Towards a sustainable and circular metals economy: the case of copper in China
Dong, D.

Author: Dong, D.
Title: Towards a sustainable and circular metals economy: the case of copper in China
Issue Date: 2021-06-16

Chapter 1

Introduction

1.1 Material resource use and challenges

The global economy has developed rapidly in recent decades. From 1970 to 2019, the global population almost doubled, and GDP increased fourfold (World Bank, 2019; Worldometer, 2020). Global economic growth has been supported by the significant increase in the use of materials, which shows that materials use has approximately tripled during this period (OECD, 2019; Schandl et al., 2018). Materials such as fossil energy and metals are used in various fields, including infrastructure, construction, and transportation. Economic growth in these sectors will further increase the use of materials. These materials include the large and growing category of non-metallic minerals and metals in buildings and infrastructure. As reported by the OECD (2019), the global population is projected to reach more than 10 billion people by 2060, an increase of around 35% from 2017 up to that date. During this period, global GDP is again expected to more than triple. The global demand for materials is consequently expected to continue growing over the coming decades. This increased use of materials will allow developing economies to mature, but it will also bring with it a series of negative consequences.

One of the concerns in this scenarios is resource availability. Resource availability is critically important since we need to know whether the available resources will be sufficient to meet the growing demand. Many of the resources used in our society are non-renewable; some of these are abundant (e.g. sand) while some are scarce (e.g. critical metals) (Ioannidou et al., 2020; Müller et al., 2014). Resource availability depends on a range of aspects besides geological scarcity, including geopolitical developments and technology development (Asiedu, 2006; Schneider et al., 2014).

A second issue refers to waste. When materials use increases, this generally leads to more waste, and hence to the need for effective and efficient waste management to achieve sustainable development. Any society with a history of rapid economic growth faces the issue of sustainable waste management, and, given the expected increase in materials use, this issue continues to raise considerable concerns. Waste is increasingly seen as a resource to be mined through reuse, recycling and/or energy recovery (Geng et al., 2019). Previous work by Forti et al. (2020) reported that around 53.6 million tons of waste from electronics and electrical appliances were generated in 2019 worldwide, of which a mere 17.4% was recycled.

Last but not least, the extraction and use of materials cause serious damage to the environment, resulting as they do in greenhouse gas (GHG) emissions and local environmental issues related to toxicity, as well as water shortages (IRP, 2019). These negative environmental impacts occur at any stage in the life cycle of materials, including material extraction, processing, manufacturing, use and/or waste disposal. Many sources mention a decoupling of materials use from associated environmental impacts as a necessity for a sustainable materials management (Crane et al., 2011; Haberl et al., 2020; Kleijn, 2012; Schandl et al., 2016; Van der Voet et al., 2005).

These issues are even more challenging for emerging economies such as China. China accounts for 19% of the global population, but was responsible for approximately 40% of materials use in 2019 (Jiang et al., 2019; OECD, 2019). Since the turn of the century, the strong economic growth in China has driven a powerful development of urbanization and build-up of infrastructure. This in turn has resulted in a massive increase in materials use. From 1995 to 2019, China's materials use more than doubled, while the population grew by 15% and GDP by a factor of 7 (Wang, H. et al., 2019; World Bank, 2019; Worldometer, 2020). In the future, overall materials use is still expected to continue increasing due to the striving for higher living standards in China, although the increase is not expected to be as rapid as in the past 25 years (OECD, 2019). At the present time, the resource related per capita GHG emissions have nearly caught up with the global average. Since China is such a large country, it is now the country with the highest resource-related GHG emissions in the world (IRP, 2019). As the largest world player, China needs to take further steps to move toward a sustainable resources use.

1.2 Transition to a circular economy

The increasing problems related to resource extraction and use have given rise to policy initiatives promoting a transition from a linear economy to a more resource-efficient and circular economy (Figure 1.1). The linear economy normally follows the "take-make-dispose" characteristics established since the Industrial Revolution. In the linear economy, virgin materials specifically for metals are extracted from the lithosphere, smelted, refined and manufactured into various products. These products are used and discarded when they no longer serve their purpose. The linear economy has led to the present global problems related to e.g. resource depletion and GHG emissions as described earlier. By contrast, a circular economy aims to keep products, components and materials in use at their highest utility and value. By sharing or leasing, products can be used more efficiently. Repair, re-use, refurbishing and remanufacturing may increase product life spans substantially. By recycling, materials can be kept in use even after the product's lifespan finally expires. In that way, the services provided by in-use stocks of products in society can be maintained while reducing the input of virgin resources, thus alleviating the negative impacts of increasing materials use (Ellen MacArthur Foundation, 2013).

