Environmental Impacts of Energy-Efficient Pyrometallurgical Copper Smelting Technologies

The Consequences of Technological Changes from 2010 to 2050

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Summary

The article analyzes and discusses the environmental and natural resource impacts, benefits, and greenhouse gas (GHG) mitigation potential associated with a long-term transition to more energy-efficient pyrometallurgical smelting technologies for the production of refined copper. Using generic data from the KGHM Polska Miedź S.A, Glogow I and II smelting facilities in Poland, this study employs life cycle assessment (LCA) to compare the environmental impacts of shaft and flash furnace-based smelting technologies. Additionally, this analysis accounts for likely technological changes in the more energy-efficient flash furnace smelting technologies and electricity generation from 2030 to 2050 to forecast the long-term impacts of copper production. Life cycle impact assessment results for copper production are characterized using the ReCiPe 2008 midpoint method. LCA results show that, for most impact categories, the flash-based technology can achieve significantly lower environmental impacts than a shaft furnace (i.e., to produce 1 ton of copper in 2010 generates, on average, a 24% lower overall impact). For climate change, transitioning from shaft furnace-based copper production to more efficient flash furnace technology leads to decreasing GHG emissions of 29% in 2010, 50% in 2030, and 56% in 2050.

Keywords:
copper
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industrial ecology
life cycle assessment (LCA)
shaft furnace

Introduction

Copper (Cu), owing to its excellent thermal and electrical conductivity, high ductility, corrosion resistance, and ease of recycling, is an essential material in modern society, used in electronics, telecommunication, energy, construction, and the automotive industries. Over recent decades, there has been a significant increase in Cu consumption in the world caused by growing demand for electricity and increasing popularity of electronic devices in everyday use. Since 1900, apparent usage of refined Cu has increased from less than 500,000 metric tonnes (t) to 21.2 million metric tonnes (Mt) in 2013. Usage over this period grew by a compound annual growth rate of 3.4% per year (ICSG 2014), and this growth has been most evident in developing countries such as China (Yang et al. 2013). Forecasts show that Cu demand could exceed 35 Mt annually by 2030 (Henson and Hancock 2014).

The production of Cu cathodes is a multistage process beginning with the mining and concentrating of ores containing Cu minerals, followed by smelting and electrolytic refining to produce a pure Cu cathode. Depending on the type of ore, Cu can be produced by pyro- or hydrometallurgical processes.
Concentrates produced from Cu sulfide ores are usually treated by pyrometallurgical processes and account for approximately 80% of total primary Cu production. All stages of Cu production require energy, whether in the form of electricity, explosives, hydrocarbon fuels (diesel, natural gas, fuel oil, coal, and coke), or in the form of the embodied energy of materials consumed (e.g., chemicals). It should be noted that energy demand for Cu production depends extensively on ore grade, which has been decreasing. During the early 1900s, Cu grades were around 1.5% to 4% Cu; however, these have declined substantially to a global average of 0.62% Cu in 2010 (Northey et al. 2014; Fthenakis et al. 2009). This means that in cases of low ore grades, the mining and processing stages can be more energy intensive than smelting when considering the full life cycle of refined Cu. On the other hand, for high Cu ore grades (≥3.0% Cu), smelting and refining can be the most energy-intensive step and can be a key contributor to life cycle environmental impacts (LCEIs) (Norgate and Haque 2010). According to the data obtained from KGHM Polska Miedź S.A. (analyzed case study), energy intensity of the individual processes (by percentage, average for 2003–2013) was as follows: mining 36%; smelting and refining 34%; and processing (including management of tailings waste) 30%. Data from literature suggest that efforts to reduce the increased greenhouse gas (GHG) emissions from mining and mineral processing—anticipated in the future as a result of falling ore grades and more finer-grained deposits—should focus on the Cu processing (i.e., milling) (Norgate and Haque 2010). However, the use of more environmentally benign smelting technologies can also improve the overall energy intensity of refined Cu production when considering the entire life cycle. It can be important for a region such as Europe, where the number of smelting plants significantly exceeds the number of Cu mining units, given that the European Commission (EC) plan for carbon dioxide (CO₂) reduction will regulate all industrial units. According to the International Energy Agency (IEA), the average energy use in Cu smelters worldwide is estimated to be 3.83 megawatt-hours (MWh)/t Cu (IEA 2007). Based on data presented in the Global Industrial Energy Efficiency Benchmarking Report prepared by the United Nations (UN) Industrial Development Organization, the best available technology (BAT) can produce Cu with just 1.75 MWh/t Cu, but the lowest energy intensity shown by international benchmarking studies is approximately 2.05 MWh/t Cu (Saygin et al. 2010). This implies that 46% of Cu smelting energy could be saved using currently available technologies. From a life cycle perspective, the introduction of new technologies can also contribute to reducing GHGs and, possibly, other environmental impacts. The mitigation of global GHG emissions requires the deployment of a variety of low-carbon energy generation technologies, as well as the reduction of energy demand by consumers and industry from a transition to more energy-efficient technologies throughout the economy.

