

Cobalt Life Cycle Analysis Update for the GREET[®] Model

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ACRONYMS

CI	Cobalt Institute
Co eq.	cobalt-content equivalent
DRC	Democratic Republic of Congo
IEA	International Energy Agency
LCA	life cycle analysis
LCI	life cycle inventory
LME	London Metal Exchange
Mt	million metric ton
Nm ³	normal cubic meter
PM	particulate matter
PM10	particulate matter 10 micrometers or less in diameter
PM2.5	particulate matter 2.5 micrometers or less in diameter
T&D	transmission and distribution
TFM	Tenke Fungurume Mine
tpy	metric ton per year
USGS	United States Geological Survey

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Update of Life Cycle Analysis of Cobalt in the GREET[®] Model

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This memo documents updates for life cycle analysis (LCA) of cobalt and cobalt chemicals production in the GREET[®] model. The updated life cycle inventory (LCI) covers material and energy flows associated with cobalt ore mining, cobalt ore processing, cobalt chemicals production, cobalt metal production, and pertinent transportation activities. Based on recent literature, industry statistics, and company reports, these updates represent current practices of the global cobalt industry, and will be incorporated into GREET 2018.

1. Introduction

Cobalt is considered as an essential element for modern society due to its applications in rechargeable batteries, alloys, electronics, catalysts, and healthcare (CI 2018a). Although cobalt occurs in a wide range of minerals in diverse geological settings, the concentrations of cobalt in the minerals are often too low to be extracted economically. As a result, cobalt is primarily produced as a byproduct of copper, nickel, and silver (Donaldson 2005). Commercially valuable cobalt deposits mainly occur in the Democratic Republic of Congo (DRC), Russia, Australia, Canada, and Cuba. The DRC dominates the world's cobalt mine production, supplying 58% of global cobalt mine production of 110,000 metric tons (t) in 2017 (USGS 2018), while China leads the world's refined cobalt production, accounting for 60% of global refined cobalt production of 116,937 t in 2017 (CI 2018b).

In the GREET[®] model, cobalt is used in precursors for cathode materials of lithium-ion batteries, additives for nickel metal hydride batteries, and catalysts for the production of various fuels, mostly in the form of cobalt chemicals. Therefore, this study focuses on the production of cobalt chemicals. Furthermore, since the present GREET modeling of the secondary production of cobalt chemicals, modeled in details in GREET's battery recycling module, still represents the

best industrial data currently available, this study focuses on primary production only. The system boundary is cradle-to-gate, and the updated LCI represents cobalt ore mining and processing in the DRC, and refined cobalt and cobalt chemicals production in China.

2. Primary Cobalt Production

Primary cobalt production by the Gécamines process is depicted in Figure 1. The Co-containing minerals extracted in the DRC are copper-cobalt ores, which provide the world's major source of cobalt, and occur as sulfides and oxides (also known as laterites) (Donaldson 2005). The production process of refined cobalt from sulfides and that from oxides are mostly the same, except that the sulfides require pretreatment by sulfatizing roasting or pressure oxidation before they can join the oxides in the leaching step (Donaldson 2005).

Historically, copper and cobalt concentrates produced in the DRC were exported to other countries for further processing (USGS 2017). As of 2017, however, major copper and cobalt producers, notably Glencore and China Molybdenum, process their copper and cobalt concentrates within the DRC, and export copper as copper cathodes and cobalt as crude cobalt hydroxide ($\text{Co}(\text{OH})_2$), in response to the DRC's pending ban on the export of copper and cobalt concentrates (Bloomberg 2017). Most of the crude $\text{Co}(\text{OH})_2$ produced in the DRC is exported to China (USGS 2017), where it is converted into chemicals such as cobalt sulfate (CoSO_4), cobalt oxide (Co_3O_4), and cobalt carbonate (CoCO_3), as well as cobalt metal (Huayou Cobalt 2018a). Refined cobalt and cobalt chemicals can also be produced by the Outokumpu process, which was used in Finland in the Kokkola plant (Donaldson 2005), the world's largest cobalt refinery (USGS 2017). However, due to limited data availability for the Kokkola plant, the Outokumpu process is not examined in this study.

2.1 Copper-cobalt Ore Mining

Data on copper-cobalt ore mining in the DRC were collected from reports and documents from three major mines: the Tenke Fungurume Mine (TFM), the Mutanda mine (hereinafter referred to as Mutanda), and the Kamoto mine (hereinafter referred to as Kamoto). Although handpicking cobalt-rich ores, also known as artisanal mining, accounted for 17% of 2015 ore production in the DRC (USGS 2017) and has raised concerns regarding humanitarian issues, it is not examined in this study, due to lack of data. Information on the three mines are summarized in Table 1. TFM and Mutanda collectively produced 63% of the DRC's cobalt output in 2017. Due to a plunge in metal prices in 2015, Kamoto was put on care and maintenance and did not produce any cobalt in 2016 and 2017. However, a series of expansion projects had been

