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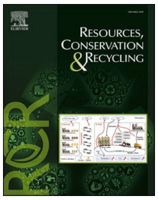

The limitations of end-of-life copper recycling and its implications for the circular economy of metals

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ABSTRACT

Increasing the recycling of metals reaching their end-of-life (EoL) is a vital circular economy approach to meet the growing demand for metals and reduce reliance on mining. To assess the potential of recycling strategies in fulfilling future metal demand and replacing primary production, we develop a novel dynamic probabilistic material flow analysis (MFA) model. Unlike previous MFA studies, our model explicitly explores the potential of recycling to reduce metal mining activities while considering uncertainties in future EoL collection and recycling rates. Focusing on copper, a critical mineral for low-carbon technologies, the model dynamically estimates the future copper stocks and flows under three different demand scenarios and probabilistic EoL collection and recycling assumptions. Our analysis reveals that the share of EoL secondary supply of overall copper demand, which currently stands at 23 %, will even under the scenario with the lowest future copper demand only be averaging 33.4 % over the next three decades. In addition, even under the most optimistic circumstances with lower than expected copper demand and very high collection and recycling rate growth, the annual share of EoL secondary supply of overall copper demand would only reach 49.6 % in 2050. Thus, primary copper extraction is expected to rise significantly until at least 2040 and under 87 % of all 30,000 modelled outcomes, primary production of copper in 2050 will still be above 2020 production levels. Consequently, we emphasise the need for alternative circular economy strategies beyond recycling, such as demand reduction and mitigating the harmful impacts of primary metal production.

1. Introduction

There is growing evidence that the accelerating efforts to decarbonise economies globally will lead to rapidly increasing demand for many key metals (Hund et al., 2020; IEA, 2021; Seck et al., 2020; Simas et al., 2022; Watari et al., 2019). One often-invoked solution to fulfil the growing demand for metals while simultaneously decelerating the primary extraction of these materials is to move towards a so-called circular economy (CE) (Zink and Geyer, 2017). Although there are over 200 definitions of the CE concept (Kirchherr et al., 2023), the CE can be broadly understood as a transformative approach towards sustainable resource use within planetary boundaries that promises to “slow, narrow and close socioeconomic material cycles by retaining value as long as possible, thereby minimizing primary resource use, waste and emissions” (Haas et al., 2020, p. 1).

The CE concept began to receive significant scholarly attention in the early 2000s in the wake of the growth of new approaches to study industrial systems, such as industrial ecology and industrial symbiosis (Blomsma and Brennan, 2017; Ghisellini et al., 2016). By the late 2000s, the concept of the CE began to also receive attention from policymakers in China (National People’s Congress, 2008) and Europe (European Commission, 2015). One of the most prominent areas of focus in the scholarship of the CE since then has been metals (Merli et al., 2018). This is not surprising, as metals, unlike many other raw materials, do not lose their intrinsic properties during recycling and can be re-used multiple times without losing their quality or functionality (Hagelüken et al., 2016). However, the majority of research and policy efforts to develop and promote CE strategies to meet the growing demand for metals and other material inputs have predominately focused on the potential offered by recycling materials found in products that have reached their end-of-life (EoL) (Ragossnig and Schneider, 2019; Schöggl et al., 2020).

The predominant focus on the EoL recycling of metal containing products in the CE literature and policy space has unarguably provided important contributions to the design and implementation of new

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recycling technologies, business models and other activities aimed at reducing primary metal production. However, there are growing questions whether increased EoL recycling efforts alone will be able to cover the expected increases in demand for many metals driven by growing populations, increased incomes and the significantly higher material intensity of low-carbon technologies (Dong et al., 2019; Reuter et al., 2013; Simas et al., 2022; Valero et al., 2018). To highlight the scale of the anticipated demand increases, Watari et al. (2021) reviewed 70 studies that forecast metal demand. They find that demand for all major metals is likely to increase continuously until 2050 with the demand for aluminium (215 %), copper (140 %), nickel (140 %) and iron (86 %) forecasted to grow significantly relative to demand in 2010. While many studies have been published on metal demand dynamics, very few studies have explicitly tackled the question of how much of this forecasted demand growth for metals can be met by recycling existing metal stocks.

Given the current scholarly focus on EoL recycling as the core CE strategy, it is essential to develop an evidence-based understanding of the potential secondary supply that can be unlocked by increasing the recycling of the in-use stock of metals at the end of their lifetime and the associated demand reduction for mined primary metals that can be achieved as a result. Even though there has been a lack of attention on estimating the potential of recycling to meet future metal demand, a few studies in recent years have at least included secondary supply forecasts in their analysis (e.g. Elshkaki et al., 2016; Gregoir and van Acker, 2022; Sverdrup et al., 2015; Watari et al., 2019). However, these studies do not explicitly investigate the potential of recycling to meet the growing metal demand and do not account for the large uncertainties in future EoL collection and recycling rates. As a result, existing studies give limited guidance on the effectiveness of recycling strategies to generate sufficient secondary supply to meet future metal demand and therefore have limited explanatory power to assess the potential of recycling to reduce the need for increased primary mineral and metal extraction.

The goal of this paper is to fill this gap by using Material Flow Analysis (MFA) to explore the potential of EoL recycling to meet future metal demand. We build on previous work that combines a dynamic MFA approach with probabilistic forecasting to develop a new methodological approach that can estimate the future scale of recycled metals availability under uncertain EoL recycling performance and demand pathways. We then apply this new method to the global copper cycle. Based on this analysis, we discuss the implications of our findings before identifying several leverage points for research and policy to generate a more realistic understanding of the role that EoL recycling can play in meeting the growing demand for minerals and metals. We conclude with ideas for a future research agenda that includes a stronger focus on developing CE strategies for the production systems of primary metal production.

