Towards a sustainable and circular metals economy: the case of copper in China

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Chapter 3

Scenarios for anthropogenic copper demand and supply in China: implications of a scrap import ban and a circular economy transition

Abstract

From 2013 on, China has implemented the "Green Fence" policy to restrict copper scrap imports, which have affected and will continue to affect its future copper supply. To explore how China's copper demand can be met in the future, including the effects of the "Green Fence" policy change, a stock-driven approach is combined with a scenario analysis. We compare two scenarios (Continuity Policy, Circular Economy) and assess the influence of the "Green Fence" policy on each. Effective measures to prolong product lifetime could lead to a significant reduction in copper demand. Given the limited scope for domestic mining, China will still have to depend largely on imports of primary material in the form of concentrates and refined copper or, otherwise, put major emphasis on its recycling industry and continue to import high-quality copper scrap. In combination with the establishment of a state-of-the-art, efficient and environmentally friendly recycling industry, secondary copper could satisfy the bulk of Chinese copper demand and this could be an opportunity for China to transition to a more circular economy with regard to copper.

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3.1 Introduction

Copper is an indispensable resource for a wide range of applications. In recent years, with China's vigorous development of their electricity infrastructure and the rise of electric vehicles, copper consumption has increased enormously. Since 2002, China has become the world's largest copper consumer. The proportion of Chinese copper consumption in global copper consumption has increased from 17% (2.6 million tons) in 2002 to 46% (8.4 million tons) in 2016 (Dong et al., 2019; MNR, 2018). Under the current policy plan, this fast-growing demand is expected to continue in the near future, which might cause future supply problems and environmental issues related to copper production (Elshkaki et al., 2016; OECD, 2019; Van der Voet et al., 2018).

Copper demand is met by both primary and secondary copper. Primary copper is the predominant resource for Chinese copper production until now, accounting for more than 65%. Secondary copper production has seen a significant development in the past few years. As a result of low generation of domestic copper scrap, the main source of secondary copper is still imported scrap. Large amounts of copper scrap have been imported since the early 1990s to meet the country's growing copper demand. Today, however, China is flooded with discarded electronic products from all over the world. At the same time, the technology and equipment for dismantling and recycling such products is relatively unsophisticated in China. Some of the dismantling plants incinerate copper scrap like motors and wires in the open air, and dump dismantling residuals, leading to serious pollution problems (Duan et al., 2011; Gradin et al., 2013). Therefore, China has implemented several policies to improve the environmental performance of its copper industry since 2013, one of which is to increase the number of inspections and restrict the import of low-quality copper scrap: the so-called "Green Fence" policy (State Council, 2013). The decision on whether or not to continue to import copper scrap will undoubtedly affect the future development of China's copper industry, and because of its sheer size consequently the global picture as well. It is therefore important to explore what impact this "Green Fence" policy will have on Chinese copper supply and how Chinese copper demand will be met.

A multitude of historical studies have been undertaken in the realm of copper supply and demand. To date, most studies have utilized MFA based on a top-down approach to calculate copper demand, which is projected by several external drivers like GDP, population and income (Babaei et al., 2015; Choi et al., 2008; Daigo et al., 2009; Deetman et al., 2018; Elshkaki et al., 2018; Glöser et al., 2013; Kapur, 2006; Singer, 2017). Some studies have adopted a bottom-up method to directly quantify copper demand, multiplying copper content by all the products that consumed within the system boundary in a given research period (Bader et al., 2011; Dong et al., 2019; Schipper et al., 2018; Zhang, L. et al., 2014). These studies quantify the number of copper products in use and arrive at copper flows using data on the copper content of these products. To explore how to meet copper demand, several scholars have investigated the broader copper cycle comprising copper production, fabrication and manufacturing, use and waste management (Bertram et al., 2003; Glöser et al., 2013; Graedel et al., 2004a; Graedel et al., 2004b; Soulier et al., 2018a; Soulier et al., 2018b; Spatari et al., 2002; Tanimoto et al., 2010). Specifically, Elshkaki et al. (2016) modelled four scenarios of global primary and secondary copper supply. Furthermore, some research has estimated potential copper scrap and analyzed the copper recycling industry (Brahmst, 2006; Daigo et al., 2007; Reijnders, 2003; Tatsumi et al., 2008; Wang et al., 2017). Wormser (1921), Tercero Espinoza and Soulier (2016), Zhang et al. (2017) and Dong et al. (2018) have focused on copper trade flows and identify the relative role of various countries in global copper-relevant value chains. With respect to copper supply, the recent literature has paid particular attention to copper ore grades and studied the environmental impacts of primary and/or secondary copper production, such as energy use, greenhouse gas (GHG) emissions and acidification issues, and proposed several strategies for reducing these impacts (Dong et al., 2017; Elshkaki et al., 2016; Giurco and Petrie, 2007; Kuipers et al., 2018; Norgate et al., 2007; Van der Voet et al., 2018).

So far, however, there have been no publications on the impact of implementing the Chinese ”Green Fence” policy on long-term copper supply and on the question of whether or not to continue to import copper scrap or even increase such imports. Based on the aforementioned special position of imported copper scrap in the Chinese copper supply chain, the purpose of this study is to explore the questions of whether or not China should continue to import scrap copper and how the country should meet its future copper demand. To this end, two copper demand scenarios (Continuity Policy (CP) scenario and Circular Economy (CE) scenario) were developed in accordance with the development path set by the Chinese government from 2005 to 2100 using a stock-driven approach in line with Dong et al. (2019). Copper supply scenarios matching this demand were then defined

based on the “Green Fence” policy. Finally, considering the many benefits of secondary copper production proposed by scholars (Alvarado et al., 2002; Elshkaki et al., 2016; Giurco and Petrie, 2007; Pfaff et al., 2018), two hypotheses are proposed that reduce primary copper production and import more copper scrap, based on two scenarios (CP and CE), explained below. The results can be used to identify possible measures and policy options in response to a future copper supply challenge in China.

3.2 Methodology and data

3.2.1 System definition of Chinese copper cycle

The Chinese copper cycle was analyzed using a system definition based on the structure presented by Soulier et al. (2018a), as shown in Figure 3.1. The model consists of mining, smelting & refining, semi-finished goods production, fabrication of end-use products, use, waste management and recycling processes. Compared with most studies on the copper cycle, we provide considerable detail on the EoL phase: obsolescence, collection, dissipation, separation and recycling. Table 3.1 shows the definition of items used for the Chinese copper cycle.

3.2.2 Modelling future copper in-use stock and copper demand

MFA has been widely used to analyze metal flows and stocks on the global and national scale. Most such studies explicitly or implicitly assume that substance flows emerge from economic activity and ultimately determine the levels of stocks (Kapur, 2006; Soulier et al., 2018b). Other approaches have acknowledged the importance of the in-use stock as the driver of flows, especially for applications with a long life span (Müller, 2006; Pauliuk et al., 2012). This method uses historical data of the in-use stock as the provider of services to society and corresponding life spans to calculate product demand

and waste generation. The difficulty with this method concerns the simulation of the future in-use stock. In this study, therefore, we first introduced a detailed analysis for modelling the future copper in-use stock based on a stock-driven method and then determined copper demand and waste generation.