A report that issued by the Ellen MacArthur Foundation (2013) provided the following definition of the circular economy:

"Circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the End-of-life (EoL) concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models."

The concept of the circular economy is based on principles such as reducing, reusing and recycling. It reconsiders waste as input, aiming to close the loop to reduce the dependence on new materials and decouple economic growth from the extraction of natural resources (Scheel et al., 2020). Many countries are developing in line with the concept of the circular economy, including the EU's *Circular Economy Action Plan* (2015) and the *European Green Deal* (2020), and the Japan's *Basic Act on Establishing a Circular Society* (2000). These policies generally involve several sectors, contain multiple goals including enhancing resource efficiency, and indicate a series of strategies to achieve these goals.

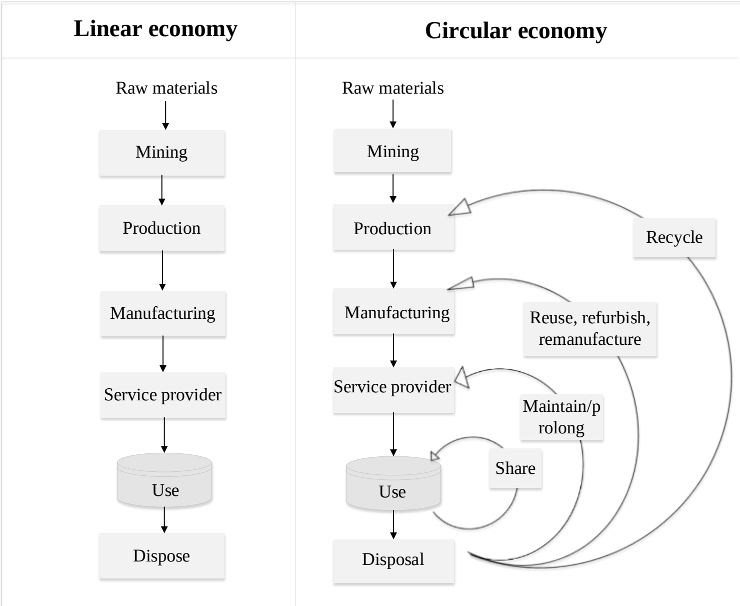

Figure 1.1 Schematic representation of the transition from a linear economy to a circular economy

China is a country that also has advanced circular economy policies (Zhu et al., 2019). The concept of the circular economy was introduced into China at the end of the last century. Since then, China has successively implemented a series of laws and regulations on the circular economy. In order to prioritize the policy initiatives in the field of environmental protection, the *Cleaner Production Promotion Law* was introduced in 2003 and updated in 2012. This law advocates improving resource utilization and reducing pollution at the source. It targets production techniques to reduce losses and emissions of pollutants in production and service sectors to reduce or eliminate health-related human and environmental impacts. From 2003 to 2008, several successful pilot projects on the circular economy were conducted to achieve higher resource efficiency and more economic benefits (Piatkowski et al., 2019; Yu et al., 2018). In 2009, China launched the *Circular Economy Promotion Law* to encourage the implementation of circular economy in industry, through investment, technical support, subsidies and other means. Following this law, China implemented the first national special plan for the development of a circular economy in 2013, *Circular Economy Development Strategy and Short-term Action Plan*. This plan focuses on waste utilization (e.g. recycling, remanufacturing), green buildings, green transportation system and green consumption. Since then, several other regulations and policies have been implemented, including circular economy measures in general regulations such as the *Five Year Plan* and *Work Plan for the Pilot Program of "Zero Waste City" Building*, and policies for specific sectors, such as the *Measures for the Management of End-of-Life Vehicles Recycling*.