2. Materials and methods

2.1. Material flow analysis

One of the well-known methodologies to quantify resource flows and understand the availability of anthropogenic stock of metalliferous materials is Material Flow Analysis (MFA) (Brunner and Rechberger, 2016). All MFA studies are based on the paradigm of industrial metabolism and use the methodological principle of mass balancing (Bringezu and Moriguchi, 2003). Despite this common foundation, MFA studies use a large range of differing methodological approaches and temporal scales (Graedel, 2019). While static MFA models with a fixed timescale of one or several years used to be the norm, various methods to dynamically model past and future stocks and flows of metals have become well-established since the early 2000s (Müller et al., 2014). In contrast to static models, dynamic MFA models not only provide a snapshot of metal cycles at one point in time, but they provide information about the behaviour of a system over time.

In a parallel development in MFA studies, it has become more common to add probabilistic elements to MFA models in order to overcome the problem of uncertain modelling inputs (Laner et al., 2014). Probabilistic approaches have been used in previous MFA studies to control the uncertainty created by data availability limitations for key model inputs (e.g. Chen et al., 2023; Gottschalk et al., 2010; Song et al., 2017; Thiébaud et al., 2018).

In recent years, scholars have started to combine these two approaches into a new approach known as dynamic probabilistic MFA (DP-MFA) (Bornhöft et al., 2016). DP-MFA approaches have been used to forecast future stocks and flows of various resources, such as urban housing stock in China (Cao et al., 2018), engineered nanomaterials (Sun et al., 2017) and rubber release from tires (Sieber et al., 2020). However, despite a growing understanding that adding probabilistic elements to dynamic MFA models can help to overcome inherent uncertainties in forecasting future material stock and flow dynamics (Bornhöft et al., 2016; Müller et al., 2014), there have so far been no studies that use a DP-MFA approach to analyse future metal cycles in the context of the rapidly growing demand for certain metals driven by the energy transition.

While a number of recent studies that attempt to forecast future metal cycles and secondary metal supply have used either dynamic MFA approaches in tandem with various scenarios for future metal demand (Baars et al., 2021; Henckens, 2021; Gregoir and van Acker, 2022; Henckens and Worrell, 2020; Simas et al., 2022; Watari et al., 2022) or other non-MFA approaches (Blagoeva et al., 2016; Dominish et al., 2019; Rizos and Righetti, 2022), all of these studies use deterministic point estimates in their modelling assumptions. This approach has a number of drawbacks. First, deterministic approaches can perpetuate inaccuracies in historic metal recycling data, potentially resulting in biased or unreliable predictions. Second, many MFA papers rely on historical extrapolation or overly optimistic assumptions regarding future metal demand and recycling rates, which can lead to an overemphasis on past experiences and neglect the feasibility of recycling assumptions.

In contrast, a dynamic probabilistic DP-MFA approach can allow for a more comprehensive and realistic treatment of uncertainties. Rather than relying on fixed point estimates, DP-MFA incorporates probabilistic elements that account for the uncertainty surrounding historical data and future projections. It can thus consider a range of possible outcomes for future metal demand, and EoL collection and recycling rates with distributional parameters based on realistic best estimates from academic studies. This provides a more nuanced view of the future metal cycles and secondary supply availability. By developing a DP-MFA model of the global copper cycle that can better account for the large uncertainties of historic metal use, future metal demand and EoL collection and recycling, this paper attempts to improve the insights from previous studies and aims to demonstrate the usefulness of adding probabilistic elements to dynamic MFA studies on future metals cycles and the forecasting of secondary supply availability of metals.

2.2. Case study: copper

There are several reasons why we selected the global copper cycle to test our modelling approach. Firstly, copper's widespread use across various sectors (Carrara et al., 2020; Hund et al., 2020) and its efficient and affordable conductivity (CDA, 2023) make it an indispensable component of the ongoing energy transition. Secondly, even before the energy transition, the common usage of copper has resulted in a substantial recyclable metal stock. Thirdly, the existence of an extensive literature on copper supply and demand modelling, coupled with the availability of historical data,[1] allows for the development of more accurate modelling assumptions and inputs. These factors position copper as an ideal case for testing and validating our modelling methodology, while also allowing us to draw more generalisable conclusions for future research on CE strategies.

2.3. Overview and design concepts of the model

The general principles underpinning this model are based on the dynamic probabilistic material flow analysis (DP-MFA) modelling approach (Bornhöft et al., 2016; Müller et al., 2014; Sun et al., 2017). Table 1 summarises the design concepts used.

The model has two stages, which both employ a DP-MFA approach. The first stage estimates past copper stocks and flows. In the second stage, the model dynamically estimates the future copper stocks and flows under three different copper demand scenarios and probabilistic EoL copper collection and recycling assumptions. Fig. 1 shows the conceptual framework of the modelling process.

Table 1
Principles and concepts used for the model, based on and adapted version of the MFA ODD protocol developed by Müller et al. (2014).

Overview	Purpose	Understanding the pathways of copper in the anthroposphere with a focus on evaluating future scenarios of secondary copper availability
	Materials (goods, substances)	Copper (17 product groups)
	Processes	Whole life-cycle of copper (Primary production and refining, fabrication, use, waste management, losses to the environment)
	Spatial and temporal scale and extent	Global, 1910 to 2050
	System overview	Simplified open-cycle loop
Design concepts	Basic principles	Dynamic probabilistic, top-down, retrospective and prospective
	Modelling approach (static, dynamic)	Inflow-driven dynamic stock modelling for annual cohorts
	Dissipation	Dissipative processes are explicitly deducted from each cohort
	Spatial dimension	Global system boundary
	Uncertainty	Mix of scenario-based (3 demand scenarios) and probabilistic (product lifetimes, future EoL collection and recycling processing efficiency rates) uncertainty considerations. Parameter uncertainty from literature. Model output uncertainty quantified via Monte-Carlo Simulations. Validation of results against available literature and via mass-balances. Sensitivity assessments via several one-at-a-time tests and visual inspection of model behaviour.

