ABSTRACT 01

Assessment of greenhouse gas emission from copper production: A case study of El Teniente Copper Mine

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ABSTRACT

The embodied energy and global warming potential (GWP) associated with copper anode production from Codelco's El Teniente operations in Chile was assessed. A life cycle inventory was developed using publically available data and input into the life cycle assessment software SimaPro. Anodes produced from this site were estimated to have an embodied energy of 44.3 MJ/kg Cu, with an associated GWP of 2.6 kg CO_2-e/kg Cu. Electricity consumption is the source of 80 to 90% of El Teniente Scope 1 and Scope 2 greenhouse gas emission. The emission factor of the SIC electricity grid was shown to have a large impact on the overall embodied emission of the copper product although about 46% electricity is sourced from hydroelectricity. Therefore, efforts to reduce the embodied greenhouse gas emission of copper anodes produced from the site should focus on reducing the sites electricity demand as well as sourcing electricity with a lower emission factor. Increasing the proportion of electricity further from hydroelectricity source instead of decreasing it from current state would assist to achieve lower GWP footprint of copper production from this site.

The specific embodied energy is higher compared with copper produced in Australia but the specific GHG is relatively lower than that of copper in Australia because of the lower GHG emission factor of electricity in Chile. However, the GHG emission factor in Chile is increasing because the proportion of hydro-electricity as part of total electricity is decreasing and fossil fuelled fired power plants is increasing.

KEYWORDS**:** Copper, Life Cycle Assessment, greenhouse gas, environment, El Teniente

INTRODUCTION

The global mined production of copper was about 16 million tonnes in 2011 with nearly 5.3 million tonnes produced from Chile (ICSG, 2012). Global per capita refined copper usage increased steadily from about 1.3 kg in 1950 to about 2.8 kg in 2010 (ICSG, 2012) and declining ore grades and increasing mine depths are placing upwards pressure on the economic and environmental cost of copper production. Chile is the largest copper producing country in the world and El Teniente operations has the largest underground copper mine in the world. A life cycle assessment (LCA) has been conducted to identify key variables that contribute to environmental impacts, objective comparisons of competing technologies to be made and enable the development of strategies for reducing environmental impacts to be developed.

This paper forms part of CSIRO's ongoing work into LCA of mining, mineral processing and metal production processes. Undertaking an LCA has several advantages as it enables the CSIRO to evaluate various aspects of mining and mineral processing. Previous LCA studies specific to copper that focused on energy consumption and GHG emission have compared different copper production processes and examined major variables such as ore grades and grind sizes (Norgate et al., 2007; Norgate and Haque, 2010; Norgate and Jahanshahi, 2010). CSIRO has conducted similar LCAs for the production of gold (Norgate and Haque, 2012), ferroalloys (Haque and Norgate, 2013) and nickel (Norgate and Jahanshahi, 2011) and is continuing to develop LCA tools for estimation of water footprints of mineral commodities (Norgate and Lovel, 2006).

There are few site specific case-studies in the open literature. The recently established CSIRO Chile International Centre of Excellence has provided the motivation for this site based case study on El Teniente operation that may be relevant for inclusion within the scope of the activities of this centre.

METHODOLOGY

The GHG emissions of copper production site were estimated from data collected from the open literature and company sustainability reports (Northey et al., 2013). An LCA of the El Teniente underground mine, concentrator and smelter operation in Chile was conducted to examine the contribution of individual processes to the embodied energy and GHG impacts of the copper anode produced. The LCA was conducted in accordance to international standards (ISO 14044, 2006) for LCA and Australian Best Practice Guidelines (Grant and Peters, 2008). A life cycle inventory table was developed for the major inputs and outputs from the individual unit processes. Primary data has been converted to develop secondary data sets where appropriate for input to a LCA model. SimaPro 7.3.3 (PRe, 2013) software was used to determine the GWP or GHG emission footprint expressed in kilogram carbon dioxide equivalent unit (kg CO_2-e) per tonne of primary copper metal.

EL TENIENTE MINE SITE: MINING METHOD, HAULING, DEWATERING AND VENTILATION

El Teniente is the largest underground copper mine in operation in the world and is located about 80 km south of Santiago. The mine extracts ore from the deposit through a block and panel caving process (Elgenklöw, 2003). The electricity required for hauling of ore to the surface was estimated to be 1.36 kWh/t ore. Dewatering practices were estimated to be 0.61 kWh/t ore with a combined pump and shaft efficiency of 50% and a mine depth of 500 m and a value of 0.22 kWh/t ore was calculated for the ventilation requirements. A value of 6.46 MJ diesel/t ore and 10.7 kWh/t ore was determined using this method. It was assumed that explosives use at El Teniente was the same as the Codelco average of 0.3 kg/t ore over the period from 2006 to 2010 (Codelco, Various).