Laws and regulations can be put into effect at micro, meso and macro level in China (Fan and Fang, 2020; Park et al., 2010). At the micro level, cleaner production, circular utilization of waste and eco-design are the main focal points. The *Clean Production Promotion Law* requires enterprises to increase the utilization rate of waste and achieve energy conservation and consumption reduction. Specifically, the *Regulations on the Management of the Recycling of Waste Electronic and Electrical Products* (initial version in 2011, updated version in 2019) and the *Implementation Plan of Extended Producer Responsibility System* (2017) pointed out that enterprises that produce electronic products are encouraged to put into practice the implementation of the extended producer responsibility (EPR) system. At the meso level, the priority is to facilitate the development of eco-industrial parks to achieve a goal of waste minimization with maximum resource efficiency through integrating management systems for water, material and energy (Geng and Doberstein, 2008). Finally, at the macro level, the laws and regulations provide an impetus for production and consumption activities to move towards a sustainable and circular economy.

In sum, Chinese circular economy policies aim for a more efficient use of materials, thereby reducing the need for primary resources as well as reducing pressure on the environment. The ideas from the circular economy policy to copper cycle in China will be applied in this thesis since copper is one of the major metals and used in many branches of modern technologies, which has made vital contributions to sustaining and improving society but also been a great concern for negative consequences such as described in section 1.1, particularly in view of declining copper ore grades (Eheliyagoda et al., 2019). Furthermore, the development of a copper cycle has a series of challenges (e.g. huge copper demand, GHG emissions) and opportunities (e.g. improving recycling) that are typical of multiple metals cycles like iron and aluminum. A deep study of Chinese copper cycle on circularity can support its transition and may provide insights into other metals as well.

1.3 The historical development of the copper cycle at global level and in China

Copper is the third most consumed metal in the world after iron and aluminum and has some very useful qualities (USGS, 2021). Its high ductility allows it to be stretched and shaped into complex surfaces without breaking. Thus, products with a wide variety of shapes and sizes can be produced for use in wires. Its good thermal and electrical conductivity enables its use in electric and electrical applications, including power generation, power transmission and personal computers. Its high resistance to corrosion makes it suitable for use in tube for pipelines (ICSG, 2020). Along with copper alloys, such as brass and bronze, copper has also become an indispensable material in construction. In addition, the antibacterial characteristic of copper allows it to play a crucial role in pollution control. In view of these properties, copper has been instrumental for economic growth and well-being in society and will most probably remain so for the foreseeable future.

Copper is mostly extracted from natural mineral deposits. Globally, the geological copper reserves[1] were estimated at 0.87 billion tons in 2019, while the remaining resources of this important and valuable metal were estimated at 5.6 billion tons in 2015, of which around 2.1 and 3.5 billion tons of copper are contained in the identified and undiscovered resources, respectively (USGS, 2017). However, as copper demand continues to rise, more low-quality copper ores are being mined, leading to an overall decrease in ore grades (Crowson, 2012). Global copper production has been increasing over the past 30 years. Copper production consists of primary and secondary production. Primary copper production has led to a considerable transmission from the lithosphere to the anthroposphere. In 2019, global refined copper production reached 24.5 million tons, of which primary copper accounts for almost 80% (USGS, 2021). Huge copper stocks are now residing in infrastructure, buildings and vehicles and will at some point in time emerge as a source of waste for secondary copper production (Kuipers et al., 2018;

[1] The term 'reserves' and 'resources' refer to the definition from the USGS. (https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf)

Watari et al., 2020). However, several studies have shown that the increase in global copper demand is much higher than the growth of secondary copper supply, which indicates that the need for primary copper is increasing (Elshkaki et al., 2016; Schipper et al., 2018). Manufactured copper products can be divided into pure copper and copper alloy products, according to their copper content. Copper alloys are made of copper as the main alloying element and are fused with other auxiliary elements to further improve the function and processing performance of copper to meet different industries and products requirements for different uses and properties. Copper processing efficiency in manufacturing is very high, and its average loss rate is less than 1% (ICA, 2021).

