Supplementary Materials

Database-driven divergence in carbon footprint estimates for Chinese refined copper supply chains

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S1. Introduction to pyrometallurgical copper production

S1.1 Overview of the Ausmelt smelting route

The conventional Ausmelt smelting route (hereafter, the "Ausmelt route") comprises four main stages:

(1) Copper concentrate, copper-bearing feed, fluxes, lump coal, and pulverized coal are charged to the Ausmelt furnace. Air, oxygen, and pulverized coal are injected through the submerged lance, producing matte, slag, and off-gas. The off-gas passes through waste-heat recovery and electrostatic precipitation before entering the

sulfuric-acid plant, while the matte–slag mixture flows to the electric settling furnace. Major emission sources are purchased electricity, coal combustion, and coal used as a reductant. The resulting matte contains approximately 60% Cu.

(2) In the electric settling furnace, electrode heating promotes matte–slag separation. Matte is tapped into ladles and transferred to converting, while slag is discharged for slow cooling. Emissions arise mainly from purchased electricity and the decomposition of carbon-containing electrode paste.

(3) Matte is converted to blister copper using oxygen-enriched air. Quartz is added as a flux to remove iron and other impurities in the slag. The blister copper is then transferred to a rotary anode furnace for fire refining.

(4) Anode plates are electrorefined to cathode copper, with nickel sulfate, copper sulfate, and anode slime recovered as by-products.

S1.2 Overview of the double-flash smelting route

The double-flash route combines flash smelting and flash converting in a continuous flowsheet. The sampled smelter uses imported flotation concentrate, which is blended and dried with steam and electricity before flash smelting. Matte is granulated and stored before grinding and flash converting; slow-cooled slag is floated, with slag concentrate recycled and tailings sold as cement raw material. Blister copper is fire-refined and cast as 99.3% Cu anodes, then electrorefined to cathode copper above 99.99% purity. Off-gas from both flash furnaces undergoes electrostatic precipitation, waste-heat recovery, purification, and cooling before conversion to 98% sulfuric acid.

S2. Overview and comparison of the LCA software packages and databases

Supplementary Table 1. Overview of the LCA software packages and their built-in databases

Software	Description	Built-in database(s)
SimaPro	SimaPro is the most widely used LCA software across major industries, consultancies, research institutes and universities, allowing systematic and transparent analysis and construction of complex life cycle models.	ecoinvent, Agri-Footprint (agriculture), ELCD (Europe), etc.
GaBi (now renamed Sphera LCA)	One of GaBi's core strengths is its proprietary GaBi database, which is renowned for its depth and precision in chemicals, plastics, advanced materials and energy systems, giving it significant industrial application.	Education Database 2020
OpenLCA	OpenLCA is a free, open-source LCA platform offering maximum flexibility and transparency. It is not bundled with any database and serves purely as a calculation platform; it therefore supports importing and managing nearly all mainstream LCA database formats, with the databases selected by the user.	Configured by the user
eBalance	eBalance is an LCA software package jointly developed by Sichuan University and IKE Environmental Technology Co., Ltd. Its defining feature is its dedication to developing and refining LCA methodology localized for Chinese applications.	Chinese Life Cycle Database (CLCD), European Life Cycle Database (ELCD), Swiss ecoinvent database (public version), etc.
eFootprint	eFootprint, launched by IKE Environmental Technology in 2013, is the world's first	Chinese Life Cycle Database (CLCD),

Software	Description	Built-in database(s)
	online LCA and carbon footprint management platform, and can be regarded as the cloud-based upgrade of eBalance.	European Life Cycle Database (ELCD)

S3. Foreground inventories of the two production systems

S3.1. Ausmelt input and output inventories

Supplementary Table 2. Input inventory of the Ausmelt route

Input material/energy (per tonne of cathode copper)	Amount
Imported copper concentrate	2.639 t
Transport (domestic copper concentrate, road)	50 km
Domestic copper concentrate	1.715 t (in the domestic copper concentrate inventory, the main energy carriers are diesel and electricity, and the main materials are explosives, steel balls and lime)
Transport (imported copper concentrate, waterway)	20000 km
Transport (imported copper concentrate, road)	40 km
Raw coal	142.8 kg
Natural gas	21.1 Nm^3
Diesel	52.4124 kg
Electricity (electricity used in mining and beneficiation of domestic copper concentrates; excluded from the subsequent electricity analysis)	888.21565 kWh
explosive	30.6299 kg
steel balls	299.03 kg
lime	49.75 kg

Input material/energy (per tonne of cathode copper)	**Amount**
Electricity (Direct purchased electricity, excluding sulfuric-acid production)	848.820 kWh
Sulfuric-acid-production electricity	291.060 kWh
Steam (internally generated from waste-heat recovery; no additional burden assigned)	1031.6 kg
Silica sand	552.2 kg
Electrode paste	1.6 kg
Oxygen	978.86987 Nm^3 (converted to electricity in the calculation)
Water	6182.6 kg
Nitrogen	25.13419 Nm^3 (converted to electricity in the calculation)
Hydrochloric acid (mass fraction of 30%)	119.5 g (corresponding to 104 mL at 20 ℃)
Sulfuric acid	8 kg
Gelatin	0.06 kg
Thiourea	0.06 kg
Avitone	0.018 kg

Note: (1) Direct purchased electricity is reported separately for the main copper-production stages and sulfuric-acid production. For the Ausmelt case, direct purchased electricity excluding sulfuric-acid production is 848.820 kWh/t Cu, while sulfuric-acid-production electricity is 291.060 kWh/t Cu, giving a total direct purchased-electricity demand of 1,139.880 kWh/t Cu. The factor of 0.976 represents the proportion of electricity purchased from the grid because 2.4% of the plant's electricity was supplied on site. The reported direct purchased-electricity values include this factor. The oxygen and nitrogen quantities are physical demands before application of the 0.976 factor. Their purchased-electricity equivalents were calculated as follows:

Oxygen electricity = 978.86987 × 0.65 × 0.976 = 620.995046 kWh/t Cu

Nitrogen electricity = 25.13419 × 0.12 × 0.976 = 2.943716 kWh/t Cu

Total electricity-related demand = 1,139.880 + 620.995046 + 2.943716 = 1,763.818762 kWh/t Cu

(2) Sulfuric-acid-production electricity is included in the modeled stage totals; Supplementary Table 2 reports it separately for transparency.

(3) Steam is generated internally from smelting waste heat and used mainly for concentrate drying. It is retained for inventory transparency and energy accounting but modeled as a burden-free internal flow, with no separate steam-production dataset or additional fuel burden, thereby avoiding double counting.

(4) Imported concentrate is reported as the actual dry physical input of 2.639 t/t cathode copper at 25.35% Cu. For background production calculations using the adopted reference grade of 29.63% Cu, the equivalent input is 2.639×0.2535/0.2963=2.257801t, approximately 2.258 t. The actual physical input, rather than the grade-normalized equivalent, is used to calculate separately modeled transport.

(5) The total diesel input of 52.4124 kg/t Cu comprises 52.4104 kg/t Cu consumed in domestic copper-concentrate mining and beneficiation and 0.002 kg/t Cu recorded by the plant for moving slag approximately 70–80 m on site. The 0.002 kg/t Cu on-site diesel value was retained as reported but could not be independently verified and appears unusually low for the described operation. Its contribution to the modeled carbon footprint is negligible.

(6) The electricity and steel-ball inputs for domestic concentrate production were reported by the plant and could not be independently verified. The reported values, particularly those for underground-mining electricity and steel balls, appear high and should be interpreted with caution. They were retained as reported and converted to the functional unit of one tonne of cathode copper using the domestic-concentrate input.