2.4. Copper stocks-and-flow model

2.4.1. Stage 1: modelling the historic copper cycle

The foundation of the analysis in this paper is a top-down global open-cycle dynamic stocks-and-flow model (Müller et al., 2014) that estimates historic copper flows and stock levels from 1910 onwards. The model comprises five conceptual ‘life stages’ or ‘cycles’:

1. Primary production and refining
2. Fabrication
3. Use
4. Waste management
5. Losses to the environment

Using the principles of the law of mass conversion, the various ‘life stages’ are expressed in a simplified system (Fig. 2).

The model follows each tonne of copper starting with primary production through to the fabrication of 17 different end-use product groups that contain copper. After fabrication, the copper contained in these products enters its use phase and remains there for different periods of time depending on each product group’s average lifetime. Using a time-cohort approach, the annual inflows to the anthropogenic copper stock is calculated by subtracting the outflow of embedded products that reach the end of their lifetime from the sum of the inflows of copper embedded in newly produced products and the copper embedded in previously produced products that are still in use. After leaving the use phase, the copper contained in these products is considered scrap and may be collected and recycled, thus re-entering the cycle together with primary copper, or is lost to landfill or other metal cycles.

The global scope of this study and the informal nature of the secondary copper market makes the collection of primary data for model inputs challenging. As a result, all model inputs are based on data from previously published studies. Data on the historic production of copper ores, refined production, historic EoL collection rates, EoL recycling processing efficiency rates, product group allocation and in-use stock residence times is taken from Glöser et al. (2013), the International Copper Study Group (ICSG) (2014, 2015, 2018, 2019, 2022) and the International Wrought Copper Council (IWCC) (2022). Although many studies use average in-use stock residence times, we use normally distributed residence times following Glöser et al. (2013), as accurate data on stock residence time is very hard to gather and therefore inherently uncertain (Eckelman and Daigo, 2008; Gorman and Dzombak, 2020; Wang et al., 2017). A detailed description of the model underlying this work, including the input data, data sources, and all relevant equations can be found in sections S1 to S3 of the *Supplementary Information (SI)*.

2.4.2. Stage 2: modelling the future copper cycle

The second stage of the model estimates the future stocks and flows of the copper cycle. In order to account for the uncertainties in future copper demand, EoL collection rates, and EoL recycling processing efficiency rates, the second stage of the model uses a blend of probabilistic forecasting and dynamic scenarios.

2.4.2.1. Future metal demand. Future demand of metals is inherently uncertain and there are a number of different ways to model this uncertainty. We chose to use scenarios to account for this uncertainty for two reasons. First, it is difficult to define probability parameters for future demand outcomes. Second, scenario-based modelling allows for results analysis with greater explanatory power than probabilistic approaches given the wide range of demand forecasts, which would produce results with very large error margins. As a result, the future copper demand in this model is based on three distinct future material demand scenarios for a range of minerals critical for the energy transition developed by the International Energy Agency (2021; 2023): (1) Stated

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[1] A wide range of industrial (see e.g., Copper Alliance, 2022; ICSG, 2022) and academic data (see e.g., Ciacci et al., 2020; Glöser et al., 2013; Henckens & Worrell, 2020; Schipper et al., 2018; Watari et al., 2019, 2022; Wiedenhofer et al., 2019) is available for copper covering collection rates, product groups in which copper has been used and many other key data required for a comprehensive MFA.

