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Chapter 6

Conclusions and General Discussion

The aim of this thesis was to explore how the copper cycle in China could develop into a sustainable and circular system. The main focus was on quantifying in-use stocks, the demand for and supply of copper, and associated environmental impacts in several scenarios for the future. The results of this thesis can be used to identify possible measures and policy options in response to future environmental and supply challenges.

This thesis starts in Chapter 2 by investigating a business-as-usual scenario (Chinese Policy or CP scenario) of the in-use stocks, and the demand for and waste generation of copper in China using dynamic Material Flow Analysis. To explore how to transition to a more sustainable development of copper, as well as the effect of the "Green Fence" policy on copper supply, a circular economy scenario (CE scenario) has been designed to compare with the CP scenario in Chapter 3. This CE scenario includes several strategies such as extending lifetimes of copper products and increasing the recycling rate of EoL products. In Chapter 4, a Prospective Life Cycle Assessment was used to analyze the environmental performance of future copper production, where the effects of the energy transition on both copper use and the environmental impacts of copper production were considered. From these combined efforts, potential options for improving the environmental performance of Chinese copper production were identified. As a final step in Chapter 5, a combination of MFA and LCA was used to identify an optimized copper waste management system, where the utilization of copper waste is maximized with minimum environmental impacts. Finally, the influence of such an optimized system on the copper cycle in China was assessed. This concluding chapter will first answer the research questions proposed in the introduction, and then discussion and make recommendations for future research.

6.1 Answer to research questions

6.1.1 Question 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 the circular economy?

Chapter 2 reports a dynamic MFA involving a bottom-up approach to quantify in-use stocks, as well as the demand for and waste generation of copper under the current Chinese policies. The results show that in-use stocks for copper in China are expected to increase significantly and reach about 400 million tons in 2050, however, with different growth rates for different copper applications. The copper stocks in infrastructure and transportation will not yet have reached saturation by 2050, while the copper stocks in buildings will likely be stabilized. The copper stock in buildings was the largest at present. In 2050, that place is expected to be taken by infrastructure, mainly the electricity grid. Buildings will then be second in size. By sub-categories, the copper stocks in the electricity infrastructure, new energy vehicles, and home appliances (including air conditioners and refrigerators) are likely to increase considerably up to 2050. As a result, the copper stock per capita is expected to increase about 10 times in the 2005 - 2050 period.

The total copper demand as well as the demand per capita also increase significantly during this period, especially in infrastructure, transportation and buildings. In 2050, under the scenario specifications made, demand will have increased by a factor of 3 compared to 2015. The main end-use sector is infrastructure, accounting for around 50% of the total copper demand by 2050, followed by transportation, buildings, and different types of durable goods.

With the increasing consumption of diverse copper-containing products, in-use stocks for copper have become a large reservoir that can be considered as an urban mine, a source of materials for the future. Domestic waste generation has been increasing in recent years, however, and most of China's copper products have not yet entered the waste stage at present. Given the 30-year overall average lifetime of copper products, the amount of copper that is now entering the waste stage is still very small, and the growth of EoL copper recycling therefore very slow. The findings of this thesis suggest that only a small part of the copper demand in 2050 under the current Chinese policies can be met through the supply of secondary copper.

6.1.2 Question 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?

In order to understand how to develop the copper cycle sustainably in China, a circular economy scenario was defined that assumed longer lifetimes of copper-containing products and a higher EoL copper recycling rate on top of the business-as-usual assumptions. This scenario has been used to explore how China's copper demand can be met up to 2100. It has also been used to assess the impact of the Chinese government proposals to restrict the import of copper scrap on the future Chinese copper supply. The results are presented in Chapter 3.

