Updated Life Cycle Inventory of Copper: Imports from Chile

by

J. Kelly, Q. Dai, and A. Elgowainy

Systems Assessment Group

Energy Systems Division

Argonne National Laboratory

September 2015

CONTENTS

TABLES

ACRONYMS

Cu	Copper
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
ICEV	internal combustion engine vehicle
LCA	life cycle analysis
LCI	life cycle inventory
LX-SX-EX	leaching solvent extraction electrowinning

Updated Life Cycle Inventory of Copper: Imports from Chile

Jarod C. Kelly, Qiang Dai, and Amgad Elgowainy

Energy Systems Division

Argonne National Laboratory

September 2015

1 INTRODUCTION

This report examines the life cycle inventory (LCI) data for copper within Argonne National Laboratory's GREET^{TM} (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model and provides updates with available literature data. An LCI provides the critical data associated with materials, fuels, and processes which are utilized within life cycle analysis (LCA). GREET serves as an LCI database as well as an LCA tool for analyzing those fuels and materials relevant to transportation with a focus on the United States. GREET is founded upon the principles of ISO 14040 standards, and it relies upon non-proprietary, open source data sets for the development of its LCI. As such, GREET relies upon continual updates and data verification to remain appropriate for the analysis of automotive and other transportation technologies. GREET uses material and process data available through academic literature and, often, LCI data that can be obtained from material industry groups.

Copper is a highly ductile and conductive material, making it the preferred electricity carrier for many electronic and electrical applications. It is widely used within the automotive industry to transport electricity via the vehicle's wiring harness. Additionally, while aluminum is widely used to carry electricity in power lines, copper is a more attractive material for the packaging constraints inherent to the limited spaces of vehicle applications. Within the automotive market, copper is primarily used in the wire form, though copper is also available as sheet, foil, and tube, and can be found in radiators (which are increasingly made of aluminum) and other heat transfer devices. This report focuses on copper wire.

Copper represents 1.29% of a conventional internal combustion engine vehicle's (ICEV) weight, and accounts for 1.00% of the vehicle's life cycle energy burden and 0.96% of its greenhouse gas burden (Argonne National Laboratory 2014). But, as vehicle technologies progress toward increased electrification, it is likely that the use of copper will increase (copper represents 10.9% of the 463 lb lithium ion battery for electric vehicles in GREET), and if coupled with vehicle lightweighting efforts (which are unlikely to include reductions in copper mass) this will increase the share of copper's burden on the total vehicle life cycle.

A GREET LCI update was conducted for copper in 2012 (Keoleian et al. 2012). That report suggested that a copper industry group would release a new LCI report in the near future. And, while that report is not publicly available (LCI data is available for purchase), thus not available for use in GREET, we have obtained that data to confirm the 2012 updates in Keoleian et al. (2012). Analysis suggests that the underlying values for copper currently within GREET are acceptable for domestic production (mining, cathode production, and wire drawing). However, future updates should be considered whenever new non-proprietary data become available.

Copper is a widely distributed mineral that is typically mined in the form of sulfide and oxide ores. Worldwide, the primary producers of copper are Chile, 31%; China, 8.7%; Peru, 7.5%; and the United States 7.3% in descending order of production (U.S. Geological Survey 2015). The United States has a net import reliance of 31% and domestic production of 69% (U.S. Geological Survey 2015). The imports come from Chile, 51%; Canada, 26%; Mexico, 13%; Peru, 6%; and other, 4% (U.S. Geological Survey 2015). A variety of tariffs, and tariff exemptions account for many of the discrepancies of worldwide production and import statistics. Domestically, 99% of copper is produced in Arizona, Utah, New Mexico, Nevada, and Montana (in descending order of production quantity) (U.S. Geological Survey 2015).

