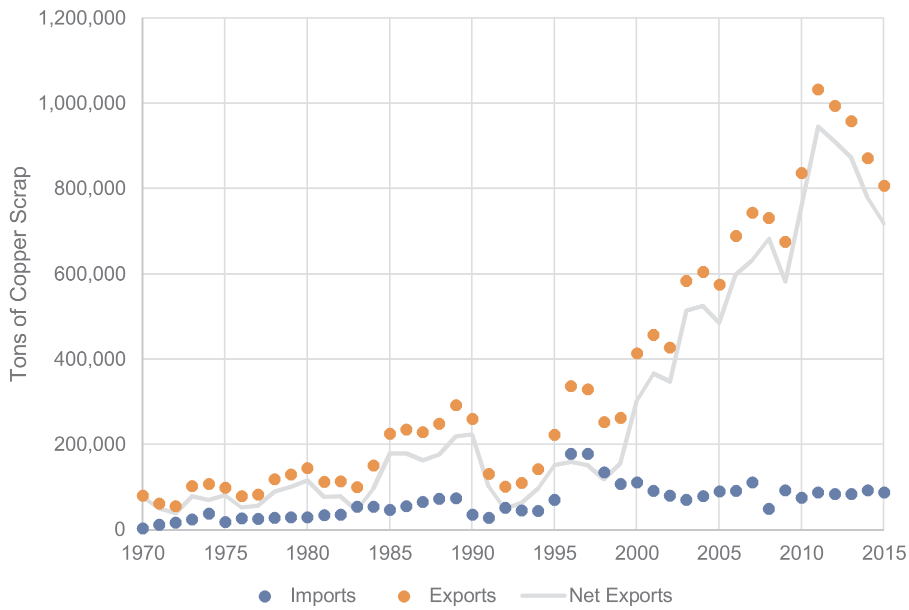

Fig. 9. Copper scrap imports and exports from the U.S., 1998–2015 (tons). Data from multiple sources; see Table SI-4.

commodity metals.

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. Fig. 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 (Krausmann et al., 2009). As the U.S. per capita copper consumption trend in Fig. 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.

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 SI-1 to SI-6). Based on processing loss rates of copper refining, approximately 7 million tons of copper accumulated in tailings from 1970 to 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 SI-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, 2013a,b). This suggests that given the current state of the copper life cycle in the U.S.,

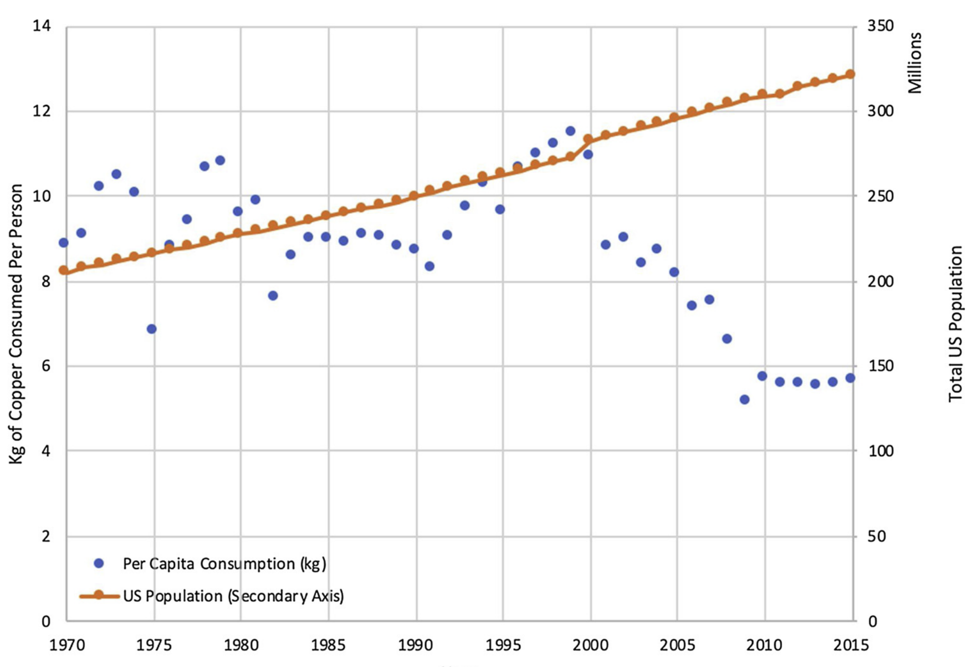

Fig. 10. Per capita copper consumption in the U.S. 1970–2015 (kg) and Total U.S. Population. Data calculated from USGS Minerals Yearbooks (USGS, 2019) and US Census Bureau (USCB, 2018).

