DOI: 10.1111/jiec.12926

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH AND ANALYSIS

Modeling copper demand in China up to 2050

A business-as-usual scenario based on dynamic stock and flow analysis

Di Dong[1] | Arnold Tukker[1,2] | Ester Van der Voet[1]

[1]Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands

[2]Netherlands Organization for Applied Scientific Research TNO, Den Haag, The Netherlands

Correspondence
Di Dong, Leiden University–Institute of Environmental Sciences, Leiden 2300 RA, The Netherlands.
Email: d.dong@cml.leidenuniv.nl

Funding information
This project received funding from the China Scholarship Council (CSC) under Grant Agreement Number: 201706400064

Editor Managing Review: Ichiro Daigo

Abstract

In this paper, we develop a dynamic stock model and scenario analysis involving a bottom-up approach to analyze copper demand in China from 2005 to 2050 based on government and related sectoral policies. The results show that in the short-term, China's copper industry cannot achieve a completely circular economy without additional measures. Aggregate and per capita copper demand are both set to increase substantially, especially in infrastructure, transportation, and buildings. Between 2016 and 2050, total copper demand will increase almost threefold. Copper use in buildings will stabilize before 2050, but the copper stock in infrastructure and transportation will not yet have reached saturation in 2050. The continuous growth of copper stock implies that secondary copper will be able to cover just over 50% of demand in 2050, at best, even with an assumed recycling rate of 90%. Finally, future copper demand depends largely on the lifetime of applications. There is therefore an urgent need to prolong the service life of end-use products to reduce the amount of materials used, especially in large-scale applications in buildings and infrastructure.

KEYWORDS
bottom-up approach, copper, dynamic stock analysis, industrial ecology, material flow analysis, scenario analysis

1 | INTRODUCTION

In today's world, copper is an essential resource that is used in a wide range of applications. Because of its unique conductive properties, it is difficult to replace. With its rapid economic development in recent decades, China has experienced pronounced growth in copper production and consumption, becoming the world's largest copper consumer in 2002. Its share in global copper demand increased from 20% in 2006 to 46% in 2016, growing year on year during that period (Schipper et al., 2018; Yang et al., 2017).

This rapidly rising demand is not expected to slow down in the coming decades. This may cause future supply problems and contribute to environmental issues. The systemic solution to these issues is to use copper more efficiently and keep copper in closed loops wherever possible. Thus, an essential first step in this direction is to understand the country's copper flows and stocks.

There has been significant research into metal flows and stocks at both the global and national level using material flow analysis (MFA). MFA studies in the past have focused mostly on flows, ignoring stocks. More recent approaches acknowledge the importance of the material stock as a driver for flows. The inflow arises when applications discarded from the use phase must be replaced by new ones. Especially for long lifetime applications, the stocks as a driver are found to be very important (Chen, Wang, & Li, 2016; Guo & Song, 2008; Soulier et al., 2018; Spatari, Bertram, Gordon, Henderson, & Graedel, 2005; Zhang, Cai, Yang, Yuan, & Chen, 2015b). In general, two different types of methods have been used to quantify flows and stocks of the major engineering metals, such as steel, copper, lead, zinc, and aluminum (Chen, Shi, & Qian, 2010; Davis et al., 2007; Graedel et al., 2013; Igarashi, Kakiuchi, Daigo, Matsuno, & Adachi, 2008; Liu, Bangs, & Müller, 2013; Yan, Wang, Chen, & Li, 2013). The first is the top-down approach. In studies using the top-down approach, the material cycle is assumed to be the driven by external drivers such as GDP, population, and per capita income projections (Kapur, 2006; Soulier et al., 2018). The approach starts from the material itself: amounts mined, and distributed over various categories of uses. Stocks in such an approach are often not included. If they are, they are mostly estimated as the difference between inflows and outflows accumulated over time. The other is the bottom-up approach, which quantifies both flows and stocks directly by identifying all the products that contain the material within the system boundary at a given time, quantifying the number of products in use, and arriving at material flows using data on the material content of these products (Müller, Hilty, Widmer, Schluep, & Faulstich, 2014). To date, most studies adopted the top-down approach (Ayres, Ayres, & Råde, 2003; Daigo, Hashimoto, Matsuno, & Adachi, 2009; Glöser, Soulier, & Tercero Espinoza, 2013; Hedbrant, 2001; Ruhrberg, 2006; Zeltner, Bader, Scheidegger, & Baccini, 1999). Due to the data intensity and the limited availability of the data required, only a few studies adopted the bottom-up approach to examine specific end-use sectors like buildings, transportation, and infrastructure (Bader, Scheidegger, Wittmer, & Lichtensteiger, 2011; Gerst, 2009; Ling, Zengwei, & Jun, 2012; Zhang, Yang, Cai, & Yuan, 2014). To compensate this part of research, it is essential to perform a more accurate estimation of copper stock by the bottom-up method. Meanwhile, several scholars have studied future generation of copper scrap and concluded that at some time in the next 30 years, China will face an explosion of copper-containing waste generated by the socio-economic system (Wang, Chen, Zhou, & Li, 2017). This scrap can be used to meet rising copper demand, at least in part, which is an issue not covered by simple scenario studies of future demand.

Against this background, this paper therefore explores copper stock, demand, and the potential of scrap copper for closing cycles in China, investigating whether China may be able to improve copper industry by combining increased copper demand with scrap recycling and a reduction of primary production.

In this study, we address three questions:

1. How great will future copper demand be in different end-use categories in China?
2. How large is the in-use stock and how much copper waste will be generated in different end-use categories in China?
3. What is the potential to close cycles, or more specifically: to what extent can copper demand be met by scrap recycling?

To address these questions, we use dynamic stock modelling to estimate the in-use stock of copper-containing products through to 2050 based on a bottom-up approach. This is translated into copper demand under a baseline scenario representing developments as indicated by either extrapolating driving forces or applying assumptions based on Chinese government policy. In this paper, we thus work with a scenario that can be characterized as business-as-usual. With this scenario, it can be assessed how the policies set by the Chinese government will affect the country's copper demand. In this scenario, no specifically copper-related policies are assumed. In the follow-up research, this scenario can be used as a baseline for comparing other scenarios that do contain specific resource-related policies such as circular economy policies.

2 | METHODOLOGY AND DATA

2.1 | Dynamic stock analysis

The core aim of this paper is to predict copper demand in mainland China through to 2050. To this end, we distinguish six main categories of copper end-use: infrastructure, transportation, buildings, consumer durables, commercial durables, and agricultural and industrial durables. These were further subdivided into 29 product categories that include novel applications such as battery charging stations and "new energy vehicles" (see Table 1). In our bottom-up approach, these 29 product categories are used to estimate future copper demand. This detailed subdivision of products and inclusion of new applications differentiates our work from earlier studies by, for example, Zhang, Yang, Cai, and Yuan (2015a).

In principle, calculating copper demand using the bottom-up method needs to factor in two important issues. The first is the change in in-use stock caused by changes in demographics, economic welfare, and government policies. The second is end-of-life replacement of products. Taking into account these two factors, we use the following formulae to estimate the quantities of interest:

$$\mathrm{CS}_{I,t} = \sum_{i=1}^{I} \left(\mathrm{P}_{i,t} \times m_{i,t}\right) \tag{1}$$

$$\mathrm{CF}^{\mathrm{in}}_{i,\,t-l} = \mathrm{F}^{\mathrm{in}}_{i,\,t-l} \times m_{i,t-l} \tag{2}$$

$$\mathrm{CF}^{\mathrm{out}}_{I,t} = \sum_{i=1}^{I} \mathrm{CF}^{\mathrm{in}}_{i,t-l} \tag{3}$$

$$\mathrm{CD}_{I,t} = \left(\mathrm{CS}_{I,t} - \mathrm{CS}_{I,t-1}\right) + \mathrm{CF}^{\mathrm{out}}_{I,t} \tag{4}$$

TABLE 1 Categories of copper demand and drivers used for calculating future copper demand (for further details, see the Supporting Information)