Chile represents the largest import share for the U.S. market at 16% (31%*51%). Therefore, this report analyzes the life cycle impacts associated with Chilean production of copper. The system boundary is cradle-to-gate for the copper cathode, thus including raw material extraction and proceeding through cathode production. Copper wire is the basic unit within GREET, so we also include that stage, but acknowledge that the wire drawing stage is based on the previous report, and not specific to Chilean production. However, most Chilean copper is imported to the United States in cathode form and thus wire drawing would occur domestically. The LCI data will be incorporated within the 2015 update to GREET's vehicle cycle model.

2 COPPER PRODUCTION

Worldwide, copper is extracted primary from two mineral ores types: sulfide and oxide. Roughly 80% of worldwide copper production (70%, for US; 65% for Chile) comes from sulfide ores, with the remainder derived from oxide ores. Sulfide ores are processed via a pyrometallurgical process, while oxide ores are processed via a hydrometallurgical process (Fthenakis, Wang, and Kim 2009; Edelstein 2013). Copper ore grades are low, with the worldwide average around 0.8% (Fthenakis, Wang, and Kim 2009), and copper is mined from both open pits and underground mines.

After mining, copper sulfide ores are crushed, ground and concentrated in a process called beneficiation. This increases the concentration of the copper to between 20 and 30% through removal of non-copper containing mineral (gangue, or tailings). In modern production practices, the copper concentrate is then sent to a smelter where roasting and smelting occur, (formerly, roasting was carried out as a separate step prior to smelting). The resulting product, matte, contains about 40% copper, and it is sent to a converter where it is combined with oxygen-enriched air to yield blister copper, 98-99% copper. Blister copper is further processed via fire refining to remove impurities and results in a copper anode of 99–99.6% copper. Finally, the copper anode is dissolved in an acidic copper sulfate solution and electrolytically refined to produce a copper cathode of 99.97-99.99% copper. SO2 is an off-gassing byproduct of copper production, but it can be economically converted to sulfuric acid to avoid SO2 emissions (Kundig and Dresher 2000).

The leach-solvent extraction-electrowinning (LX-SX-EX) process can be used to recover copper from both copper oxide ores and residual copper in old mine waste dumps, and its use within the industry is seen as adjunct to conventional smelting, rather than substitutional ("Innovations: How Hydrometallurgy and the SX/EW Process Made Copper the 'Green' Metal" 2015). Crushed ores are typically heaped into leach pads where a leaching solution, sulfuric acid, is applied in order to dissolve the contained copper and recover it in a pregnant leach solution. The copper is then concentrated within a solvent-extraction plant. The concentrated copper solution is then sent to an electrowinning cell, where copper is plated onto electrolysis cathodes. The sulfuric acid is processed, recovered and reused within the leaching process. Recovery rates for copper from oxide ores are between 60% and 70%.

2.1 CHILEAN COPPER

Chilean copper is recovered from both sulfide and oxide ores. The Chilean Copper Commission has detailed mining statistics and data concerning the life cycle energy and greenhouse gas (GHG) emissions associated with copper production (Chilean Copper Commission 2012; Pimentel Hunt 2009). The data from those reports represent the vast majority of Chilean copper production (approaching 99%) (Pimentel Hunt 2009). Data for energy consumption is broken out by "fuel" and "electricity" as well as production stages including mining, concentrating, smelting, refining, LX-SX-EX, and services. Thus, we can distinguish between the pyrometallurgical and hydrometallurgical pathways.

From a fuels perspective, both Chilean reports provide only the primary energy within each step, but not each step's specific fuel input as required in GREET. However, the Pimentel Hunt report does indicate that in 2008 the direct fuel use was 79.6% diesel, 16.7% Enap 6 (residual oil), and 1.7% natural gas on an energy content basis (Pimentel Hunt 2009). This leaves 2% unaccounted for, so we have divided each value by 98% to scale them up resulting in 81.2%, 17.1%, and 1.7% for diesel, residual oil, and natural gas, respectively. This can be applied to the bulk production of copper, but is not appropriate for a stage-by-stage analysis since no details are provided regarding the fuel use associated with individual stages. Table 1 shows the fuel input, electricity input, and total energy per ton of refined copper cathode for each stage in 2012. Note that in all tables rounding may contribute to slight disparities between totals and constituent parts.