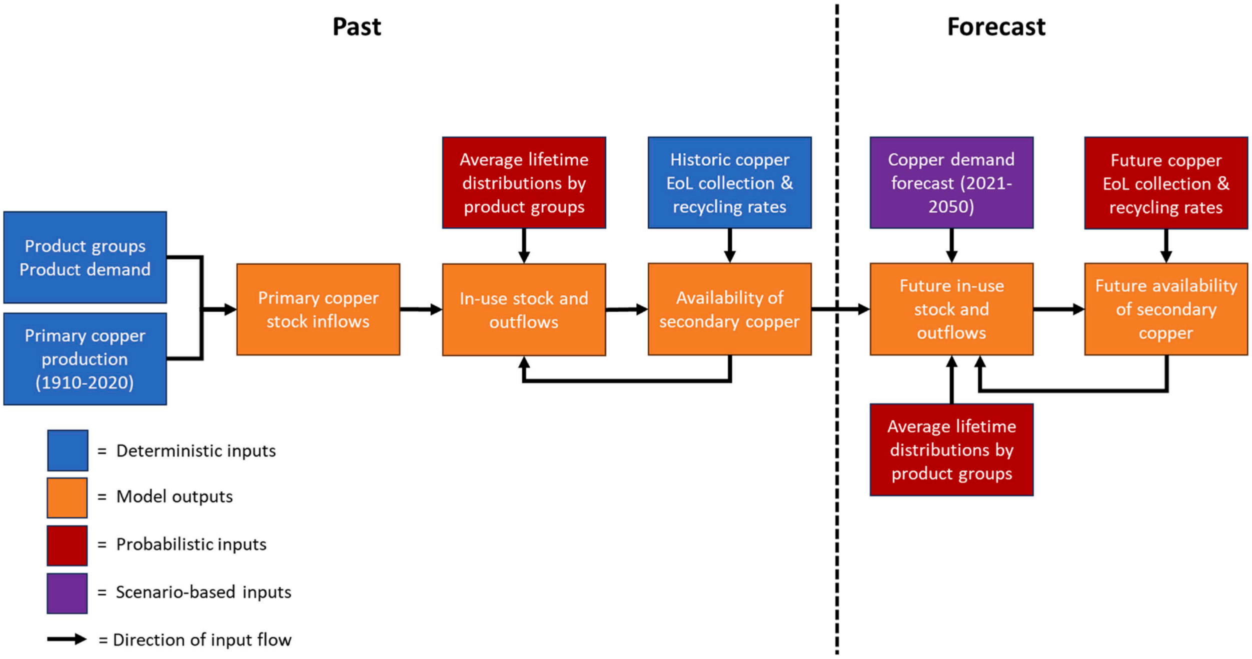

Fig. 1. Conceptual framework of the modelling process.

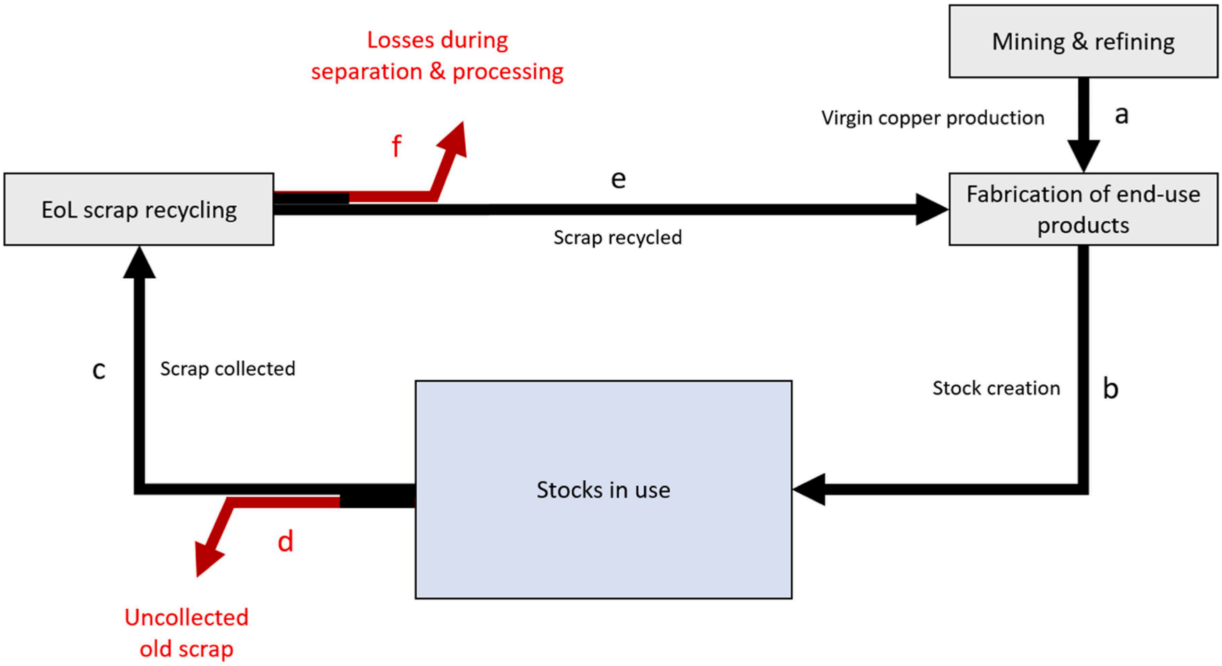

Fig. 2. Global copper stocks and flows model. Arrows and letters represent the flows and boxes indicate the processes. Note that 'Stocks in use' include cumulative sum of all the stock created until a given time (see Box S1.1 in the SI for more information).

Policies Scenario (STEPS), (2) Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 Scenario (NZE) (Table S2.2 in the SI explains the demand scenarios in more depth).

The choice to use the IEA's scenarios was made because we wanted to use demand scenarios for multiple warming pathways that have been derived bottom-up from estimated future use of copper applications, as we believe that this accounts better for ongoing changes in material intensity of technologies and the impact of technology deployment speed on absolute material demand. In contrast, most other metal demand forecasts only provide forecasts for one specific climate warming scenario and often use a top-down approach that extrapolates past material intensity and resource use dynamics into the future.[2] Although the IEA's projections do use relatively conservative technology adoption rates and only account for limited material efficiency gains, its recent publication date, the availability of three different demand scenarios with varying warming potential based on the same methodology, and its wide use in policy circles make their use a good choice.

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[2] See Watari et al. (2022) for a good overview of recent demand forecast studies on copper.

2.4.2.2. Future end-of-life collection and recycling. We take a different path to account for the inherent uncertainty in the future EoL recycling of copper-containing products. Instead of using scenarios, we employ probabilistic methods to forecast the growth rate of two key EoL recycling indicators: the EoL collection rate and the EoL recycling processing efficiency rate. We chose this approach for two key reasons. First, due to the informal nature of metal recycling activities in many parts of the world, even current recycling data has large error margins (Reuter et al., 2013). Second, there are studies that estimate achievable future recycling rates for copper (e.g., Ciacci et al., 2017; Watari et al., 2019; Abdelbaky et al., 2021; Rizos and Righetti, 2022), which makes it possible to derive appropriate parameters for probability distributions.

Given the sparse data availability on previous EoL collection rate increases, we chose a normally distributed linear growth rate to simulate future EoL collection rates. Linear increases are widely used in the literature (e.g. Ciacci et al., 2017; Henckens, 2021; Schipper et al., 2018). The parameters of the distributions are based on the literature (Table S2.2 in the *SI*).