In this article, life cycle assessment (LCA) is used to examine the environmental impacts of energy-efficient Cu production technologies through a case-study comparison of two pyrometallurgical facilities in Europe. Further, this analysis estimates the future changes in the life cycle impacts of Cu smelting and refining from 2010 to 2050 as smelting technologies improve and as global electricity mixes change subsequent to the IEA’s climate-change mitigation scenarios (IEA 2014). LCA results are used to estimate the future GHG mitigation potential of efficient Cu smelting technologies and analyze the possible environmental co-benefits, risks, and trade-offs that may result from a transition to more efficient Cu production.

This article was written in conjunction with a series of reports by the UN Environment Program (UNEP) International Resource Panel that will quantify and compare the environmental and natural resource impacts and benefits of using demand-side, energy-efficient technologies to mitigate GHG emissions from now until 2050. This report uses a common methodology, system boundary and background life cycle inventory data, to compare technologies on the same basis.

The Global Copper Market

The demand for Cu is affected by a number of factors, including changes in global economic and industrial production, as well as global financial conditions and geopolitical factors. According to the International Copper Study Group (ICSG), the global production of Cu mines in 2013 was 18.1 Mt of Cu. The largest producer of mined Cu was Chile (5.8 Mt of Cu in 2013). World smelter production reached 16.8 Mt in 2013, of which China accounted for over one third, followed by Japan (9%), Chile (8%), and the Russian Federation (5%), and refined Cu was over 21 Mt in 2013. In terms of demand for refined Cu, China now accounts for over 40% of the world’s consumption (ICSG 2014).

Cu has a solid foundation for growth in the long term. Although China’s economy may grow at a slower pace than in previous years, this country still remains the main catalyst for the prices of many commodities. Increasing urbanization and the growth of investments in the energy sector will be the main drivers of Cu consumption in China. Apart from China, increased demand for Cu may also come from other developing economies, including India, Brazil, Russia, Turkey, and Indonesia. By 2050, experts expect the global demand for Cu to grow by as little as 60% to as much as 300% compared to the present day (Edelstein 2008, 2012, 2013; MCS 2014; Northey et al. 2014; Kishita et al. 2012).

Overview of Copper Smelting Technologies

There are two main routes for primary Cu production: pyrometallurgical and hydrometallurgical. Pyrometallurgical processes, including the technologies analyzed in this article, are the most common, accounting for around 80% of primary Cu produced globally. These processes employ high-temperature chemical reactions to extract Cu usually from concentrates with approximately 17% to 30% Cu content. This concentrate is then dried and processed into a matte with 50% to 70% Cu content. Matte is
then converted into Cu blister containing approximately 99% Cu. Finally, the blister is electrorefined into 99.99% Cu cathodes (see figure S1 in the supporting information available on the Journal’s website). Hydrometallurgical processes, in which Cu sulfide and low-grade oxide ore are leached in a solvent extraction and electro winning process (SX-EW), are not analyzed in this article, but are discussed briefly in the Supporting Information on the Web.

Currently, the following pyrometallurgical technologies are used for the preparation of Cu from sulfide concentrates: OUTOKUMPU process (flash furnace); INCO process (flash furnace); MITSUBISHI process; electric furnaces; NORANDA process; TENIENTE converter; CONTOP process; ISASMELT process; shaft furnaces; and flame furnaces. Two of these technologies dominate Cu production methods used in the world, the OUTOKUMPU flash furnace (more than 30% of production) and smelting Cu matte in flame furnaces (approximately 25% of production), which, after shaft furnaces, are the oldest units used for smelting Cu sulfide concentrates. The following are currently considered to be BATs:

- A continuous process of smelting on Mitsubishi and Outokumpu/Kennecott principles and converting copper matte
- A copper concentrate smelting process in a flash furnace (Outokumpu Flash Smelting)
- The ISASMELT process has similar characteristics
- The technology for smelting directly into blister copper in a flash furnace
- The Noranda, El Teniente, Contop, and INCO processes provided with adequate environmental protection equipment (EC 2001)

**Energy Use**

The main factors affecting energy use in the life cycle of Cu production are the mining phase, concentrate processing (percent sulfur and iron), the smelting technology, the degree of oxygen enrichment in the process, and the generation and use of process heat. The consumption of energy in European pyrometallurgical Cu production is relatively low compared to other regions (Fthenakis et al. 2009). This is the result of using larger-scale technologies based on flash smelting that are characterized by lower primary energy use in comparison to other available technologies. The energy consumption by existing smelting technologies is shown in figure S2 in the supporting information on the Web. Less energy-efficient reverberatory furnaces are among the greatest energy consumers per metric tonne of anode Cu (Najdenov et al. 2012). The most energy-efficient processes are the Outokumpu (the energy-efficient technology analyzed in this case study) as well as the INCO technology and the Mitsubishi and Noranda (with oxygen) processes. Consequently, this LCA focuses on the modified one-stage OUTOKUMPU flash smelting technology, comparing it to the older, less energy-efficient shaft furnace technology and quantifying the benefits in terms of energy savings, environmental impact, and GHG mitigation potential. In addition, a forecast regarding potential improvements in the technology and changes in energy mix was performed for the years 2030 and 2050.