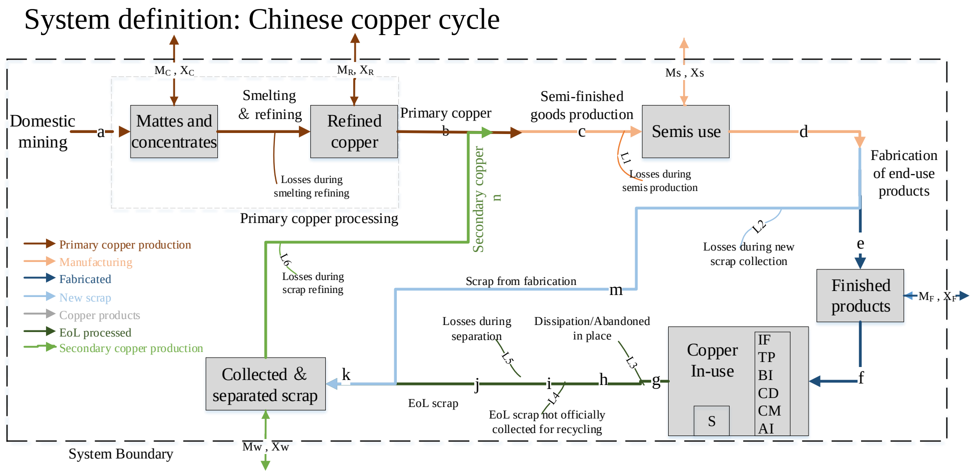

Figure 3.1 Chinese copper cycle: estimated future primary and secondary copper supply

3.2.2.1 Modelling future copper in-use stock

To estimate the in-use stock of copper, we refer to the method and data described in Dong et al. (2019). End-use copper products were divided into six main categories: infrastructure, buildings, transportation, consumer products, commercial products and agricultural & industrial durables. These consist of 29 sub-categories that include new energy applications, for instance, battery charging stations and new energy vehicles. To calculate the in-use stock of each copper product from 2005 to 2100, one or more drivers in demographics, product features, economic welfare and government policies are used, such as population, urbanization rate, copper content, GDP and Chinese government policy related to future activity levels. In order to better observe long-term waste copper generation and copper supply, we extended the study period further than Dong et al. (2019), through to 2100. The various drivers and the data used to generate the time series from 2050 to 2100 are discussed below. Drivers and data for the period up to 2050 are described in Dong et al. (2019).

Population. We used the population figures projected by the United Nations Population Division (United Nations, 2017). The population of China is expected to start decreasing from around 2030 onwards and reach around 1.02 billion in 2100 (Figure S3.1).

GDP. We used the future GDP of China projected by OECD and the University of Denver, expressed in 2010 USD Purchasing Power Parities, as shown in Figure S3.1 (IFs, 2017; OECD, 2018).

Urbanization. Urbanization rate is a key variable in estimating the in use-stock of products, because the per capita product ownership in urban and rural areas in China varies greatly. We assumed it follows a logistic function and to be 60% in 2020, 75% in 2050 and 80% in 2100 (Hu et al., 2010a; Li and Qi, 2011; United Nations, 2018).

Copper intensity. The copper intensity of each copper product was derived from Dong et al. (2019) and is shown in Table S3.1. Future trends in copper intensities are difficult to forecast since technology development could increase or decrease copper intensity in some applications, e.g. development in alternative materials and substitutes for copper. However, due to the superior performance of copper, substitution is minimal so far (ICA, 2017). Therefore, with the exception of buildings, copper intensities were therefore assumed to remain unchanged. A sensitivity analysis in Section 3.5 briefly addresses the implications of different copper intensities.

Policy plans. For estimations from 2005 to 2050, the 11th, 12th and 13th Five-Year Plans and the medium and long-term plans for each industry sector and reports by consultancy organizations (CNREC, 2017; ICA, 2013; Macquarie, 2015) were used, as reported in Dong et al. (2019). For the period from 2050 to 2100 there is no relevant government policy for all the categories, however. The in-use stock of copper applications from 2050 to 2100 was therefore estimated based on one or more of the above five drivers, with no allowance made for possible additional policies. Detailed assumptions are provided in the Supporting Information.

Table 3.1 Definition of items used for the Chinese copper cycle

Process	**Symbol**	**Name**
Use	S	In-use stock
	IF	Infrastructure
	TP	Buildings
	BI	Transportation
	CD	Consumer durables
	CM	Commercial durables
	AI	Agricultural & industrial durables
	LT	Lifetimes of copper products
	f	Domestic final demand
Trade of finished products	M_F	Import of finished products
	X_F	Export of finished products
Fabrication	e	Production of finished products
	Ex	Fabrication efficiency
	m	Scrap from fabrication (new scrap)
	L2	Loss during new scrap collection
	SR	Loss rate during new scrap collection
Trade of semi-finished goods	M_S	Import of semi-finished goods
	X_S	Export of semi-finished goods
Manufacturing	c	Production of semi-finished goods
	d	Semi-finished goods to fabrication
	L1	Loss during manufacturing
	FR	Loss rate during manufacturing
Smelting & refining	b	Primary copper supply to manufacturing
Trade of primary copper	M_c	Import of copper concentrates
	X_c	Export of copper concentrates
	M_r	Import of refined copper
	X_r	Export of refined copper
Domestic mining	a	Domestic extraction
Waste management and recycling	L3	Dissipation/abandoned copper in place
	DR	Dissipation/abandoned rate in place
	h	Total copper content in EoL scrap
	g	Generation of EoL scrap
	CR	EoL scrap collection rate
	i	EoL copper collected
	PR	EoL separation rate
	L5	Losses during separation
	j	EoL copper recycled (old scrap)
	k	Collected & separated domestic scrap
	L6	Loss during scrap refining

Process	**Symbol**	**Name**
	SRR	Loss rate during scrap refining
	n	Secondary copper supply to manufacturing
Trade of copper scrap	M_W	Import of copper scrap
	X_W	Export of copper scrap

3.2.2.2 Modelling future copper demand

To estimate copper demand and waste, we adopted a stock-driven approach, as originally presented by Müller (2006), Pauliuk et al. (2012) and Pauliuk (2014). We calculated the copper flows into the stock in year t_0 that have survived for t years using Normal distribution of lifetimes. The Normal distribution is commonly used for general reliability analysis (Ayres et al., 2003; Bader et al., 2011; Glöser et al., 2013; Hu et al., 2010b). The lifetime distribution *f(t)* in the form of a probability density function (PDF), the likelihood of failure *F(t)* in the form of a cumulative distribution function (CDF) and the survival function (*SF(t)*) of the normal distribution are given by:

$$\mathrm{f(t)} = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{t-\mu}{\sigma})^2} \quad (3.1)$$

$$\mathrm{F(t)} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-t^2}{2}} dt \quad (3.2)$$

$$\mathrm{SF(t)} = 1 - \mathrm{F(t)} \quad (3.3)$$

where t is the time step, μ is the mean lifetime of the respective product and σ is the standard deviation of the lifetime distribution. The SF distributions of copper products are shown in Figure S3.2.

The survival function presents the fraction of copper products consumed in year (t') that are still in use in year t. We then calculated the copper content in surviving copper products (CSR) from the copper consumption in all products CC_i of previous years (t') as follows:

$$CSR_i(t) = \sum_{t'}^{t} CC_i(t') \times SF_i(t - t') \quad (3.4)$$

$$CC_i(t') = PC_i(t') \times \theta_i(t') \quad (3.5)$$

$$CC_i(t) = CS_i(t) - CSR_i(t) \quad (3.6)$$

$$CD_i(t) = CC_i(t) - (CS_i(t) - CS_i(t-1)) \quad (3.7)$$

where i is the type of copper product, $CS_i(t)$ is the in use stock of copper in each product in year t. $CD_i(t)$ is the discarded copper in each product in year t. $PC_i(t')$ is the consumption of copper products in year (t'). $\theta_i(t')$ is the copper content of each product in year t.

3.2.3 Modelling future primary and secondary copper supply

Copper demand is met by primary and secondary copper. To estimate the future primary and secondary copper supply, we first estimated the future supply of secondary copper (n, Figure 3.2) from EoL scrap (j), new scrap generated in the fabrication process (m) and scrap coming from international trade (M_w, X_w). Next, we estimated the demand for finished (f) and semi-finished (c) products. Finally, the amount of primary copper (b) was estimated through backwards calculation from this final demand via manufacturing of semi-finished products and trade. Part of this primary copper comes from domestic mining (a). The remainder was assumed to be imported (M_{cr}, X_{cr}). The simple stock-driven model for estimating future copper supply is shown in Figure 3.2. The detailed calculation steps can be found in the Supporting files.