		Driver					
Category	**Subcategory**	**GDP**	**Population**	**Urbanization rate**	**Copper intensity**	**Lifespan (year)**	**Future activity levels as projected in policy plans**
Infrastructure	Electricity generation	–	–	–	1–2 kg/kW (Table S5 in Supporting Information S1)	30	National Energy Administration of China; Entri Company
	Electricity distribution & transmission	–	–	–	0.00041 kg/kWh	30	National Energy Administration of China
	Electronic communication	√	√	√	890 kg/m^3	20	–
	Charging infrastructure	–	–	–	20 kg (point) 15,000 kg (station)	15	Electric vehicle charging infrastructure development guidelines; mid- and long-term development plan for automotive industry
	Street and traffic lights	–	√	–	890 kg/m^3	12 (Traffic) 25 (Street)	–
	Rail lines and metro systems	–	–	–	6.06 (subways, ordinary-speed rail), 8.07 (high-speed rail) tonne/km	30	Mid- and Long-Term Railway Network Plan; 13th Five-Year Plan; China National North Car company
Transportation	Conventional cars	√	√	–	15 kg/unit	11	Traffic Management Bureau of Public Security Ministry
	Conventional buses	√	√	–	109 kg/unit	12	–
	Trucks	√	–	–	20 kg/unit	11	–
	Motorcycles	√	√	–	1.55 kg/unit	12	China Association of Automobile Manufacturers

(Continues)

TABLE 1 (Continued)

		Driver					
Category	Subcategory	GDP	Population	Urbanization rate	Copper intensity	Lifespan (year)	Future activity levels as projected in policy plans
	Trains	√	–	–	115 (Freight-rail cars), 1299 (passenger, rolling), 2960 (locomotive) kg/unit	26	Mid- and Long-Term Railway Network Plan
	New energy vehicles	–	–	–	75 (car) 250 (Bus) kg/unit	13	Technology roadmap for energy-saving and new energy vehicles; long-term development plan for automotive industry
Buildings	Residential buildings	√	√	√	0.35–1.01 kg/m^2 (Figure S3 in Supporting Information S1)	20 (rural) 35 (urban)	Rapid development of urban and rural development
	Service buildings	√	√	√	–	40	–
Consumer durables	Air conditioners	√	√	√	8.19 kg/unit	13	China Household Electrical Appliances Association
	Refrigerators	√	√	√	2 kg/unit	12	China Household Electrical Appliances Association
	Washing machines	√	√	√	1.8 kg/unit	10	China Household Electrical Appliances Association
	TVs	√	√	√	0.52 kg/unit	9	–
	Microwaves	√	√	√	0.9 kg/unit	9	–

(Continues)

TABLE 1 (Continued)

		Driver					
Category	Subcategory	GDP	Population	Urbanization rate	Copper intensity	Lifespan (year)	Future activity levels as projected in policy plans
	Heaters	√	√	√	0.01 kg/unit	8	–
	Cell phones	√	√	√	0.0003 kg/unit	4	–
	Landlines	√	√	√	0.10 kg/unit	7	–
	Computers	√	√	√	0.08 kg/unit	7	–
	Range hoods	√	√	√	0.2 kg/unit	14	–
Commercial durables	Printers	–	√	√	0.18 kg/unit	7	–
	Landlines	–	√	√	0.1 kg/unit	7	–
	Fax machines	–	√	√	0.1 kg/unit	8	–
Agricultural, Industrial durables	Agricultural durables	–	√	–	16–30 kg/unit (Table S21 in Supporting Information S1)	15–22 (Table S21 in Supporting Information S1)	Made in China 2025; 13th Five-Year Plan
	Industrial durables	√	–	–	23–53 kg/unit (Table S22 in Supporting Information S1)	15	–

Note. The "–" in this table means that the driver is not used to projections for this product.

Here, i represents the product of each subcategory, such as residential buildings, household appliances or vehicles. I is the total number of product categories. t is the model year. CS_t is the total copper stock in all products. $P_{i,t}$ is the physical quantity of each product used, such as the number of cars or mileage of railway. $m_{i,t}$ is the copper intensity of each product. $CF^{out}_{i,t}$ is the outflow of discarded or obsolete products i in year t, which equals to the sum of $CF^{in}_{i,t-l}$, the inflow of products use i in the year t – l, l is the average lifetime of each product i. $CS_{I,t}$ and $CS_{I,t-1}$ are the total in-use stock of copper in year t and year t – 1, respectively. $CD_{I,t}$ is the total copper demand of all products I. An example was given in Appendix 3 in Supporting Information S1.

Owing to a paucity of data, however, for certain product categories such as power generation and transmission and agricultural and industrial durables, Equations (1)–(4) were not used to calculate copper demand, this being estimated directly based on demand for copper products, as formulated in Equation (5). In essence, future copper demand was estimated by taking future activity levels in a specific sector (e.g., electricity generation) from Chinese policy plans and multiplying this by figure for copper intensity. We use the method of Schipper et al. (2018) to calculate the copper outflow.

$$CD_t = D_t \times m_t \tag{5}$$

where CD_t is the copper demand for power generation. D_t is the installed capacity of power. The detailed calculation methods applied for the each of the 29 products can be found in Appendix 3 in Supporting Information S1.

2.2 | Scenario analysis

In this article, only a business-as-usual scenario is developed. Future demand is modelled based on one or more of the following six drivers: GDP, population, urbanization rate, copper intensity, product lifespan, and future activity levels under Chinese government policy, briefly discussed in a generic sense below. The method used to calculate future copper demand in each of the 29 categories is described in detail in the Supporting Information and summarized in Table 1.

2.2.1 | Population

Population is a key driver of consumption. Because of slow population growth, in 2014, the Chinese government cancelled its "One Child Policy" and implemented a "separate two-child" and "two-child policy" to prevent populous decline. China is still the most populous country in the world, and will continue to maintain steady growth in the coming years. Researchers have undertaken projections of China's future population and explained related changes in the number of households (Han, Wang, Ouyang, & Cheng, 2011; Zalmon, Carvalho, & Ferreira, 1998). Here, we use the population figures projected by the United Nations Population Division, which indicates that the population of China will start decreasing from around 2030 onward, as shown in Table S1 in Supporting Information S1.

2.2.2 | GDP

In recent years, China's economic growth has slowed. Moreover, the Chinese government is shifting its sights from high economic growth to more sustainable economic development. China's future GDP has been enumerated in the study (Li & Qi, 2011), which cited from IEA (International Energy Agency, 2010) and UNDP (United Nations Development Program, 2009). The Chinese government aims to achieve a growth rate of 6.56% during the 13th Five Year Plan. In this study, figures for future GDP have also been taken from the United Nations Development Program. Past and future trends in per capita GDP are shown in Figure S1 and Table S1 in Supporting Information S1.

2.2.3 | Urbanization rate

The urbanization rate is a crucial variable for the estimated in-use stock of products, as per capita product ownership is quite different in urban and rural areas of China. Under the 13th Five Year Plan, the Chinese government seeks to achieve an urbanization rate of 60%. For the long term, we compared the urbanization rate cited in previous research (Li & Qi, 2011) with the Chinese government's goal and worked with figures of 60% (2016–2020), 65% (2021–2030), 70% (2031–2040), and 75% (2041–2050). Past and future trends are shown in Figure S1 and Table S1 in Supporting Information S1.

2.2.4 | Copper intensity

Copper intensity affects the copper demand of all end-use products. Although copper products have already been studied by many scholars, because of the huge variety of products and different manufacturing standards in various countries, very few data are in fact available on the exact copper intensity of each product. At the same time, owing to technological improvement, lifestyle changes, and policy requirements, copper intensity is also changing. It is difficult to forecast how the copper intensity of individual products will change in the future. With the exception of

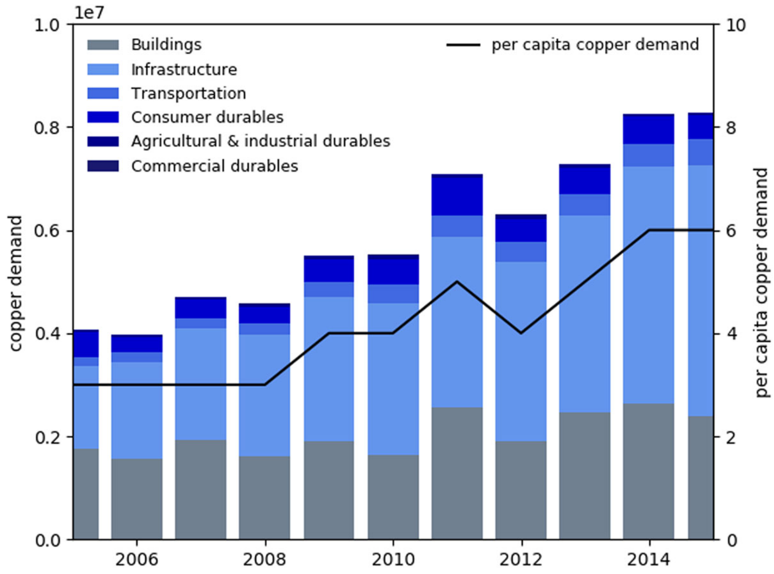

FIGURE 1 Chinese copper demand from 2005 to 2015 (metric tons/year, source: China Non-Ferrous Metal Industry Report, 2015). Underlying data used to create this figure can be found in Supporting Information S2

buildings, copper intensity has therefore been assumed to remain unchanged. Detailed data on the copper intensity of each end-use product are reported in Table 1 and in the Supporting Information.