2.4.2.3. Uncertainty quantification. We used Monte Carlo uncertainty analysis to quantify the uncertainties in our results. We ran 10,000 simulations for each of the three demand scenarios using the software @Risk. Each simulation uses a different combination of product group lifetime distributions, EoL collection and EoL recycling processing efficiency growth rates.

2.5. Methodological limitations

The model does not attempt to capture the full complexity of the copper life cycle as done in previous work on global copper stocks and flows (e.g. Graedel et al., 2004, 2011; Glöser et al., 2013; Ciacci et al., 2017). It is rather an attempt to build a simplified, but robust model that allows us to simulate the future availability of recycled copper supply in relation to the expected demand for copper under different collection, recycling processing efficiency and demand scenarios.

The model therefore makes a number of simplifying assumptions. Most importantly, it does not account for stocks and flows of new scrap,[3] as the vast majority of it is reused immediately in the fabrication process (Glöser et al., 2013). Therefore, new scrap does not act as a demand substitute for primary production and can be ignored for the purpose of this study. We also make other simplifying assumptions regarding scrap stocks, product groups and residence times, the economics of copper recycling and copper prices, future copper supply dynamics, as well as policy changes. A more detailed explanation of the methodological limitations can be found in S3 of the *SI*.

3. Results

3.1. Global in-use copper stocks and outflows

The global annual primary copper production has increased from 0.85 million metric tonnes (Mt) in 1910 to more than 20 Mt in 2020. Due to its durable nature, a significant part of the cumulative copper production is still in use today, either because it is still resident in the technosphere for the first time or because it has been recycled one or more times. The size of this in-use stock and the flows from this stock into the global waste management system are the key determinants of the potential for future secondary supply production.

We find that the in-use stock of copper has grown rapidly over the past century. While it was only around 60 Mt in 1960, we estimate that it has grown to over 460 Mt in 2020 (Fig. 3a). We further estimate that 29 % of this in-use stock has already been recycled at least once. However, more than 100 Mt of copper that reached the end of its life have also been lost to landfills and other recycling loops, or have been abandoned in place since 1910. We back-tested the validity of these results and our historic model inputs by comparing the estimated in-use stock with the existing scientific literature. The results showed that our findings are within a margin of error of less than 4 % of two comparable studies (Fig. S1 in the *SI*).

The in-use stock will continue to grow in the coming years. We estimate that the in-use copper stock will increase by between 150 and 290 Mt by 2040. Even under the most conservative STEPS scenario, the in-use stock of copper has the highest likelihood to reach ca. 650 Mt in 2040, which represents a 41 % increase compared to 2020 stock levels (Fig. 3b). While in-use stock will rise rapidly, so will the outflows of copper-containing products that reach the end of their life. In-use stock outflows will rise from ca. 16 Mt per annum in 2020 to a range of between 30 Mt (STEPS) and 33Mt (NZE) in 2050 (Fig. 3c). However, contrary to the future increase in-use stock where we can observe a significant difference between the outcomes of the three demand scenarios, the difference between the three demand scenarios is much less pronounced when it comes to stock outflows.

The main reason for this is the long in-use residence time of copper-containing products. It takes 23 years on average for a tonne of in-use copper to reach the end of its life. Accordingly, a tonne of copper that reaches the end of its life today will on average have been processed and fabricated around the last millennium. Since then, primary copper production has grown from ca. 13 Mt to more than 20 Mt today. Similarly, a tonne of copper that reaches the end of its life in 2040 will have on average been processed and fabricated in 2017. Accordingly, most of the in-use stock outflows by 2040 are driven by past production of copper. As a result, future production growth of copper-containing products driven by the energy transition only has a relatively small impact on stock outflows until the mid- to late-2040s.

3.2. Evolution of secondary copper availability

As the outflow of in-use stock determines the availability of scrap material, a similar dynamic can be observed when it comes to the growth of the secondary copper supply. Even under the very strongly front-loaded future demand growth of the NZE scenario, annual production of secondary supply will only be ca. 10 % higher than under the most modest demand growth estimates of the STEPS scenario (Fig. 4a). Nonetheless, the secondary supply of copper will grow significantly under all scenarios. Annual production of secondary copper will at least double from around 6 Mt in 2020 to over 15 Mt by 2040 due to an average annual growth rate of secondary supply of 2.9 % (STEPS), 3.1 % (APS) and 3.3 % (NZE). All scenarios follow a similar growth trajectory with a peak in secondary supply growth in the first half of the 2020s, before falling off thereafter (Fig. 4c). This dynamic can be explained by unprecedented relative growth in primary copper production in the latter half of the 1990s of over 5 % per annum (USGS, 2015), statistical base effects and limits imposed by the finite amount of copper products that reach the end of their life each year. As a result of this steady growth, the annual share of secondary copper that will be available to meet overall copper demand will increase steadily for all scenarios until 2050 (Fig. 4b & d).

The results of our analysis show that the share of EoL secondary supply of overall copper demand, which currently stands at 23 % will even under the scenario with the lowest demand (STEPS) only average 33.4 % over the next three decades. The lowest average share would be achieved under the NZE scenario where 31 % of total copper demand between 2021 and 2050 would be supplied by secondary material. The key determinants that explain the differences in outcomes are the amount of demand increases and the timing of demand growth. While larger overall demand increases lower the share of secondary supply, quicker demand increases lead to a faster growth in-use stock and larger stock outflows in the 2040s.

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[3] New scrap is the waste that is produced during the fabrication process.

