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

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Chapter 4

Assessing the future environmental impacts of copper production in China: implications of the energy transition

Abstract

Copper demand in China is expected to grow considerably over the coming decades, driving energy use and environmental impacts related to copper production. To explore the environmental impacts of copper production in China, we used a variant of Life Cycle Sustainability Analysis that combined the Life Cycle Assessment methodology with the Chinese copper demand projections from 2010 to 2050. The results indicate that the environmental impacts of pyrometallurgical copper production are expected to increase more than twofold during this period and remain the largest contributor to the environmental footprint. Secondary copper production emits the least pollutions. Increasing the share of secondary copper production is the most environmental friendly option for copper production. To this end, China may focus on improving the classification of waste copper products and recycling infrastructure for end-of-life management. Hard coal use and production are crucial contributors to climate change in the context of copper production. Cleaning up copper production processes and improving energy efficiency would also help reduce environmental impacts. Energy transition can significantly reduce the environmental impacts of copper production, but it also can increase copper requirement. It does not visibly contribute to reduce human toxicity as well.

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4.1 Introduction

Copper production is a basic raw material industry that provides one of the key non-ferrous metals for infrastructure and buildings. It is also energy intensive as energy is used in the whole life cycle of copper production, including mining, beneficiation, smelting and refining, not only in the directly processes but also through the indirectly production of inputs, e.g. electricity generation. Globally, copper production requires around 600 million Gj of energy annually and contributes 0.21% of total greenhouse gases (John, 2012). On the other hand, copper demand has been increasing in the past decade and will continuously expand due to growing population, developed infrastructure and the application of copper-intensive technologies. A further consequence of this is the occurrence of serious environmental pollution and ecological damage, including biodiversity and water-quality losses, around mining sites.

Life Cycle Assessment is a methodology that is widely used to assess the environmental impacts of products and materials (Norgate, 2001; Norgate et al., 2007; Van Genderen et al., 2016). The environmental impacts per unit (kilogram) metal production (steel, aluminum, zinc and lead, among others) have been analyzed by various authors based on the inputs and outputs of production processes (Davidson et al., 2016; Zhang et al., 2016). Tan and Khoo (2005), Nunez and Jones (2016) and Farjana et al. (2019a) studied environmental impacts of primary aluminum production. Ferreira and Leite (2015) and Gan and Griffin (2018) analyzed environmental impacts of iron ore mining and processing . However, Farjana et al. (2019b) pointed out that many LCA studies have an incomplete coverage of production processes due to data limitations. Several scholars investigated the environmental impacts of mining processes with LCA, and identified key contributors to one or more impact categories (coal, Burchart-Korol et al. (2016); gold, Haque and Norgate (2014); nickel, Khoo et al. (2017); rare earth elements, Weng et al. (2016); uranium, Parker et al. (2016)).

LCA studies of copper production have been published as well. Some scholars have distinguished different copper production routes and have compared the environmental impacts of primary (pyrometallurgical and hydrometallurgical) and secondary production (Hong et al., 2018; Kuipers et al., 2018; Wang et al., 2015). More specifically, Song et al. (2014) and Kulczycka et al. (2016)

have quantified the environmental impacts of copper production processes based on specific technologies and explored potential options for reducing the energy use and environmental pressure associated with these processes. These studies have generally focused on assessing the environmental impacts of product manufacture using LCA and discussed the impacts per kilogram production.

However, analyzing the environmental impacts of copper production requires not only calculating the environmental impacts of producing one kilogram of copper. To assess the impacts of copper production, the total amount of produced copper has to be considered. Life Cycle Sustainability Analysis (LCSA) takes a life cycle approach but has a wider perspective (Guinée, 2016), which has been applied to assess the prospective environmental impacts and large scale system. On the one hand, it can include different types of impacts in addition to environmental ones, especially economic and social impacts. On the other hand, it can widen the spatial and temporal scope to include larger systems and future developments, such as the total use of materials and products in an economy and future developments. Plenty of publications have applied the LCSA method to analyze one or more aspects of environmental, social and economic impacts of production and use of products (Atilgan and Azapagic, 2016; Finkbeiner et al., 2010; Guinee et al., 2011; Keller et al., 2015; Nzila et al., 2012; Onat et al., 2016). Some studies have broadened the scope at global level by multiplying impacts per kg by global supply (in kg), in an attempt to assess past and future developments scenarios (Ayres et al., 2003; Norgate and Jahanshahi, 2011; Van der Voet et al., 2018). At lower scale levels it is more complicated: environmental impacts of mining are different per location, and copper production does not match copper consumption due to imports and exports, which is difficult to trace in many cases. Therefore, this study provides a comprehensive framework to assess environmental impacts of copper production at a national scale level, in this case, China. China is one of the world's largest economies. Presently, it accounts for 35% of global refined copper production. China has become the world's largest copper consumer and now uses 46% of global copper supply. Moreover, the Chinese copper demand is expected to rise considerably in the future (OECD, 2019; Zhang, L. et al., 2015a). Considering the intensive energy consumption, the total amount of energy consumed in the mining and beneficiation processes of the non-ferrous metals industry in China was around 3.5 billion Standard Coal units in 2015, with copper mining and beneficiation accounting for one-quarter of this figure (CNMIA, 2016). This number is likely to rise, given the increasing copper use in infrastructures, buildings and transportation, especially the increase use of renewable energy to power infrastructure and vehicles. Therefore, it is important to understand the copper production and consumption system to formulate recommendations for a more sustainable copper metabolism.

In this paper, we assessed the environmental impacts of copper production implied by projected future copper demand and supply of China. To this end, the objectives are:

- To assess the environmental impacts of 1 kg of copper produced by pyrometallurgical, hydrometallurgical and secondary production using LCA.
- To assess the environmental impacts of copper production combined with copper supply scenarios for meeting demand scenarios.
- To identify potential options for improving the environmental performance of Chinese copper production and consumption, by means of contribution analysis and other analysis.

In our explorations of the future, we include climate and energy policies to assess the impact of renewable energy use on copper demand, which may go up considerably as a result of electrification. On the other hand, copper production related to impacts per kg may go down as a result of a cleaner production of energy, which is included in our assessment as well. Furthermore, the imported copper concentrates and imported copper scrap and its differences in impacts compared to domestic copper production in China were explored in this study. The data used for domestic production represents China's average situation instead of a typical enterprise.