**Global Copper Demand and Future Technological Changes**

Owing to the rapid development of modern technologies, particularly in electricity generation, a continuous increase in the demand for metals and materials, including Cu, is expected (Hertwich et al. 2015). Many existing sustainability scenarios aim to solve the problems of climate change and they often assume the availability of various energy-saving products (e.g., electric vehicles) (Kishita et al. 2012). The IEA BLUE Map scenario in the Energy Technology Perspectives (ETP) offers a comprehensive, long-term analysis of trends in the energy sector and of those technologies that are essential to achieving an affordable, secure, and low-carbon system (IEA 2010). In their work, Kishita and colleagues (2012) estimate long-term metal demand based on the ETP 2010 scenarios, showing that the scenarios may require almost 4 times more Cu in 2050 than is produced in 2010. Consequently, new Cu processing technologies may be needed to achieve the goals of reducing overall energy consumption and GHG emissions, lowering production costs, and managing investments and technology risks.

In the late 1970s, reverberatory furnaces were the most common Cu smelting technology in the world. This technology is being phased out in favor of more energy-efficient flash furnaces and other smelting furnaces, such as the Outokumpu process in Europe (flash furnace, as in the KGHM Głogow II smelter, presented as technology B) that made up 70% of production by 1994. This process, together with the Mitsubishi process, is still considered to be a BAT. The Outokumpu furnaces, together with the Teniente Converters, are also dominant in South and Central America, particularly Chile (ESU and IFEU 2008).

In the field of pyrometallurgy, there is a clear trend away from multistep batch operations toward a continuous one-step operation from concentrate to blister. Several promising technologies have been introduced, particularly the flash furnace-based technologies (e.g., Outokumpu and INCO). There are strong indications that incremental improvements will eventually enable fully continuous operation, as pioneered by Mitsubishi (Ayres et al. 2002).

**Methods**

**Goal and Scope**

The goal of this study is to assess the GHG emission mitigation potential of primary Cu production technologies that are more efficient compared to the typical, existing technologies currently in use, and to investigate the potential environmental benefits, risks, and trade-offs from deploying those technologies. The scope of this study is to provide a comparative assessment from cradle to gate environmental impacts of pyrometallurgical Cu production technologies used in Europe.
from present day to 2050. For this case study, a modified one-stage OUTOKUMPU flash smelting technology (inputs and outputs data coming for KGHM Polska Miedź S.A., Glogów II smelter in Poland—generic data for 2012) was selected as a more energy-efficient technology (presented in results as technology B). Production of Cu from concentrate based on shaft furnace Cu smelting technology was chosen as the baseline technology (KGHM Glogow I smelter, presented in results as technology A). The system boundary for both smelting technologies covers all downstream processes, including materials inputs (Cu concentrates, Cu scrap, blister Cu, Cu matte, and semifinished products), operation inputs (water, air, oxygen, and chemicals), and energy used (electricity and heat) in different stages (smelting, converting, fire refining, and electro-refining—presented in figures 1 and 2 and table S3 in the supporting information on the Web). Upstream processes include emissions to air, water (in the form of disposal of waste water), and produced waste.

The functional unit of this study is 1 metric ton (t) of refined Cu (99.99% purity, grade A according to BS EN 1978:1998). The LCEIs of Cu production are presented using the ReCiPe 2008 midpoint method (Goedkoop et al. 2013).

**Hybrid Life Cycle Assessment Model of Electricity Generation and Materials Production in 2010, 2030, and 2050**

For the computation of the life cycle impacts of upstream electricity generation and materials production involved in the production of refined Cu, this analysis uses the THEMIS model (Technology Hybridized Environmental-Economic Model with Integrated Scenarios) that was developed for the aforementioned UNEP reports and elaborated by Hertwich and colleagues (2015). THEMIS is an integrated hybrid model (Suh 2004) comprised of nine regionalized versions of the ecoinvent 2.2 database (ecoinvent Center 2010), the EXIOBASE multiregional input-output database (Tukker et al. 2013), and original life cycle models of current and future low-carbon electricity generating technologies (Hertwich et al. 2015). Electricity mixes in each region and year of the model are given by IEA business as usual (baseline scenario) and climate-change mitigation (BLUE Map) scenario, including generation from renewable energy technologies and fossil fuel–based generation utilizing carbon capture and sequestration. Further, the THEMIS model accounts for future changes in the materials and energy efficiency of energy technologies and major economic sectors from 2010 to 2050.

**Life Cycle Inventory of Energy-Efficient Smelting Technology**

The Outokumpu flash furnace is currently one of the most energy-efficient and widely available technologies used in the world’s Cu smelters, and it was chosen to represent current, energy-efficient Cu production (technology B). The advantage of this process is that blister Cu is produced directly from dried concentrate. Dried Cu concentrate is injected, together with an appropriate amount of oxygen-enriched air, through a set of burners into the reaction shaft of the flash furnace. Inside the reaction shaft, the Cu concentrate melts and settles at the bottom of the furnace whereas the sulfur and organic carbon it contains are incinerated, followed by the oxidation of iron, Cu, and the dissolution of carbonates. The final product of the flash furnace process is Cu blister (with approximately 99% Cu) and slag with 11% to 15% Cu content. Cu blister is then refined in stationary anode furnaces. The Cu anodes are then sent to the electrowinning process with the final product being tradable Cu cathodes (grade A Cu according to BS EN 1978:1998). The slag from the flash furnace process is sent to an electric

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**Figure 1** Copper production flowchart for LCA based on shaft and flash furnace in KGHM Polska Miedź S.A. LCA = life cycle assessment.
furnace, where the remaining Cu is extracted. Some of the resultant sulfur dioxide (SO\textsubscript{2}) emissions are recovered and used in the production of sulfuric acid. With both technologies, dust and slag containing lead are treated in a Dorschel furnace to produce pure lead as a co-product. The environmental impacts and benefits of sulfuric acid and lead co-products are calculated using the avoided burden approach. Casts of slag from the flash furnace, which contain approximately 11% to 15% Cu, are sent to an electric furnace where the Cu is removed and reused.