2.2.5 | Lifespan

Product lifespan has a direct impact on outflows. Extending product lifespan can reduce waste generation and demand for primary copper. In China, many products have a very short average lifespan. Some scholars have estimated that urban buildings in this country have a life expectancy of approximately 30–40 years (Song, 2005). One study (Hu, Bergsdal, van der Voet, Huppes, & Müller, 2010) of housing stock assumed that its service life follows a normal distribution, while other scholars, focusing on vehicles, took their service life to be consistent with the Weibull distribution. Normal or Weibull distributions are often assumed for product lifespans. Which of these is adopted will affect the copper outflow projected for a particular time. However, compared with using the average lifespans of all copper-containing products, assuming a distributed lifespan serves mainly to make the calculation results smoother and has no great impact on values when long time series are involved. A reflection on the differences can be found from Figure S2 in Supporting Information S1. This is also reflected in other studies (Maung, Hashimoto, Mizukami, Morozumi, & Lwin, 2017; Spatari et al., 2005). While acknowledging that life span distributions are often used, it is our conviction that no major errors are introduced by merely using averages, as shown in Table 1.

2.2.6 | Policy plans

The data used for forecasting future use of copper-containing products originate from the 13th Five-Year Plan, statistical data and the mid- and long-term plans for each sector of industry (Made in China 2025), reports by consultancy organizations and several other publications (Elshkaki & Graedel, 2013; Krausmann et al., 2017; Wiedenhofer, Steinberger, Eisenmenger, & Haas, 2015). These policies and data serve as the basis for our business-as-usual scenario projection. We refer to Table 1 with detailed assumptions provided in Appendix 2 in in Supporting Information S1.

3 | RESULTS AND DISCUSSION

3.1 | Past trend of copper demand

Chinese copper demand has grown rapidly since 2004 as shown in Figure 1. Estimates based on dynamic material flow analysis show that it was almost 4 million tonnes (Mt) in 2005, almost 20% of global copper demand in that year, rising very significantly to more than 8 Mt in 2015, which is nearly 45% of global copper demand. In addition, the per capita copper demand stood at 6 kg in that year. Prior to the 1980s, China focused mainly on industrial and agricultural development. With the urbanization drive initiated in 2004; however, the consumption of copper in infrastructure and buildings increased rapidly, gradually becoming a major source of copper consumption. We compared our results on copper demand with the figures published by the China Non-Ferrous Metals Industry Association (see Figure 1). For 2005 and 2015, these were approximately 4 million metric tons and 10 million metric tons, respectively (Bo Zhao, 2011; Non-ferrous metal industry operation report, 2015), slightly higher than our estimates in 2015. As explained in Appendix 1 in Supporting Information S1, the estimation in this paper do not encompass all copper products, whereas it already contains most of the copper products, which determines the future development trend of copper demand.

3.2 | Future trend of copper demand

Figure 2a reports total demand for copper, demand per main category, and per capita demand from 2005 to 2050. Total copper demand is expected to increase significantly over time, becoming about six times higher in 2050 than in 2005. The main end-use sector is infrastructure, accounting for around 50% of total copper demand by 2050, followed by transportation (25–30%), buildings (5–10%), consumer durables (5–10%), agricultural and industrial durables and commercial durables (both less than 1%).

This means the amount of copper used in infrastructure, transportation, and buildings is expected to increase most. Given economic growth, national investment in infrastructure will continue to grow rapidly, especially in power facilities, railway construction (high-speed rail), and urban rail transit. The consumption intensity of copper in these applications is significantly higher than in other uses. In particular, the copper content of new power-sector equipment, including solar and wind, is very high. In addition, there is will be a pronounced surge in copper demand from the use of new charging piles and charging stations as the use of new energy vehicles grows (Figure 2b).

In contrast to the substantial increase in copper use in infrastructure, demand for copper in the building sector is expected to maintain a steady but slow increase up to 2030, subsequently decreasing somewhat before slowly rising again from 2045 to 2050. This increased demand might be the results of four different developments:

- Rapid urbanization, requiring construction of large numbers of city dwellings.
- Increased per capita living space as a result of rising prosperity.
- Increased copper intensity of buildings due to safety measures, quality assurance, and flexibility measures.
- Shantytown renovation: the Chinese government has adopted a 3-year renovation program for 2018–2020 to reconstruct 15 million sets of shantytown buildings.

In other sectors, growth of copper demand is also evident in transportation, due to a projected rapid increase in use of new energy vehicles (NEV) with their relatively high copper content. While China has not implemented a ban on the sale of traditional-fuel vehicles, it has formulated a series of credit and subsidy policies to actively and systematically promote development of NEV.

Besides total copper demand, due consideration also needs to be given to per capita demand (Figure 2a). At present, this is less than 10 kg in China. As discussed in more detail in Section 4, this is about half that of other industrialized countries like Japan and South Korea, which indicates there is still substantial scope for growth in Chinese copper consumption. Our projections in Figure 2 indeed suggest that Chinese copper consumption will rise to about 18 kg per capita by 2050.

3.3 | In-use stock and copper waste

From approximately 26 Mt in 2005, China's copper stocks are increasing very rapidly and are projected to reach more than 400 Mt in 2050. As shown in Figure 3a, this increase is due mainly to the long-term growth of copper use in infrastructure, followed by buildings and transportation. In most of the subcategories, such as electricity generation, cars, and air conditioners, the copper stock is likewise set to increase until 2050 (Figure 3b). In that year, buildings will still have the second largest copper stocks; while the number of service buildings will continue to increase until 2050, the residential building stock will likely stabilize from 2045 onward. Infrastructure will hold the greatest copper stocks in 2050, with power generation and transmission the largest contributor. Our assessment suggests that the amount of copper used in this area will not yet have reached saturation in 2050.

There will also be major changes in per capita copper stocks, as shown in Figure 3a. The total copper stock of 30.5 Mt in 2005 translates to about 23.3 kg per capita, but this will increase to 290 kg per capita by 2050. Literature studies on Chinese copper stocks show a similar trend (Qiang, Wang, & Lu, 2012; Terakado, Takahashi, Daigo, Matsuno, & Adachi, 2009b; Zhang et al., 2015a). As discussed in more detail in Section 4 (see Table 3), all studies show that this value for China is much lower than in other developed countries.

The period prior to 2030 is one of material accumulation, with relatively little generation of waste. Subsequently, an increasing amount of scrap will be generated from long-lived applications in buildings, infrastructure, and durable products. This means the outflow will increase from 0.5 Mt in 2005 to about 15 Mt in 2050 (Figure 4a). At the same time, though, certain new applications, such as charging stations and NEV, will not yet have begun moving in to the waste phase (Figure 4b).

