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Global copper cycles and greenhouse gas emissions in a 1.5 °C world

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ABSTRACT

Moving towards a 1.5 °C world could fundamentally alter the future copper cycle through two key drivers: the implementation of decarbonization technologies and the imposition of an emissions budget on production activities. This study explores the impact of these drivers on the global copper cycle using a dynamic material flow analysis, coupled with an optimization technique. The results show that global final demand for copper could increase by a factor of 2.5 between 2015 and 2050, reaching 62 million metric tons, with approximately 4% of the increase coming from copper used in renewable energy-based power plants and 14% coming from electric vehicles. While there are sufficient resources to meet this growing demand, the greenhouse gas emissions of the copper cycle could account for approximately 2.7% of the total emissions budget by 2050, up from 0.3% today. Assessment of possible mitigation efforts by the copper industry shows that this can be halved, but will still be 35% short of the emissions budget target based on proportional responsibility, i.e., applying the same mitigation rate to all sectors. Rather, collective action is required by all stakeholders interacting with the copper cycle to bridge the mitigation gap, including through efforts to drive advanced sorting, higher fabrication yields, extended product lifetimes, and increased service efficiency of in-use copper stock.

1. Introduction

The scientific evidence is clear: to avoid the devastating impacts of climate change, anthropogenic greenhouse gas (GHG) emissions must be reduced rapidly and substantially to limit the rise in global mean temperature to less than 1.5 °C relative to pre-industrial levels (IPCC, 2021). The question, of course, is, how can this be achieved? A large body of evidence has identified the need for replacing fossil fuel-based technologies with renewable energy and switching to electric vehicles by around the middle of this century (IEA, 2020a, 2020b; Rogelj et al., 2018). However, the feasibility of such climate change mitigation strategies involving large-scale technological deployment is poorly understood from the perspective of material use. Decarbonization technologies, including renewable energy and electric vehicles, require a variety of metals in vast quantities for their functionality (Watari et al., 2020). A good example is copper, which has excellent electric and thermal conductivity, processability, and corrosion resistance. All of these features make copper an essential component of decarbonization technologies (European Copper Institute, 2014). The increased use of electric vehicles and the continued development of renewable energy-based power plants are illustrative of copper's significance. Battery electric vehicles use three times as much copper as conventional gasoline-powered vehicles due to the high demand for wiring harnesses and drive motors (International Copper Association, 2017). The same trend is true for renewable energy-based power plants, which use more than twice as much copper per unit of electricity generation capacity as typical thermal power plants in heat exchangers, turbines, transformers, etc. (The World Bank, 2017). In this context, several studies have identified the potential for increased demand for copper in the energy sector, together with the various associated environmental, social, and governance risks (de Koning et al., 2018; Elshkaki and Graedel, 2013; Lèbre et al., 2020; Watari et al., 2021c).

Of particular importance in the context of climate change could be the GHG emissions associated with copper production. While significant efforts have been made to improve energy efficiency in the copper industry, demand growth, together with declining ore grades, has

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completely offset the improvement, leading to continued increases in GHG emissions from copper production (Azadi et al., 2020; Rötzer and Schmidt, 2020). Currently, GHG emissions from copper production account for only 0.3% (approximately) of total emissions (Hertwich, 2021); however, the combination of growing demand and declining ore grades has the potential to increase this percentage substantially. Since cumulative GHG that can be released into the atmosphere to meet the 1.5 °C climate target, i.e., emissions budget, is extremely limited, production activities will need to be conducted within specific emission limits (IPCC, 2018). These perspectives suggest that two critical components of climate change mitigation—deployment of decarbonization technology and adoption of the emissions budget—could be the main drivers of the future copper cycle, composed of mining, processing, fabrication, use, disposal, and recycling. The critical questions here are: how, when, and to what extent will the global copper cycle change in a 1.5 °C world, and what interventions are needed to reconcile climate change mitigation with a sustainable copper cycle?

Despite the importance of the issue, the energy system models that underpin the scientific debate on climate change mitigation strategies do not cover the copper cycle and thus cannot answer these questions (Pauliuk et al., 2017). While some studies are emerging to help us better understand the feedback between the copper cycle and energy systems in the context of prospective life cycle assessment (Harpprecht et al., 2021), what is needed to address this comprehensively is a complementary system model that explores the entire metal cycle and its associated impacts. Several studies based on the principles of material flow analysis (MFA) have taken important steps to fill this gap by developing future scenarios of the copper cycle (Ciacci et al., 2020; Elshkaki et al., 2016; Kuipers et al., 2018; Northey et al., 2014; Schipper et al., 2018; Yokoi et al., 2022). However, they do not consider the impact of expanded decarbonization technologies on the demand side, nor the impact of the emissions budget on the supply side. Although global scenarios for six major metal cycles have been developed under an emissions budget in line with the 2 °C target (Watari et al., 2021a), the developed scenarios sidestep the 1.5 °C target that is currently a central issue in the debate now underway in the climate change community (IPCC, 2018). It also does not take into account differences in recycling processes depending on scrap grade, resulting in a poor representation of the actual cycle. Without a clear picture of the future copper cycle in a 1.5 °C world, it is difficult to determine science-based targets and responsibilities for individual actors in the copper cycle, including governments, miners, refiners, manufacturers, waste processors, and general consumers.

This study addresses these knowledge gaps by characterizing the evolution of the global copper cycle in line with a transition to a 1.5 °C world. Our approach builds upon dynamic MFA, coupled with a detailed dataset of GHG emission factors, the emissions budget, and optimization routines. This data-driven approach allows for the systematic quantification of multiyear copper cycles under the emissions budget while ensuring a dynamic mass balance of stocks and flows in the system. We first estimate the global copper cycle and associated GHG emissions through 2050 in a world without an emissions budget, identifying this as the "business-as-usual" scenario. The model then explores a series of alternative scenarios harmonized with an emissions budget limiting global mean temperature rise to less than 1.5 °C.

2. Methodology

2.1. Modeling the historical copper cycles

The starting point of the analysis is a proper understanding of the historical copper cycle. This is explored by a system model covering a series of copper cycles consisting of mining, processing, fabrication, in-use stocks, disposal, recycling, and international trade in each process, in the form of ore, semi-finished and finished products, and scrap. Data on international trade are developed from the BACI database (CEPII. BACI (Base pour l'Analyse du Commerce International), 2018), taking into account 288 product categories (Nakajima et al., 2019). Data on the production of ores, refined copper, and semi-finished products are obtained from various statistical data sources (British Geological Survey, 2020; International Copper Study Group, 2020; U.S. Geological Survey, 2020; World Bureau of Metal Statistics, 2020). Other model input data characterizing the copper cycle are based on several material flow analysis studies (see Tables S1-S4 in the Supplementary Information for more details).