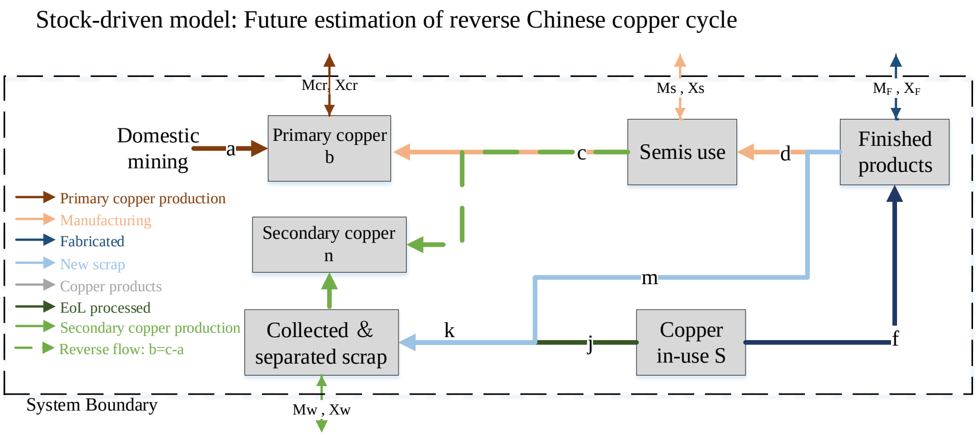

Figure 3.2 Stock-driven model: Future estimation of reverse Chinese copper cycle

3.2.3.1 Secondary copper production

Domestic secondary production-EoL scrap (old scrap). Copper scrap from

EoL products (j), also called old copper scrap, refers to copper scrap from products that have been used by consumers or other end-users. It is a huge potential resource. The generation of copper scrap in China is forecasted to increase massively in the future owing to the historical rise in copper consumption and stocks (Dong et al., 2019; Soulier et al., 2018b; Wang et al., 2017). Recovery of old copper scrap generally goes through two stages: pretreatment and recycling. The pretreatment stage refers to the collection and separation of mixed copper scrap and removal of other waste on the surface of scrap products to obtain a single and relatively pure variety of copper scrap. There is a certain amount of dissipation or abandoned copper in place in the pretreatment stage; for example, some copper scrap is not collected, such as underground cables that are just left in the ground. In addition, some copper use is at least partly dissipative in nature (e.g. copper used in fungicides; material loss through abrasion or corrosion or copper and copper alloy parts in architecture and machinery, ammunition), or present in too small quantities in products to be practically collected for recycling (e.g. brass rivets and zippers in clothing). Dissipative losses (L3) occur mainly during the use phase of copper applications due to corrosion and abrasion and are accounted for in their entirety on a market-by-market basis at the time products leave the use phase. Some of the dissipated copper will become part of sewage sludge and might be reused as a fertilizer. However, as copper is not recycled from this flow, sewage sludge and its copper content are not included in waste management.

Copper scrap is usually divided into six types: construction and demolition waste, end of-life vehicles, municipal solid waste, waste of electrical and electronic equipment, industrial electrical waste, and industrial non-electrical waste (Ruhrberg, 2006; Schlesinger et al., 2011; Soulier et al., 2018b). To estimate the amount of EoL copper recycled, the generation of EoL scrap (g), the collection rate of EoL scrap (CR, for flows i), the dissipation rate (DR, for flows h, L3) and loss rate of separation (PR, for flow i, L5) for each type were used based on Soulier et al. (2018b). We matched the rate for each of the copper sub-categories to the six types in their study.

Domestic secondary production-New scrap. New copper scrap is generated during the fabrication of copper products, in amounts that depend on the fabrication efficiency. As a result of the upgrading of equipment and continuous technological innovation, copper product fabrication efficiency increased from 80% in 1990 to 89% in 2016. In this study, we assumed it remains unchanged in the future. To estimate new scrap from fabrication, we assumed a collection efficiency of 95%, leading to a loss rate (SR, for flow L2) of 5%.

Imported copper scrap. The customs codes of the General Administration of Customs of the People's Republic of China (GACC) for imported solid wastes are divided into ten categories, corresponding to different types of solid waste, including waste paper, waste plastics and metal scrap. Among them, "category 6" and "category 7" contain copper. We therefore likewise divided imported copper scrap into two categories: "category 6" and "category 7" (Table 3.2). High-grade Category 6 scrap and brass scrap with a clear classification and little impurities (copper content above 95%) can be directly processed and used. Part of the lower-grade red copper scrap and brass scrap (copper content ranging from 70% to 95%) is also Category 6 scrap and can be imported, but needs to be smelted again. Lower copper content scrap belongs to Category 7.

Under the "Green Fence" policy, category 7 scrap will no longer be allowed to be imported from 2019 onwards, while imports of category 6 scrap will be restricted as of July 2019 and will be gradually phased out as well. To estimate future imports and exports of category 6 scrap, the historical relationship between GDP and the volume of imports and exports of copper scrap was used.

Total secondary copper supply. The secondary copper utilized in Chinese production derives from three sources: new copper scrap, old copper scrap and imported copper scrap. Based on the calculation of these three elements, secondary copper supply is estimated using equation (8).

$$F_{n,t} = F_{m,t} + F_{j,t} + M_{w,t} - X_{w,t} \times (1 - SRR) \qquad (3.8)$$

where $F_{n,t}$ is future secondary copper supply, $M_{w,t}$ and $X_{w,t}$ are future import and export of copper scrap and SRR is the loss rate during scrap refining, which is related to flow $L6$.

Table 3.2 Overview of the "Green Fence" policy: categories 6 and 7 of imported copper scrap

Customs code	Scrap category	Scrap covered	Copper content	Import timeline	Sources
7404000010	7	Precipitated copper	40%	Automatic import from 2013.01.01 Restriction from 2014.01.01 Ban from 2015.01.01	Automatic import license of China (2014); Automatic import license of China (2015)
7404000010	7	Low-grade waste cables, waste motors, waste transformers and other hardware	20%-70%	Automatic import from 2013.01.01 Restriction from 2015.01.01 Ban from 2018.12.31	Automatic import license of China (2014); Catalogue for Administration of Import of Solid Wastes (2018, 06); Catalogue for Administration of Import of Solid Wastes (2018, 68)
7404000090	6	Bright copper, No.1, No.2 and clean or new yellow, red and semi-red brass	70-99.9%	Restriction from 2019.07.01	Catalogue for Administration of Import of Solid Wastes (2018, 68)

3.2.3.2 Manufacturing and fabrication

To satisfy final domestic demand, we analyzed the production of semi-finished (c) and finished (d) products. The international trade simulation of semi-finished and finished products was based on the historical relationship between GDP and the volume of imports and exports of semi-finished products and finished products, respectively (Figure S3.4). Using these numbers on trade together with a loss rate (FR) of 1% during semi-finished goods production and a fabrication efficiency (F_{Ex}) of 89% during finished goods production, we determined the copper input for production of semi-finished goods.

3.2.3.3 Primary copper production

Primary production-Domestic copper mining. The starting point for calculating primary copper is modelling of domestic copper mining (a). As it is unknown how domestic production of copper concentrates will develop in the future, we referred to historical data on copper mining, primary copper trade and primary copper supply to project the share of domestic mining in primary copper supply (as shown in Figure S3.3). To estimate future domestic mining, we extrapolated the share of domestic primary production in total supply based on the data from 2006 to 2015 (a rate of change of -1.5% per year).

Total primary copper supply. Having determined the copper input required for production of semi-finished products, we set primary supply to cover the difference between recycled supply from secondary sources and the required production input:

$$F_{b,t} = F_{c,t} - F_{n,t} \qquad (3.9)$$

$$MX_{cr,t} = F_{b,t} - F_{a,t} \qquad (3.10)$$

where $F_{b,t}$ is future primary copper supply in year t, $MX_{cr,t}$ is net trade of primary copper in year t, $F_{a,t}$ is future domestic copper mining in year t and $F_{c,t}$ is future domestic production of semi-finished products in year t.

