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Assessing China’s potential for reducing primary copper demand and associated environmental impacts in the context of energy transition and “Zero waste” policies

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ABSTRACT

To conserve resources and enhance the environmental performance, China has launched the “Zero waste” concept, focused on reutilization of solid waste and recovery of materials, including copper. Although several studies have assessed the copper demand and recycling, there is a lack of understanding on how different waste management options would potentially reduce primary copper demand and associated environmental impacts in China in the context of energy transition. This study addresses this gap in view of a transition to low-carbon energy system and the optimization of copper waste management combining MFA and LCA approaches. Six types of waste streams (C&DW, ELV, WEEE, IEW, MSW, ICW) are investigated in relation to various “Zero waste” strategies including reduction, reuse (repair, remanufacturing or refurbishment), recycling and transition from informal to formal waste management. Under present Chinese policies, reuse and recycling of copper containing products will lead to a somewhat lower dependency on primary copper in 2100 (11187Gg), as well as lower total GHG emissions (64869 Gg CO2-eq.) and cumulative energy demand (1.18x10ˆ12 MJ). Maximizing such “Zero waste” options may lead to a further reduction, resulting in 65% potential reduction of primary copper demand, around 55% potential reduction of total GHG emissions and total cumulative energy demand in 2100. Several policy actions are proposed to provide insights into future waste management in China as well as some of the challenges involved.

1. Introduction

To improve the efficiency of resource use, China is transitioning from a linear, ‘take-make-dispose’ economy to a circular economy that aims to maintain products, components and materials at their highest utility and value (NDRC, 2017). Waste management is a key element of moving towards a circular economy, and is particularly relevant for metals where supply constraints may emerge in the future. Solid waste is a heterogeneous waste stream from a wide range of sources in the economy that, unless properly managed, can lead to considerable resource losses and cause serious environmental damage. To further promote the development of waste management, China has introduced the “Zero

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Abbreviations: CP scenario, Chinese Policy scenario; CR, Collection rate; C&DW, Construction & Demolition Waste; CED, Cumulative energy demand; EoL, End-of-life; ELV, End-of-life Vehicles; FPR, Formal processing rate; REoF, Fraction of collected ELV copper reused; FSoIC, Fraction of formal sorting and dismantling from informal collection; REoF, Fraction of reuse from formally collected copper; REoIF, Fraction of reuse from informally collected copper; FoFC, Fractions of formal collection; FoIFC, Fractions of informal collection; GHG, Greenhouse gas; ICW, Imported copper waste; IEW, Industrial Equipment Waste; IFPR, Informal processing rate; LCA, Life cycle assessment; MFA, Material flow analysis; MSW, Municipal Solid Waste; IPR, Processing rate of incineration & treatment of ash; SRR, Smelting and refining rate; TC scenario, Technical & Circular scenario; WMS, Waste management system; WEEE, Waste of Electrical & Electronic Equipment.

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waste" concept and applied it to selected cities to minimize landfill and greenhouse gas (GHG) emissions through waste prevention, reuse and recycling (Song et al., 2015; State Council, 2018). Effective and efficient management of these potentially large waste streams is a complex issue, requiring careful consideration of aspects like scarcity and security of supply of specific resources, besides costs, energy efficiency and the environmental impacts of recovery options. There have been numerous studies on waste management that have comprehensively analyzed the technologies, costs, feasible strategies, and social and environmental performance based on the 'reduce', 'reuse' and 'recycle' principles (Das et al., 2019; Giusti, 2009; Kaufman et al., 2010).

One of the benefits of effective waste management is that valuable metals can be efficiently recycled (IEA, 2021). Copper is widely used in buildings, transportation and infrastructure, and is particularly critical in energy transition (Dong et al., 2019; IEA, 2021). However, low-carbon energy systems usually require more copper, which is expected to accelerate future copper use (Eheliyagoda et al., 2019; Watari et al., 2020). Accordingly, this increased use of copper will result in an increase of the copper stock and, over time, of copper waste generation.

With respect to copper waste management, most previous studies have focused on recycling. These research has highlighted various strategies, such as enhanced collection rate and recycling rate, and their implications on the availability of recycled copper (Dong et al., 2020a; Pfaff et al., 2018; Soulier et al., 2018b; Wang et al., 2019; Yoshimura and Matsuno, 2018) From the view of environmental analysis, several studies focused on the assessment of GHG emissions of secondary copper production that includes the process of copper recycling, and/or compared with the environmental performance of primary copper production (Ciacci et al., 2020; Hong et al., 2018; Kuipers et al., 2018; Northey et al., 2013; Rötzer and Schmidt, 2020; Van der Voet et al., 2018). These studies suggest that increased use of secondary copper over the next few decades may contribute to reducing GHG emissions. However, other studies have found significant economic and organizational barriers to the implementation of circular economy options and greater use of secondary copper (Fu et al., 2017; Rubin et al., 2014). While such studies have provided a useful basis for exploring copper recycling and its GHG emissions, little effort has been made to distinguish the GHG emissions between different types of copper waste and investigate reuse strategies (repair, remanufacturing or refurbishment) rather than recycling options for copper in China. Studies on specific copper-containing products (e.g. electronic products) provide important information for understanding the treatment of copper waste at product level (Fiore et al., 2019; Ruhrberg, 2006; Santini et al., 2011). However, given that copper comes from a variety of waste products and that treatment technologies for these products differ widely, a systematic analysis of various types of waste may provide a more comprehensive decision-making basis for optimizing the copper waste management system (WMS) and even the copper lifecycle as a whole.

To this end, this article integrates dynamic material flow analysis (MFA) with prospective life cycle assessment (LCA) to explore China's potential to reduce its primary copper demand, and associated GHG emissions and cumulative energy demand (CED) considering the transition to a low-carbon energy system and the optimization of its copper waste management corresponding to proposed "Zero waste" strategies. In our previous publications, we have already modelled the in-use stocks of copper in China, and their future development assuming energy transition of power generation (Dong et al., 2020a; Dong et al., 2020b). In this paper, we will focus on the waste system to complete the assessment of China's copper cycle and the options to move from a linear to a circular economy for copper by addressing the following questions:

(1) How will the copper waste generation and secondary copper production develop in the coming decades, considering important developments such as China's "Zero waste" strategies and the energy transition of electricity generation?
(2) To what extent could primary copper demand be reduced through an optimized waste management system that follows China's "Zero waste" strategies?
(3) Which environmental benefits and trade-offs can be expected from such an optimized waste management system for the copper cycle as a whole?

This research contributes to the understanding on how different waste management options would potentially reduce primary copper demand and associated environmental impacts in China. The methods used to answer these questions are discussed in Section 2, while Section 3 reports and discusses the results and presents some of the implications.

2. Material and methods

2.1. Historical copper production and associated environmental impacts

Fig. 1 depicts the analytical framework of the integration of MFA and LCA of Chinese copper cycle, the detailed description of which and definitions for each type of waste streams can be found in Fig. S1. This approach comprises the following steps.

2.1.1. In-use stocks for copper

The first step is to calculate the retrospective in-use stock of copper in China from 2005 to 2017, applying a bottom-up method (Dong et al., 2020a; Dong et al., 2019). The copper-containing products were divided into buildings, infrastructure, transportation, consumer products, agricultural & industrial durables and commercial products. To estimate future developments of the in-use stock, several other drivers including GDP, population, urbanization rate and government policies were used, as illustrated in Appendix 1.

2.1.2. Copper waste management

Following the classifications described by Ruhrberg (2006) and Soulier et al. (2018b), five domestic waste streams are distinguished: Construction & Demolition Waste (C&DW), End-of-life Vehicles (ELV), Waste of Electrical & Electronic Equipment (WEEE), Municipal Solid Waste (MSW) and Industrial Equipment Waste (IEW). Imported copper waste (ICW), as the main input of secondary copper production before the implementation of China's "Green Fence" policy, was also considered in this study. The "Green Fence" policy has been implemented since 2013 to restrict the import of low-quality copper scrap (State Council, 2013), as described by Wang et al. (2019) and Dong et al. (2020a). The historical copper waste generation from end-of-life (EoL) copper products in China was explored using a stock-driven MFA method, which was estimated based on in-use stocks and lifespans of copper-containing products.

