

Quantifying longevity and circularity of copper for different resource efficiency policies at the material and product levels

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Funding information

This work was supported by grant no. 7635.521(15) from the Ministry of Science, Research and the Arts of Baden Württemberg (Germany).

Editor Managing Review: Wei-Qiang Chen.

Abstract

Resource efficiency strategies are emerging on policy agendas worldwide. Commonly, resource efficiency policies aim at decreasing losses at the waste management stage and, thus, diverge from public interest in more comprehensive resource efficiency measures that include a focus the earlier material life cycle stages. Just in recent years, improvements in the lifetimes of products and increased repair and reuse ability have become policy objectives in some countries. However, the effectiveness of policy measures is usually not assessed, even though it is crucial to support informed policy-making and efficiently decrease the environmental impact of resource use. In this paper, we provide such an assessment for the copper cycle, the third most consumed metal with sharply increasing demand. Under current practices, in Western Europe and North America, 50% and 44% of the losses by 2050 occur at end-of-life collection, and only 2% of losses take place at the recovery stage; in Middle East and Africa for 19% and 54%, respectively. By 2050, most copper would be lost in China with a proportion of 58%. We evaluate the resource efficiency by quantifying the two key parameters, circularity and longevity, that is, how often and how long the material is in use in the anthroposphere. Our results show that the current global longevity of high-grade copper is 47 ± 2.5 years, and a copper atom is used in 2.1 ± 0.1 applications on average. Ambitious political measures across the life cycle can increase longevity by 85% and circularity by 45%.

KEYWORDS

copper, environmental policy, material flow analysis (MFA), MaTrace, resource efficiency, societal metabolism

1 | INTRODUCTION

In 2009, Rockström et al. (2009) introduced the concept of planetary boundaries to define the environmental limits within which humanity can safely operate. At the global level, humanity has already surpassed the boundaries on the rate of biodiversity loss and is at increasing risk to transgress the planetary boundary of climate change (Steffen et al., 2015). The mining and processing of materials play a substantial role in crossing these boundaries. Already, resource extraction and processing contribute to approximately 50% of global greenhouse gas (GHG) emissions and cause 90% of biodiversity loss and water stress (IRP, 2019). Rising income levels and consumerism, among other factors, are predicted to

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exacerbate this process even further. Among all materials, the fastest growth rate is predicted for metal extraction which is projected to increase by 126% between 2017 and 2060 (OECD 2019). With a mining production of 20.6 million metric tons in 2018 (International Copper Study Group, 2019), copper is the third most consumed metal in the world, exceeded only by iron and aluminum (U.S. Geological Survey, 2019). Due to the increase of copper-intensive low-carbon energy technologies and the electrification of transport, copper demand in particular is bound to increase in the near future (Deetman, Pauliuk, Van Vuuren, Van Der Voet, & Tukker, 2018; Schipper et al., 2018; Vidal, Goffé, & Arndt, 2013). CO₂ emissions of primary refined copper, including the mining, shipping, smelting, and refining stages, average between 1.6 and 3.4 tonnes (t) CO₂/t copper (Farrell, 2009; Grimes, Donaldson, & Gomez, 2008) and account for 0.3% of today's global energy consumption (Fizaine & Court, 2015). This share might increase up to 2.4% by 2050 (Elshkaki, Graedel, Ciacci, & Reck, 2016). Thus, reducing the environmental footprint of copper supply to meet GHG emission targets is imperative (Mudd et al., 2012). Furthermore, among all mass metals, primary copper production has the highest environmental impact per kilogram of produced metal in four categories: eutrophication, land use, photochemical oxidation, and freshwater aquatic eco-toxicity (OECD, 2019).

In this study, resource efficiency refers to using copper more sustainably by maximizing the ratio of value to resource use with value meaning the useful services provided by copper in products, and resource use meaning the primary copper extracted from ore needed to provide these services. This involves maintaining that value by keeping resources in use for longer and decreasing the environmental impacts associated with the whole life cycle of resources, from their extraction to their disposal (UNEP, 2018). Thus, in a more resource-efficient system, primary metal production would be reduced while the same or even more metal-related services could be provided and thus environmental pressures could be reduced. By using secondary copper resources, for example, the effect on eutrophication, land use, photochemical oxidation, and freshwater aquatic eco-toxicity can be mitigated by factors of 4, 11, 5, and 55, respectively, (OECD, 2019) and CO₂ emissions per metric ton of copper can be reduced by 70–85% when sourcing copper from scrap through recycling (Cui & Forssberg, 2003; Grimes et al., 2008).

Despite this known potential for decreasing environmental pressures by using secondary resources, the average global end-of-life (EoL) recycling rate, that is, the percentage of copper that is recovered as secondary material from EoL products, is only 43% in 2015 (OECD, 2019). This comparatively low EoL recycling rate of copper, as well as the growing consumption of copper-containing products, limit the degree to which secondary copper currently is used in production to around 30% (the average global "recycled content") (International Copper Study Group, 2019; OECD, 2019).

Most current resource-efficiency policy approaches do not take into account aspects of lifecycle thinking or the earlier steps of the waste hierarchy (Wilts, Von Gries, & Bahn-Walkowiak, 2016) as defined in Article 4 of the waste framework (Directive 2008/98/EC) of the European Parliament and Council (2008) which prioritizes waste prevention in the following order: prevention, preparing for reuse, recycling, other recovery. Approximately 53% of all policy approaches to closing technical material loops only target the waste management sector and recycling (Kaźmierczyk et al., 2016) and only a few countries such as Japan, the European Union, the United States, and China have already introduced policies targeting more efficient use of resources (Ghisellini, Cialani, & Ulgiati, 2016). Thus, for efficiently shifting toward a more resource-efficient economy, policy instruments, and market incentives that help overcome the conventional waste management structures are needed (Wilts et al., 2016).

Evaluation methods for the various resource-efficiency strategies (RES) are crucial to assess the effectiveness of policy instruments (Figge, Thorpe, Givry, Canning, & Franklin-Johnson, 2018). Robust resource-efficiency indicators are required to characterize the resource efficiency of material cycles as a whole (Kaźmierczyk et al., 2016) to complement the process-based RE indicators. Therefore, this study quantifies and discusses two such indicators, which are particularly suitable with regard to circular economies. The first indicator measures the resource efficiency by how often a material is (re-)used in a product, namely its circularity (Eckelman & Daigo, 2008; Matsuno, Adachi, & Kondo, 2006). The second indicator quantifies the timespan a resource is in use in the anthroposphere, its longevity (Eckelman & Daigo, 2008; Franklin-Johnson, Figge, & Canning, 2016). Both parameters measure the resource efficiency of the technological copper cycle on material level (Moraga et al., 2019). However, when longevity and circularity are evaluated individually, they are of limited use for interpreting resource efficiency. With high circularity, a resource could be used very often but only for a short time. In contrast, high longevity might implicate that a resource is used for an extended time in one product but not in a circular way (Figge et al., 2018). Therefore, we take the reciprocal potential of the two parameters into consideration in our evaluation of resource efficiency.