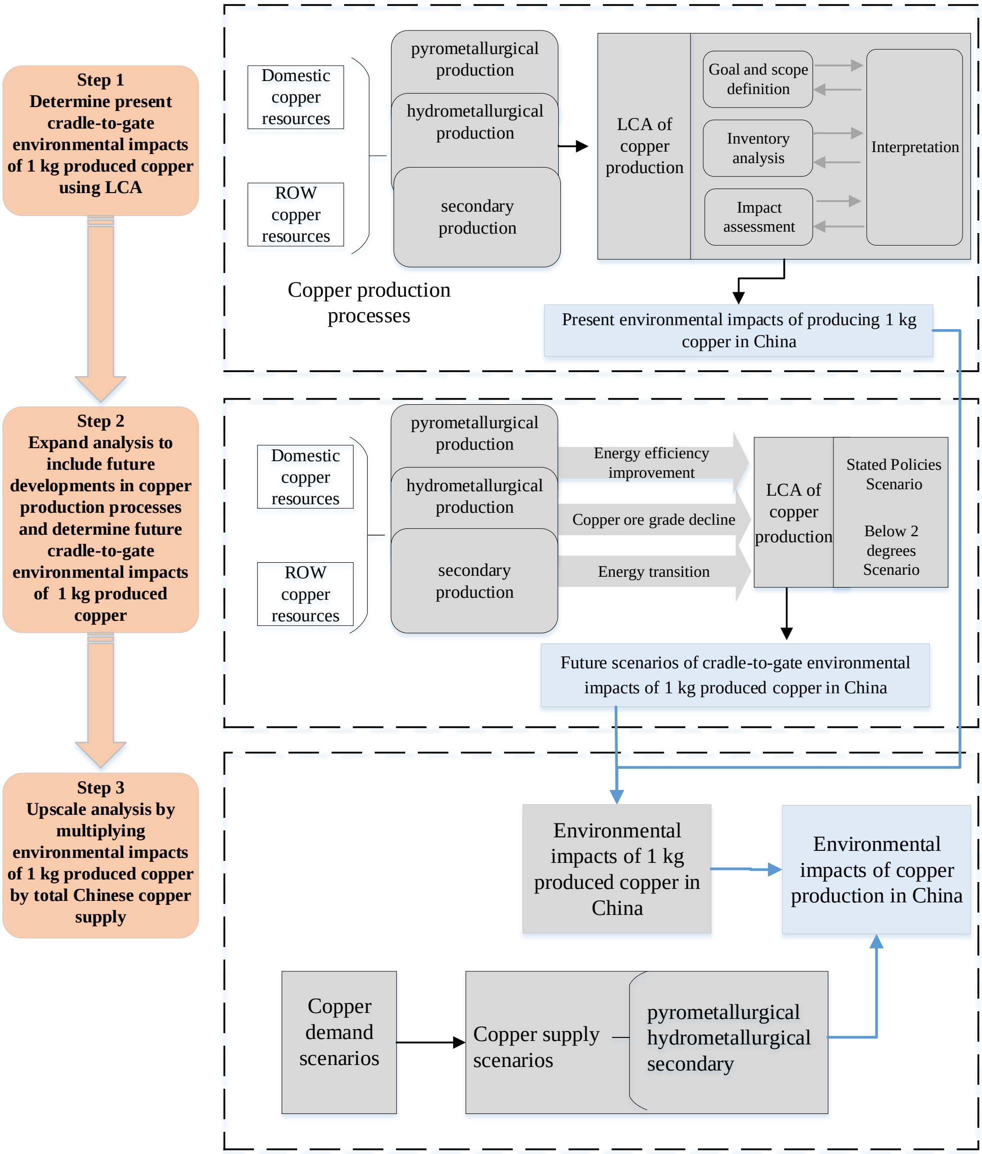


Figure 4.1 Framework of assessing future environmental impacts of copper production; "ROW" = Rest of the world

4.2 Methodology and data

To assess the environmental impacts of copper production combined with Chinese copper demand scenarios, in essence we used a variant of Life Cycle Sustainability Analysis (LCSA) as presented by Guinée (2016), but without including economic social or economic impacts (note further the abbreviation

LCSA is not meant to indicate a social assessment). In our case study on China, we focus the upscaling and forecasting. Or, alternatively formulated, we applied the LCA methodology not on a typical small-scale functional unit, but on the total current and future Chinese copper demand. The methodology comprises the following steps (Figure 4.1).

4.2.1 Methodology

4.2.1.1 Step 1 Determine present cradle-to-gate environmental impacts of 1 kg produced copper using LCA

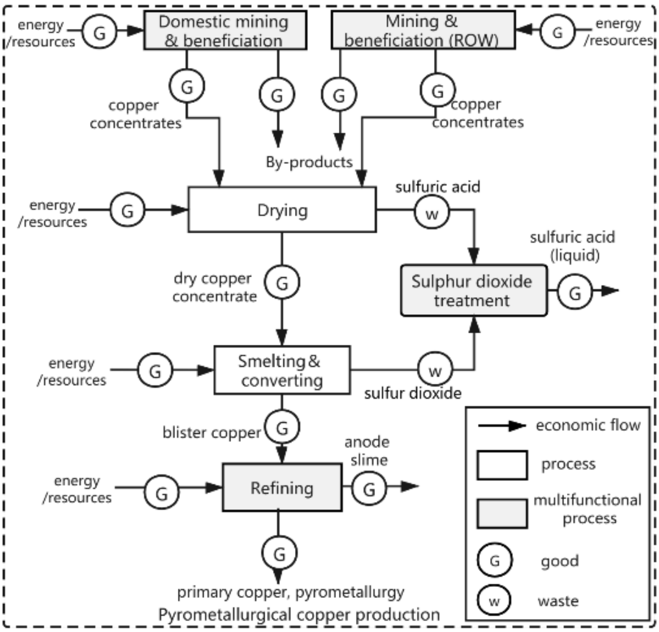
1) Copper production system

The "copper production system" refers to the technological routes adopted by the industries to produce copper. At present in China, there are three basic routes: pyrometallurgical (primary production), hydrometallurgical (primary production) and secondary production. Pyrometallurgical production is currently the dominant route in China, in general use for sulfide copper concentrates (Wang et al., 2015). In this study we distinguish the following main processes of this technology: mining & beneficiation, drying, smelting & converting, and refining (Figure 4.2).

Because of the continuous decline in quality of copper ore and the increase in complex minerals that are difficult to handle, China is shifting towards hydrometallurgical production (Wang et al., 2012). In this study this production route comprises the following main processes: mining, beneficiation, leaching & extraction, and electrowinning (Figure 4.2). In many cases this route still needs to be combined with pyrometallurgical production and depends on the grade and type of copper concentrates involved.

Secondary copper production can use the pyrometallurgical as well as the hydrometallurgical production route (Kuipers et al., 2018). The more modern hydrometallurgical technology has been used for recycling some EoL products, especially waste circuit boards and lithium-ion batteries (Liu et al., 2019; Perez et al., 2019). However, this method has not been applied on a large scale in China based on the investigation of the main copper recycling plants. Also in view of data issues, the secondary production presented in this study is assumed to follow the pyrometallurgical production route. The relevant processes are generally divided into two elements: pretreatment and recycling. Pretreatment includes collection and classification of the mixed waste copper and removal of other wastes on its surface to obtain a single stream of relatively pure waste copper. Copper recycling consists of smelting and converting followed by refining (Figure 4.2).

Besides domestic production, a significant amount of copper is imported from abroad as well. Imported copper concentrates have become an important source of copper production and are expected to remain so for decades to come. We therefore also included the impacts of imported copper concentrates, accounting for the variations in mining and beneficiation processes in other countries by taking a global average for imported copper concentrates. For secondary production, we included both domestic and imported scrap.