The findings made clear that the Chinese copper cycle could reduce its primary input significantly under the circular economy scenario. Extending the lifetimes of copper-containing products may lead to a decrease in the overall copper demand in the second half of the century, while maintaining the functionality of the in-use stocks. Regarding copper supply, the imported copper scrap was the principal source for secondary copper production in China before implementing the "Green Fence" policy. The scrap import restriction or ban will reduce secondary copper production significantly. Domestic copper scrap will become the main source of secondary production in the future; however, even with an increasing availability of domestic scrap and an assumed high copper recycling rate, the share of secondary copper supply can only increase to 60% in 2100.

There will be a substantial gap between Chinese copper demand and the amount of scrap available domestically throughout the 21^{st} century. In the future, this gap needs to be closed either by domestic mining of primary copper, or through imports of concentrates and refined copper. Meanwhile, China will still have to put major emphasis on its recycling industry to reach the high recycling rates assumed in the CE scenario. If China wants to further reduce primary production, an important suggestion is that they should continue to import copper scrap. Another reason for this proposal is that importing high-quality copper scrap instead of copper ore or refined copper is an environmentally beneficial option. In combination with the establishment of a state-of-the-art, efficient and environmentally friendly recycling industry, this could be an opportunity for China to transition to a more circular economy with regard to copper.

6.1.3 Question 3- What are the environmental benefits and drawbacks related to present and future copper production in China, and how could the environmental performance be improved in the future?

Copper production consumes a lot of energy and releases harmful emissions along its life cycle. To understand the environmental benefits and drawbacks related to future copper production in China, a prospective LCA approach was used and up-scaled with several prospective changes related to copper production.

In Chapter 4, the future environmental impacts of pyrometallurgical, hydrometallurgical and secondary copper production in China were assessed with the prospective changes of declining copper ore grade, energy efficiency improvement of production processes and the transition of the electricity supply towards a renewable system (named as the Below 2 degree, B2D scenario), and compared with the business-as-usual scenario. The main finding was that the environmental impacts of the production of 1 kg copper in the B2D scenario are considerably lower than that of the business-as-usual scenario. However, the energy transition by shifting from fossil fuels to renewable energy in the B2D scenario will increase copper demand by more than 10% compared to the business-as-usual scenario. As a result, the total environmental impacts of copper production in the B2D scenario are no lower than that of the business-as-usual scenario.

The results also support the idea that the environmental impacts of production of 1 kg secondary copper are much lower than those of primary copper. Pyrometallurgical and hydrometallurgical production are both highly energy-intensive. Pyrometallurgical copper production is the largest contributor to the environmental impacts of copper production, and this is not expected to change until 2050.

To further explore options to reduce the environmental impacts of copper production, China's copper waste management system was assessed in some detail. The aim of Chapter 5 was to optimize this waste management system by applying more circular economy and "Zero waste" strategies. Optimization in this context means: to produce as much secondary copper as possible, with as little environmental impacts as possible. The waste streams were divided into six types, including C&DW, ELV, WEEE, MSW, IEW and ICW. The circular economy strategies consist of waste prevention, reuse (including repair, remanufacturing or refurbishment), and the recycling of copper-containing products, as well as the transition from informal recycling to formal recycling.

Combining with the environmental impacts of primary copper production in Chapter 4, the main conclusion was that under the present Chinese policies, the reuse and recycling of copper-containing products will lead to somewhat lower GHG emissions and lower energy demand for total copper production. Maximizing such circular economy strategies may lead to a further reduction, but can also be counter-productive if applied too stringently. GHG emissions related to secondary copper production may become greater than those of primary copper production despite lower per kg GHG emissions of secondary production, depending on the copper content of those waste streams and the need for transport. The environmental impacts of secondary copper produced from the different types of waste (C&DW, ELV, WEEE, IEW, MSW, ICW) are different, attributable mostly due to the differences in impacts by mechanical processing and collection & transportation.

The findings and discussion on the options to improve the environmental performance of copper production in Chapters 4 and 5 suggest that increasing the share of secondary copper production is the most environmentally friendly option. To this end, the copper waste management system needs be improved, which requires actions across the full product lifecycle, including waste prevention and circular economy strategies to the EoL products as well as early-stage product design. An optimized copper waste management system is expected to reduce pressures associated not only with copper ore extraction and refinery, but also with copper waste disposal. Such an expansion from waste management to life cycle management may be the best way to reduce the environmental impacts of copper production in China.

