

SUPPORTING INFORMATION

Quantifying the life-cycle health impacts of a cobalt-containing lithium-ion battery

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Table S1. Implementation of work-environment characterization factors (CF_{WE}) in processes of the production system. Work environment categories were obtained from Scanlon et al. (2015), except for the artisanal cobalt mining. **Bold** processes are created by the authors, mainly based on Dai et al. (2018), *italic* processed are from Chordia et al. (2021) and all other processes are from the Ecoinvent database (version 3.7.1). The processes have been categorized to the category deemed most suitable.

Work environment categories	Processes
Artisanal cobalt mining	Copper-cobalt ore mining, artisanal
212234 Copper Ore and Nickel Ore Mining	Copper-cobalt ore mining, industrial
325188 All Other Basic Inorganic Chemical Manufacturing	<p>Battery-grade cobalt sulfate production market for ammonium bicarbonate ammonium bicarbonate Cutoff, U market for hydrochloric acid, without water, in 30% solution state hydrochloric acid, without water, in 30% solution state Cutoff, U market for soda ash, dense soda ash, dense Cutoff, U <i>Sodium metabisulfite production</i> market for sulfuric acid sulfuric acid Cutoff, U market for magnesium oxide magnesium oxide Cutoff, U market for ammonia, anhydrous, liquid ammonia, anhydrous, liquid Cutoff, U market for lithium hydroxide lithium hydroxide Cutoff, U market for manganese sulfate manganese sulfate Cutoff, U market for nickel sulfate nickel sulfate Cutoff, U market for lithium hexafluorophosphate lithium hexafluorophosphate Cutoff, U market for chemicals, inorganic chemical, inorganic Cutoff, U</p>
325199 All Other Basic Organic Chemical Manufacturing	<p>market for carboxymethyl cellulose, powder carboxymethyl cellulose, powder Cutoff, U market for N-methyl-2-pyrrolidone N-methyl-2-pyrrolidone Cutoff, U market for tetrachloroethylene tetrachloroethylene Cutoff, U market for chemical, organic chemical, organic Cutoff, U market for dimethyl carbonate dimethyl carbonate Cutoff, U market for ethylene carbonate ethylene carbonate Cutoff, U market for butadiene butadiene Cutoff, U market for styrene styrene Cutoff, U</p>
331411 Primary Smelting and Refining of Copper	<p>Hydrometallurgical ore processing market for copper, cathode copper, cathode Cutoff, U</p>
324110 Petroleum Refineries	<p>market for kerosene kerosene Cutoff, U market for sulfur sulfur Cutoff, U</p>

	market for diesel, burned in building machine diesel, burned in building machine Cutoff, U market for paraffin paraffin Cutoff, U
327410 Lime Manufacturing	market for lime, hydraulic lime, hydraulic Cutoff, U
212399 All Other Nonmetallic Mineral Mining	market for limestone, crushed, for mill limestone, crushed, for mill Cutoff, U
325181 Alkalies and Chlorine Manufacturing	market for sodium hydroxide, without water, in 50% solution state sodium hydroxide, without water, in 50% solution state Cutoff, U
221112 Fossil Fuel Electric Power Generation	market for electricity, medium voltage electricity, medium voltage Cutoff, U – CN-SGCC market for electricity, medium voltage electricity, medium voltage Cutoff, U – KR market group for electricity, medium voltage electricity, medium voltage Cutoff, U
211111 Crude Petroleum and Natural Gas Extraction	market for heat, central or small-scale, natural gas heat, central or small-scale, natural gas Cutoff, U market for heat, from steam, in chemical industry heat, from steam, in chemical industry Cutoff, U market for heat, district or industrial, natural gas heat, district or industrial, natural gas Cutoff, U
221119 Other Electric Power Generation	market for electricity, medium voltage electricity, medium voltage Cutoff, U – CD market for electricity, medium voltage electricity, medium voltage Cutoff, U – SE
484121 General Freight Trucking, Long-Distance, Truckload	market group for transport, freight, lorry, unspecified transport, freight, lorry, unspecified Cutoff, U
483111 Deep Sea Freight Transportation	market for transport, freight, sea, bulk carrier for dry goods transport, freight, sea, bulk carrier for dry goods Cutoff, U
334412 Bare Printed Circuit Board Manufacturing	<i>Lithium-ion cell production in gigafactory</i>
562211 Hazardous Waste Treatment and Disposal	market for hazardous waste, for incineration hazardous waste, for incineration Cutoff, U
325182 Carbon Black Manufacturing	
325211 Plastics Material and Resin Manufacturing	market for polyvinylfluoride polyvinylfluoride Cutoff, U market for polyethylene, high density, granulate polyethylene, high density, granulate Cutoff, U
325120 Industrial Gas Manufacturing	market for oxygen, liquid oxygen, liquid Cutoff, U market for nitrogen, liquid nitrogen, liquid Cutoff, U