1.1 | Research gap, goal, and scope

To quantify the resource-efficiency indicators longevity and circularity of copper, we trace a specific cohort of copper through the copper cycle until all material is lost. Ghosh input-output (IO) models (Guerra & Sancho, 2011), Markov chain models (Matsuno et al., 2006), and MaTrace models (Nakamura et al., 2014) apply this material-tracing perspective. Eckelman and Daigo (2008) apply Markov chain modeling to copper. MaTrace has previously been applied to the steel cycle in Japan (Nakamura et al., 2014) and at a global level (Pauliuk, Kondo, Nakamura, & Nakajima, 2017), to the cobalt cycle in the EU (Godoy León, Blengini, & Dewulf, 2020), and for chromium and nickel as alloying elements in the steel cycle (Nakamura, Kondo, Nakajima, Ohno, & Pauliuk, 2017). However, a detailed investigation into the impact of policy strategies for resource efficiency on the longevity and circularity of the global copper cycle remains to be conducted. This study addresses the following research questions:

- At which material cycle stages and regions does most of the copper mined today get lost under business as usual (BAU) and with different resource-efficiency improvement strategies?
- How do the longevity and circularity indicators change under different policy instruments?
- What can we learn from these findings regarding the effectiveness of different resource-efficiency policies making globally and in specific regions?

The focus of this study is on the political instruments targeting the Consumer & Electronics sector, as it is among the sectors with the most abundant copper use (International Wrought Copper Council, 2016) with the waste electrical and electronic equipment (WEEE) creating the largest and fastest-growing waste stream regarding copper content (Dalrymple et al., 2007; Glöser, Soulier, & Espinoza, 2013; Ongondo, Williams, & Cherrett, 2011). We present the scenario results for future regional and sectoral distribution of all copper mined in 2015 under different operational scenarios for the material cycle industries. We analyze at which life stages losses to landfills and the environment occur, focusing on different regions with different resource-efficiency policies in place. Furthermore, we use the material cycle performance indicators longevity and circularity to evaluate the resource efficiency of the copper cycle in the different scenarios and discuss the political implications of our findings for different regions as well as on a global level.

2 | MATERIALS AND METHODS

To answer the research questions, we trace one cohort of copper through the cycle until the material is lost in the environment or due to non-functional recycling. In this study, the dynamic material flow model MaTrace Copper is used to capture copper use in multiple sectors.

2.1 | The MaTrace copper model

MaTrace_Global (https://github.com/stefanpauliuk/MaTrace_Global) is a multi-regional adaptation of MaTrace (Nakamura et al., 2014), a dynamic, inflow-driven material cycle model. We selected MaTrace_Global as a starting point for this study since it fulfills all requirements to answer our research questions, and is open source and, thus, adaptable to the copper cycle. The modeled system in MaTrace Copper represents the natural environment, the use phase, the waste management industries, the re-melting processes, and the manufacturing sectors, as well as the markets for EoL products, scrap, secondary metals, and final products (Figure 1). The natural environment functions as the source and the sink of copper in the model. Potentially reversible losses and irreversible losses function as sinks in the model. Reversible losses might occur in landfills and as obsolete stocks. Irreversible losses can occur due to corrosion and abrasion in the use phase and when copper becomes part of sewage sludge or trapped in another metal cycle.

All stocks, flows, and losses are accounted for based on their copper content. The spatial scope of MaTrace Copper depicts the world economy divided into nine regions r (Figure 2). We chose the regions r due to data availability and similarities of waste management strategies. The copper cycle is exemplified by four transformation processes (use A , waste sorting B , copper recovery C , and manufacturing D) as well as four markets (EoL market trade I , waste/scrap market II , secondary metal market III , and final product trade IV) (Figure 1). MaTrace Copper differentiates 17 product groups p within 5 sectors, and 6 types of scraps s (see Figure 2). For EoL products from the Consumer & Electronics sector, the officially reported and the informal collection are considered separately. The model input is all primary copper entering the technosphere in the year 2015 ($t = 0$), which is traced through the cycle for 286 years t from 2015 to 2300 within the corresponding 286 product age-cohorts t' . For a better visibility, we display results in this paper just until 2100. Copper is distributed to the product groups within each region according to the respective sector split D . The lifetime of each product cohort L is a truncated normal distribution around the average lifetime L' with lower bound 0. This distribution determines the number of products reaching EoL and leaving the use phase at time t . Within the use phase, losses occur due to dissipation σ or as obsolete stocks ω . The collection efficiency γ determines the share of EoL products collected for further treatment. Collected EoL products that are not reused are transformed to scrap. Copper scrap is separated and sorted with yield ϕ . The further refinement occurs by electrolytic refining or for clean copper scrap by direct re-melting with efficiency ϑ .

Losses at the manufacturing stage are not considered as actual losses to the environment since most material lost in manufacturing is directly recycled internally ($F_{D,r}$) (Schlesinger, King, Sole, & Davenport, 2011). Only high-grade secondary copper is considered to stay in the cycle, while non-functional recycling of copper into other alloys is regarded as a loss.

2.2 | Resource-efficiency evaluation parameters

The resource efficiency of the copper cycle is assessed for BAU and for 16 different resource-efficiency scenarios by quantifying the average technological lifetime of copper (longevity) and the average number of applications a copper atom is used in (circularity). An indicator dashboard is used