Supplementary Table 3. Output inventory of the Ausmelt route

Output product	Output
Cathode copper	1 t
Sulfuric acid	2.646 t

S3.2. Double-flash input and output inventories

Supplementary Table 4. Input inventory of the double-flash route

Input material/energy (per tonne of cathode copper)	Amount
Imported copper concentrate	3.922 t
Transport (imported copper concentrate, waterway)	20,000 km
Transport (imported copper concentrate, road)	40 km
Natural gas	37.0 Nm^3
Electricity(Direct purchased electricity, excluding sulfuric-acid production)	450.280 kWh
Sulfuric-acid-production electricity	407.000 kWh
Steam (internally generated from waste-heat recovery; no additional burden assigned)	683.0 kg
Silica sand	531.6 kg
Limestone	76.5 kg
Oxygen	1025.36885 Nm^3 (converted to electricity in the calculation)
Water	1.9 t
Nitrogen	134.73361 Nm^3 (converted to electricity in the calculation)
Sodium carbonate	7.1 kg
Sodium hydroxide	20.0 kg

Note: (1) Direct purchased electricity is reported separately for the main

copper-production stages and sulfuric-acid production. For the double-flash case, direct purchased electricity excluding sulfuric-acid production is 450.280 kWh/t Cu, while sulfuric-acid-production electricity is 407.000 kWh/t Cu, giving a total direct purchased-electricity demand of 857.280 kWh/t Cu. The factor of 0.976 represents the proportion of electricity purchased from the grid because 2.4% of the plant's electricity was supplied on site. The reported direct purchased-electricity values include this factor. The oxygen and nitrogen quantities are physical demands before application of the 0.976 factor. Their purchased-electricity equivalents were calculated as follows:

Oxygen electricity = 1,025.36885 × 0.65 × 0.976 = 650.493998 kWh/t Cu

Nitrogen electricity = 134.73361 × 0.12 × 0.976 = 15.780000 kWh/t Cu

Total electricity-related demand = 857.280 + 650.493998 + 15.780000 = 1,523.554 kWh/t Cu

Sulfuric-acid-production electricity is included in the modeled stage totals; Supplementary Table 4 reports it separately for transparency.

(2) Steam is generated internally from smelting waste heat and used mainly for concentrate drying. It is retained for inventory transparency and energy accounting but modeled as a burden-free internal flow, with no separate steam-production dataset or additional fuel burden.

(3) Imported concentrate is reported as the actual dry physical input of 3.922 t/t cathode copper at 26.00% Cu. For background production calculations using the adopted reference grade of 29.63% Cu, the equivalent input is 3.922×0.26/0.2963=3.441512 t, approximately 3.442 t. Separately modeled maritime and road transport use the actual physical input of 3.922 t.

Supplementary Table 5. Output inventory of the double-flash route

Output product	Output
Cathode copper	1 t
Sulfuric acid	3.7 t

Note: Electricity-demand reconciliation between the two observed systems: direct

purchased-electricity demand is 1,139.880 kWh/t Cu for Ausmelt and 857.280 kWh/t Cu for double-flash, while oxygen- and nitrogen-production electricity is 623.938762 and 666.274 kWh/t Cu, respectively. Total electricity-related demand is therefore 1,763.818762 versus 1,523.553998 kWh/t Cu, a difference of 240.264764 kWh/t Cu within the common smelting-and-refining boundary. Upstream electricity for concentrate mining and beneficiation is excluded.

S4. Background datasets and proxy selections

S4.1. Background datasets for the Ausmelt route

Modeling notes:

1. Where a required process was unavailable in the designated database, ecoinvent 3.11 was used as a proxy. It was selected as the general-purpose reference database and was the latest version available when the modeling was completed.
2. GaBi required the most extensive supplementation. Open-pit mining, underground mining, and domestic-concentrate beneficiation lacked multiple datasets and were therefore supplemented with ecoinvent 3.11. The integrated domestic-concentrate model was retained as a whole rather than replacing only its electricity dataset, which would have reduced internal consistency and interpretability.
3. Selected missing materials in eBalance and eFootprint were also represented with ecoinvent 3.11 proxies.
4. Following the ISO 14044 requirement that cut-off criteria be defined and disclosed by the practitioner, this study adopted author-defined cut-off thresholds. An input for which no appropriate dataset or defensible proxy was available was omitted only if it represented less than 1% of the reference-product mass, the cumulative mass of all omitted inputs remained below 5%, and the input was not judged to have potentially disproportionate energy use, emissions, or climate-change significance. Water was not excluded under the 1% mass cut-off. The plant reported the quantity of water used but did not specify its source or supply process. In the GaBi configuration, this quantity was retained as an unspecified natural-resource water flow. The flow contributes 0 kg CO_2e directly under IPCC 2021 GWP100; source-specific abstraction, pumping,

treatment, and delivery could not be modeled from the available data.

5. Imported concentrate is represented by regional production datasets combined using import-mass weights. SimaPro uses ecoinvent 3.10; OpenLCA and the GaBi imported-concentrate proxy use ecoinvent 3.11. International shipping is modeled separately.

Supplementary Table 6 lists the unit processes and background datasets used to model the Ausmelt route in each LCA tool.

Supplementary Table 6. Background dataset selections for each LCA software package in the Ausmelt route

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Open-pit ore mining	Diesel	Diesel {GLO}| market group for | Cut-off, S - Copied from ecoinvent S	diesel {GLO}| market group for diesel | Cut-off, S(from ecoinvent 3.11)	Diesel (after transport) (CN)-CLCD-China 0.8.1 2012	Diesel (hydrorefining) (unclassified)-CLCD-China 0.9	diesel {GLO}| market group for diesel | Cut-off, S
	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S(from ecoinvent 3.11)	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Bulk emulsion explosive	Explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S(from ecoinvent 3.11)	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S(from ecoinvent 3.11)	Emulsion explosive (unclassified)-CLCD-China 0.9	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S
	Carbon dioxide (emission)	Carbon dioxide	Carbon dioxide	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossile)
	Methane (emission)	Methane	Methane	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossile)
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		carbon dioxide multiplied by a GWP of 265)	carbon dioxide multiplied by a GWP of 265)			
	Diesel	Diesel {GLO}| market group for | Cut-off, S - Copied from ecoinvent S	diesel {GLO}| market group for diesel | Cut-off, S(from ecoinvent 3.11)	Diesel (after transport) (CN)-CLCD-China 0.8.1 2012	Diesel (hydrorefining) (unclassified)-CLCD-China 0.9	diesel {GLO}| market group for diesel | Cut-off, S
Undergr ound ore mining	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S(from ecoinvent 3.11)	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Detonatin g cord	Polyethylene, high density, granulate {GLO}| market for	polyethylene, high density, flakes, recycled {RER}|	Polyethylene–high-density polyethylene–high	High-density polyethylene-HDPE (unclassified)-CLCD-	polyethylene, high density, flakes, recycled {RER}|