Copper waste management generally involves a sequence of stages including waste collection & transportation, sorting & dismantling, reuse, recycling, secondary smelting & refining. To model the Chinese copper WMS, the following variables were applied corresponding to the aforementioned stages: collection rate (CR) was used in the process of waste collection & transportation to represent the collected copper by generated copper from EoL products, of which fractions of formal (FoFC) and informal (FoIFC) collection were distinguished; for the sorting & dismantling process, REoF and REoIF refer to the copper flow from formally and informally collected copper enter to reuse respectively, FSoIC defines the fraction of formal sorting and dismantling from informal collection; for the recycling, secondary smelting & refining processes, formal processing rate (FPR) and informal processing rate (IFPR) refer to the recycled copper by copper entered formal and informal smelting and refining process respectively, of which processing rate of incineration & treatment of ash (IPR) was specified for municipal solid waste. Detailed definitions of these variables and description of waste management system in China are to be found in Appendix 1.

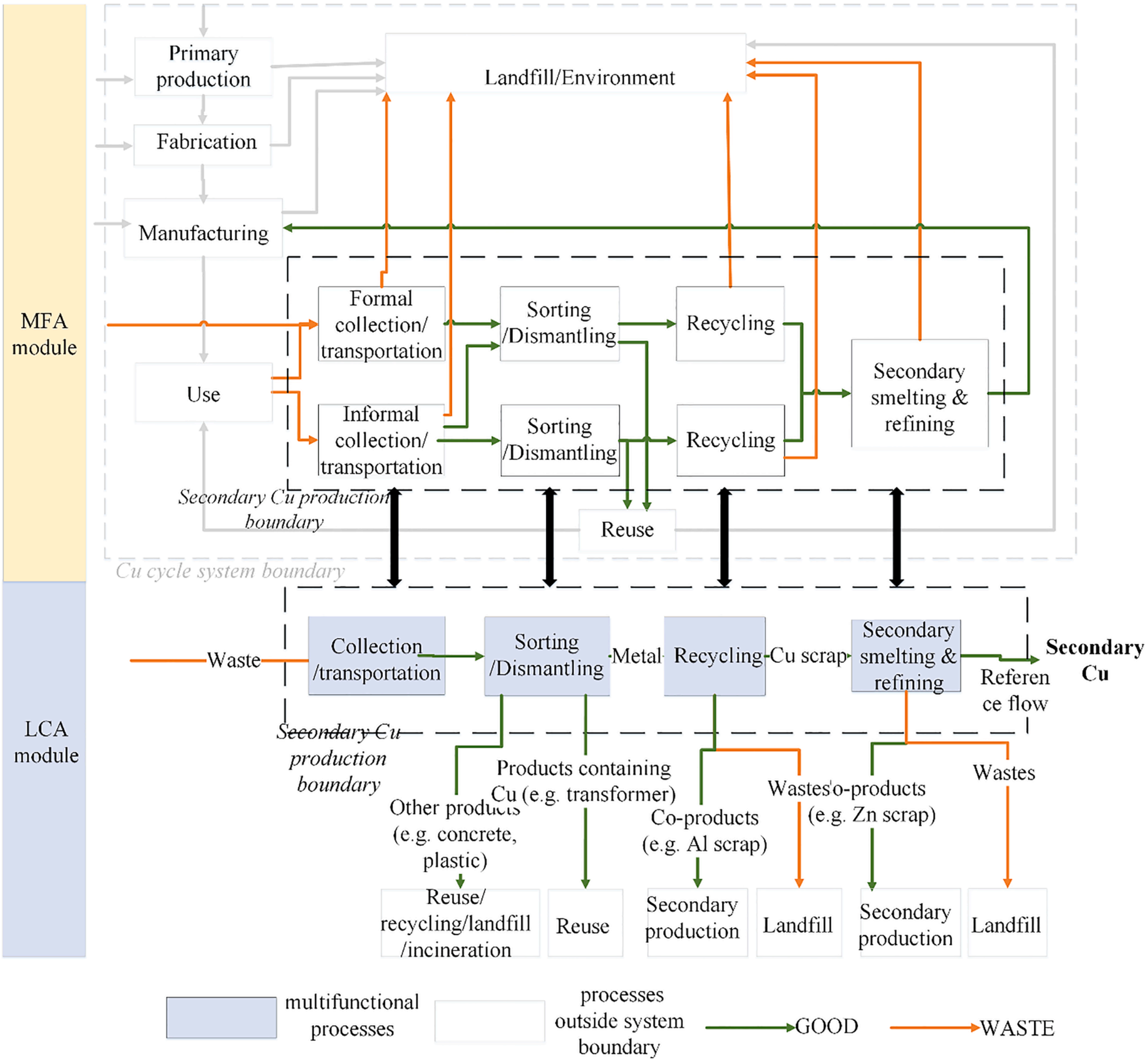

Fig. 1. Copper cycle system boundary and definition for China: schematic representation of the MFA and LCA combination on the secondary copper production. The MFA processes (collection & transportation, sorting & dismantling, recycling, secondary smelting & refining) are represented by the same LCA processes. The black dash line refers to the system boundary of secondary copper production. The gray dash line refers to the system boundary of copper cycle. Note: The formal and informal production processes (from collection to refining) are not distinguished in LCA module.

2.1.3. *Production of secondary and primary copper*

Secondary copper is produced from the aforementioned EoL scrap (old scrap, including imported waste) and new scrap generated during the fabrication and manufacturing of copper products. The present fabrication and manufacturing efficiency of copper is 99% and 89%, respectively (CNMIYC, 2018). The current smelting and refining rate (SRR) of copper in secondary copper production is already quite high, with figures of 97%-99% for all waste types (Soulier et al., 2018b).

Estimate of primary copper production is a reverse logic of copper cycle, starting from the calculation of production of finished copper products based on copper demand and manufacturing efficiency, as shown in Fig. S5. Net imports of semi-finished and finished products were derived from UN Comtrade (Table S9, Fig. S6). The amount of primary copper supply (including domestic and imported copper) is determined by the production of domestic semi-finished goods and fabrication efficiency.

2.1.4. *Modelling the environmental impacts of secondary copper production*

The main goal of this assessment is to quantity the environmental impacts of secondary copper production and the functional unit is 1 kg secondary copper produced from six types of waste streams in China. Secondary copper production is broken down into several foreground processes including collection & transportation, mechanical processing (sorting & dismantling, recycling), secondary smelting and refining for each of the different waste streams separately, as depicted in Figs. S1 and S4. The energy input for the foreground processes is presented in Table S10.The energy and resource inputs associated with direct secondary production are defined as background processes. Furthermore, the following specifications were considered:

(1) To allocate the environmental impacts in multifunctional processes, we used two different methods: mass-based allocation for collection & transportation and sorting & dismantling, and economic allocation for recycling and secondary smelting and the refining process, according to the economic value of the outputs (other than Cu, e.g. Fe, Al, Zn). The economic data (e.g. price), materials content and processing efficiency of recycling for co-products were reported in Tables S3-7 and S12 in Appendix 3.

(2) For recycling, it is important to note that the processing efficiency as defined here refers to material recycling and does not include any type of product (part) reuse.

(3) Formal and informal recycling are not distinguished here for reasons of data availability.

(4) The energy mix used for electricity production in background systems was set according to the share of fossil fuels and renewable energy in current Chinese electricity production, as shown in Fig. S2.

(5) The environmental impacts were conducted using the CMLCA 6.0 software. The Ecoinvent 3.4 database was used to model the background system (Moreno Ruiz et al., 2017). As climate change is considered as one of the big challenges, and energy is an important aspect for the environmental impacts of metal production, GHG emissions and CED of the CML2001 impact categories were used to conduct the analysis (Guinée, 2001).

(6) A contribution analysis was conducted to identify the contribution of each production process to total GHG emissions and CED. We also performed a sensitivity analysis on the choice of allocation methods and the influence of reuse fraction.