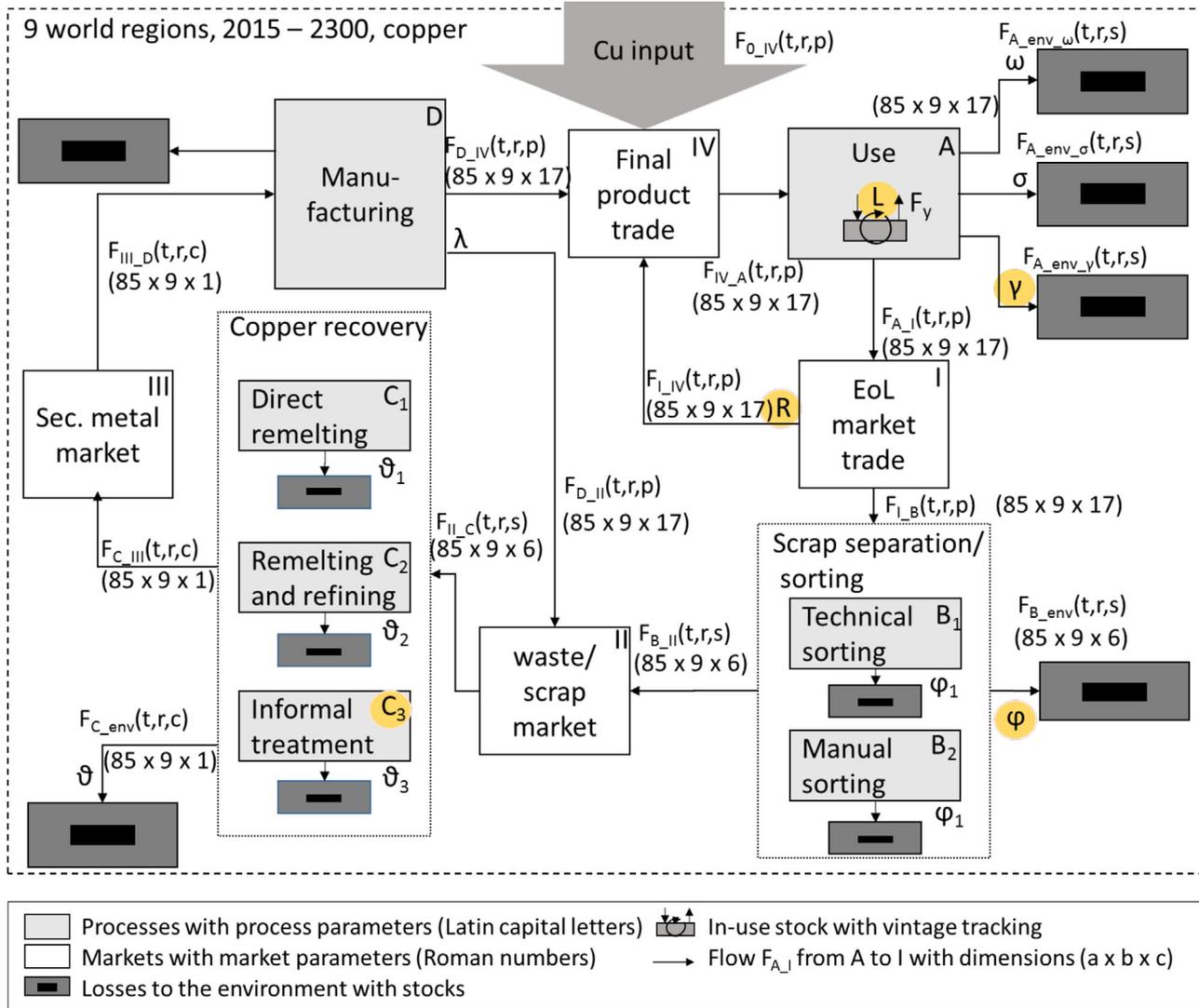


FIGURE 1 System definition and dimensions for tracing copper through its life cycle using MaTrace Copper. The yellow circles indicate the parameters which are influenced by the resource efficiency instruments in the scenario analysis. Flows are indicated by start and finish processes. Exemplary flow names are given. Flow dimension parameters are t : time (years); r , regions; p , products; s , scrap classes; c , secondary copper grades. Dimensions of flows are displayed for 1 year

to evaluate different RES based on Figge et al. (2018). Here the average longevity τ is calculated by adding up the mass of the material in the use phase S_{rpt} in different product groups p , regions r , and for each discrete time interval Δt :

$$\tau = \frac{1}{\sum_{p,r} S_{rpt0}} \sum_{t,p,r} S_{rpt} \Delta t. \quad (1)$$

The average circularity is calculated by

$$n = \frac{1}{\sum_{p,r} S_{rpt0}} \sum_{t,p,r} F_{IV_A,rpt}, \quad (2)$$

with Flow $F_{IV_A,rpt}$ from market IV to process A as defined in the system definition (Figure 1).

2.3 | Central process steps of the copper cycle

The purity of copper scrap determines the treatment process. Low-grade copper scrap is smelted and refined in a primary or secondary scrap smelter. Higher-grade scrap is fire refined, then electro-refined. The purest copper scrap, which is mainly manufacturing waste, is often melted and

Scope of the model				
Sectors	Product groups p	Recycling route t	Scrap classes	Regions r
Building & Construction (B&C)	Plumbing	Direct re-melting	Construction and demolition waste (C&D) Waste of electrical and electronic equipment (WEEE) Municipal solid waste (MSW) EoL Vehicles (ELV) Industrial electrical waste (IEW) Industrial non-electrical waste (INEW)	China India RO ASIA LAM MEA WE NAM RO OECD REF
	Building plant	Re-melting and refining		
	Architecture	For Sector C&E: Formal and informal collection and sorting		
	Communication			
Infrastructure	Electrical Power			
	Telecommunication			
Industrial	Power Utility			
	Electrical Industrial			
Transport	Non elec. Industrial			
	Electrical Automotive			
Consumer & Electronics (C&E)	Non electr. Automotive			
	Other transport			
	Consumer			
	Cooling			
	Electronic			
	Diverse			
	Powder			
Symbol	Model parameter [dimensions]	Data availability	Uncertainty	MCS SA
Global parameters:				
F_0_8	Copper input at year 2015	Global	low	✗ ✗
L	Lifetime of products	Global	low	✓ ✓
Efficiency parameters:				
λ	Fabrication efficiency	Global	low	✗ ✓
ω	Obsolete Stocks	Global	low	✓ ✓
σ	Dissipative Losses	Global	low	✓ ✓
γ	Collection rate in the formal recycling sector	C&E all regions/ other global	low/medium	✓ ✓
γ_{inf}	Collection rate in the informal recycling sector	C&E all regions	high	✓ ✓
φ	Formal scrap sorting efficiency	Global	low	✓ ✓
φ_{inf}	Informal scrap sorting efficiency	C&E all regions	high	✓ ✓
ϑ	Copper recovery efficiency	Global	low	✓ ✓
ϑ_{inf}	Informal copper recovery efficiency	AGG to 3 common recycling types	high	✓ ✓
Process transformation parameters:				
A	EoL Products to scrap transformation	Global, specific for WE	low	✓ ✗
B	Scrap to recycling route transformation	Global, specific for WE	low	✓ ✗
C	Refining to secondary metal transformation	Global, specific for WE	low	✗ ✗
D	Sector split	AGG for C,I,WE,UC, MAF	low	✓ ✗
Trade and reuse parameters:				
X	Multiregional reuse matrices	All regions	medium	✗ ✗
Ψ	Multiregional WEEE-trade matrices	All regions	medium	✗ ✗

