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Copper in-use stocks accounting at the sub-national level in China

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ABSTRACT

Copper in-use stocks play an important role in copper cycle. Investigating copper in-use stocks is essential to realize more efficient and sustainable utilization of copper resources. A systematic analysis at the sub-national level is still inadequate, especially for those sub-regions of the studied area. In order to fill the research gap, this study uses Chinaös Sichuan Province as a case to assess copper in-use stock and its spatial distribution at the sub-national level in China. Employing a bottom-up modelling approach, this study calculates the copper in-use stocks in Sichuan and its 21 prefectural sub-regions in 2014. Our results show that, 1) copper in-use stocks of the whole province were 1,891 Gg and the amount of in-use stocks per capita was 23 kg, which is far below the level of the developed countries and implies significant growth potential in the future. 2) Among all the categories calculated, residential buildings, non-residential buildings, automobiles, air conditioners, power substations, refrigerators, power transmission and distribution cables were the main reservoirs of copper and collectively took nearly 80% of the total stocks. Stocks per capita for the prefectural sub-regions in Sichuan are relatively close, ranged from 17.1 to 28.8 kg. 3) Distinction between rural and urban copper in-use stocks indicates Sichuanös rural copper stocks occupy an indispensable proportion. 4) The stocks density for prefectural regions varied from 149 kg/km^2 to 34,302 kg/km^2, indicating significant imbalance of spatial distribution characteristic and an unignorable intra-provincial disparity.

1. Introduction

Copper is an essential industrial metal used widely in electricity transmission, electronics, transportation, machinery, and construction area due to its excellent electrical conductivity and ductility. Although current industry system relies substantially on copper ore, copper recycling can greatly relieve the reliance on primary copper resources and reduce corresponding environmental burdens. Given that copper contained in products has been accumulating considerably in China in the recent two decades (Zhang et al., 2014), in-use stocks could be potential reservoirs of secondary copper resources and play an increasingly important role in copper recycling in the future (Muller et al., 2014; Pauliuk and Müller, 2014).

Most existing studies on copper in-use stocks focused on the national and city levels. Countrywide studies assessed copper in-use stocks at the macro level, such as in the US (Gordon et al., 2006; Zeltner et al., 1999), Australia (Van Beers and Graedel, 2007), China (Zhang et al., 2015; Zhang, 2008), and Japan (Daigo et al., 2009). Besides, accounting of city-level stocks was conducted at the micro level, especially for some big cities, such as Stockholm (Sörme et al., 2001), Cape Town (Van Beers and Graedel, 2003), New Haven (Drakonakis et al., 2007), Nanjing (Zhang et al., 2012) and Shanghai (Zhang et al., 2014). Using a bottom-up modelling approach, these studies calculated the overall quantity and analysed it using patterns of copper in-use stocks, such as the composition, stocks per capita, and changing trends. Despite these efforts, there is still a knowledge gap, that is, a comprehensive understanding of copper in-use stocks is still missing at the meso level or, specifically, at the sub-national level for China.

China provinces usually have large population and vast area, the quantity of which may be similar or even bigger than middle-sized European countries. For example, Sichuan province had a population of 81.4 million and an area of 486 thousand square kilometres (sq. km) in 2014 (National Bureau of Statistics of China (NBSC, 2015), while Italy had a population of 60.8 million (World Bank, 2019a) and an area of

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301 thousand sq. km at the same time (World Bank, 2019b). Studying these provinces as integrated ones may omit important information about its internal composition. Provinces comprise several prefectural regions, but prefectural regions may differ greatly from each other, even within the same province. Under this circumstance, copper stocks' total quantity or average quantity per capita cannot reveal the non-negligible internal diversity. Outliers, such as the most developed and populated capital of the province, and the uninhabited but vast prefectural region, may also significantly influence the average quantity. On the other hand, previous researches focused on mega cities which are already well-urbanized while the national urbanisation rate for China is only 54.8% (National Bureau of Statistics of China (NBSC, 2015), indicating the existence of large rural population and area. Whether copper in-use stocks in the numerous less-urbanized regions or rural regions should be ignored has not been discussed yet.

Furthermore, a study may not be sufficient to provide support for local policies and governmental actions if it only focused on the aggregated conditions of the province or single city. For example, three national ministries in China together promoted the construction of fifty Resource Circular Utilization Bases (National Development and Reform Commission (NDRC, 2018a) around the country, in order to improve the recycling rate of wastes. Site selection of the bases has been done specifically to the prefectural level, rather than divided roughly in accordance with the Provincial Division. Therefore, provincial and prefectural research may together provide valuable information with regard to spatial distribution and the structure of provincial copper in-use products, distinguish the difference in copper stocks among sub-regions, and thus help policy-makers devise measures that are more adaptable to local conditions.

China has experienced a significant increase in copper consumption in the past few decades, along with rapid development of the economy and society. It is currently the world's largest producer and consumer of refined copper. Its production of refined copper grew from 299 Gg in 1978 to 7,649 Gg in 2014, while the consumption increased from 408 Gg to 9450 Gg during the same period (National Bureau of Statistics of China (NBSC, 1979, 2015). This implies a continuous and substantial transfer of copper from the lithosphere to anthroposphere in various forms of copper-containing products, retained as copper in-use stocks. In China's administrative system, provincial governments act as the connection between the central and prefectural governments, with latter carrying out and implementing the policies from the central government on one hand, and guiding and supervising the city-level actions on the other. Provincial and prefectural governments in China implement policies from central government in conjunction with local conditions, and therefore sub-national studies may directly provide scientific support for local governments.

This study attempts to fill this research gap by using Sichuan Province as a case. The reasons why Sichuan is selected include the following: First, Sichuan consists of 1 super capital (taking up 35% of total gross domestic product [GDP] and 18% of total population) and 20 other diversified prefectural sub-regions with great disparities in terms of economic development, population and administrative area. This enables us to gain knowledge about the province's internal diversity of copper in-use stocks. Second, Sichuan is an inland province with a large population (81.4 million in 2014), large administrative area (486 thousand sq. km), relatively low urbanisation rate (46.3% in 2014) and unique geographical conditions (many high mountain areas). Previous studies showed that demographic and geographical factors profoundly affect the quantity and distribution of material in-use stocks (Fishman et al., 2015, 2016; Han and Xiang, 2013; Zhang et al., 2017). Third, Sichuan is very rich in hydropower (ranking first in China) with a large number of power stations, substations and transmission facilities, which are important sinks for copper in-use stocks (Glöser et al., 2013; Zhang et al., 2015).

This study examines the amount, composition, and spatial distribution of copper in-use stocks in Sichuan and its 21 sub-regions in the year 2014. A bottom-up approach is employed, because it utilizes detailed information about products, industries, and locations. This article is organized into five sections. A detailed description of methodology is presented in Section 2 after this introduction. Then, we report results for the whole province and its sub-regions in Section 3. A comparison with other studies and spatial structure analysis are provided in Section 4. Section 5 concludes.

2. Methods

2.1. Bottom-up modeling approach

Two basic methods are employed in estimating the in-use stocks of materials: the bottom-up approach and top-down approach (Gerst and Graedel, 2008; Müller, 2006). The top-down method derives information from material flows and calculates material stock using the cumulative difference between the inflow and outflow (Chen and Graedel, 2015). Inflows are quite different in various systems, while outflows are often calculated from inflows with assumed lifetime distribution functions. The top-down method relies strongly on inflow data, consequently it is often used for nation-wide accounting. The bottom-up approach aggregates copper reservoirs in all related products, and it employs inventory data and copper content parameters. The bottom-up approach can be represented by Eq. (1):

$$S = \sum_{i}^{n} N_i \times c_i, \tag{1}$$

where S is the copper in-use stock of the targeted region, N_i is the quantity of product i, c_i is the copper content of product i, and n is the total number of final products. Based on in-depth data for different products, the bottom-up method is able to provide detailed information on in-use stocks' distribution among the industries as well as the spatial distribution among sub-regions.

2.2. Category identification

This study employs a cross-sectional analysis and a bottom-up approach to investigate 45 products from five main end-users, including infrastructure, buildings, transportation, consumer durables, machinery, and equipment. We consult experts from the China Nonferrous Metals Industry Association (CNIA), and we carefully compare the category identification with existing studies to avoid any overlap and ensure completeness. Inventories of five main end-users are shown in Fig. 1 and explained as follows.