The basic principle of the model is the law of mass conservation. The series of copper cycles are represented in a simplified system, as shown in Fig. 1. In this case, most of the copper-containing products, such as buildings and cars, remain in use for an extended period of time. Thus, the accumulation of copper-containing products in society, i.e., the in-use copper stock, is calculated by a lifetime model based on the specific lifetime of each product category. This is a time-cohort-based approach where in-use copper stock is derived from the sum of the copper inflows embedded in the surviving products each year (Müller et al., 2014). The analysis in this domain is essentially based on our previous work (Watari et al., 2021a) but has been updated to 2015 using new data. We confirmed the validity of the model and parameters set in this study by comparing the estimated in-use stock and secondary refined production with the existing scientific literature and statistical data (Fig. S2 in the Supplementary Information).

2.2. Modeling the future copper cycles

2.2.1. Business-as-usual scenario

The possible future development of the metal cycle has so far been explored mainly by two approaches: an inflow-driven approach and a stock-driven approach (Watari et al., 2021b). The inflow-driven approach attempts to directly determine future metal flows using socioeconomic variables such as GDP and the urbanization rate. In contrast, the stock-driven approach is based on the concept that future metal flows will be driven by stock dynamics. This concept is supported by the idea that our service demand is linked to in-use metal stocks, as metals do not perform their functions only at the moment of consumption, like fossil fuels, but continue to perform their functions while they remain in society as products and infrastructure. A literature review of 70 existing studies in this domain indicates that the stock-driven approach, which can take into account the stock saturation mechanism, is more suitable for investigating long-term development paths, as the inflow-driven approach lacks a mechanistic explanation of metal cycles and service provision (Watari et al., 2021b). Therefore, this study adopts a stock-driven approach to explore the future development of the copper cycle.

Assuming that the level of services is linked to the level of copper in-use stocks, a world where all world regions gradually benefit from the services provided by copper in-use stocks in the same way that high-income countries do today can be represented by the growth curve as expressed in Eq. (1) (Liu et al., 2013; Pauliuk et al., 2013).

$$X_{7,\mathrm{BAU}}(t) = \mathrm{POP}(t)\frac{x_{7,\mathrm{sat}}}{1+\left(\frac{x_{7,\mathrm{sat}}}{x_{7,t_0}}-1\right)\exp(\alpha(1-\exp(\beta(t-t_0))))} \quad (1)$$

where $X_{7,\mathrm{BAU}}(t)$ denotes the in-use copper stock in year t, $x_{7,\mathrm{sat}}$ stands for the per capita stock saturation level, and x_{7,t_0} represents per capita stock in the scenario initial year t_0. Additionally, α and β are shape parameters

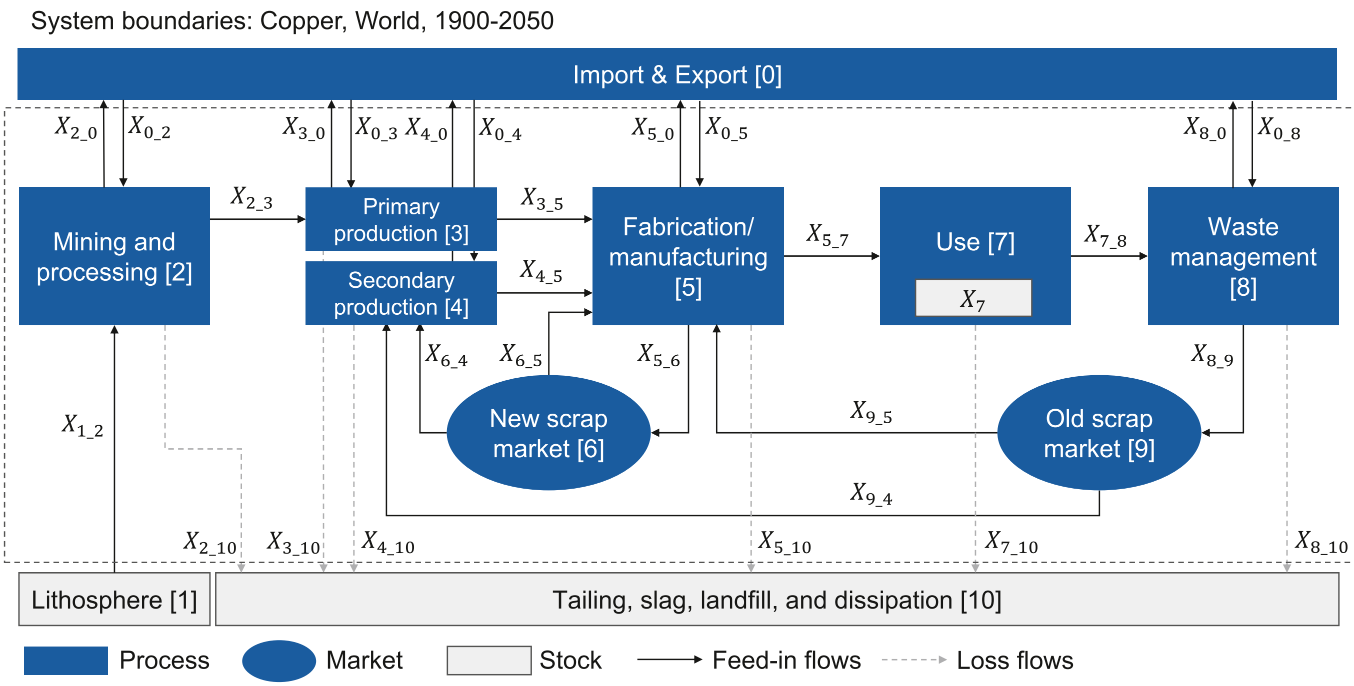

Fig. 1. System definition of anthropogenic copper cycles.

that determine the growth pattern of the curve. POP(t) is the population data obtained from the Shared Socioeconomic Pathways (SSP) 2, which represents a middle-of-the-road scenario (Fricko et al., 2017).