In China, the (primary) copper reserves were estimated at 26 million tons in 2019, while the identified resources were estimated at 114.4 million tons up to 2018 (MNR, 2020). A decline in the average grade of copper ore has also been observed in China, which could be attributed to the high copper demand and improved mining technologies (CNMIA, 2019). China is the world's main producer of refined copper, accounting for about 40% of the global production in 2019. In the past two decades, copper production in China has increased by more than 7 times, with imported copper ores and concentrates accounting for a major part (MNR, 2020). In China, copper semi-finished goods and final products are far more export-oriented than Europe (OECD, 2019). As one of the emerging economies, China has also experienced a substantial growth in copper consumption and since 2002 has been the world's largest consumer of copper. Its share in the global copper demand more than doubled between 2002 and 2019, growing year by year during this period (ICGS, 2021; MNR, 2020). Copper waste generation has been increasing in recent years; however, even though the recycling rate for copper has been increasing and is somewhat higher in China than the global average, around half of the generated waste was still lost.

This trend is expected to continue in coming decade, at global level and in China, which has raised concern regarding the future availability of copper and the associated energy use and environmental pressures (Eheliyagoda et al., 2019; OECD, 2019). The increasing demand for copper indicates that copper production is expected to increase as well, in the form of primary and/or secondary copper. Primary copper supply depends on the aforementioned copper reserves and resources, as well as on copper mining technologies. Future exploration could lead to an increase in copper reserves and resources; innovative technologies may also increase the success in mining complex ores, and reduce environmental impacts. These deposits are likely to provide a part of the future copper supply.

However, energy consumption is normally more intensive in primary production than secondary production. By passing mining and beneficiation processes allows for a much lower energy use for secondary copper production (Hong et al., 2018; Northey et al., 2013). Furthermore, the declining copper ore grade will result in more energy being required for primary production (Ayres et al., 2003; Rötzer and Schmidt, 2020). Energy efficiency considerations therefore point in the direction of increasing the share of secondary copper production. This is particularly important in countries like China, where fossil fuels still account for a large part of the energy sources. This knowledge makes it all the more important that we ourselves realize that primary copper consumed today will be the source of secondary copper to be reused and recycled in due time in the future. With the foreseeable increasing copper demand on the one hand and the need to reduce environmental pollution on the other, it is likely that a combination of primary and secondary copper supply will be required in the future.

1.4 The link between circular economy policies and the copper cycle in China

In this thesis, the transition from a linear economy to a circular economy has been linked to copper in China. Table 1.1 shows China's circular economy measures, and their translation to copper. Recycling is strongly promoted as an effective way to alleviate resource scarcity and mitigate the environmental pressure associated with copper production and use. With regard to the secondary copper produced from EoL products, this consists of waste collection, sorting, dismantling, shredding, separation, secondary smelting and refining processes. The energy use for recycling copper from EoL products mainly depends on its purity and the efficiency of the recycling system, but in general the energy requirement in secondary production could be 85% less than that of primary production (Chen, J. et al., 2019). Most of the policies that propose to encourage and facilitate the construction of waste recycling system, such as the waste classification standard and measures for remanufacturing of vehicle motors, can be translated into terms of improving copper reuse and recycling. Copper recycling in China has improved considerably in recent years. However, due to the long lifetimes of copper products (an average 30 years), most of China's copper products have not entered their retirement period, resulting in a shortage of domestic copper scrap for the development of recycling industry (Wang, J. et al., 2019). Until recently, the imported copper scrap was the main source for secondary copper production in China. The implementation of the "Green Fence" policy in 2013 put a stop to this, leaving domestic scrap as the main source for secondary production. Even with the increasing copper recycling rate in China, only around 25% of the copper demand was met by recycled copper in 2019, while in Europe almost 50% of the copper demand was already being met by recycled copper (Ciacci et al., 2020; Soulier et al., 2018a). This suggests that it is necessary to further improve the recycling system and to consider other strategies.

Some policies listed in Table 1.1 focus on the extraction and processing of non-ferrous metals, aiming to enhance the mining rate, tailings utilization and energy efficiency. From 1992 to 2018, the loss rate of underground mining and open pit mining of copper decreased by 30% and 50% in China, respectively (CNMIA, 2019). Other policies aim to reduce demand by extending the lifetimes of products (e.g. electrical and electronic equipment). Promoting green design in the *Work Plan for the Pilot Program of "Zero-Waste City" Building* is another measure at an early stage of the product life cycle, which could also result in longer lifespans. The same is true of the measures aimed at improving product disassembly and recyclability to obtain more reuse and recycling of the materials at their end of life.