Infrastructure here refers to the system of public works, including roads, utility lines and public buildings (Statistical Division of United Nations, 2000). It includes the power generation, transmission and distribution system, telecommunication system, transportation facilities, water pipes and gas pipes. Buildings include all materials within the building's enclosure for building functions and exclude equipment not built into the building. Buildings are further categorised into residential buildings and non-residential buildings. Transportation here includes all types of vehicles including automobiles, railway vehicles, airplanes, metro vehicles and electric scooters. In this study, consumer durables are durable goods acquired by households for final consumption and used repeatedly or continuously over a period of a year or more (Organisation for Economic Co-operation and Development (OECD, 2001a), including important home appliances, and mobile phones. Machinery and equipment refer to the types of equipment other than those acquired by households for final consumption (Organisation for Economic Co-operation and Development (OECD, 2001b), and they are further categorised into manufacturing, construction, and agricultural machinery (Wang and Graedel, 2010).

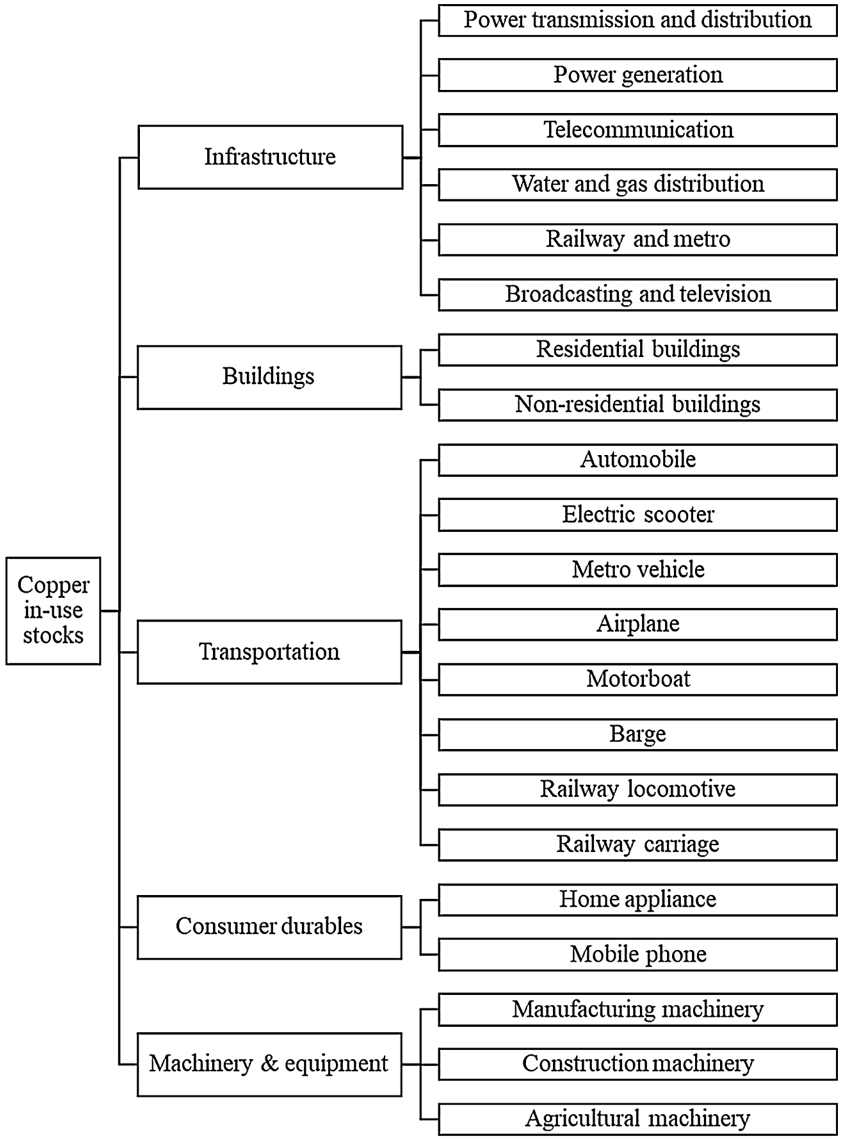

Fig. 1. Categories and subcategories of copper in-use stocks in Sichuan.

2.3. Data acquisition and calculation

In this study, inventory data are mainly gathered from the Statistical Yearbook of Sichuan Province, Sichuan Transportation Yearbook, Sichuan Electric Power Companies, and Statistical Compilation of Electric Power Industry. Missing data are estimated after consulting experts or collected from prefectural statistical bulletins and chronicles. Product specifications, economic indicators, and expert opinions are used to calculate copper content parameters. Missing parameters are estimated based on related literature. Indispensably, first-hand data and parameters are collected carefully from related companies and experts. For example, this study expands the estimation methods of the power transmission and distribution system, which is the biggest part of the infrastructure section and may provide a good reference for future study. Estimation methods of each end-user are shown in Table 1.

2.3.1. Infrastructure

Copper plays an important role in enabling generation, transmission, and distribution of electricity; provides the material basis for certain information transmission and acts as an integral part of water and gas distribution. The subcategories and specific products in infrastructure include the following: electricity transmission and distribution system, electricity power station, telecommunication cables, water and gas distribution facilities, railway and metro facilities, television network, and streetlight and signal light facilities.

2.3.1.1. Power transmission and distribution system. The system of power transmission and distribution is built upon transformers and wires, in which copper is widely used. Copper is electrically conductive, but it is also heavy, soft, and expensive compared with other common metals. Therefore, the cores of underground cables are made of copper, but those of overhead lines are mainly made of aluminium (Wang, 2017). To achieve urban amenity, state grid companies use cables instead of overhead lines, and so cables are mainly located in Chengdu (Chen et al., 2017). We employ an estimation method for cable copper in-use stocks based on cable voltage levels as well as the common types and length of the cable, which is provided by engineers (Chen et al., 2017; Ran et al., 2017), from the State Grid Sichuan Electric Power Company and State Grid Chengdu Power Supply Company (SGCPSC). Copper in-use stocks in transformers are also calculated in a similar way based on a former study (Qiao, 2012). He calculated the parameters of substations based on sample surveys and estimated the parameters of power station based on detailed analysis on main copper-containing component, stator coils. Moreover, the power transmission and

Table 1
Calculation methods of copper in-use stocks in Sichuan.