Concentrator

Concentration at El Teniente takes place at the Sewell and Colon Concentrating plants. Electricity requirements of 5.74 kWh/t ore and 6.29 kWh/t ore were calculated for the SAG mills and Ball mills respectively. Steel grinding ball consumption was assumed to be the same as the 2005-2010 average of 0.7 kg/t ore. Electricity requirements of 2.3 kWh/t ore were estimated for flotation. Diesel fuel and SF203 are used as collectors in the Colon circuit and it is assumed that 25 g of each per tonne of concentrate is required to produce a 30.8% Cu concentrate (Bulatovic et al., 1998). A value of 3.41 kWh/t ore for pumping was estimated (Metso, 2003). Tailings from the concentrator are transported 87 km via a pipeline to the current tailings storage facility that is located at an altitude of 230 m, while the plant is at an altitude of 1900 m (Kelm et al., 2009).

Caletones Smelter

Caletones smelter is located at El Teniente. The site is only able to store one day worth of concentrate due to its location in the Andean mountain range. Therefore, the smelter must run in conjunction with the concentrator to enable continuous production (Demetrio et al., 2000). The oxidation of sulphur is exothermic and allows the furnaces to remain at temperature with very little fuel input.

Life Cycle Inventory Data

A life cycle inventory table was developed for El Teniente that includes the major material and energy inputs and outputs from the site. This was developed on the basis of the 2010 production output of 405,375 tonnes of copper anodes from the site. Where no information was available for an individual process at El Teniente, data was sourced from similar processes occurring at other copper production sites. A summary of the life cycle inventory data is shown in Table 1.

Table 1 Life cycle inventory for El Teniente mine site estimated for 2010 production rates (based on various sources and authors expert judgement for adaptation and modification where appropriate)

Underground Mine	**Inputs**		**Unit**	**Outputs**		
Drilling, Blasting, Loading	Ore (0.97% Cu)	47,000,000	t			
	Diesel	303,784	GJ			
	Electricity	503,065,817	kWh			
	Explosives	14,100	t			
Hauling	Electricity	64,037,500	kWh	Mined Ore	47,000,000	t
Dewatering	Electricity	28,726,950	kWh			
Ventilation	Electricity	10,156,526	kWh			
Concentrator	**Inputs**			**Outputs**		
SAG Mills	Mined Ore	47,000,000	t			
	Electricity	269,782,939	kWh			
Ball Mills	Electricity	295,861,956	kWh			
	Steel Balls	32,900	t			

Flotation Cells	Electricity	107,998,800	kWh	Concentrate	1,354,378	t
	Diesel Oil	33,859	kg	Mo in Conc.	5,617	t
	SF203	33,859	kg	Tailings	45,515,000	t
Pumping	Electricity	147,493,710	kWh			
Smelter	**Inputs**			**Outputs**		
Teniente Smelting Furnaces	Concentrate	1,354,378	t			
	Fuel Oil	290,250	GJ			
	Silica Flux	116,090	t			
	Refractories	730	t			
Peirce Smith Converters	Refractories	1,824	t			
	Silica Flux	10,418	t			
Fire Refining and Casting	Natural Gas	1,013,439	GJ	Cu Anode	405,375	t
Slag Cleaning Furnaces	Electricity	824,633	kWh	Slag	1,209,731	t
	Fuel Oil	445,966	GJ			
	Reductant	7,276	t			
	Refractories	1,370	t			
Gas Cleaning and Acid Plant	V_2O_5	217,001	kL	H_2SO_4	834,621	t
	Electricity	382,534,581	kWh	Emission to Air		
	Water	163,523	t	As	155	t
				CO_2	20,837	t
				SO_2	166,692	t
Oxygen Plant	Electricity	106,183,255	kWh			

Boundaries of Analysis

The life cycle inventory only includes the consumption or flow of materials and energy that physically occurs within the boundaries of the El Teniente operational site. Further analysis conducted using SimaPro expanded the analysis to include the upstream production of the material and energy sources by third parties. Electricity consumption by generation source was required for input for individual processes in SimaPro. The inputs are shown in Table 2.