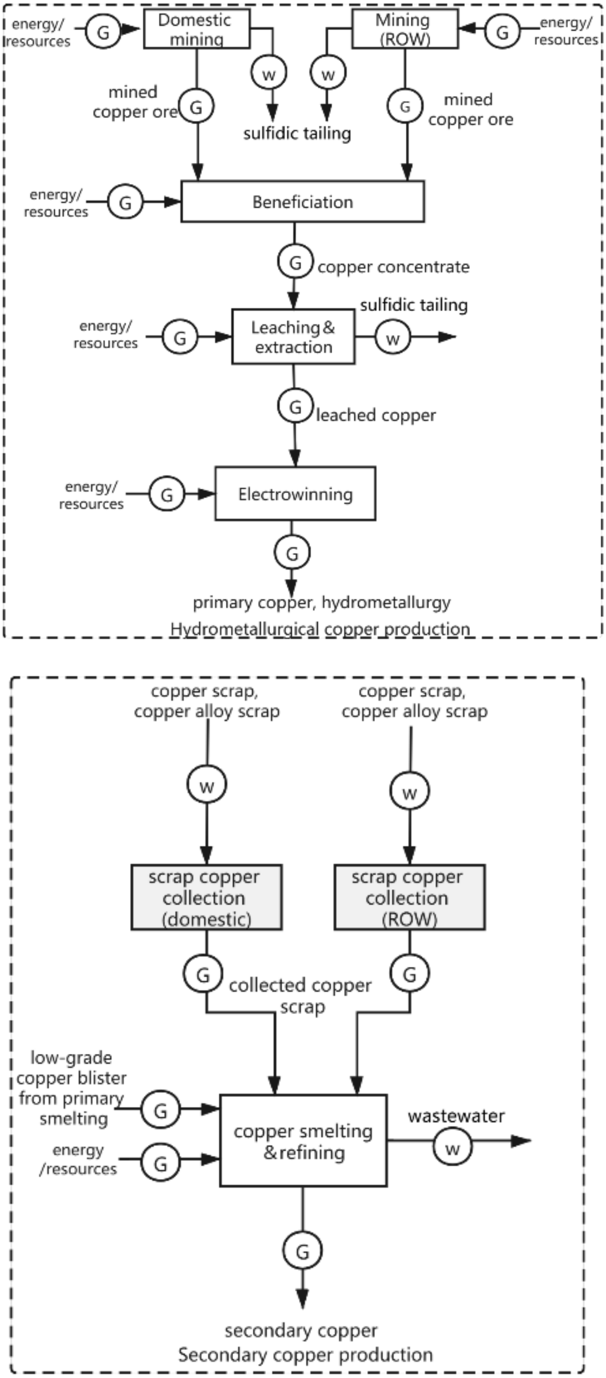


Figure 4.2 Chinese copper production system: pyrometallurgical, hydrometallurgical and secondary copper production

2) LCA of the present copper production system

The LCA methodology is widely used to assess the environmental impacts of metal production system (Liu et al., 2011; McMillan and Keoleian, 2009). It comprises four main phases: 1) goal and scope definition, 2) life cycle inventory, 3) life cycle impact assessment, and 4) interpretation (ISO, 2006a). For our assessment of the present environmental impacts of producing 1 kg copper, we took the following specifications:

- The goal is to assess the environmental impacts of copper production in China. The scope is cradle-to-gate production of 1 kg refined copper in China by pyrometallurgical, hydrometallurgical and secondary production.
- Life cycle inventory of the present copper production system. For the foreground processes related to copper production, separate data were collected. The mining and beneficiation processes associated with pyrometallurgical and hydrometallurgical production include domestic production in China and the rest of the world. The copper scrap refined in secondary production similarly derives from both domestic collection and imports. Allocation is part of the LCI stage (see the blue processes in Figure 4.2). Environmental impacts need to be partly allocated to by-products of copper mining, such as Molybdeen (Mo) and Silver (Ag). To this end, the partition method of economic allocation was adopted on the basis of revenue (market price multiplied by amount produced). The inputs and outputs of producing 1 kg refined copper with three technologies in 2015 is shown in Table 4.1. In addition, we used the Ecoinvent 3.4 database for the background processes of copper production system (Moreno Ruiz et al., 2017).
- The life cycle environmental impacts were conducted using the CMLCA 6.0 software and the CML2001 impact categories (CML, 2016; Guinée, 2002), which include eight commonly used indicators: acidification potential, climate change, freshwater aquatic ecotoxicity, human toxicity, photochemical oxidation (summer smog), abiotic depletion of resources-fossil fuels, abiotic depletion of resources-elements and cumulative energy demand.
- In the interpretation stage, a contribution analysis to identify the impacts in

different production processes was conducted. Sensitivity analysis on energy efficiency and copper ore grade were performed to examine the variability of environmental impacts due to data uncertainty.

Table 4.1 Inputs and outputs of the production process, scaled to the production of 1 kg refined copper with three technologies in 2015

	Material	**Pyrometallurgy**	**Hydrometallurgy**	**Secondary**	**Unit**
Economic inflows	Electricity	1.65E+00	3.97E+00	4.11E-01	kWh
	Diesel	1.23E+00	1.86E+00	8.80E-03	MJ
	Limestone	1.11E+00	2.77E-01	7.39E-02	kg
	Sulfuric acid	1.11E-02	2.45E-01	6.80E-03	kg
	Hard coal	3.21E-01	-	1.86E-01	kg
	Coke	2.70E-01	-	1.12E-01	kg
	Natural gas	4.44E-02	-	4.92E-01	m^3
	Oxygen	2.63E-01	-	9.14E-02	kg
	Xanthate	1.67E-02	-	-	kg
	Butylamine	1.99E-02	-	-	kg
	Heavy fuel oil	2.05E-02	-	-	MJ
	Copper extractant	-	6.19E-03	-	kg
Economic outflows	Refined copper	1.00E+00	1.00E+00	1.00E+00	kg
	Molybdenum concentrate	4.11E-03	-	-	kg
	Sulfidic tailing	9.70E+01	5.54E+02	-	kg
	Sulfur dioxide	4.45E-01	-	3.00E-03	kg
	Sulfuric acid	1.20E+00	-	-	kg
	Waste water	5.68E-03	1.41E-01	1.00E-03	m^3
Environmental resources	Copper ore	1.10E+02	3.07E+02	-	kg
	Imported-copper concentrate	2.41E+00	-	-	kg
	Domestic copper scrap	-	-	1.31E+00	kg
	Imported-copper scrap	-	-	5.73E-01	kg
	Molybdenum ore	2.64E+00	-	-	kg
	Water	1.17E+00	2.20E-02	1.17E+00	m^3
Environmental emissions	Carbon dioxide	5.88E+00	7.37E+00	1.59E+00	kg
	Antimony	4.49E-09	-	3.00E-06	kg
	Carbon monoxide	2.94E-08	-	2.00E-03	kg
	Dioxins	9.80E-15	-	-	kg
	Arsenic	3.36E-08	-	2.00E-06	kg
	Mercury	1.12E-09	-	-	kg

	Material	Pyrometallurgy	Hydrometallurgy	Secondary	Unit
	Nickel	1.79E-06	-	1.00E-06	kg
	NMVOC	1.47E-08	-	-	kg
	Particulates	1.14E-02	-	2.82E-04	kg
	Sulfur dioxide	2.28E-01	6.80E-02	3.00E-03	kg
	Water	6.52E-02	1.66E-01	1.76E-04	m^3
	Zinc	4.26E-06	-	3.75E-04	kg
	Leaching residues	-	2.76E+02	-	kg

Table 4.2 Main assumptions and data sources in assessing environmental impacts of producing 1 kg copper

Variables	**Stated Policies Scenario (SP)**	**Below 2°C Scenario (B2D)**	**Data source**
Ore grade decline	Chinese copper ore grade from 2016 to 2050 modeled using historic time series. The ore grades related to imported copper concentrates are based on global trends.		China Nonferrous Industry Statistical Yearbook, Kuipers et al. (2018), Northey et al. (2014)
Energy efficiency, foreground processes	Primary pyrometallurgical production: • Domestic production based on historical trends of Chinese mine production • Global level production: global historical trend data were used. • Primary hydrometallurgical production: • conservative estimate of 1% annual improvement of all processes, both for China and the world. • Secondary production: • scrap collection changes in efficiency assumed for China or the world. • refining: the same energy efficiency improvement rate of pyrometallurgical production.		China Nonferrous Industry Statistical Yearbook, Jiang et al. (2006); Kuipers et al. (2018); Ruan et al. (2010).
Energy transition, background processes	Domestic: the SP Scenario. Global: the New Policies scenario from IEA (IEA, 2017).	Domestic: the B2D Scenario. Global: the 450 scenario from IEA (2017), consistent with the goal of limiting global temperature rise to 2°C.	CNREC (2017), (IEA, 2017), ecoinvent v3.4 database (Moreno Ruiz et al., 2017)

4.2.1.2 Step 2 Expand analysis to include future developments in copper production processes

This step models future changes in the foreground and background systems and determines the resultant changes in environmental impacts of producing per kg copper. These impacts are affected by numerous variables associated with the various links in the copper production chain, including copper ore grade decline, energy efficiency improvements, the energy mix used for electricity production and transport (which the energy transition may alter substantially) and changes in material transport requirements (Norgate et al., 2007; Van der Voet et al., 2018; Vieira et al., 2012). Our analysis took into account ore grade decline, energy efficiency improvements and changes in electricity mix. Main assumptions are summarized in Table 4.2.