Subcategory	Formula	Parameter description	Parameter values and data sources
Power transmission and distribution system	$S_{\text{pss},1\text{-}4} = \sum_i^4 N_{\text{pss},i} \times VC_i \times C_{\text{vc},i}$ $S_{\text{pss},5} = N_{pss,5} \times C_{pss,5} \times AF_{pss,5}$	$S_{pss,1\text{-}4}$: Cu stocks in power substations $N_{pss,i}$: Number of power substations, i VC_i: Average variable capacity of power substations, i $C_{vc,i}$: Cu content per MVA $S_{pss,5}$: Cu stocks in 10 KV power substations $N_{pss,5}$: Number of 10 KV power substations, i $C_{pss,5}$: Cu content per 10 KV power substations $AF_{pss,5}$: Adjustment factor for 10 KV power substations (i = 1, 2, 3, 4: 500, 220, 110, 35 KV)	$N_{pss,i}$ (i = 1, 2, 3, 4) (Chen et al., 2017) VC_i (i = 1, 2, 3, 4) = 1700, 280, 80, 6 MVA (Chen et al., 2017) $C_{vc,i}$ (i = 1, 2, 3, 4) = 70, 180, 400, 1000 kg/MVA (Qiao, 2012) $N_{pss,5}$ (Ran et al., 2017) $C_{pss,5}$ = 50 kg (Ran et al., 2017) $AF_{pss,5}$ = 2.65 (Ran et al., 2017)
	$S_{\text{pc},1\text{-}3} = \sum_i^3 L_{\text{pc},i} \times CS_{\text{pc},i} \times NC_{\text{pc},i} \times \rho$ $S_{\text{pc},4} = L_{\text{pc},4} \times CS_{\text{pc},4} \times NC_{\text{pc},4} \times \rho \times AF_{\text{pc},4}$	$S_{pc,1\text{-}3}$: Cu stocks in power transmission and distribution cables $L_{pc,i}$: Length of power transmission and distribution cables, i $CS_{pc,i}$: Cross-sectional area of core in power transmission and distribution cable, i $NC_{pc,i}$: Number of pairs of core for power transmission and distribution cables, i ρ: Cu density $S_{pc,4}$: Cu stocks in 10 KV power transmission and distribution cables $L_{pc,4}$: Length of 10 KV power transmission and distribution cables, $CS_{pc,4}$: Cross-sectional area of core in 10 KV power transmission and distribution cable $NC_{pc,4}$: Number of pairs of cores for 10 KV power transmission and distribution cables $AF_{pc,4}$: Adjustment factor for 10 KV power transmission and distribution cables (i = 1, 2, 3: 220, 110, 35 KV)	$L_{pc,i}$ (i = 1, 2, 3) (Chen et al., 2017) $CS_{pc,i}$ (i = 1, 2, 3) = 1600, 700, 350 mm^2 (Chen et al., 2017) $NC_{pc,i}$ (i = 1, 2, 3) = 3 (Chen et al., 2017) $\rho = 8.92 \times 10^3$ kg/m^3 $L_{pc,4}$ (Ran et al., 2017) $CS_{pc,4}$ = 120 mm^2 (Ran et al., 2017) $NC_{pc,4}$ = 1 (Ran et al., 2017) $AF_{pc,4}$ = 2.65 (Ran et al., 2017)
Power generation system	$S_{\text{ps}} = \sum_i^4 IC_i \times C_{\text{ic},i}$	S_{ps}: Cu stocks in power stations IC_i: Total installed capacity of power stations, i $C_{ic,i}$: Cu content per MW (i = 1, 2, 3, 4: 0-199, 200-399, 400-699, > 700 MW)	IC_i (i = 1, 2, 3, 4) (China Electric Council (CEC, 2015; Lin and Liu, 2013) $C_{ic,i}$ (i = 1, 2, 3, 4) = 100, 130, 175, 296 kg/MW (Qiao, 2012)
Telecomm-unication system	$S_{tb} = (A_u + A_t) \times L_{tb} \times CS_{tb} \times NC_{tb} \times 2 \times \rho$	S_{tb}: Cu stocks in telecommunication base stations A_u: Urban area A_t: Township area L_{tb}: Cable length per km^2 CS_{tb}: Cross-sectional area of core in telecommunication base cable NC_{tb}: Number of pairs of cores for telecommunication base cable	A_u, A_t (SPBS, 2015) L_{tb} = 1.5 km/km^2 (Zhang et al., 2015) CS_{tb} = 0.2^2 X π mm^2 (Zhang et al., 2015) NC_{tb} =300 (Zhang et al., 2015)
	$S_{UTP} = N_{\text{tc},ps} \times L_{UTP} \times CS_{UTP} \times NC_{UTP} \times 2 \times \rho$	S_{UTP}: Cu stocks in telecommunication UTPs $N_{tc,ps}$: Number of phone subscribers L_{UTP}: Branch loop Length of UTP CS_{UTP}: Cross-sectional area of core in UTP NC_{UTP}: Number of pairs of cores in UTP	$N_{tc,ps}$ (Sichuan Provincial Bureau of Statistics (SPBS, 2015) L_{UTP} = 30 m/household (Zhang et al., 2015) CS_{UTP} = 0.25^2 X π mm^2 (Xundao (Shen Zhen) Corp. Co., 2018a) NC_{UTP} = 8 (Xundao (Shen Zhen) Corp. Co., L., 2018a)
Water and gas distribution system	$S_{\text{wp}} = L_{wp} \times C_{wp}$	S_{wp}: Cu stocks in water pipes L_{wp}: Length of water pipes C_{wp}: Copper content per water pipe length	L_{wp} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) C_{wp} = 90 kg/km (Yan, 2017)
	$S_{\text{gp}} = RL_{gp} \times C_{gp}$	S_{gp}: Cu stocks in gas pipes L_{gp}: Length of gas pipes C_{gp}: Copper content per gas pipe length	L_{gp} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) C_{gp} = 90 kg/km (Yan, 2017)
Railway and metro facilities	$S_{\text{rlc}} = RL_{hh} \times CS_{rlc} \times \rho \times 2$	S_{rlc}: Cu stocks in railway contact wires R_{hh}: Ratio of region and whole province household number L_{trlc}: Length of whole province railway contact wires CS_{rlc}: Cross-sectional area of railway contact wires	R_{hh} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) L_{trlc} (National Bureau of Statistics of China (NBSC, 2015) CS_{rlc} = 120 mm^2 (Ministry of Railways of People's Republic of China (MOR, 2005)
	$S_{\text{mlc}} = L_{mlc} \times CS_{mlc} \times \rho \times 2$	S_{mlc}: Cu stocks in metro contact wires L_{ml}: Length of metro contact wires CS_{mlc}: Cross-sectional area of metro contact wires	L_{ml} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) CS_{mlc} = 120 mm^2 (Ministry of Railways of People's Republic of China (MOR, 2005)
Broadcasting and television network	$S_{\text{tv}} = N_{hh} \times L_{\text{tv}} \times CS_{\text{tv}} \times \rho$	S_{tv}: Cu stocks in broadcasting and television network N_{hh}: Household number L_{tv}: Branch loop Length of coaxial cable CS_{tv}: Cross-sectional area of coaxial cable	N_{hh} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) L_{tv} = 30 m/household (Assumed) CS_{tv} = 0.25^2 X π mm^2 (Xundao (Shen Zhen) Corp. Co., L., 2018b)

(continued on next page)

Table 1 (*continued*)

Subcategory	Formula	Parameter description	Parameter values and data sources
Streetlights and traffic lights facilities	$S_{st} = [N_{st} \times H_{st} + D_{st} \times (N_{st} - 1)] \times CS_{st} \times NC_{st} \times \rho$	S_{st}: Cu stocks in streetlights N_{st}: Streetlights number H_{st}: Streetlights average height D_{st}: Average distance between streetlights CS_{st}: Cross-sectional area of core in streetlights cable NC_{st}: Number of pairs of core in streetlights	N_{st} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) H_{st} = 9 m (Assumed) D_{st} = 35 m (Assumed) CS_{st} = 16 mm^2 (Zhang et al., 2015) NC_{st} = 3 (Zhang et al., 2015)
	$S_{tr} = [H_{tr} \times L_{hw}/D_{tr} + L_{hw}] \times CS_{tr} \times NC_{tr} \times \rho$	S_{tr}: Cu stocks in traffic lights H_{tr}: Traffic lights average height L_{hw}: Length of high way D_{tr}: Average distance between traffic lights CS_{tr}: Cross-sectional area of core in traffic lights cable NC_{tr}: Number of pairs of core in traffic lights	H_{tr} = 5 m (Standardization Administration of the People's Republic of China (SAC, 2016) L_{hw} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) D_{st} = 1000 m (Assumed) CS_{st} = 0.75 mm^2 (Zhang et al., 2015) NC_{st} = 4 (Zhang et al., 2015)
Residential buildings	$S_{rb} = N_{rhh} \times C_{rhh} + N_{uhh} \times C_{uhh}$	S_{rb}: Cu stocks in residential buildings N_{rhh}: Number of rural households C_{rhh}: Cu in-use stocks per rural household N_{uhh}: Number of urban households C_{uhh}: Cu in-use stocks per urban household	N_{rhh}, N_{uhh} (Sichuan Provincial Bureau of Statistics (SPBS, 2015) C_{rhh} = 20 kg/household (Zhang et al., 2015) C_{uhh} = 30 kg/household (Zhang et al., 2015)
Non-residential buildings	$S_{nrb} = AF_{rn} \times N_{rhh} \times C_{rhh} + AF_{un} \times N_{uhh} \times C_{uhh}$ $AF_{rn} = A_{n,r,nrb}/A_{n,r,rb}$ $AF_{un} = A_{n,u,nrb}/A_{n,u,rb}$	S_{nrb}: Cu stocks in non-residential buildings AF_{ru}: Adjustment factor for rural non-residential buildings AF_{un}: Adjustment factor for urban non-residential buildings $A_{n,r,nrb}$: National rural non-residential area $A_{n,r,rb}$: National rural residential area $A_{n,u,nrb}$: National urban non-residential area $A_{n,u,rb}$: National urban residential area	$A_{n,r,nrb}$ = 6.03 × 10^9 m^2 S (Ministry of Housing and Urban-Rural Development (MOHURD, 2015a, b) $A_{n,r,rb}$ = 31.775 × 10^9 m^2 (Ministry of Housing and Urban-Rural Development (MOHURD, 2015a, b) $A_{n,u,nrb}$ = 16.719 × 10^9 m^2 (Ministry of Housing and Urban-Rural Development (MOHURD, 2015a, b; Wang et al., 2015) $A_{n,u,rb}$ = 34.35 × 10^9 m^2 (Ministry of Housing and Urban-Rural Development (MOHURD, 2015a, b; Wang et al., 2015)
Transportation	$S_{trans} = \sum_i^8 N_{trans,i} \times C_{trans,i}$ $N_{trans,2} = N_{hh} \times NPH_{trans,2}$	S_{trans}: Cu stocks in transportation conveyance $N_{trans,i}$: Conveyance number, i $C_{trans,i}$: Cu content per transportation conveyance $NPH_{trans,2}$: Transport vehicle number per hundred household (i = 1, 2, 3, 4, 5, 6, 7, 8: automobile, electric scooter, metro vehicle, airplane, motorboat, barge, railway locomotive, railway carriage)	$N_{trans,1}$ (Sichuan Provincial Bureau of Statistics (SPBS, 2015) $N_{trans,2}$ (Sichuan Provincial Bureau of Statistics (SPBS, 2015) $N_{trans,3}$, $N_{trans,5}$, $N_{trans,6}$ (DOTSP, 2015) $N_{trans,4}$ (Development Planning Division for Civil Aviation Administration of China (CACC, 2015; Planespotters.net, 2014) $N_{trans,7}$, $N_{trans,8}$ (SRG, 2017) $C_{trans,1}$ = 24 (Hao et al., 2017) $C_{trans,2}$ = 1.6 kg (Liu, 2017) $C_{trans,4}$ = 786 kg (Copper Development Association (CDA, 2009; Ministry of Housing and Urban-Rural Development (MOHURD, 2015a, b) $C_{trans,i}$ (i = 3, 5, 6, 7, 8) = 4173, 800, 35, 4990, 832 kg (Copper Development Association (CDA, 2009)
Consumer durables	$S_{dur} = \sum_i^8 N_{dur,i} \times C_{dur,i}$ $N_{dur,i} = N_{hh} \times NPH_{dur,i}$	S_{dur}: Cu stocks in consumer durables $N_{dur,i}$: Consumer durable number, i $C_{dur,i}$: Cu content per consumer durable $NPH_{dur,i}$: Consumer durable number per hundred household (i = 1, 2, 3, 4, 5, 6, 7, 8: air conditioner, refrigerator, washing machine, television, dish sterilizer, dish washer, personal computer and mobile phone)	$NPH_{dur,i}$ (Sichuan Provincial Bureau of Statistics (SPBS, 2015) $C_{dur,1}$ = 8.9 kg (Jiang et al., 2016; Li et al., 2011) $C_{dur,i}$ (i =2, 3) = 1.87, 1.24 kg (Jiang et al., 2016) $C_{dur,4}$ = 0.405 kg (Li et al., 2011) $C_{dur,i}$ (i = 5, 6) = 5, 5 kg (Copper Development Association (CDA, 2009) $C_{dur,7}$ = 0.41 kg (Guo et al., 2017; Li et al., 2011) $C_{dur,8}$ = 0.01356 kg (Yu et al., 2016)
Machinery and equipment	$S_{m\&e,t} = F_{m\&e,in,t} - F_{m\&e,out,t} + S_{m\&e,t-1}$ $F_{m\&e,out,t} = \sum_{y=2004}^{2014} (F_{m\&e,in,t-y} \times d_{m\&e,y})$ $F_{m\&e,in} = k_{m\&e} \times IV_{m\&e} \times CF_{m\&e}$ $k_{m\&e} = CC_{n,m\&e}/IV_{n,m\&e}$	$S_{m\&e}$: Cu stocks in machinery and equipment $F_{m\&e,in}$: Cu inflow of machinery and equipment $F_{m\&e,out}$: Cu outflow of machinery and equipment $d_{m\&e}$: Normal distribution with a mean of 15 years and standard deviation of 5 year $k_{m\&e}$: Coefficient of national fixed assets investment for machinery and equipment between national copper consumption in machinery and equipment manufacturing $IV_{m\&e}$: Fixed assets investment for machinery and equipment $CF_{m\&e}$: Copper conversion factor in machinery and equipment manufacturing process $CC_{n,m\&e}$: National copper consumption in machinery and equipment manufacturing $IV_{n,m\&e}$: National fixed assets investment for machinery and equipment	$d_{m\&e}$ (Assumed) $IV_{m\&e}$ (Sichuan Provincial Bureau of Statistics (SPBS, 2015) $CF_{m\&e}$ = 0.9 (Assumed) $CC_{n,m\&e}$ (CNIA, 2015) $IV_{n,m\&e}$ (National Bureau of Statistics of China (NBSC, 2015)