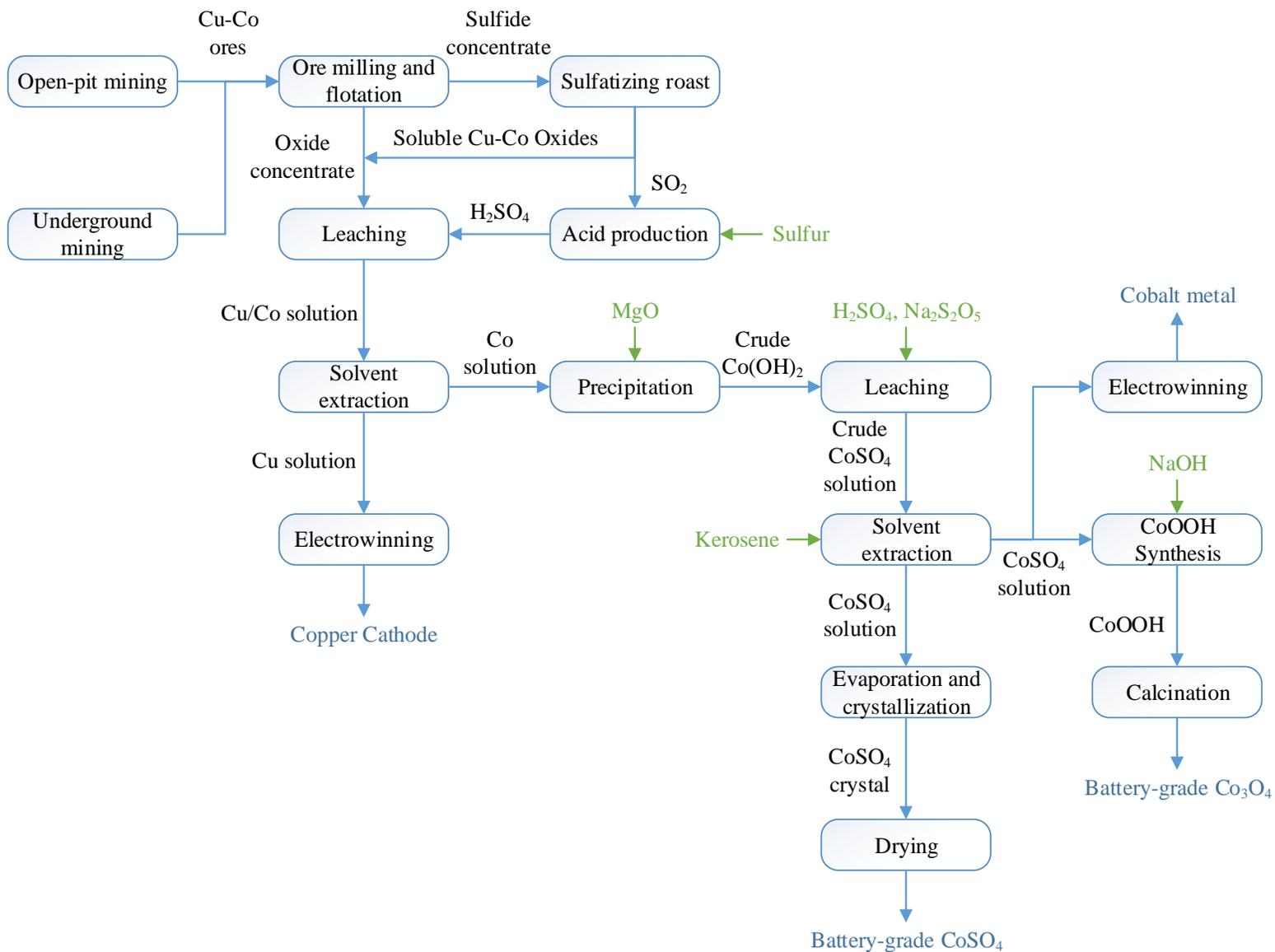


Figure 1. Process flow diagram of refined cobalt and cobalt chemicals production. Green texts represent material inputs; blue texts represent products.

completed during this time, increasing the cobalt capacity of Kamoto to 30,000 t per year. Production at Kamoto resumed in December 2017. In addition, a few planned expansion projects had started, which will further increase the production capacity to 40,000 t of cobalt per year by 2019 (Kamoto Copper Company 2018). Therefore, data from the three mines were all used in the compilation of the LCI.

Table 1. Information of three major cobalt mines in the DRC

	TFM	Kamoto	Mutanda
Ore type	Oxide/sulfide ^a	Sulfide/oxide ^c	Oxide/Sulfide ^f
Mining method	Open-pit ^a	Underground/open-pit ^c	Open-pit ^f
Fuel source for mining equipment	Diesel ^a	Electricity ^c	N/A
2017 reported reserve	Cu content (%)	2.37% ^b	3.15% ^d
	Co content (%)	0.32% ^b	0.51% ^d
	Quantity (Mt)	185 ^b	138 ^d
2017 Production	Cu produced (t Cu)	213,843 ^b	4,900 ^e
	Co produced (t Co)	16,419 ^b	0 ^e

- a. Nilsson and Simpson 2014
- b. China Molybdenum 2018a
- c. Kamoto Copper Company 2018
- d. Glencore 2018a
- e. Glencore 2018b
- f. Wimberley *et al* 2011

The material and energy flows associated with mining of 1 t of copper-cobalt ore in the DRC are summarized in Table 2. The diesel consumption for mining at TFM was calculated based on maximum fleet size, average operating hours per year, and fuel use per hour for each type of mining equipment used on-site. Detailed information on the diesel use calculation can be found in Appendix A. This study chose to use energy consumption data from TFM because the data source is more recent, and the bottom up calculation is more accountable and transparent. The water consumption estimate for TFM was also chosen for this study, as it was based on a detailed water balance analysis (Golder Associates, 2007). Estimated particulate matter (PM) emissions include those from crushing, drilling, blasting, and material handling, as well as those from road entrainment and wind erosion resulting from mining activities (Golder Associates, 2007).

The material and energy flows for mining at TFM were then converted into an inventory representative of per-unit-mass of cobalt mined. This conversion requires knowledge of the ore grade. However, ore grade of a single mine typically varies over time (Komoto Copper Company 2018, Nilsson and Simpson 2014, Wimberley *et al* 2011). In order to capture the industrial average over the lifetime of the three mines, this study adopted the 2017 reserve-weighted average ore grade, which is 2.44% Cu, and 0.47% Co. In addition to the ore grade, deriving an inventory of per-unit-mass of cobalt mined also entails allocation, as copper is co-produced with cobalt in the mining and hydrometallurgical ore processing steps. In this study, both mass allocation and economic value allocation were explored. Mass allocation was carried out based on the assumed ore grade, while economic value allocation was conducted based on the ore

grade together with the average global copper and cobalt prices during 2007-2016. Details of the economic value allocation are described in Appendix B.