Six types of copper scrap from end-use sectors are generally distinguished: construction and demolition waste (C&D), municipal solid waste (MSW), end-of-life vehicles (ELV), waste electrical and electronic equipment (WEEE), industrial electrical waste (IEW), and industrial non-electrical waste (INEW) (Soulier et al., 2018). Much of this scrap is collected and separated for recovery, which is of relevance for the development of the

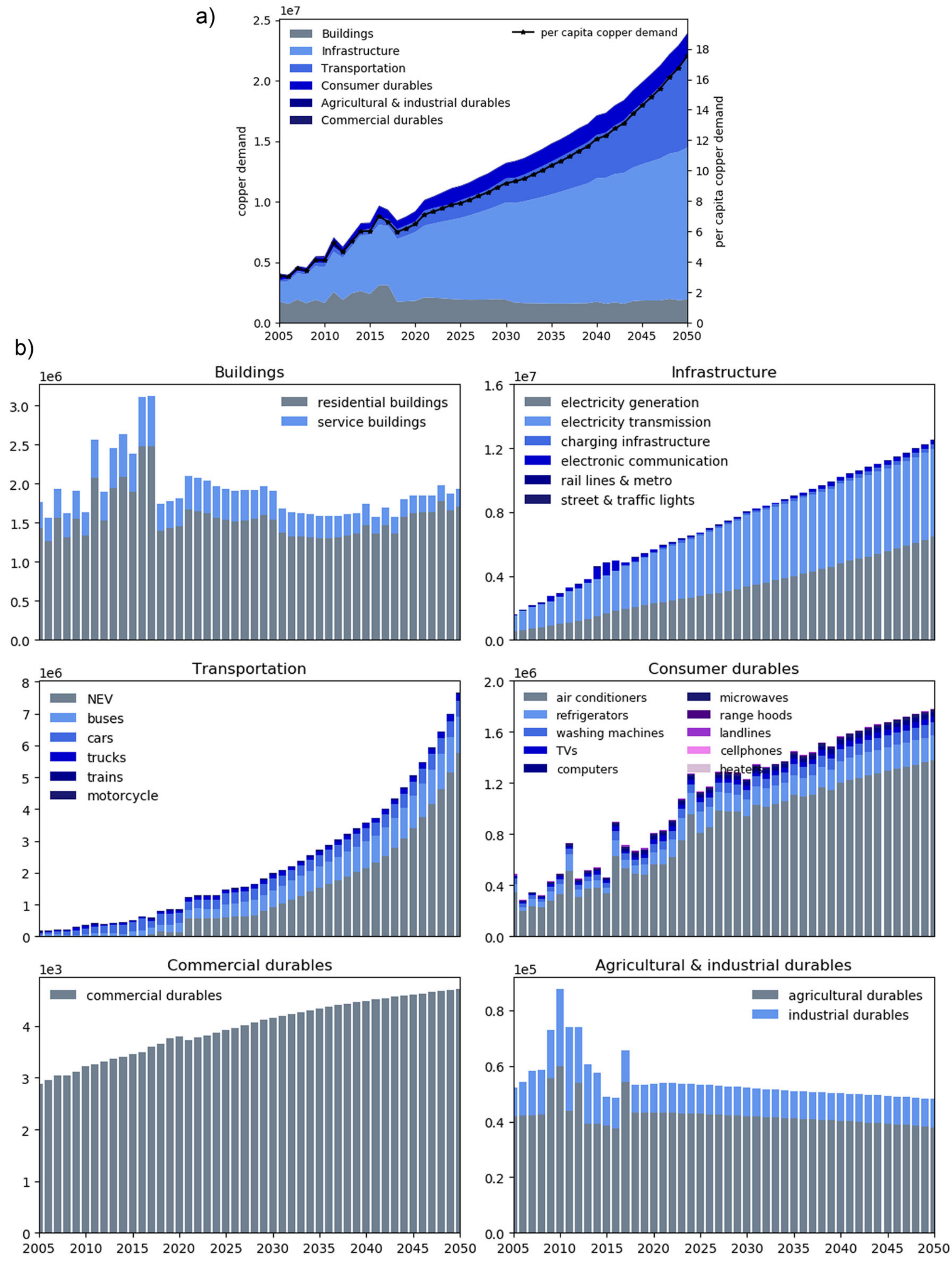

FIGURE 2 Copper demand of China from 2005 to 2050: (a) aggregate and per capita copper demand by end-use category (copper demand: metric tons/year; per capita copper demand: kg/capita/year); (b) detailed copper demand by product group within each end-use category (metric tons/year).Underlying data used to create this figure can be found in Supporting Information S2

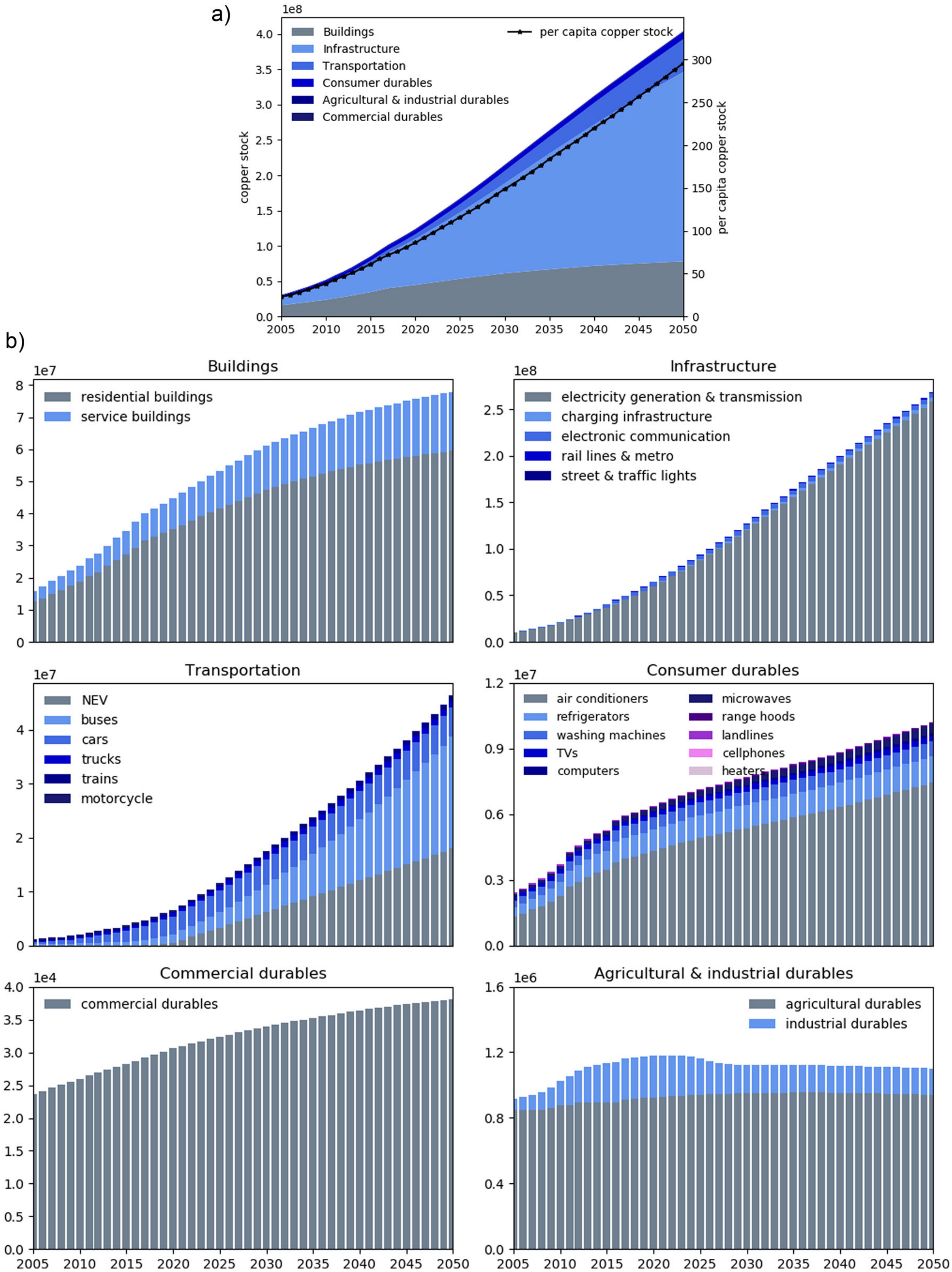

FIGURE 3 Copper stock of China from 2005 to 2050: (a) aggregate and per capita copper stock by end-use category (copper stock: metric tons; per capita copper stock: kg/capita); (b) detailed copper stock by product group (metric tons). Underlying data used to create this figure can be found in Supporting Information S2

TABLE 2 Studies on Chinese copper demand and in-use stock, 2005, 2010, 2030, and 2050

	Copper demand (Mt/year)				In-use stock (Mt)			
Source	2005	2010	2030	2050	2005	2010	2030	2050
Zhang et al. (2014)	5.3	7.9	–	–	–	–	–	–
Zhang et al. (2015b)	–	–	10.1	10.9	–	–	140	163–171
Zhang et al. (2015a)	–	–	–	–	30	48	–	–
Soulier et al. (2018)	–	8.6	–	–	–	50	–	–
Yang et al. (2017)	3.6	7.6	15.4	–	–	–	–	–
OECD (2019)	–	–	~18	~24	–	–	~200	~450
Terakado et al. (2009a)	–	–	–	–	25	–	–	–
Maung et al. (2017)	–	–	–	–	35–40	60–70	–	–
This paper	4.1	5.5	13.2	23.9	30.5	51.9	215	404

Note. The "–" in this table means that there is no available data from the corresponding reference for this year.