Note: CEC = China Electric Council; SPBS = Sichuan Provincial Bureau of Statistics; NBSC = National Bureau of Statistics of China; MOR = Ministry of Railways of People's Republic of China; SAC = Standardization Administration of the People's Republic of China; MOHURD = Ministry of Housing and Urban-Rural Development; DTSP = Department of Transportation of Sichuan Province; CACC = Civil Aviation Administration of China; SRG = Sichuan Railway Group Co., Ltd.; CDA = Copper Development Association; CNIA = China Nonferrous Metals Industry Association.

distribution networks are divided into two categories: public network and private networks. The public network refers to a network built by state grid companies, while private networks refers to those not built by them. Most public networks are above 10 KV, and private networks are widely built in 10 KV networks (Ran et al., 2017). Therefore, the gap between a 10-KV public network and a total 10-KV network should be considered, and an adjustment factor is suggested by engineers from the SGCPSC (Ran et al., 2017).

2.3.1.2. Power station. In electric power stations, copper is mainly used in generators, which have a variety of copper coils. The higher is the installed capacity, the less copper is consumed for unit capacity (Qiao, 2012). The locations and capacities of power stations in Sichuan are collected from the Reshaping Economic Geography of Sichuan (Lin and Liu, 2013) and Statistical Compilation of Electric Power Industry (China Electric Council (CEC, 2015).

2.3.1.3. Telecommunication system. Telecommunication base stations and cables are the main parts of a telecommunication system, wherein copper is widely used. Most telecommunication cables now have fibre optic cores, but the branches connected to buildings are commonly unshielded twisted pair (UTP) cables. Thus, the copper in-use stock of cables is calculated using the branch loop length per household and UTP specification, as shown in Table 1. Parameters from related literature (Zhang et al., 2012) and product specifications (Xundao (Shen Zhen) Corp. Co., L., 2018a) are used in this case.

2.3.1.4. Water and gas distribution system. Pipes are the main facilities of water and gas distribution system. Prestressed concrete cylinder pipes (PCCP) are most commonly used in the water distribution system, while steel pipes are often used in gas distribution systems. In China, copper water pipes are used only in prime residential areas, and copper is used mostly in valves, pumps, and compressors in the forms of lead brass and tin bronze. copper in-use stocks in water and gas distribution are obtained based on pipe length data from the Sichuan Statistic Yearbook (Sichuan Provincial Bureau of Statistics (SPBS, 2015) and parameters of copper per kilometre calculated by an engineer from Ningbo Jiekelong Precision Manufacturing Co., Ltd (Yan, 2017).

2.3.1.5. Railway and metro facilities. Contact wire delivers current to electric locomotives, and it is the main copper sink in railway and metro facilities. The specification of contact wire in railway and metro can be found in the related standards (Ministry of Railways of People's Republic of China (MOR, 2005). For railway, we are able to obtain only its total length in Sichuan Province (National Bureau of Statistics of China (NBSC, 2015), and so we allocate the length of the railways among the 21 prefectural sub-regions according to household numbers. For metro, Chengdu is the only prefectural region that has a metro system, and the length data are collected from the Sichuan Statistic Yearbook (Sichuan Provincial Bureau of Statistics (SPBS, 2015).

2.3.1.6. Broadcasting television network. Similar to telecommunication cables, television cable branches connected to buildings are often coaxial cables with a copper core. Using the specification of the cable (Xundao (Shen Zhen) Corp. Co., L., 2018b), copper in-use stocks can be estimated.

2.3.1.7. Streetlights and traffic light. Wires are used to power and connect streetlights and traffic lights. The distance between two lights and the average height of lights is assumed according to the China standards (Ministry of Housing and Urban-Rural Development (MOHURD, 2015a,b; Standardization Administration of the People's Republic of China (SAC, 2016). The copper in-use stocks in this sector can be estimated based on data provided in the Sichuan Statistic Yearbook (Sichuan Provincial Bureau of Statistics (SPBS, 2015) and parameters referred in related literature (Zhang et al., 2012).

2.3.2. Buildings

Buildings are one of the most important repositories of anthropogenic metal, where copper is mainly contained in wires, valves, fittings, built-in appliances, and plumbing. Building wires are connected to 10 KV cables at the end of the distribution network via transformers, and thus there is no overlap with infrastructure. The usage of wires and plumbers varies greatly among buildings, and so we made the estimation based on copper in-use stocks per household from related literature (Zhang et al., 2012) and based on households from the Statistic Yearbook of Sichuan (Sichuan Provincial Bureau of Statistics (SPBS, 2015). As for non-residential buildings, we assumed the same copper stocks per square metre. The area of residential buildings in Sichuan is calculated using residential area per capita and residential population. However, data on areas of non-residential buildings in Sichuan are not available. The ratio of residential and non-residential areas at the national level were used to make the estimation based on prior literature (Wang et al., 2015) and data from the Statistical Communique of Urban and Rural Construction (Ministry of Housing and Urban-Rural Development (MOHURD, 2015a,b).