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		polyethylene, high density, granulate | Cut-off, S	market for polyethylene, high density, flakes, recycled | Cut-off, S(from ecoinvent 3.11)	density (CN))-CLCD-China 0.8.1 2012	China 0.9	market for polyethylene, high density, flakes, recycled | Cut-off, S
	Modified ammonium nitrate–fuel oil explosive	Explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S(from ecoinvent 3.11)	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S(from ecoinvent 3.11)	Emulsion explosive (unclassified)-CLCD-China 0.9	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S
	Rock emulsion explosive	Explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S(from ecoinvent 3.11)	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S(from ecoinvent 3.11)	Emulsion explosive (unclassified)-CLCD-China 0.9	explosive, tovex {GLO}| market for explosive, tovex | Cut-off, S
	Digital electronic	Chromium steel pipe {GLO}| market	chromium steel pipe {GLO}| market for	Carbon steel–steel mix	Electronic detonator (unclassified)-CLCD-	chromium steel pipe {GLO}| market for

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	detonator	for chromium steel pipe | Cut-off, S	chromium steel pipe | Cut-off, S(from ecoinvent 3.11)	(CN))-CLCD-China 0.8.1 2012	China 0.9	chromium steel pipe | Cut-off, S
	Digital detonator lead wire	Aluminium around steel bi-metal wire, 3.67mm external diameter {GLO}| market for aluminium around steel bi-metal wire, 3.67mm external diameter | Cut-off, S	aluminium around steel bi-metal wire, 3.67mm external diameter {GLO}| market for aluminium around steel bi-metal wire, 3.67mm external diameter | Cut-off, S(from ecoinvent 3.11)	aluminium around steel bi-metal wire, 3.67mm external diameter {GLO}| market for aluminium around steel bi-metal wire, 3.67mm external diameter | Cut-off, S(from ecoinvent 3.11)	aluminium around steel bi-metal wire, 3.67mm external diameter {GLO}| market for aluminium around steel bi-metal wire, 3.67mm external diameter | Cut-off, S(from ecoinvent 3.11)	aluminium around steel bi-metal wire, 3.67mm external diameter {GLO}| market for aluminium around steel bi-metal wire, 3.67mm external diameter | Cut-off, S
	Carbon dioxide (emission)	Carbon dioxide	Carbon dioxide	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossile)

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Methane (emission)	Methane	Methane	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossile)
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as carbon dioxide multiplied by a GWP of 265)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as carbon dioxide multiplied by a GWP of 265)	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide
Beneficiation of domestic copper concentr	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium	Central China grid electricity–Central China grid electricity transmission–to user	Central China grid electricity (user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
ate		voltage | Cut-off, S	voltage | Cut-off, S(from ecoinvent 3.11)	(CN))-CLCD-China 0.8.1 2012		voltage | Cut-off, S
	Lime	Lime, hydrated, packed {RoW}| market for lime, hydrated, packed | Cut-off, S	hydrated lime, packed {GLO}| market for hydrated lime, packed | Cut-off, S(from ecoinvent 3.11)	Lime production–market average (CN))-CLCD-China 0.8.1 2012	Lime-CLCD-China 0.9	hydrated lime, packed {GLO}| market for hydrated lime, packed | Cut-off, S
	Steel grinding balls	Cast iron {GLO}| market for cast iron | Cut-off, S	cast iron {GLO}| market for cast iron | Cut-off, S(from ecoinvent 3.11)	Carbon steel–steel mix (CN))-CLCD-China 0.8.1 2012	Converter carbon steel (non-alloy steel)-CLCD-China 0.9	cast iron {GLO}| market for cast iron | Cut-off, S
	Pine oil	Coconut oil, crude {GLO}| market for coconut oil, crude | Cut-off, S	coconut oil, crude {GLO}| market for cottonseed oil, crude | Cut-off, S(from ecoinvent 3.11)	coconut oil, crude {GLO}| market for cottonseed oil, crude | Cut-off, S(from ecoinvent 3.11)	coconut oil, crude {GLO}| market for cottonseed oil, crude | Cut-off, S(from ecoinvent 3.11)	coconut oil, crude {GLO}| market for cottonseed oil, crude | Cut-off, S
	Xanthate	Sodium ethyl	sodium ethyl xanthate	Xanthate-CLCD-Chi	Xanthate-CLCD-Chin	sodium ethyl

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		xanthate {GLO}| market for sodium ethyl xanthate | Cut-off, S	{GLO}| market for sodium ethyl xanthate | Cut-off, S(from ecoinvent 3.11)	na 0.8.1 2012	a-ECER 0.8	xanthate {GLO}| market for sodium ethyl xanthate | Cut-off, S
	Conveyor belt	Transport, freight, conveyor belt {GLO}| market for transport, freight, conveyor belt | Cut-off, S	transport, freight, conveyor belt {GLO}| market for transport, freight, conveyor belt | Cut-off, S(from ecoinvent 3.11)	transport, freight, conveyor belt {GLO}| market for transport, freight, conveyor belt | Cut-off, S(from ecoinvent 3.11)	transport, freight, conveyor belt {GLO}| market for transport, freight, conveyor belt | Cut-off, S(from ecoinvent 3.11)	transport, freight, conveyor belt {GLO}| market for transport, freight, conveyor belt | Cut-off, S
Copper concentrate pretreatment	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off,	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
			S(from ecoinvent 3.11)	0.8.1 2012		
	Imported copper concentrate	Copper concentrate, sulfide ore {AU/CL/CA/ID/KZ/ROW/RU/US}| copper mine operation and beneficiation, sulfide ore | Cut-off, S	Copper concentrate, sulfide ore {AU/CL/CA/ID/KZ/ROW/RU/US}| copper mine operation and beneficiation, sulfide ore | Cut-off, S(from ecoinvent 3.11)	Copper concentrate–imported copper concentrate–copper grade generally 20%—40%, average approximately 25% (CN)-CLCD-China 0.8.1 2012	Imported copper concentrate (compliant with YS/T318-2007 Copper Concentrate; copper grade 25.00%)-CLCD-China 0.9	Copper concentrate, sulfide ore {AU/CA/CL/ID/KZ/RoW/RU/US} | copper mine operation and beneficiation, sulfide ore | Cut-off, S
	Transport (domestic copper concentrate) (road)	Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	GLO: Truck, Euro 5, 28 - 32t gross weight / 22t payload capacity ts <u-so> (associated fuel: CN: Diesel mix at refinery ts)	Truck transport–heavy-duty diesel truck transport (30t)–China–30t (CN)-CLCD-China 0.8.1 2012	Heavy-duty diesel truck transport (18t payload) (heavy-duty truck)-CLCD-China 0.9	Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Transport (imported copper concentrate) (road)	Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	GLO: Truck, Euro 5, 28 - 32t gross weight / 22t payload capacity ts <u-so> (associated fuel: CN: Diesel mix at refinery ts)	Truck transport–heavy-duty diesel truck transport (30t)–China–30t (CN)-CLCD-China 0.8.1 2012	Heavy-duty diesel truck transport (18t payload) (heavy-duty truck)-CLCD-China 0.9	Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| market for transport, freight, lorry, 16-32 metric ton, diesel, EURO 6 | Cut-off, S
	Transport (imported copper concentrate) (sea)	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | Cut-off, S	GLO: Bulk commodity carrier, average, ocean going ts <u-so> (associated fuel: CN: Heavy fuel oil at refinery (1.0 wt.% S) ts)	Dry bulk carrier transport–dry bulk carrier transport (2500t)–China-2500t (CN)-CLCD-China 0.8.1 2012	Dry bulk carrier transport (2500t payload) (2500t payload)-CLCD-China 0.9	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods, heavy fuel oil | Cut-off, S
Ausmelt furnace	Processed natural gas	Natural gas, production mixture, to energy use |	CN: Natural gas mix ts	Natural gas (after transport) (CN)-CLCD-China-	Natural gas (national average) (unclassified)-CLCD-	natural gas, high pressure {CN}| market for natural