2.1.5. *Integration of MFA and LCA*

Finally, to integrate MFA and LCA, the amounts of secondary copper produced from these six types of waste were multiplied by the corresponding impacts per kg and per year, and summed to yield a total, given by Equation (1):

$$EIS_{x,t} = \sum_{x=1}^{n} (EI_{x,t} \times M_{x,t}) \tag{1}$$

where x represents the copper waste types (x = 1, 2, 3…n), t refers to the time period, $EI_{x,t}$ is the GHG emission (kg CO2-eq./kg) or cumulative energy demand (MJ/kg) of producing 1 kg copper by each waste type x in year t, $M_{x,t}$ is the production of secondary copper by each type of waste x in year t, and $EIS_{x,t}$ is the total GHG emission (kg CO2-eq./year) or cumulative energy demand (MJ/year) of secondary copper production.

2.2. *Scenarios of copper production and associated environmental impacts*

In view of the technology development and climate change mitigation in the accelerating the transformation of copper cycle to circular economy, the Chinese Policy (CP) scenario and the Technical & Circular (TC) scenario have been designed. Several circular economy strategies are considered, including waste reduction, reuse (repair, remanufacturing or refurbishment), recycling and transition from informal to formal waste management, as shown in Table S8.

The **CP scenario** assumes that the future development of copper-containing products will continue the current trends, and the future technologies used throughout the copper waste management remain equivalent to the practical levels of 2017. Therefore, to model future in-use stocks and waste for copper, the energy supply for electricity production will follow the roadmap as laid out by the Chinese government (Fig. S2, left) and lifetimes of copper-containing products were assumed to remain unchanged. Moreover, the efficiencies of copper waste management and secondary copper production were assumed to remain constant, with 2017 levels of reuse (formal and informal), recycling (formal and informal), secondary smelting and refining.

In the **TC scenario** there is significantly improved circular use of copper, facilitated by diffusion of novel technologies currently available at laboratory or pilot scale but with the potential for future application at industrial scale. The enhanced share of renewable energy supply for electricity production under the roadmap as laid out by the Chinese government was projected (Fig. S2, right). Lifetimes of copper-containing products were assumed to be extended. Moreover, improved processing rates and reuse fractions of each type of waste streams were assumed, based on information on improved separation and processing techniques, while it was also assumed that policies will be implemented to encourage higher CRs. The collection rates of copper from C&DW and ELV were assumed to be 95% in 2100, considering that these two waste categories can be collected and managed by professional companies and can achieve very high rates in China, similar to those in other countries (Graedel et al., 2004; Pfaff et al., 2018; Ruhrberg, 2006; Yoshimura and Matsuno, 2018). For the other waste categories, future collection rates were modelled based on the relationship between historical collection rate and waste generation rate, as described by Magalini et al. (2014). In view of China's proactive policies on reuse of ELV products, spare parts and components, the fraction of collected ELV copper reused (REoF) was assumed to be 50% in 2100. The REoFs of other waste categories were assumed to be twice the current level in 2100. Smelting and refining rates of all types of copper waste were assumed to be 99% in 2100.

In addition to the different specific assumptions, future imported copper waste was projected based on past trends of brass copper for both scenarios since the "Green Fence" policy of imported copper scrap shows that Standard recycled brass copper are not solid waste and can be imported freely from November 2020. To model future secondary and primary copper production, the future fabrication and manufacturing efficiency of copper were assumed to remain constant as well in both scenarios (Dong et al., 2020a). The definitions and assumptions for CP and TC scenarios are shown in Table 1.

To assess future environmental impacts of 1 kg secondary copper production, corresponding to the MFA module, processing efficiency improvements in foreground systems and changes of the electricity production mix in background processes were considered. For copper processing efficiency, changes in sorting & dismantling (refers to REoF), recycling (refers to FPR, IPR) and smelting & refining (refers to SRR) processes were assumed to be in line with the trends in Table 1. The target processing efficiencies of co-products in recycling and smelting & refining processes in 2100 in the TC scenario were assumed to be enhanced to the same level as copper in 2100. If the 2017 level was already higher than the 2100 level in the TC scenario, however, processing efficiencies were assumed to remain unchanged. For the background processes, the future electricity production mix was assumed to be in accordance with China's electricity production roadmaps for fossil fuels and renewables resulting in lower GHG emissions over time.

3. Results and discussion

3.1. *Copper waste management and secondary copper production*

Fig. 2 depicts the historical (2005–2017) copper waste management and secondary copper production in China, followed by future projections up to 2100 under the CP and TC scenarios. Total copper waste generation shows an increasing trend in both scenarios, as a result of significant upward developments in socioeconomic conditions and demographics. Under the CP scenario, more waste is generated than that under the TC scenario, attributable to the assumption of the extended lifetimes of copper products in the TC scenario, which will reduce copper waste generation. For detailed waste sources as shown in Fig. 3, although in the past ICW accounted for almost half the total amount of waste generated, because of present restrictions on the import of copper waste, the ICW category is expected to decline in the future. Consequently, copper in C&DW is expected to contribute most to the aggregated copper waste generation expectedly in the coming decades.

Looking beyond generated copper waste, copper waste management is expected to be considerably improved in China along with the circular economy strategies under the TC scenario. While the amount of copper waste deposited in landfills will increase in both scenarios from 2005 to 2100, in the TC scenario relative amount of copper waste losses are anticipated to be reduced substantially, from around 30% of total copper

Table 1

Data and circular strategies applied for modelling MFA and LCA modules: the in-use stocks, waste generation and management system for copper in 2017 in the Chinese Policy and Technical & Circular scenarios. Efficiency improvement assumed in 2100 in the Technical & Circular scenario.

Scenarios	In-use stocks	Waste generation	Waste Management										Secondary smelting & refining
			Types	Collection& transportation	Sorting/dismantling					Recycling/incineration			
				CR	FoFC	FoIFC	FSoIC	REoF	REoIF	FPR	IFPR	IPR	SRR
CP scenario *(2017–2100) and TC scenario (2017)*	Energy supply of electricity production (Fig. S2, left)	Regular lifetimes of copper-containing products	C&DW	81%(Soulier et al., 2018b)	100%			4%(MOHURD, 2005; Zhao and Rotter, 2008)		90%(Soulier et al., 2018b; Zhao and Rotter, 2008)			99%
			ELV	79%(Soulier et al., 2018b; Zhang et al., 2014)	30%(Chen et al., 2018; NDRC, 2008)	70%		10%(CELVE, 2019; NDRC, 2008)	50%(Chen et al., 2018)	55%(Soulier et al., 2018b)	55%(Soulier et al., 2018b)		97%
			WEEE	75%(Zhang et al., 2015)	17%(Chi et al., 2014; Salhofer et al., 2016)	93%	30%(Chi et al., 2014)	10%(Chi et al., 2014; MEEC, 2006)	10%(Chi et al., 2014)	55%(Soulier et al., 2018b)	20%(Liu et al., 2006; Soulier et al., 2018b)		97%
			MSW	63%(Soulier et al., 2018b)	100%							20%(Soulier et al., 2018b)	99%
			IEW	83%(Soulier et al., 2018b)	100%					75%(Soulier et al., 2018b)			97%
			ICW	100%(Dong et al., 2020a; GACC, 2018)	100%					82%(Dong et al., 2020a)			97%
TC scenario *(2100)*	Energy supply of electricity production (Fig. S2, right)	Extended lifetimes of copper-containing products based on technical support	C&DW	95%(Pfaff et al., 2018; Ruhrberg, 2006; T. E. Graedel et al., 2013; Yoshimura and Matsuno, 2018)	100%			8%(MOHURD, 2019; NDRC, 2017)		97%(Pita and Castilho, 2018)			99%
			ELV	95%(Pfaff et al., 2018; Ruhrberg, 2006; T. E. Graedel et al., 2013; Yoshimura and Matsuno, 2018)	100%			50%(CELVE, 2019) (MIIT, 2020; State Council, 2019)	50%(Chen et al., 2018)	90%(Molteni, 2017)			
			WEEE	88%(Magalini et al., 2014)	80%(Steuer et al., 2018)		100%	20%(CHARI, 2018; MEEC, 2018)		96%(Meng et al., 2018; Pita and Castilho, 2018; Zhang et al., 2011)			
			MSW	80%(Magalini et al., 2014)	100%							80%(Holm et al., 2018; Muchová and Rem, 2006)	
			IEW	89%(Magalini et al., 2014)	100%					96%(Pita and Castilho, 2018; Soulier et al., 2018a)			
			ICW	100%	100%					96%(Dong et al., 2020a) (GACC, 2018)			