Production of Cu from concentrate based on the shaft furnace smelting was chosen as the baseline (less energy efficient) technology (technology A). In this case, the mixed and briquetted concentrate containing around 30% Cu is combined with converter slag and coke and used as charge material for the shaft furnaces. Smelting this charge produces matte Cu that is an alloy of Cu sulfides, iron, and waste slag. During the process of converting matte Cu, iron and sulfur are oxidized, resulting in 98.5% pure Cu (blister). The remaining impurities are removed by fire refining in the anode furnaces. The resulting cast anodes are then sent to an electrorefinery within which the Cu in the anodes is dissolved in an electrolyte solution and, as a result of being subjected to a constant current, redeposits on cathode starter sheets creating the final product—cathode Cu with a content of 99.99% pure Cu (grade A according to BS EN 1978:1998).

The production of by-products (i.e., refined silver, gold, palladium-platinum concentrate, and selenium) from the anode slimes resulting from Cu electrorefining were not included in this analysis.

These two technologies are implemented in Poland and are used for Cu concentrate processing in the same plant. The average Cu content in extracted ore amounted to 1.57% (i.e., it equaled 481,700 t of Cu in 2013). The total amount of Cu in concentrate produced reached the level of 428,800 t of Cu. Cu content in concentrate reached 23.10% Cu in 2013. The amount of silver (Ag) in concentrate amounted to 1,199 t of Ag (KGHM 2013). The sulfide ore contains many accompanying elements. The approximate reserves of these element in Polish sulfide ore were (2013) as follows: cobalt, 121,500 t; molybdenum, 68,710 t; nickel, 56,380 t; selenium, 5,451,160 t; Ag, 103,180 t; and vanadium, 139,110 t (Szuflicki et al. 2014). In the case of hard-to-remove contaminants, such as arsenic (As) or antimony (Sb), their average content in copper ore deposits are: As, 207 milligrams per kilogram (mg/kg); Sb, 1.1 mg/kg (Bojakowska et al. 2011).

**Inventory Model**

The inventory models cover all material and energy inputs at different stages of the process (smelting, converting, fire
refining, and electro-refining). In the case of the output data, the following are taken into consideration: emissions to air; water and soil (in the form of disposal of waste water); and waste produced (table S3 in the supporting information on the Web).

**Potential Technological Improvements:**
**Energy-Efficient Technologies from 2010 to 2050**

The potential technological improvements to Cu production technologies (modified one-stage OUTOKUMPU flash smelting technology) are based on the research of the NEEDS project (New Energy Externalities Developments for Sustainability), which outlines the possible reductions in energy consumption and environmental emissions from Cu production (ESU and IFEU 2008). According to the reports, process energy use can be uniformly reduced by 6% across the different energy sources (electricity, coal, and so on). In a very optimistic scenario, a reduction of 20% is possible, attaining energy consumption similar to the INCO process (table S4 of the supporting information on the Web). Table 1 summarizes the assumptions regarding future energy use and selected air emissions. In addition to direct improvements to Cu production technologies, the global electricity mix was modified in years 2030 and 2050 to follow the IEA BLUE Map (2-degree) scenario for climate-change mitigation. These changes can also affect the LCEIs of copper production.

**Life Cycle Impact Assessment Results**

This section presents the life cycle impact assessment (LCIA) results for Cu production technologies based on the functional unit (1 t of refined Cu), comparing technologies A and B in year 2010 and showing the potential future changes in impacts by 2030 and 2050. First, the LCIA results are shown for the production of 1 t of Cu. Second, this section will present the environmental benefits and possible energy savings (1 kilowatt-hour [kWh] per amount of refined Cu produced) that resulted from technological changes in refined copper production, and will use scenario analysis to estimate the long-term potential savings of energy and GHG emissions.

**Environmental Impacts of Refined Copper Production in 2010, 2030, and 2050: A Comparison of Technologies A and B**

There are two possible dimensions for making a technological comparison between refined Cu production technologies. The first one is a comparison between the baseline technology (technology A) and energy-efficient Cu production (technology B), given the same 2010 electricity mix. The second comparison can be made between the results for energy-efficient Cu production (technology B) carried out in 2010, 2030, and 2050 and obtained by including the electricity mix in each year. Figure 2 shows the LCEIs of production of 1 t of refined Cu produced in Organization for Economic Cooperation and Development (OECD) Europe (RER), where the results are presented as a percentage of the impacts of the baseline technology (technology A) in 2010, allowing an exploration of the environmental benefits of producing Cu using a more energy-efficient process. The detailed results for all impact categories can be found in table S5 in the supporting information on the Web.