In some cases, policies are not specifically targeted; they are applicable to both primary and secondary copper producers. For example, the *Proposals of the Central Committee of the Communist Party of China on Formulating the Fourteenth Five-Year Plan for National Economic and Social Development and the Long-term Goals for 2035* aims to promote the clean, low-carbon, safe and efficient use of energy. Measures that serve to reduce the use of fossil energy (e.g. hard coal in electricity production) may indirectly cut down the environmental impacts of both primary and secondary copper production.

Table 1.1 Circular economy policies and implications for copper in China

Policy title	Content	Implications for copper	Year
Cleaner Production Promotion Law	• Conserve resources, reduce energy consumption and the emissions of key pollutants. • Adopt reasonable exploration and mining techniques for mineral to protect the environment, prevent pollution, and improve the level of resource utilization.	• Improvement of energy efficiency in copper production • Improvement of copper mining rate	2003, 2012
Circular Economy Promotion Law	• Non-ferrous metal enterprises will replace fuel oil with clean energy such as clean coal, petroleum coke, and natural gas. • Encourage and promote the construction of waste recycling systems, e.g. waste collection and utilization facilities. • Support the remanufacturing of parts from EoL vehicle (ELV) and engineering machinery.	• Reduction of fuel oil use in copper production • Increase of copper recycling rate • Increase of copper reuse from ELVs	2009
Circular Economy Development Strategy and Short-term Action Plan	• Accelerate the development of pressure leaching, bio-metallurgy and other technologies, processes and equipment for copper, aluminum and other minerals. • Promote the high-value utilization of recycled metals such as secondary copper and aluminum. • Reduce the comprehensive energy consumption in non-ferrous metal production. • Improve waste classification, collection, transportation and recovery. By 2015, the recycling rate of main categories including waste from metal, plastic, paper, vehicles, WEEE will reach 70%.	• Increased share of hydrometallurgical copper production • Increased share of secondary copper in copper use • Improvement of energy efficiency in copper production • Increase of copper reuse and recycling from ELVs, WEEE and engineering machinery	2013

Policy title	Content	Implications for copper	Year
	• Establish reverse logistics for recycling systems and construct remanufacturing industries.		
“Made in China 2025” strategy	• The comprehensive utilization rate of industrial solid waste will reach 73% and 79% by 2020 and 2025, respectively.	• Increase of copper recycling rate of industrial solid waste	2015
Work Plan for the Pilot Program of “Zero-Waste City” Building	• Guided by the green lifestyle, promote the reduction of domestic waste. Support the development of a sharing economy and reduce the wasting of resources. • Reduce generation and improve utilization of construction and demolition waste. • Focus on electrical and electronic products, implement the EPR system. • Promote green design to improve product disassembly and recyclability.	• Reduction of copper waste generation from buildings, infrastructure and WEEE • Increase the copper recycling rate • Increase copper reuse • Reduce of energy use in copper recycling	2018
China’s Energy Development in the New Era	• Accelerate the increase in the proportion of non-fossil energy in energy supply.	• Improvement of renewable energy use in copper production and electricity production	2020
Measures for the Management of End-of-Life Vehicle Recycling	• Dismantled ELV engines, steering gears, transmissions, front and rear axles, and frames (also named “Five Assembly”) that are eligible for remanufacturing can be sold to companies with remanufacturing capabilities in accordance with relevant state regulations and reused after remanufacturing. Dismantled parts (other than the “Five Assembly” of ELV) meeting the compulsory national standards and eligible for reuse can be sold as “Reused ELV Assembly”.	• Increase in copper reuse and recycling from ELVs	2019