3.2.4 Design of copper demand and supply scenarios

Two copper demand scenarios are explored: the Continuity Policy (CP) scenario and the Circular Economy (CE) scenario. They are summarized in Table 3.3. Both scenarios were constructed based on the same stock as estimated above. In the CE scenario, we modeled reduced demand by assuming that re-use, refurbishing and waste prevention will lead to extended lifetimes of copper products. Lifetimes have a direct impact on outflow, which means that extending product lifetime can reduce copper scrap generation in a determined period of time. Therefore, to model the waste generation before

2016, the lifetimes of end-use copper applications in the CP and CE scenarios were assumed to be the same. For the period from 2017 to 2100, we kept the lifetimes of end-use copper applications constant in the CP scenario, while in the CE scenario we extended the lifetimes of 29 sub-categories of end-use copper applications with a logistic regression based on the current level. The average lifetimes of copper products under sub-categories (e.g. cables in buildings) were assumed to be the same with the average lifetimes of sub-categories. Detailed lifetimes of each sub-categories can be found in Table S3.1 of appendix 1.

To explore how the country should meet its future copper demand, copper supply scenarios (CP and CE) were designed corresponding to the CP and CE demand scenarios (Table 3.3). Compared with the CP supply scenario, higher recycling rates were applied in the CE supply scenario. Recycling rates determine how much copper waste is recyclable from EoL copper products. An increase in the EoL recycling rate therefore means more copper remains in the cycle as a valuable secondary resource, while permanent losses to landfill, dissipation and other material cycles are reduced. Under the CP scenario, the recycling rate, which is determined by the collection rate (83%) and processing rate (20%~90%, category-specific), was assumed to remain constant from 2016 onwards (Table S3.3). Under the CE scenario, the collection rate and processing rate were assumed to increase from the 2016 value under the CP scenario to 90% and 95% for each end-use sub-category in 2100, with a linear regression.

Regarding the importance of secondary copper in the copper supply chain and the benefits of moving toward a more circular economy, we propose two hypotheses based on the CP (Hypothesis 1, H1) and CE (Hypothesis 2, H2) scenarios. In these hypotheses, all Chinese copper demand (from the CP and CE scenarios) is met by secondary copper.

Table 3.3 Summary of copper demand and supply scenarios

Scenario	Scenario description	Common parameters	Parameter changes	
			Lifetime	Recycling rate
Demand perspective				
Continuity Policy scenario	A scenario for future development that assumes there will be certain changes under activities of population, economic development and government policies, so that the copper industry can be expected to change and develop correspondingly.	GDP, Population, Urbanization rate, Copper intensity and Chinese government policy	Regular lifetimes of copper products	-
Circular Economy scenario	A scenario for future development based not only on certain changes in demographics, economic welfare and government policies, but also on a reduction of copper demand, e.g. due to prolonged product lifetimes.		Extended lifetimes of copper products	-
Supply perspective				
Continuity Policy scenario	A supply scenario to meet the Continuity Policy scenario for copper demand.	"Green Fence" policy on imported copper scrap	-	Constant recycling rates of EoL products
Circular Economy scenario	A supply scenario to meet the Circular Economy scenario for copper demand, and encourage the reduction, recycling and reuse of copper.		-	Higher recycling rates of EoL products

3.2.5 Data source

The data used for estimating copper demand were derived mainly from Dong et al. (2019) and other publications and reports, as specified above. The historical data on fabrication efficiency, loss rates during copper production (semis production, new scrap collection, scrap refining, separation, dissipation) were taken mainly from Soulier et al. (2018a), Soulier et al. (2018b) and Pfaff et al. (2018). Data on historical trade of copper products were taken from the United Nations Comtrade Database and China Nonferrous Metals Industry Association, as shown in Figures S3.3 and S3.4. To examine the robustness of the results according to the data used, a sensitivity analysis was conducted. Detailed definitions of and data on the items used for the Chinese copper cycle are provided in Table S3.3. The Supporting files can be found online at https://doi.org/10.1016/j.resconrec.2020.104943.

3.3 Results and discussion

Here, we present results and discussions for the historical copper supply of China (Section 3.3.1), the resulting of future copper demand (Section 3.3.2), the resulting of future copper supply (Section 3.3.3), the discussions on sustainability performance of future Chinese copper cycle (Section 3.3.4) and uncertainty and limitations of this study (Section 3.3.5).

3.3.1 The historical copper supply of China: pre- and post-implementation of the “Green Fence” policy

Figure 3.3a shows copper supply in China between 2005 and 2016 from our model, compared to statistical data. To meet the country’s growing demand, the supply of both primary and secondary copper have increased in our model. Primary copper has served as the main source, with imported primary copper accounting for more than 70%.

Secondary copper production has increased in recent years, but its share in total copper supply has been declining. Before the implementation of the “Green Fence” policy, secondary copper was satisfied mainly by imported copper scrap. In 2005, the imported scrap, domestic new scrap and domestic old scrap accounted for 51%, 34% and 15% of total scrap supply, respectively. After the implementation of the policy, secondary copper has been supplied mainly by domestic scrap (new and old scrap). Generation of new copper scrap is determined mainly by the processing efficiency of fabrication and the loss rate of new scrap collection, which means that the increased processing efficiency has contributed to slower growth of new scrap generation.

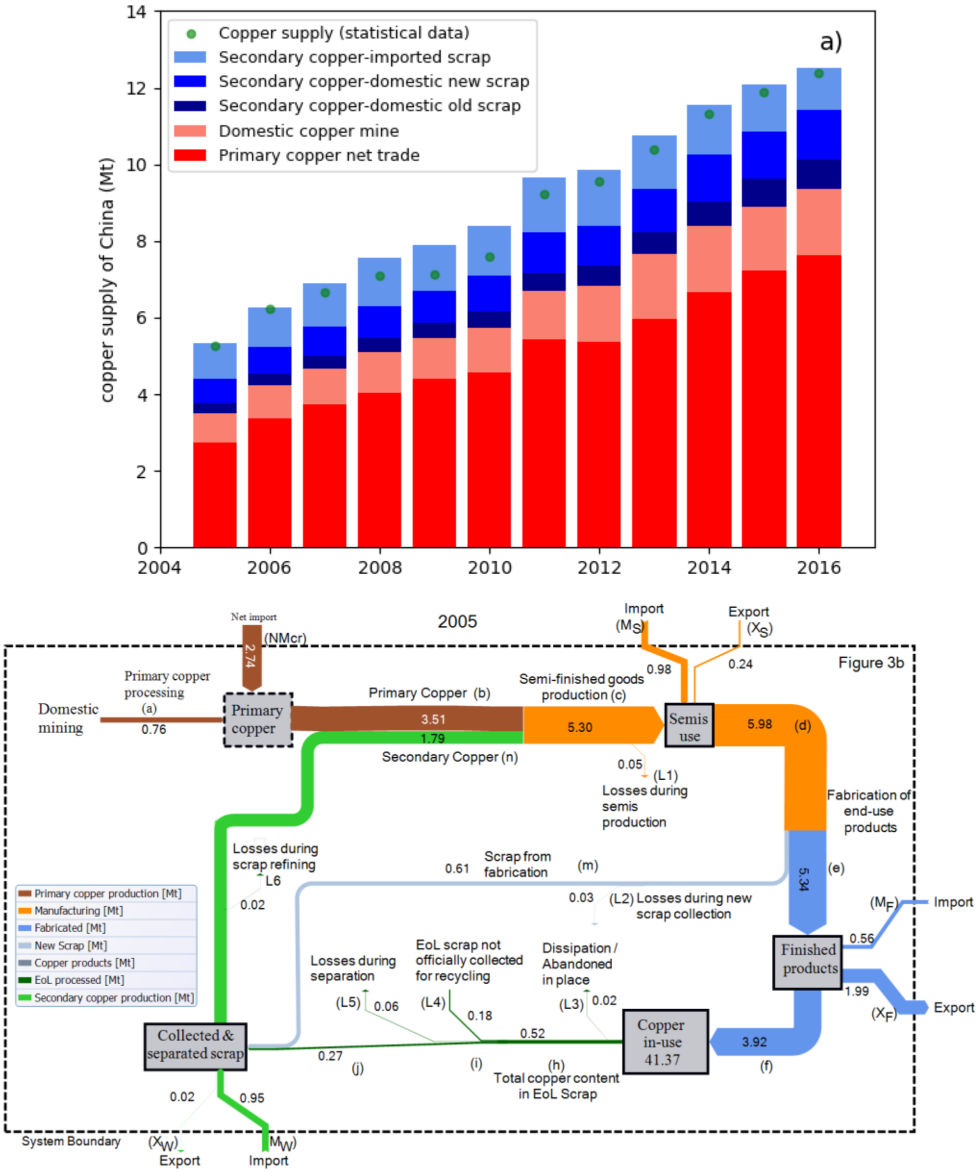

Figure 3.3 a) Copper supply of China from 2005 to 2016; b) copper cycle of China in 2005