Table 2 El Teniente estimated electricity consumption by source (Central Energía, 2012)

Electricity	**Hydro**	**Gas**	**Oil**	**Coal**	**Biomass**	**Wind**	**Total**
Annual (MWh)	831,987	434,080	271,300	198,953	54,260	18,086	1,808,667

RESULTS

Energy Demand & Greenhouse Gas Emission

The contribution of each site process to the embodied energy of copper anodes produced at El Teniente as well as the energy consumed on-site is displayed in Figure 1. The production of copper from El Teniente results in the release of GHG emissions into the atmosphere due to the various processes associated with the site (mainly energy consumption). GHG emissions associated with a product or processes are commonly grouped into three different scopes: Scope 1 emissions encompass those that are directly released on-site from point or diffuse sources. Scope 2 emissions occur as a result of the purchase of intermediate energy (i.e. electricity or steam) that has been produced off-site. Scope 3 emissions occur off-site during the production of associated input materials or services.

The embodied global warming potential (GWP) of a product represents the combined sum of Scope 1, Scope 2 and Scope 3 GHG emissions. An estimate of the embodied GWP was produced in SimaPro and can be seen in Figure 1; with estimates of scope 1 and 2 emission as well Codelco's own reported data for 2010 also shown. GWP is expressed in terms of kilograms of carbon dioxide equivalent per kilogram of copper anode (kg CO_2-e/kg Cu).

DISCUSSION

Energy Consumption

Codelco reports electricity and fuel consumption for El Teniente. The on-site energy consumption for El Teniente in 2010 was 22.1 MJ/kg Cu, of which 5.0 MJ/kg Cu was due to the consumption of fuels and 17.1 MJ/kg Cu was due to the consumption of electricity. The modelled on-site energy consumption of 22.63 MJ/kg Cu represents a 2.5% deviation from the reported data (see Figure 1). It is likely that the concentrator uses more energy, particularly electricity, than what has been modelled. The energy requirements for milling of ore is likely to be underestimated as only the main mills are included in the estimation of energy requirements. There is, however, a significant number of smaller mills which would need to be included in the total to give a more complete understanding (e.g. smaller Vertimills).

There is a lack of information in the literature regarding the operation of the flotation circuit, along with water and slurry pumps within the operation. A more complete understanding of the operation and the ability to provide a more accurate assessment of the energy requirements of the pumps and flotation cells would require additional data regarding the flow rates of water, air and slurry between unit processes. The under allocation of electricity to the concentrator is associated with an over allocation to the mine and smelter. The smelter is likely to use less electricity than what was calculated, particularly for the requirements of the acid plant. Additional information regarding the capture of waste heat and any generation of steam or electricity from this process is required to gain a more accurate estimate for this process. The over allocation of electricity to the mine site will be within the 'drilling, blasting, loading' stage of production. Due to a lack of information regarding these processes, the remaining electricity which was not accounted for elsewhere in the site was allocated to these processes, which is the source of the known over allocation to mining.

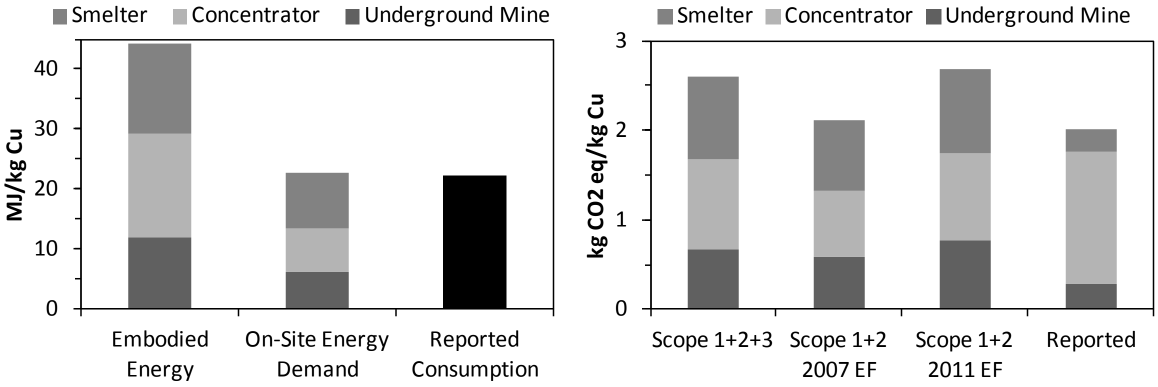

Figure 1 El Teniente copper specific energy and GWP by major process area. Two estimates are provided for Scope 1 and 2 emissions using the 2007 SIC emission factor (EF) and an estimated 2010 SIC EF.