TABLE 3 Studies on copper demand and in-use stock at different scale levels, 2010 and 2050

	Copper demand (Mt/year)		Per capita copper demand (kg/capita/year)		In-use stock (Mt)		In-use stock per capita (kg/capita)	
Scale	2010	2050	2010	2050	2010	2050	2010	2050
Global	16.6[a] (2005)	60[a]	2.5[a] (2005)	–	–	–	–	–
Global	22[b]	62[b]	3.2[b]	6.4[b]	–	–	–	–
Global	–	–	–	–	330[c] (2005)	–	50[c] (2005)	–
Global	–	–	–	–	–	381–588[i]	–	–
OECD	8.7[b]	9.33[b]	9.1[b]	9.6[b]	–	–	–	–
REF[h]	1.7[b]	3.45[b]	4.2[b]	8.5[b]	–	–	–	–
ASIA[h]	8.7[b]	31.33[b]	2.4[b]	6.7[b]	–	–	–	–
ALM[h]	3[b]	16.12[b]	1.6[b]	4.9[b]	–	–	–	–
Developing countries	–	–	–	–	200[d]	700[d]	30[d]	75[d]
Industrialized countries	–	–	–	–	200[d]	300[d]	160[d]	225[d]
United States	–	–	–	–	70[j]	–	~230[j]	–
Italy	–	–	–	–	~20[j]	–	~350[j]	–
Germany	–	–	–	–	~20[j]	–	~230[j]	–
India	0.3[e]	4–9[e]	0.3[e]	2.9–6.3[e]	–	–	–	–
Japan	–	–	–	–	18.7[f] (2005)			
25[j]	–	146[f] (2005)						
170[j]	–							
Switzerland	–	–	8[g]	9[g]	–	–	–	–
China (cf. Table 2)	7.6–8.6	11–24	–	–	48–70	163–450	~50	–
This paper	5.5	23.9	4.1	17.5	51.9	404	38.7	296

Note. The "–" in this table means that there is no available data from the corresponding reference for this year. Unless otherwise specified, retrospective data are for 2010. Some data cited from the literature are only approximate.
[a]Schipper et al., 2018.
[b]Ayres et al., 2003.
[c]Glöser et al., 2013.
[d]Gerst, 2009.
[e]Kapur, 2006.
[f]Daigo et al., 2009.
[g]Bader et al., 2011.
[h]Supporting Information.
[i]Yoshimura & Matsuno, 2018.
[j]Maung et al., 2017.

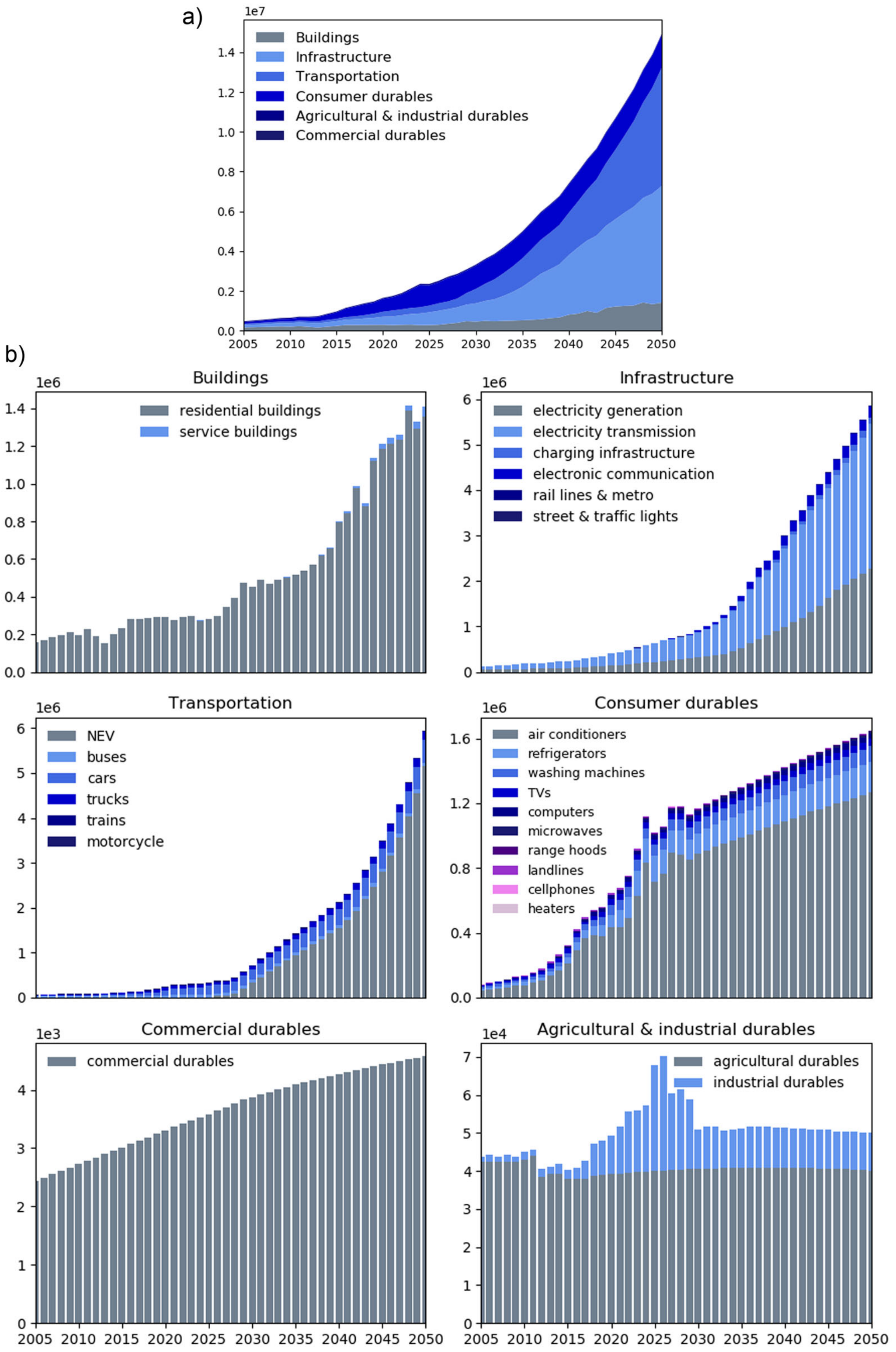

FIGURE 4 Waste copper of China from 2005 to 2050: (a) aggregate copper waste by end-use category (metric tons); (b) detailed copper waste by product group (metric tons). Underlying data used to create this figure can be found in Supporting Information S2

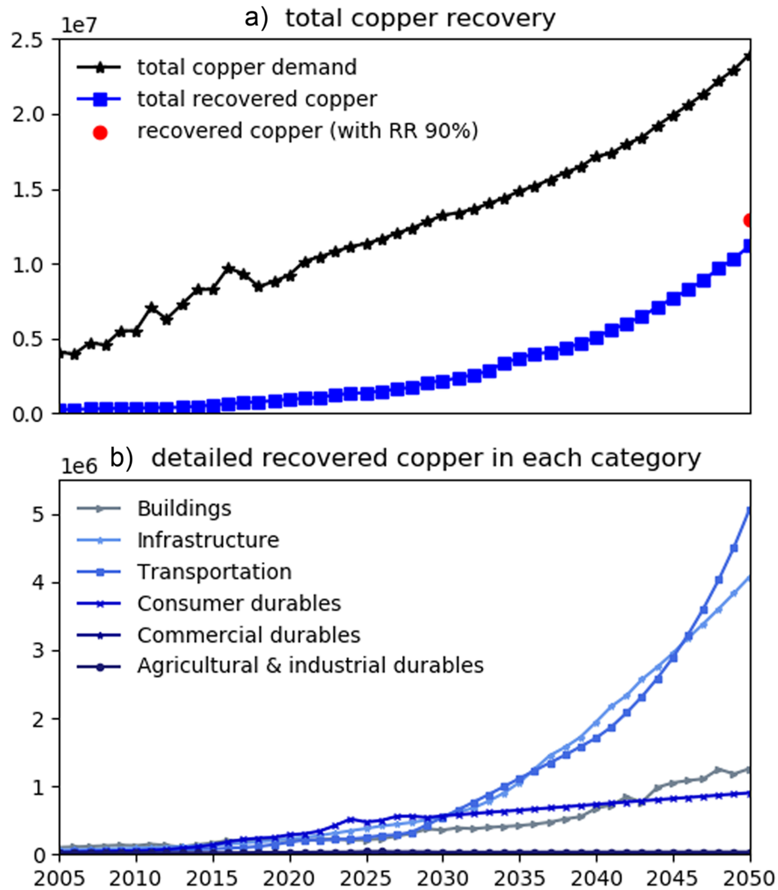

FIGURE 5 Estimated copper recovery in China from 2005 to 2050 based on current European recycling rates as shown in Table S23 in Supporting Information S1. Note: (a) the point "recovered copper (with RR 90%)" indicates copper recovery based on an assumption of 90% of EoL recycling rate for each product. Underlying data used to create this figure can be found in Supporting Information S2