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		Natural gas, processed, for energy use, at plant		Public 0.8.1 2012	China 0.9	gas, high
	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Raw coal	Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, S	CN: Hard coal mix ts	Raw coal–after raw-coal transport–after transport (CN))-CLCD-China 0.8.1 2012	Anthracite-CLCD-China 0.9	hard coal {CN}| market for hard coal | Cut-off, S
	Diesel	Diesel {GLO}| market group for |		Diesel (after transport)	Diesel (hydrorefining) (unclassified)-CLCD-	diesel {GLO}| market group for

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		Cut-off, S - Copied from ecoinvent S		(CN)-CLCD-China 0.8.1 2012	China 0.9	diesel | Cut-off, S
	Silica sand	Silica sand {GLO}| market for silica sand | Cut-off, S	DE: Silica sand (Excavation and processing) ts	Silica sand (CN)-CLCD-China 0.8.1 2012	Ordinary silica sand (SiO_2 content 90%～99%)-CLCD-China 0.9	Silica sand {GLO}| market for silica sand | Cut-off, S
	Electrode paste	Anode, paste, for aluminium electrolysis {GLO}| market for anode, paste, for aluminium electrolysis | Cut-off, S	Not found; negligible	Electrode paste (CN)-CLCD-China 0.8.1 2012	Electrode paste-CLCD-China-ECER 0.8	anode, paste, for aluminium electrolysis {GLO}| market for anode, paste, for aluminium electrolysis | Cut-off, S
	Oxygen	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		high to medium voltage | Cut-off, S		transmission–to user (CN))-CLCD-China 0.8.1 2012		high to medium voltage | Cut-off, S
	Water	Water, fresh	Not modeled as a separate GaBi process (direct GWP100 contribution of water as a natural-resource flow: 0 kg CO_2e; water source and supply process unspecified).	Surface water–unspecified source, industrial use {renewable water resource}	Fresh water {renewable water resource}	Fresh water
	Carbon dioxide (emission)	Carbon dioxide	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossile)
	Methane (emission)	Methane	Methane [Organic emissions to air (group VOC)]	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossile)

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as carbon dioxide multiplied by a GWP of 265)	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide
Converter blowing	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Processed	Natural gas,	CN: Natural gas mix ts	Natural gas (after	Natural gas (national	natural gas, high

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	natural gas	production mixture, to energy use | Natural gas, processed, for energy use, at plant		transport) (CN)-CLCD-China-Public 0.8.1 2012	average) (unclassified)-CLCD-China 0.9	pressure {CN}| market for natural gas, high
	Oxygen	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Silica sand	Silica sand {GLO}| market for silica sand | Cut-off, S	DE: Silica sand (Excavation and processing) ts	Silica sand (CN)-CLCD-China 0.8.1 2012	Ordinary silica sand (SiO_2 content 90%～99%)-CLCD-China 0.9	Silica sand {GLO}| market for silica sand | Cut-off, S
	Water	Water, fresh	Not modeled as a	Surface water–	Fresh water	Fresh water

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
			separate GaBi process (direct GWP100 contribution of water as a natural-resource flow: 0 kg CO_2e; water source and supply process unspecified).	unspecified source, industrial use {renewable water resource}	{renewable water resource}	
	Carbon dioxide (emission)	Carbon dioxide	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossil)
	Methane (emission)	Methane	Methane [Organic emissions to air (group VOC)]	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossil)
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		impact was approximated as carbon dioxide multiplied by a GWP of 265)				
	Processed natural gas	Natural gas, production mixture, to energy use | Natural gas, processed, for energy use, at plant	CN: Natural gas mix ts	Natural gas (after transport) (CN)-CLCD-China-Public 0.8.1 2012	Natural gas (national average) (unclassified)-CLCD-China 0.9	natural gas, high pressure {CN}| market for natural gas, high
Anode furnace	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Oxygen	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	0.8.1 2012 Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Nitrogen	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Water	Water, fresh	Not modeled as a separate GaBi process	Surface water–unspecified source,	Fresh water {renewable water	Fresh water

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
			(direct GWP100 contribution of water as a natural-resource flow: 0 kg CO_2e; water source and supply process unspecified).	industrial use {renewable water resource}	resource}	
	Carbon dioxide (emission)	Carbon dioxide	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossile)
	Methane (emission)	Methane	Methane [Organic emissions to air (group VOC)]	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossile)
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		approximated as carbon dioxide multiplied by a GWP of 265)				
Electrore fining	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Sulfuric acid	Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, S	DE: Sulphuric acid (96%) ts	Sulfuric acid–sulfuric acid (China market average)-98% (CN)-CLCD-China 0.8.1 2012	Sulfuric acid–market average (unclassified)-CLCD-China 0.9	sulfuric acide {ROW}| market for sulfuric acid | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Hydrochloric acid	Hydrochloric acid, without water, in 30% solution state {RoW}| market for hydrochloric acid, without water, in 30% solution state | Cut-off, S	Not found; negligible	Hydrochloric acid — hydrochloric acid (31%) production — 31% (CN)-CLCD-China 0.8.1 2012	Hydrochloric acid (31%) (unclassified)-CLCD-China 0.9	Hydrochloric acid, without water, in 30% solution state {RoW}| market for hydrochloric acid, without water, in 30% solution state | Cut-off, S

S4.2. Background datasets for the double-flash route

Modeling notes:

1. Where a required process was unavailable in the designated database, ecoinvent 3.11 was used as a proxy, consistent with the Ausmelt modeling procedure.

2. The double-flash route required fewer cross-database substitutions than the Ausmelt route. In the GaBi configuration, ecoinvent 3.11 proxies were used for imported concentrate and three sulfuric-acid-production reagents: sodium hydrosulfide, polyacrylamide, and the hypochlorite reagent (modeled using sodium hypochlorite).

3. Following the ISO 14044 requirement that cut-off criteria be defined and disclosed by the practitioner, this study adopted author-defined

cut-off thresholds. An input for which no appropriate dataset or defensible proxy was available was omitted only if it represented less than 1% of the reference-product mass, the cumulative mass of all omitted inputs remained below 5%, and the input was not judged to have potentially disproportionate energy use, emissions, or climate-change significance. Water was not excluded under the 1% mass cut-off. The plant reported the quantity of water used but did not specify its source or supply process. In the GaBi configuration, this quantity was retained as an unspecified natural-resource water flow. The flow contributes 0 kg CO_2e directly under IPCC 2021 GWP100; source-specific abstraction, pumping, treatment, and delivery could not be modeled from the available data.

4. Imported concentrate follows the regional production-dataset weighting procedure described in Section S5. The GaBi proxy uses ecoinvent 3.11 and the same import-mass weights as OpenLCA. No global concentrate-market dataset is used for this input.

Supplementary Table 7 lists the background datasets used to model the double-flash route in each LCA tool.