Table 2. Material and energy flows for mining 1t of copper-cobalt ore

	TFM	Kamoto
Energy consumption (kWh/t ore mined)		
Diesel	163 ^a	0 ^c
Electricity	0 ^a	61.7 ^c
Water consumption (gal/t ore mined)	45.3 ^b	725 ^c
Emissions (kg/t ore mined)		
PM10	1.44 ^b	N/A
PM2.5	0.148 ^b	N/A

a. Nilsson and Simpson 2014

b. Golder Associates 2007

c. Kamoto Copper Company 2006, for underground mining

2.2 Hydrometallurgical Ore Processing

The mined copper-cobalt ore is sent to a hydrometallurgical plant for further processing. After going through a milling process, which reduces the ore size to one that is suitable for subsequent mineral extraction and leaching processes, the ore is converted into an enriched concentrate by flotation (Kamoto Copper Company 2018). Concentrate containing sulfides needs to undergo sulfatizing roasting or pressure oxidation first, which converts sulfides into more soluble oxides, before the concentrate can enter the leaching tank, whereas concentrate containing oxides can be fed to the leaching step directly. Sulfides roasting or oxidation can produce SO₂ gas, which can be an environmental concern if emitted to the atmosphere. However, SO₂ emissions from cobalt sulfides processing in the DRC are not emitted. The hydrometallurgical plants at TFM and Mutanda both have on-site acid plants, which supply sulfuric acid (H₂SO₄) needed for the leaching process (Nilsson and Simpson 2014, Wimberley *et al* 2011). Also, an acid plant is currently under construction at Kamoto (Kamoto Copper Company 2018). The on-site acid plant helps reduce operation costs for hydrometallurgical ore processing, because the required feedstock, sulfur, is cheaper than sulfuric acid. In addition, the production of sulfuric acid from sulfur is an exothermic process. The heat released from the process can be harvested to produce steam or electricity, to partially satisfy the energy requirement of the hydrometallurgical plant (China Molybdenum 2018b, Nilsson and Simpson 2014). SO₂ gas produced from the ore roasting or oxidation processes is therefore a resource to the cobalt producers, and is captured and subsequently converted into sulfuric acid in the acid plant, along with SO₂ gas produced from sulfur roasting.

Besides sulfuric acid, SO₂ gas is also added to the leaching tank to facilitate the leaching process, by converting Co³⁺ into soluble Co²⁺ (Kamoto Copper Company 2018). The leached slurry then undergoes several solvent extraction and stripping steps, which further increase the

concentrations of copper and cobalt, and separate them out as a copper-rich solution and a cobalt-rich solution. The copper-rich solution is fed to the electrowinning system, where copper cathode is produced. The cobalt-rich solution goes through a few precipitation steps to remove iron, aluminum, and manganese impurities, and to recover contained copper. In the end, cobalt is precipitated out as Co(OH)_2 by reacting with magnesium oxide (MgO) (Golder Associates, 2007).

Table 3. Material and energy flows for hydrometallurgical ore processing

		TFM	Kamoto	Hanrui
Reference year		2013	2017	2017
Plant capacity (t/yr)	Ore	5,110,000 ^a	12,000,000 ^d	N/A
	Cu	195,000 ^a	300,000 ^d	20,000 ^f
	Co	15,000 ^a	30,000 ^d	5,000 ^f
Process yield	Cu	95% ^b	85% ^d	90-95% ^f
	Co	85% ^b	65% ^d	80% ^f
Electricity consumption (MWh/yr)		788,400-805,920 ^a	1,314,000-1,576,800 ^d	82,161 ^f
Water consumption (gal/yr)		2,082,738,944 ^c	5,371,472,165 ^e	207,984,625 ^f
Materials consumption (t/yr)	H_2SO_4	--- ^a	1,224,000 ^d	N/A
	SO_2	--- ^a	271,200 ^d	N/A
	Sulfur	166,857 ^a	N/A	N/A
	Limestone	217,080 ^c	N/A	N/A
	Lime	79,056 ^c	N/A	N/A
	NaOH	9,526 ^c	N/A	N/A
	MgO	17,618 ^c	N/A	N/A
Emissions (t/yr)	SO_2	1,522 ^c	N/A	N/A

a. Nilsson and Simpson 2014

b. Tenke Mining Corp 2007

c. Converted from values in Golder Associates 2007, adjusted by plant capacity

d. Kamoto Copper Company 2018

e. Converted from values in Kamoto Copper Company 2006, adjusted by plant capacity

f. Hanrui Cobalt 2017

The material and energy flows for hydrometallurgical ore processing are summarized in Table 3. The data was based on operations at Kamoto, TFM, and a recently-announced project by Hanrui Cobalt (hereinafter referred to as Hanrui). Each of the three hydrometallurgical plants are powered by electricity. It can be observed from Table 3 that, adjusted by capacity, the material and energy flows do not vary significantly among the three plants. For instance, normalized to a copper production capacity of 1,000 t per year, the electricity requirements of the three plants range from 4,043 to 5,256 MWh per year, while the water consumptions range from 10.4 to 17.9 million gallons per year. To make subsequent allocation easier, data from TFM was selected to compile the LCI for this study. In addition, a process yield of 80% for Co was assumed in this study for the ore processing stage. Note that the combined consumption of sulfuric acid and SO_2 at Kamoto can be converted into a sulfur consumption of 45kg/t ore (Kamoto Copper Company 2018), which is comparable to the sulfur consumption of 33kg/t ore

at TFM (Nilsson and Simpson 2014). SO₂ emissions include those from the acid plant stack, as well as those from scrubbers and vents in the hydrometallurgical plant (Golder Associates, 2007).

Since the electrowinning step only produces copper, the electricity consumption for copper electrowinning is deducted from the total electricity consumption of the hydrometallurgical plant. The remaining electricity consumption is then allocated between copper and cobalt. Similarly, since MgO is only used for Co(OH)₂ precipitation, all MgO consumption is attributed to cobalt production, while the rest of the material consumptions are allocated between copper and cobalt. Details of allocation for hydrometallurgical ore processing can be found in Appendix C.

2.3 Refined Cobalt Chemicals Production

The crude Co(OH)₂ produced in the DRC, with an assumed cobalt content of 35% (Huayou Cobalt 2018b, Hanrui 2017), is then sent to China for further refining. The top three refined cobalt producers in China, Huayou Cobalt, GEM, and Jinchuan, accounted for over 60% of China's total refined cobalt output in 2016 (Xu 2017). GEM produces cobalt chemicals mostly in the form of nickel manganese cobalt hydroxide (GEM 2018). Although CoSO₄, a chemical of interest in this study, is an intermediate product from nickel manganese cobalt hydroxide production, material and energy flows specific to CoSO₄ production is not reported by GEM. Therefore, refined cobalt production at GEM is not examined in this study. Refined cobalt production at Jinchuan is not included in this study, either, due to lack of data.

Huayou Cobalt produced 23,720 t of refined cobalt as various cobalt-containing products in 2017, representing 34% of China's refined cobalt production, and 20% of global refined cobalt production in that year. Refined cobalt products of Huayou Cobalt are produced at their Tongxiang plant and Quzhou plant (Huayou Cobalt 2018c). The Tongxiang plant primarily produces battery-grade CoSO₄ and Co₃O₄, while the Quzhou plant primarily produces battery-grade Co₃O₄ (Huayou Cobalt 2018a).