The El Teniente fuel and electricity requirements can be compared with the average requirements of the Chilean copper industry. COCHILCO compiled the average electricity and fuel consumption for Chilean copper mines for the years 2004-2008 as shown in Tables 3 (Pimentel, 2009). These averages are reported in terms of the major process involved in the site (i.e. underground/open pit mining, concentrator plant, SX-EW, refining, etc.). The Chilean average reported energy requirements for underground mining in 2008 was 3,397 MJ/t Cu, which is much lower than the value of 6130 MJ/t Cu found in this study.

El Teniente extracts material from the ore body using an underground mining method (specifically box and panel caving). The choice of mining technique has a large influence on the overall energy requirements of copper production. Generally underground mines consume more energy per tonne of ore than open pit mines. This is demonstrated in Figure 2 that shows the reported annual energy requirements for 31 different copper mines (site-wide energy; not mine specific energy) expressed per tonne of ore mined.

Table 3 Modelled El Teniente on-site energy demand and 2008 Chilean averages (Pimentel, 2009)

	Electricity (MJ/t Cu)		**Fuel (MJ/t Cu)**		**Total (MJ/t Cu)**		
	El Teniente	Chile	El Teniente	Chile	El Teniente	Chile	Difference
UG Mine	5,382	2,099	750	1,298	6,132	3,397	81 %
Concentrator	7,292	8,209	-	233	7,292	8,442	-14 %
Smelter	4,347	3,692	4,855	5,170	9,202	8,862	3.8 %
Total	**17,021**	**14,000**	**5,605**	**6,701**	**22,626**	**20,701**	**3.9 %**

It can be noted that a range of years are included depending on when energy data was reported for the operation, and so multiple data points for individual mines may be presented with each point representing a different year of production.

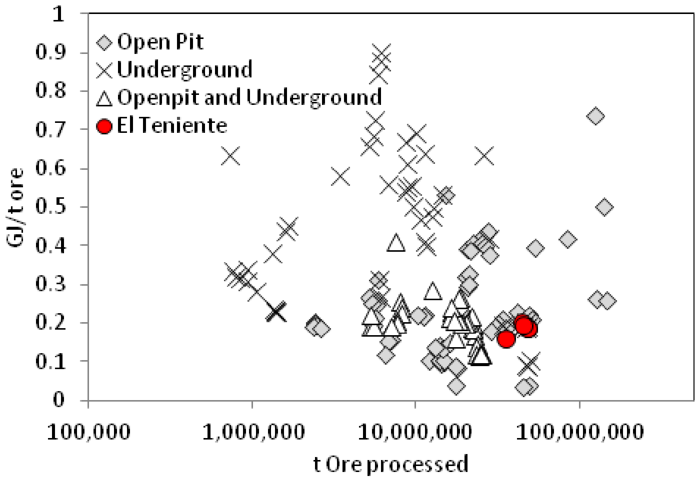

Figure 2 Energy requirements for open pit and underground mines

Greenhouse Gas Emission

The majority of GHG emission produced as a result of El Teniente's operations are related to the electricity. Codelco reported in 2009 that electricity accounted for 87% of El Teniente's Scope 1 and 2 greenhouse gas emissions (our results were between 81.6% and 85.5% depending on the electricity emissions factor). Consequently, the most potential for GHG emission reduction at El Teniente involves optimising their operations to reduce process electricity consumption via increases in efficiency, avoidance of electricity use and changes in the GHG intensity of the sources of electricity that supplies the mine site. Therefore, any efforts by Codelco to reduce emission should include actions to promote technologies with lower emission such as gas renewable or hydro-electricity.

Trends in Energy Consumption and GHG Emission

Copper specific on-site energy consumption is shown in Figure 3 for the period 2001-2010 (Codelco, Various). Fuel use at El Teniente has remained fairly constant over this period averaging 5.7 MJ/kg Cu. However, the electricity consumption for El Teniente is quite variable over this time period. Electricity consumption averaged 15.5 MJ/kg Cu but has varied between 10.5 MJ/kg Cu in 2003 to 17.8 MJ/kg Cu in 2008. The total on-site energy consumed per kg of copper anode produced is highly dependent on the trends in electricity consumption. The total on-site energy consumed averaged 21.89 MJ/kg Cu for this period, ranging from 16.6 MJ/kg Cu in 2003 to peaking at 23.6 MJ/kg Cu in 2008.