Supplementary Table 7. Background datasets selected for the double-flash route in each LCA tool

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Copper concentrate mining, beneficiati	Imported copper concentrate	Copper concentrate, sulfide ore {AU/CL/CA/ID/K	Copper concentrate, sulfide ore {AU/CL/CA/ID/KZ/ ROW/RU/US}|	Copper concentrate–imported copper concentrate–copper grade generally	Imported copper concentrate (compliant with YS/T318-2007	Copper concentrate, sulfide ore {AU/CA/CL/ID/KZ/ RoW/RU/US} |

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
on, and transport		Z/ROW/RU/US}| copper mine operation and beneficiation, sulfide ore | Cut-off, S	copper mine operation and beneficiation, sulfide ore | Cut-off, S(from ecoinvent 3.11)	20%—40%, average approximately 25% (CN)-CLCD-China 0.8.1 2012	Copper Concentrate; copper grade 25.00%)-CLCD-China 0.9	copper mine operation and beneficiation, sulfide ore | Cut-off, S
	Transport (imported copper concentrate) (sea)	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | Cut-off, S	GLO: Bulk commodity carrier, average, ocean going ts <u-so> (associated fuel: CN: Heavy fuel oil at refinery (1.0 wt.% S) ts)	Dry bulk carrier transport–dry bulk carrier transport (2500t)–China-2500t (CN)-CLCD-China 0.8.1 2012	Dry bulk carrier transport (2500t payload) (2500t payload)-CLCD-China 0.9	Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods, heavy fuel oil | Cut-off, S
	Transport (imported copper concentrat	Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| transport,	GLO: Truck, Euro 5, 28 - 32t gross weight / 22t payload capacity ts <u-so>	Truck transport–heavy-duty diesel truck transport (30t)–China–30t	Heavy-duty diesel truck transport (18t payload) (heavy-duty truck)-CLCD-China	Transport, freight, lorry 16-32 metric ton, EURO6 {RoW}| market for transport,

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	e) (road)	freight, lorry 16-32 metric ton, EURO6 | Cut-off, S	(associated fuel: CN: Diesel mix at refinery ts)	(CN)-CLCD-China 0.8.1 2012	0.9	freight, lorry, 16-32 metric ton, diesel, EURO 6 | Cut-off, S
Pretreatment	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD -China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
Flash smelting	Processed natural gas	Natural gas, production mixture, to energy use | Natural gas, processed, for energy use, at plant	CN: Natural gas mix ts	Natural gas (after transport) (CN)-CLCD-China-Public 0.8.1 2012	Natural gas (national average) (unclassified)-CLCD -China 0.9	natural gas, high pressure {CN}| market for natural gas, high pressure | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD -China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Silica sand	Silica sand {GLO}| market for silica sand | Cut-off, S	DE: Silica sand (Excavation and processing) ts	Silica sand (CN)-CLCD-China 0.8.1 2012	Ordinary silica sand (SiO_2 content 90%～99%)-CLCD-China 0.9	Silica sand {GLO}| market for silica sand | Cut-off, S
	Carbon dioxide (natural-gas emissions)	Carbon dioxide	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossile)

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Methane (emission)	Methane	Methane [Organic emissions to air (group VOC)]	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossile)
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as carbon dioxide multiplied by a GWP of 265)	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide
Flash converting	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China	Central China grid electricity (to user) (unclassified)-CLCD -China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		from high to medium voltage | Cut-off, S		0.8.1 2012		voltage | Cut-off, S
	Processed natural gas	Natural gas, production mixture, to energy use | Natural gas, processed, for energy use, at plant	CN: Natural gas mix ts	Natural gas (after transport) (CN)-CLCD-China-Public 0.8.1 2012	Natural gas (national average) (unclassified)-CLCD-China 0.9	natural gas, high pressure {CN}| market for natural gas, high pressure | Cut-off, S
	Silica sand	Silica sand {GLO}| market for silica sand | Cut-off, S	DE: Silica sand (Excavation and processing) ts	Silica sand (CN)-CLCD-China 0.8.1 2012	Ordinary silica sand (SiO_2 content 90%～99%)-CLCD-China 0.9	Silica sand {GLO}| market for silica sand | Cut-off, S
	Limestone	Limestone, unprocessed {RoW}| market for limestone,	DE: Limestone ($CaCO_3$; washed) tslimestone, unprocessed |	Limestone–limestone mining (CN)-CLCD-China-Public 0.8.1 2012	Limestone (unclassified)-CLCD-China 0.9	Limestone, unprocessed {RoW}| market for limestone, unprocessed |

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Oxygen	unprocessed | Cut-off, S Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD -China 0.9	Cut-off, S Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Nitrogen	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage |	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD -China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	Water	Cut-off, S Water, fresh	Not modeled as a separate GaBi process (direct GWP100 contribution of water as a natural-resource flow: 0 kg CO_2e; water source and supply process unspecified).	Surface water–unspecified source, industrial use {renewable water resource}	Fresh water {renewable water resource}	Fresh water
	Sodium carbonate	Soda ash, dense {GLO}| soda ash production, dense, Hou's process | Cut-off, S	DE: Soda (Na_2CO_3) ts	Soda residue–soda residue (pyrometallurgical treatment of copper anode slime–	Soda residue-CLCD-China 0.8.1 2012	Soda ash, dense {GLO}| soda ash production, dense, Hou's process | Cut-off, S

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
				electrorefining) (CN)-CLCD-China 0.8.1 2012		
	Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S - Copied from ecoinvent S	DE: Sodium hydroxide mix (50%) ts	Liquid caustic soda–caustic soda (30%)–market average-30% (CN)-CLCD-China 0.8.1 2012	Liquid caustic soda–caustic soda (30%)–market average-30% (CN)-CLCD-China-ECER 0.8	Sodium hydroxide, without water, in 50% solution state {ROW}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, S
	Carbon dioxide (natural-gas emissions)	Carbon dioxide	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossile)
	Carbon	Carbon dioxide	Carbon dioxide	Carbon dioxide	Carbon dioxide	Carbon

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
	dioxide (limestone emissions)		[Inorganic emissions to air]	(fossil) {emission to air (unspecified)}	(fossil) {emission to air (unspecified)}	dioxide(fossile)
	Methane (emission)	Methane	Methane [Organic emissions to air (group VOC)]	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossile)
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as carbon dioxide multiplied by a GWP of 265)	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide
Anode furnace	Processed natural gas	Natural gas, production	CN: Natural gas mixts	Natural gas (after transport)	Natural gas (national average)	natural gas, high pressure {CN}|

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
refining		mixture, to energy use | Natural gas, processed, for energy use, at plant		(CN)-CLCD-China-Public 0.8.1 2012	(unclassified)-CLCD-China 0.9	market for natural gas, high pressure | Cut-off, S
	Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Oxygen	Electricity, medium voltage {CN-CCG}| electricity voltage transformation	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
		from high to medium voltage | Cut-off, S		0.8.1 2012		voltage | Cut-off, S
	Nitrogen	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD -China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Water	Water, fresh	Not modeled as a separate GaBi process (direct GWP100 contribution of water as a natural-resource	Surface water–unspecified source, industrial use {renewable water resource}	Fresh water {renewable water resource}	Fresh water

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
			flow: 0 kg CO_2e; water source and supply process unspecified).			
	Carbon dioxide (natural-gas emissions)	Carbon dioxide	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide(fossile)
	Methane (emission)	Methane	Methane [Organic emissions to air (group VOC)]	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane(fossile)
	Nitrous oxide (emission)	Carbon dioxide*265(nitrous oxide is unavailable in this	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Electrorefining	Electricity	database; its impact was approximated as carbon dioxide multiplied by a GWP of 265) Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD -China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
	Water	Water, fresh	Not modeled as a separate GaBi process (direct GWP100	Surface water–unspecified source, industrial use {renewable water	Fresh water {renewable water resource}	Fresh water

Unit process	Material/ energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
			contribution of water as a natural-resource flow: 0 kg CO_2e; water source and supply process unspecified).	resource}		

S4.3. Background datasets and proxies for sulfuric acid production

Modeling note: For sulfuric acid production, selected missing datasets in eBalance and eFootprint were supplemented with ecoinvent 3.11. In the GaBi Education configuration, sodium hydrosulfide, polyacrylamide, and the hypochlorite input were also modeled using ecoinvent 3.11 proxies. Their contributions are included in the reported GaBi results and quantified in the note to Supplementary Table 9.