6.1.4 Question 4- What is the potential to close the copper cycle in China?

Since increasing the supply of secondary copper is a crucial way to alleviate both resource supply constraints and environmental pressure, it is important to understand the potential to close the copper cycle in China. There are many aspects that have to be considered in this context. The chapters in this thesis all provide pieces of that puzzle.

The overall conclusion is that neither at present nor in the future will copper scrap be a sufficient source of copper. Secondary copper production will not be able to meet copper demand under the current Chinese policies in China, even assuming high recycling rates. A large amount of primary copper supply will be still needed. However, with several more circular economy strategies including extending the lifetimes of copper-containing products, the increasing copper recycling rate, increasing copper reuse and the transition from informal to formal recycling, the share of secondary copper supply could increase to 80% in 2100. Accordingly, this could mitigate some of the pressures associated with copper ore extracting and processing, and achieve the dematerialization of the copper cycle in China.

However, to completely close the Chinese copper cycle is challenging. Several barriers, such as the establishment of adequate recycling technologies as well as recycling infrastructure, need to be overcome. Moreover, there are constraints in the availability of secondary resources, and environmental trade-offs may be expected on the path towards a circular economy at global level. Finally yet importantly, stock dynamics imply that secondary supply can catch up only if demand levels off. This could occur with more circular measures in the CE scenario in 2100 since the in-use stocks for copper will likely stabilize at that time; meanwhile, the copper demand is expected to decline.

6.1.5 Overall research question: how can the copper cycle in China be transformed into a circular and sustainable economy?

By and large, this thesis revealed four major prerequisites that need to be fulfilled to establish a circular and sustainable economy for copper cycle in China.

(1) circular design of copper-containing products,

(2) increased reuse or recycling, particularly formal reuse or recycling,

(3) a transition of the energy system towards renewable sources,

(4) a saturation of the in-use stocks.

Early-stage design is key to the principles of circular economy, aiming at keeping the products in use as long as possible. By designing products that use less raw materials, and products that can be easily shared, repaired, remanufactured, refurbished or recycled, the lifetimes of the copper-containing products can be lengthened, resulting in a lower copper demand.

Reuse can reduce the volumes of copper waste requiring treatment and often is more environmentally friendly since no new materials have to be produced. From that point of view, policies to support the organization of reuse (second-hand markets, remanufacturing plant) centers and networks, are an essential part of a successful implementation of the circular economy. Recycling however remains an essential part of a circular economy as all products at some point will end up as waste. To increasing the copper recycling rate, enhancing the collection rate is probably the most important strategy. Therefore, a waste management system needs to be constructed as a socio-technical system, including people's decision-making on how they handle waste, which probably requires a transformation of our consumer culture.

Renewable energy systems play an essential role in shifting towards a sustainable society in general and copper cycle in particular. The emissions related to copper production are for a large part related to the energy use of those processes. A fossil free energy system therefore reduces emissions of copper production considerably.

The analysis of copper stocks and flows in this thesis shows that the Chinese copper cycle is still far from closed. Even when copper reuse and recycling are assumed to improve significantly, closing copper loops cannot be achieved. This is mostly due to the expectation that copper stocks still grow by 2050. As a result, the demand will still be larger than the supply of secondary copper. An essential requirement for closing cycles is therefore a saturation of the in-use stocks. Secondary supply could then catch up with demand. Primary copper extraction could then be reduced, leading to lower environmental impacts of copper production and a more sustainable copper cycle in China.

6.2 Discussion and recommendations

In this thesis, the in-use stocks, demand and supply of copper in China and the associated environmental impacts are explored using dynamic MFA and prospective LCA. This provides insights that are relevant for identifying options to move toward a sustainable and circular economy of the Chinese copper cycle. This systems analysis is valuable, but has a rather limited scope. Many relevant aspects related to economy, policy and society have not been taken into account. Below, a critical step back is taken to identify limitations and potential bottlenecks that need to be the focus of further research in this field.