2.3.1 Battery-grade CoSO₄ production

In 2016, the Tongxiang plant of Huayou Cobalt produced 1,675 t of cobalt in the form of CoSO₄, 2,189 t as Co₃O₄, 1,456 t as Co(OH)₂, 256 t as CoCO₃, and 114 t as cobalt oxide (CoO), from a mixed feed of crude Co(OH)₂ and concentrated cobalt ore. An expansion project is underway, to increase battery-grade CoSO₄ production capacity of the plant by 2,600 t of cobalt content (hereinafter referred to as Co eq.) per year. Once completed, the plant will have a total refined cobalt production capacity of 9,000 t Co eq. per year, of which battery-grade CoSO₄ production accounts for 50% (Huayou Cobalt 2018b). Also, after the expansion, the plant will use crude Co(OH)₂ as the only cobalt feed, which aligns well with the assumption of this analysis. Ideally, the LCI should be compiled based on data specific to battery-grade CoSO₄ production at the Tongxiang plant. However, with data currently available, it is not possible to

separate the material and energy requirements pertaining to battery-grade CoSO_4 production from those of the entire plant. Therefore, the estimated material and energy flows for the Tongxiang plant after the expansion, presented in Table 4, were chosen in this study to represent battery-grade CoSO_4 production. Steam use at the Tongxiang plant was converted into natural gas use for GREET implementation, based on a conversion process described in Appendix D.

Table 4. Material and energy flows for 1 ton Co eq. of battery-grade CoSO_4 production from crude Co(OH)_2 (Huayou Cobalt 2018b)

Estimated Energy Consumption				
	Quantity	Unit	Quantity	Unit
Natural gas	830,225	Nm^3/yr	2.91	mmBtu/ton Co eq.
Steam	75,769	t/yr	19.15	mmBtu/ton Co eq.
Electricity	30,060,000	kWh/yr	10.34	mmBtu/ton Co eq.
Estimated Water Consumption				
	Quantity	Unit	Quantity	Unit
Water	491,667	t/yr	13,092	gal/ton Co eq.
Estimated Material Consumption				
	Quantity	Unit	Quantity	Unit
Crude Co(OH)_2^*	25,714	t/yr	2.86	ton/ton Co eq.
NaOH (32%)	76,927	t/yr	8.55	ton/ton Co eq.
H_2SO_4 (95%)	23,598	t/yr	2.62	ton/ton Co eq.
HCl (30%)	42,284	t/yr	4.70	ton/ton Co eq.
Limestone	504	t/yr	0.06	ton/ton Co eq.
Lime	202	t/yr	0.02	ton/ton Co eq.
Kerosene	423	t/yr	0.05	ton/ton Co eq.
P204**	37	t/yr	0.004	ton/ton Co eq.
P507**	41	t/yr	0.005	ton/ton Co eq.
$\text{Na}_2\text{S}_2\text{O}_5$	720	t/yr	0.08	ton/ton Co eq.
NH_4HCO_3	5,166	t/yr	0.57	ton/ton Co eq.
Na_2CO_3	796	t/yr	0.09	ton/ton Co eq.

* Intermediate product.

**The consumed quantity is negligible. The chemical is therefore excluded from the LCI.

After the expansion, purchased crude Co(OH)_2 will be treated with sulfuric acid first, which leaches cobalt out as CoSO_4 . Sodium metabisulfite ($\text{Na}_2\text{S}_2\text{O}_5$) will be added to the leaching step also, to convert remaining Co^{3+} into Co^{2+} . The leached solution will then undergo several precipitation steps to remove iron and aluminum, solvent extraction by P204 to remove other impurities, another solvent extraction by P207 to separate cobalt from nickel, stripping by sulfuric acid to produce refined CoSO_4 , and finally evaporation and crystallization followed by filtration and drying to produce battery-grade CoSO_4 crystals (Huayou Cobalt 2018b). Although the Tongxiang plant also produces ammonium chloride, crude manganese hydroxide, and crude nickel carbonate as byproducts (Huayou Cobalt 2018b), these chemicals are not significant in either quantity or economic value. Therefore, all material, energy, and water consumptions at the Tongxiang plant were attributed to refined cobalt products. It should be noted that other cobalt

products of the Tongxiang plant, such as Co_3O_4 and CoO , are produced via further processing of refined CoSO_4 . These further processing steps incur additional material and energy consumptions, which were also ascribed to battery-grade CoSO_4 production in this study for the reason discussed above. Therefore, the LCI shown in Table 4 is a conservative estimate. Also note that the consumption rate of 32% sodium hydroxide (NaOH) was converted into one for 100% NaOH in GREET, and the same applies to the consumed 95% H_2SO_4 and 30% HCl .

2.3.2 Battery-grade Co_3O_4 production

In 2016, the Quzhou plant of Huayou Cobalt produced 14,995 t Co eq. of refined cobalt chemicals (Huayou Cobalt 2018c), 63% as Co_3O_4 , 15% as CoO , 15% as cobalt metal, 4% as cobalt oxalate (CoC_2O_4), and 3% as CoCO_3 (Huayou Cobalt 2016, Huayou Cobalt 2015). At the Quzhou plant, refined CoSO_4 or cobalt chloride (CoCl_2) is reacted with ammonium bicarbonate (NH_4HCO_3) to produce a CoCO_3 slurry. The produced CoCO_3 slurry then goes through centrifugation, filtration, and washing, to produce a concentrated CoCO_3 solution. The solution subsequently undergoes flash evaporation, drying, and an iron-removal step, to produce a refined CoCO_3 solid. The solid is then calcined to produce battery-grade Co_3O_4 powder (Huayou Cobalt 2016).