Supplementary Table 8. Background datasets selected for sulfuric acid production in each LCA tool

Material	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Processed	Natural gas, production	CN: Natural gas	Natural gas (after	Natural gas	natural gas, high pressure

natural gas	mixture, to energy use | Natural gas, processed, for energy use, at plant	mix ts	transport) (CN)-CLCD-China-Public 0.8.1 2012	(national average) (unclassified)-CLCD-China 0.9	{CN}| market for natural gas, high pressure | Cut-off, S
Electricity	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S	CN: Electricity grid mix ts	Central China grid electricity–Central China grid electricity transmission–to user (CN))-CLCD-China 0.8.1 2012	Central China grid electricity (to user) (unclassified)-CLCD-China 0.9	Electricity, medium voltage {CN-CCG}| electricity voltage transformation from high to medium voltage | Cut-off, S
Water	Water, fresh	Not modeled as a separate GaBi process (direct GWP100 contribution of water as a natural-resource flow: 0 kg CO_2e; water source and supply process unspecified).	Surface water–unspecified source, industrial use {renewable water resource}	Fresh water {renewable water resource}	Fresh water

Liquid caustic soda	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S - Copied from ecoinvent S	DE: Sodium hydroxide mix (50%) ts	Liquid caustic soda–caustic soda (30%)–market average-30% (CN)-CLCD-China 0.8.1 2012	Caustic soda (30%) (unclassified)-CLCD-China 0.9	Sodium hydroxide, without water, in 50% solution state {ROW}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, S
Calcium carbonate	Limestone, unprocessed {RoW}| market for limestone, unprocessed | Cut-off, S	DE: Limestone ($CaCO_3$; washed) tslimestone,	Limestone–limestone mining (CN)-CLCD-China-Public 0.8.1 2012	Limestone (unclassified)-CLCD-China 0.9	Limestone, unprocessed {RoW}| market for limestone, unprocessed | Cut-off, S
Calcium hydroxide	Lime, hydrated, packed {RoW}| market for lime, hydrated, packed | Cut-off, S	DE: Calcium hydroxide ($Ca(OH)_2$; dry; slaked lime) (EN15804 A1-A3) ts	Hydrated lime–hydrated lime (CN)-CLCD-China 0.8.1 2012	Hydrated lime (unclassified)-CLCD-China 0.9	hydrated lime, packed {RoW}| market for hydrated lime, packed | Cut-off, S
Polyferric sulfate	Polyaluminium chloride {GLO}| market for polyaluminium chloride |	Ignored	Basic aluminum chloride/polyaluminum chloride/PAC	Basic aluminum chloride\polyaluminum	aluminium chloride {GLO}|market for aluminium chloride | Cut-off, S

	Cut-off, S		(CN)-CLCD-China 0.8.1 2012	chloride\PAC-CLCD-China-ECER 0.8	
Sodium hydrosulfide	Sodium hydrosulfide {GLO}| market for sodium hydrosulfide | Cut-off, S	Sodium hydrosulfide {GLO}| market for sodium hydrosulfide | Cut-off, S(from ecoinvent 3.11)	Sodium hydrosulfide {GLO}| market for sodium hydrosulfide | Cut-off, S(from ecoinvent 3.11)	Sodium hydrosulfide {GLO}| market for sodium hydrosulfide | Cut-off, S(from ecoinvent 3.11)	Sodium hydrosulfide {GLO}| market for sodium hydrosulfide | Cut-off, S
Polyacrylamide	Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, S	Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, S(from ecoinvent 3.11)	Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, S(from ecoinvent 3.11)	Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, S(from ecoinvent 3.11)	Polyacrylamide {GLO}| market for polyacrylamide | Cut-off, S
Carbon dioxide (calcium carbonate	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide	Carbon dioxide(fossile)

decomposition)					
Carbon dioxide (natural-gas emissions)	Carbon dioxide [Inorganic emissions to air]	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide (fossil) {emission to air (unspecified)}	Carbon dioxide	Carbon dioxide(fossile)
Methane (emission)	Methane [Organic emissions to air (group VOC)]	Methane (fossil) {emission to air (unspecified)}	Methane (fossil) {emission to air (unspecified)}	Methane	Methane(fossile)
Nitrous oxide (emission)	Nitrous oxide (laughing gas) [Inorganic emissions to air]	Nitrous oxide {emission to air (unspecified)}	Nitrous oxide {emission to air (unspecified)}	Carbon dioxide*265(nitrous oxide is unavailable in this database; its impact was approximated as carbon dioxide multiplied by a GWP of 265)	Nitrous oxide
Hydrogen	hydrogen peroxide,	DE: Hydrogen	Hydrogen peroxide–	Hydrogen peroxide	hydrogen peroxide, without

peroxide solution (30 wt%)	without water, in 50% solution state {ROW}| market for hydrogen peroxide, without water, in 50% solution state | Cut-off, S	peroxide ts	hydrogen peroxide (50%, concentration method)–50% (CN)-CLCD-China 0.8.1 2012	(unclassified)-CLCD-China 0.9.6	water, in 50% solution state {ROW}| market for hydrogen peroxide, without water, in 50% solution state | Cut-off, S
Calcium hypochlorite(modeled using sodium hypochlorite as a proxy)	sodium hypochlorite, without water, in 15% solution state {ROW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S	sodium hypochlorite, without water, in 15% solution state {ROW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S(from ecoinvent 3.11)	sodium hypochlorite, without water, in 15% solution state {ROW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S(from ecoinvent 3.11)	sodium hypochlorite, without water, in 15% solution state {ROW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S(from ecoinvent 3.11)	sodium hypochlorite, without water, in 15% solution state {ROW}| market for sodium hypochlorite, without water, in 15% solution state | Cut-off, S

Supplementary Table 9. Rationale and contributions of the proxy dataset selections in the sulfuric acid production process

Proxy material	Carbon footprint value (kg CO_2eq/t H_2SO_4)
Sodium hydrosulfide	13.087
Polyacrylamide	1.591
Calcium hypochlorite (modeled using sodium hypochlorite)	4.913

Note: The GaBi models include ecoinvent 3.11 proxies for sodium hydrosulfide and polyacrylamide. Their combined contributions before economic allocation are 38.84 kg CO_2e/t Cu for Ausmelt and 54.31 kg CO_2e/t Cu for double-flash, at sulfuric-acid outputs of 2.646 and 3.7 t H_2SO_4/t Cu, respectively. Both GaBi models also include a hypochlorite input represented by a sodium-hypochlorite proxy, contributing 13.00 kg CO_2e/t Cu for Ausmelt and 18.18 kg CO_2e/t Cu for double-flash. The sulfuric-acid-production proxy totals before economic allocation are therefore 51.84 and 72.49 kg CO_2e/t Cu, respectively. These are modeled contributions, rather than estimates of omitted inputs.