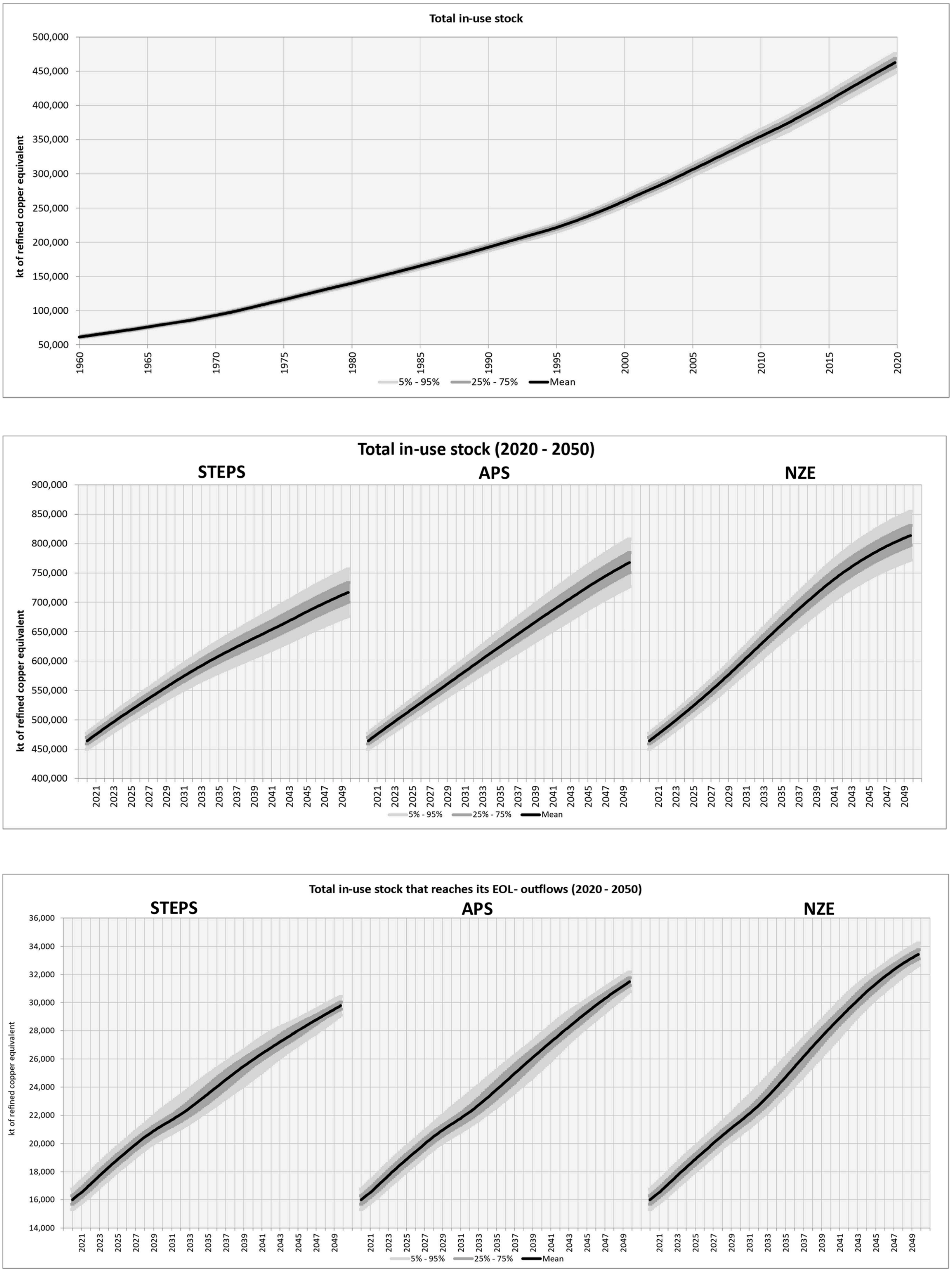

Fig. 3. a: Evolution of the historic in-use stock of copper (1960–2020) b: Total in-use stock of copper under each of the three IEA scenarios (2020 to 2050) c: Total in-use stock of copper that reaches its end-of-life under each of the three IEA scenarios (2020 to 2050).