FIGURE 2 Scope and resolution of MaTrace Copper and parameter description. The dimension of the parameters and their data availability is indicated. All parameters are assigned low (10%), medium (20%), and high (39%) uncertainty. For the regional scope, the brackets indicate which regions were considered most comparable, in case of data unavailability. AGG, aggregated; MCS, Monte Carlo simulation; SA, sensitivity analysis; RoASIA, rest of Asia; LAM, Latin America and Mexico; MEA, Middle East and Africa; WE, Western Europe; NAM, North America (without Mexico); RO OECD, rest of OECD; REF, countries from the reforming economies of Eastern Europe and the former Soviet Union

cast without refining (Schlesinger et al., 2011). Alloy scrap is generally recycled directly into new alloys (Schlesinger et al., 2011). Pinkham (2013) states that there is an equal ratio of refined to directly re-melted copper in the recycling process. However, the direct re-melting of scrap does not always restore the main function of copper, its conductivity, in a way that it can be used again for wiring. We will henceforth refer to recycling practices that do not restore primary copper quality and functionality as non-functional recycling. Large-scale down-cycling via direct re-melting (e.g., of copper in brass and bronze) only works due to an increase in total copper demand. This is problematic since the demand of copper especially increases in sectors where high-grade copper is needed (Lee & Shin, 2018).

Challenges faced by the secondary copper producers include the mixture of copper with other materials, the unpredictability of the quantities of available materials and objects, and its location due to copper scrap often being distributed over large areas (Schlesinger et al., 2011). Inefficient collection practices are a main reason for low EoL recovery rates (Ciacci, Harper, Nassar, Reck, & Graedel, 2016). Separation and processing of copper scrap also lead to copper losses (Ciacci et al., 2016). Furthermore, losses occur in recovery processes in which copper becomes an impurity as in steel recycling, where copper currently cannot be removed once in the melt (Daehn, Serrenho, & Allwood, 2017).

2.4 | Input data

We compiled data for copper use, transformation processes, and market trade for nine regions to obtain a realistic picture of the copper treatment and use across the globe in the year 2015. The year 2015 was chosen because the most up-to-date data was available for this year, although in some cases it was necessary to rely on older data. For regions where no data was available, data was taken from a country with similar recycling structures (see Supporting Information S1). The scope of the model is exemplified by the definition of the model parameters, their dimension, and their data availability (Figure 2). For the informal recycling for which data were not abundant, the categorization from Manhart (2010) in (1) Low-Tech, Low Yields, Severe Pollution; (2) Mid-tech, Medium Yields, Extreme Pollution; (3) High-Tech, High Yields, Low Pollution was taken and the following categorization made:

Low-Tech, Low Yields, Severe Pollution	MEA, RoOECD
Mid-tech, Medium Yields, Extreme Pollution	China, India, LAM, REF
High-Tech, High Yields, Low Pollution	RoOECD, NAM, WE

Depending on the data source, low, medium, and high uncertainty was assigned with 10% uncertainty if peer-reviewed data was found, 20% uncertainty if data was found in non-peer-reviewed sources, and 30% uncertainty if plausible assumptions had to be made. The respective data sources and the data processing are described in detail in Supporting Information S1.

The BAU scenario continues current process parameters and trade patterns. The BAU scenario serves merely as a reference for the scenario analysis and shall not be seen as particularly likely or unlikely.

2.5 | Model implementation of resource-efficiency strategies

For the scenario analysis, policy and institutional framework conditions that improve the resource efficiency of the system, and therefore decrease the demand of primary copper are translated into parameter changes in the model. In this study, we analyze the effect of policy measures that are currently discussed in regional policy strategies across the globe. The five strategies which we evaluate in this study are

REU - Increase R	the amount of products which are being reused and repaired, e.g., by tax breaks for repair activities or standards for repairable design
COL - Increase γ	the share of EoL products collected for further processing, e.g., by take-back requirements
SOR - Increase φ	the sorting yield, e.g., by "produced for recycling" standards
REC - Increase ϑ	the recovery yield of copper from scrap, for example, by improved refining technologies or by approaches often referred to as "best of two worlds" (e.g., Davis & Garb, 2015)
LIF - Increase L	the lifetime of products, e.g., by durability standards for products or warranty laws

For each of the five strategies, we defined a moderate and an ambitious scenario and combined the ambitious scenarios to six further RES. The combinations of the five single RES describe RE policy bundles, which represent often discussed political strategies.

The Low_hierarchy scenario represents a strategy focusing on the lower end of the waste hierarchy (Directive 2008/98/EC). The lower end of the waste hierarchy includes recycling, other recovery, and disposal. Thus, the Low_hierarchy scenario combines an improvement in the collection

rate with increasing recovery rates in the informal recycling sector. The Strategies for Sustainable Consumption (SSC) scenario is a combination of resource-efficiency measures that can be achieved by creating greater consumer awareness. SSC can affect the durability, the availability of repair information, and encourage reuse activities (Allwood, Ashby, Gutowski, & Worrell, 2011; Montalvo, Peck, & Rietveld, 2016). Furthermore, a shift in social norms and, consequently, a better understanding can positively promote the right handling of mobile phones for recycling (Yushkova & Feng, 2017). The SSC also includes an increase in the collection rate of Consumer & Electronics.

Other approaches include, for example, closing material loops as part of extended producer responsibility (EPR) policies. This is an approach to increase producers' responsibility to include the post-consumer stage (OECD, 2001). EPR policy approaches can be utilized in various ways but have so far mainly focused on the EoL stage of the product cycle. This study analyzes two EPR scenarios focusing on improvements that can be achieved by resource-conscious eco-design leading to an increased sorting rate combined with more durability (EPRdura) and increased reuse (EPRreuse).

The implementation of these strategies is translated into parameter changes in the model (Table 1). The moderate scenarios are based on best-practice examples in representative countries. The ambitious scenarios represent very progressive futures taking into account limitations, for example, arising from product design and compounds and alloys used in a product since these metallurgical and product-design aspects restrain the maximum reachable EoL recycling rate due to thermochemical constraints (Reuter, van Schaik, Gutzmer, Bartie, & Abadías-Llamas, 2019). In Supporting Information S1 of this paper, details on the scenario development and the physical and logistical limits we took into account are provided.