S5. Imported-concentrate weighting and reconciliation

Supplementary Table 10. Import-mass weights and regional production factors for imported concentrate in ecoinvent 3.10 and 3.11

Region	Import-mass share (%)	ecoinvent 3.10 production factor (kg CO_2e/kg)	ecoinvent 3.11 production factor (kg CO_2e/kg)
AU	1.81	1.49	1.47
CA	1.43	1.24	1.19

Region	Import-mass share (%)	ecoinvent 3.10 production factor (kg CO_2e/kg)	ecoinvent 3.11 production factor (kg CO_2e/kg)
CL	35.56	1.20	1.23
ID	2.08	1.65	1.63
KZ	5.94	0.906	0.88
RU	1.59	1.13	1.12
RoW	49.82	1.17	1.13
US	1.77	1.31	1.30
Total	100.00	—	—

Note:(1) The same import-mass weights were applied to ecoinvent 3.10 and 3.11. Calculations used unrounded normalized weights and the available regional production factors; the ecoinvent 3.10 aggregate retained the author-reported value because full-precision regional 3.10 factors were unavailable. Values in the table are displayed at reduced precision for readability, with ecoinvent 3.11 factors rounded to two decimal places. Therefore, weighted factors calculated from the displayed values may differ slightly from those used in the models. These factors precede study-level economic allocation between cathode copper and sulfuric acid and exclude the separately modeled international shipping leg. RoW denotes sources mapped to the rest-of-world production dataset.

For example, the Ausmelt imported-concentrate proxy contribution in Supplementary Table 14 is 2,642.02 kg CO_2e/t cathode copper. Dividing this contribution by the actual dry input of 2,639 kg gives approximately 1.001 kg CO_2e/kg actual feed. Dividing it by the grade-converted input

of approximately 2,257.801 kg instead gives approximately 1.170 kg CO_2e/kg reference-grade concentrate. Similarly, the double-flash contribution of 4,028.20 kg CO_2e/t cathode copper gives approximately 1.027 when divided by the actual input of 3,922 kg, but approximately 1.170 when divided by the grade-converted input of 3,441.512 kg. These differences reflect the mass basis used in the denominator, rather than conflicting production factors.

Supplementary Table 11. Reconciliation of imported-concentrate factors, production contributions, and sensitivity results

Configuration	Common-basis factor (approx.)	Ausmelt production contribution, before allocation	Double-flash production contribution, before allocation	Ausmelt ±10% sensitivity, after allocation	Double-flash ±10% sensitivity, after allocation
SimaPro	1.185	2676.00	4078.00	262.32	396.65
OpenLCA	1.170	2642.02	4028.20	258.99	391.80
GaBi	1.170	2642.02	4028.20	258.99	391.80
eFootprint	1.191	2689.38	4099.28	263.64	398.72
eBalance	0.631	1424.00	2169.98	139.59	211.06

Note: Common-basis factors are expressed in kg CO_2e/kg dry concentrate at the adopted reference copper grade of 29.63%. Production contributions and sensitivity magnitudes are expressed in kg CO_2e/t cathode copper. Production contributions precede economic allocation between cathode copper and sulfuric acid. Sensitivity magnitudes represent 10% of the corresponding production contribution after economic allocation, with transport held constant. The copper allocation fractions are approximately 98.03% for Ausmelt and 97.26% for double-flash.

S6. Controlled parameter-transfer verification

Supplementary Table 12. Controlled parameter-transfer check for the double-flash case

Configuration	System model	Carbon footprint (t CO_2e/t Cu)	Paired difference
SimaPro–ecoinvent 3.10	Cut-off	6.2748	Reference model
OpenLCA reconstruction using ecoinvent 3.10 parameters exported from SimaPro	Cut-off	6.2753	+0.008% versus the SimaPro reference
OpenLCA–ecoinvent 3.11	Cut-off	6.193	−1.31% versus the reconstructed ecoinvent 3.10 case

Note: Ecoinvent 3.10 was not imported natively into OpenLCA and independently relinked. The OpenLCA model was reconstructed using the corresponding inventory parameters exported from the SimaPro–ecoinvent 3.10 model, with exported values available to three decimal places. The 0.008% residual therefore evaluates the numerical fidelity of the parameter transfer and model reconstruction. It does not evaluate whether SimaPro and OpenLCA independently link and characterize their native implementations of ecoinvent in the same manner. The reconstructed ecoinvent 3.10 case uses a 0.914 kg CO_2e/kWh Central-China electricity factor. The OpenLCA–ecoinvent 3.11 result is estimated to be 1.31% lower than this reconstruction; the comparison uses the transferred inventory and does not include a separate OpenLCA recalculation.

S7. Inter-configuration differences and emission contributions

S7.1. Electricity-related emissions

Supplementary Table 13. Electricity-related emissions calculated using a consistent smelting-and-refining boundary

Configuration	Electricity emission factor (kg CO_2e/kWh)	Ausmelt before allocation (kg CO_2e/t Cu)	Ausmelt after economic allocation (kg CO_2e/t Cu)	Double-flash before allocation (kg CO_2e/t Cu)	Double-flash after economic allocation (kg CO_2e/t Cu)
SimaPro–ecoinvent 3.10	0.914	1,612.1	1,580.4	1,392.5	1,354.4
GaBi Education Database 2020	0.813	1,434.0	1,405.7	1,238.6	1,204.7
eBalance–CLCD 0.8.1	0.679	1,197.6	1,174.0	1,034.5	1,006.1
eFootprint–CLCD 0.9	0.550	970.1	951.0	838.0	815.0
OpenLCA–ecoinvent 3.11	0.879	1,550.4	1,519.8	1,339.2	1,302.5

Note: Electricity-related emissions include direct purchased electricity for concentrate pretreatment, smelting, converting, anode-furnace refining, electrorefining, and sulfuric-acid production, plus electricity for oxygen and nitrogen production. Electricity embedded in upstream concentrate mining, beneficiation, transport, and other aggregated background datasets is excluded. Total electricity-related demand is 1,763.818762 kWh/t

Cu for Ausmelt and 1,523.553998 kWh/t Cu for double-flash. Before allocation, emissions equal electricity demand × electricity emission factor; after allocation, the result is multiplied by the route-specific copper economic-allocation fraction (98.03% for Ausmelt; 97.26% for double-flash).

S7.2. Proxy contributions in the two production systems

Before economic allocation, the cross-database proxies listed in Supplementary Table 14 contribute 4,512.69 kg CO_2e/t cathode copper. The sulfuric-acid-production proxies for sodium hydrosulfide, polyacrylamide, and sodium hypochlorite contribute a further 51.84 kg CO_2e/t cathode copper, giving a combined proxy contribution of 4,564.53 kg CO_2e/t cathode copper. This total includes the imported-concentrate proxy and accounts for 67.78% of the GaBi Ausmelt deterministic result. Applying the same copper-allocation factor to the proxy contributions and the total result leaves this share unchanged.

Values are process-level contributions in kg CO_2e/t cathode copper before study-level economic allocation. The imported-concentrate contribution uses grade-converted background inputs and excludes the separately modeled international shipping leg.