Note: Collection rate (CR), formal processing rate (FPR), informal processing rate (IFPR), processing rate of incineration (IPR), fraction of formal (FoFC) and informal (FoIFC) collection, fraction of reuse from formal collected copper (REoF), fraction of reuse from informal collected copper (REoIF), as well as fraction of formal sorting and dismantling from informal collection (FSoIC). Construction & Demolition Waste (C&DW), End-of-life Vehicles (ELV), Waste of Electrical & Electronic Equipment (WEEE), Municipal Solid Waste (MSW) and Industrial Equipment Waste (IEW). Imported copper waste (ICW). Take the C&DW as an example, the collection rate of copper is 81% in 2017, of which 100% is assumed to be from formal collection. From the collected copper, 4% is reused, the rest goes to the recycling process. The processing rate of recycling process of copper is 90%, the rest goes to the landfill.

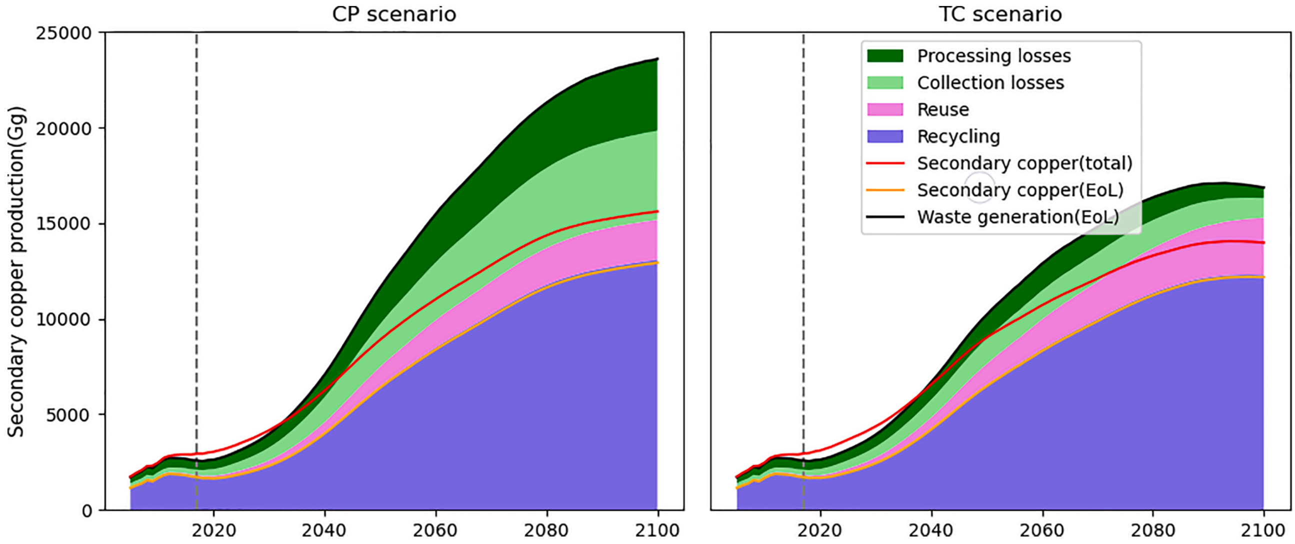

Fig. 2. Copper waste management and secondary copper production from 2005 to 2100 in the Chinese Policy (CP) and Technical & Circular (TC) scenarios in China: total copper waste generation and its destination, and secondary copper production. Secondary copper (total) includes secondary copper produced from EoL waste and new scrap. The vertical black dashed line marks the boundary between historical data and future scenarios.

waste generated in 2005 to less than 10% in 2100. Because more copper is kept in the economy by either reuse or recycling in the TC scenario, while in the CP scenario this number will remain fairly unchanged. Moreover, with the higher recycling rates in the TC scenario, the amount of copper recycling and cumulative secondary copper are almost equivalent to that in the CP scenario in 2100, even though far less copper waste is generated in the TC scenario, which indicating that higher collection rate and recycling rate are of importance to save resources.

The findings also show that reuse of waste will promote circulating copper significantly. Reused copper accounted for 3% of generated waste in 2017, however, the proportion is expected to reach more than 15% in 2100 in the TC scenario. Specifically, reuse of copper components in ELV is very likely to already increase over the next few decades, with a major shift from informal to formal reuse in the TC scenario. Moreover, there was a relatively important informal market for direct reuse of WEEE, accounting for over half copper reuse in 2017. In addition, cumulative reused copper in the TC scenario is also slightly greater than in the CP scenario, of which the ratio of cumulative copper reuse to generated waste is expected to increase from ~ 8% to ~ 13%.

Whether recycling is always the preferred option depends on the type of waste. Compared with other kinds of domestic waste, due to the high recycling rate of copper in C&DW and the high volume of C&DW generated, the copper recycled from this waste stream accounts for the largest proportion and will remain so in future in both scenarios. Copper recycled from ELV batteries is worthy of close attention. With the increasing uptake of electric vehicles, the share of copper recycled from ELV batteries in total copper recycling is expected to increase by 4% from 2017 to 2100 in the TC scenario. In certain sectors (ELV, WEEE) informal recycling has dominated in the past. In the TC scenario, however, professional recycling, which is much more efficient and far less polluting, is assumed to gradually take over, with informal copper recycling projected to disappear entirely by 2100. With regard to the MSW, copper recycling from bottom ash, which has been challenging owing to technical limitations accounting for only 0.1% of copper waste generated in 2017, offers major scope for improvement in the future.

The cumulative flow of copper waste management and secondary copper production from 2005 to 2100 is shown in Fig. 4. During this period, in the CP scenario cumulative copper losses during collection and recycling accounts for 35% of generated copper waste, while in the TC scenario this ratio is expected to decrease to be less than 20%. However, the cumulative secondary copper production in the CP scenario will still a bit higher than that in the TC scenario. We demonstrate that extending lifespans of copper products in the TC scenario reduces available scrap for secondary copper production, offsetting the benefits of improved copper collection and recycling rates and generating a cumulative decrease in secondary copper production of 834222Gg by 2100.

3.2. GHG emissions and energy demand related to per-kg secondary copper production

GHG emissions and cumulative energy demand of secondary copper production from different waste types in China were also projected. The results are shown in Fig. 5 for GHG emissions and Fig. S8 for cumulative energy demand. In both CP and TC scenarios, the GHG emissions and cumulative energy demand are expected to decline for all types of waste, with an unsurprising sharp decrease through to mid-century and a relatively gradual decrease thereafter. One possible reason is that further environmental benefits from energy transition and increased recycling are like to be limited by the lower waste quality. This is especially true for MSW, a clear reflection of the decoupling of energy consumption and environmental impacts resulting from the energy transition (Ciacci et al., 2020; Guan et al., 2018). In the case of secondary copper production from C&DW, future potential reduction of GHG emissions and cumulative energy demand is modest in both scenarios, implying that the low-carbon transition (specifically electricity) and improved processing efficiency play a smaller role for this waste stream than in the other cases. One possible reason for this is that the processing rate of C&DW is already quite high. Moreover, C&DW will almost certainly become the main contributor to the environmental impacts of aggregate secondary copper production from all types of waste, because it is the single largest source of secondary copper. The environmental impacts of secondary copper production from ELV are likely to decrease significantly in both scenarios, though the difference between the two scenarios is only minor.