2.3.3. Transportation

Eight types of vehicles are included in this part. As transport vehicles travel from place to place, their number in a specific place is difficult to determine. Therefore, we only consider copper stocks in vehicles owned by Sichuan's residents and companies. Data are mainly gathered from the Statistic Yearbook of Sichuan (Sichuan Provincial Bureau of Statistics (SPBS, 2015), Sichuan Transport Yearbook (Department of Transportation of Sichuan Province (DTSP, 2015), and Statistical Data on Civil Aviation of China (Development Planning Division for Civil Aviation Administration of China (CACC, 2015), while the necessary calibrations are made based on another public data source (Planespotters.net, 2014). Parameters are collected from related literature, reports, and personal communication with experts.

2.3.3.1. Automobiles. Copper mainly exists in heating, ventilation, and air conditioning systems; generators; motors; controllers; and electrical and electronic devices of automobiles. Data are collected from the Statistic Yearbook of Sichuan (Sichuan Provincial Bureau of Statistics (SPBS, 2015), while the parameters are obtained from related literature (Hao et al., 2017).

2.3.3.2. Railway vehicles. Railway vehicles are categorised into locomotives and carriages, and data provided by Sichuan Railway Group Co., Ltd. (Luo, 2017) are counted in this part. Parameters of the copper densities of locomotive and carriage are collected from the Copper Development Association. Thus, railway vehicle copper in-use stocks can be obtained at the provincial level. However, this calculation cannot be done at the prefectural level, because the Sichuan Railway Group Co., Ltd. cannot be split into prefectural regions.

2.3.3.3. Electric scooters. Copper in-use stocks in electric scooters mainly exist as electric motors and wires. According to the data provided by Jining Huanyu Electromechanical Co., Ltd. (Liu, 2017), the average copper content of most used Y-series, three-phase motors is 1.6 kg. Thus, copper in-use stocks can be calculated upon combining the data of households and electric bicycles per 100 households from the Sichuan Statistical Yearbook (Sichuan Provincial Bureau of Statistics (SPBS, 2015).

2.3.3.4. Metro vehicles. Chengdu is the only prefectural region in Sichuan that had a metro system in 2014. Copper in metro vehicles mainly exists in locomotive engines, each containing 4.2 tons of copper (Copper Development Association (CDA, 2009). Data are gathered from the Sichuan Transport Yearbook (Department of Transportation of Sichuan Province (DTSP, 2015).

Table 2
Copper in-use stocks of different subcategories in Sichuan.

Category	Sichuan, 2014 Copper stocks (Gg)	Sichuan, 2014 Stocks/capita (kg)	Sensitivity
Infrastructure	*192.4*	*2.4*	*2.0%*
Power stations	*7.9*	*0.1*	*0.1%*
Substations	*74.9*	*0.9*	*0.8%*
Power transmission and distribution cables	*50.7*	*0.6*	*0.5%*
Telecommunication cables	*14.1*	*0.2*	*0.1%*
Water and gas pipes	*5.7*	*0.1*	*0.1%*
Railway and metro facilities	*10.0*	*0.1*	*0.1%*
Broadcasting & television network	*1.7*	*0.0*	*0.0%*
Street light & traffic lights	*27.3*	*0.3*	*0.3%*
Buildings	*1014.8*	*12.5*	*10.7%*
Residential buildings	*765.7*	*9.4*	*8.1%*
Non-residential buildings	*249.1*	*3.1*	*2.6%*
Transportation	*191.1*	*2.3*	*2.0%*
Automobiles	*159.6*	*2.0*	*1.7%*
Electric scooters	*9.8*	*0.1*	*0.1%*
Airplane	*0.1*	*0.0*	*0.0%*
Vessels	*6.1*	*0.1*	*0.1%*
Metro vehicles	*1.6*	*0.0*	*0.0%*
Railway vehicles	*13.8*	*0.2*	*0.1%*
Consumer Durables	*268.2*	*3.3*	*2.8%*
Refrigerators	*51.3*	*0.6*	*0.5%*
Washing machine	*34.4*	*0.4*	*0.4%*
Dish sterilizers	*7.3*	*0.1*	*0.1%*
Dish washers	*0.9*	*0.0*	*0.0%*
Personal computers	*4.2*	*0.1*	*0.0%*
Air conditioners	*153.9*	*1.9*	*1.6%*
Televisions	*15.2*	*0.2*	*0.2%*
Mobile phones	*0.9*	*0.0*	*0.0%*
Machinery and equipment	*224.5*	*2.8*	*2.4%*
Total stock	***1891.0***	*23.2*	–

2.3.3.5. Airplane. Many types of energy, electrical, and electronic equipment in aircraft contain copper. The fleets of Sichuan Airlines Co., Ltd. and Chengdu Airlines Co., Ltd. are counted here, and they had registered a total of 112 aircrafts in 2014 (Development Planning Division for Civil Aviation Administration of China (CACC, 2015; Planespotters.net, 2014). About 2% of the operating empty weight comes from copper (Copper Development Association (CDA, 2009). We choose the most popular aircraft in Sichuan, Airbus A320-200, as the sample of the whole fleet, and it has a no-load weight of 39,300 kg (Ministry of Housing and Urban-Rural Development (MOHURD, 2015a,b). Fifteen aircrafts from Chengdu Airlines Co., Ltd. are directly counted in Chengdu, while 97 aircrafts from Sichuan Airlines Co., Ltd. are distributed to prefectural regions based on local airport passenger throughput (Development Planning Division for Civil Aviation Administration of China (CACC, 2015).

2.3.3.6. Vessels. A motor ship is a complex system containing a large amount of copper. A barge, however, hardly has a power and transmission system, and it thus contains much less copper. The copper in-use stocks are calculated based on copper per vessel (Copper Development Association (CDA, 2009) and number of vessels (Sichuan Provincial Bureau of Statistics (SPBS, 2015).

2.3.4. Consumer durables

Due to excellent electrical conductivity and thermal conductivity, copper is widely used in consumer durables. Eight types of consumer durables are counted in this study, including air conditioner, refrigerator, washing machine, television, dish steriliser, personal computer, dish washer, and mobile phone. Data of each product are calculated based on the number of households and number of consumer durables per 100 households from the Sichuan Statistical Yearbook. The copper content of consumer durables have been studied widely, and the related parameters are collected from a variety of literature (Guo et al., 2017; Jiang et al., 2016; Li et al., 2011; Yu et al., 2016).

2.3.5. Machinery and equipment

There are many types of machinery and equipment, and they can be categorised into manufacturing, construction, and agricultural machinery, with each having various products. For example, manufacturing machinery includes general machinery, petrochemical machinery, mining machinery, light industry machinery, and so on. Due to data availability, it is very difficult to calculate the copper stocks in each product. Therefore, an estimation method based on fixed assets data and copper consumption data is applied. First, the coefficient $k_{m\&e}$ is calculated, which refers to national copper consumption in machinery and equipment manufacturing (China Nonferrous Metals Industry Association (CNIA, 2015) divided by national fixed assets investment for machinery and equipment (National Bureau of Statistics of China (NBSC, 2015). Second, each year's fixed assets investment for machinery and equipment in Sichuan (Sichuan Provincial Bureau of Statistics (SPBS, 2015) $IV_{m\&e}$ is collected. Third, we multiply $k_{m\&e}$, $IV_{m\&e}$, and a conversion factor, which represents copper conversion efficiency in the machinery and equipment manufacturing processes. The formulas are shown in the last section of Table 1. Thus, each year's inflow data on copper in-use stocks can be obtained. Finally, we apply a normal distribution function of an average lifetime of 15 years and standard deviation of 5 years (Melo, 1999), and we use a dynamic material flow method to estimate copper in-use stocks of each prefectural region in this part.

3. Results

3.1. Provincial copper in-use stocks

In 2014, the total copper in-use stocks amounted to 1,891 Gg, which were almost 3 times the copper reserves (National Bureau of Statistics of China (NBSC, 2015). This result is close to the value from a previous study (Zhang et al., 2015), ranging from 1,556 Gg to 2,624 Gg for Sichuan's copper in-use stocks. Based on the permanent population, copper stocks at the provincial level only amounted to 23.2 kg/capita, which is much lower than the global average even in the year 2010, that is, 50 kg/capita (Glöser et al., 2013), let alone those for developed countries (Daigo et al., 2009; Drakonakis et al., 2007; Gordon et al., 2006). This result indicates that copper stocks in Sichuan would probably experience an obvious increase in the future. Detailed results for provincial copper in-use stocks are provided in Table 2.