3 | RESULTS

3.1 | Losses at various life stages

Losses of copper mined in 2015 can be mitigated with different RES (Figure 3). Under BAU (Figure 3a), the amount of copper in the infrastructure sector and the building and construction sector is rising in the first 15–25 years due to the long average lifetimes in these sectors and secondary copper entering the cycle again. This secondary copper mainly originates from recycled copper scrap, leaving the use phase from products from the Consumer & Electronics, the Transport, and the Industry sectors with shorter average lifetimes. The Consumer & Electronics sector has a rapid decrease of embodied secondary copper from 2015 due to short lifetimes compared to products in the other sectors and inefficient waste management practices. In sum, the Transport and the Industrial sector represent only 18% of copper mined in 2015 and play a minor role in our evaluation. The total amount of copper in the use phase is decreasing rapidly, with 54% of copper lost after 35 years in 2050 under BAU.

Under the BAU scenario, the main sink for copper mined in 2015 is the low collection rate at EoL where 55% of all losses occur by 2050 (Figure 3a). The second-largest cause of losses is the separation and sorting (SOR) process, in which 27% of the copper is lost by 2050, followed by 12% of copper losses at the copper recovery stage in the refinement process, mainly in the informal sector. Sinks like obsolete stocks and dissipative losses only contribute to total losses of 1% and 5%, respectively (Figure 3a).

RES can improve the situation. In the best case, the combination of all five ambitious scenarios (All_amb, Figure 3d), 71% of copper is still in use in 2050, which equates to 5000 kt of additional copper compared to BAU. Almost 60% of these losses are avoided by the better collection at EoL and 22% due to an improvement of copper recovery from the informal recycling sector. Better scrap SOR leads to an increase of 15% of copper still in use in 2050. SSC (Figure 3b) lead to an increase to 65% of copper still in use by 2050, and measures focusing on the lower waste hierarchy (Low_hierarchy, Figure 3c) increase the embodied copper in the use phase to 60%. These results show that copper is lost at all life stages, though EoL collection is the main reason for losses. It is also evident that political measures in the Consumer & Electronics sector have a remarkable impact on the resource efficiency of the copper cycle.

3.2 | Longevity and circularity across scenarios

If the global copper cycle continues to operate as today (BAU scenario), copper will remain in the technosphere for 47 ± 2.5 years, and a copper atom will be used 2.1 ± 0.1 times on average. Figure 4 depicts the circularity and longevity of the five single RES in their moderate and ambitious scenarios and of the combination scenarios. The errors are indicating the 1σ confidence interval. Ambitious single RES, such as increased collection rates, increased sorting yields, and increased efficiencies in informal treatment, can increase the average lifetime of copper in the technosphere by 5, 9, and 5 years, respectively (scenarios COLamb, SORamb, and RECamb). The number of times a copper atom is used on average can be increased under these RES to, respectively, 2.3, 2.3, and 2.2. Encouraging ambitious reuse (REUamb) does increase the longevity of copper by 1 year and improves the circularity to 2.2. This rather small effect on longevity and circularity is due to the trade-off between reducing losses by encouraging the reuse of short-lifetime products and the desire to keep copper in the use phase for a long time. Latter would be encouraged by using it in sectors with long average lifetimes, which favors the application of secondary copper in the Building & Construction or Infrastructure sector. Ambitious standards for the durability of Consumer & Electronic products improve longevity by 14 years compared to BAU (scenario LIFamb in Table 1) but do not affect circularity. It is visible that an improvement in longevity not necessarily leads to an improvement in circularity and vice versa.

TABLE 1 Description of resource efficiency strategies (RES) used for scenario modeling

Scenario	RES	Description
BAU		Represents static copper cycle with data from 2015
REUmod	Increase R	Increase the reuse of C&E by 5%
COLmod	Increase γ	Increase global collection rate of C&E by 10%
SORmod	Increase φ	Increase sorting yield by 10%
RECmod	Increase ϑ	Increase efficiency of copper recovery of IR to 80%
LIFmod	Increase L	Increase lifetime of all C&E products by 100%
REUamb	Increase R	Increase reuse of C&E (and ELV) by 20%
COLamb	Increase γ	Increase global collection rate of C&E to 85%
SORamb	Increase φ	Increase sorting yield by 30%
RECamb	Increase ϑ	Increase efficiency of copper recovery to 95%
LIFamb	Increase L	Increase lifetime of all C&E products by 250%
Low_hierarchy	Increase $\gamma \wedge \vartheta$	COLamb and RECamb
SSC	Increase R, $\gamma \wedge L$	REUamb, COLamb and LIFamb
EPRdura	Increase $\varphi \wedge L$	SORamb and LIFamb
EPRreuse	Increase R $\wedge \varphi$	REUamb and SORamb
All_mod	Increase R, $\gamma, \varphi, \vartheta \wedge L$	REUmod, COLmod, SORmod, RECmod, and LIFmod
All_amb	Increase R, $\gamma, \varphi, \vartheta \wedge L$	REUamb, COLamb, SORamb, RECamb, and LIFamb

The scenarios shown in Figure 3 are indicated with bold text.

Note that the scenarios do not make statements about the likelihood of certain futures but illustrate how the resource efficiency of copper changes if improvement strategies are implemented. RES, resource efficiency strategy; Low_hierarchy, policy instruments targeting the low waste hierarchy; EPR, extended producer responsibility; SSC, strategy for sustainable consumption; EPRdura, EPR + durability standards; EPR reuse, EPR + incentives promoting reuse; RES with mod indicating the moderate scenario and with amb indicating the ambitious scenario.