While this approach can comprehensively cover products widely used in society today, it is unable to consider the possibility of a massive expansion of specific products such as decarbonization technologies. Consequently, the growth of in-use copper stocks related to power plants and vehicles is estimated separately based on a more bottom-up method linked to the energy system scenario. Specifically, the in-use copper stocks for these technologies are calculated by multiplying the electricity generation capacity and vehicle fleet described in the energy system scenarios by the copper intensity of each technology. The technologies considered in this study include 11 electricity generation technologies (coal, oil, gas, nuclear, biomass, hydro, geothermal, solar photovoltaics, concentrating solar thermal power, onshore wind, offshore wind) and four vehicle types (internal combustion engine vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles). Future capacity and fleets are derived from the SSP scenario database (Riahi et al., 2017) and the IEA's Energy Technology Perspectives (IEA, 2017). The scenarios used here are SSP2-RCP1.9 and B2DS, respectively (Fig. S3 in the Supplementary Information). Historical capacity and fleets are obtained from several statistical databases (Earth Policy Institute, 2018; The Institute of Energy Economics Japan, 2017; U.S. Energy Information Administration, 2018). The copper intensity and average lifetime of each technology are taken from the relevant scientific literature (Tables S5-S7 in the Supplementary Information).

By determining the future stock growth pattern, the inflow required in year t, $X_{5\_7,\mathrm{BAU}}(t)$, to achieve the estimated stock growth can be computed by the following:

$$X_{5\_7,\mathrm{BAU}}(t) = X_{7,\mathrm{BAU}}(t) - X_{7,\mathrm{BAU}}(t-1) + \sum_{t'=0}^{t}\left((1-\omega)X_{5\_7,\mathrm{BAU}}(t')\varphi(t-t')\right) \tag{2}$$

where ω and ϕ denote the in-use dissipation loss rate and lifetime distribution, respectively. Importantly, the business-as-usual scenario does not take into account the emissions budget and thus reflects a world in which copper use can be expanded without constraints.

We investigate the validity of the scenario by comparing the estimated refined copper demand with 54 data points from previous studies (de Koning et al., 2018; Elshkaki et al., 2018, 2016; Halada et al., 2008; Kapur, 2005; Kuipers et al., 2018; Schipper et al., 2018; Tokimatsu et al., 2017).

2.2.2. Emissions budget scenario

The copper cycle under the emissions budget is explored using an optimization routine based on the system model described above. This model treats the world as a single region; thus, the trade flows are not further considered here ($X_{i,0} = 0\ \forall i,\ X_{0,j} = 0\ \forall j$). The optimization routine determines the annual copper supply ($X_{3\_5} + X_{4\_5} + X_{6\_5} + X_{9\_5}$) to maximize the in-use stock available under the emissions budget within the scenario period. The core equations of the model are shown below.

$$\text{maximize}: \quad X_7(t) = \sum_{t'=0}^{t}\left((1-\omega)X_{5\_7}(t') - X_{7\_8}(t')\right) \tag{3}$$

$$\text{subject to}: \quad X_7(t) \le X_{7,\mathrm{BAU}}(t) \tag{4}$$

$$X_{5\_7}(t) = \lambda(t)\left(X_{3\_5}(t) + X_{4\_5}(t) + X_{6\_5}(t) + X_{9\_5}(t)\right) \tag{5}$$

$$X_{7\_8}(t) = \sum_{t'=0}^{t}\left((1-\omega)X_{5\_7}(t')\varphi(t-t')\right) \tag{6}$$

$$X_{8\_9}(t) = \gamma(t)X_{7\_8}(t) \tag{7}$$

$$X_{9\_5}(t) = \mathrm{CSR\_old}(t)X_{8\_9}(t) \tag{8}$$

$$X_{9\_4}(t) = X_{8\_9}(t) - X_{9\_5}(t) \tag{9}$$

$$X_{5\_6}(t) = \xi(t)(1-\lambda(t))\left(X_{3\_5}(t)+X_{4\_5}(t)+X_{6\_5}(t)+X_{9\_5}(t)\right) \tag{10}$$

$$X_{6\_5}(t) = \mathrm{CSR\_new}(t)X_{5\_6}(t) \tag{11}$$

$$X_{6\_4}(t) = X_{5\_6}(t) - X_{6\_5}(t) \tag{12}$$

$$X_{4\_5}(t) = \theta(t)(X_{6\_4}(t)+X_{9\_4}(t)) \tag{13}$$

$$E_{\mathrm{pri}}(t)X_{3\_5}(t) + E_{\mathrm{sec}}(t)X_{4\_5}(t) + E_{\mathrm{direct}}(t)\left(X_{6\_5}(t)+X_{9\_5}(t)\right) \le \mathrm{Budget}\ (t) \tag{14}$$

where the system variables and parameters are defined as follows. X_7: Copper-containing products in use (In-use copper stock). X_{5_7}: Inflow of copper-containing products. X_{7_8}: Outflow of copper-containing product. X_{3_5}: Primary refined copper. X_{4_5}: Secondary refined copper. X_{6_5}: Directly melted high-grade new scrap. X_{9_5}: Directly melted high-grade old scrap. X_{8_9}: Collected old scrap. X_{9_4}: Low-grade old scrap for smelting and refining. X_{5_6}: Collected new copper scrap. X_{6_4}: Low-grade new scrap for smelting and refining. E_{pri}: GHG emission intensity for primary refined production. E_{sec}: GHG emission intensity for secondary refined production. E_{direct}: GHG emission intensity for direct melting. ω: In-use dissipation rate. φ: Lifetime distribution. λ: Fabrication yield. γ: Old scrap collection rate. ξ: New scrap collection rate. θ: Secondary refined production yield. CSR_old: Clean scrap ratio of collected old scrap. CSR_new: Clean scrap ratio of collected new scrap. Budget: GHG emissions budget. $X_{7,\mathrm{BAU}}$: In-use copper stock in the business-as-usual scenario.

The emissions budget allocated to the copper cycle is determined based on the annual emissions mitigation rates in fossil fuels and industry to keep the global temperature rise below 1.5 °C relative to pre-industrial levels (Rogelj et al., 2018) (Table S13 in the Supplementary Information). This reflects the assumption that the copper cycle contributes to emissions reduction pathways in proportion to other sectors, as in several previous studies on different material cycles (Cao et al., 2020; Liu et al., 2013; Ryan et al., 2020; van Ewijk et al., 2020). The GHG emission intensities associated with primary and secondary refined production and direct melting are based on life cycle assessment studies and are assumed to change over time due to changes in electricity systems and ore grades (Tables S10-S12 and Fig. S4 in the Supplementary Information) (Ciacci et al., 2020; Kuipers et al., 2018; Van der Voet et al., 2019). In this case, we assume that the ratio of pyrometallurgical and hydrometallurgical process to primary refined copper production route will remain unchanged from the current level, with pyrometallurgical process at 81% and hydrometallurgical process at 19% (International Copper Study Group, 2020). The future electricity system is based on the SSP2-RCP1.9 for consistency with the business-as-usual scenario. That is, we assume that the copper production process is directly connected to the grid electricity supply, and thus electricity-related GHG emissions (i.e., indirect emissions) are assumed to be decarbonized along with an energy transition to a 1.5 °C emission pathway.