Among the five categories, buildings played a dominant role with a share of 53.7% (1,015 Gg) of the total, in which residential buildings occupied 40.5% (766 Gg) and non-residential buildings occupied 13.2% (249 Gg), as shown in Fig. 2. The quantities of copper stocks in infrastructure, transportation, consumer durables, machinery and equipment were very close at, respectively, 10.2% (192 Gg), 10.1% (191 Gg), 14.2% (268 Gg), and 11.9% (224 Gg). Except for residential and non-residential buildings, the first five subcategories with the most copper in-use stocks were automobiles (8.4%, 159.6 Gg), air conditioners (8.1%, 153.9 Gg), power substations (4.0%, 74.9 Gg), refrigerators (2.7%, 51.3 Gg), and power transmission and distribution cables (2.7%, 50.7 Gg). Moreover, almost 80% of copper in-use stocks sink in these seven subcategories, which should be considered as the most important secondary copper reservoirs above the ground.

For this bottom-up study, data and parameters were drawn from a variety of sources, most of which did not clearly indicate the level of uncertainty. Therefore, we performed a sensitivity analysis to evaluate the influence of each sector on the overall result. We varied each category and subcategory in Table 2 by 20% and measured the effect of such a change on total copper stocks. For most categories, the effect of the change is almost negligible. For the residential buildings sector, a 20% change alters the overall estimate of in-use stocks by 8.1%.

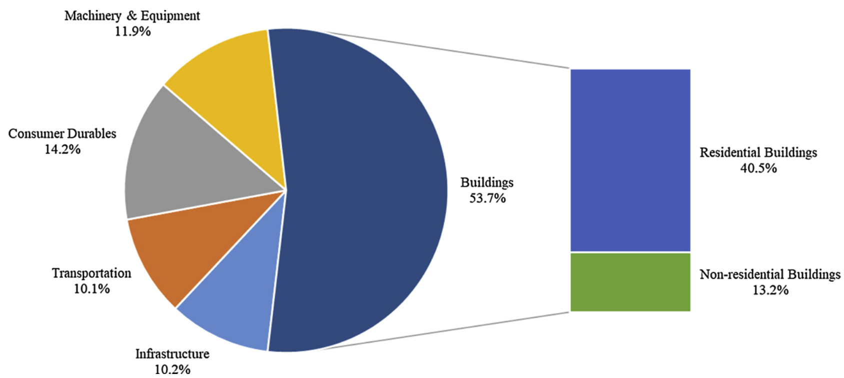

Fig. 2. Composition of copper in-use stocks in Sichuan.

3.2. Copper in-use stocks for 21 sub-regions

At the prefectural level in Sichuan Province, the quantities of copper in-use stocks varied greatly, as shown in Fig. 3. As the capital of and the only megacity in Sichuan, Chengdu (CD) had the biggest population (14.4 million, accounting for 35% of total GDP) and the largest GDP (1005.6 billion CNY, accounting for 18% of total population). Correspondingly, it also had the largest amount of copper in-use stocks (416 Gg), accounting for 22% of the whole province, which were almost 20 times those for Aba (AB, 21 Gg). Including Chengdu, the top five regions took up 46% of the total provincial stocks. On a per capita basis, Chengdu had the highest value of stocks at 28.8 kg/capita, followed by Panzhihua (PZH, 27.1 kg/capita) and Deyang (DY, 25.5 kg/capita). Liangshanzhou (LSZ) had the lowest copper stocks per capita at 17.1 kg/capita.

Compositions of copper stocks in all the sub-regions are shown in Fig. 4. The biggest part across all the regions was always the building section, ranging from 39% (Ganzi, GZ) to 67% (Bazhong, BZ). Two-thirds of the prefectural regions had building proportions ranging from 51% to 64%. For other sectors, infrastructure ranged from 5% (Ziyang, ZY) to 29% (Ganzi, GZ), transport ranged from 5% (Ziyang, ZY) to 19% (Chengdu, CD), machinery and equipment ranged from 5% (Nanchong, NC) to 25% (Panzhihua, PZH), and consumer durables ranged from 9% (Panzhihua, PZH) to 18% (Ziyang, ZY). Among these sub-regions, Chengdu had the highest transportation proportion (19%) for copper stocks. It is also the biggest transportation hub in southwestern China, which had the second largest population of automobiles and highest car ownership among all Chinese cities. Panzhihua (PZH) had the highest proportion of machinery and equipment (25%) for copper stocks; it is a famous industrial region whose secondary industry accounted for 74% of its GDP. Ganzi had the highest proportion of infrastructure (29%) for copper stocks. It is very rich in hydropower, with abundant power generation facilities and numerous transmission substations, but it has the lowest population density, urbanisation rate, and GDP per capita among all prefectural regions.

3.3. Distinction between urban and rural copper in-use stocks

Sichuan's urbanisation rate for 2014 was 46.3% (SPBS, 2014), which is significantly lower than the national average (54.8% (National Bureau of Statistics of China (NBSC, 2015)), and it ranked 25th among all 31 provinces in China. This study distinguishes urban and rural copper stocks in Sichuan and tries to reveal their roles in different economic contexts. Stocks for buildings and consumer durables are especially selected in this study because the two categories were major carriers (68%) for copper stocks. Since Sichuan Statistics Yearbook provides the data of urbanisation rate (Organisation for Economic Co-operation and Development (OECD, 2003), which is interpreted as the proportion of urban population to the total. We take the advantages that the statistics could support both calculation for rural and urban stocks separately, thus, the calculation methods are already illustrated in Sections 2.3.2 and 2.3.4. The result shows that rural copper stocks for buildings (495 Gg) and consumer durables (46 Gg) reached a total of 541 Gg, accounting for 29% of all types of copper stocks. For the building section, rural stocks take up 49%, while rural stocks for consumer durables take up only 17% of the total consumer durables' stock. Based on the resident population, average rural copper stocks per capita for buildings and consumer durables are respectively 11 kg and 1 kg,

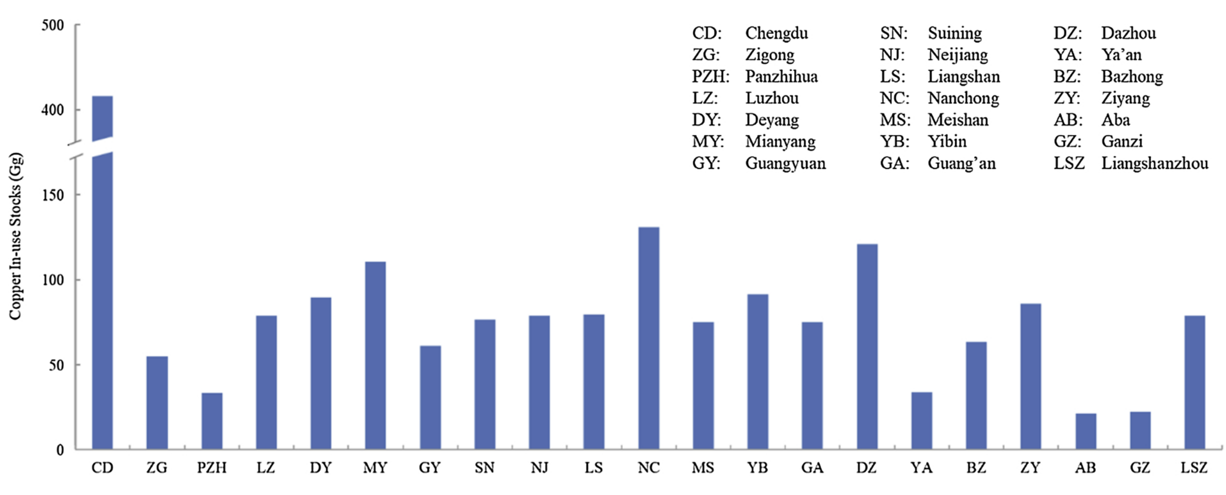

Fig. 3. Amounts of copper in-use stocks in the 21 prefectural regions in Sichuan.