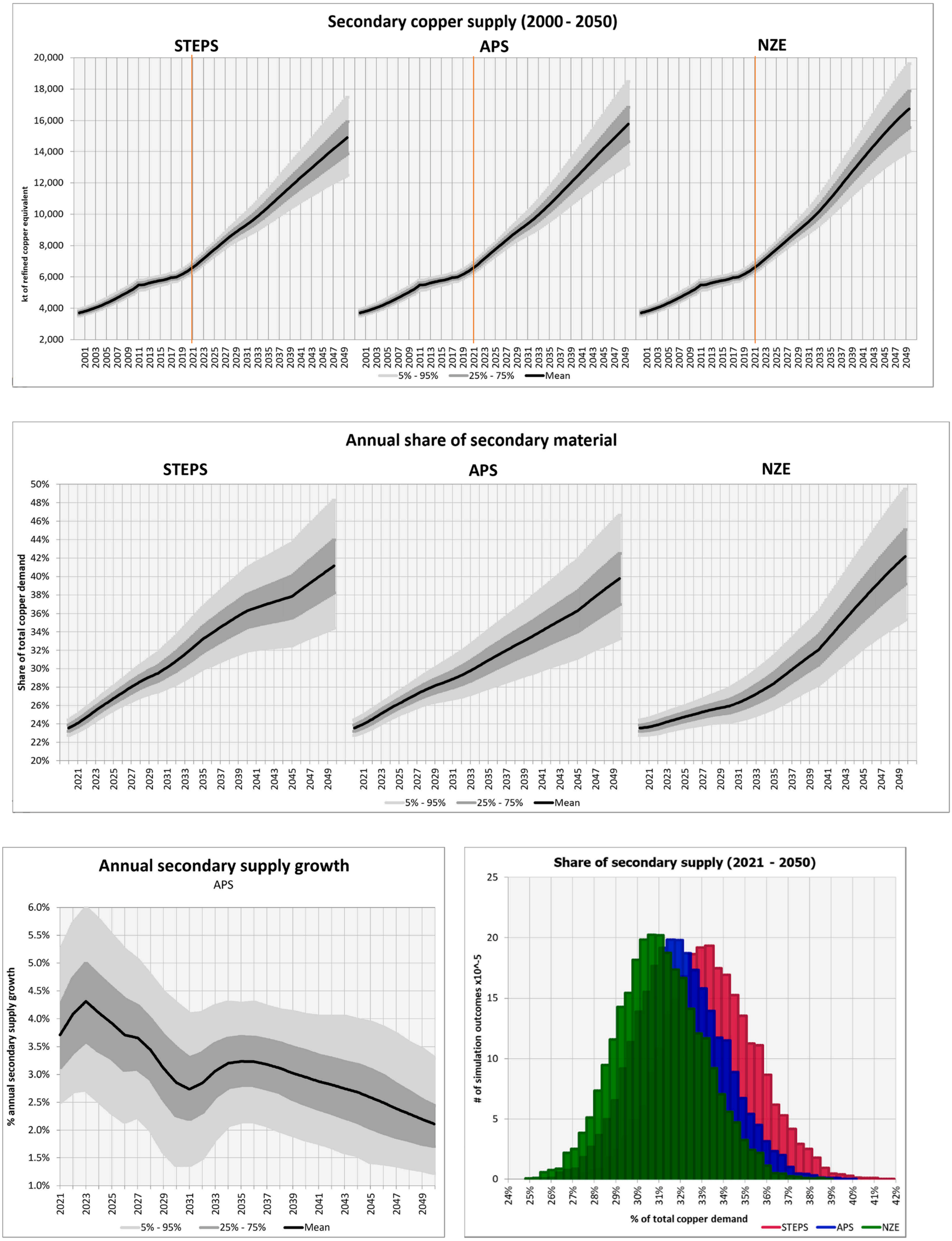

Fig. 4. a: Volume of secondary copper supply under each of the three IEA demand scenarios (2000 –2050). Red line = forecast b: Annual share of total copper demand supplied by recycled material under the three IEA scenarios (2020 to 2050) c: Future annual recycled material growth rate under the APS scenario (2021 – 2050) d: Share of total copper demand supplied by secondary material (2021 – 2050).

Total peak copper demand over the next 30 years is projected to be 36 % (STEPS), 48 % (APS) and 52 % (NZE) higher than current demand. Although the STEPS scenario has the lowest demand growth rate of the three scenarios, it also has the lowest absolute demand increases and thus displays the highest average share of secondary material over the coming three decades. However, as a consequence of the higher total demand for copper and subsequent higher growth in primary production and in-use stock inflows under the NZE scenario, by 2050 the NZE scenario displays the highest annual share of total copper demand supplied by recycled material (Fig. 4b). But even under the most optimistic circumstances of the NZE scenarios with very high collection and recycling rate growth (95th percentile outcome), the annual share of EoL secondary supply of overall copper demand would only reach 49.6 %.

3.3. Impacts on primary copper production

Thus, it becomes clear that despite rapidly growing volumes of secondary copper supply, large increases in the total demand for copper will not slow the need for primary copper production growth for some time to come. We find that under all demand pathways primary production will increase at least into the late 2020s (Fig. 5). In addition, in 87 % of modelled outcomes across all three scenarios, primary production of copper in 2050 will still be above 2020 production levels.

Under the APS and NZE scenarios, primary production will continue to grow until at least 2040. We can observe a reduction of primary production under STEPS in the 2030s before rebounding growth in the early 2040s, as total copper demand accelerates at its fastest pace from 2040 onwards in this scenario, while previously slower demand growth leads to smaller in-use stock outflows that are available for recycling. Only 28 % of all modelled outcomes under the STEPS scenario would reduce primary production of copper in 2050 below 2020 levels, while under APS and NZE only 2.2 % and 9 % of modelled outcomes respectively would meet this threshold. Therefore, only under the STEPS scenario might primary production be replaced sufficiently by secondary material to fall back to current production levels in 2050. All other scenarios will with great likelihood require higher primary copper production in 2050 than in 2020.

4. Discussion

Our dynamic forecast of the future global copper cycle illustrates the unique challenges that many countries and industries will face: how to meet the growing demand for metals while reducing their reliance on the extraction of primary metals. We find that recycling as a CE strategy, while important, is insufficient to decrease the demand for the primary extraction of copper before 2050 under all three demand scenarios we modelled. This suggests that although advances in recycling are essential if we are to reduce the primary production of copper, our analysis shows that there is a less than 7.5 % overall probability that total copper demand will be sufficiently met by additional recycling capacity to reduce primary copper production by 2050. As a result, even with large advances in recycling technology and scrap collection efforts, dozens of new copper mines would have to be opened to increase primary metal extraction and replace the anticipated decreases in production from existing operations, as many large copper mines will reach the end of their useful life before 2050 and average copper ore grades continue to fall (Northey et al., 2014; Tabelin et al., 2021).