Compared to GREET 2 (v. 2014), the weighted average mining (~90% open pit and 10% underground) energy for Chile is greater than U.S. production (6.495 MMBtu per ton_Cu_cathode versus 2.150 MMBtu per ton_Cu_cathode), and copper smelting and refining via pyrometallurgy is also greater (20.591 MMBtu per ton_Cu_cathode versus 19.782 MMBtu per ton_Cu_cathode). The energy use during Chilean hydrometallurgy is less than that during pyrometallurgy, at only 13.207 MMBtu per ton_Cu_cathode. Again, note that there is no energy input information by fuel types for the stages comprising the pyrometallurgy or the hydrometallurgy, only total energy, so the mining and subsequent processing stages are combined in later analysis (Tables 2 and 3).

TABLE 1. Energy inputs for various stages of Chilean copper production (Chilean Copper Commission 2012)

Process stage	MMBtu fuel per ton_Cu_cathode	MMBtu electricity per ton_Cu_cathode	Total MMBtu per ton_Cu_cathode
Open Pit mining	6.369	0.508	6.877
Underground Mine	0.905	2.025	2.930
Mine (weighted avg)	5.834	0.661	6.495
Concentrating	0.173	9.512	9.686
Smelter	3.878	3.366	7.244
Electrolytic Refining	1.267	1.153	2.420
LW/SX/EW	2.656	9.309	11.965
Services	0.661	0.581	1.241

The pyrometallurgical process consists of mining, concentrating, smelting, electrolytic refining and services. Table 2 shows the total energy for those processes. The hydrometallurgical process consists of mining, LX-SX-EX and services and is presented in Table 3. In both instances the weighted average of open pit and underground mining are used.

TABLE 2. Energy use in Chilean copper cathode via a pyrometallurgical route

	(MMBtu per ton_Cu_cathode)
Diesel	9.595
Residual oil	2.013
Natural gas	0.205
Electricity	15.273
Total	27.086

TABLE 3. Energy use in Chilean copper cathode via a hydrometallurgical route

	(MMBtu per ton_Cu_cathode)
Diesel	7.433
Residual oil	1.559
Natural gas	0.159
Electricity	10.552
Total	19.702

According to the U.S. Geological Survey (USGS), 370,000 metric tons of refined copper was imported to the U.S. from Chile in 2011, but no distinction is made regarding its production mix (pyrometallurgical, or hydrometallurgical) (Edelstein 2013). However, the bulk production, by production route, is available from the USGS for the total production of Chile in the years 2007-2011, and the average production during those years was 63% via the pyrometallurgical route and 37% via hydrometallurgical (Edelstein 2013). Based on that, and the data presented in Tables 2 and 3, the weighted average energy consumption for Chilean produced copper is calculated and shown in Table 4. The total energy burden is 24.338 MMBtu, while combined energy consumption for mining and processing (up to but not including wire drawing) within GREET 2 (v. 2014) is 21.932 MMBtu.

TABLE 4. Energy use in Chilean copper cathode using a weighted average of both the pyrometallurgical and hydrometallurgical routes

	(MMBtu per ton_Cu_cathode)
Diesel	8.790
Residual oil	1.844
Natural gas	0.188
Electricity	13.516
Total	24.338

Copper production emissions largely derive from the emissions associated with fuel combustion, either onsite or through electricity generation. However, there are still some process emissions associated with copper production, namely SO2 and particulate matter (PM10, diameter of 10 micrometers or less). Despite efforts to convert SO2 emissions to sulfuric acid, some will still be lost to the atmosphere. The previous GREET copper update identifies SO2 (125,927.305 g/ton Cu product) and PM10 (54.447 g/ton Cu product) emissions associated with North American copper production, and those will be applied to Chilean copper production (Keoleian et al. 2012).