1) Copper ore grade

Ore grade decline is already occurring and is expected to continue in the future (Northey et al., 2014). Several studies have analyzed the energy inputs related to mining and beneficiation and established that energy use rises as ore grade declines (Alvarado et al., 2002; Ballantyne and Powell, 2014; Calvo et al., 2016; Norgate and Jahanshahi, 2010). The likely further decline of ore grade will therefore drive up the energy requirements of copper production (Mudd et al., 2013; Northey et al., 2014).

Using the historical data on copper ore grade in the China Nonferrous Industry Statistical Yearbook (CNMIA, 2016), we applied the power regression method reported by Crowson (2012) to simulate the change in copper ore grade up to 2050.

$$G = \mu * y^{-\varepsilon} \quad (4.1)$$

Where G is the copper ore grade in year y. The parameters μ and ε are regression parameters, These parameters are calculated to match the past trend as closely as possible. The past and projected future trend of copper ore grade in China is shown in Figure S4.1.

To estimate the energy requirements of copper production we applied the power regression model, as presented by Northey et al. (2014). This model defines the relationship between copper ore grade and energy inputs for mining and beneficiation processes for different type of copper extraction sites as follows:

$$E = \alpha \times G^{-\beta} \quad (4.2)$$

where G represents the ore grade, E is the energy use for obtaining copper concentrate in MJ per kg and the parameters α and β are regression parameters calculated by Northey et al. (2014) . This equation can be used to describe the accelerating growth of energy use due to declining ore grade. The trends of copper ore grade and energy requirements are reported in the Supporting Information.

For the ore grade of imported copper concentrates, we adopted the assumptions of Kuipers et al. (2018) for the global level, indicating that energy consumption will increase on average by 0.66% per year between 2010 and 2050, as shown in Figure S4.2.

2) Energy efficiency

The International Energy Agency (IEA) pointed out that energy efficiency is one of the keys to advancing the transformation of the global energy system and addressing environmental issues associated with energy consumption (IEA, 2017). Energy efficiency improvements depend on numerous factors, including production technology, energy structure and pricing, of which technology is the most fundamental (Wei et al., 2016).

Since 1990 China has gradually developed its copper production technology, resulting in an improvement in the energy efficiency of production processes. The future energy efficiency of pyrometallurgical mining and beneficiation was estimated using historic data from 1995 to 2015 in China Nonferrous Industry Statistical Yearbook. The energy efficiency of the smelting and refinery processes improved considerably from 1995 to 2007 and slightly from 2007 to 2015 (Figure S4.3). Based on the past trends, the energy efficiency improvements of mining & beneficiation, smelting & converting and refining of pyrometallurgical copper production were assumed of 0.95%, 0.71% and 0.7% per year, respectively. Consideration of imported copper concentrate, the average energy consumption in mining and beneficiation process in other countries, we used the global level data presented by Kuipers et al. (2018), as shown in Table S4.1.

Data on the average energy requirements for Chinese hydrometallurgical production from 2006 to 2009 are also available (Hong et al., 2018; Jiang et al., 2006; Ruan et al., 2010; Song et al., 2014). Given this short period, no accurate trend in energy efficiency improvement could be established for hydrometallurgical production. It has previously been observed from other research, though, that technological innovation can increase it by 1-4% per year (Marsden, 2008; Wiechmann et al., 2010), as reported in Table S4.2. We used a conservative estimate of 1% annual improvement in energy efficiency for mining, beneficiation, leaching and electrowinning process in China. For the mining and beneficiation process of hydrometallurgical production in other countries, we worked with the same assumptions as for domestic production.

For secondary copper production we found no data on efficiency improvement. As this is allied to pyrometallurgical production, we assumed no changes in the energy efficiency in the copper scrap collection process either in China or elsewhere and the same improvement rate in the energy efficiency of the refining process in China.

3) Energy supply mix

China Renewable Energy Center (CNREC) has developed two energy supply scenarios in China Renewable Energy Outlook 2017 based on current development status (CNREC, 2017). This report focuses on specifying a feasible path for China's low-carbon transition until 2050 and the measures required to address barriers to renewable energy development in the near term. The "Stated Policies Scenario (SP)" examines the impact of current strategic energy transformation policies, while the "Below 2°C scenario (B2D)" explores the measures China needs to implement to fulfill its obligations under the Paris Agreement.

These scenarios define two roadmaps for Chinese electricity production from 2016 to 2050, as shown in Figure 4.3 and Table S4.3. The share of fossil fuels goes down, not just in a relative sense but also absolutely. Under the SP Scenario, fossil fuel use will peak in 2025, while under the B2D scenario this will already be in 2020. There is accelerated adoption of renewable energy technologies in both scenarios, but in the B2D scenario take-up is faster. In both scenarios nuclear power and wind energy come to provide the bulk of electrical power. In the B2D scenario, solar power generation increases to become the second largest source.

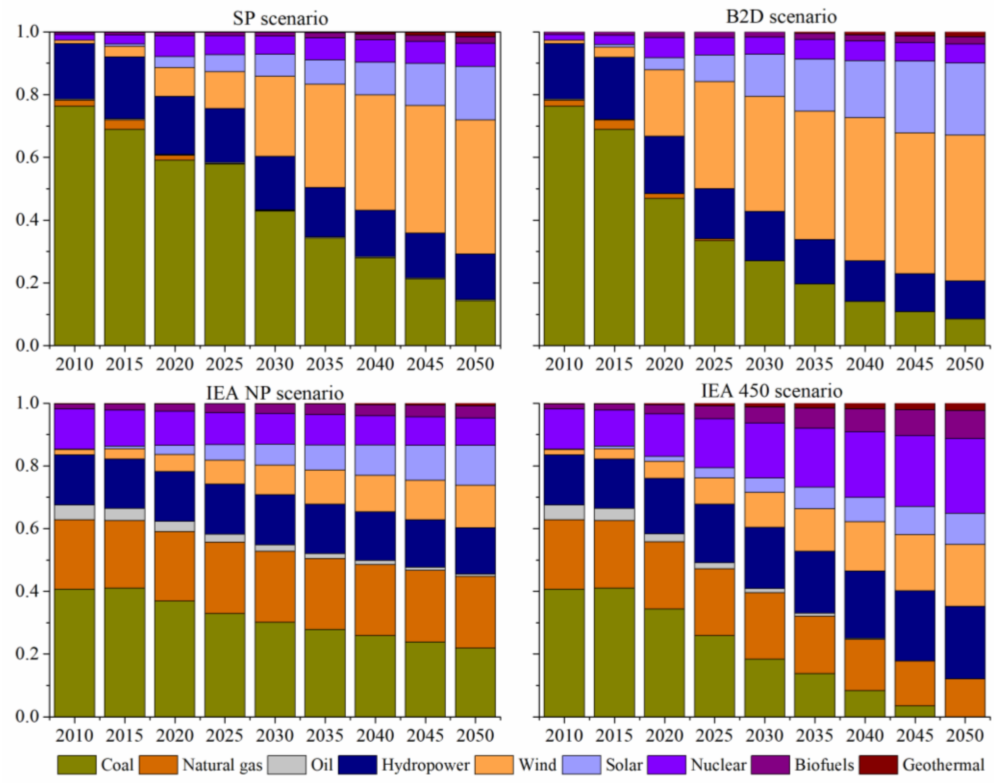


Figure 4.3 Electricity supply mix scenarios for background system of China: Stated Policies scenario (SP scenario) and Below 2 Degree scenario (B2D scenario), the world: IEA New policies scenario (IEA NP scenario) and IEA 450 scenario.