These findings are also not unique to copper. Considering the comparatively high recycling rate for copper and the substantial existing in-use stock, the inability of secondary supply to fully replace primary production for copper raises serious concerns for other critical minerals required for the energy transition, most of which have significantly lower existing in-use stocks and recycling capacity. It suggests that other energy transition minerals, such as lithium, will likely encounter even larger constraints, as despite their lower in-use residence times, their very low existing in-use stock levels place a natural cap on EoL material that becomes available for recycling in the short-term. These insights therefore also have significant implications for the debates on the CE of metals and the supply security of minerals critical to the energy transition, as they raise serious questions regarding the adequacy of the currently predominant focus of CE strategies on EoL recycling. This is not to say that EoL recycling does not have an important part to play in transitioning metal supply chains towards more circular modes of production and consumption. However, EoL recycling should be seen as just one of various CE strategies and other CE strategies should receive heightened – if not equal – attention (Allwood, 2014).

There is growing evidence that despite the dominant focus on EoL recycling strategies, demand-side CE strategies, such as product lifetime

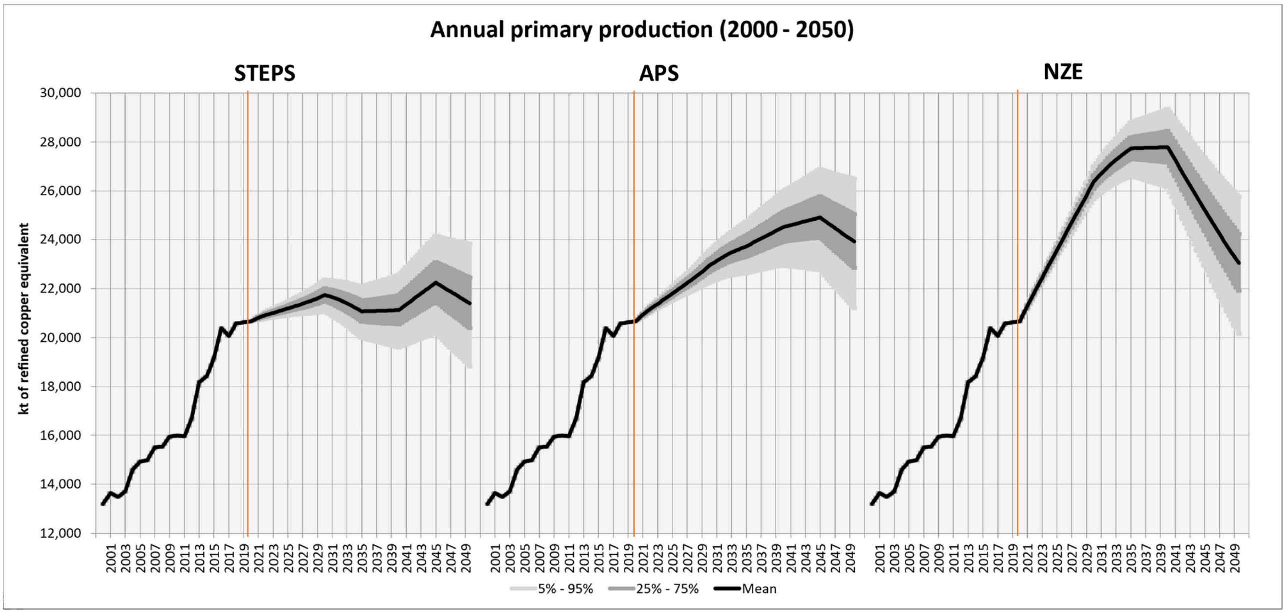

Fig. 5. Volume of required primary copper extraction to fulfil demand under each of the three IEA demand scenarios (2000 –2050). The red line marks the start of the forecast period in 2021.

extensions and changed consumption practices (e.g. sharing of electric vehicles), have the same or even greater potential to reduce primary resource demand than EoL recycling (Watari et al., 2021, 2022). While this calls for a new effort to develop a suite of CE strategies and policies that reduce demand for metals, the large increases in primary production of metals that we are likely to see in the coming decades point towards another important part of the metal life-cycle that can be leveraged to at least reduce the potential environmental and social impact of growing primary metal production: the application of CE strategies in the industrial extraction systems of primary metals.

In recent years the topics of resource governance and responsible sourcing of minerals have received renewed attention (Ali et al., 2017; Dominish et al., 2019; Sovacool et al., 2020; Watari et al., 2021b). While these are important debates given the historic failures of the mining industry to extract materials responsibly and to the benefit of host countries and communities (Lèbre et al., 2020), they take place in a silo that sits mostly outside the scholarship and policy efforts aimed at promoting CE principles and strategies. This is arguably a lost opportunity, as the value proposition of the CE paradigm lies in its approach to offer a systems-solution framework that can promote more sustainable production and consumption practices and business models across industries and value chain segments. There is ample evidence of CE principles being successfully applied to transform business models and production systems not just in mid- and downstream parts of global value chains, but also in the upstream production of raw materials (Ellen MacArthur Foundation, 2023). Therefore, to support industry and policy decision-makers, the research community must explore how CE thinking applies to mining production systems. This could include investigating existing CE strategies in mining, assessing policy readiness to incentivize CE adoption by mining companies, and adapting strategies from other sectors. Regional sharing of mining infrastructure and reusing mining waste products should also be considered to reduce extraction process waste.

To conclude, we have shown that in the case of copper, even under optimistic EoL recycling assumptions, primary production will continue to rise over the coming decades and will with very high likelihood still be above current levels by 2050. Further analysis on other metals will be required to strengthen these insights, but our findings support the argument that in addition to ramping up EoL recycling efforts, a stronger focus must be placed on developing other CE strategies if we are to move towards more circular metal cycles in the short- to medium-term.

CRediT authorship contribution statement

Konstantin Born: Conceptualization, Methodology, Software, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Mehmet Metehan Ciftci:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107318.

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