circular economy. Not all end-of-life products are indeed reprocessed, though, with some fraction being landfilled or left in the environment as "hibernating" stocks: the underground cables used for power transmission, for example.

3.4 | Potential for circularity: Fraction of new demand covered by outflow/waste

China is undergoing a period of rapid development and consuming huge amounts of copper as a key material for its infrastructure. At the same time, though, the country lacks sufficient copper resources, which means copper recycling is very important. As is well-known, there is no difference in the quality of copper from secondary and primary production and although certain applications involve irrecoverable losses, such as buried cables and copper compounds used as animal food supplements, for most copper applications a significant degree of recycling is possible. At the same time, the environmental pollution associated with the mining of copper ores required to meet the country's huge copper demand can also promote development of a circular economy. Compared with mined copper concentrates, reuse of scrap copper has the advantages of high recovery rates, low energy consumption, and reduced pollution. Not only does copper recycling require up to 85% less energy than primary production (ICA, 2013); it is also a highly eco-efficient way of reintroducing a valuable material into the economy. In assessing the potential for a circular economy with respect to copper scrap, recycling the first question that needs to be answered is how much recyclable scrap is produced relative to overall demand. Detailed information on estimating the amount of recyclable copper is provided in Appendix 4 in Supporting Information S1.

Figure 5 shows China's copper recycling potential for various end-use applications from 2005 to 2050. Over this period, the amount of recoverable copper increases from 0.25 Mt to 11 Mt, driven by the increasing copper outflow from stock-in-use. This increase holds across all copper applications, but to varying degrees. In particular, copper recovered from applications in the transportation sector will increase very significantly, from about 37,000 tonnes in 2005 to over 5 Mt in 2050. After 2030, the amount of copper recovered from the infrastructure sector will also increase rapidly.

In our analysis, we used waste copper recovery rates varying from 25% to 89% for the various waste categories in different years (see Table S23 in the Supporting Information on the Web). Under these assumptions, copper recovery will be able to meet only about 40% of Chinese copper demand by 2050. The question, therefore, is whether this percentage can be boosted, and to what extent. The scrap recovery rates assumed here are based on average European data and are higher than those currently seen in China are. While scientific and technological progress will mean China's copper recovery rate will in all likelihood continue to rise in the future, it is still an open question whether even with an enhanced recovery rate recycling can meet the country's enormous demand for this metal. To explore whether enhanced levels of copper recovery can indeed cover aggregate demand, we therefore assumed a recovery rate of 90% for every product and industry, a similar figure to that presently achieved in Western Europe (Ruhrberg, 2006). Under this assumption, copper recovery in China rises to approximately 13 Mt in 2050. Compared with the total copper demand of around 24 Mt projected for that year, recycled copper will still not even come close to meeting demand (Figure 5). The main reason for this is that in 2050, China's economy will not yet have attained a steady state, but will still be increasing the copper stocks bound up in infrastructure and other sectors. Primary copper will therefore still be a crucial source of copper in China for decades to come.

3.5 | Sensitivity analysis

We now assess the influence of variations in product lifetime on the results obtained in this study. The shorter the lifetime, the more waste copper will be generated and the greater demand for copper will be. When it comes to the largest copper applications, in buildings and infrastructure, long and varying lifetimes are reported (Buchner, Laner, Rechberger, & Fellner, 2015; Huang, Shi, Tanikawa, Fei, & Han, 2013). For China in particular, however, the literature suggests that building lifetime is between 20 and 40 years (residential and non-residential building). We found no quantitative evidence for longer building lifetimes over the past few decades. Owing to changes in building materials and maintenance, the lifetime of buildings constructed in recent years and in the future will be longer. To compare with the business-as-usual scenario, we performed a sensitivity analysis, increasing residential building lifetime to varying degrees, as shown in Figure S4 in Supporting Information S1. This indicates that the longer the lifetime of residential buildings is, the less waste copper is generated. Over the next 10 years, the change is not large, but on the longer term, the reduction in copper waste generation is considerable.

A second sensitivity analysis was carried out for the transportation sector, varying the assumed lifetime of conventional cars, conventional buses, and new energy vehicles between 8 and 18 years to assess the impact on copper waste generation; for further details see Appendix 3 in Supporting Information S1. When the lifetime of these three types of vehicle is boosted to 18 years, copper waste is reduced by over half after only 8 years (see Figure S5). As the sensitivity analysis shows, future copper waste is very sensitive to product lifetime. In order to reduce copper demand, one key option is therefore to extend the service life of end-use products, especially the applications with long lifetime. This is anticipated to have a considerable impact on both demand and waste streams, and is an issue we may want to take up in our future research on circular economy scenarios for China.

4 | REFLECTION AND DISCUSSION

4.1 | Comparison of global and Chinese copper demand and stocks

To put our results into a broader perspective, we now compare them with the results of earlier studies on copper flows and in-use stocks, as summarized in Table 2. For China, the most detailed databases of copper stocks and flows have been compiled in the studies of Yang et al. (2017), Zhang et al. (2014), Zhang et al. (2015b), and Zhang et al. (2015a). These studies had a very similar aim to our own: to provide estimates of present and future copper stocks as well as future demand in China. Terakado, Ichino, Daigo, Matsuno, and Adachi (2009a) used a dynamic MFA approach to estimate in-use stocks up to 2005, while Soulier et al. (2018) and Zhang et al. (2014) combined a top-down with a bottom-up approach to study in-use stock, concluding that China's copper stocks were around 50 Mt in 2010 and may gradually increase to a peak of 163–171 Mt by 2050. Another study cited in Zhang's research estimates that in-use stock will peak at 190–220 Mt in 2060. Maung et al. (2017) also used a dynamic stock model to report a figure of 60–70 Mt for in-use copper stock in 2010.

As Table 2 shows, the results of our study are similar to those of other studies for 2010 and 2015, but differ for future years. In the present study, both demand and in-use stock are estimated higher in 2050. We attribute this difference to two factors. First, we used a slightly different categorization of copper applications, distinguishing 29 subcategories and including new energy applications such as new energy vehicles and charging infrastructure, both of which will require huge amounts of copper. We also modelled demand at a more detailed level than most other studies, leading to slightly different outcomes overall. Second, we worked with different assumptions regarding future developments. In particular, our simulation is based on current government policies rather than assuming that the level of development in 2050 will mirror that of last year, which makes a great deal of difference. For example, the addition of new energy applications according to already existing government policy leads to quite different results for infrastructure compared with the other studies. While for some categories, such as the built environment, copper stocks are expected to stabilize in our study as well (see Figure 3, we find that in 2050 China's total copper stocks and demand will still not yet have peaked).

Table 3 compares the results of our study with those of studies on other countries and regions as well as the world as a whole. Copper stocks in China will increase from 23 to 30 kg per capita in 2005 to around 300 kg per capita in 2050. This is faster growth than the average for industrialized countries as well as the average for developing countries. By 2050, Chinese copper stocks are expected to be close to the present level of the developed world. China is presently at the stage of rapidly increasing its in-use stocks, a stage that has already occurred in the developed countries and is expected to occur in certain developing countries later, or at a slower pace than in China. The very high per capita demand, associated with the build-up of China's stock could decline after 2050 to the level needed to maintain the stock.