Technology B, the energy-efficient Cu processing technology, shows lower environmental impacts in almost all categories considered. On average, producing 1 t of Cu in 2010 using this technology (gray line with square marker in figure 2) generates 21% lower impacts than producing the same amount of Cu with technology A (red dashed line in Figure 2). For climate change, production of 1 t of refined Cu using technology B instead of A decreases GHG emissions from 7.65 t CO$_2$-eq in 2010 (↓29%). The highest reduction in environmental impact can be achieved for fossil depletion (decrease 1.59 t oil-eq to 0.58 t oil-eq; ↓64%), ozone depletion (decrease by almost 47%), terrestrial acidification (decrease 50.22 kg SO$_2$-eq to 28.10 kg SO$_2$-eq), and urban land occupation (39% reduction). Cumulative energy demand (CED) decreased by almost 30% from 77.18 gigajoules (GJ) (21.44 MWh) to 54.30 GJ (15.08 MWh). There is only one impact category, terrestrial eco-toxicity, for which technology B resulted in a 3 times higher environmental impact compared to technology A. In this case, the production steps of Anode 99.3% Cu and Cu blister 98.7% Cu contribute to higher terrestrial eco-toxicity.

### Table 1  Assumed energy consumption and selected air emissions (low population density area) for future primary copper production

| Energy source/Scenarios | Unit       | Present | 2030     | 2050     |
|-------------------------|------------|---------|----------|----------|
| Natural gas             | MJ/t Cu    | 6.1E+03 | 3.7E+03  | 3.6E+03  |
| Electricity mix         | kWh/t Cu   | 1.1E+03 | 6.6E+02  | 5.9E+02  |
| Hard coal coke          | Mg/t Cu    | 8.0E-02 | 8.0E-02  | 8.0E-02  |
| Heat from nonrenewable source | GJ/t Cu | 1.2E+00 | 1.2E+00  | 1.2E+00  |
| Heavy fuel oil          | tonne/t Cu | 3.8E-03 | 3.8E-03  | 3.8E-03  |
| Air emissions           | kg/kg Cu   | 1.7E+00 | 1.3E+00  | 1.1E+00  |

**Source:** Own calculation based on ESU and IFEU (2008).

CO$_2$ = carbon dioxide; t Cu = tonnes copper; MJ = megajoules; kWh = kilowatt-hours; Mg = megagrams; GJ = gigajoules; kg = kilograms.
Another question is how the environmental impacts change owing to the direct efficiency improvements to technology B and the potential decarbonization of the electricity mix. The effects of technology B improvements can be seen in figure 2 (dark blue line with circular marker for 2030 year; yellow line for 2050 year) and in table S5 in the supporting information on the Web. By 2030 and 2050, results show lower impacts for technology B in all impact categories. Greater reductions in environmental impacts are obtained by technology B improvements between 2010 and 2030, rather than further improvements in between 2030 and 2050. In a first case, the average reduction of environmental impacts was almost 34% whereas it was only around 8.5% for the second case. The technological modifications introduced by 2030 mostly resulted in decreasing impacts in the following categories: terrestrial acidification (from 28.10 kg SO\textsubscript{2}-eq to 6.78 kg SO\textsubscript{2}-eq; 76% reduction for 1 t of refined Cu); ozone depletion (from 0.2 grams [g] trichlorofluoromethane [CFC-11]-eq to 0.083 g CFC-11-eq; 58% reduction); CED (from 54.30 GJ to 22.18 GJ; 58% reduction); climate change (from 5.44 t CO\textsubscript{2}-eq to 2.66 t CO\textsubscript{2}-eq; 52% reduction); terrestrial eco-toxicity (from 1.53 kg 1,4-dichlorobenzene [1,4-DCB]-eq to 0.91 kg 1,4-DCB-eq; 40% reduction); and for fossil depletion (from 578.95 kg oil-eq to 352.39 kg oil-eq; 39% reduction). The smallest reduction (7.8%) was observed for agricultural land occupation (from 131.74 square meters per year [m\textsuperscript{2}/a] to 121.51 m\textsuperscript{2}/a).

Further improvements in technology B by 2050 result in smaller improvements in impacts (table S5 in the supporting information on the Web). The highest reductions in impacts were obtained in the following categories: terrestrial eco-toxicity (from 0.91 kg 1,4-DCB-eq to 0.69 kg 1,4-DCB-eq; 24% reduction); ozone depletion (from 0.083 g CFC-11-eq to 0.066 g CFC-11-eq; 21% reduction); and fossil depletion (from 352.39 kg oil-eq to 284.69 kg oil-eq; 19% reduction).

Contribution analyses for technologies A and B in the year 2010 show that the dominant contributor is the process of briquette 19% to 22% Cu production, which includes the embodied upstream impacts of Cu concentrate production (the graphical results of contribution analysis can be found on figures S4 and S5 in the supporting information on the Web), particularly for the following environmental impacts: human toxicity (98% technology A, 74% technology B); freshwater eco-toxicity (77% technology A, 99% technology B); freshwater eutrophication (99% technology A, 80% technology B); metal depletion (100% technology A, 81% technology B); and water depletion (100% technology A, 78% technology B). However, whereas the production of Cu briquette 19% to 22% Cu in case of technology A is responsible for 87% contribution, the average contribution of this element in technology B falls to 51%.