Policy title	**Content**	**Implications for copper**	**Year**
Catalogue for Administration of Import of Solid Wastes	• Restriction or ban of imported solid wastes.	• Reduction of imported copper waste	2018
Implementation Scheme of Municipal Solid Waste (MSW) Classification System	• By the end of 2020, laws, regulations and standards relating to waste classification shall be established in basic form. In cities implementing compulsory classification of waste the recycling rate shall exceed 35%.	• Increase of copper recycling from MSW	2017
Provisions on the Standards for Compulsory Retirement of Motor Vehicles	• The standard prescribes the compulsory retirement of motor vehicles meeting the standards for being discarded. • The standard specifies the maximum service life and mileage of motor vehicles.	• Lifetimes of copper-containing products (vehicles)	2013
Discarded Household Appliance and Electronic Product Pollution Control Technology Policy	• Establish a relatively complete recycling system for WEEE, adopt schemes conducive to recycling and reuse, and gradually increase the recycling and reuse rate. • Encourage use of modular design, lifetime convergence of components and parts, easy maintenance, easy upgrade design, etc., in order to extend product service life. • Encourage use of fewer different and more readily recyclable materials, use internationally accepted standards to mark parts (materials), adopt designs and processes that facilitate dismantling of waste products and improve recycling rate.	• Increase of copper reuse and recycling from WEEE • Lifetimes of copper-containing products	2006

1.5 Methods for analyzing the copper cycle and associated environmental impacts

Increased demand has led to an accumulation of considerable stocks of materials in the anthroposphere, and the recycling of materials from these waste streams has become more and more important (Müller et al., 2014). To analyze the activities that can help to realize a more circular use of copper, such as waste collection and mechanical processing, knowledge of material cycles with respect to geographic location, accumulated quantities, material content in products, energy requirement is needed. Analytical tools, such as material flow analysis (MFA) and life cycle assessment (LCA), are useful to quantify and evaluate these activities and the associated environmental performance, and therefore to provide potential policy measures and decisions on circular economy. Below we introduce these methods and how they can be combined to support the analysis of the potential for a circular use of copper in China.

1.5.1 Material flow analysis

MFA is a method for the quantitative analysis and evaluation of the input and output of materials in a system based on the main principle of mass balance (Brunner and Rechberger, 2003). The applications of this method in the field of sustainability and the circular economy have increased significantly in recent years, which provides a comprehensive and systematic account of a defined physical system to support decision makers (Eriksen et al., 2020; Geng and Doberstein, 2008; Virtanen et al., 2019). This approach evaluates different systems in terms of the system spatial scale (e.g. regional economy, national economy, eco-industrial park), materials (goods or substances), system temporal scale (e.g. static or dynamic) and inclusion of processes (e.g. the whole life cycle or a specific process).

Significant research has been conducted on metals cycles in the anthroposphere based on a MFA approach. Chen and Graedel (2012) reviewed the anthropogenic cycles of 59 elements at different scale levels, including the major engineering metals iron, aluminum, copper and lead. Specifically for copper, some research constructed a comprehensive technological copper cycle treating a series of life stages (e.g. mining and processing, manufacturing, use, and waste management) at different spatial and time levels (Bertram et al., 2003; Guo and Song, 2008; Spatari et al., 2002). With the development of emerging technologies, the MFAs of other metals, such as lithium and rare earth elements, were also investigated (Geng et al., 2021; Sun et al., 2017). Most of these MFAs refer to a "snapshot" of flows at a specific point in time. This provides some insight in the metabolisms of these metals but does not address the dynamics of resource use and resulting changes over time in stocks and flows. Estimations of past and future flows can be used to assess the influence of drivers for resource use and related environmental problems, and they can support investment planning in infrastructures for mining, production, and waste management (Müller, 2006). The methodology of dynamic MFA was developed by Baccini and Bader (1996), afterwards Baccini and Bader (1996) and Melo (1999) constructed a copper cycle system in the United States and an aluminum cycle system in Germany, respectively. Since then, a number of dynamic MFAs on retrospective and prospective analysis of metals have been established, which provide information on reservoir stocks and on the evolution of stocks and flows over time (Elshkaki and Graedel, 2013; Elshkaki et al., 2005; Eriksen et al., 2020; Glöser et al., 2013; Yan et al., 2013; Yoshimura and Matsuno, 2018).

1.5.2 Life cycle assessment

LCA is an analytical tool specifically designed to assess the environmental impacts relating to the whole life cycle of production of a material, including processes of virgin ore extraction, refining, manufacturing, use and waste management for metal, for example (Guinée, 2002; Tukker, 2000). The ISO framework of LCA provided a definition for LCA as "*The collection and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*" (ISO, 2006a, b). The European Commission's Integrated Product Policy Communication even identified LCA as the best framework for assessing the potential environmental impacts of products (European Commission, 2003). Although the ISO standard defines LCA and provides a general framework for conducting an assessment, it leaves much to interpretation by the practitioner. As a result, LCA studies have been criticized for producing different results for seemingly the same product, which can be attributed to methodological choices such as the inclusion of processes, the use of different databases, the use of different allocation methods, and the use of different impact categories. Nevertheless, when applied transparently it can provide very relevant information about a product or material over its life cycle.