Also shown on Figure 3 is the reported copper specific GHG emissions over the same period, 2001-2010 (Codelco, Various). Emissions are categorised into direct, indirect and total. Direct GHG emission is the result of fuel being burnt on-site and indirect GHG emission is the emission associated with the use of electricity on-site which has been produced from off-site generators. Direct emission follows closely with the steady downward trend in fuel consumption. The indirect emissions have increased since 2001 because of a considerable increase in fossil fuel based generating capacity within Chile's central electricity grid, Sistema Interconnectado del Central (SIC). For example, the emission factor for electricity provided by the SIC grid has increased from 0.2 kg CO_2-e/kWh in 2001 to 0.36 kg CO_2-e/kWh in 2007 (Pimentel, 2009). The emission factor for 2011 was estimated using SimaPro to be 0.48 kg CO_2-e/kWh.

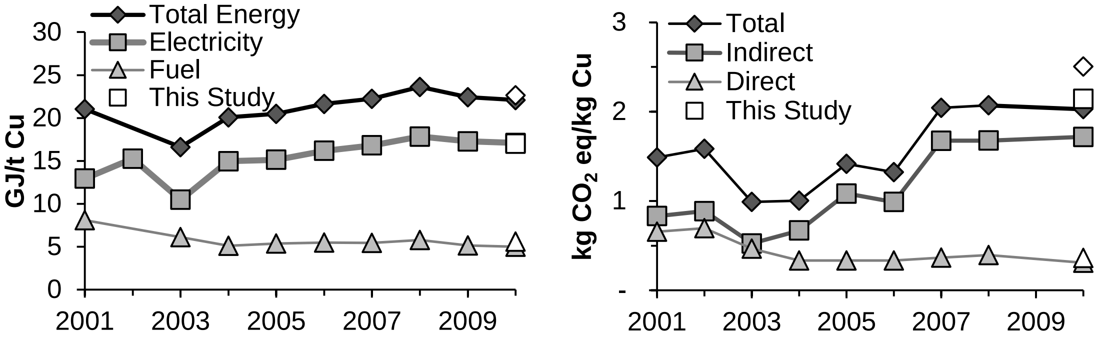

Figure 3 El Teniente on-site copper specific energy consumption and greenhouse gas emissions; reported values shown in grey (Codelco, Various).

Allocation of Impacts

El Teniente also produces and molybdenum concentrate as a co-product. Table 6 provides a comparison between mass and economic allocation to the metal products of El Teniente.

Table 6 Comparison of site wide mass and economic allocation

	Cu Allocation		**Mass Allocation**					**Economic Allocation**				
	GJ/t	**t CO_2 eq/t**	%	TJ	**GJ/t**	t CO_2 eq	**t CO_2 eq/t**	%	TJ	**GJ/t**	t CO_2 eq	**t CO_2 eq/t**
Cu	44.27	2.6	98.6	7,623	**43.7**	1,034,447	**2.6**	94.0	16,805	**41.6**	986,409	**2.4**
Mo			1.4	245	**43.7**	14,396	**2.6**	6.0	1,063	**189**	62,435	**11.1**

Economic allocation based on 2010 average prices: $7539/t Cu; $34,290/t Mo

CONCLUSIONS

The life cycle inventory was developed for El Teniente and Caletones Smelter, has been used to determine the embodied energy and greenhouse gas emission associated with copper anode product from this site. El Teniente produced anodes were modelled to have an embodied energy of 44.3 MJ/kg Cu with associated embodied GHG emission of 2.6 kg CO_2-e/kg Cu. The specific embodied energy is higher compared with copper produced in Australia but the specific GHG is relatively lower than that of copper in Australia because of the lower GHG emission factor of electricity in Chile. However, the GHG emission factor in Chile is increasing because the proportion of hydro-electricity as part of total electricity is decreasing and fossil fuelled fired power plants is increasing. The modelled direct energy demand of the processes within El Teniente's operational boundary was 22.6 MJ/kg Cu and agrees well with the 22.07 MJ/kg Cu reported by Codelco, there exists large uncertainty in the allocation of energy consumption to specific processes within the site. Electricity consumption is the source of 80-90% of the scope 1 and 2 greenhouse gas emission associated with El Teniente Scope. The emission factor of the SIC electricity grid was shown to have a large impact on the overall embodied emission of the copper product. Therefore, efforts to reduce the embodied greenhouse gas emission of copper anodes produced from the site should focus on reducing the sites electricity demand as well as sourcing electricity with a lower emission factor.

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