Table 5. Material and energy flows for 1 ton Co eq. of battery-grade Co_3O_4 production from CoSO_4 (Huayou Cobalt 2016)

Estimated Energy Consumption				
	Quantity	Unit	Quantity	Unit
Natural gas	250,000	Nm^3/yr	2.25	mmBtu/ton Co eq.
Steam	20,000	t/yr	13.00	mmBtu/ton Co eq.
Electricity	120,000	kWh/yr	0.11	mmBtu/ton Co eq.
Estimated Water Consumption				
	Quantity	Unit	Quantity	Unit
Water	48,000	t/yr	3,287	gal/ton Co eq.
Estimated Material Consumption				
	Quantity	Unit	Quantity	Unit
$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}^*$	7,945	t/yr	2.27	ton/ton Co eq.
$\text{CoSO}_4 \cdot 7\text{H}_2\text{O}^*$	7,105	t/yr	2.03	ton/ton Co eq.
NaOH (32%)	7,000	t/yr	2.00	ton/ton Co eq.
NH_4HCO_3	6,475	t/yr	1.85	ton/ton Co eq.
EDTA**	12	t/yr	0.0035	ton/ton Co eq.

* Intermediate product.

**The consumed quantity is negligible. The chemical is therefore excluded from the LCI.

The material and energy flows specific to battery-grade Co_3O_4 powder production, shown in Table 5, were reported in an inspection and acceptance report for one of the expansion projects at the Quzhou plant (Huayou Cobalt 2016), and were used in this study to compile the LCI for battery-grade Co_3O_4 production. Process CO_2 emission from thermal decomposition of

CoCO₃ during the calcination step was calculated based on stoichiometry, and estimated to be 0.75 ton per ton of Co eq. Co₃O₄ produced. Again, steam use at the Quzhou plant was converted into natural gas use for GREET implementation (see Appendix D), and 32% NaOH consumption was converted into 100% NaOH consumption in GREET.

2.4 Refined Cobalt Metal Production

Refined metallic cobalt is produced from electrolysis of CoSO₄ or CoCl₂ solutions in electrowinning cells (Donaldson 2005). The estimated electricity requirements for metallic cobalt production via electrowinning range from 5,000 kWh to 6,500 kWh per t of cobalt metal produced for plants based in Zambia and the DRC, and range from 3,100 kWh to 3,700 kWh per t of cobalt metal produced for plants based in the rest of the world (Bleivas 2011). Since the DRC and Zambia accounted for less than 10% of global refined cobalt production in 2015 (USGS 2017), and the cited electricity consumption estimate did not consider renovations at the plants based in Zambia and the DRC over recent years (Bleivas 2011), an electricity consumption of 3,400 kWh per t of cobalt metal produced was assumed in this study. The LCI for metallic cobalt production from electrowinning of CoSO₄ is given in Table 6.

Table 6. Material and energy flows for 1 ton of metallic cobalt production via electrowinning of CoSO₄

Estimated Energy Consumption				
	Quantity	Unit	Quantity	Unit
Electricity	3,400	kWh/t Co eq.	10.525	mmBtu/ton Co eq.
Estimated Material Consumption				
	Quantity	Unit	Quantity	Unit
CoSO ₄ *	2.630	t/t Co eq.	2.630	ton/ton Co eq.

*Intermediate product.

2.5 Electricity Mix for Refined Cobalt Production

As can be observed from Tables 3-6, refined cobalt and cobalt chemicals production is electricity-intensive. Because the environmental impacts associated with electricity consumption are predominantly determined by the net consumption amount and the electricity mix, it is imperative in an LCA to use the electricity mix representative of electricity actually consumed during the production processes.

Table 7. Electricity mix and T&D loss of electricity consumption for cobalt production in the DRC and China

	T&D loss	Electricity mix						
		Coal	Oil	Natural gas	Nuclear	Hydro	Biomass	Other
The DRC	21%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%
China	5%	70.1%	0.2%	2.5%	2.9%	19.3%	0.9%	4.1%

For hydrometallurgical ore processing in the DRC, all of the purchased power by TFM, Kamoto, and Matunda is hydroelectricity (China Molybdenum 2018b, Nilsson and Simpson 2014, Wimberley *et al* 2011). However, the transmission and distribution (T&D) loss for the electricity used at the three mines was not disclosed. The 2014 national average T&D loss of the DRC, reported by the World Bank (World Bank 2018), was therefore used as a proxy for electricity consumption by hydrometallurgical ore processing in this study. For refined cobalt and cobalt chemicals production, the electricity mix and T&D loss for electricity consumption in the Tongxiang plant and the Quzhou plant were not disclosed, either. The 2015 national average grid mix and 2014 national average electricity T&D loss of China, were therefore used as a proxy for electricity consumption for refined cobalt and cobalt chemicals production in this study. The 2015 national grid mix of China was obtained from the International Energy Agency (IEA) website (IEA 2018). Again, the T&D loss was obtained from the World Bank (World Bank 2018). The assumed electricity mixes and T&D losses are summarized in Table 7. For diesel and natural gas consumptions, default production pathways and fuel combustion emission factors in GREET were assumed in this study, since the production and combustion technologies of diesel and natural gas are unlikely to exhibit strong regional variation.

2.6 Transportation for Refined Cobalt Production

Due to the geographical distribution of cobalt production activities, and the lack of transportation infrastructure and chemical industry in the DRC, large quantities of consumables and intermediate products need to be transported over long distances between material depots and various production and processing facilities along the supply chain of refined cobalt. Therefore, transportation activities associated with refined cobalt production, as shown in Table 8, were considered in this study. Although the data in Table 8 were based on crude Co(OH)_2 production at TFM in the DRC, and refined cobalt and cobalt chemicals production at Huayou Cobalt in China, they should be representative of all cobalt production activities in both the DRC and China, because international transportation distances are much longer than domestic transportation distances for all the materials examined. Detailed transportation information for each material is listed in Appendix E.

Table 8. Transportation of consumables and intermediate product for refined cobalt production

	Distance ^a (miles)	Mode ^b
Sulfur	1,547	18% by truck, 82% by rail
lime	286	100% by truck
MgO	1,964	100% by truck
NaOH	1,964	100% by truck
diesel	286	100% by truck
Co(OH)_2	9,731	17% by truck, 83% by ocean tanker

a. Tenke Mining Corp 2007

b. Golder Associates 2007

2.7 Auxiliary Materials for Refined Cobalt Production

The production of refined cobalt consumes various reagents, some of which do not exist in GREET 2017, and need to be added to GREET 2018. These reagents include sulfur, Na₂S₂O₅, and NH₄HCO₃. The LCIs for the production of sulfur, Na₂S₂O₅, and NH₄HCO₃ are presented in Table 9.