At the same time, although the EoL recycling rate has increased, most of China's copper products had not entered its retirement period prior to 2016, given the 30-year overall average lifetime of copper products, resulting in very slow growth of EoL copper recycled in China. Limited domestic copper mining implied that primary copper production within China was insufficient to meet historical copper demand. At the same time, the "Green Fence" policy has affected the copper supply structure of China, resulting in inadequate copper scrap for producing secondary copper and consequently in the need to import more primary copper.

3.3.2 Copper demand projections for China

Figure 3.4 shows the developments of the copper stock and copper demand in the CP and CE scenarios up to 2100. The copper stock in China (identical under the CP and CE scenarios) is increasing rapidly owing to the enduring growth of copper use in power generation and transmission, buildings and transportation. Infrastructure is expected to hold the greatest copper stock, within which electricity applications account for the largest fraction. The stock of buildings will likely stabilize in the latter half of the century and still occupies the second largest copper stock.

Copper demand is expected to increase in near future, with different growth rates for different copper categories in the CP scenario, reaching a level in 2100 around 2.9 times higher than in 2016. Unsurprisingly, copper demand is lower in the CE scenario, since extended lifetimes of copper products mean a slower replacement rate and hence reduced demand. As a result, copper demand peaks around 2050 and then gradually declines in the CE scenario. Previous studies show different trends of future Chinese copper demand due to different methods, considered copper products and assumptions. For a short-term estimation, Yang et al. (2017) and Wang, J. et al. (2019) estimate the demand in 2030 to be around 15.4 and 12 Mt respectively. The outcomes in our model are comparable and in the range of existing studies. Adopting a long-term perspective, Zhang, L. et al. (2015a) estimated that demand will peak in 2042 with around 8.3 Mt and decline until 2080 to around 7 Mt. The values are very low in comparison with our results. Possible reasons for this large difference might be categorization of copper products that had been included and assumptions in model. In this study we included new energy applications that will demand major amounts of copper. In particular, our simulation is conducted according to the government development plans rather than assuming that the development level in 2050 is based on the regression of the previous year's data, such as the electricity generation and demand plan, which makes a vast difference. Subsequently, OECD (2019) displayed that the demand will increase to around 27 Mt in 2060 based on a central baseline scenario, which fits better with our results.

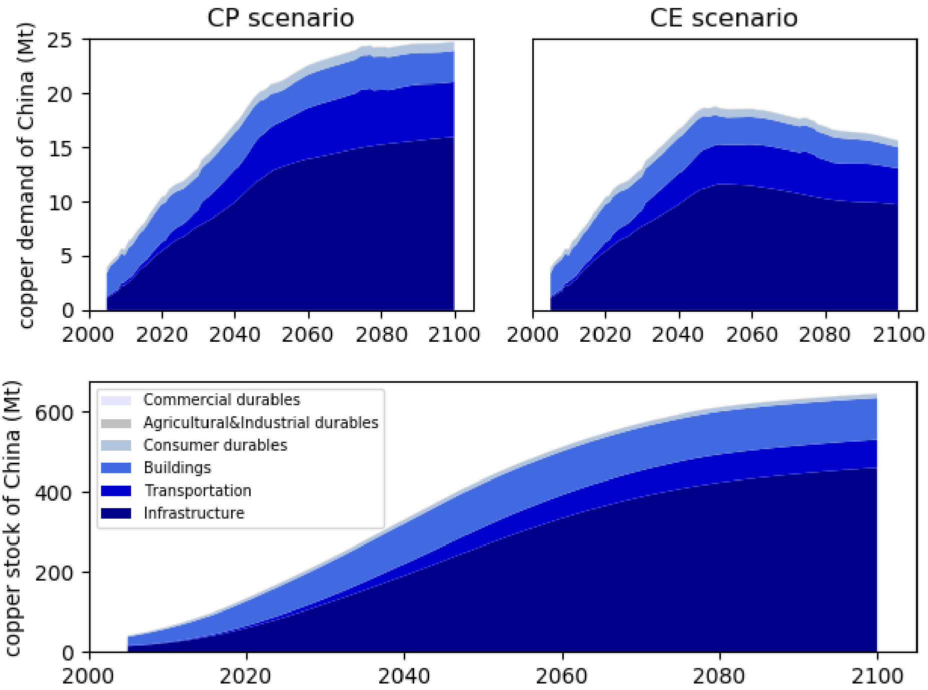

Figure 3.4 CP and CE scenarios of copper stock and final domestic copper demand in China up to 2100

In both scenarios, demand for copper is generated predominantly by the infrastructure sector, followed by transportation, buildings, consumer durables, agricultural & industrial durables and commercial durables. Note that the CP and CE scenarios are both based on the same projection of in-use copper stock, with the differences in copper demand emerging through different replacement rates under different lifetime assumptions.

3.3.3 Copper supply projections for China

Figure 3.5 shows the copper supply scenarios for China up to 2100. Primary copper supply reaches its maximum around the year 2060 and then declines in the CP scenario, whereas this point is already reached before mid-century in the CE scenario. Moreover, the proportion of primary copper to total copper supply decreases after 2020 in both scenarios. By then, production of secondary copper has gradually increased and become a major source of copper supply. In 2100, secondary copper will supply 55% of copper demand in the CP scenario, while this figure will be 60% in the CE scenario.

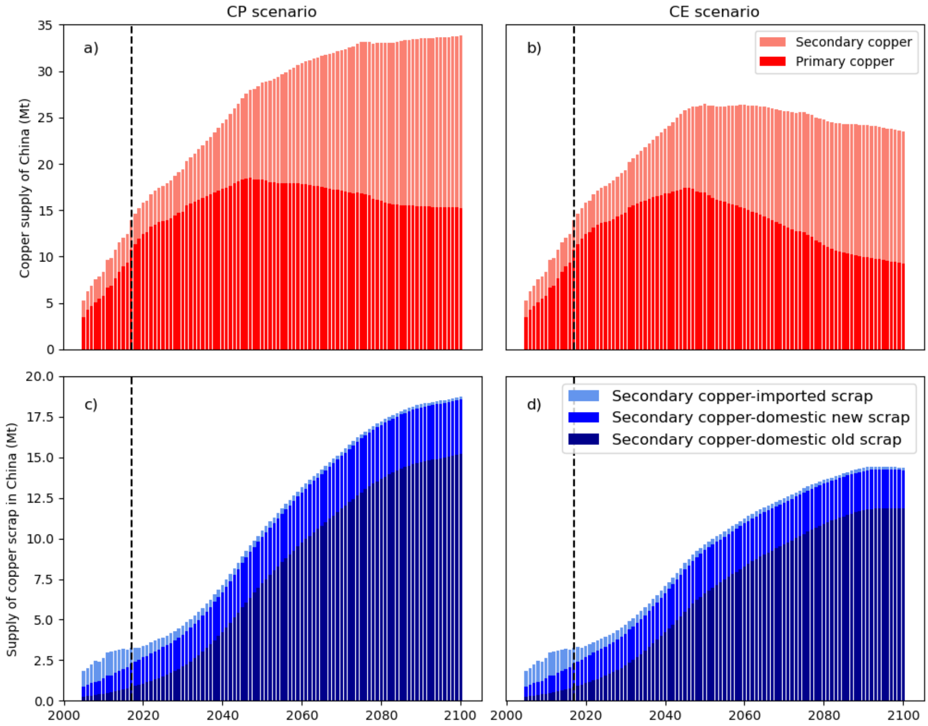

Figure 3.5 Chinese copper supply scenarios from 2005 to 2100. The vertical dashed line marks the boundary between historical data and future scenarios. Copper supply in the CP (a) and CE (b) scenario. Different scrap sources for secondary copper production in CP (c) and CE (d) scenario.