The second significant contributor in technology A is the production of Cu matte, 52% to 56% Cu (Cu stone), which shows noteworthy contribution within the scope of the natural resource input-related impact categories (agricultural land occupation 30%, CED total 26%, and fossil depletion 28%). For technology B, the contribution of the process of Anode, 99.3% Cu production in technology B is much larger compared to technology A: The arithmetic mean contribution of all impact categories increases from a 1% for technology A to 25% for technology B.

**Scenario Analysis**

Scenario analysis was performed to quantify the aggregate GHG emissions and CED for Cu production from 2010 to 2050, accounting for changes in Cu processing technologies, market shares, and global electricity mixes. The results are first presented based on the environmental benefits coinciding with 1 kWh of saved energy. In the second scenario analysis, the environmental impacts resulting from direct improvements in...
to Cu smelting technologies were compared to the environmental impacts resulting from changes to European electricity generation and materials production.

The environmental impacts resulting from Cu production must be put into context, given that further growth of in-use stock is highly dependent on growing economic output, which leads to ever increasing per capita in-use stock in the industrialized and developing world (Gerst 2009). Therefore within the last scenario analysis, the LCIA results were referenced against the global demand for refined Cu, taking into account the share in the market of individual technologies.

**Changes in Greenhouse Gas Emissions and Cumulative Energy Demand as the Consequences of Technological Changes within the Production of Refined Copper, per 1 Kilowatt-Hour Saved Energy**

The first scenario analysis assesses the reductions in environmental impacts calculated per 1 kWh of energy saved owing to technological change from 2010 to 2030. Two situations were assumed:

1. Transition from technology A (Copper_RER_tech_A_2010) to technology B (Copper_RER_tech_B_2010) in the production of refined copper
2. Development of technology B (Copper_RER_tech_B_2010) through improvements implemented by 2030 (Copper_RER_tech_B_2030)

Based on the collected inventory data, it was estimated that producing 1 t of Cu using the technology A is associated with the consumption of 4.66 MWh of energy (electricity and heat), which is approximately 17.75% more than the average energy use of Cu smelters worldwide assumed for this period (3.83 MWh/t Cu). Producing the same amount of Cu with technology B in 2010 requires just 3.63 MWh/t Cu, a reduction of 22.12%. This level of energy consumption is close to the global average use, but is still far from the value of BAT (1.75 MWh/t Cu). The likely changes in technology B by 2030 would decrease energy intensity to the level of 2.47 MWh/t Cu, 32% less energy than 2010. Based on the above data, the “s” scaling factors were determined for both situations according to the following equations (equations 1 and 2).

\[
s_1 = \frac{-1 \text{kWh}}{(E_{\text{Copper_RER_tech_B_2010}} - E_{\text{Copper_RER_tech_A_2010}})} = \frac{-1}{3.63 \times 10^3 - 4.66 \times 10^3} = 9.70 \times 10^{-4}\]

\[
s_2 = \frac{-1 \text{kWh}}{(E_{\text{Copper_RER_tech_B_2030}} - E_{\text{Copper_RER_tech_B_2010}})} = \frac{-1}{2.47 \times 10^3 - 3.63 \times 10^3} = 8.62 \times 10^{-4}\]

The result for the first situation (s1) indicates that producing 9.70 \times 10^{-4} t Cu (970 g) using technology B in 2010 instead of producing the same amount of Cu by technology A results in an energy savings of 1 kWh. By introducing the forecasted changes to technology B in 2030, 1 kWh of energy savings can be obtained by producing 8.62 \times 10^{-4} t Cu (862 g). Table 2 and figure 2 show the reductions in impacts for individual impact categories, accounting from both types of technological change and calculated using the following relationship (equations 3 and 4):

\[
\text{Impact of saving 1 kWh} = s_1 \times (L_{\text{IC} \text{opper_RER_tech_B_2010}} - L_{\text{IC} \text{opper_RER_tech_A_2010}})\]

\[
\text{Impact of saving 1 kWh} = s_2 \times (L_{\text{IC} \text{opper_RER_tech_B_2030}} - L_{\text{IC} \text{opper_RER_tech_B_2010}})\]
The results presented show two important insights. First, both fore- and background technological changes lead to increasing environmental benefits per kWh of energy saved, as evidenced by the negative values of the results. The second question is which technological change gives the greatest potential environmental benefits per kWh of energy saved? In terms of percent decrease, both types of technological changes result in a similar reductions in impact on climate change, given that both the transition from technology A to B in 2010 and further improvements in technology B from 2010–2030 reduce GHG emissions by 29%.

Comparison between Changes in Greenhouse Gas Emissions and Cumulative Energy Demand in Foreground and Background Processes

Using LCA, the potential environmental impacts are estimated, related to the entire production system, including the impacts from direct emissions during Cu production as well as the embodied, life cycle impacts of materials and energy production. The scenario analysis considers two types of changes: (1) direct improvements to Cu processing (foreground system; FS) and (2) the changing European and global electricity production system (background system; BS), as prescribed by the IEA Blue Map scenario. As a result, a number of situations can be examined, showing the individual and combined effects of technological improvements in the foreground system and decarbonization of electricity (background) on the overall environmental impacts of Cu production.