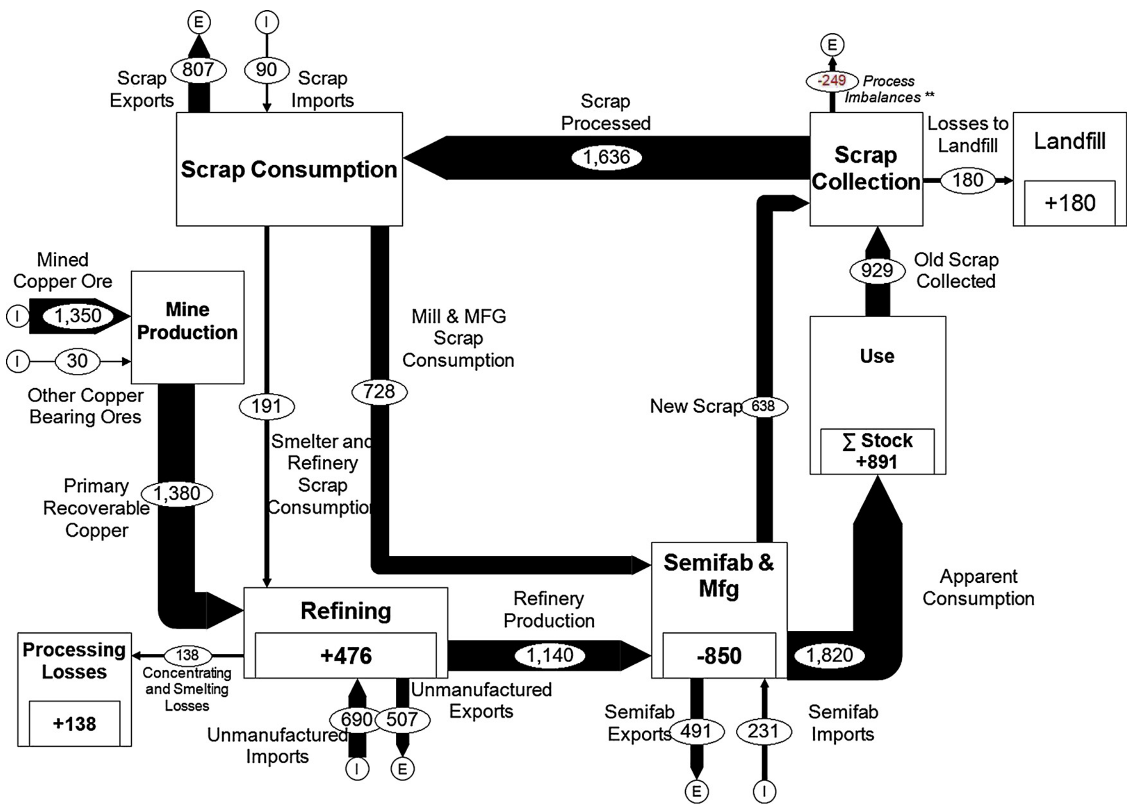

Fig. 11. Stocks and flows of copper in the U.S. economy (in thousand metric tons) in year 2015.The total dynamic materials flow analysis is graphically represented in Fig. 12, where the data for each year (1970–2015) of the data series for each flow have been summed. All flows shown are collected data;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

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 Fig. 11. This shows the most recent year of collected data in this study (2015), which can be contrasted with Fig. 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.

These stocks and flows diagrams, and the data used to produce them in the 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., 2004), 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.