The future environmental impacts of 1 kg secondary copper production are still expected to be much lower than those of primary copper production, even when secondary production in the CP scenario is compared with primary production in the TC scenario, which obviously indicates the potential benefits of copper recycling. This finding holds not only for aggregate secondary production but also for secondary production from each type of waste considered in this study. However, it is worth noting that this finding may not always hold, and due consideration will always need to be given to several key variables (e.g. waste

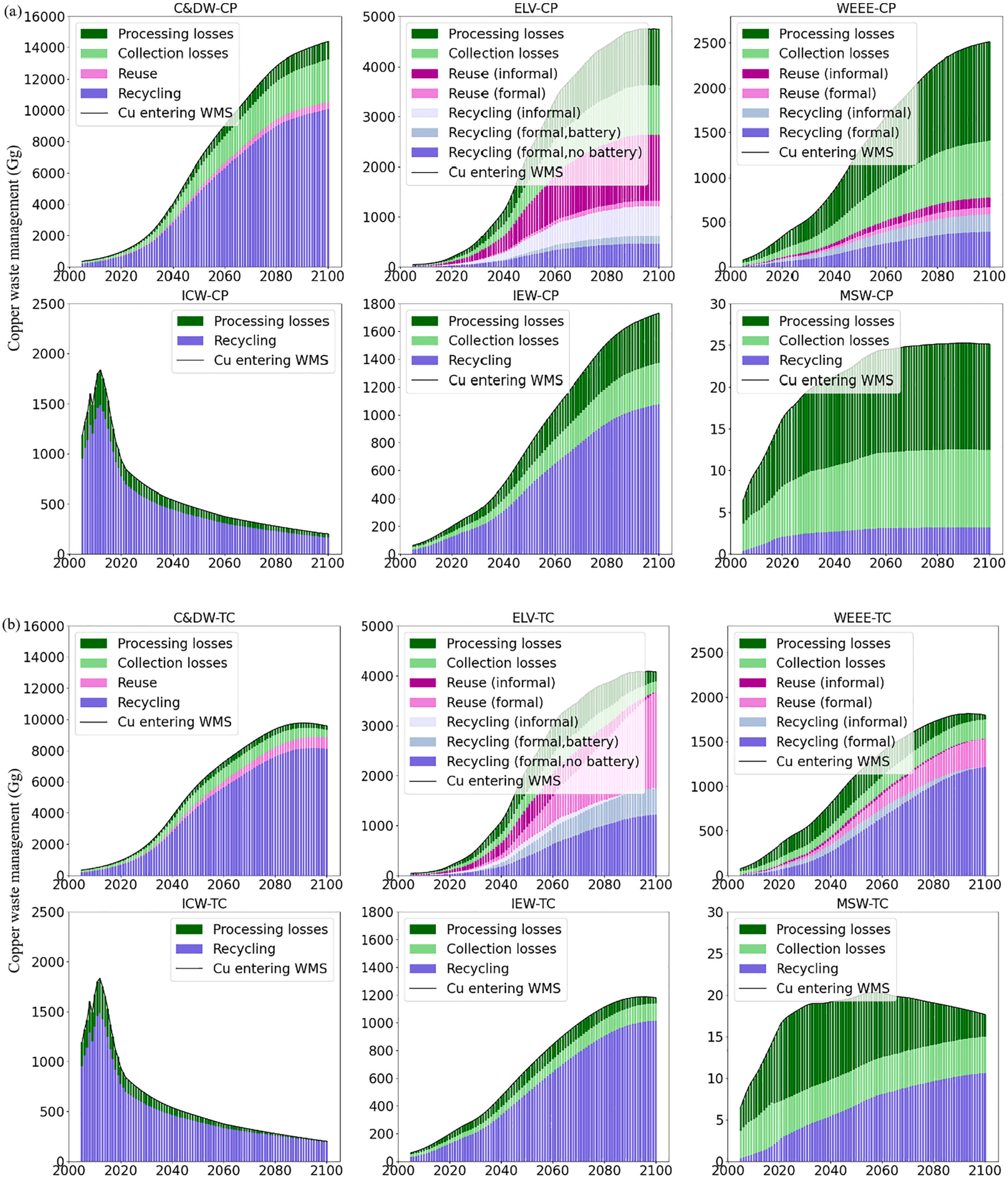

Fig. 3. Copper waste management and secondary copper production from 2005 to 2100 in the Chinese Policy (CP) and Technical & Circular (TC) scenarios in China: (a) by waste streams in the CP scenario. (b) by waste streams in the TC scenario. Construction & Demolition Waste (C&DW), End-of-life Vehicles (ELV), Waste of Electrical & Electronic Equipment waste (WEEE), Municipal Solid Waste (MSW), Industrial Equipment Waste (IEW), Imported Copper Waste (ICW).

quality, recycling technology, energy sources, geographical location) as well as modeling assumptions (e.g. allocation method) and analysis made on a case-by-case basis. For example, the cumulative energy demand of 1 kg secondary copper production from C&DW is almost the same as that of primary copper production in Germany in 2014, probably because the copper content of C&DW from rebuilding is relatively low (0.00245 g/g), indicating that more energy is required in processing (Schäfer and Schmidt, 2020). In addition, previous studies have generally posited that informal recycling with suboptimal treatment can cause a variety of environmental and human health issues, while in determining the environmental impacts of secondary copper production no distinction was made between formal and informal recycling due to specific data limitations in this study (Foelster et al., 2016; Hong et al., 2015; Vergara et al., 2016).