LCA has been used to assess the environmental performance of metals, both for primary and secondary production (Farjana et al., 2019b; Tan and Khoo, 2005; Zamagni et al., 2013). The environmental impacts per unit (e.g. kilogram) metal production, such as steel, copper and aluminum, have been assessed by several scholars (Davidson et al., 2016; Hong et al., 2010). Tan and Khoo (2005) and Nunez and Jones (2016) studied the environmental impacts of primary aluminum production in a cradle-to-gate analysis. Others specified environmental impacts of secondary metal production (Chen, Y. et al., 2019; Mercante et al., 2011; Song et al., 2013). In several of these publications, a contribution analysis was added to identify hotpots in the production chain (Khoo et al., 2017; Weng et al., 2016). From such studies, it appears that closing the cycle will be highly beneficial, not only from the perspective of resource conservation, but also from an environmental point of view (Kuipers et al., 2018; Van der Voet et al., 2018).

1.5.3 Integration of MFA and LCA

The integration of MFA and LCA is advantageous and has been used in many studies, especially for complex systems that consist of multiple products and services. As stated by Brunner and Rechberger (2003), it is necessary to include environmental impact assessment in MFA. Using integrated combined LCA and MFA method, a more synergetic analysis of the system and its material flows can be provided. This is also relevant for the assessment of circularity options.

Combining MFA and LCA has been applied on waste management systems in a fair number of studies, focusing on materials and environmental impacts (Nakem et al., 2016; Padeyanda et al., 2016). This combination has particularly been used to study WEEE, estimating the environmental impacts of collection, mechanical processing and recovery processes, and identifying the potential strategies to optimize waste treatment (Assefa et al., 2005; Kiddee et al., 2013; Wäger et al., 2011). Some studies, such as Venkatesh et al. (2009), Rincón et al. (2013) and Rochat et al. (2013), have evaluated material requirements in systems such as infrastructure, construction and educational services, and at the same time assessed energy use or GHG emissions. A few studies analyzed the environmental impacts of metal recycling, with emphasis on GHG emissions, to support for shifting toward circular development (Farjana and Li, 2021; Sevigné-Itoiz et al., 2014). Even though many studies have been conducted with this approach in recent years, several challenges including system boundaries and allocation principles still need to be overcome.

1.6 Research aims and questions

Taking into account that most modern technologies rely on copper, it is of crucial importance to secure future supply by closing copper cycles, thereby also reducing environmental pressure. The motivation behind this research is to understand how the concept of the circular economy can be used to foster the sustainable development of the copper cycle in China. The aim of this research is therefore to explore *how the copper cycle in China can be transformed into a sustainable and circular economy*. This overall aim will be supported by answering the following research questions:

1. How are copper demand, in-use stocks and waste generation expected to develop under the current Chinese policies related to general economic development, the energy transition and ambitions with regard to circular economy? (Chapter 2)
2. How could China meet its future copper demand in the context of moving towards a circular economy, and how may this be affected by the import restrictions of copper scrap? (Chapter 3)
3. What are environmental benefits and drawbacks related to present and future copper production in China, and how could the environmental performance be improved in the future? (Chapters 4 and 5)
4. What is the potential to close the copper cycle in China? (Chapters 2, 3 and 5)

1.7 Thesis outline

The thesis consists of 6 chapters (see Figure 1.2).

Chapter 1 starts with the resources use and challenges on resources availability, waste generation and management and environmental impacts of resources production, and the need for resource efficiency and the transition to a circular economy. The Chinese circular economy policies are presented, and the idea of the transition is introduced to copper cycle, firstly describing the historical development of the copper cycle at global level and in China, and then linking the Chinese circular economy policies to the copper cycle. This chapter also presents the methods used in this thesis for analyzing the copper cycle, together with the research questions and the organization of the thesis.