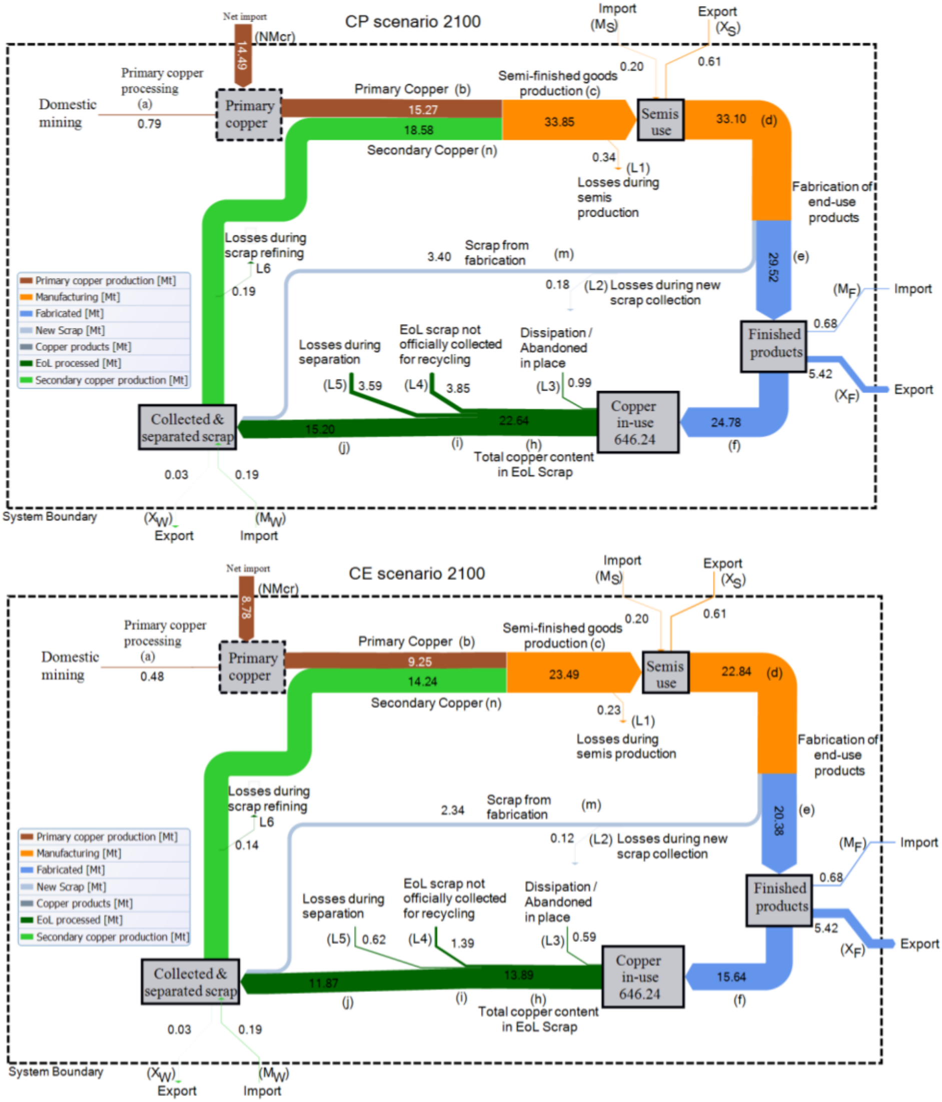

Figure 3.6 Future copper cycle of China in 2100 under the CP and CE scenarios

As mentioned above, before the implementation of the "Green Fence" policy, imported copper scrap played an important role in Chinese secondary copper production. However, with the increase in the generation of old copper scrap in China, both scenarios show that domestic old copper scrap will become the main source of secondary production. As shown in Figure 3.6, in the CP scenario, the proportion of old scrap to total copper scrap increases from 19%

in 2013 to approximately 81% in 2100. In the CE scenario, the proportion is even higher, with 83% in 2100. Comparing the two scenarios, we find there is 9% less domestic scrap in the CE scenario than in the CP scenario in 2050, with the figure rising to 30% in 2100. The reason for this is the time delay between copper use in production and scrap generation, especially for products with long lifetimes. Longer product lifetimes will reduce the amount of scrap generated, while increased copper recycling rates will boost secondary copper production. Future copper demand in China will therefore be satisfied substantially through increased copper recycling from domestic old scrap.

3.3.4 Discussion on sustainability performance of future Chinese copper cycle

As part of the transition to a circular economy in China's industrialization and urbanization process, the copper industry is also actively exploring moving from a linear development pattern to a circular economy pattern. Given this process of transformation along with implementation of the "Green Fence" policy, our scenarios point to a number of opportunities as well as challenges for the future development of the Chinese copper industry.

3.3.4.1 Prospective development of circular economy for copper demand

Copper is widely used in buildings, transportation, home appliances and industrial machinery, which implies that Chinese copper demand is expected to grow continuously as these sectors develop further. In order to reduce the environmental burden caused by the copper production related to this expanded copper demand, many scholars have proposed that the prime option should be to simply reduce copper demand. At the same time, though, they also recognize that copper demand is not readily reduced by cutting back on the use of copper products (Dong et al., 2019; Elshkaki et al., 2018; Van der Voet et al., 2018), which will not be easy to realize in China since it is still in the midst of development. Additionally, China is currently shifting from a fossil-based energy system to a renewables-based energy system. In particular, electrification of the energy system, a key strategy in the energy transition, requires massive amounts of copper.

Extending the lifetimes of copper products is an obvious option to achieve slower replacement rates and thus reduce future copper demand. Furthermore, many studies have shown that extending product lifetimes is not only beneficial to consumers, but can also alleviate the environmental burden caused by waste treatment by reducing the amount of waste that has to be dealt with, and thus achieve the goal of a more circular economy (Ardente and Mathieux, 2014; Wang et al., 2017). However, a product's lifetime is determined during the design stage, when establishing such matters as product structure and material selection. Another option is to repair and reuse products that would otherwise be scrapped. This option is also related to product design, since easy replacement and easy maintenance of product parts will facilitate product reuse and repair, thus extending lifetimes. Although product design is complex, it is certainly an effective way to lengthen copper product lifetimes, maintaining the copper's value for as long as possible by keeping it in the economic system.

3.3.4.2 Challenges in primary copper production

Worthy of discussion are the copper supply projections in this paper, since they are built on the assumption that no limitations exist on copper reserves in China. However, such limitations do exist. A report issued by the China Geological Survey states that copper reserves and identified resources of China in 2016 are 28 and 101.1 Mt, respectively (CGS, 2016). It can be seen that China's domestic copper production has been increasing in recent years, but it is still unable to meet Chinese copper demand. Based on our results, domestic primary copper production is not and will not be adequate to meet the required amount of primary copper, and China will have to import substantially more copper ore or refined copper (as shown in Figure 3.7). Consequently, the share of imported primary copper in total primary copper supply is likely to increase significantly, which is undoubtedly a supply security issue worth considering for the Chinese copper industry. This is in agreement with Wang, J. et al. (2019) who show a large gap between Chinese copper demand and supply in the future. Furthermore, on the global level, Mohr (2010) and Northey et al. (2014) have provided projections of future potential copper production and concluded that global copper production will peak around 2032 and rapidly decline thereafter (Figure 3.7b). Following these projections, China would not have enough primary copper sources to import from in the future.