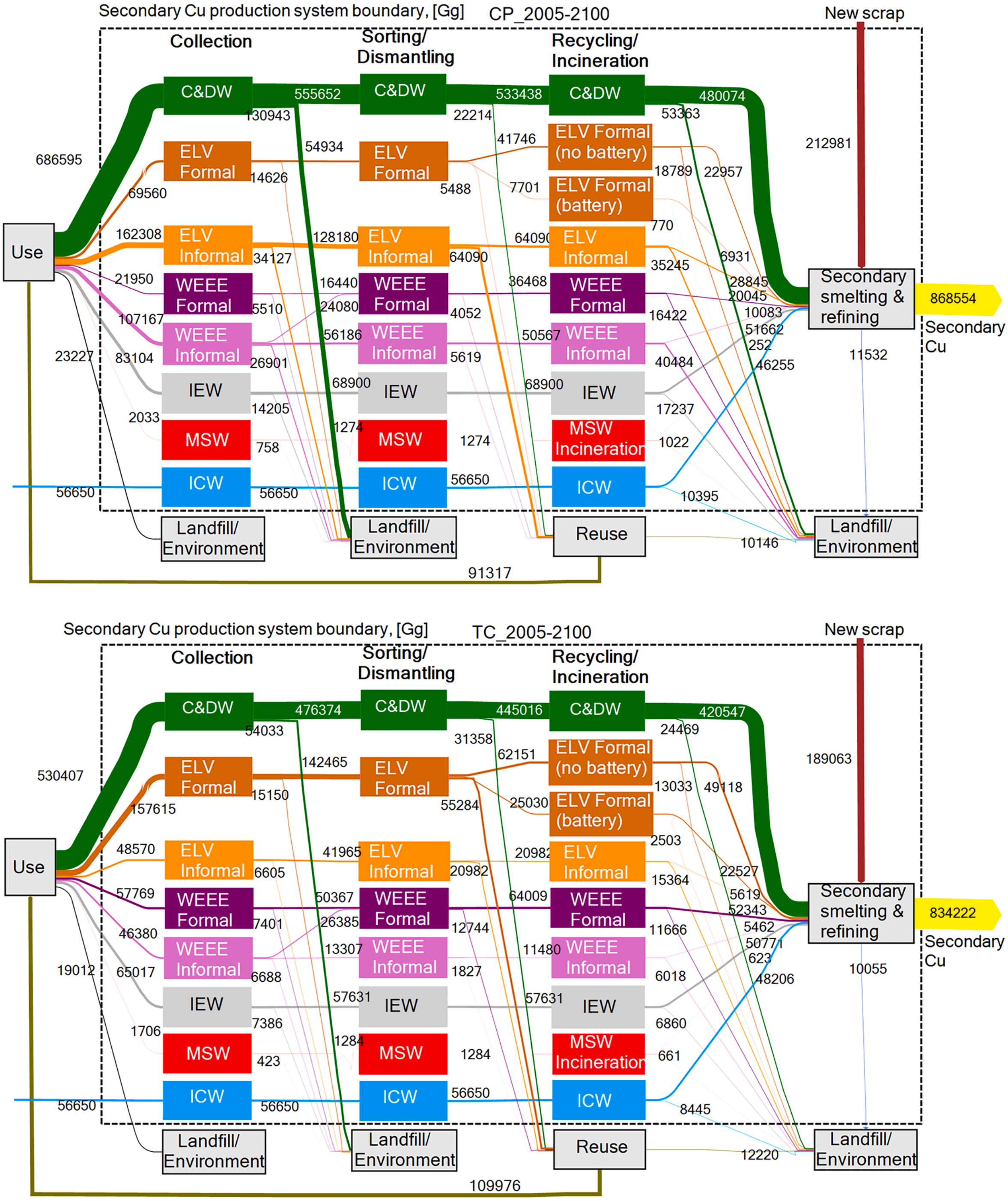

Fig. 4. Sankey diagram of cumulative copper waste management and secondary copper production in China from 2005 to 2100 in the Chinese Policy (CP) and Technical & Circular (TC) scenarios. The flow from use to landfill/Environment represents dissipations/abandoned copper in place.

With respect to reuse, this study has quantified the environmental impacts of production of 1 kg Cu-containing products for reuse, as reported in Table S15. Production of 1 kg metal for recycling and 1 kg Cu-containing products for reuse have the same cumulative energy demand based on the mass allocation method in sorting & dismantling process. However, the environmental impacts of re-used 1 kg copper is not assessed in this study since the re-used process (remanufacturing or refurbishment) is out of the secondary production system boundary. While assessing the environmental impacts of one specific material (e.g. copper) in a remanufactured products may be challenging, it is common knowledge that reuse, especially direct re-use as a second-hand product, is more environmental as compared to recycling since no new materials have to be processed (Zhang et al., 2020). The energy use embodied in a remanufactured product could range from 15% to 85% of that for a new product. Xu (2013) has even pointed out that this is the best option for disposing of waste and reducing environmental impacts. There may sometimes be a trade-off, however, when products are reused but newer products are more energy-efficient, although this trade-off will become smaller as more renewables are used.

In addition, in terms of contributing processes, secondary smelting and refining account for the bulk of GHG emissions and cumulative energy demand for all types of waste. The differences of GHG emissions and cumulative energy demand among the six types of waste are due mainly to differences in impacts of mechanical processing and collection

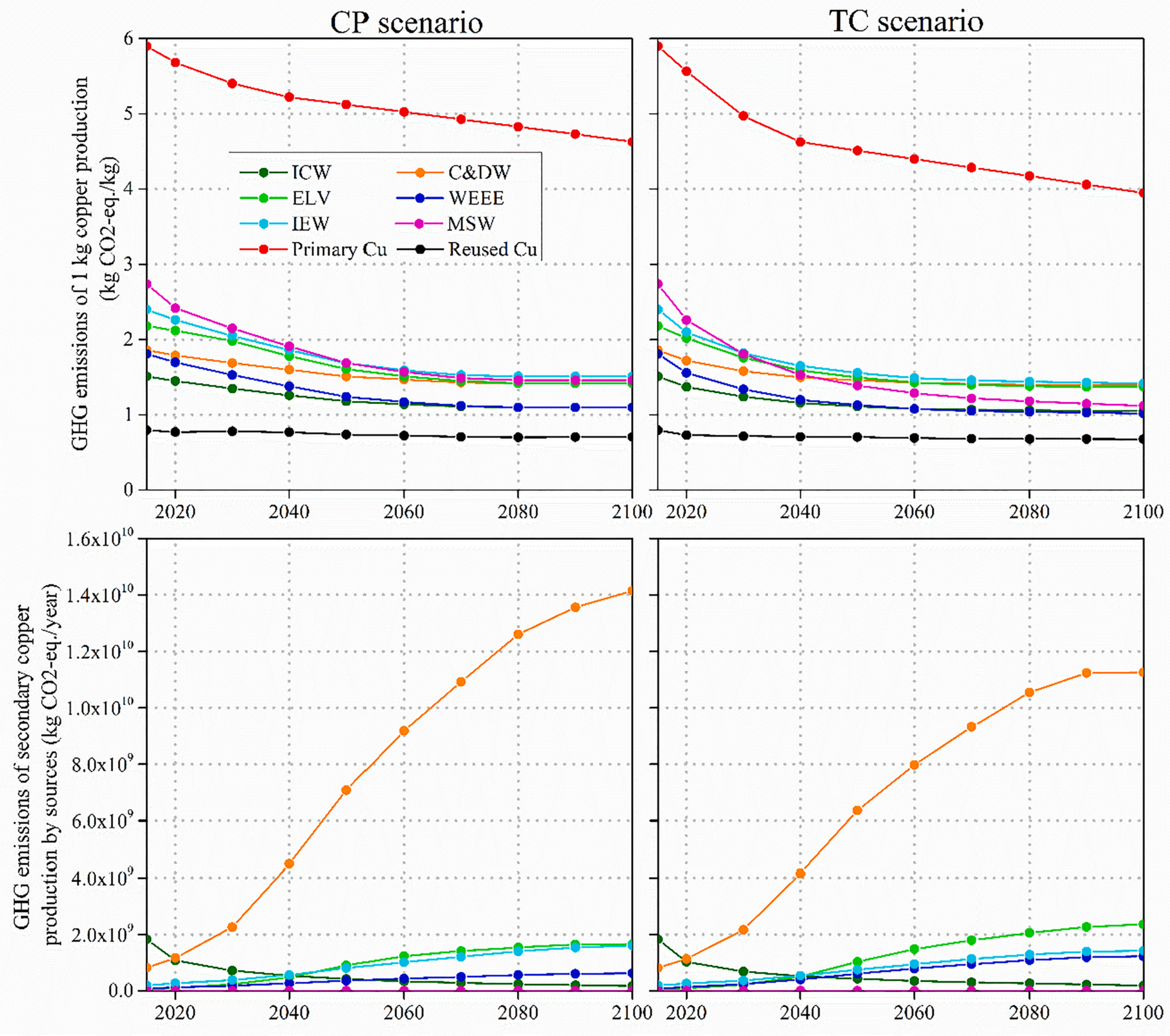

Fig. 5. GHG emissions of copper production: 1 kg and total copper production from different waste types and comparison with copper reuse in Chinese Policy (CP) and Technical & Circular (TC) scenarios. The primary copper is derived from Dong et al. (2020b) and represents an average value based on pyrometallurgical and hydrometallurgical production in the respective CP and TC scenarios. Data for reused copper is roughly assumed to be 50% of secondary production (Ardente et al., 2018; ICA, 2013).

& transportation (Fig. S7), which depend on the purity of the waste and the copper grade. Copper waste originated from the transport and power cable could be of higher quality, resulting relatively lower GHG emissions and energy requirements.