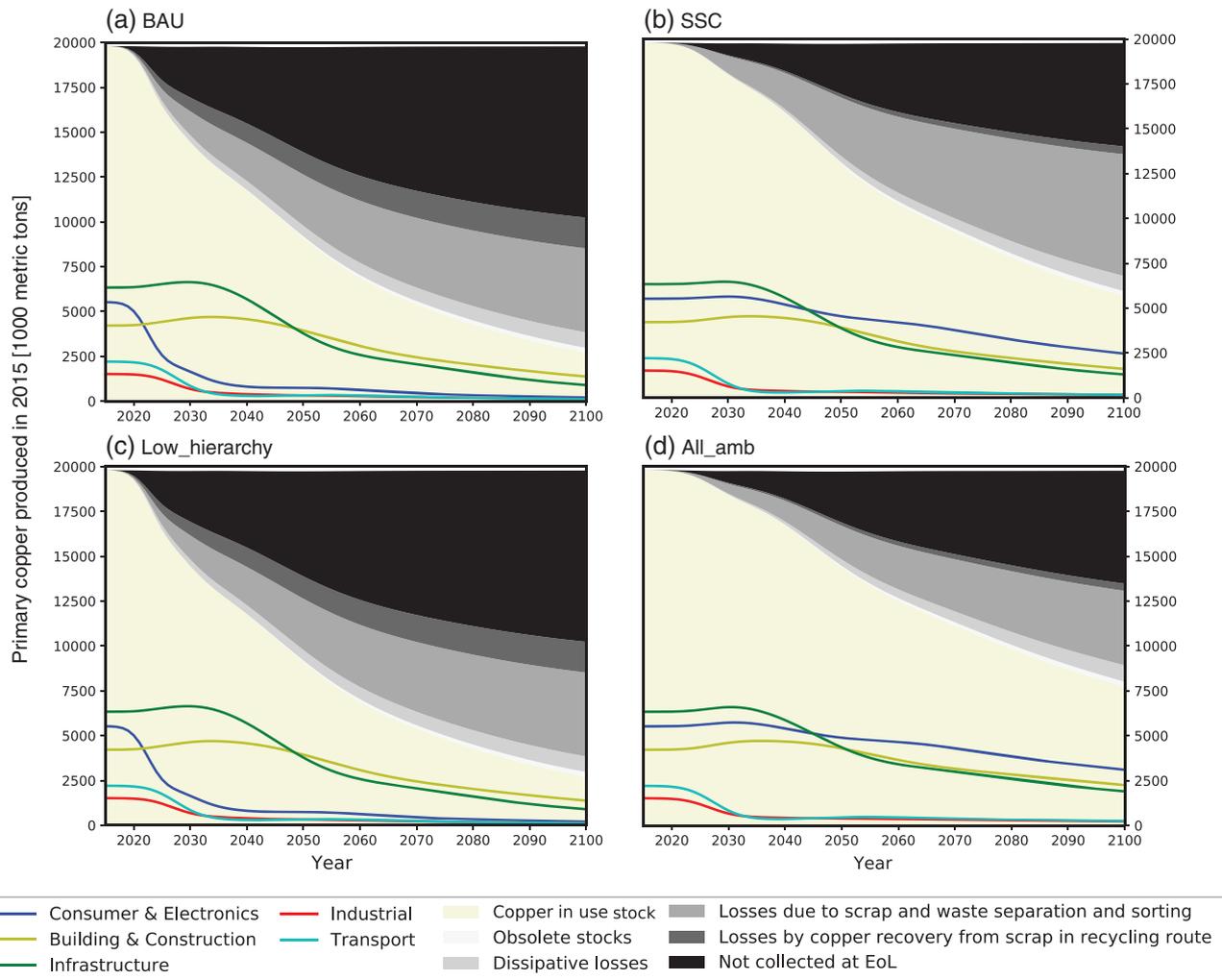


FIGURE 3 Tracing all copper consumed in 2015 until 2100 under the BAU (a), SSC (b), Low_hierarchy (c), and All_amb scenarios (d). The colored lines show the breakdown of the total copper stock in the five target sectors. The beige area is the sum of these in-use copper stocks. The grey shaded areas depict the losses at five different life stages. Underlying data used to create this figure can be found in Supporting Information S2

The combination of all five RES leads to an extension of the average lifetime of copper in the technosphere of 20 years under moderate assumptions (scenario All_mod) and to an extension of 40 years under ambitious assumptions (scenario All_amb). Combinations of policies across the life cycle are clearly more effective than single RES or combinations focusing on the lower waste hierarchy. Even with moderate RE improvements across the lifecycle, the All_mod shows a larger increase in longevity and circularity compared to all ambitious single RES and compared to most of the combined scenarios.

3.3 | Regional evaluation of losses and resource-saving potentials

In the nine regions, the RES are not equally effective in increasing resource efficiency since different regions show different copper use and treatment patterns and infrastructures.

Figure 5a shows how copper in 2050 is attributed to different life stages in Western Europe (WE), China, Middle East and Africa (MEA) and North America (NAM) under BAU by 2050. WE and NAM represents the loss patterns of regions with high-technological registered recycling technology and infrastructure and no to a small informal recycling sector similar to rest of OECD countries (RoOECD). Chinas loss patterns are similar to India, Latin America and Mexico (LAM), and countries from the reforming economies of Eastern Europe and the former Soviet Union (REF) which all are countries with medium to high registered recycling technology and infrastructure and a medium to large informal recycling sector. MEA has a low registered recycling technology and infrastructure with a large informal recycling sector like rest of Asia (RoASIA).

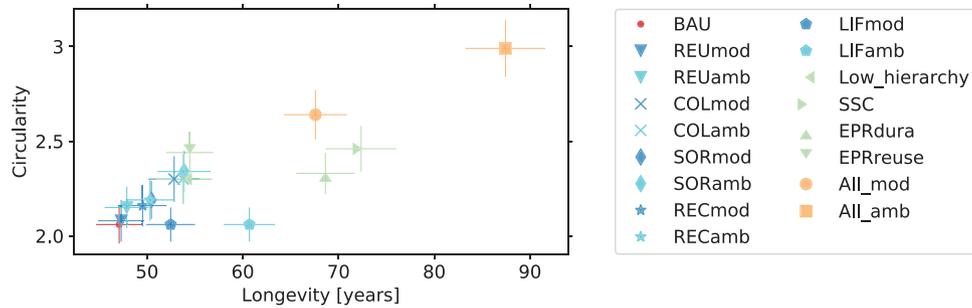


FIGURE 4 Different resource efficiency scenarios affect circularity and longevity in different ways. The red dot shows the BAU scenario, the blue dots the moderate and ambitious single resource efficiency strategies, and the green and the yellow dots are combinations of these. Scenarios are described in Table 1. The most effective way to increase both longevity and circularity are the scenarios combining all policy instruments across the life cycle (All_mod and All_amb). The error bars show the range of results of the MC simulation with 1000 runs with a 1σ confidence interval. Underlying data used to create this figure can be found in Supporting Information S2