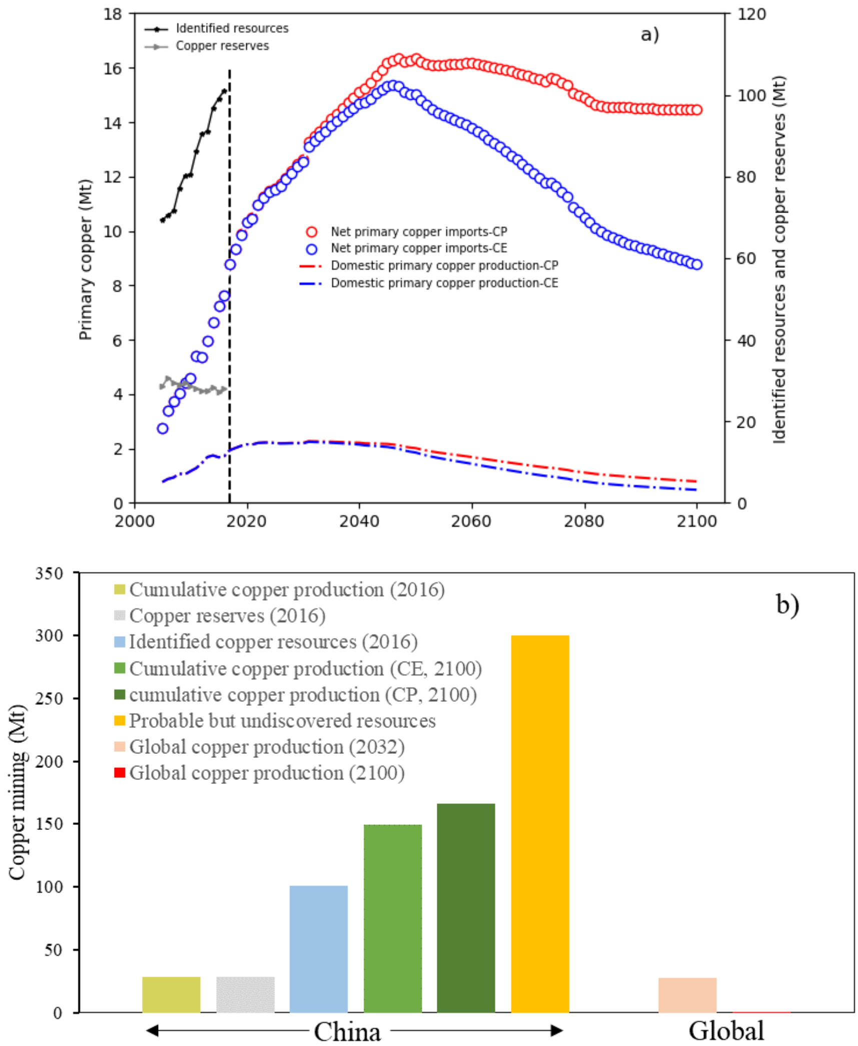

Figure 3.7 a) Right y-axis: Domestic primary copper production, copper reserves, identified copper resources in China (data: National Bureau of Statistics of China and Ministry of Natural Resources of China); left y-axis: domestic primary copper production and primary copper that needs to be imported in CP and CE scenarios. The vertical dashed line marks the boundary between historical data and future scenarios; b) Copper mining in China and the world (global data source: Mohr (2010) and Northey et al. (2014)).

Despite these projections, future Chinese primary copper production is unlikely to be physically limited. On the one hand, to ensure long-term supply security in line with the National Mineral Resource Planning (MNR, 2016), the Government will likely provide strong support to domestic exploration as well as overseas acquisition. Copper reserves are likely to increase in the future as additional deposits are discovered and/or new technology or economic variables improve their economic viability (e.g. probable but undiscovered resources in Figure 3.7b). Under these assumptions, the potential cumulative copper production up to 2100 might be satisfied by domestic resources. On the other hand, improved copper refining and copper recycling technologies and possibly the use of copper substitutes will also reduce demand for primary copper or total copper. No matter what kind of developments occur in the future, however, the issue of security of supply of primary copper remains relevant for China owing to its high import dependence.

3.3.4.3 Opportunities and risks for China related to the import of copper scrap

One possible way to improve security of supply is to increase reasonable proportion of secondary production. As the amount of copper scrap generated domestically in China increases, the implementation of this measure becomes more feasible. It has the additional advantage that the environmental impacts of producing 1 kg of secondary copper are much less than that for 1 kg of primary copper (Kuipers et al., 2018; Norgate, 2001; Van der Voet et al., 2018). It has been pointed out that the energy requirements and associated GHG emissions of secondary copper production may surpass those of primary copper production with EoL recycling rates approaching 100% (Norgate, 2004; Schäfer and Schmidt, 2020). This implies that primary production and secondary production need to be balanced to minimize energy consumption and environmental impacts in a circular economy scenario. However, considering the advantage of conservation of natural resources and utilization of waste, increasing secondary production is still an important long-term option to achieve a circular economy.

Relying entirely on secondary production is also problematic for additional reasons. If China were to rely solely on secondary production, the amounts of copper scrap that would have to be imported would be quite substantial in both scenarios, especially in the CP scenario (Figure 3.8). According to the data presented by Elshkaki et al. (2016) and Schipper et al. (2018), global copper scrap availability is expected to reach around 25 Mt in 2040 and 50 to 220 Mt in 2100, depending on the scenario. In fact, China would use around 24 Mt or 23 Mt of copper scrap, of which around 17 Mt are from imports, under the hypotheses (H1 and H2) where secondary production dominates in 2040. This is a major share of all the EoL scrap expected to be generated globally in 2040, which clearly is not feasible. Furthermore, some countries or regions proposed to transition to a more circular economy and will increase recycling. What this indicates, then, is that other countries will also need large amounts of scrap and there would be a major shortage of copper scrap if China decides to move to a completely closed-loop economy before mid-century. By 2100, however, China would use half or less of global copper scrap. In the CP scenario, therefore, China will probably face an even tighter scarcity of copper scrap.

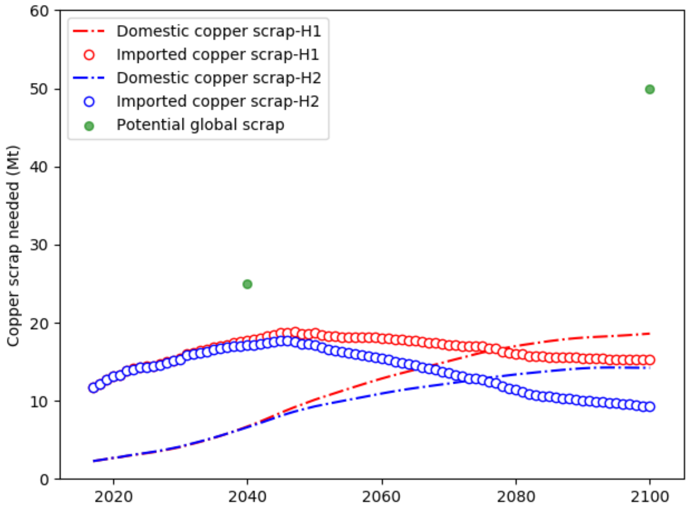

Figure 3.8 H1/H2: Domestic copper scrap supply and required imported copper scrap under the CP and CE scenarios, assuming a phase-out of primary production. Calculations based on the assumption that Chinese copper demand under the CP (H1)/CE (H2) scenario is met solely by secondary copper produced under the corresponding CP (H1)/CE (H2) supply scenario. Data of potential global scrap is derived from Elshkaki et al. (2016) and Schipper et al. (2018) that ranges from 50 to 220 Mt in 2100. Here we used the least value (50 Mt) in 2100.

Therefore, the implementation of “closing the loop” on the national level is challenging because of domestic resources availability, environmental benefits and trade-offs on the way towards a circular economy on the global level. It may mean that creating a circular economy at the global level will take some time, not just because it is hard to organize, but because it can only be established after stock saturation has occurred on a global scale, so copper demand will no longer be growing, allowing scrap generation to catch up.