When it comes to per capita copper demand, China's was similar to the global average in 2010, but lower than that of the OECD countries. For the future, our calculations suggest that by 2050 China's per capita copper demand will be significantly higher than the world average, OECD countries, and certain developed countries, such as Switzerland. This is probably due to mainly the fact that in 2050, China will still be catching up with reaching the stock levels of OECD countries, as explained further below. In that year, China's per capita copper demand will be more than four times higher than in 2010 and about 15 times higher than that of India in 2010. In 2050, aggregate copper stocks in developing countries are expected to be more than three times what they were in 2010 and more than twice as in-use stock per capita in 2010 (Gerst, 2009). This indicates that India will undoubtedly become a major player in terms of copper demand. While there is extensive informal recycling in developing countries, appropriate recycling infrastructure for end-of-life management of complex products is presently lacking. As waste streams will undoubtedly increase, greater efforts to recover and manage scrap copper in these countries would be very beneficial.

4.2 | Limitations

There are several issues of relevance for forecasting copper demand that were not taken into account in this study. Below we discuss three of them.

4.2.1 | Copper intensity

While copper intensity is a key factor determining both copper stocks and future copper demand, there are very few accurate data available on many products, especially when it comes to possible changes in the years ahead. In this study, the copper intensity of most products except buildings was taken to remain fixed. However, previous studies have shown that the amount of copper used in products has changed over time. For some products, such as buildings, cars, and electrical and electronic equipment, the amount of copper is increasing (Charles, Douglas, Hallin, Matthews, & Liversage, 2017). In some cases, it seems likely that copper use will decline as it is replaced by other materials (see below). For lack of quantitative information, however, in this study we made no allowance for possible future changes in copper intensity.

4.2.2 | Copper substitution

Copper demand may be reduced as a result of substitution, at either the material or product level. Graedel, Harper, Nassar, and Reck (2015) have shown it is quite difficult to find suitable alternatives for copper quickly, though, one reason being that such alternatives will have to be produced in large quantities. Nevertheless, in some of its applications copper has already been replaced or is expected to be so by aluminum, titanium, or optical fiber. This could reduce copper demand to some extent. At the same time, though, novel technologies requiring copper are also being developed at present, leading to a potential increase in copper demand. For example, recent studies have pointed to the possibility of replacing silver by copper in silicon-based photovoltaic solar technology (García-Olivares, 2015). Given the rather speculative nature of this broad topic, we have not attempted to modify our demand projections by introducing assumptions on substitution.

4.2.3 | Other applications of copper in China

With all its appealing properties, copper is gradually being applied in new applications in addition to those considered in this paper. Since these new applications are only just on the market, we considered their development too speculative and so ignored them in our study. However, some of them may be relevant for future copper demand in China.

One example is the use of copper in non-polluting heating equipment. Copper is used in the heat exchangers for air-source heat pumps, for example, requiring an average of over 10 kilograms per unit. To address the problem of smog, the Chinese government has decreed that 28 cities must substantially reduce the burning of bulk coal. In these cities, scattered coal burning is an important winter heating source. Using electrical heating or air-source heat pumps instead of coal would improve local air quality substantially. Use of air-source heat pumps in fact increased about 28 times in just a single year, from 2015 to 2016. If the heat pump market continues to develop according to the current trend, this would increase copper demand significantly.

A second example is provided by the copper cages used in mariculture (a new type of aquaculture). One of the tasks set out in the Chinese government's 13th Five Year Plan, is to build 10,000 deep-sea cages for mariculture. Each cage uses 20 kg of copper with even more required for the associated fencing. While this is still relatively little compared to total Chinese copper demand, this sector may expand further, becoming relevant in the future.

5 | CONCLUSIONS AND OUTLOOK

In this study, we adopted a dynamic stock model and scenario analysis involving a bottom-up approach to analyze copper demand in China from 2005 to 2050, based on a series of drivers including GDP, population growth, urbanization level, and government policy plans. In the business-as-usual scenario, both aggregate and per capita copper demand are set to increase significantly over time, especially in infrastructure, transportation, and buildings. Between now and 2050, total demand for copper will rise by a factor of almost 3. It should be noted, though, that our estimates make no allowance for a possible increase in copper content in certain applications nor for any new applications, which means the copper demand in the baseline scenario for 2050 may be in fact be an underestimate.

The copper stock in infrastructure and transportation will not yet have reached saturation by 2050 but will then still be growing. Stock in buildings will be virtually stabilized, though, which means per capita demand in this segment will no longer be significantly rising. Our calculations show that aggregate demand in 2050 cannot be met through the use of secondary copper, even if a recycling rate of 90% is assumed. In the baseline scenario, then, there would appear to be no way China's copper industry can achieve a completely circular economy in the short term.

Given the projected increase in Chinese copper demand through to 2050, we can only conclude that a major quantity of raw materials will need to be mined and processed, which will have a pronounced environmental impact, particularly in light of the challenges involved in improving the environmental footprint of copper production and processing. As demand continues to rise, copper will become even more important as a source of greenhouse gas emissions than it is at present (Van der Voet, Van Oers, Verboon, & Kuipers, 2018).

One development not explicitly addressed in this study is the coming energy transition. While renewable energy technologies will reduce GHG emissions, they will also mean increased demand for copper, leading to increased GHG emissions from this industry (Deetman, Pauliuk, Van Vuuren, Van der Voet & Tukker, 2018). In this respect, the balance between reducing the environmental impact of new energy technologies and increased copper use in new energy devices is an issue requiring due attention.

Copper recovery is another aspect of major relevance for environmental impacts, given that secondary production via recycling requires up to 85% less energy than primary copper production. Based on the present research, we can only conclude that under baseline assumptions, a very large inflow of primary copper will still be needed up until 2050. For China at least, increasing the scrap recovery rate will not be sufficient to meet copper demand in 2050, when aggregate new demand will be almost twice as high as the total copper outflow from all sectors combined.

Our results show that China's economy will be reliant on an increasingly large supply of primary copper. It is therefore important to develop alternative development scenarios in which copper demand is sustainably fulfilled. A circular economy scenario could be an effective way to reduce primary production and therefore also reduce the environmental impacts associated with copper production. In future research, we intend to focus on developing alternative scenarios, exploring different options for improving the sustainability of China's copper supply.

ACKNOWLEDGMENTS

We are grateful to Nigel Harle of Gronsveld for improving the English of this paper. Many thanks to three anonymous reviewers whose comments improved the presentation of our work.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA ACCESSIBILITY

Data pertaining to copper demand, copper stock, and waste copper employed for figures in the present study are available in Supporting Information S2.

ORCID

Di Dong https://orcid.org/0000-0001-7637-340X
Arnold Tukker https://orcid.org/0000-0002-8229-2929
Ester Van der Voet https://orcid.org/0000-0003-0788-9570

REFERENCES

Ayres, R. U., Ayres , L. W., & Råde , I. (2003). The life cycle of copper, its co-products and byproducts. *Eco-Efficiency in Industry and Science*, *7*(5), 318–336.

Bader, H.-P., Scheidegger, R., Wittmer, D., & Lichtensteiger, T. (2011). Copper flows in buildings, infrastructure and mobiles: A dynamic model and its application to Switzerland. *Clean Technologies and Environmental Policy*, *13*(1), 87–101.

Buchner, H., Laner , D., Rechberger , H., & Fellner , J. (2015). Dynamic material flow modeling: An effort to calibrate and validate aluminum stocks and flows in Austria. *Environmental Science & Technology*, *49*(9), 5546–5554.

Charles, R. G., Douglas, P., Hallin, I. L., Matthews, I., & Liversage, G. (2017). An investigation of trends in precious metal and copper content of RAM modules in WEEE: Implications for long term recycling potential. *Waste Management*, *60*, 505–520.

Chen, W., Shi, L., & Qian, Y. (2010). Substance flow analysis of aluminium in mainland China for 2001, 2004 and 2007: Exploring its initial sources, eventual sinks and the pathways linking them. *Resources Conservation & Recycling*, *54*(9), 557–570.

Chen, W., Wang, M., & Li, X. (2016). Analysis of copper flows in the United States: 1975–2012. *Resources Conservation & Recycling*, *111*, 67–76.

Daigo, I., Hashimoto, S., Matsuno, Y., & Adachi, Y. (2009). Material stocks and flows accounting for copper and copper-based alloys in Japan. *Resources Conservation & Recycling*, *53*(4), 208–217.