For the global electricity supply mix, we took the “New Policies (NP)” scenario and “450” scenario from IEA (2012) as corresponding to the Chinese SP and B2D scenarios, the latter being consistent with the policy goal of limiting global temperature rise to 2°C. The trends embodied in the NP and 450 scenarios are shown in Figure 4.3.

4.2.1.3 Step 3 Upscaling: Upscale analysis by multiplying environmental impacts of producing 1 kg copper by total Chinese copper supply

The aim of this step is to specify the shares of the three production routes in meeting Chinese copper demand. For future copper demand scenarios, we designed the Stated Policies scenario and Below 2°C scenario, which basically adopted the results from Dong et al. (2019). The copper demand scenarios were modeled with a dynamic material flow analysis, information on this step can be found in the Supporting information. Then the next step is to translate copper demand scenarios into copper supply scenarios. Main assumptions and data sources for copper demand and supply scenarios are summarized in Table 4.3.

Table 4.3 Main assumptions and data sources for copper demand and supply scenarios

Variables	Stated Policies Scenario (SP)	Below 2°C Scenario (B2D)	Data source
Ratio domestic/imported copper concentrates	The share of domestic production was 42% and 30% in 2010 and 2015, respectively. The latter figure was assumed for both pyro- and hydrometallurgical production up to 2050, under both scenarios.		China Nonferrous Industry Statistical Yearbook, UN Comtrade
Ratio domestic/imported copper scrap	The proportion of domestic copper scrap in the total copper scrap used to produce secondary copper increased from 49% to 96% as a result of import restrictions between 2010 and 2050.		Dong et al. (2019), UN Comtrade
Copper demand	SP scenario	B2D scenario	Dong et al. (2019)
Secondary copper production	In both scenarios the secondary copper will increase based on the domestic copper scrap that generated from use phases.		Supporting information
Ratio pyro/hydro primary production	Modeled based on historical data, as shown in appendix 2 in Supporting information.		the United States Geological Survey (USGS)

1) Translate copper demand scenarios into copper supply scenarios

The primary and secondary copper production was measured based on assumptions of the in-use stock, semi and finished copper production. To establish future trends in the primary production routes, we applied regression analysis to historical data and projected the results into the future. With the decline of copper ore grade and the requirement to reduce the cost of copper production, hydrometallurgy is more widely used in copper production. We modeled the shares of pyrometallurgical and hydrometallurgical routes in Chinese primary copper production to 2050 based on the historical data from

2004 to 2015 (Figure S4.4). As stated above, the Chinese copper supply derives from both domestic production and imports, broken down further into pyrometallurgical, hydrometallurgical and secondary production from 2010 to 2050. Additional details are provided in the Appendix 2 of Supporting Information.

2) Assess environmental impacts of copper supply scenarios

The SP and B2D supply scenarios were correspondingly translated from Stated Policies scenario and Below 2°C scenario of copper demand, which were then assessed as to their environmental impacts. Each scenario has two (domestic and foreign) times three (pyrometallurgical, hydrometallurgical and secondary) different production routes that correspond to a time series impact assessment per kg produced copper. In each scenario, the amounts of copper produced via these six routes were multiplied by the corresponding impacts per kg. The impacts for these six routes were then summed to yield a total.

4.2.2 Data

Data sources were summarized in Tables 4.2 and 4.3. The data on electricity production and other processes related to copper production in the background system were derived from the ecoinvent v3.4 database, which has updated a lot of data for the region ‘China’. Compared with previous research on China (Jiang et al., 2006; Ruan et al., 2010; Song et al., 2014; Wang et al., 2015), the present study included the data of imported copper and statistical data that represents China’s average situation instead of a typical enterprise for each constituent process of the three copper production routes, especially with respect to energy and resource use in foreground processes and electricity production in background processes. Detailed information can be found online at https://doi.org/10.1016/j.jclepro.2020.122825.

4.3 Results and discussion

4.3.1 Present environmental impacts per kg produced copper

Table 4.4 presents the environmental impacts of per kg copper produced in China by the three production routes in 2015. Pyrometallurgical and hydrometallurgical production are both highly energy-intensive.

Table 4.4 Environmental impacts of producing 1 kg copper by pyrometallurgical, hydrometallurgical and secondary production in 2015

Category	Pyro-	Hydro-	Secondary	Unit
CED	81.72	95.393	24.073	MJ
AD-e	0.8	0.633	0.0578	kg antimony-eq.
AD-f	85.8	98.7	27	MJ
PO	0.0131	0.00295	0.000651	kg ethylene-eq.
HT	193	634	16.3	kg 1,4-DCB-eq.
FE	132	443	9.88	kg 1,4-DCB-eq.
CC	5.88	7.37	1.59	kg CO2-eq.
AC	0.354	0.134	0.0163	kg SO2-eq.

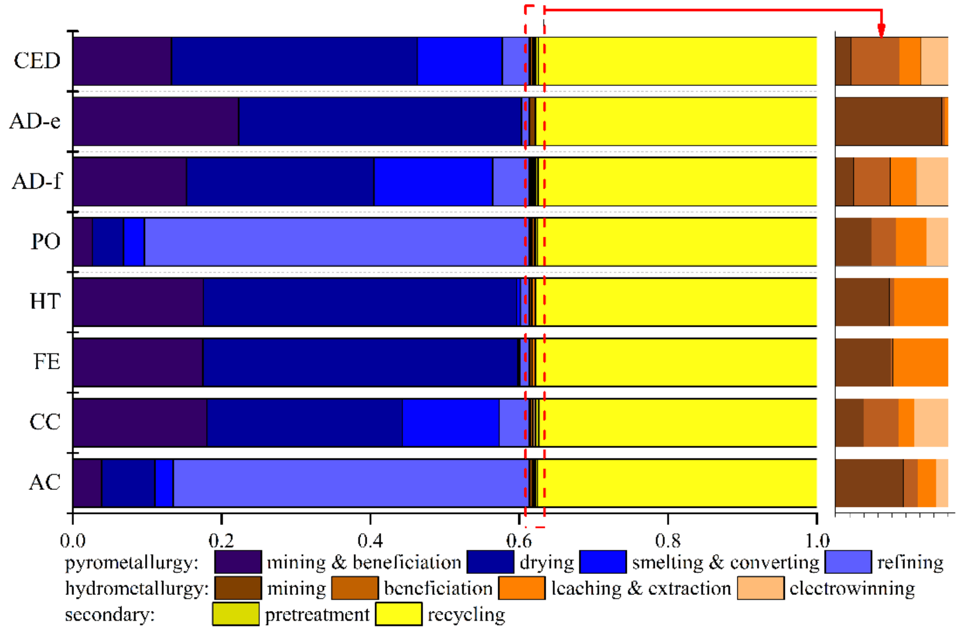


Figure 4.4 Contribution of processes from three different production routes (mix of production routes in year 2015: pyrometallurgical 61.35%, hydrometallurgical 0.80 %, secondary 37.85%) to the cradle-to-gate environmental impacts of 1 kg copper production in China. Contribution is given per impact category: acidification (AC), climate change (CC), freshwater aquatic ecotoxicity (FE), human toxicity (HT), photochemical oxidation (PO), abiotic depletion of resources-fossil fuels (AD-f), abiotic depletion of resources-elements (AD-e) and cumulative energy demand (CED); detailed data refers to the appendix 4 in SI.