Table 3 summarizes environmental impacts for nine defined situations in relation to climate change (Figure 3), whereas analogous results for cumulative energy demand are presented in table S6 and figure S6 in the supporting information on the Web. Table 3 presents the GHG emissions calculated for production of 1 t of Cu by using technology B in all analyzed periods and technological variants. The rows of table 3 represent various technological variants (foreground system) whereas the columns relate to the electricity mix (BS) representative for analyzed years. For example, a result of 5.44 kilotonnes CO$_2$-eq means that the GHG emissions associated with the production of 1 t of Cu by using the technology representative for year 2010 and the electricity mix suitable for the same year. Figure 3 shows the reductions in GHG emissions per 1 t of Cu owing to
The article uses LCA to examine the environmental implications associated with the use of two prominent pyrometallurgical technologies for the production of refined Cu: a Cu shaft furnace smelting technology (technology A), and a modified one-stage OUTOKUMPU flash smelting technology (technology B, KGHM 2014). One of the goals of the study was to assess the potential mitigation of global GHG emissions resulting from the deployment of more energy-efficient technologies, and to quantify possible future effects of technological changes in Cu production expected by the years 2030 and 2050.

LCA results show that, for most impact categories, the energy-efficient technology (technology B) can achieve significantly lower environmental impacts in almost every category. To produce 1 t of Cu in 2010 using this technology generates, on average, a 24% lower overall impact than producing the same amount of Cu using the less energy-efficient, baseline technology (technology A).

In Europe and some other developed countries, there are strong policies for the reduction of GHG emissions (e.g., the European Union [EU] aims to reduce domestic GHG emissions to at least 40% below the 1990 level by 2030). These policies will not only impact energy producers, but also materials producers such as Cu smelters in the EU (mainly Germany, Poland, Spain, and Belgium) that produce approximately 2.5 Mt of Cu per year. The EU climate targets could be achieved by changes to the electricity grid mix (i.e., investment in low-carbon energy technologies) as well as by investing in more energy-efficient materials production technologies, such as the efficient Cu production technology. The overall life cycle energy consumption of producing refined copper is still highly dependent on ore grade, which is likely to decline over time. Assuming an average content of ore at 0.8% Cu, the concentrate production stage (mining and ore processing) is the most energy-intensive stage in the life cycle of Cu. Declining ore grades, together with the likelihood of more finely grained and complex deposits in the future, will increase the energy and GHG impacts of these stages (Norgate and Haque 2010). It is therefore important to reduce the energy demand of other Cu production phases, including smelting, where more environmentally friendly technologies that do not depend on the state of Cu ore grades may be more easily scaled up and deployed across the globe in order to minimize or offset the effects of increased GHG emissions and direct energy consumption resulting from declining ore grades.

### Discussion and Conclusions

The article focuses mainly on the environmental consequences of producing 1 t of Cu using technologies A and B in different years given different global electricity generation scenarios. In order to place the results of this analysis in a broader context, scenario analyses are used to estimate the total annual environmental impacts of Cu production. These LCIA results are calculated based on estimates of the forecasted annual demand for Cu by 2050 and the expected market shares of both technologies (Figure 4) (ICSG 2013). Table 4 presents the assumptions used for this scenario analysis. The global demand for Cu was estimated for 2010, 2030, and 2050 based on estimates from literature (Kishita et al. 2012; Northey et al. 2014), statistical reports (U.S. Geological Survey Minerals Yearbooks) Edelstein 2008, 2012, 2013; MCS 2014), and the authors’ own calculations. Two possible scenarios are considered for demand in 2050. The first scenario (2050) assumes a lower bound for global annual Cu demand (30.52 Mt per year), whereas the second (2050°) assumes an upper bound (78.12 Mt per year). Next, the estimated demand in each year (defined as “total” in table 4) was multiplied by the market share for each technology to give the total amount of Cu produced by each technology in each year. These values were treated as the new functional unit (in place of 1 t of Cu) for which the LCIA results were calculated. Table 5 presents the GHG emissions related to world demand for Cu produced by technologies A and B in each year.

### Table 5 Emissions of GHGs related to estimated global demand for refined copper covered by technology “A” and “B”

| Technology type | 2010 | 2030 | 2050′ | 2050° |
|-----------------|------|------|-------|-------|
| Technology A    | 2.3E+01 | Out of use | Out of use | Out of use |
| Technology B    | 6.9E+01 | 8.7E+01 | 4.7E+01 | 1.2E+02 |
| Total (A+B)     | 9.3E+01 | 8.7E+01 | 4.7E+01 | 1.2E+02 |

Note: The first scenario (2050′), assumes a lower bound for global annual copper demand (30.52 Mt per year), while the second (2050°) assumes an upper bound (78.12 Mt per year). GHG = greenhouse gas; Mt = megatonnes; CO₂-eq = carbon dioxide equivalent.

### The Environmental Effects of Technological Changes in the Production of Refined Copper: Forecasts Related to Global Copper Demand and Market Shares of Technologies

The article uses LCA to examine the environmental implications associated with the use of two prominent pyrometallurgical technologies for the production of refined Cu: a Cu shaft furnace smelting technology (technology A), and a modified one-stage OUTOKUMPU flash smelting technology (technology B, KGHM 2014). One of the goals of the study was to assess the potential mitigation of global GHG emissions resulting from the deployment of more energy-efficient technologies, and to quantify possible future effects of technological changes in Cu production expected by the years 2030 and 2050.