3.2. *Use-phase results*

A look at the subsystem comprising the use phases for copper is shown in Fig. 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 SI-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

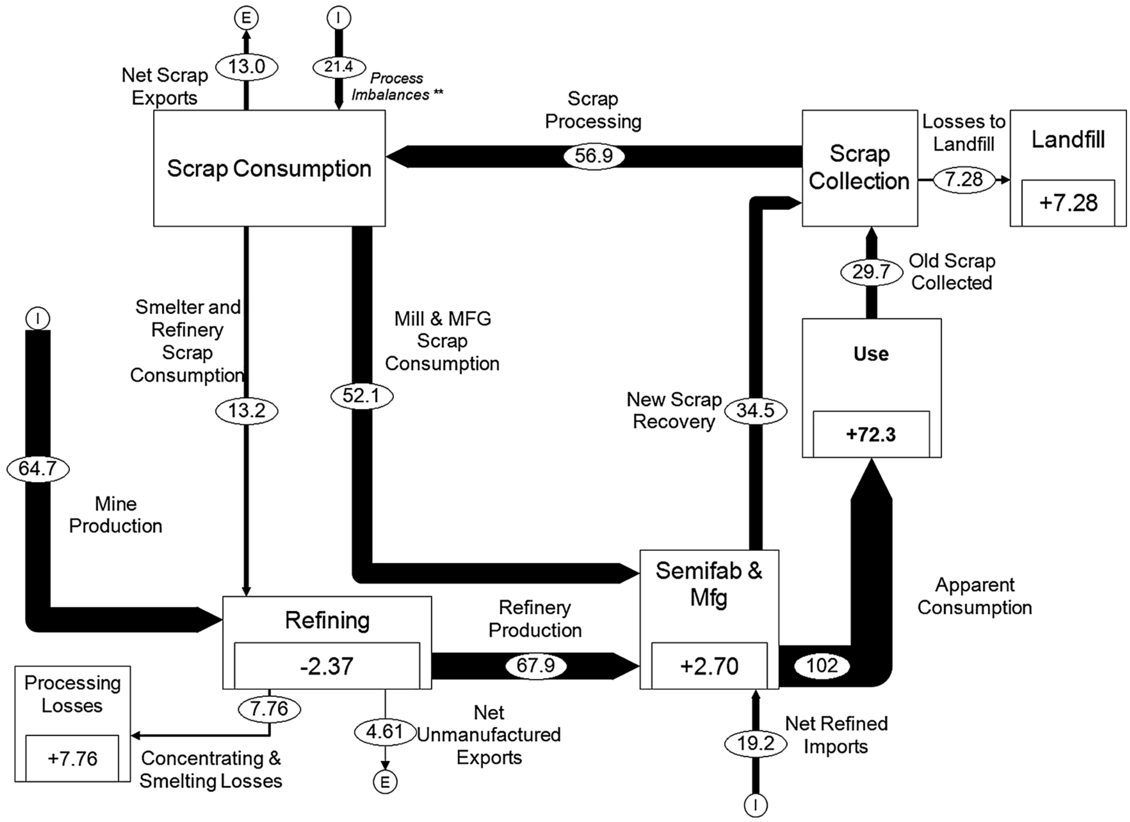

Fig. 12. Total dynamic stocks and flows of copper in the U.S. economy (in million metric tons), from 1970 to 2015. All flows shown are collected data; the only calculated values are stocks and process imbalances, marked**.

copper accumulated among the use phases from 1970 to 2015, over 38 million tons have accumulated in buildings and infrastructure. The second highest accumulation from 1970 to 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.

The lifetime of materials in building construction and electric utilities is long, but as is shown in Fig. 14, consumption of copper by both of these sectors has slowed significantly since 2000, which means that