Pyrometallurgical production contributes the most to acidification, photochemical oxidation (summer smog) and depletion of abiotic resources-elements, with these impacts due mainly to the mining, beneficiation and drying processes (Figure 4.4). Hydrometallurgical production contributes more to cumulative energy demand and toxicity, owing mainly to the mining, leaching and extraction processes. Both production processes primarily produce sulfuric acid, sulfur dioxide and large amounts of toxic chemicals. As one would expect, secondary production always has the lowest environmental impact for producing 1 kg copper, for the reason that it does not involve the early stages of mining, beneficiation and drying.

4.3.2 Future environmental impacts per kg produced copper in different scenarios

Developments of the per-kg environmental impacts until 2050 in the two scenarios are shown in Tables S4.8-S4.13 in the Supporting Information. We restrict ourselves to analysis of three key impact categories: climate change, human toxicity and cumulative energy demand in the main discussion. The developments are shown graphically in Figure 4.5.

The overall trends with respect to climate change, human toxicity and cumulative energy demand are similar in the two scenarios. Climate change exhibits a clear downward trend, while human toxicity shows a gradual rise in three copper production routes. The assumptions regarding to the energy transition mean the cumulative energy demand decreases in pyrometallurgical and secondary production, and a slight increase in hydrometallurgical production. In absolute terms, secondary production still scores much lower than primary production on all environmental impacts, which confirms that secondary copper production always has considerably lower impacts than primary copper production in per kg (Norgate, 2001; Song et al., 2014). An interesting finding is that the climate change impact of hydrometallurgical production declines, while energy demand increases. The assumed rate at which the energy efficiency of hydrometallurgical production improves is insufficient to offset the increase in energy use due to declining copper ore grade. The declining quality of copper ore appears to be a key factor on increasing environmental performance, with the assumed decline driving up energy use by more than the gains from the assumed improvement in energy efficiency. On the other hand, the higher energy requirements are met more by renewable sources, leading to a decline in energy-related greenhouse gas emissions. Since the extent to which these assumed developments will actually occur is fairly uncertain, we conducted a sensitivity analysis on energy efficiency improvement and declining copper ore grade.

All the environmental impacts of 1 kg copper production are lower in the B2D scenario than in the SP scenario. This result indicates that the energy transition could reduce the environmental impacts of copper production, and thus could offset the increase caused by the decline in copper ore grade.

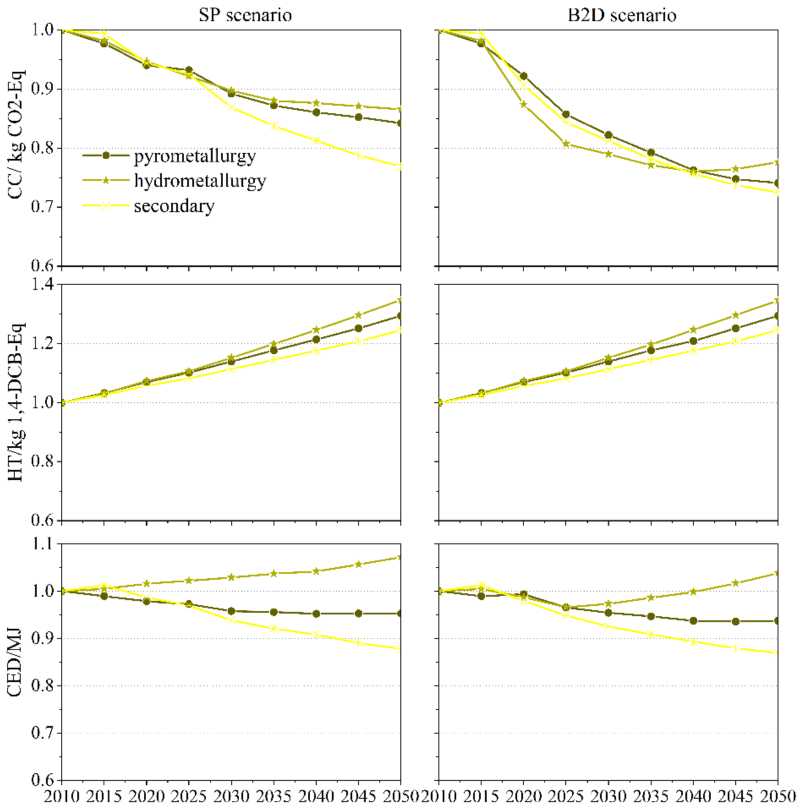


Figure 4.5 Developments in cradle-to-gate environmental impacts of 1 kg copper production in China from 2010-2050 for three copper production technologies (2010 = 1), climate change (CC), human toxicity (HT), cumulative energy demand (CED).

4.3.3 Environmental impacts of Chinese copper supply scenarios

Figure 4.6 provides an overview of Chinese copper demand and supply scenarios. Both scenarios of copper demand are expected to increase considerably, especially for Below 2°C scenario. This is due to the fact that the energy transition assumed under the Below 2°C scenario requires a larger amount of copper. For the copper supply, pyrometallurgical production is still the leading production technology under both scenarios. Secondary copper production is expected to increase as a result of increased domestic copper scrap generation and higher collection and recycling rate in China. There is no difference in domestic copper scrap production between the two scenarios, though, because copper scrap generation is a result of past developments rather than future policies. However, combined with China's restrictions on import of copper scrap as an environmental protection measure, the volume of imported foreign scrap is expected to fall. In a growing market, this will need to be replaced by either domestic scrap or primary production.

The reduction of environmental impacts per-kg appears to be counteracted by the growth in copper production for all three shown impacts categories. Overall, the impacts of copper production via all three production routes are projected to more than double from 2010 to 2050. The impacts of pyrometallurgical production are still expected to contribute most to the aggregate impacts of copper production, since it is still assumed to be the dominant mode of production.

The most striking finding is that the impacts of both scenarios are fairly similar. While the per-kg impacts are lower in the B2D scenario, copper demand is in fact lower in the Stated Policies scenario (SP supply scenario). The levelling off of the trend in both scenarios can be attributed to the growth of the share of secondary production.

Multiplying the environmental impacts of production of 1 kg copper by the copper supply scenarios, we obtained insight into the potential environmental impacts of copper supply scenarios from 2010 to 2050. Figure 4.7 presents the results for climate change, cumulative energy demand and human toxicity of the two copper supply scenarios for China. The complete results for all the impacts in each supply scenario are reported in Tables S4.14-S4.19.