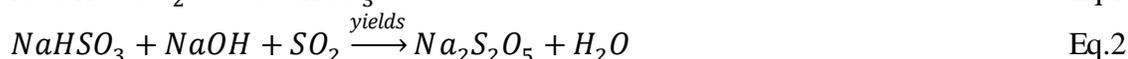
Table 9. LCI of auxiliary materials for refined cobalt production

	Sulfur	Na ₂ S ₂ O ₅	NH ₄ HCO ₃
Energy use (mmBtu/ton material produced)			
Total Energy	0.287	---	---
Coal	0.087	---	---
Natural gas	0.200	---	---
Water use (gal/ton material produced)	177.6	---	54.6
Material use (ton/ton material produced)			
NaOH	---	0.421	---
SO ₂ *	2.000	0.674	---
NH ₃	---	---	0.215
CO ₂ *	---	---	0.557

* Assumed to have no upstream burden.

At present, almost all sulfur is produced by the Claus process, which recovers SO₂ emission from oil and gas production processes, and converts it into sulfur and sulfuric acid (The Sulfur Institute 2018). The production pathway of sulfuric acid in GREET is based on the Claus process. Therefore, the existing LCI of sulfuric acid in GREET 2017 was adapted in this analysis to represent sulfur production, based on the sulfur content in sulfuric acid.

Na₂S₂O₅ is produced industrially by reacting NaOH with a saturated sodium hydrogensulfite (NaHSO₃) solution in an SO₂-containing atmosphere, while NaHSO₃ is commercially prepared by treating NaOH with SO₂ (Barbera *et al* 2000). The chemical reactions are given below:



Material requirements of NaOH and SO₂ were estimated based on stoichiometric calculation. Since the production processes do not involve any heat-intensive or electricity-intensive steps, the energy consumption for the production of Na₂S₂O₅ was assumed to be negligible. Also, since SO₂ gas is a byproduct of many chemical processes, it is assumed to have no upstream burden.

NH₄HCO₃ is produced at industrial-scale by reacting ammonia gas and CO₂ gas with water (Zapp *et al* 2000). The chemical reaction is as follows:



Again, material requirements of CO₂ and NH₃, as well as water consumption, were calculated based on stoichiometry. The reaction is exothermic (Zapp *et al* 2000), so no energy consumption was assumed. For the same reason as SO₂ gas, CO₂ gas was assumed to have zero upstream burden.

3. Cradle-to-gate LCI of Primary Refined Cobalt Production

The cradle-to-gate LCIs for the production of refined cobalt and cobalt chemicals by production stages, based on mass allocation and economic value allocation, are presented in Table 10, and the cradle-to-gate LCIs for different cobalt products, based on mass allocation and economic value allocation, are presented in Table 11. Note that the LCI for Cu-Co mining shown in Table 2 was further adjusted by the Co yield of 80% for cobalt ore processing. For the rest of the production stages, no adjustment for material loss was made, since material flows for these stages indicate 100% cobalt conversion efficiency, which is reasonable as the value of cobalt is high, and the conversion technologies are well established.

The LCI of 1 ton of battery-grade CoSO₄ is the sum of LCIs of ore mining, ore processing, and CoSO₄ production from crude Co(OH)₂ in Table 10, multiplied by the cobalt content of CoSO₄. Since the production pathway of CoSO₄ can also be used for CoCl₂ production, the LCI of 1 ton of battery-grade CoSO₄ was adjusted based on cobalt content to represent the LCI of 1 ton of battery-grade CoCl₂. The LCIs of 1 ton of battery-grade Co₃O₄ and CoO were compiled in the same fashion, taking into account the additional production stage of Co₃O₄ production from CoSO₄. The LCI of 1 ton of metallic cobalt is the sum of LCIs of ore mining, ore processing, CoSO₄ production from crude Co(OH)₂, and cobalt electrowinning in Table 10.

The cobalt LCIs in GREET 2017 were placeholder values based on data for nickel production (Burnham *et al* 2006). Therefore, a comparison of the existing LCIs with the proposed ones was not made in this study. It should be pointed out that the Cobalt Institute (CI) commissioned an LCA study of the global cobalt industry. The study was concluded in 2016, and the compiled cradle-to-gate data represented 30% of global refined cobalt production in 2012 (CI 2018c). The CI generously shared the LCA report and the dataset with us. However, the CI study focused on the production of cobalt metal, and the cradle-to-gate dataset did not provide stage-by-stage material and energy flows, which made it impossible to tease out information specific to the production of cobalt chemicals. Also, the CI study did not cover cobalt production in China, the biggest supplier of cobalt products for the U.S. (USGS 2018). In addition, the CI dataset only reported material and energy flows in the biosphere, while purchased energy and materials (i.e., flows in the technosphere) are needed in the GREET model. For these reasons, the CI study was not used in this analysis. Moreover, due to the differences in system boundary, geographical coverage, and reference year, the LCA results of this study would not be directly comparable with those of the CI study.

Table 10. Cradle-to-gate LCI of 1 ton Co eq. production by production stages

	Mass Allocation		Economic Value Allocation		CoSO ₄ production	Co ₃ O ₄ production	Co electrowinning
	Mining	Ore processing	Mining	Ore processing			
Energy consumption							
Diesel (mmBtu/ton)	21.571	---	70.909	---	---	---	---
Electricity (mmBtu/ton)	---	6.706	---	29.333	10.340	0.106	10.525
Natural gas (mmBtu/ton)	---	---	---	---	26.838	18.494	---
Water consumption							
Fresh water (gal/ton)	1,760	8,997	5,785	39,355	13,092	3,287	---
Material consumption							
Sulfur (ton/ton)	---	0.721	---	3.153	---	---	---
Limestone (ton/ton)	---	0.938	---	4.102	0.056	---	---
Lime (ton/ton)	---	0.342	---	1.494	0.022	---	---
NaOH (ton/ton)	---	0.041	---	0.180	2.735	0.640	---
MgO (ton/ton)	---	1.175	---	1.175	---	---	---
H ₂ SO ₄ (ton/ton)	---	---	---	---	2.570	---	---
HCl (ton/ton)	---	---	---	---	1.409	---	---
Kerosene (ton/ton)	---	---	---	---	0.047	---	---
Na ₂ S ₂ O ₅ (ton/ton)	---	---	---	---	0.080	---	---
NH ₄ HCO ₃ (ton/ton)	---	---	---	---	0.574	1.850	---
Na ₂ CO ₃ (ton/ton)	---	---	---	---	0.088	---	---
Non-fuel-combustion Process Emissions							
PM10 (g/ton)	55,849	---	183,592	---	---	---	---
PM2.5(g/ton)	5,764	---	18,949	---	---	---	---
SO ₂ (g/ton)	---	6,575	---	28,760	---	---	---
CO ₂ (g/ton)	---	---	---	---	---	680,400	---