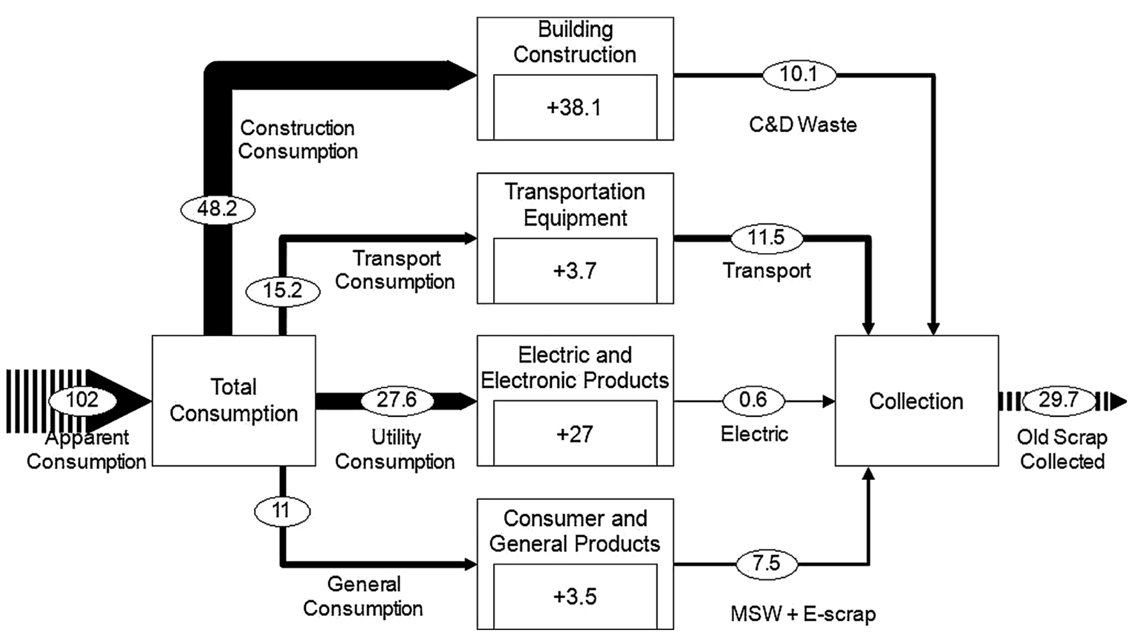

Fig. 13. U.S. Cumulative use-phase subsystem stocks and flows (in thousand metric tons) for 1970–2015.

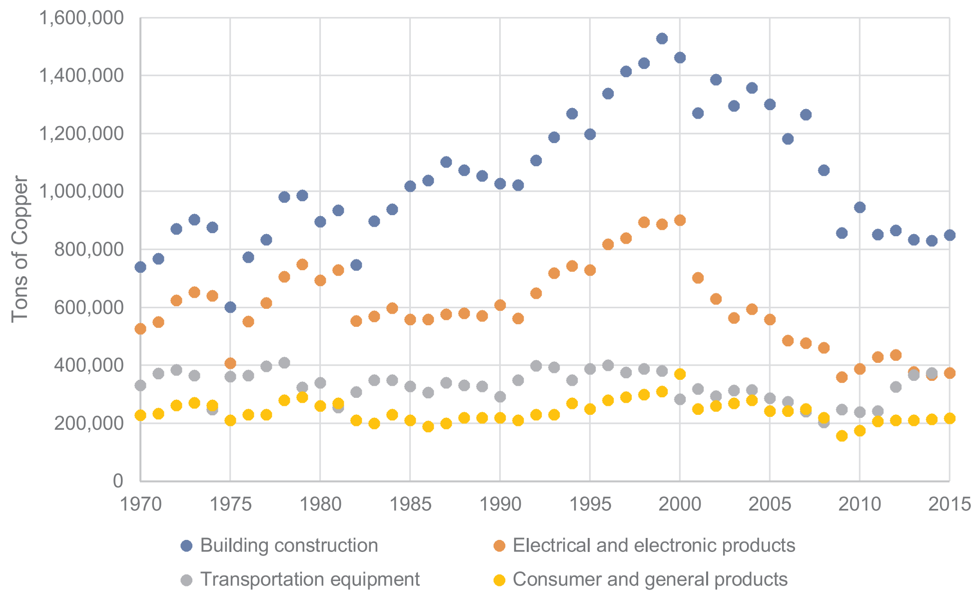

Fig. 14. Historical trends in U.S. copper use-phase consumption by sector: building construction, electric utilities, transportation equipment, and consumer and general goods.

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, 2013a,b). Thus, improving collection from building infrastructure and electric utilities is likely to be the most profitable for secondary copper processors.

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 Fig. 13, it is important to note that in 2015 of the 257 thousand tons of copper collected, 47% was landfilled (see Tables SI-5 and SI-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 to 2015 (see Table SI-6).

3.3. 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 2, 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., 2004; 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. (2004) 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. (2004) 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 Fig. 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.

4. 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 Fig. 13. These results vary significantly from other materials: Aluminum, for example, is estimated to have only 48% of accumulation inuse stock (Chen and Graedel, 2012).

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 (Fig. 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, 2013a,b), 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104542.

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