221310 Water Supply and Irrigation Systems	market for water, deionised water, deionised Cutoff, U
236210 Industrial Building Construction	market for electronic component factory electronic component factory Cutoff, U U market for precious metal refinery precious metal refinery Cutoff, U
562212 Solid Waste Landfill	market for waste polypropylene waste polypropylene Cutoff, U (80%)
562213 Solid Waste Combustors and Incinerators	market for waste polypropylene waste polypropylene Cutoff, U (20%) market for waste rubber, unspecified waste rubber, unspecified Cutoff, U
482111 Line-Haul Railroads	market group for transport, freight train transport, freight train Cutoff, U
212112 Bituminous Coal Underground Mining	market for graphite, battery grade graphite, battery grade Cutoff, U
111110 Soybean Farming	market for fatty acid fatty acid Cutoff, U (40%)
111120 Oilseed (except Soybean) Farming	market for fatty acid fatty acid Cutoff, U (60%)
331312 Primary Aluminum Production	market for aluminium, wrought alloy aluminium, wrought alloy Cutoff, U (70%)
331111 Iron and Steel Mills	market for steel, low-alloyed, hot rolled steel, low-alloyed, hot rolled Cutoff, U U
331314 Secondary Smelting and Alloying of Aluminum	market for aluminium, wrought alloy aluminium, wrought alloy Cutoff, U (30%)
331419 Primary Smelting and Refining of Nonferrous Metal (except Copper and Aluminum)	market for nickel, class 1 nickel, class 1 Cutoff, U

Table S2. Mining of cobalt in 2020. Source: Shedd (2020).

Country	Cobalt mined (metric tons)	Cobalt mined (%)
DRC	95,000	70%
Russia	6,300	5%
Australia	5,700	4%
Philippines	4,700	3%
Cuba	3,600	3%
Canada	3,200	2%
Papua New Guinea	2,800	2%
China	2,300	2%
Morocco	1,900	1%
South Africa	1,800	1%
Madagascar	700	1%
United States	600	<1%
Other countries	6,400	5%
Total	135,000	100%

Table S3. Unit process dataset for artisanal copper-cobalt mining in the DRC. CD=the DRC.

Input flow	Flow type	Amount	Unit	Linked upstream process
Cobalt	Elementary flow, resource in ground	0.0047	kg	-
Copper	Elementary flow, resource in ground	0.024	kg	-
Inert rock	Elementary flow, resource in ground	0.97	kg	-
Output flow	Flow type	Amount	Unit	Linked downstream process
Copper-cobalt ore, CD	Product flow	1	kg	-

Table S4. Unit process dataset for industrial copper-cobalt mining in the DRC. CD=the DRC, GLO=global, U=linked to unit process datasets. Source: Dai et al. (2018).

Input flow	Flow type	Amount	Unit	Linked upstream process
Cobalt	Elementary flow, resource, in ground	0.0047	kg	-
Copper	Elementary flow, resource, in ground	0.024	kg	-
Inert rock	Elementary flow, resource, in ground	0.97	kg	-
Water, unspecified natural origin, CD	Elementary flow, resource, unspecified	0.00017	m ³	-
Diesel, burned in building machine	Product flow	0.16	kWh	market for diesel, burned in building machine diesel, burned in building machine Cutoff, U - GLO
Output flow	Flow type	Amount	Unit	Linked downstream process
Copper-cobalt ore, CD	Product flow	1	kg	-
Particulates, <10 µm	Elementary flow, emission to air	0.0014	kg	-
Particulates, <2.5 µm	Elementary flow, emission to air	0.00015	kg	-

Table S5. Unit process dataset for hydrometallurgical ore processing in the DRC. CD=the DRC, RoW=rest of world, U=linked to unit process datasets. Source: Dai et al. (2018) with economic allocation between copper (7,300 USD/ton) and the cobalt content in the crude cobalt hydroxide (43,000 USD/ton).