Davis, J., Geyer, R., Ley, J., He, J., Clift, R., Kwan, A., … Jackson, T. (2007). Time-dependent material flow analysis of iron and steel in the UK: Part 2—Scrap generation and recycling. *Resources Conservation & Recycling*, *51*(1), 118–140.

Deetman, S., Pauliuk, S., van Vuuren, D. P., van der Voet, E., & Tukker, A. (2018). Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. *Environmental Science & Technology*, *52*(8), 4950–4959.

Elshkaki, A., & Graedel, T. (2013). Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *Journal of Cleaner Production*, *59*, 260–273.

García-Olivares, A. (2015). Substituting silver in solar photovoltaics is feasible and allows for decentralization in smart regional grids. *Environmental Innovation and Societal Transitions*, *17*, 15–21.

Gerst, M. D. (2009). Linking material flow analysis and resource policy via future scenarios of in-use stock: An example for copper. *Environmental Science & Technology*, *43*(16), 6320.

Glöser, S., Soulier, M., & Tercero Espinoza, L. A. (2013). Dynamic analysis of global copper flows: Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. *Environmental Science & Technology*, *47*(12), 6564–6572.

Graedel, T. E., Harper, E. M., Nassar, N. T., & Reck, B. K. (2015). On the materials basis of modern society. *Proceedings of the National Academy of Sciences*, *112*(20), 6295–6300.

Guo, X., & Song, Y. (2008). Substance flow analysis of copper in China. *Resources Conservation & Recycling*, *52*(6), 874–882.

Han, H., Wang, H. W., Ouyang, M. G., & Cheng, F. (2011). Vehicle survival patterns in China. *Science China Technological Sciences*, *54*(3), 625–629.

Hedbrant, J. (2001). Stockhome: A spreadsheet model of urban heavy metal metabolism. *Water Air & Soil Pollution Focus*, *1*(3–4), 55–66.

Hu, M., Bergsdal, H., van der Voet, E., Huppes, G., & Müller, D. B. (2010). Dynamics of urban and rural housing stocks in China. *Building Research & Information*, *38*(3), 301–317.

Huang, T., Shi, F., Tanikawa, H., Fei, J., & Han, J. (2013). Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. *Resources, Conservation and Recycling*, *72*, 91–101.

International Copper Association (ICA). (2013). Retrieved from copper recycling.pdf https://copperalliance.org/wordpress/wp-content/uploads/2013/03/ica-copper-recycling-1405-A4-low-res.pdf

Igarashi, Y., Kakiuchi, E., Daigo, I., Matsuno, Y., & Adachi, Y. (2008). Estimation of steel consumption and obsolete scrap generation in Japan and Asian countries in the future. *Isij International*, *93*(12), 782–791.

Kapur, A. (2006). The future of the red metal—A developing country perspective from India. *Resources Conservation & Recycling*, *47*(2), 160–182.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., … Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences*, *114*(8), 1880–1885.

Li, H., & Qi, Y. (2011). Comparison of China's carbon emission scenarios in 2050. *Advances in Climate Change Research*, *2*(4), 193–202.

Ling, Z., Zengwei, Y., & Jun, B. (2012). Estimation of copper in-use stocks in Nanjing, China. *Journal of Industrial Ecology*, *16*(2), 191–202.

Liu, G., Bangs, C. E., & Müller, D. B. (2013). Stock dynamics and emission pathways of the global aluminium cycle. *Nature Climate Change*, *3*(4), 338.

Maung, K. N., Hashimoto, S., Mizukami, M., Morozumi, M., & Lwin, C. M. (2017). Assessment of the secondary copper reserves of nations. *Environmental Science & Technology*, *51*(7), 3824–3832.

Müller, E., Hilty, L. M., Widmer, R., Schluep, M., & Faulstich, M. (2014). Modeling metal stocks and flows: A review of dynamic material flow analysis methods. *Environmental Science & Technology*, *48*(4), 2102–2113.

OECD. (2019). *Global material resources outlook to 2060*. Paris: OECD Publishing.

Qiang, Y., Wang, H.-M., & Lu, Z.-W. (2012). Quantitative estimation of social stock for metals Al and Cu in China. *Transactions of Nonferrous Metals Society of China*, *22*(7), 1744–1752.

Ruhrberg, M. (2006). Assessing the recycling efficiency of copper from end-of-life products in Western Europe. *Resources Conservation & Recycling*, *48*(2), 141–165.

Schipper, B. W., Lin, H. C., Meloni, M. A., Wansleeben, K., Heijungs, R., & Voet, E. V. D. (2018). Estimating global copper demand until 2100 with regression and stock dynamics. *Resources Conservation & Recycling*, *132*, 28–36.

Song, C. H. (2005). Whole life and high-grade quality-stick to the implement housing performance certification. *Housing Science*, *290*(8), 287–302.

Soulier, M., Pfaff, M., Goldmann, D., Walz, R., Geng, Y., Zhang, L., & Tercero Espinoza, L. A. (2018). The Chinese copper cycle: Tracing copper through the economy with dynamic substance flow and input-output analysis. *Journal of Cleaner Production*, *195*, 435–447.

Spatari, S., Bertram, M., Gordon, R. B., Henderson, K., & Graedel, T. E. (2005). Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecological Economics*, *54*(1), 37–51.

Graedel, T. E., van Beers, D., Bertram, M., Fuse, K., Gordon, R. B., Gritsinin, A., … Memon, L. (2013). Multilevel cycle of anthropogenic copper. *Environmental Science & Technology*, *38*(4), 1242–1252.

Terakado, R., Ichino, T. K., Daigo, I., Matsuno, Y., & Adachi, Y. (2009a). Estimation of in-use stock of copper in China, Korea and Taiwan. *Journal of the Japan Institute of Metals*, *73*(11), 833–838.

Terakado, R., Takahashi, K. I., Daigo, I., Matsuno, Y., & Adachi, Y. (2009b). In-use stock of copper in Japan estimated by bottom-up approach. *Journal of the Japan Institute of Metals*, *73*(9), 713–719.

Van der Voet, E., Van Oers, L., Verboon, M., & Kuipers, K. (2018). Environmental implications of future demand scenarios for metals: Methodology and application to the case of seven major metals. *Journal of Industrial Ecology*, *23*, 141–155.

Wang, M., Chen, W., Zhou, Y., & Li, X. (2017). Assessment of potential copper scrap in China and policy recommendation. *Resources Policy*, *52*, 235–244.

Wiedenhofer, D., Steinberger, J. K., Eisenmenger, N., & Haas, W. (2015). Maintenance and expansion: Modeling material stocks and flows for residential buildings and transportation networks in the EU25. *Journal of Industrial Ecology*, *19*(4), 538–551.
Yan, L., Wang, A., Chen, Q., & Li, J. (2013). Dynamic material flow analysis of zinc resources in China. *Resources Conservation & Recycling*, *75*(2), 23–31.
Yang, J., Li, X., & Liu, Q. (2017). China's copper demand forecasting based on system dynamics model: 2016–2030.
Yoshimura, A., & Matsuno, Y. (2018). Dynamic material flow analysis and forecast of copper in global-scale: Considering the difference of recovery potential between copper and copper alloy. *Materials Transactions*, *59*(6), 989–998.
Zalmon, I., Carvalho, G., & Ferreira, C. A. (1998). Regional population projections for China. *Higher Education in Europe*, *23*(XXIII), 351–356.
Zeltner, C., Bader, H. P., Scheidegger, R., & Baccini , P. (1999). Sustainable metal management exemplified by copper in the USA. *Regional Environmental Change*, *1*(1), 31–46.
Zhang, L., Yang, J., Cai, Z., & Yuan, Z. (2014). Analysis of copper flows in China from 1975 to 2010. *Science of the Total Environment*, *478*, 80–89.
Zhang, L., Yang, J., Cai, Z., & Yuan, Z. (2015a). Understanding the spatial and temporal patterns of copper in-use stocks in China. *Environmental Science & Technology*, *49*(11), 6430–6437.
Zhang, L., Cai, Z., Yang, J., Yuan, Z., & Chen, Y. (2015b). The future of copper in China—A perspective based on analysis of copper flows and stocks. *Science of the Total Environment*, *536*, 142–149.

SUPPORTING INFORMATION

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

How to cite this article: Dong D, Tukker A, Voet E. van der. Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. *J Ind Ecol*. 2019;23:1363–1380. https://doi.org/10.1111/jiec.12926