2.3. Strategy assumption

In addition to the electricity system, the future copper cycle under the emissions budget is contingent on several important parameters. Thus, we envision that the following six strategies will be implemented individually and simultaneously. The rates and levels of implementation are meant to be ambitious but not unrealistic based on the scientific literature and technology roadmaps. The key assumptions are described below (further details are provided in Table S9 in the Supplementary Information).

- *Energy efficiency improvement*: Energy efficiency will gradually approach the theoretical maximum as the best available technologies become more widely adopted (Wyns and Khandekar, 2020). Specific options to achieve this include smarter and integrated control systems, increased efficiency of burners, and increased heat recovery.
- *Electrification*: The energy demands of low- and medium-temperature processes such as space heating, steam generation, and drying will be electrified with already established technologies such as compression heat pumps, mechanical vapor recompression, electric boilers, infrared heaters, microwave heaters, and high frequency heaters (Madeddu et al., 2020). We do not consider the electrification of high-temperature processes here, since both primary copper smelting and secondary production via scrap fed into primary smelters derive a fairly large portion of the heat supply from the oxidation of sulfide minerals, and thus the portion of heat derived from fossil fuels is considerably smaller (Goonan, 2004).
- *Aggressive recycling*: The old scrap collection rate will approach the theoretical maximum by overcoming the difficulties in collection and separation associated with product miniaturization, the complexity of material compositions, and combinations to meet the demand for better functionality (Ciacci et al., 2015; Dong et al., 2020; Wang et al., 2021).
- *Advanced sorting*: The clean scrap ratio of collected old scrap will be increased through sensor-based sorting technologies (e.g., x-ray fluorescence (XRF) and laser-induced breakdown spectroscopy (LIBS)) that enable the separation of alloy types and specific alloys for direct melting with minimal or no loss of quality (Loibl and Tercero, 2021).
- *Fabrication yield improvements*: Fabrication yields will be increased to 95% through such measures as minimizing the amount of trimming and machining in the fabrication and manufacturing process (Liu et al., 2013; Milford et al., 2013).
- *Lifetime extension*: Product lifetime will be extended through durable design, repair, remanufacturing, and component reuse. We set up the possibility of product lifetime extension by referring to several literature sources (Table S14 in the Supplementary Information) (IRP, 2020; Klose and Pauliuk, 2021; Milford et al., 2013; Olave et al., 2020; Pakenham et al., 2021; Watari et al., 2021c).

3. Results

3.1. Historical evolution of in-use copper stock

The evolution pattern of global in-use copper stocks from the past to 2015 varies widely depending on the income-based country group

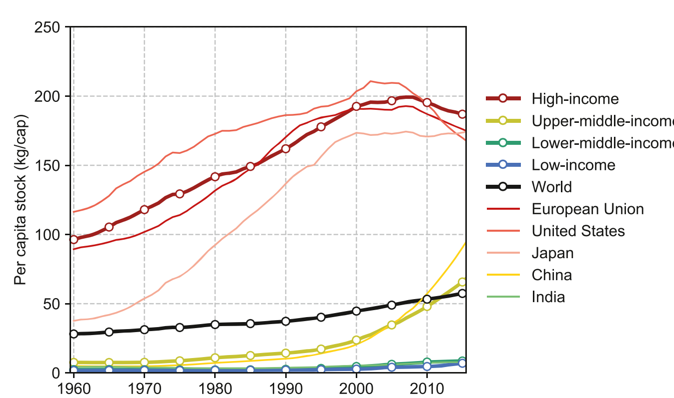

Fig. 2. Per capita in-use copper stock around the world by income-based country group, 1960–2015. The classification of income group is based on the World Bank's classification (The World Bank, 2021). The 2015 classification is used throughout the period (Table S17 in the Supplementary Information). The five countries/regions with the largest stocks (i.e., European Union, United States, Japan, China, and India) are also shown.

(Fig. 2). Current high-income countries, including the European Union, the United States, and Japan, experienced continuous growth in per capita copper stocks until around 2000, after which they gradually stabilized at approximately 180 kg/capita. On the other hand, upper-middle-income countries, including China, increased their per capita copper stock at an accelerated rate since roughly 2000. Still, the 2015 level remains approximately half that of the current high-income countries. Lower-middle and low-income countries, including India, have shown signs of rapid growth in recent years; however, their levels remain around 10 kg/capita. These trends provide a solid foundation for exploring how copper use may evolve in the future. Given the stock development trend observed here, the stock saturation level used in the business-as-usual scenario was set using the 2015 value in current high-income countries (Table S8 in the Supplementary Information).

3.2. Future copper cycles in the business-as-usual scenario

Under the business-as-usual scenario, global final demand (inflow) for copper will increase 2.5-fold from 2015 to 2050, reaching approximately 62 million metric tons (Mt), of which roughly 4% will come from renewable energy-based power plants and 14% from electric vehicles (Fig. 3). Battery electric vehicles are the primary driver of this growth, accounting for 10% of final demand in 2050. Such a prominent impact from renewable energy-based power plants and electric vehicles is brought about by the approximately 33-fold increase in their copper demand from 2015 to 2050, which is much larger than the approximately 2-fold increase in other sectors. Nevertheless, it is important to note that demand in 2050 will still be dominated by other sectors, with the building and construction sector, excluding power plants, accounting for the largest share at 31%, followed by the consumer and electronics sector at 22% (Fig. S5 in the Supplementary Information). End-of-life wastes (outflow) will also continue to increase within the scenario period, but remain at about half of final demand in 2050, or about 35 Mt, due to the continued expansion of in-use stock.

A comparison of the estimated refined copper demand with 54 data points from previous studies confirmed that the estimates for both 2030 and 2050 are in good agreement with these previous studies (Fig. 4). The difference between this study and the median of previous studies for the year 2030 is only 6%, while the estimate for the year 2050 is 7% larger than the median of the previous studies. This latter difference is likely due to the fact that our study considers separately the expansion of decarbonization technologies, which account for 18% of total demand in 2050. Overall, these observations indicate that the global demand for copper presented in this study is quite reasonable in light of other scientific studies.