LCA results show that, for most impact categories, the energy-efficient technology (technology B) can achieve significantly lower environmental impacts in almost every category. To produce 1 t of Cu in 2010 using this technology generates, on average, a 24% lower overall impact than producing the same amount of Cu using the less energy-efficient, baseline technology (technology A).

In Europe and some other developed countries, there are strong policies for the reduction of GHG emissions (e.g., the European Union [EU] aims to reduce domestic GHG emissions to at least 40% below the 1990 level by 2030). These policies will not only impact energy producers, but also materials producers such as Cu smelters in the EU (mainly Germany, Poland, Spain, and Belgium) that produce approximately 2.5 Mt of Cu per year. The EU climate targets could be achieved by changes to the electricity grid mix (i.e., investment in low-carbon energy technologies) as well as by investing in more energy-efficient materials production technologies, such as the efficient Cu production technology. The overall life cycle energy consumption of producing refined copper is still highly dependent on ore grade, which is likely to decline over time. Assuming an average content of ore at 0.8% Cu, the concentrate production stage (mining and ore processing) is the most energy-intensive stage in the life cycle of Cu. Declining ore grades, together with the likelihood of more finely grained and complex deposits in the future, will increase the energy and GHG impacts of these stages (Norgate and Haque 2010). It is therefore important to reduce the energy demand of other Cu production phases, including smelting, where more environmentally friendly technologies that do not depend on the state of Cu ore grades may be more easily scaled up and deployed across the globe in order to minimize or offset the effects of increased GHG emissions and direct energy consumption resulting from declining ore grades.
According to the results of this analysis, a transition from technology A to B and further improvements to technology B by 2030 and 2050 can reduce GHG emissions from Cu production by 29% and 38% compared to present day. Further technological changes projected by the NEEDS project show even greater opportunities to reduce GHGs. Owing to a major shift from hard coal to natural gas and a reduction in direct energy consumption, the cumulative CO$_2$-eq emissions are expected to be reduced in 2050 by 34% and 45% per 1 kg of copper production, in relation to today’s value in the realistic-optimistic and very optimistic scenario, respectively (ESU and IFEU 2008).

The expected global demand for refined Cu and the approximate market shares of production technologies were used to estimate the overall GHG emissions from Cu production. According to this scenario analysis, technologies A and B cover the total demand in 2010 of 15.79 Mt of Cu. In 2030, the use of technology of B was anticipated to produce 22.52 Mt, an increase of 43%, as technology A is phased out. Production of this amount of Cu is associated with GHG emissions of approximately 86.89 kt CO$_2$-eq. Further, results show that an increase in global Cu demand will not necessarily lead to a proportional increase in emissions, and that an overall reduction in environmental impacts from Cu production may be possible. Such a reduction in energy consumption and GHG emissions may be possible by phasing out the less energy-efficient processing technologies (such as technology A), further improving the energy efficiency of existing BATs (including the Outokumpu process) and decarbonizing global electricity generation. The uncertainty associated with these results and the sensitivity of results to assumptions is explored further in the Supporting Information on the Web.

The analysis in this article does account for the allocation of the environmental impacts of production co-products (such as refined silver, gold, palladium-platinum concentrate, and selenium). Their recovery could contribute to additional environmental and economic benefits (production of co-products can reach up to 20% of the value of primary Cu production).

Regarding technological improvements, the major trends in Cu melting, refining, and electrowinning involve hydrometallurgical methods and further improvements in pyrometallurgy. SX-EW, a process that can have environmental and economic advantages, is used to process low-grade oxide ores and some copper production waste. The use of this technology has greatly increased in recent years and improvements in the energy intensity of this technology and waste management (using aqueous acid) could contribute to this technology having a large market share in the production of refined copper in the future. It should be noted that energy demand for copper production in both pyro- and hydrometallurgical processes depends extensively on ore grade (Norgate and Jahanshahi 2010). Concentrates produced from Cu sulphide ores are usually treated by pyrometallurgical processes, which account for approximately 80% of total primary Cu production. Therefore, the results presented in this analysis show the environmental benefits resulting from the use of pyrometallurgical technologies, which are mostly flash furnace based (a modified one-stage OUTOKUMPU process).

The technology improvements assumed in this analysis and a wider use of flash furnace–based technologies (replacing shaft furnace–based technologies) can contribute to a general reduction in environmental burdens, GHG emissions, and energy demand for this technology. Given the likely market shares of different technologies assumed in the models, flash furnace–based technologies may continue to dominate until 2030 owing to their higher energy efficiency. The deteriorating quality of deposits and technological improvements in subsequent years may contribute to an increased use of technologies based on solvent extraction, which are not considered in this article.

Further research is needed to determine whether future declines in ore grade will outweigh the environmental benefits calculated for efficient Cu production in this article, or whether decarbonization of electricity and increased energy efficiency in Cu production will be sufficient to help meet global climate goals and reduce the overall environmental burdens associated with refined Cu production.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides a technological overview of the hydrometallurgical process used in copper production, a discussion of the environmental implications of current efficient technology in copper production, an overview of the inventory model, a review of potential technological improvements, a detailed analysis of the environmental impacts, and a sensitivity and uncertainty analysis.