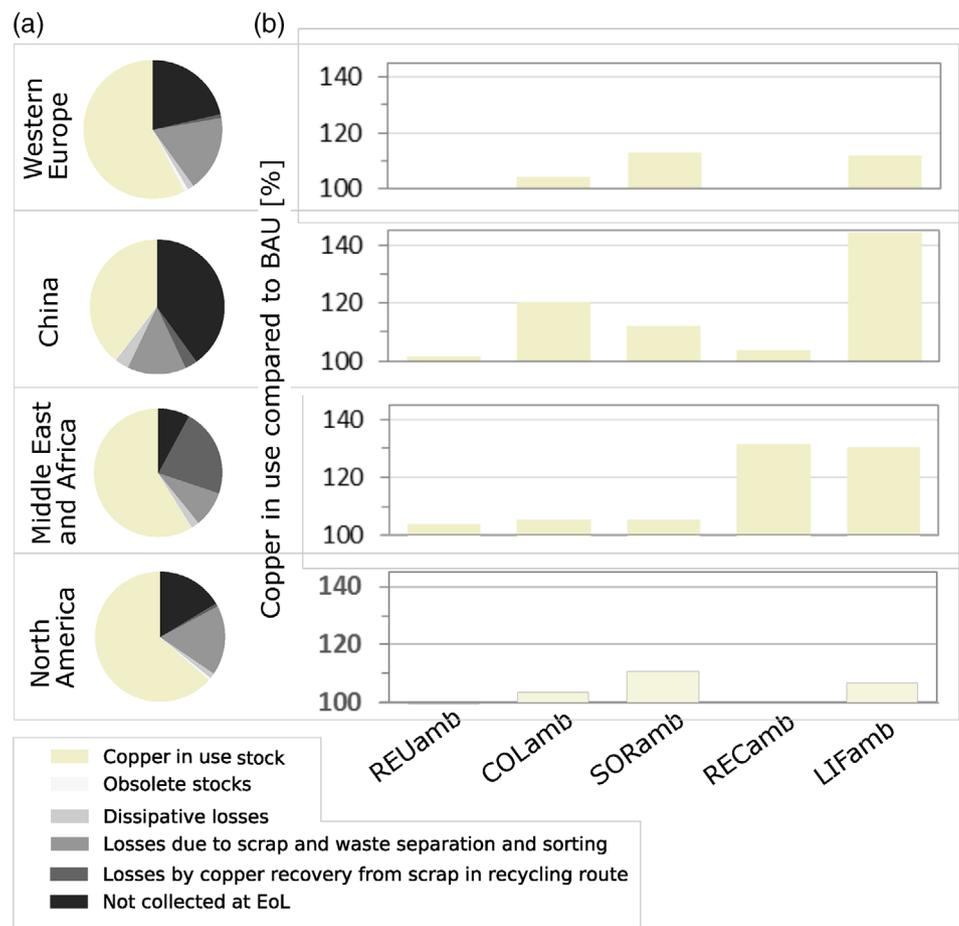


FIGURE 5 Copper produced from copper ore in 2015 and lost in WE, China, MEA, and NAM by 2050. (a) The share of these losses at different life stages and copper still in use by 2050 for BAU scenario. (b) The increase of copper still in use by 2050 under all five single ambitious resource efficiency strategies. Underlying data used to create this figure can be found in Supporting Information S2

In WE 50% of all losses occur due to not collecting copper-containing EoL products. In NAM, these losses account for 44%. In China, losses at the collection stage contribute to 66% of the total copper lost in 2050. In MEA losses at EoL collection only account for 19% of all copper lost by 2050. In contrast, the share of losses by copper recovery from scrap at the refining stage is much higher in MEA compared to WE and China. The percentage of copper lost at the scrap separation stage is, in particular, high in WE and NAM. Losses by copper recovery account in MEA for 54%, in China for 5%, and WE and NAM for 2%.

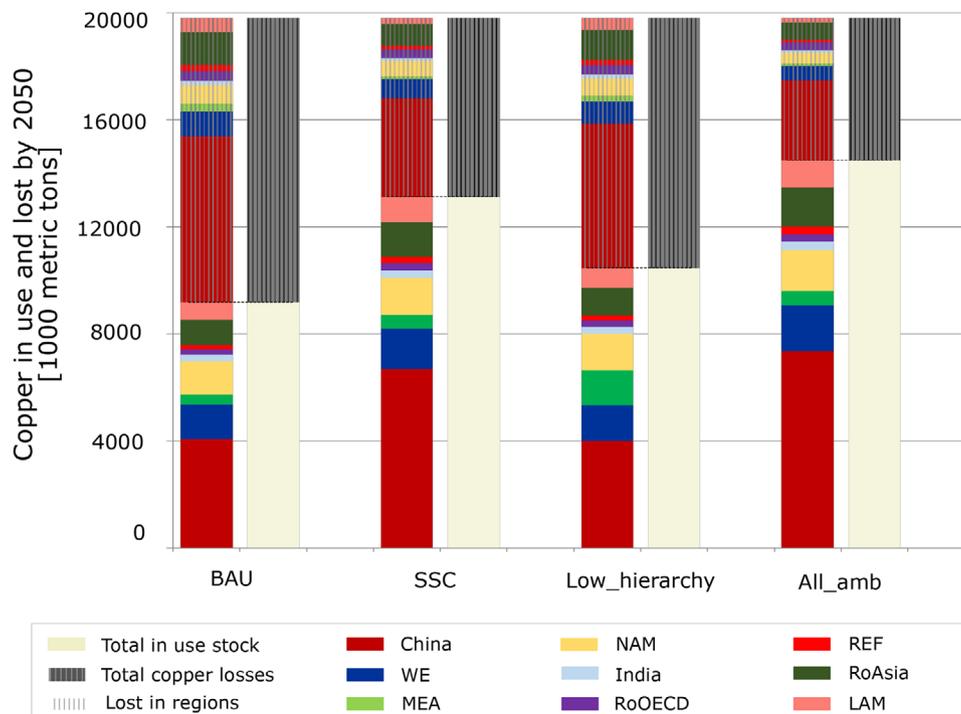


FIGURE 6 Regional distribution of losses of the copper produced from ore in 2015 to 2050. For each scenario, the right bar graph shows the split of the copper into total losses by 2050 and the fraction remaining in use. The left bar graphs show copper in use and sum of losses in all regions in both the use and the loss fraction. Underlying data used to create this figure can be found in Supporting Information S2

Figure 5b shows the copper in use under the five different ambitious RES by 2050 for WE, China, MEA and NAM. An increase in reuse (REU) does not have a big effect on copper in use in WE and NAM but can increase copper in use by 2050 by 16% in MEA compared to BAU. In WE, an increase in waste SOR has the biggest effect (12%). In China, targeting the lifetime of products (LIF) has the highest effect and can increase the copper in use by 42% compared to BAU (Figure 5b). In MEA the largest improvements in resource efficiency can be achieved by an increase of efficiency of copper recovery (REC) with increasing copper in use by 30%.