Table 11. Cradle-to-gate LCI of 1 ton of cobalt products

	Mass Allocation					Economic Value Allocation				
	CoSO ₄	CoCl ₂	Co ₃ O ₄	CoO	Co metal	CoSO ₄	CoCl ₂	Co ₃ O ₄	CoO	Co metal
Energy consumption										
Diesel (mmBtu/ton)	8.202	9.791	15.838	16.965	21.571	26.963	32.187	52.064	55.769	70.909
Electricity (mmBtu/ton)	6.481	7.737	12.593	13.490	27.571	15.085	18.008	29.207	31.285	50.198
Natural gas (mmBtu/ton)	10.205	12.182	33.284	35.653	26.838	10.205	12.182	33.284	35.653	26.838
Water consumption										
Fresh water (gal/ton)	9,069	10,826	19,924	21,342	23,850	22,142	26,433	45,170	48,384	58,233
Material consumption										
Sulfur (ton/ton)	0.274	0.327	0.529	0.567	0.721	1.199	1.431	2.315	2.480	3.153
Limestone (ton/ton)	0.378	0.451	0.730	0.782	0.994	1.581	1.887	3.053	3.270	4.158
Lime (ton/ton)	0.138	0.165	0.267	0.286	0.364	0.577	0.688	1.113	1.193	1.516
NaOH (ton/ton)	1.056	1.260	2.508	2.687	2.776	1.108	1.323	2.610	2.796	2.915
MgO (ton/ton)	0.447	0.533	0.862	0.924	1.175	0.447	0.533	0.862	0.924	1.175
H ₂ SO ₄ (ton/ton)	0.977	1.166	1.887	2.021	2.570	0.977	1.166	1.887	2.021	2.570
HCl (ton/ton)	0.536	0.640	1.035	1.109	1.409	0.536	0.640	1.035	1.109	1.409
Kerosene (ton/ton)	0.018	0.021	0.035	0.037	0.047	0.018	0.021	0.035	0.037	0.047
Na ₂ S ₂ O ₅ (ton/ton)	0.030	0.036	0.059	0.063	0.080	0.030	0.036	0.059	0.063	0.080
NH ₄ HCO ₃ (ton/ton)	0.218	0.261	1.780	1.906	0.574	0.218	0.261	1.780	1.906	0.574
Na ₂ CO ₃ (ton/ton)	0.034	0.040	0.065	0.070	0.088	0.034	0.040	0.065	0.070	0.088
Non-fuel-combustion Process Emissions										
PM10 (g/ton)	21,236	25,351	41,006	43,924	55,849	69,809	83,335	134,798	144,392	183,592
PM2.5(g/ton)	2,192	2,617	4,232	4,534	5,764	7,205	8,601	13,913	14,903	18,949
SO ₂ (g/ton)	2,500	2,985	4,828	5,171	6,575	10,936	13,054	21,116	22,619	28,760
CO ₂ (g/ton)	---	---	499,570	535,125	---	---	---	499,570	535,125	---

Appendix A: Calculation of Diesel Consumption by Mining Equipment.

The information of mining equipment deployed at TFM is listed in Table A1. The fuel use in gal/hr for Caterpillar equipment was looked up in Caterpillar's manual for estimating owning and operating costs (Caterpillar 2018). The upper bound fuel use value was selected for this study, assuming all of the equipment will operate with a high load factor. For non-Caterpillar equipment, if fuel use per hour was not reported by the manufacturer, the fuel use data of a similar piece of Caterpillar equipment was used as a proxy.

The total diesel consumption of the entire mining fleet was calculated to be 22,082,558 gallons per year, which translated into a diesel consumption of 3.92 gallons for 1 ton of Cu-Co ore mined.

Table 12. Information of mining equipment fleet at TFM

Equipment ^a	Max fleet size ^a	Avg. operating hrs/yr ^a	Fuel use (gal/hr)	Fuel use (gal/yr)	Matched Equipment
CAT 772 Haul Truck, 45 t	29	5,600	15.6	2,533,440	
CAT 777 Haul Truck, 90 t	33	5,600	24.8	4,583,040	777D
Mercedes Haul Truck, 50 t	22	5,600	18.7	2,303,840	CAT773F, matched based on payload
Grizzly Feeder	5	5,600	12.0	336,000	FT2650 grizzly feeder and jaw crusher ^b
CAT 988 Front End Loader	17	5,600	17.2	1,637,440	
CAT 992 Front End Loader	2	5,270	32.0	337,280	
RH120E Front Shovel	8	6,670	81.6	4,354,176	CAT5230B, matched based on engine output
RH90C Front Shovel	1	6,670	81.6	544,272	CAT5230B, matched based on engine output
T1255 Surface Miner	5	4,030	31.8	640,770	Engine option 1 ^c
ROC L8 Drill	4	5,600	40.4	904,960	CAT C15 engine ^d
DM45 Drill	5	5,600	40.4	1,131,200	CAT C15 engine ^e
CAT D8R Track Dozer	8	4,710	14.2	535,056	D8T
CAT D10N Track Dozer	6	4,720	25.8	730,656	D10T
CAT 824G-RTD Rubber Tired Dozer	5	4,720	15.8	372,880	824H
Rock Saw Drill/Excavator	4	2,550	16.1	164,220	CAT 345 Hydraulic Excavator
CAT 14M Grader	3	4,710	10.5	148,365	
CAT 16M Grader	5	4,710	12.3	289,665	
CAT 345 Hydraulic Excavator	2	4,730	16.1	152,306	Tier 2
CAT 772 Water Truck	2	4,740	15.6	147,888	
CAT 777 Water Truck	2	4,740	24.8	235,104	777D
			Total	22,082,558	

a. Nilsson and Simpson 2014

b. http://www.madisa.com/sites/default/files/producto/ficha/ficha_kpiji_plantamovil_FT2650_en_1.pdf

c. <http://www.vermeer.com.au/equipment/natural-resources-mining/surface-miners/t1255-chain-drive-surface-miner/>

d. [https://atlascope.com/showrooms/Atlas+Copco/Boring+and+Drilling+Machines/Blasthole+Drilling+Rigs/ROC+L8\(25\)+L8\(30\)/56ce1d2f27818699158b8685/](https://atlascope.com/showrooms/Atlas+Copco/Boring+and+Drilling+Machines/Blasthole+Drilling+Rigs/ROC+L8(25)+L8(30)/56ce1d2f27818699158b8685/)

e. <https://www.atlascope.com/en-my/mrba/products/drill-rigs/surface-blasthole-drill-rigs/dm45-and-dm50>