Uncertainty is a common challenge to any long-term scenario research. The forward-looking study of copper cycle in terms of resource use and environmental performance in this thesis does not aim for predicting precise future, but for explorations of potential patterns and trends that assumed based on multiple parameters. Such an analysis may cause a degree of uncertainty due to data availability and quality as well as the methods used for research, however, it could provide guidance for long-term critical assessment.

High-quality data from reliable sources are essential for convincing results. For the Chinese copper cycle, the main uncertainty of data for copper production concerns the statistic accuracy of data that the copper companies and regional government provide. The data regarding to primary copper production and energy use is well-established on the whole, while the data about copper recycling and reuse still needs to be greatly improved. In other words, the copper cycle is an illustration of the need to improve and develop more reliable and robust data on waste streams in China. In addition, a bottom-up dynamic MFA stock model was used in this thesis. In this approach, in-use stocks of products are the starting point. Each of these products has a life span, and for each of these products different driving forces determine its behavior over time. Inflows (demand) and outflows (discarded products) are calculated from stock dynamics. These stocks and flows of products are translated into stocks and flows of copper using information of the copper content of each product. This is a data intensive exercise, since these copper-containing products may have different growth trends, requiring specific stocks models. Data collection needs to be done for each separate product.

This is not only an elaborate process, but also fraught with difficulty: missing data, uncertain data, indirectly estimated data and suchlike. The fact that in MFA mass balances have to be closed can help to fill in data gaps and force to assess a best fit if data sets are used that lead to an unbalanced total. The result of this process is often highly uncertain, for instance due to estimate of in-use lifetimes of products, that may deviate in practice significantly from estimates made now. An alternative would be a top-down approach of MFA that projects material flows based on some drivers such as population and GDP (Schiller et al., 2017; Schipper et al., 2018). However, this approach does not capture essential system characteristics related to stock dynamics and especially stock saturation that net additions to stocks stop growing. Material demand estimated based on the two approaches can be expected to be similar in a short period of growth, such as the comparison results by Schipper et al. (2018). On the longer run, we expect stock saturation, which is an essential step in the realization of a circular economy. This process is completely missed by a top-down approach. Despite difficulties and uncertainties, a preference for the bottom-up approach can be indicated.

The copper content of products is an important factor in determining copper stocks. Copper contents of products and appliances have changed in the past and will change in the future. However, in our scenarios, we have kept material contents constant except for a rough estimation of its changes in buildings. A sensitivity analysis assessing the influence of changes in copper content shows the effect of its change on total copper demand. It merely seems to lead to rather straightforward relatively modest changes. In some cases, copper is substituted altogether by different materials, leading to a reduced demand. Around 0.24 million metric tons of copper have been substituted with different other materials globally in 2016, in power cables, winding wires, copper tubes, and telecom cables (ICA, 2016). This indicates that such substitution does indeed take place, with consequences for the amount of present copper stocks and future available copper waste. Aluminum is considered to have the greatest potential for replacing copper in energy infrastructure, other materials such as stainless steel, zinc and PVC (e.g. building water supply system) may be used as substitutes in other products (Månberger and Stenqvist, 2018; Xiong et al., 2020). On the other hand, copper is substituting other materials: for example, silver is substituted with copper in photovoltaic power plants (García-Olivares, 2015). Another relevant effect of copper substitution is the environmental impacts related to the production of the substitutes. Several studies have investigated the environmental impacts of aluminum, steel and zinc production, which shows that primary aluminum has higher energy requirements and corresponding CO_2 emissions per kg production than copper while the impacts of primary steel and zinc are lower than that of copper (Van der Voet et al., 2018; Van Genderen et al., 2016). Regarding secondary production, an analysis of 48 metals and their application in various products by Schäfer and Schmidt (2020) shows that in many cases the metal concentration in EoL products is lower than that in natural ores. Recycling of this kind of metal is impeded by such low concentrations. These substitution and technological developments have not yet been included in the scenarios in this thesis. For future research, more analysis is still needed to assess the long-term use and impacts of substitution.