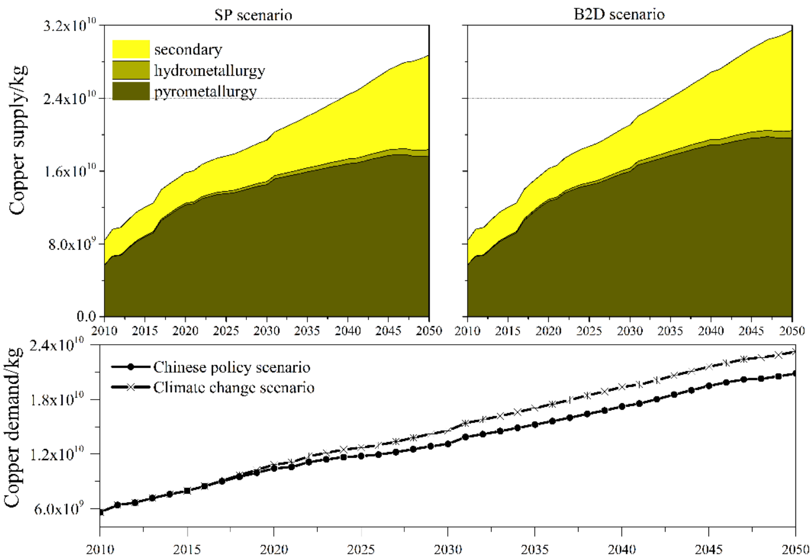


Figure 4.6 Copper demand and supply scenarios of China from 2010 to 2050

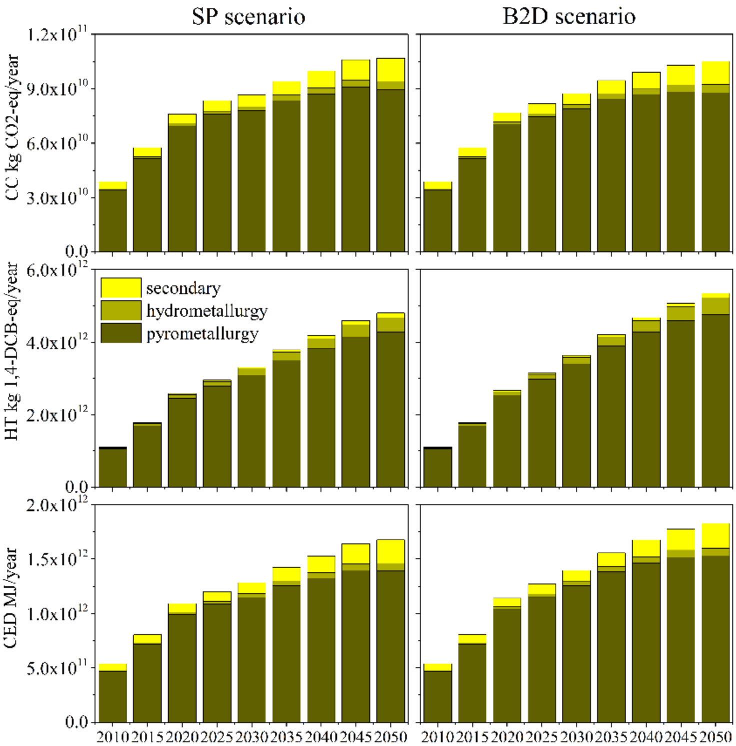


Figure 4.7 Environmental impacts of copper supply scenario of China per year.

4.3.4 Uncertainties analysis

In this study the LCSA method was used to estimate the environmental impacts of Chinese copper production, encompassing domestic copper production and imported copper, and taking into account three variables: energy efficiency improvement, energy transition and copper grade decline. The results were analyzed from aspects on copper production technology and scenarios analysis. There are several uncertainties in the results, however, owing to limited data or the assumptions made in the scenarios.

First, improved production process data need to be obtained, in particular on the energy efficiency of hydrometallurgical and secondary production processes. The results of LCA are often affected by changes in inventory data inputs, making these a major source of uncertainty in LCA. To examine the effect of variables on the environmental impacts of copper production, sensitivity analysis was performed using varying assumptions on energy efficiency improvement and ore grade decline. As Figure S4.5 shows, if the energy efficiency of the three copper production routes remains constant from 2015 onwards, the environmental impact is about 1-6% higher than the improved energy efficiency model in both scenarios, though the rate of change is lower in the B2D scenario. Copper ore grade also has an important influence on the results, as shown in Figure S4.6 a constant grade for pyrometallurgical and hydrometallurgical production will reduce impacts by around 1-15% in both scenarios. Because of the energy transition, the impacts are far lower in the B2D scenario, furthermore.

Second, we made several assumptions about the potential development of copper demand and copper supply. There is no doubt that the results stemming from these assumptions have a high degree of uncertainty. It should be borne in mind, though, that scenario analysis is not concerned with predicting the future, but with exploring the implications of the continuation of present developments and of the present policies from the Chinese government. In the scenario analysis conducted in this study, this means to examine alternative future Chinese copper supply scenarios.

Table 4.5 Studies on environmental impacts of copper production at different scale levels (Functional unit: 1 kg copper)

Country or region	**Production process**	**Impact category**	**Value**	**Source**
Global	Metal production and refining	CC	4.3~8.9	Norgate (2001)
		AC	0.03	
		CED	51	
	Copper ore processing	CC	4.5	Rötzer and Schmidt (2020)
	Primary production	CC	2.8	Nuss and Eckelman (2014)
		CC	6.44	Van der Voet et al. (2018)
		CED	106	
		AC	0.08	Kuipers et al. (2018)
		HT	184	
	Secondary production	CC	1.58	Van der Voet et al. (2018)
		CED	22.4	
		AC	0.02	Kuipers et al. (2018)
		HT	6.77	
Australia	Mining and smelting	CC	2.5~8.5	Memary et al. (2012)
		AC	0.05~0.5	
	In-situ leaching mining	CC	4.78	Haque and Norgate (2014)
Canada	Primary production	CC	2.3	Northey et al. (2013)
Chile	Primary production	CC	1.1~3.9	
South Africa	Primary production	CC	8.5	
USA	Primary production	CC	4.44	
Japan	Primary production	CC	2.5	Adachi and Mogi (2007)
India	Secondary production	CC	1.5	Chaturvedi et al. (2012)
Poland	Primary production	CC	5.44~7.65	Kulczycka et al. (2016)
		AC	0.03~0.05	
China	Primary production, specific copper production site	CC	1.91	Hong et al. (2018)
		HT	0.09	
		AC	0.01	
	Secondary production	CC	0.69	
		HT	0.22	
		AC	0.002	
	Primary production	CC	3.42	Chen, J. et al. (2019)
		AC	0.02	

Country or region	Production process	Impact category	Value	Source
		HT	1.79	
	Secondary production	CC	0.32	
		AC	0.001	
		HT	0.22	
	Primary, pyrometallurgical production, 2015	CC	5.88	This study
		AC	0.35	
		CED	81.72	
	Primary, hydrometallurgical production, 2015	CC	7.37	
		AC	0.13	
		CED	95.39	
	Secondary production	CC	1.59	
		AC	0.016	
		CED	24.07	

4.3.5 Critical analysis of environmental impacts of copper production: comparison with other countries or regions

To put our results into a broader perspective, we compared them with results of studies on the environmental impacts of copper production at global and national level: main copper producing countries including Chile, the United States, Australia, Canada, South Africa, India and Poland (Table 4.5). In view of the scope of the selection of studies, a comparison is possible on the impact categories of climate change, acidification potential and energy consumption of copper production. The ranges of impact value are quite large – a factor 2 for energy demand, a factor 8 for climate change and orders of magnitude for acidification, both for primary and secondary production. Results for China are not exceptional, they fall within the range of the studies included in the comparison. The reasons for these differences are not apparent. They may be due to methodological choices, calculation procedures or data uncertainty. They may also be real-world reasons related to the use of different production technologies, different ore qualities or local energy mixes.

4.3.6 Discussion and identifying options to improve the environmental performance of copper production

While these uncertainties have some impact on the accuracy of the results, they are unlikely to change the overall trend of increased environmental impacts of aggregate copper supply as copper demand continues to grow. This implies a need to further reduce the environmental impacts of copper production, to which end several options can be identified.