Appendix B: Economic Value Allocation

Economic value allocation for ore mining and processing was based on 10-yr average London Metal Exchange (LME) prices for copper and cobalt during 2007-2016, as shown in Table A2 (Kamoto Copper Company 2018). The LME price for cobalt was not available for 2007. The average annual spot cathode price for that year reported by USGS was used as a proxy (USGS 2009). The annual prices were then converted into prices in 2016 dollars to account for inflation, using the consumer price index inflation calculator provided by the Bureau of Labor Statistics (Bureau of Labor Statistics 2018).

Economic value allocation of the material and energy flows between copper and cobalt was then carried out based on allocation factors calculated by equations A1 and A2.

$$\text{Allocation factor}_{Cu} = \frac{\text{Price}_{Cu} \times \text{Quantity}_{Cu}}{\text{Price}_{Cu} \times \text{Quantity}_{Cu} + \text{Price}_{Co} \times \text{Quantity}_{Co}} \quad \text{Eq.A1}$$

$$\text{Allocation factor}_{Co} = \frac{\text{Price}_{Co} \times \text{Quantity}_{Co}}{\text{Price}_{Cu} \times \text{Quantity}_{Cu} + \text{Price}_{Co} \times \text{Quantity}_{Co}} \quad \text{Eq.A2}$$

Table 13. 2007-2016 copper and cobalt prices

	Cu (\$/t)	Co (\$/t)	Cu (2016\$/t)	Co (2016\$/t)
2007	\$ 7,119	\$ 67,351	\$ 8,183	\$ 77,418
2008	\$ 6,956	\$ 79,719	\$ 7,988	\$ 91,552
2009	\$ 5,150	\$ 35,031	\$ 5,758	\$ 39,165
2010	\$ 7,535	\$ 41,337	\$ 8,300	\$ 45,534
2011	\$ 8,821	\$ 30,005	\$ 9,437	\$ 32,100
2012	\$ 7,949	\$ 28,783	\$ 8,359	\$ 30,266
2013	\$ 7,326	\$ 27,029	\$ 7,590	\$ 28,001
2014	\$ 6,859	\$ 30,866	\$ 7,052	\$ 31,736
2015	\$ 5,494	\$ 29,233	\$ 5,608	\$ 29,839
2016	\$ 4,863	\$ 26,433	\$ 4,863	\$ 26,433
10-yr Avg.	\$ 6,807	\$ 39,579	\$ 7,314	\$ 43,204

Appendix C: Allocation for Hydrometallurgical Ore Processing

As discussed in the main text, the energy consumption for copper electrowinning is only associated with copper production, and needs to be excluded from the total energy requirement of the ore processing plant before allocation is carried out. The electricity consumption for copper electrowinning ranges from 5.6 mmBtu to 6.3 mmBtu per ton of copper produced (Leonard 1988). In this study, an energy consumption of 5.6 mmBtu/ton Cu was assumed, which is equivalent to 1.8kWh/kg Cu. The electricity use for copper electrowinning at TFM was therefore calculated to be 351,000 MWh/yr. Subtracting this amount from the total plant electricity use of 805,920 MWh/yr, the remaining electricity use was found to be 454,920 MWh/yr. The material and energy flows for ore processing to be allocated between 195,000 t per year (tpy) copper and 15,000 tpy cobalt produced at TFM are summarized in Table A3.

Table 14. Material and energy flows to be allocated for ore processing

Electricity consumption (MWh/yr)	454,920
Water consumption (gal/yr)	2,082,738,944
Materials consumption (t/yr)	
Sulfur	166,857
Limestone	217,080
Lime	79,056
NaOH	9,526
Emissions (t/yr)	23,490
SO ₂	1,522

Appendix D: Converting Steam Use into Natural Gas Use

The conversion of steam use into natural gas use was based on heat balance. It was assumed that the heat released from natural gas combustion was used to produce a steam of 300°C from room temperature (25°C) water in the boiler. The default boiler efficiency in GREET, 80%, was used in this study. The natural gas consumption for the production of 1kg steam is therefore calculated as follows:

$$\text{Natural gas use} = \frac{h_{g@300^{\circ}\text{C}} - h_{f@25^{\circ}\text{C}}}{\eta_{\text{boiler}}} = \frac{2749.6\text{kJ/kg} - 104.83\text{kJ/kg}}{0.8} = 3306\text{kJ/kg}$$

Appendix E: Transportation Distances and Modes

Most of the chemicals and fuel consumed for mining and ore processing in the DRC are obtained from Zambia or South Africa and transported to the mining sites and processing plants in the DRC (Kamoto Copper Company 2018, Golder Associates 2007). The only chemical that is produced domestically in the DRC is limestone. At TFM, limestone is produced in a nearby quarry, so transportation for limestone was not considered in this study. Transportation within the DRC is all done by trucks, while transportation between the DRC and Zambia or South Africa can be done by rail, except for the transportation of crude $\text{Co}(\text{OH})_2$, which is considered to be a hazardous material and is not allowed to be transported by rail (Golder Associates 2007). The transportation distances and modes for the consumed chemicals and fuel are listed in Table A4.

Table 15. Transportation distances and modes for consumed chemicals and fuel for mining and ore processing

	Departure	Arrival	Distance (km)	Mode
Sulfur	Dar es Salaam	Ndola	2,030	Rail
	Ndola	TFM	460	Truck
Lime	Ndola	TFM	460	Truck
MgO	Durban	TFM	3,160	Truck
NaOH	Durban	TFM	3,161	Truck
Diesel	Ndola	TFM	460	Truck
Crude $\text{Co}(\text{OH})_2$	TFM	Dar es Salaam	2,490	Truck
	Dar es Salaam	Shanghai	12,971	Ocean tanker
	Shanghai	Tongxiang/Quzhou	200	Truck

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