More efficient resource use by moving from a linear to a circular economy may cause rebound effects. In other studies, authors found that increasing efficiency of e.g. energy carriers or resource use can even lead to a 'backfire' effect - energy use or material use has become so efficient and cheap, that more use takes place instead of less, even beyond initial levels (Font Vivanco et al., 2016). A large body of literature has discussed the interplay between circular economy and rebound effects, mainly focusing on lower energy cost and efficiency improvements (Binswanger, 2001; Figge and Thorpe, 2019; Zink and Geyer, 2017). For example, improving efficiency leads to less energy cost, thus the users could spend the resulting savings on other products and services. The improving efficiency also could lower energy price, which in turn may cause more energy consumption. Another aspect of rebound is opportunity costs. Several circular economy polices target at enhancing material recycling, which means that the option of reuse cannot be chosen as a priority for the same source of secondary material. We refer to the discussion in Chapter 5 on copper reuse and recycling. Many policies related to resource efficiency regarding to copper have been implemented in China (see Table 1.1), however, further research on the rebound effects and related social as well as economic consequences induced from those policies is needed. In addition to the rebound effects, the transition to a circular economy of copper cycle may have other undesirable side effects. The analysis in this thesis is only focus on copper stocks and flows, the assumptions and changes of these flows may have implications for other resources. This is specifically true for copper reuse and recycling from various waste streams, since multiple co-products (e.g. Fe, Al) are processed simultaneously as well.

One direction of model development concerns expansion to include other aspects besides technology. This thesis focused on physical models, and the emphasis was on scenarios that describe the overall development of the copper cycle and its associated environmental impacts. Improving the environmental performance by optimizing the technical parameters (e.g. recycling rate, energy transition) is important, but there are other important considerations as well. Physical models therefore should be used in a wider context. For example, improving the collection rate and formalizing the recycling system involves economic and behavioral changes to become effective, however, strong emphasis on recycling may cause some rebound effects such as more disposable products consumption. Connecting physical models (e.g. MFA of waste management system) to models describing behavioral changes may give insights in these potential rebound effects. LCSA could be used to assess social and/or economic impacts of copper production (Guinée, 2016). Adding social and or economic information in the assessment could help for a better optimization of measures (e.g. lower production costs) in the copper cycle. Moreover, integrating the MFA with other economic models (e.g. Computable General Equilibrium models (CGE)) can give additional insights into economy-wide implications of policy measures focused on specific materials or sectors. This combination of MFA with CGE has been used for the Chinese building sector by Cao et al. (2019) to ensure that both mass and monetary balances would hold, and to assess economy-wide rebound effects of a saturation of building stock availability per capita via prospective modeling. In addition, the MFA can also be linked to spatially explicit models, such as the GIS-based models, which could give spatially explicit information on the environmental stocks and flows and hence where the (future) urban mine is concentrated (Verhagen et al., 2021; Yang et al., 2020).

6.3 Final remarks

The transition to a circular economy is an important ambition for China and other countries in the world. Copper is critical to the transition to a circular economy. This thesis explores the future copper demand and supply as well as associated environmental impacts, and addresses how the copper cycle in China can be transformed in a circular way. China currently consumes around 50% of the copper globally. With copper being very relevant for infrastructure development in other fast developing countries in the world, a transition towards a circular economy in China is likely to provide an important reduction of the pressure on copper demand for those countries. Since copper is a global market commodity, international partnerships are greatly needed to transfer the experiences of how to realize such transitions, but also to see how the circularity of copper flows across nations best can be organized. From a methodological perspective, this thesis provides a perspective on the integration of MFA and LCA. Such an approach could be very supportive to future research on other materials for which a transition to circularity is required, in order to move towards a sustainable development in the world.