The results suggest which policy measures have the highest improvement potential for different regions and emphasize that in emerging and industrialized economies, in particular, these measures should be targeted at the beginning of the life cycle. Contrarily, in MEA, an improvement in the waste management sector to increase copper recovery in informal recycling has the highest potential for a more circular copper cycle.

Figure 6 shows copper in the use phase and the losses by 2050 under the BAU, SSC, Low_hierarchy, and the All_amb scenario. By 2050, most copper is lost in China, with a proportion of 58%. Under the All_amb scenario, the losses in China only decrease by 3%, but the amount lost is reduced by 4700 kt, whereas WE can mitigate its copper losses by 640 kt. This finding emphasizes the importance of better governance of copper-containing products in particular in China since most of the copper is lost here.

4 | DISCUSSION

Political measures can actively increase the resource efficiency of the copper cycle. The choice of these measures is of great importance to by how much longevity and circularity are enhanced. The results of this study show that well-chosen political instruments in the Consumer & Electronics sector can have a major influence on both longevity and circularity of the copper cycle. Since the Consumer & Electronics sector is a sector with a short average lifetime, the implementation of resource-efficiency measures could provide quick results. Thus, the performance of the Consumer & Electronics sector as well as WEEE treatment could play a considerable role in the planning of a more circular supply of copper in the future.

4.1 | Implications for policy-makers

A real resource-efficient economy with a high longevity *and* circularity hinges on the choice of policy instruments that increase both measures. Only a combination of resource-efficiency instruments along the life cycle of products can increase circularity as well as longevity notably. The results of the MaTrace simulation illustrate that to improve the longevity and circularity of copper resource-efficiency measures targeting the copper recovery in informal recycling, the reuse rate, and the lifetime of a product are essential. This important finding underlines existing policy recommendations for resource efficiency, which suggests mixes of policy instruments to “create a coherent set of incentives across the product lifecycle” (OECD, 2016).

Furthermore, another obstacle in addressing resource efficiency with political instruments in the Consumer & Electronics sector is the lack of comprehensive data and systematic studies undertaken to determine material flows in e-waste handling. Therefore, even for the well-studied copper cycle, efforts from governments and the research community are needed to enable a greater understanding and finding the best pathways for a more resource-efficient future. Hence, our study stresses that resource governance for sustainable development is not only crucial for critical metals but also for bulk materials like copper (Ali et al., 2017).

4.2 | Regional indications

The regional analysis shows that in our current economic system, China is a major player in the copper cycle, with a share of almost 50% of resource-saving potentials by 2050. Increasing resource efficiency in Chinese copper waste management must be a crucial objective of global resource-efficiency policy efforts to decrease primary copper demand in the future. The regions show different resource-efficiency improvements under different scenarios. For all regions, however, a policy mix along the life cycle is more effective compared to a focus on the lower waste hierarchy. Generally, in countries with a pronounced informal recycling sector, the collection is more efficient than in the formal recycling sector. Thus, it would be desirable to support actors in the informal sector to improve occupational standards and to ensure high-quality recycling of EoL copper-containing goods.

4.3 | Comparison with former studies and uncertainties

The average lifetime of copper in the technosphere of 60 years, calculated by Eckelman and Daigo (2008), lies outside the error range of our result. Their assessed number of times a copper atom is used on average was 1.9 and therefore lies inside our error range. Since there is no uncertainty evaluation available from Eckelman and Daigo (2008), it is not possible to identify whether the error ranges also overlap in terms of longevity. Nevertheless, the data published by Eckelman and Daigo (2008) for Europe suggests already that there are several reasons which could lead to this discrepancy. They assume a 100% transition from products to waste management without considering not collected copper items and reuse. Furthermore, a lack of transparency challenges a coherent evaluation of this study as it remains unknown whether the authors have included the informal waste treatment sector.

However, although the total value for longevity and circularity are very uncertain, the trends under the different RES are maintained. Nonetheless, the scenarios cannot be seen as predictions of the futures but as “what-if” scenarios, showing how RE instruments in the Consumer & Electronics sector influence the RE of the copper cycle.

4.4 | Limitations and outlook on future research and application of this study

This study provides an example of RE assessment of material cycles and its improvement under different RES. Assessing the RE of the copper cycle without considering linkages to other material cycles is a limitation of this study since it might lead to impact shifting when substituting copper, for example, with other materials like aluminum and silver. In future RE assessments, the different material cycles should be linked to reveal potential co-benefits and trade-offs of resource-efficiency measures. For example, a combined assessment of the steel and the copper cycle would help to assess optimized copper recovery rates from contaminated steel scrap as performed by Daehn, Serrenho, and Allwood (2019). Furthermore, considering product-specific material compositions and compounds with the MaTrace perspective would help assess resource-efficient product-design and ideal product-specific waste management practices with taking into consideration thermodynamic simulations. Assessments as performed, for example, by Reuter, Van Schaik, and Ballester (2018), Rönnlund et al. (2016), and van Schaik and Reuter (2010), which consider these aspects, were used for the scenario definition of this MaTrace copper study. In a further step, these assessments could be used to introduce more metallurgical detail at the product level.

Another interesting future research direction would be the inclusion of potential rebound effects in the scenario analysis. Rebound effects related to resource-efficiency measures are often related to a higher demand for resources due to price effects or substitutability (Zink & Geyer, 2017). Since future resource demand is not an explicit input variable in MaTrace copper, these rebound effects might particularly influence the sector split. Figge and Thorpe (2019) discuss the symbiotic rebound effect, which is related to opportunity costs between different RES, that is, an increase in recycling might lead to decreased reuse and vice versa. In future research, it would be interesting to quantify these rebound effects and assess their impact on the effectiveness of different RES.

Assessing RE with MaTrace reveals the potential for efficient policy-making also at the country and region levels. By identifying the low hanging fruits, a structured resource-efficiency assessment can help to shift political efforts from low impact measures (e.g., measures on the lower waste hierarchy) to hotspots of wasteful resource management (e.g., low lifetimes). Therefore, an assessment of the effectiveness of RE instruments should be applied widely in regional but also in global policy-making to inform the transition toward a more resource-efficient world.

ACKNOWLEDGMENT

The authors thank Simon Glöser for sharing some of his valuable experience in copper cycle modeling.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Klose S, Pauliuk S. Quantifying longevity and circularity of copper for different resource efficiency policies at the material and product levels. *J Ind Ecol.* 2021;1–15. <https://doi.org/10.1111/jiec.13092>