3.3. *Potential for reducing primary copper demand and associated GHG emissions and energy demand*

Fig. 6 shows projections of primary copper production in China and associated GHG emissions and cumulative energy demand through to 2100. Primary copper demand and associated environmental impacts are obviously much lower in the TC scenario than in the CP scenario in 2100, with around 65% and 75% potential reduction, respectively. The TC scenario also demonstrates that implementation of circular economy strategies can reduce cumulative primary copper demand by 20% until 2100 compared to the CP scenario. This means optimized copper waste management system (TC scenario) is expected to not only mitigate the environmental impacts associated with copper ore extraction and processing but also those associated copper waste disposal, which would lead simultaneously to dematerialization and improved environmental sustainability of the copper cycle in China. From the perspective of copper cycle, overall GHG emissions in the TC scenario are expected to potentially reduce 55% in 2100 compared to that of the CP scenario. Furthermore, in the CP scenario, total cumulative GHG emissions are very likely to increase approximately linearly, while in the TC scenario they are expected to gradually decline over the years, potentially leading to about 25% lower cumulative GHG emissions in the TC scenario in 2100 compared with the CP scenario (Fig. S9). Another interesting finding is that the GHG emissions and CED of copper production are expected to peak between 2040 and 2050 in both scenarios, attributable to a number of factors including copper demand, changes in the recycling system (e.g. recycling rate) and the Chinese energy transition, and probably also related to the climate target of carbon emissions peaking in China around 2030, indicating further net improvements in the decades thereafter. Long-term projection in the TC scenario also indicates that copper demand in China is expected to continue growing and around 20% of primary copper will still be needed in 2100. To reach carbon neutral of copper cycle, electrification and improvement of

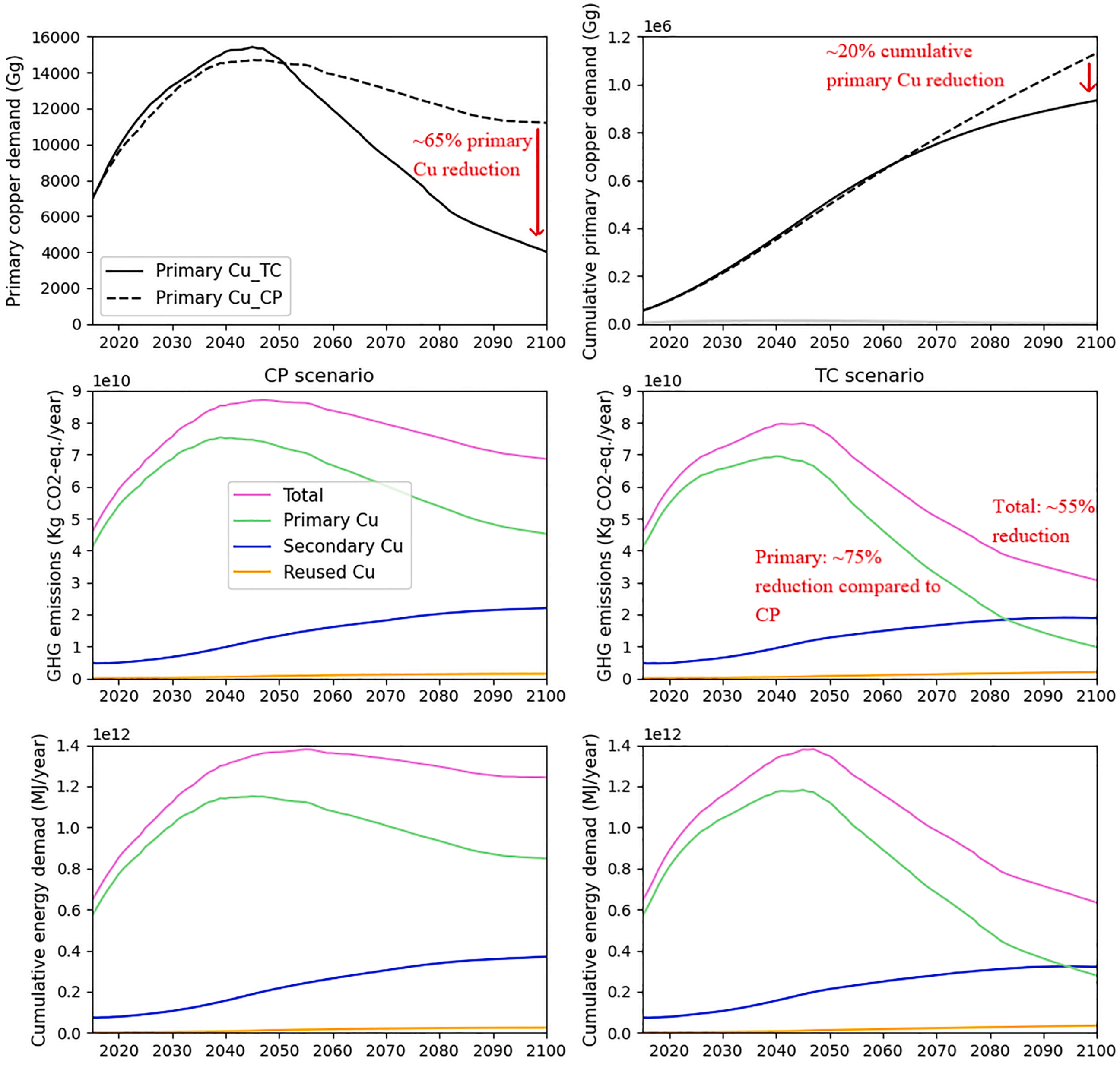

Fig. 6. Primary copper demand, GHG emissions and cumulative energy demand of primary, secondary and reused copper production in Chinese Policy (CP) and Technical & Circular (TC) scenarios. Cumulative primary copper demand presents the demand from 2005 to 2100.

renewable-based electricity as well as other measurements (e.g. material efficiency, low-carbon technologies) should be combined (IEA, 2021).

As a result of the steadily improving recycling rates in the TC scenario, even though the volume of copper waste generated is far lower, aggregate secondary copper production is not that different compared with the CP scenario and even higher relative to the total copper supply. As a result, the dynamics of secondary copper production combined with the scenario projections of environmental impacts per kg of secondary copper produced result in similar outcomes in the CP and TC scenarios or in other words, the environmental impact reduction in the TC scenario is a result of the reduced demand for primary copper. Moreover, GHG emissions related to secondary copper production may in fact come to exceed those of primary copper production despite lower per kg GHG emissions of secondary production.

From the perspective of optimizing the use of copper (or other materials), reuse is better than recycling, since this extends copper lifetimes in original products, parts or components and results in reduced volumes of waste requiring treatment. At the same time, the environmental impacts of the total volume copper reused are far lower than those associated with secondary copper production, as calculated in this study. Given that the crucial significance of the modeling assumption with respect to copper reuse, a sensitivity analysis of the impacts of reuse fraction on copper production and associated environmental impacts was conducted. As Fig. S11 shows, increasing 60% of copper reuse could result in a 10% reduction of GHG emissions and CED for secondary copper production and a slight reduction of those for total copper production.

3.4. Critical analysis of potential for reducing primary copper demand and associated environmental impacts

To put our results into a broader perspective, we compared them with results of studies on copper waste management options and associated environmental impacts. Some of that research has concluded that specific "Zero waste" options including waste reduction, improvement of collection rate and recycling could enhance the copper waste management and increase available scraps for secondary copper production, which is in line with our results (Gorman and Dzombak, 2020; Soulier et al., 2018b; Wang et al., 2019). Wang et al. (2017) tested the impacts of extending lifespans of copper products, displaying that the amount of copper scrap will be expected to reduce 25% if the lifespans of products increase 20% in due time. Eheliyagoda et al. (2019) estimated the impacts of copper recycling rate on Chinese copper cycle, and believed that the cumulative primary copper demand will be likely to reduce 60% if the copper recycling rate increases from 20% to 90%. Our estimations on lifespans and recycling rate fall within the range of these studies. However, in our case up to 55% of primary copper could be avoided, which is in part due to the additional consideration of reuse. Regarding to the potential environmental benefits of "Zero waste" options, previous research mainly assessed the environmental impacts of per unit secondary copper production, and concluded that the environmental impact of 1 kg secondary copper is around 1/8 that of the 1 kg primary copper production in China (Chen et al., 2019), which is a bit lower compared with our results (~1/3). This difference may be caused due to the data used for separated waste streams or calculation procedures. For other aspects, Ryter et al. (2021) analyzed the emission impacts of China's copper waste import ban, showing that the copper waste import ban could increase the primary copper demand and result in a cumulative increase in 13 Mt CO2-eq. emissions by 2040.