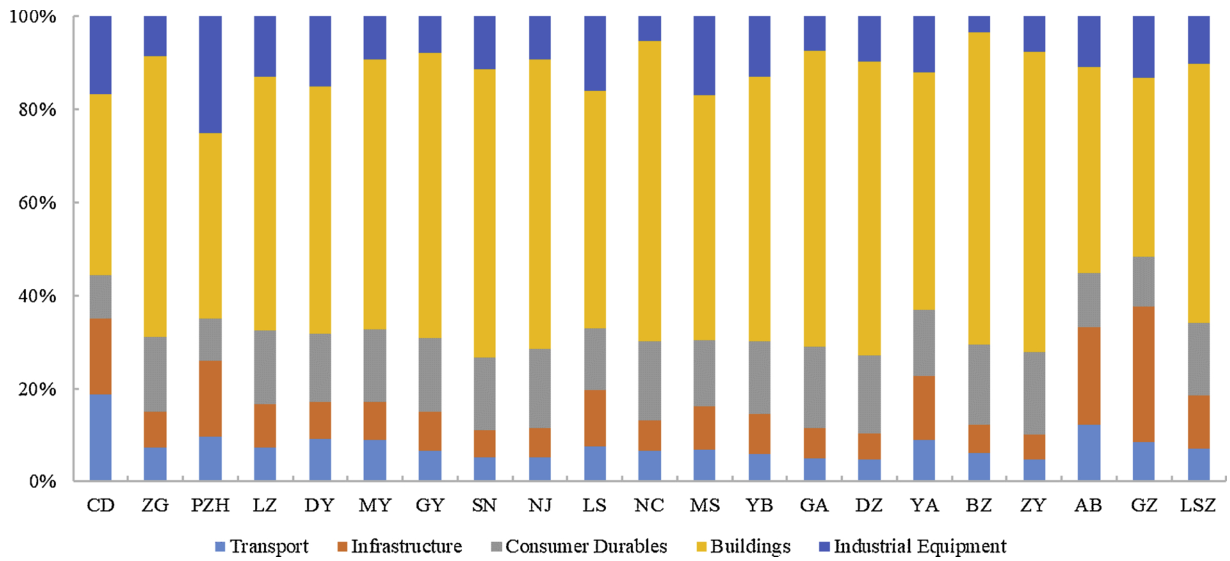

Fig. 4. Composition of copper in-use stocks in Sichuan prefectural regions.

but they are 14 kg and 6 kg in urban regions. These results indicate that Sichuan's rural copper stocks may not only be accumulated in the urban region, they still have indispensable proportions at both provincial level and prefectural level. Urbanization rate in Chengdu is 70.3%, with 137 Gg copper stocks in the urban region and 64 Gg in rural regions. However, comparability urbanisation rate of Dazhou is 39.4% whose copper stocks in the urban and rural regions reached 37 Gg and 39 Gg respectively.

4. Discussion

4.1. Comparison with other regions

The amount and composition of copper in-use stocks are useful to reflect the lifestyle, economic context, and development level in the region (Fishman et al., 2015; Han and Xiang, 2013). Table 3 shows results from other studies for copper in-use stocks in other areas which could be benchmarks when we analyse Sichuan. Copper in-use stocks per capita in China range from 23 kg/capita to 60 kg/capita in different studies, but all of them are much lower than those in developed countries, such as Australia, Japan, Sweden, and the USA. This result reflects the intensive use of copper in developed countries, possibly driven by their matured economy and wealthy lifestyle. For example, steel pipes and even copper pipes are preferred for water distribution in developed countries. In contrast, PCCPs are used commonly in China. In another case, housing area per capita in Sichuan was around 34 m^2 in 2014 (Sichuan Provincial Department of Housing and Urban-Rural Development, 2018), which was much lower than in developed countries such as the USA and Australia.

Table 3
Amount comparison with other regions/countries.

Region	Copper in-use stocks per capita (kg/capita)	Time	Source
Stockholm, Sweden	170	1995	Sörme et al., 2001
US	238	1999	Gordon et al., 2006
Australia	240	2002	van Beers and Graedel, 2007
New Haven, CT, US	144	2005	Gordon et al., 2006
Japan	146	2005	Ichiro Daigo et al., 2009
Shanghai, China	38.4	2012	Zhang et al., 2014
China	36-44	2012	Zhang et al., 2015
China	60	2015	Soulier et al., 2018
Global	50	2010	Glöser et al., 2013
Sichuan, China	23	2014	This study

In addition, Sichuan's copper stocks per capita were also lower than the average level of China in other studies: 36 kg/capita to 44 kg/capita in 2012 (Zhang et al., 2015) and 60 kg/capita in 2015 (Soulier et al., 2018). One reason for this obvious difference is Sichuan's huge low-income population. Sichuan's GDP was 2,853.7 billion CNY in 2014, which ranked 8th among all 31 provinces in China, however, it only ranked 22nd in GDP per capita. In 2014, nearly 6 million people in Sichuan depended on minimum living allowances to survive. Another critical reason for the difference is the systematic divergence between the bottom-up and top-down approaches. The bottom-up method focuses on the main in-use products and cannot consider all copper-containing products, while the top-down method includes all products entering the national boundary and may overestimate the in-use stocks because of the existing hibernating stocks.

Comparisons for each type of copper in-use stocks per capita among Sichuan and other regions are presented in Table 4. The infrastructure section shows a significant difference among global average, Sichuan, Chengdu, and Shanghai. The Fraunhofer Institute (Glöser et al., 2013) estimated the global average in 2010 using a top-down method while others applied bottom-up methods. In this study, the power transmission and distribution system (PTDS, including cables and substations) and the streetlight and signal light facilities (SSLF) are the biggest two copper sinks for Sichuan (PTDS 65%, SSLF 14%) and Chengdu (PTDS 83%, SSLF 8%), while water pipes (WP, 59%) and PTDS (42%) are the biggest two copper sinks for Shanghai (Zhang et al., 2014). The big gap in WP section occurs because Shanghai used copper pipes much more intensively while other regions in China often used PCCPs (Zhang et al., 2014), including Sichuan and Chengdu. Copper stocks per capita in PTDS of Shanghai are also significantly higher than those in the other two cities in terms of absolute values. The obvious higher urbanisation level of Shanghai may be one of the reasons for the difference, as mentioned in Section 2.3.1.1. Moreover, the differences in parameters and calculation methods may systematically influence the relative magnitude among the four regions.

In building section and transportation section, the differences in main variables may cause the gaps in copper stocks considering the methods applied are similar. In building section, per-capita housing area and copper stocks in building section for global average, Sichuan, Chengdu, and Shanghai are both successively lower: global average (57.4 m^2/capita (Rew.ca, 2017)), Sichuan (39.5 m^2/capita (Sichuan

Table 4
Comparison of each type of copper in-use stocks per capita with other regions.

Copper in-use stocks per capita (kg/capita)	Global, 2010 (Glöser et al., 2013)	Sichuan, 2014 (This Study)	Chengdu, 2014 (This Study)	Shanghai, 2012 (Zhang et al., 2014)
Infrastructure	7.5	2.4	4.7	22.3
Buildings	27.5	12.5	11.2	8.8
Transportation	5	2.3	5.4	2.9
Consumer durables	5	3.3	2.7	4.2
Machinery and equipment	5	2.8	4.8	0.2
Total	50	23.2	28.8	38.4

Provincial Bureau of Statistics (SPBS, 2015)), Chengdu (37.9 m^2/capita (Sichuan Provincial Bureau of Statistics (SPBS, 2015)), Shanghai (35.1 m^2/capita (Shanghai Bureau of Statistics (SBS, 2015)). For global average housing area per capita, there are no official data to our best knowledge and other national results can be used as related evidence, such as 43.8 m^2/capita for Germany (Statistisches Bundesamt, 2014), 74.3 m^2/capita for the USA (Moura et al., 2015), and 50 m^2/capita for Italy (Enerdata.eu, 2008). In transportation section, the main copper sink is automobile. In 2014, car ownership and copper stocks in transportation section for Chengdu, global average, Sichuan and Shanghai are also successively lower as well: Chengdu (217 vehicles/thousand capita (Sichuan Provincial Bureau of Statistics (SPBS, 2015)), global average (178 vehicles/thousand capita (The International Organization of Motor Vehicle Manufacturers (OICA, 2019)), Shanghai (105 vehicles/thousand capita (Shanghai Bureau of Statistics (SBS, 2015)), Sichuan (82 vehicles/thousand capita (Sichuan Provincial Bureau of Statistics (SPBS, 2015)). In consumer durables section, the parameters and calculation methods are close and so the differences are possibly due to the gap in overall quantity of products, which is greatly influenced by the level of affluence. In machinery section, the methods are so different that the results may only reflect the development level of secondary industry.

4.2. Spatial structure analysis of copper in-use stocks

Spatial characteristics of Sichuan's prefectural copper in-use stocks are shown in Fig. 5. On a per capita basis, the difference among stocks was smaller, as shown by the similar colour gradation in Fig. 5(a). The largest (CD, 28.8 kg/capita) was only 1.7 times the smallest (LSZ, 17.1 kg/capita). For copper stocks density, that is, copper in-use stocks per sq. km, the province's average amount was 3,890 kg/km^2, while Chengdu reached 34,302 kg/km^2, which was much higher than the second-ranked Deyang (DY, 15,141 kg/km^2) and more than 200 times the lowest-ranked Ganzi (GZ, 149 kg/km^2), as shown in Fig. 5(b). Comparing the coefficient of variation (CV) for these two data sets, the data for copper stocks per capita have a CV of 13%, and data for copper stocks density have a CV of 85%. This result demonstrates the big imbalance among Sichuan's prefectural copper stocks on per sq. km basis.