Reducing copper demand is the first and most obvious option. Several studies indicate that copper demand is closely related to GDP (Schipper et al., 2018; Soulier et al., 2018b). Once a certain GDP threshold is reached, copper demand may become saturated. However, this will not be easy to realize in 2050 in a country like China, which is still in the midst of development. During this period, China will be shifting from a fossil-based to a renewables-based energy system. In particular, electrification – all the more important in view of the energy transition – requires massive amounts of copper. It is also evident from our research (Below 2°C scenario of copper demand) that the use of new energy will lead to increased copper demand. As a result, Chinese copper demand is expected to continue to grow, a trend that cannot readily be halted before 2050.

Substitution of copper by other materials is a second option to consider (Batker and Schmidt, 2015). Substitution of copper by another material is an option to reduce demand, but poses challenges as well. It is by no means straightforward to find suitable alternatives that have the same functionality and can be produced in equally large quantities. Replacing copper by other materials is therefore not always feasible, especially for electricity infrastructure (Graedel et al., 2015). Primary aluminum is considered to have the greatest potential for replacing copper in energy infrastructure. Unfortunately aluminum has even higher climate change and energy demand impacts per kg than copper (Li and Guan, 2009; Van der Voet et al., 2018). In view of lower environmental impacts, secondary aluminum may be a more effective substitute for copper. Depending on required performance and application, other products may also be eligible for partially replacing copper, such as stainless steel, zinc and plastics. However, further study is still needed to assess the long-term use and impacts of these substitutes, to develop a broader understanding of more environmentally compatible copper alternatives.

The energy transition deserves greater attention. Hard coal use and production are the principal sources of GHG emissions in pyrometallurgical production in 2015 and 2050 of SP scenario, as shown in Figure 4.8. With the energy transition, the climate change impact for all processes is expected to decline, especially for hard coal. Extending its policy of encouraging use of renewables, China could initiate a drive to use renewable energy instead of hard coal for copper production, as implemented at the Zaldivar copper mine in Chile (Antofagasta et al., 2018). This is the first copper mine in the world to use 100% renewables, such as wind and solar. It is expected to lead to a reduction in greenhouse gas emissions of about 350,000 tonnes per year. A further bolstering of the energy transition in the foreground and background systems is therefore a promising option for reducing the overall environmental impacts of copper production.

Cleaning up copper production processes and improving energy efficiency are further options for reducing impacts**.** To comprehensively reduce or eliminate environmental pollution, clean production systems should be applied across the board to the entire copper production chain. An extremely important first step is therefore to identify the origins of impacts occurring in the various links in the chain. This option has close connection to the energy transition, for example when traditional coal is replaced by low-sulfur clean coal or other clean fuels (Figure 4.8). Another approach is by way of technological innovation and improved plant and equipment. While technological innovation is crucial for improving energy efficiency, additionally presented in sensitivity analysis, it is a challenging issue. Previous studies have reported a boom in technological innovation in copper production in the mid-20th century. Prior to that, the technology had remained unchanged for 65 years (Council, 2002; Radetzki, 2009). Truly substantial efficiency improvements are not to be anticipated unless a completely new production process is developed, a perspective that is unlikely to have any impact before 2050.

While energy efficiency improvements and energy transition have an important role to play in reducing most of the impacts of copper production, these make no obvious contribution to reduce human toxicity. The main impact of declining ore grade is on the direct environment of copper mine (Table S4.7). There will inevitably be increased production of tailings, which can leach out into the runoff after mixing with rainwater and affect human health. To reduce this impact, further comprehensive recycling of tailings is required.

Increasing the share of secondary copper production is probably the most important option of all. As this study has confirmed, secondary copper production has lower per-kg environmental impacts. This option hinges on the amount of available copper scrap in China. However, given that domestically generated scrap will only be able to cover just over 50% of demand in 2050, the scope for this option appears to be fairly limited in China. Currently, the copper recycling rates in China are somewhat lower than in Europe (Soulier et al., 2018a; Soulier et al., 2018b). Although several studies argue for promoting increased copper recovery (Brahmst, 2006; Giurco and Petrie, 2007; McMillan et al., 2012), this is difficult to implement since it involves technical improvements to a range of processes, including product design, disassembly and end-of-life collection. An appropriate recycling infrastructure for end-of-life management of complex products is presently lacking as well. Therefore, to protect the environment of recycling facilities and achieve high copper recovery rates, the waste management sector needs to reorganize. In addition, China has taken steps to restrict the import of copper scrap, limiting the potential for recycling even further. Against this background, improving the efficiency of copper scrap collection and processing as well as reconsideration of import restrictions stand out as potentially very effective options.

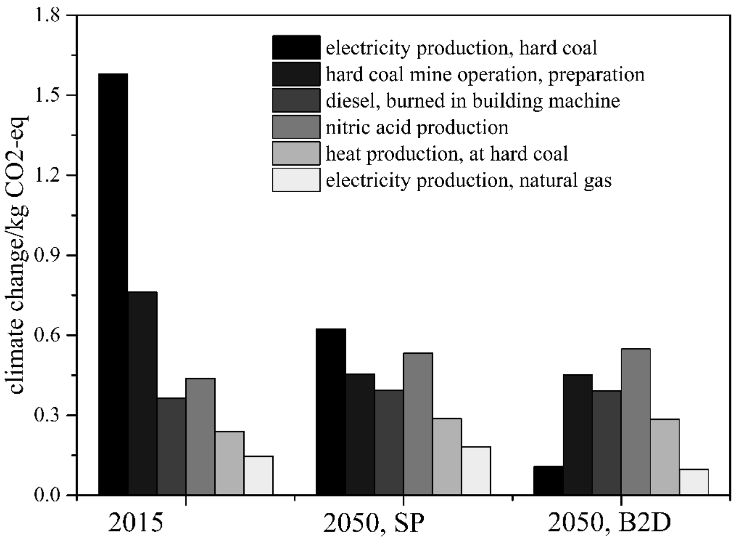


Figure 4.8 Main sources (original processes) of GHG emissions in pyrometallurgical production in SP and B2D scenarios in 2015 and 2050

4.4 Conclusions

The environmental impacts of 1 kg of copper and total supply of copper produced by pyrometallurgical, hydrometallurgical and secondary production from 2010 to 2050 were assessed using LCSA. Moreover, we identified the potential options for improving the environmental performance of Chinese copper production and consumption. This study provides strong support for establishing how to reduce the environmental impacts of copper production, permitting a better examination of the challenges confronted by China's copper industry and thus enabling better identification of solutions to these challenges.

The results indicate that the environmental impacts of pyrometallurgical copper production are expected to increase more than twofold during this period, which means this will remain the largest contributor to the environmental footprint. Secondary copper production is the most environmentally friendly production route, increasing the share of secondary copper production is the most relevant option for reducing the environmental impacts of copper production. To this end, China may focus on improving the classification of waste copper products and recycling infrastructure for end-of-life management.

Hard coal production and use are crucial contributors to climate change in the context of copper production. Cleaning up copper production processes and improving energy efficiency would also help reduce environmental impacts. The energy transition has the potential to significantly reduce the environmental impacts of copper production, but it also will increase copper demand considerably.

Energy efficiency improvements and energy transition do not visibly contribute to reduce human toxicity. With the declining ore grade, further comprehensive production of copper mine and recycling of tailings is required.

Further research into the possibilities for a circular economy, by exploring options to reduce demand via repair, reuse, refurbishing, remanufacturing and recycling, is recommended. It will be important information to support the transition towards a sustainable resource use, in China and in the world.