The cumulative ore requirement during the scenario period is approximately 1240 Mt contained Cu at maximum, which is well below the currently identified resources of 3035 Mt contained Cu (Mudd and Jowitt, 2018). In practice, the resources data are likely to show increases over time, as mining companies take the approach of drilling and producing a portion of the deposit and using the proceeds to expand resources and reserves rather than immediately determining the full extent of the deposit. In fact, another database indicates that since 1950, there has consistently been, on average, 40 years of reserves and 200 years of resources remaining (U.S. Geological Survey, 2020). Together with this dynamic nature of resources data, it is reasonable to conclude that natural copper resources will not be physically depleted within the next several decades.

However, GHG and other emissions associated with the copper cycle can be problematic. If the current trend in energy efficiency and

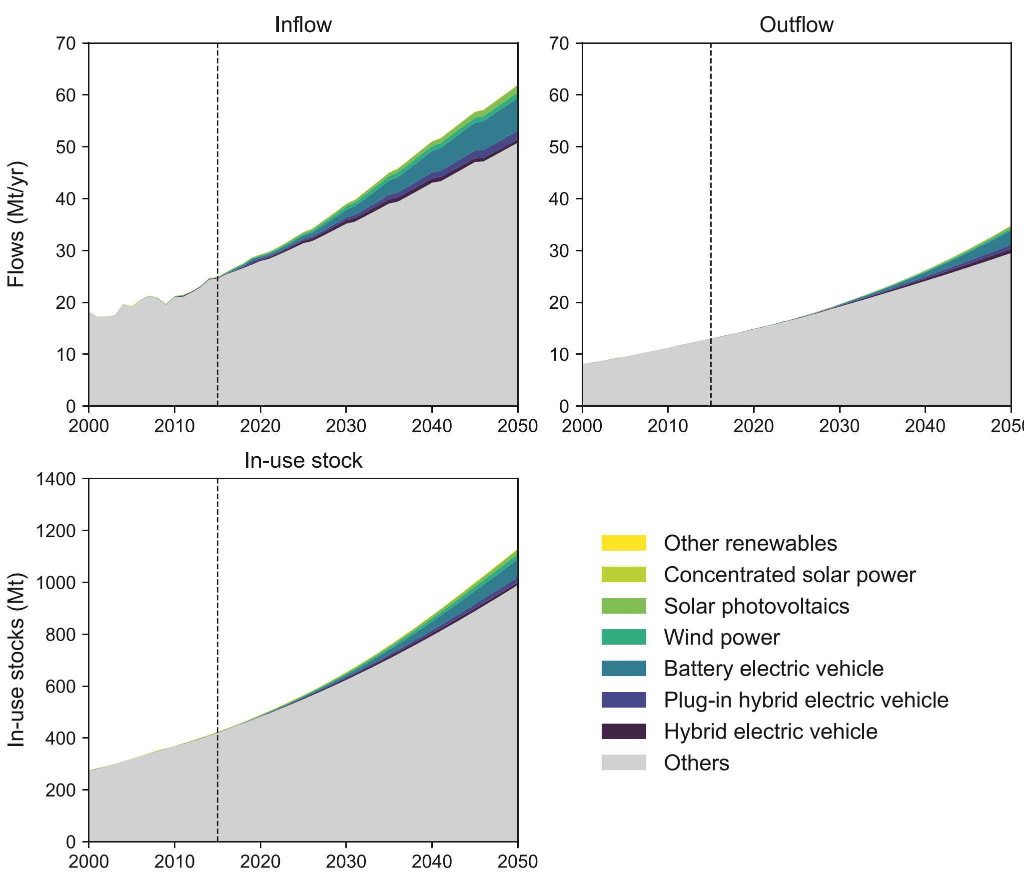

Fig. 3. Global copper inflow, outflow, and in-use stock in the business-as-usual scenario, 2000–2050. The vertical dashed lines mark the year in which the future scenarios begin (2015). “Others” includes building and construction, infrastructure, transport, industrial equipment, and consumer and electronic, excluding power plants and vehicles.

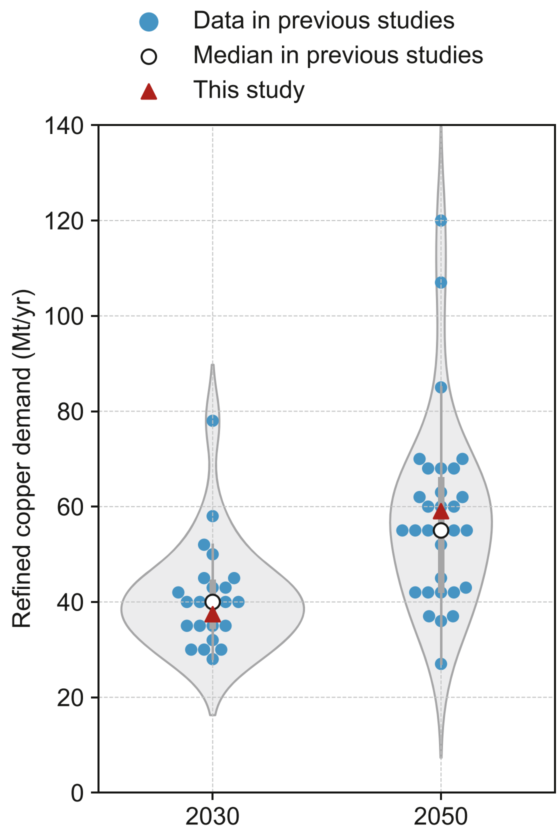

Fig. 4. Comparison of refined copper demand estimates in this study with 54 data points in previous studies. The gray area shows the probability density of the data in previous studies, smoothed by kernel density estimation. (Data taken from de Koning et al., 2018; Elshkaki et al., 2018, 2016; Halada et al., 2008; Kapur, 2005; Kuipers et al., 2018; Schipper et al., 2018; Tokimatsu et al., 2017.).

recycling continues, GHG emissions from the copper cycle will double by 2050, reaching approximately 240 Mt-CO_2eq. (Fig. 5). Consequently, the share of the copper cycle in the total emissions budget will increase at an accelerated rate, reaching roughly 2.7% by 2050, up from approximately 0.3% in 2015. A combination of energy efficiency improvements, electrification, and aggressive recycling—all of which are currently at the center of the climate change mitigation debate—can halve emissions from the 2050 copper cycle compared to no strategy. However, it is clearly not sufficient for the copper cycle to contribute proportionally to emission mitigation targets for fossil fuels and industry and thereby leave a substantial mitigation gap. Specifically, an additional reduction of approximately 35% is required to close this gap.