Chapter 2 develops a dynamic stock model and business-as-usual scenario 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 per capita and total copper demand are both set to increase substantially, especially in infrastructure, transportation and buildings. It will not be possible to close the copper cycle, even if all copper waste is recycled, in the period up to 2050.

Chapter 3 explores a circular economy scenario of copper demand from 2005 to 2100 in China based on a dynamic stock model, and compares this scenario to the business-as-usual scenario as in Chapter 2. This Chapter also assesses the influence of the “Green Fence” policy restricting the import of copper scrap. Based on the analysis, the additional measures to achieve a circular economy beyond the current Chinese policies could be to prolong the lifetimes of copper products and increase the processing efficiency of copper production. In combination with these measures and the establishment of a state-of-the-art and efficient copper recycling industry, secondary copper could satisfy the bulk of Chinese copper demand, which could be an opportunity for Chinese copper cycle to transition to a more circular economy.

Chapter 4 assesses the environmental impacts of copper production from 2010 to 2050 in China using a LCA approach. The technology routes of copper production considered in this chapter are pyrometallurgical, hydrometallurgical and secondary production. Several variables are considered to model future changes in the foreground and background systems of copper production, including declining copper ore grade, energy efficiency improvements of production processes and a changing background system as a result of the ongoing energy transition. Moreover, potential options are identified for improving the environmental performance of Chinese copper production.

Chapter 5 continues to investigate how to minimize the copper losses and environmental impacts of copper production in the future by designing an optimum copper waste management system based on various "Zero waste" strategies including waste prevention, reuse (repair, remanufacturing or refurbishment) and recycling. Copper waste streams are divided into six types in this chapter, including 5 types of domestic waste streams and an imported waste stream. These "Zero waste" strategies as well as the transition from informal recycling to formal recycling are considered as possible models of the waste management system. The environmental benefits and drawbacks of such an optimized waste management system for the copper cycle are also discussed.

In Chapter 6, all results are combined to present the answers to the research questions. Discussion and recommendations are provided for future research based on the findings of Chapters 2 through 5.

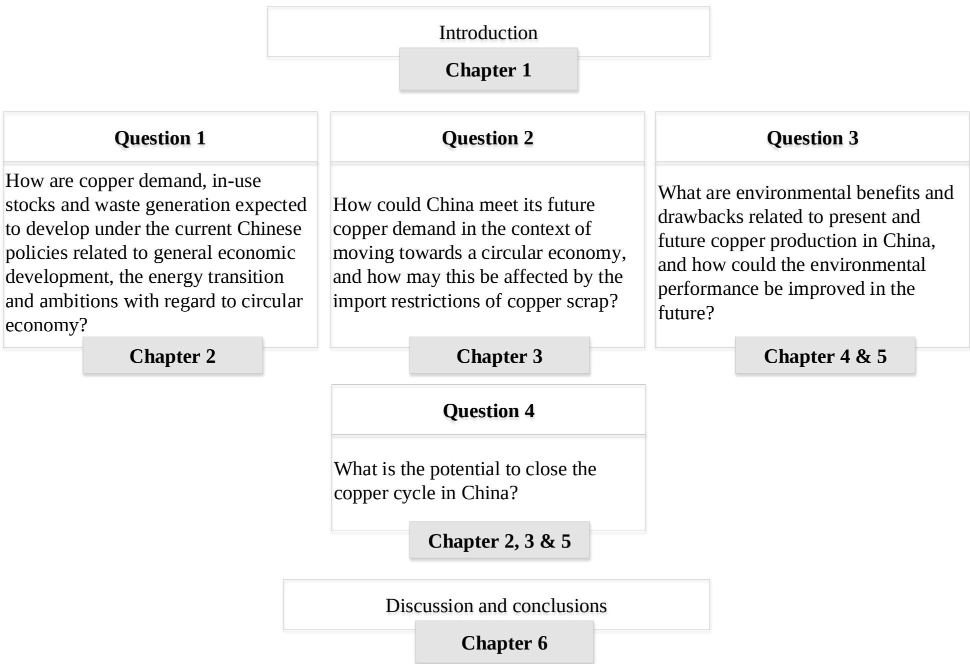

Figure 1.2 Conceptual scheme of the thesis