As mentioned previously, wire drawing will occur in the U.S. since Chilean copper is imported into the U.S. in cathode form. Wire drawing energy data available in GREET 2 (v.

2014) are presented in Table 5 along with the resulting total Chilean energy burden for one ton of copper wire. Those values, along with the process emissions mentioned above, will be included within GREET 2 (2015 model) and the electricity consumed for Chilean copper production will be specifically associated with the Chilean grid. Data for the Chilean grid mix comes from the International Energy Agency and transmission and distribution loss data comes from the World Bank (7% loss), for 2012 and 2011 data, respectively, (International Energy Agency 2015; The World Bank 2015). The Chilean grid mix is shown in Table 6.

TABLE 5. Energy use in average Chilean copper cathode and converting that to drawn wire (Argonne National Laboratory 2014)

	Chilean copper (MMBtu per ton_Cu_cathode)	Wire drawing (U.S.) (MMBtu per ton_ Cu_wire)	Total (MMBtu per ton_ Cu_wire)
Diesel	8.790	0	8.790
Residual oil	1.844	0.839	2.683
Natural gas	0.188	0	0.188
Coal	0	0.012	0.012
Electricity	13.516	1.631	15.147
Total	24.338	2.482	26.820

TABLE 6. Chilean electricity grid mix for 2012 (International Energy Agency 2015)

Fuel source	Share of electricity production
Residual oil	8.8%
Natural gas	18.4%
Coal	36.3%
Nuclear	0.0%
Biomass	7.0%
Others	29.5%

REFERENCES

Argonne National Laboratory. 2014. "GREET 2 (Vehicle-Cycle Model)." October 3. https://greet.es.anl.gov/greet_2_series.

Chilean Copper Commission. 2012. "Yearbook: Copper and Other Mineral Statistics 1993-2012." http://www.cochilco.cl/english/statistics/yearbook.asp.

Edelstein, Daniel L. 2013. *2011 Minerals Yearbook - Copper*. Reston, Virginia: U.S. Department of the Interior, U.S. Geological Survey.

Fthenakis, Vasilis, Wenming Wang, and Hyung Chul Kim. 2009. "Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics." *Renewable and Sustainable Energy Reviews* 13 (3): 493–517.

"Innovations: How Hydrometallurgy and the SX/EW Process Made Copper the 'Green' Metal." 2015. Accessed July 13. http://www.copper.org/publications/newsletters/innovations/2001/08/hydrometallurgy.html.

International Energy Agency. 2015. "IEA - Report: Chile: Electricity and Heat for 2012." Accessed July 27. http://www.iea.org/statistics/statisticssearch/report/?country=CHILE&product=electricityandheat&year=2012.

Keoleian, Gregory, Shelie Miller, Robert De Kleine, Andrew Fang, and Janet Mosley. 2012. "Life Cycle Material Data Update for GREET Model." *Report No. CSS12-12*. https://greet.es.anl.gov/publication-greet2-lca-update.

Kundig, K. J. A., and W. H. Dresher. 2000. "Copper." In *Kirk-Othmer Encyclopedia of Chemical Technology*. John Wiley & Sons, Inc. http://onlinelibrary.wiley.com/doi/10.1002/0471238961.0315161607051518.a01.pub3/abstract.

Pimentel Hunt, Sara Inés. 2009. "Energy and Greenhouse Gas Emissions in the Chilean Copper Mining Industry." Intellectual Property Registration No. 181718. Chilean Copper Commission.

The World Bank. 2015. "Electric Power Transmission and Distribution Losses." Accessed July 27. http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS.

U.S. Geological Survey. 2015. *Mineral Commodity Summaries 2015: U.S. Geological Survey*. http://dx.doi.org/10.3133/70140094.