3.3. Future copper cycles under the emissions budget

One way to close the mitigation gap is through innovation in production-side technologies. However, closing the gap solely through such innovation would require reducing the emission intensity of primary refined production routes by at least 52% by 2030 and by at least 95% by 2050 relative to 2015. Technology options could include electrification of the high-temperature processes (>1000 °C), use of bio-based materials and synthetic fuels, and implementation of carbon capture, utilization, and storage. However, given the substantial length of time required for technological transition (Nelson and Allwood, 2021), sufficient mitigations could be difficult to achieve in time. We need to be prepared for such a case by exploring how, when, and to what extent future copper cycles will change under the emissions budget if production-side technological innovations fail to scale up sufficiently in time.

We estimated that, under the 1.5 °C emissions budget, primary refined production peaks by 2023 at the latest in all scenarios and then declines gradually through 2050 (Fig. 6). This is approximately seven years earlier than under the 2 °C emissions budget (Watari et al., 2021a). On the other hand, recycling-related production increases significantly over time and exceeds primary refined production by around 2040 in all scenarios. However, production activities using both new and old scrap as raw material eventually slow down due to the limited quantity of available scrap.

Consequently, the per capita copper stock available under the emissions budget could be constrained in comparison to the business-as-usual scenario (Fig. 7). If the situation for production-side technologies does not improve, the per capita copper stock will be limited to approximately half that in the business-as-usual scenario by 2050. Such constraints can be relaxed to some extent with the ambitious implementation of energy efficiency improvements, electrification, and aggressive recycling, which are central strategies in the current climate change mitigation debate. Nevertheless, the per capita stock would remain approximately 32% below the stock level in the business-as-usual scenario. The addition of advanced sorting, fabrication yield improvement, and lifetime extension hold promise of increasing the available in-use stock but would still limit the available stock in 2050 to

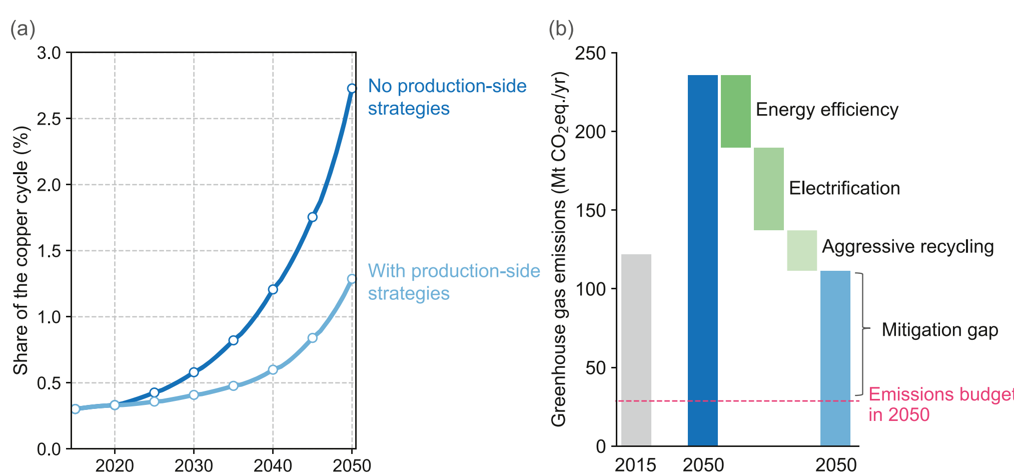

Fig. 5. GHG emissions associated with the global copper cycle, 2015–2050: (a) Share of the copper cycle in the total emissions budget for fossil fuels and industry; (b) Waterfall chart showing the extent to which different production-side strategies reduce GHG emissions from the global copper cycle in 2050. Note that since the electricity generation system is based on SSP2-RCP1.9, decarbonization of indirect emissions is already incorporated in all scenarios.

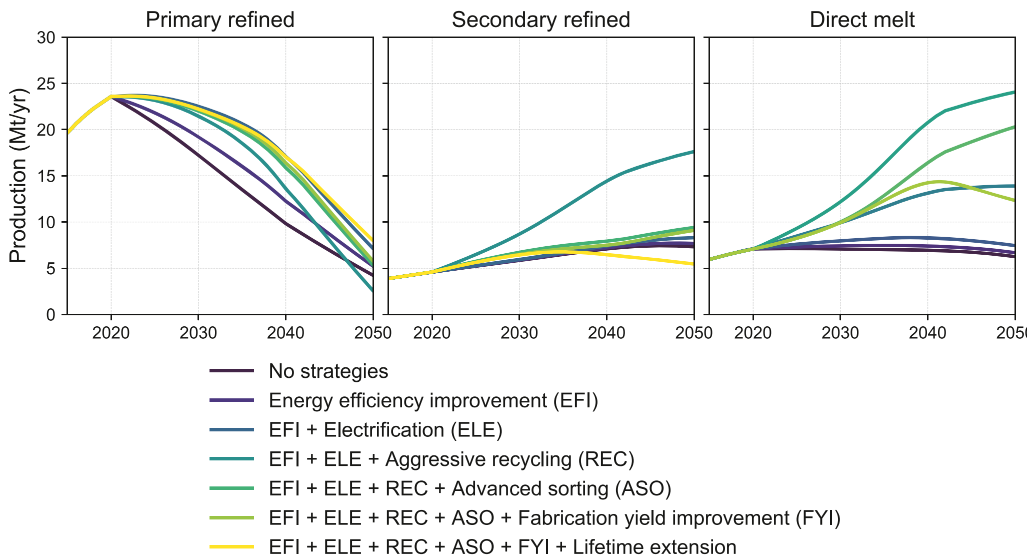

Fig. 6. Global copper production available under the emissions budget, 2015–2050. Primary refined, Secondary refined, and Direct melt correspond to X_{3_5}, X_{4_5}, and ($X_{6\_5} + X_{9\_5}$) in Fig. 1, respectively.