In-use stocks directly provide services for human society and act as the engine of material cycle. The establishment and renewal of in-use stocks consume resources, while the retirement of in-use stocks generates end-of-life scrap. Sichuan's prefectural regions may generate very different quantities of copper scrap due to the huge difference of stocks distribution. Not only stocks density but also stocks quantity of prefectural regions varied greatly. Data for stocks quantity have a CV of 90%, even bigger than those of stocks density. The big differences in both stocks quantity and stocks density indicate that it is important to select the site for scrap collection and spatial distribution of stocks needs to be considered when doing so. In addition, this study also provides the results on category distribution which may help analyse the quality and accessibility of copper scraps. Both category distribution and spatial distribution of potential copper scraps can provide scientific support for related policies, such as improving the recycling system, promoting the development and utilization of "urban mines", carrying out major demonstration projects for resource recycling (National Development and Reform Commission (NDRC, 2017a), etc.

Taking the Building of Resource Circular Utilization Bases in China as an example, National Development and Reform Commission (NDRC) and Ministry of Housing and Urban and Rural Development (MOHURD) promulgated Instructions on Promoting the Building of Resource Circular Utilization Bases (National Development and Reform Commission (NDRC, 2017b), which commits to promoting the integration of urban infrastructure, the sorting of garbage and the recycling of resources. Fifty resource circular utilization bases have been built across China and four of them are located in Sichuan, that is, in Chengdu, Nanchong, Yibin and Mianyang, as shown by blue dots in Fig. 5. These bases had relatively higher stocks density, but they were not always the biggest carriers of copper in-use stocks, except for Chengdu. Using stocks quantity and stocks density as indicators to discuss the site selection of these bases may provide a helpful and quantitative perspective. According to the Guidelines for Development of Resource Circular Utilization Base Construction Plans (National

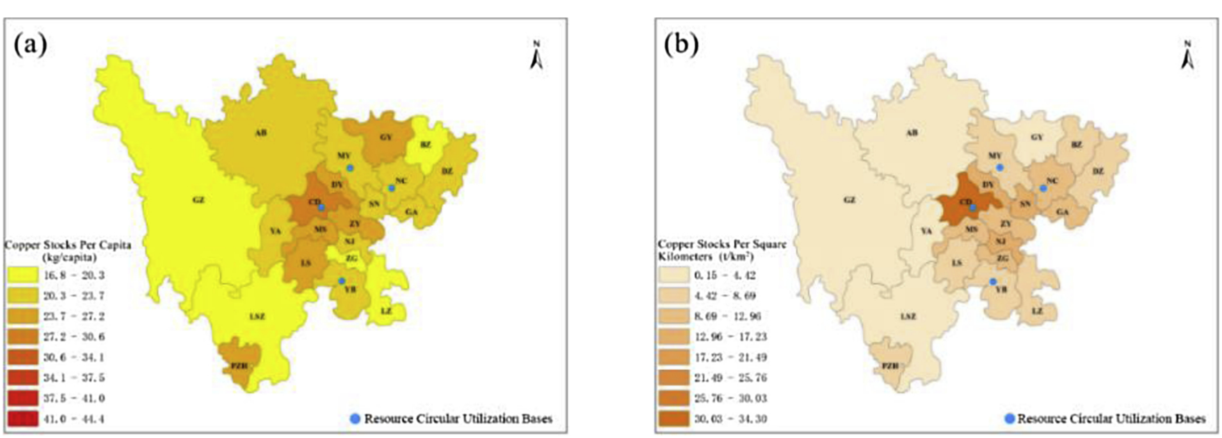

Fig. 5. Spatial structures of Sichuan's prefectural regions: copper in-use stocks per capita (a) and copper in-use stocks per sq. km (b).

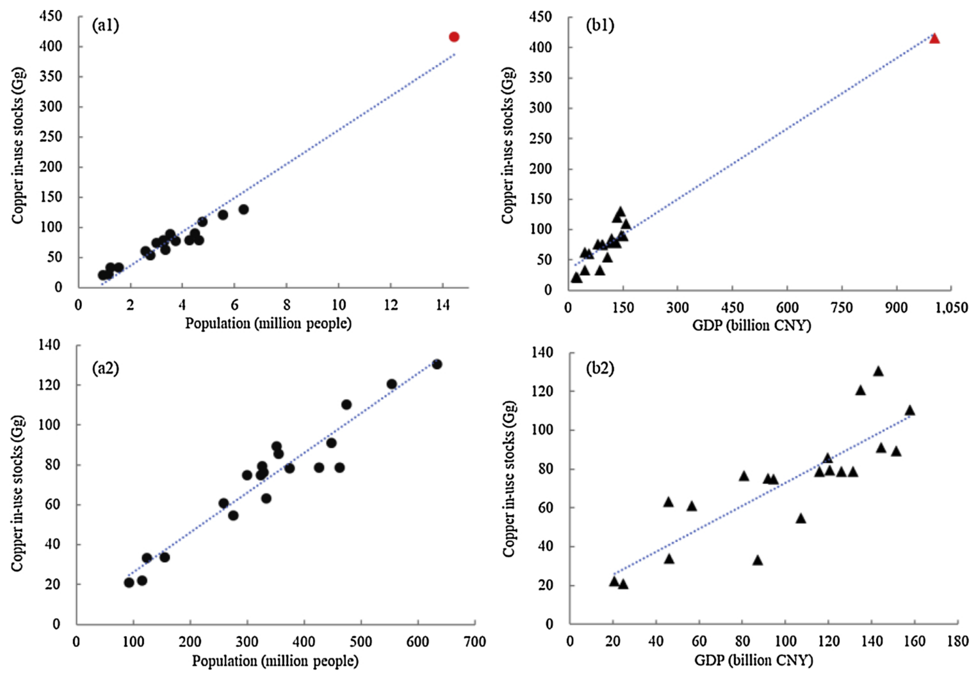

Fig. 6. Linear regression analysis: copper in-use stocks and population (a) and copper in-use stocks density and GDP density (b).

Development and Reform Commission (NDRC, 2018b), the potential generation of scraps, specifically the forecasting amounts in future 3 years, needs to be provided to apply for the construction of the base. Therefore, aggregated stocks result of this study may provide independent references for both local and central government on assessment of the bases. However, more comprehensive assessment and longer time-series statistics need to be studied considering the resource circular utilization bases treat various resources rather than copper only.

Linear regression analysis is used to study the relationship between copper stocks and population as well as between copper stocks and GDP. As shown in Fig. 6(a1) and (b1), Chengdu, represented by red dots, always acts as an outlier. Therefore, data without Chengdu are analysed to remove the impact of the outlier. In Fig. 6(a2), we can observe a strong linear relationship between copper in-use stocks and population. Based on calculation of the R-squared and p-value, the linear relationship is proved. In Fig. 6(b2), a positive correlation can be observed as well, but the regression result is not significant, indicating that there is no direct linear relationship between copper in-use stocks and GDP. This result shows that copper in-use stocks are affected positively both by population and GDP but in different patterns.

5. Conclusions

This study accounts for and characterises the copper in-use stocks in Sichuan Province and its 21 prefectural sub-regions in 2014, from the perspectives of amount, category, and spatial distribution. Our results show that Sichuan had total copper stocks of 1,891 Gg, stock density of 3,890 kg/km^2, and stock per capita of 23 kg/capita in 2014. The amount of stocks per capita in Sichuan was significantly lower than that of developed countries, implying great growth potential. Our results also show an imbalance of copper stocks' distribution across those categories. Almost 80% copper stocks are located in seven categories: residential buildings, non-residential buildings, automobiles, air conditioners, power substations, refrigerators, and power transmission and distribution cables. The result also distinguishes between urban and rural copper stocks in buildings and consumer durables, showing that Sichuan's rural copper stocks may not be as fertilised as in the urban region, but they also cannot be neglected.

At the prefectural level, the magnitudes of copper stocks on per capita basis are close, ranging from 17.1 kg/capita to 28.8 kg/capita. Category distribution patterns are also similar, showing relative consistency in copper use among all 21 prefectural regions. However, the wide range of stocks density, between 149 kg/km^2 and 34,302 kg/km^2, reveals the large imbalance of copper stocks' spatial distribution. The regression analysis indicates that both GDP and population have positive effects on copper stocks density, and the impact from population is more direct.

Above all, this study can provide useful knowledge for the local industry and government, with detailed information on the location and category of copper in-use stocks. Relevant future research can be expanded along two lines: (1) exploring the changing trends and dynamics behind sub-national copper stocks over time; (2) further illustrating the relationship between copper in-use stocks and socio-economic drivers, thus uncovering the inherent connections among material in-use stocks, people's lifestyle, and location of recycling parks.

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