Considering that the production of domestic copper scrap and primary copper are still unable to meet current copper demand in China, the most reasonable way forward, by and large, is probably somewhere between a major dependence on primary copper import and a major dependence on scrap imports. Given that secondary copper production has (up to a certain point, see above) less environmental impact than primary copper production, China should still consider importing copper scrap to partially meet its copper demand. An increase of high-quality copper scrap imports instead of importing copper ore or refined copper is a feasible and environmentally beneficial option for further development of China's copper industry. This option may indeed force more industries, in China as well as elsewhere, to establish facilities for copper dismantling and recycling.

3.3.5 Uncertainty and limitations

Exploring copper demand and supply throughout the 21st century involves significant uncertainty. A simulation exercise like the present one does not aim for precise numbers, but for patterns and trends reproducible under many different simulation parameters and assumptions. The long-term projections of GDP, population, copper content, trade and many other parameters are based on historical data and policy-oriented inference. Although our simulation is based on reliable historical data and policies, there is no mechanism for unambiguously indicating the future development trajectory, especially for the trend post-2050 and trade in copper-containing products. However, it is highly likely that the output of Chinese copper scrap will increase significantly under any assumption, which will accelerate the development of secondary copper supply.

As pointed out above, the lifetimes of copper products are absolutely crucial for the modelling of copper demand and supply. Glöser et al. (2013) found that the effect of changing the shape (functional form) of product lifetime distributions is small compared with the effect of changes in average lifetimes. To investigate the effect of changes in average lifetimes, an initial sensitivity analysis was therefore carried out in which it was assumed that the average lifetime of each sub-category in the CE scenario deviates in the same way (either all shorter or all longer) and in the same proportion. A +10% or -10% change in the average lifetime of each sub-category was assumed. The results indicate that, as could be expected, copper demand is lower in the scenario with longer copper product lifetimes (Figure 3.9). Over the next 20 years, the difference between the effects of +10% lifetimes and -10% lifetimes on secondary copper supply is limited, but in the long term it is considerable.

In addition to uncertainties in average lifetimes, there is considerable uncertainty concerning the recycling rate of copper scrap. In the CE scenario, the recycling rate is determined by the loss rate during separation and the collection rate. The separation rate was modeled to be around 95% in 2100, which is already a very high recovery efficiency. To examine the effect of variable recycling rates, therefore, only the collection rate was considered and assumed to change by ±5%. Higher collection rates could increase the amount of recycled copper, thus improving the secondary copper supply, as shown in Figure 3.9. Several studies have also found that the recycling rate is the most important indicator for analyzing the efficiency of EoL copper products treatment and have recommended that it be improved (Graedel et al., 2011; Ruhrberg, 2006). This is not easy to implement, however, since it involves technical updates to a range of processes, including product design, disassembly and material separation (Glöser et al., 2013; Ruhrberg, 2006; Spatari et al., 2002).

Copper content is another key factor in determining copper stocks, but it is difficult to make any reliable forecast for future changes. In some applications, such as power plants (e.g. using copper to substitute Ag in Photovoltaic power plant), new energy technologies and new energy vehicles, the copper content is rising (Månberger and Stenqvist, 2018). In other cases, copper content could be decreasing due to substitution by other materials. Aluminum is considered to have the greatest potential for replacing copper in energy infrastructure, but primary aluminum has higher energy requirements and corresponding CO_2 emissions per kg production than copper (Van der Voet et al., 2018). Given the required properties, other products may also be eligible for partially replacing copper, for example through stainless steel, zinc and plastics, but this could come with the drawback of more difficult recycling (García-Olivares, 2015). Furthermore, it is by no means straightforward to find suitable alternatives that have the same functionality and can be produced in equally large quantities (Commission, 2017). Therefore, more analysis is still needed to assess the long-term use and impacts of these substitutes.

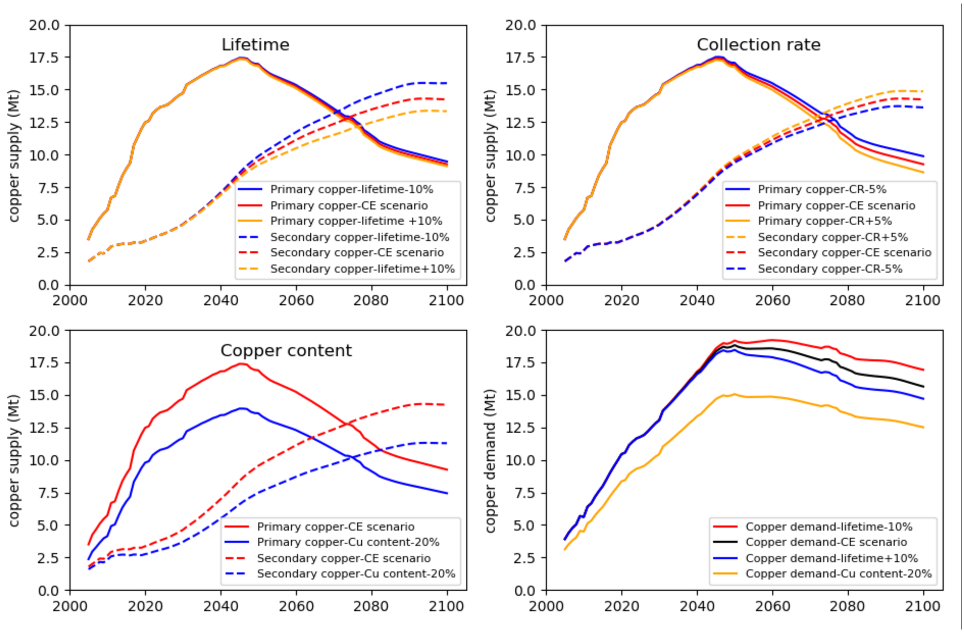

Figure 3.9 Sensitivity analysis of copper product lifetimes, recycling rate and copper content based on CE scenario

Even though copper content data are quite uncertain, a sensitivity analysis was conducted to examine the effect of it to copper demand and supply. The copper content of each sub-category was assumed to be 20% less than current level based on CE scenario. The results show that reducing copper content would lead to rather straightforward changes: reducing the copper content by 20% would decrease the demand by the same percentage (Figure 3.9).

3.4 Conclusions and implications

In this study, we used a stock-driven method to estimate the implications of a continuity policy scenario ("Green Fence" policy: ban of cat. 7 scrap and restrictions on cat. 6) and a circular economy scenario ("Green Fence" policy: ban of cat. 7 scrap and restrictions on cat. 6; increasing product lifetimes and recycling rates) for copper demand and supply in China up to 2100. We explored the scenarios with respect to the question of how China's copper demand can be met, and what impact Chinese government proposals to ban the import of copper scrap will have on the Chinese copper supply. On the basis of our results, we suggest that China could benefit from an increase in secondary copper supply by importing more copper scrap. Although certain limitations may affect the accuracy of the results, current trends of primary and secondary copper supply are unlikely to change significantly. There are therefore still good grounds for drawing the following conclusions.

- Before implementing the "Green Fence" policy, primary copper was the main source of China's copper supply. Imported copper scrap was the major source of secondary copper production, mainly because domestic old scrap production was not yet significant.
- Effective measures to increase product lifetimes could lead to significantly reduced copper demand. Under the assumptions made in this study, decreasing copper demand in the second half of the century appears possible.
- The contribution of secondary copper to total supply is likely to steadily increase in the coming decades as a result of increased availability of domestic scrap. When combined with decreasing copper demand (CE scenario), secondary copper could provide the bulk of China's copper supply towards the end of the century.
- However, there will be a substantial gap between Chinese copper demand and the amount of scrap available domestically. In the future, this gap needs to be closed by means of domestic mining or through imports. Given the limited scope for domestic mining, China will still have to depend largely on imports of primary material in the form of concentrates and refined copper or, otherwise, put major emphasis on its recycling industry and continue to import scrap. In this manner, secondary sources would be able to meet a large part of China's growing copper demand. In combination with the establishment of a state-of-the-art, efficient and environmentally friendly recycling industry, this could be an opportunity for China to transition to a more circular economy with regard to copper.