3.5. Uncertainty analysis

This systematic analysis of the effects of copper waste management on copper cycle is valuable, but still has many uncertainties and limitations. Scenario analyses and forward-looking perspectives can provide guidance for the improvement of the copper cycle in terms of resilience and environmental sustainability, and anticipate related changes in waste management dynamics, thereby providing a basis for long-term critical assessment. At the same time, though, they involve significant uncertainties, among others the limits on statistical data availability, especially with respect to copper reuse. Several key variables for modelling dynamic copper projections, such as demographics and economic drivers (e.g. GDP, population, copper content, urbanization rate) and other drivers related to production efficiency, have been discussed in previous studies (Dong et al., 2020a; Eheliyagoda et al., 2019; Soulier et al., 2018b; Wang et al., 2019).

In particular, a change in the method used for allocating the multifunctional processes involved in copper production might result in very different environmental outcomes. A sensitivity analysis on mass allocation was therefore conducted, employing the mass allocation method for all multifunctional processes. As Figs. S10 and S11 show, the environmental impacts of mass allocation are in line with the trends yielded by economic allocation. Because of the substantial spread in the price of recycled copper and co-products, however, economic allocation yields a greater spread of environmental impacts for certain waste streams (e.g. WEEE and C&DW) compared with mass allocation.

4. Conclusions and policy implications

In this study, the methods of dynamic MFA and prospective LCA are combined to model the copper stock-flow dynamics, explore the environmental impacts of secondary copper production from different waste streams and investigate the potential for reducing primary copper demand and associated environmental impacts in China. The Technical & Circular scenario, as an optimized system, reflects a transition towards minimum waste generation, maximum copper recycling and reuse and improved environmental sustainability. If the future process efficiencies such as collection, reuse and recycling rate could be enhanced to the level that assumed in the Technical & Circular scenario, 65% of primary copper demand and 55% of total GHG emissions in 2100 would be potentially reduced compared with the Chinese Policy scenario. This systematic analysis of the effects of copper waste management on copper cycle is valuable and can provide some policy recommendations to manage this optimization appropriately.

Waste prevention should be the first priority. Extending the lifetimes of copper products is the prime direction to be considered, given the wealth of research indicating that this can reduce waste generation significantly, in line with the guiding principle of the "Zero waste" concept (Gharfalkar et al., 2015; State Council, 2018). Compared to the Chinese Policy scenario, Technical & Circular scenario indicates that copper waste generation could be reduced more than 30% in 2100 due to lifetime extension of copper-containing products. Such a transition is not straightforward in China, however, especially for copper products with already long lifetimes, as in buildings and infrastructure. For products with shorter lifetimes, whether to extend the lifetime of the integral product (e.g. reuse) or only parts thereof (e.g. remanufacturing, refurbishment) or undertake recycling to keep the materials circulating longer than the product itself depends on the remaining qualities and function of the product concerned.

Reuse is preferable to recycling, but might be hard to implement in all China's industries. On the one hand, the increasing complexity of materials and product functions requires appropriate technologies to effectively and efficiently dismantle and remanufacture, which will undoubtedly become a huge challenge over time (Chang et al., 2017; Vanegas et al., 2018). Furthermore, high spare-part costs make remanufacturing of certain products unprofitable as well (Seliger et al., 2006). On the other hand, its success will depend very much on government policy and consumer acceptance of reused (including remanufactured) products. For instance, the future policies related to ELV reuse in the Technical & Circular scenario are more active, accordingly, the ratio of reused copper to generated waste in the Technical & Circular scenario is 15% higher than that of in the Chinese Policy scenario. Consumer awareness could affect the availability of repair information and high likely encourage reuse activities (Allwood et al., 2011; Klose and Pauliuk, 2021). Therefore, supporting the organization of reuse (second-hand markets, remanufacturing plants) centers and networks, including through enabling technologies and constructing standards of reusable products, could motivate this important contributor to the successful implementation of reuse of WEEE and ELV.

Recycling is the main option for utilizing EoL copper products in China at present, with informal recycling playing a major role in the ELV and WEEE sectors (Fig. 4). An optimized waste management system, represented in this study by the Technical & Circular scenario, aims to maximize the flow of copper to the formal recycling sector and then to dismantle and separate uniformly, leading to maximum recycled material and environmental benefits. Furthermore, decisions to formalize recycling procedures need to consider not only resources and the environment, but also social and economic impacts. Several studies have demonstrated that in addition to the challenge of implementing policies to combat informal recycling, the employment afforded to informal workers (e.g. approximately 0.77% of the population of Haidian district in Beijing were involved in informal waste management in 2013) and the profits accruing from recycled products are factors that also need to be considered, potentially complicating this transition (Chi et al., 2011; Linzner and Salhofer, 2014; Steuer et al., 2018). Therefore, in the short term, policies could support and nurture leading recycling companies to explore various forms of cooperation with informal recyclers, such as the small workshops of WEEE recycling. With regard to increasing the copper recycling rate, enhancing the collection rate is probably the most important strategy for maximizing recyclables since more than 10% of generated copper waste is lost during collection (Fig. 2). A waste collection system on MSW and C&DW especially needs to be construed as a socio-technical system, aligning people's decision-making to policy goals. For the C&DW, refined sorting technologies and facilities to separate waste as well as training for operators are highly recommended to be used at construction demolition sites. Collection rates are a function of consumer behavior. Troschinetz and Mihelcic (2009) have suggested that the willingness of consumers to collaborate to the collection process depends on their level of environmental awareness. For the MSW, it is also recommended to continue to strengthen publicity and guidance, and specifically promote the favorable and digital recycling. In addition, given the projected benefits of reduced pollution (e.g. toxic gases, slag), hydrometallurgical technologies for recycling waste circuit boards and lithium-ion batteries of WEEE and ELV deserve greater attention, particularly as these have not yet been applied on any major scale in China.

Reducing copper waste and improving copper circularity require actions across the full product lifecycle, not merely the EoL stage. **Early-stage design** plays a major role in determining whether EoL products (or parts, components or materials) are amenable to direct reuse, remanufacturing, refurbishment or recycling, from where whether they are reusable or which parts/components/materials should be removed needs to be think over holistically to anticipate minimum waste at their end of life (Ciacci et al., 2020; Ghisellini et al., 2016; Mendoza et al., 2017). Beyond the practical feasibility of recycling, the environmental impacts of different materials should also be considered in the design phase. It should be noted, though, that because the lifetime of certain copper products may be as long as decades, new designs will have no direct and immediate impact on waste management, although they will facilitate circularity in the future.

Waste quality is a very crucial aspect to assess copper waste management and associated environmental impacts. Copper waste is complex, and the quality of it varies. As known from this study, due to the different waste quality from different copper use applications, the environmental impacts of copper recycling may differ strikingly. Several few studies also have concluded that the energy use of recycling largely depends on the waste quality (Corsten et al., 2013; Wang et al., 2021b). Some copper waste probably only needs managed by collection or simple physical removal of covering without the smelting refining process in other countries, for example, copper cable in infrastructure, which may result in even lower environmental impacts (Schäfer and Schmidt, 2020). However, some impurities caused by undesirable copper alloying elements are hard to be removed, which could reduce the quality of copper waste (Ayer et al., 2016; Muchova et al., 2011). Therefore, waste quality in addition to quantity may be worthy of further attention in waste management and assessing environmental impacts of secondary copper production, and consequently, data in this field needs to be improved in the future.

The notions of “Zero waste” or “circular economy” highlight the importance of secondary resources, and this study, while limited in scope, provides insights into future opportunities for improved waste management in China as well as some of the challenges involved. To reap the full benefits in terms of resource efficiency and reduced environmental impacts, more measures from supply side and demand side (e.g. light-weight design, low-carbon technologies and substitutes) are needed in the future (Wang et al., 2021a). This analysis explores the waste management, it’s potential to reduce primary copper demand and associated GHG emissions and cumulative energy demand. With copper being very relevant for infrastructure development in other fast developing countries in the world, a transition towards a circular economy in China is likely to provide an important reduction of the pressure on copper demand for those countries. From a methodological perspective, this analysis provides a perspective on the integration of MFA and LCA. Such an approach could be very supportive to future research on other materials for which a transition to circularity is required, in order to move towards a sustainable development in the world.

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Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.04.006.

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