Input flow	Flow type	Amount	Unit	Linked upstream process
Copper-cobalt ore	Product flow	46	kg	80% Industrial copper-cobalt mining in the DRC -CD (Table S4) 20% Artisanal copper-cobalt mining in the DRC - CD Table S3)
Electricity, medium voltage	Product flow	4.1	kWh	market for electricity, medium voltage electricity, medium voltage Cutoff, U - CD
Lime, hydraulic	Product flow	0.70	kg	market for lime, hydraulic lime, hydraulic Cutoff, U - RoW
Limestone, crushed, for mill	Product flow	1.9	kg	market for limestone, crushed, for mill limestone, crushed, for mill Cutoff, U - RoW
Magnesium oxide	Product flow	0.32	kg	market for magnesium oxide magnesium oxide Cutoff, U - GLO
Sodium hydroxide, without water, in 50% solution state	Product flow	0.085	kg	market for sodium hydroxide, without water, in 50% solution state sodium hydroxide, without water, in 50% solution state Cutoff, U - GLO
Sulfur	Product flow	1.5	kg	market for sulfur sulfur Cutoff, U - GLO
Transport, freight, lorry, unspecified	Product flow	2.7	t•km	market group for transport, freight, lorry, unspecified transport, freight, lorry, unspecified Cutoff, U - GLO
Transport, freight, sea, bulk carrier for dry goods	Product flow	13	t•km	market for transport, freight, sea, bulk carrier for dry goods transport, freight, sea, bulk carrier for dry goods Cutoff, U - GLO
Water, unspecified natural origin, CD	Elementary flow, resource, unspecified	70	liter	-
Output flow	Flow type	Amount	Unit	Linked downstream process
Crude cobalt hydroxide, CD	Product flow	1	kg	-
Sulfur dioxide	Elementary flow, emission to air	0.014	kg	-
Oxidic tailings	Waste flow	22	kg	market for non-sulfidic tailing, off-site non-sulfidic tailing, off-site Cutoff, U - GLO
Sulfidic tailings	Waste flow	22	kg	market for sulfidic tailings, from copper mine operation sulfidic tailings, from copper mine operation Cutoff, U - ZM

Table S6. Unit process dataset for battery-grade cobalt sulfate production in China. CD=the DRC, CN=China, RoW=rest of world, GLO=global, U=linked to unit process datasets, SGCC=State Grid Corporation of China, ZJ=Zhejiang. Source: Dai et al. (2018).

Input flow	Flow type	Amount	Unit	Linked upstream process
Crude cobalt hydroxide, CD	Product flow	1.1	kg	Hydrometallurgical ore processing - CD (Table S5)
Ammonium bicarbonate	Product flow	0.22	kg	market for ammonium bicarbonate ammonium bicarbonate Cutoff, U - RoW
Hydrochloric acid, without water, in 30% solution state	Product flow	1.8	kg	market for hydrochloric acid, without water, in 30% solution state hydrochloric acid, without water, in 30% solution state Cutoff, U - RoW
Kerosene	Product flow	0.019	kg	market for kerosene kerosene Cutoff, U - RoW
Lime, hydraulic	Product flow	0.0076	kg	market for lime, hydraulic lime, hydraulic Cutoff, U - Row
Limestone, crushed, for mill	Product flow	0.023	kg	market for limestone, crushed, for mill limestone, crushed, for mill Cutoff, U - Row
Soda ash, dense	Product flow	0.034	kg	market for soda ash, dense soda ash, dense Cutoff, U - GLO
Sodium hydroxide, without water, in 50% solution state	Product flow	3.3	kg	market for sodium hydroxide, without water, in 50% solution state sodium hydroxide, without water, in 50% solution state Cutoff, U - GLO
Sodium metabisulfite	Product flow	0.030	kg	Production of metabisulfite (Table S7)
Sulfuric acid	Product flow	1.0	kg	market for sulfuric acid sulfuric acid Cutoff, U - RoW
Electricity, medium voltage	Product flow	1.2	kWh	market for electricity, medium voltage electricity, medium voltage Cutoff, U - SGCC
Heat, central or small-scale, natural gas	Product flow	1.2	MJ	market for heat, central or small-scale, natural gas heat, central or small-scale, natural gas Cutoff, U - RoW
Heat, from steam, in chemical industry	Product flow	7.7	MJ	market for heat, from steam, in chemical industry heat, from steam, in chemical industry Cutoff, U - RoW
Water, unspecified natural origin, CN	Elementary flow, resource, unspecified	0.019	m ³	-
Output flow	Flow type	Amount	Unit	Linked downstream process
Battery-grade cobalt sulfate, CN-ZJ	Product flow	1	kg	-

Table S7. Unit process dataset for production of sodium metabisulfite. Source: Dai et al. (2018).

Input flow	Flow type	Amount	Unit	Linked upstream process
Sodium hydroxide, without water, in 50% solution state	Product flow	0.42	kg	market for sodium hydroxide, without water, in 50% solution state sodium hydroxide, without water, in 50% solution state Cutoff, U - GLO
Output flow	Flow type	Amount	Unit	Linked downstream process
Sodium metabisulfite, GLO	Product flow	1	kg	-

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