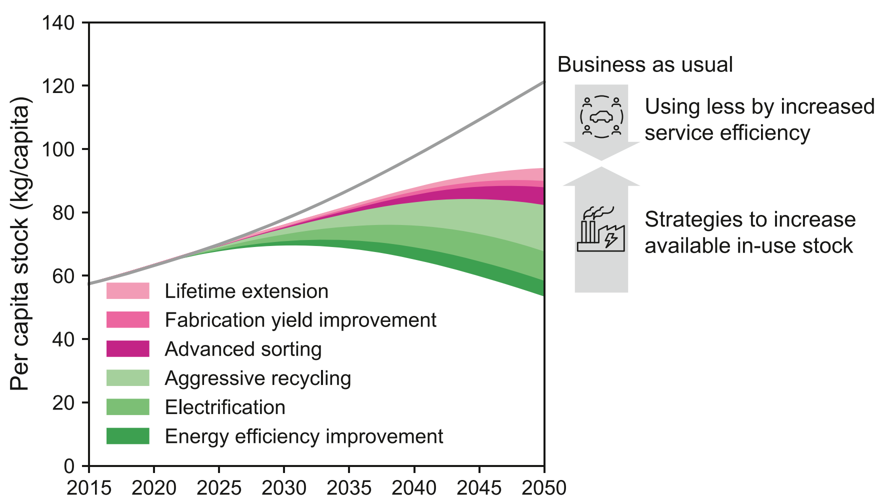

Fig. 7. Global copper in-use stock available under the emissions budget, 2015–2050. The business-as-usual scenario is presented as a comparison, showing the gaps that cannot be filled by strategies to increase the available in-use stock.

a level 23% lower than the available stock level in the business-as-usual scenario. This means that our service demands (e.g., mobility, housing, and communication) will need to be met with approximately 23% less per capita stock by 2050 relative to the case without the emissions budget. In absolute terms, the global per capita copper stock will converge at roughly 94 kg/cap, which is approximately half the level of current high-income countries.

3.4. Comparison of the scale of change in the copper cycle

A more intuitive comparison of the copper cycle in a world with and without the emissions budget can be obtained from the Sankey diagram (Fig. 8). In the business-as-usual scenario for 2050, all flows are more than doubled compared to 2015, and a large portion of the losses are derived, especially in the end-of-life phase. On the other hand, the emissions budget scenario for 2050 with various strategies reduces the losses in the end-of-life phase, with 90% of the end-of-life copper waste collected as old scrap. Furthermore, in 2015, about 70% of the collected old scrap was reintroduced to the smelting and refining process due to quality issues, but the emissions budget scenario for 2050 treats most of it through direct melting by using more advanced sorting technologies (e.g., XRF and LIBS). Combining these factors with improved fabrication yields enables the same level of final demand as in 2015 to be supplied with approximately 60% less copper content in the ores and approximately 40% less refined copper. This, together with low-carbon production processes, will provide society with the same amount of copper-containing products as in 2015 while reducing associated GHG emissions by 80%. The maps presented here help explain which flows will change, how, and to what extent, and enable an exploration of key intervention opportunities in the transition to a 1.5 °C world from a material cycle perspective.

4. Discussion

4.1. There is no silver bullet

Our data-driven analysis of the multiyear copper cycle illustrates the unique challenges that many materials industries will face: how to meet the growing demand for material services while staying within the emissions budget for production activities. In this context, the analysis

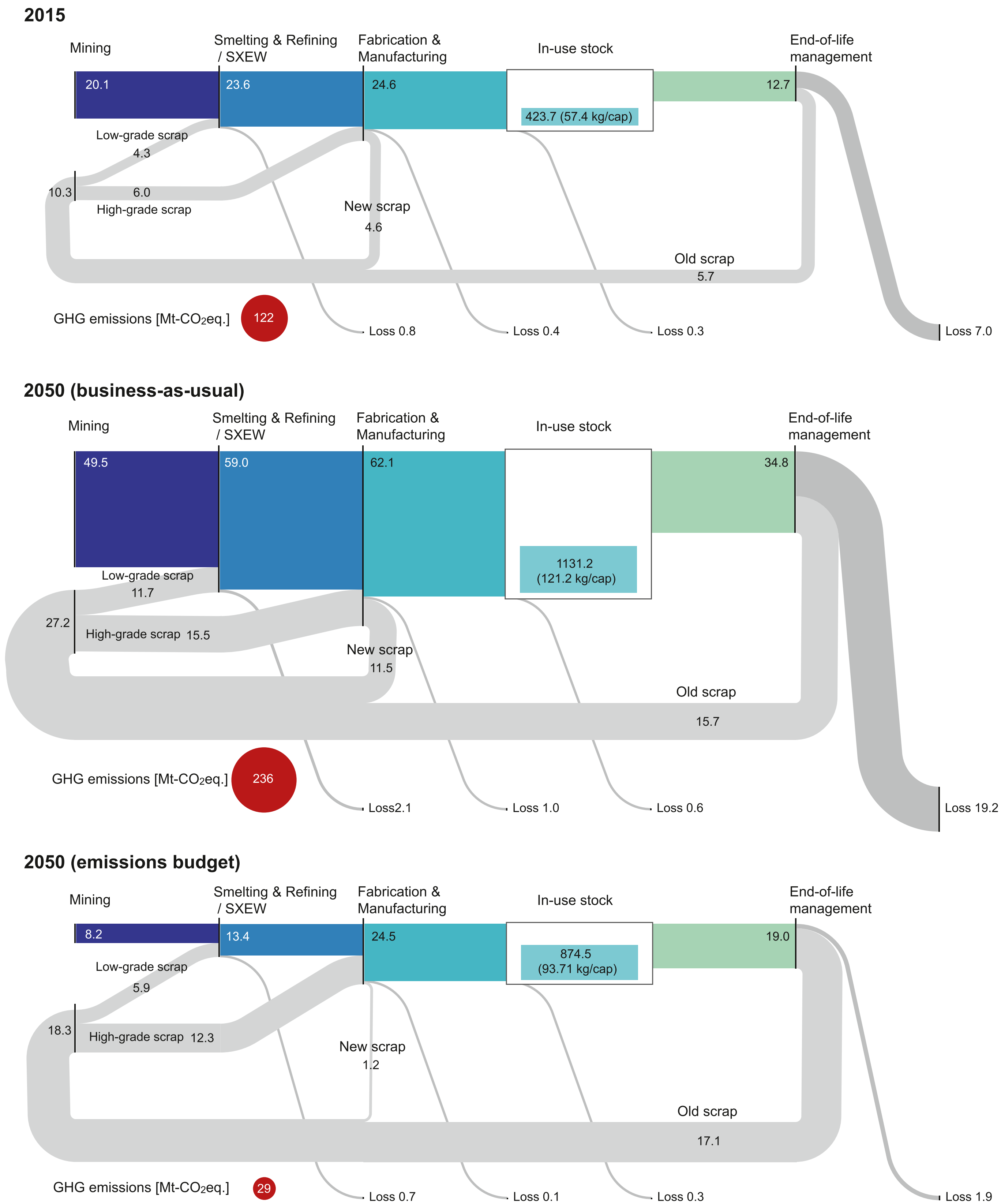

Fig. 8. Sankey diagram showing the global copper cycle in 2015, 2050 in the business-as-usual scenario, and 2050 in the emissions budget scenario. The emissions budget scenario implements all the strategies described in the methodology section. All flows are shown to scale in Mt/yr; in-use stocks shown in the box are in Mt and scale differently than flows. The numbers in the lower left circle show annual GHG emissions associated with the global copper cycle. The Sankey diagrams were designed with floWeaver (Lupton and Allwood, 2017).

confirms that there is no silver bullet to deliver adequate emissions abatement. Rather, what is needed is a concurrent and ambitious implementation of a suite of strategies that span the whole material cycle, including not only the mining, smelting, and refining phases but also the product design, manufacturing, use, and end-of-life phases. These include advanced sorting, fabrication yield improvement, and lifetime extension.

Still, in the case of copper, even after the ambitious implementation of these strategies, our service demand will need to be met with approximately 23% less in-use copper stock than in the business-as-usual scenario by 2050. An important question here is whether this is achievable. We conducted a simplified bottom-up analysis based on a literature review and found that a 23% reduction in demand is quite possible through various measures that would increase service efficiency, such as enhanced sharing practices and better scheduling (Table S15 in the Supplementary Information). The answer, then, is yes, we can meet our service demands with copper use levels consistent with the emissions budget. However, we need to change the way we use copper-containing products to make them more materially efficient. This observation, together with the key drivers of demand growth estimated in this study, highlights the importance of not only strategies for expanding the market share of decarbonization technologies but also strategies for producing and using them in a material-efficient manner. This is especially true for battery electric vehicles, which will account for more than 10% of final copper demand in 2050. Policies to promote electric vehicles sales, such as banning the sale of gasoline-powered vehicles from a particular year (IEA, 2020b), need to be considered from this perspective. In these cases, the trade-offs between material efficiency, material performance, and energy efficiency should be carefully assessed on a life cycle basis to ensure optimal policy and product design outcomes.

The findings here call into question the existing scenario design, which is heavily biased towards end-of-life recycling (Watari et al., 2021b). While, as shown in this study, recycling plays an important role in reducing GHG emissions from the copper cycle, recycling alone does not deliver the required scale of emissions reduction due to the limited quantity and quality of available scrap. Thus, recycling should be positioned as just one of the various strategies that can be applied throughout the copper cycle. In this regard, it is important to note that this study may overestimate the benefits of recycling as it does not consider the potential for increased energy consumption and hence GHG emissions due to lower metal concentrations in scrap. As demonstrated in several previous studies (Schäfer and Schmidt, 2021, 2019; Wang et al., 2021), if metals are too diluted in the technosphere, their recycling may require more energy than the primary production process. In such a case, the importance of other strategies increases even more.

4.2. Implications for business activities

This study also has implications for business activities in the materials industry. Currently, many in the copper industry are expecting new business opportunities from the increased demand driven by the expansion of decarbonization technologies. However, our analysis shows that although demand in such specific sectors could grow in a transition to a 1.5 °C world, total refined copper production could be constrained by the emissions budget. This may suggest the need for the copper industry to explore in advance other business opportunities should this occur. Examples include developing high-performance materials that provide similar functionality with less usage and the recovery of by-product metals. In particular, many of the copper by-product metals that are essential for decarbonization technologies are currently recovered at very low efficiencies in the primary production process (e.g., tellurium: 5%, selenium: 5%, cobalt: 50%, rhenium: 60%), leaving significant room for improvement (Wang et al., 2018). Improving the recovery rate of these critical metals that are currently stranded in considerable quantities in tailings, slags, and slimes during the mining, smelting, and refining processes could provide an important business opportunity. Alternatively, it may be desirable to explore how emissions budgets should be set for sectors whose growth enables emissions reductions to occur in other sectors. In this case, however, as the time remaining is extremely limited, we need to have the discussion and come to a decision as soon as possible.

4.3. Role of stakeholders

Another essential perspective emerging from our analysis relates to the role of the stakeholders. The traditional approach, which expects and promotes technological innovation on the production side, generally requires only the efforts of miners, smelters, and refiners, with the appropriate support of government policy (Giurco and Petrie, 2007). Yet, as demonstrated in this study, such efforts alone may not be sufficient to achieve the necessary emissions reduction in the time remaining. If this is indeed the case, a more extensive, system-wide solution is required, with actions not only by miners, smelters, refiners, and governments, but by all the stakeholders involved in the copper cycle, including product designers, urban planners, property owners, manufacturers, general consumers, and waste processors. Ultimately, what is needed is a shared future vision that can encourage collective action among all the various stakeholders. In this regard, our study can provide scientific support and provide a methodological basis for exploring material cycles in a 1.5 °C world from a broad, system-wide perspective.

4.4. Opportunities for further work

We recognize that the modeling approach demonstrated in this study has several challenges that will need to be addressed in the future, in addition to the data uncertainties and simplifying assumptions detailed in Table S16 in the Supplementary Information. First, it is important to note that the analysis simply compares supply and demand, and does not consider their dynamic interaction through price fluctuations in the actual market. Consequently, the results should be interpreted as an illustrative scenario rather than a future forecast. In addition, this study only provides a rough assessment of the technological potential for in-use copper stock reduction through improved service efficiency in each sector on a global scale. In order to support concrete policy design, more bottom-up modeling approaches are required at the specific product and country level, moving beyond aggregated sectoral and global assessments. Since such efforts have increasingly emerged in recent years (Pauliuk et al., 2021; Zhong et al., 2021), integrating the framework presented in this study with an appropriate high-resolution modeling approach would be an important step in providing truly holistic support for environmental policy design and business innovation.

CRediT authorship contribution statement

Takuma Watari: Conceptualization, Methodology, Software, Investigation, Visualization, Writing – original draft. **Stephen Northey:** Conceptualization, Writing – review & editing. **Damien Giurco:** Writing – review & editing. **Sho Hata:** Writing – review & editing. **Ryosuke Yokoi:** Writing – review & editing. **Keisuke Nansai:** Conceptualization, Methodology, Writing – review & editing. **Kenichi Nakajima:** Conceptualization, Methodology, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Supplementary materials

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