Supplementary Table 14. Contributions of the proxy datasets in the Ausmelt route

Selected material	Carbon footprint value (kg CO_2e/t Cu)
Diesel (open-pit mining)	164.10
Electricity (open-pit mining)	44.01
Mixed emulsion explosive (open-pit mining)	48.48
Diesel (underground mining)	47.50
Electricity (underground mining)	691.08
Detonating cord (underground mining)	0.59
Modified ANFO explosive (underground mining)	55.72

Selected material	Carbon footprint value (kg CO_2e/t Cu)
Rock emulsion explosive (underground mining)	31.91
Digital detonator (underground mining)	20.43
Digital detonator leg wire (underground mining)	8.03
Electricity (domestic copper concentrate beneficiation)	45.59
Lime (domestic copper concentrate beneficiation)	50.58
Steel balls (domestic copper concentrate beneficiation)	547.94
Pine oil (domestic copper concentrate beneficiation)	18.10
Xanthate (domestic copper concentrate beneficiation)	87.80
Conveyor belt (domestic copper concentrate beneficiation)	0.077
Electricity (pre-treatment)	8.74
Imported copper concentrate	2642.02

Before economic allocation, the imported-concentrate proxy in Supplementary Table 15 contributes 4,028.20 kg CO_2e/t Cu. The double-flash sulfuric-acid-production proxies in Supplementary Table 9—sodium hydrosulfide, polyacrylamide, and a hypochlorite input modeled using sodium hypochlorite—contribute a further 72.49 kg CO_2e/t Cu. Their combined cross-database proxy contribution is 4,100.69 kg CO_2e/t Cu, accounting for 70.01% of the unallocated deterministic GaBi double-flash result.

Supplementary Table 15. Rationale and contributions of the proxy dataset selections in the double-flash route

Selected material	Carbon footprint value (kg CO_2e/t Cu)
Imported copper concentrate	4028.20

Across Tables S6, S7, and S8, cross-database proxies account for 67.78% of the deterministic GaBi Ausmelt result and 70.01% of the deterministic GaBi double-flash

result. Proxy shares in the other configurations range from 0% to 2.19%. These shares compare process contributions and total footprints on the same pre-allocation basis; applying each route's copper-allocation factor leaves its share unchanged. Ecoinvent datasets are treated as native rather than proxy data in SimaPro and OpenLCA because ecoinvent is the designated principal background database in those configurations.

S7.3. Characteristics of the electricity datasets

Supplementary Table 16. Characteristics of the electricity datasets and system models adopted in the LCA configurations

LCA Platform & Database	Geographic scope and delivery level	Temporal information	Meaning and source of temporal information	Electricity Emission Factor (kg CO_2e kWh^{-1})
SimaPro (Ecoinvent 3.10)	Central-China grid; database-native electricity-supply boundary	2021–2023	Applicability interval reported in the official ecoinvent metadata	0.914
GaBi (Education Database 2020)	Whole-China national grid mix; database-native electricity-supply boundary	2020	Database release/version year	0.813
OpenLCA (Ecoinvent 3.11)	Central-China grid; database-native electricity-supply boundary	2021–2024	Applicability interval reported in the official ecoinvent metadata	0.879

LCA Platform & Database	Geographic scope and delivery level	Temporal information	Meaning and source of temporal information	Electricity Emission Factor (kg CO_2e kWh^{-1})
eFootprint (CLCD-China 0.9)	Central-China grid; end-user electricity	2020	Database release/version year	0.550
eBalance (CLCD-China 0.8.1)	Central-China grid; end-user electricity	2012	Database release/version year	0.679
OpenLCA–ecoinvent 3.10, controlled calculation	Central-China grid; database-native electricity-supply boundary	2021–2023	Applicability interval reported in the official ecoinvent metadata	0.914

Note: All electricity factors are life-cycle carbon-footprint factors, not direct-combustion factors; the CLCD end-user datasets therefore include upstream electricity supply. The datasets are not fully harmonized in geography, delivery level, or background-modeling boundary. ecoinvent metadata provide applicability intervals of 2021–2023 for version 3.10 and 2021–2024 for version 3.11. For GaBi, eFootprint, and eBalance, process-specific reference periods were unavailable, so database release or version years are reported only as coarse indicators of vintage. These dates are not treated as equivalent statistical reference years or used to infer a direct relationship between dataset age and electricity carbon-footprint factor.

S8. Sensitivity analysis

S8.1. Allocation sensitivity

Supplementary Table 17. Allocation sensitivity of the SimaPro–ecoinvent 3.10 double-flash and Ausmelt cases

Route	Allocation scenario	Copper allocation fraction or treatment	Carbon footprint (t CO_2e/t Cu)	Change from base case	Calculation formula
Double-flash	Economic allocation, 615 CNY/t H_2SO_4	97.26%	6.275	Reference	6.451575 × 0.9726
Double-flash	Economic allocation, zero-value boundary	100.00%	6.452	+0.177 (+2.82%)	6.451575 × 1
Double-flash	Mass allocation	21.28%	1.373	−4.902 (−78.12%)	6.451575 × [1 / (1 + 3.7)]
Double-flash	System expansion	Avoided burden: 0.411 t CO_2e/t Cu	6.041	−0.234 (−3.73%)	6.451575 − (3.7 × 0.111)
Ausmelt	Economic allocation, 615 CNY/t H_2SO_4	98.03%	7.126	Reference	7.269373 × 0.9803
Ausmelt	Economic allocation, zero-value boundary	100.00%	7.269	+0.143 (+2.01%)	7.269373 × 1
Ausmelt	Mass allocation	27.43%	1.994	−5.132 (−72.02%)	7.269373 × [1 / (1 + 2.646)]

Route	Allocation scenario	Copper allocation fraction or treatment	Carbon footprint (t CO_2e/t Cu)	Change from base case	Calculation formula
Ausmelt	System expansion	Avoided burden: 0.294 t CO_2e/t Cu	6.976	−0.150 (−2.11%)	7.269373 − (2.646 × 0.111)

Note: (1) The zero-value case is a boundary scenario, not an observed annual market price. Under system expansion, the avoided burden is subtracted from the unallocated joint-system result; economic allocation and system expansion are not applied simultaneously. Sulfuric-acid output is expressed on a 100% H_2SO_4-equivalent basis. (2) The 2025 cathode-copper price used for economic allocation was calculated from the January–December monthly national market-monitoring values reported by the China Price Information Network: 73,942.37, 76,576.55, 79,522.43, 77,860.11, 78,703.08, 78,998.17, 79,861.41, 79,366.03, 81,010.39, 85,407.93, 86,953.92, and 92,822.24 CNY/t. Their arithmetic mean was 80,918.72 CNY/t, which was rounded to 80,919 CNY/t for the economic-allocation calculations. The sulfuric-acid price of 615 CNY/t represents the documented 2025 annual average.

S8.2. Maritime transport distance sensitivity

To evaluate the uncertainty associated with the assumed maritime transport distance, a one-at-a-time sensitivity analysis was performed for the double-flash case using the eBalance–CLCD-China 0.8.1 and eFootprint–CLCD-China 0.9 configurations. The baseline distance of 20,000 km was varied by ±30%, corresponding to 14,000 km and 26,000 km. Maritime transport emissions were assumed to vary linearly with transport distance under the unchanged background transport datasets. Road transport emissions and all other life-cycle inventory parameters remained constant.

The baseline maritime transport emissions before economic allocation were 1,153.550014 and 664.9387582 kg CO_2e/t Cu for eBalance and eFootprint,

respectively. The corresponding road transport emissions were 11.39978836 and 30.39285339 kg CO_2e/t Cu.

The carbon footprint under an alternative maritime distance was calculated as follows:

$$CF(D) = CF_0 + E(sea,0) \times \alpha \times (D / D_0 - 1)$$

where CF(D) is the total carbon footprint under maritime distance D; CF_0 is the baseline total carbon footprint; E(sea,0) is the baseline maritime transport emission before economic allocation; α is the copper economic-allocation factor of 0.9726 used in these calculations; and D_0 is the baseline maritime distance of 20,000 km.

The baseline total carbon footprints after economic allocation were 4,578.11 and 5,817.81 kg CO_2e/t Cu for eBalance and eFootprint, respectively. The results are summarized in Supplementary Table 18.

Supplementary Table 18. Sensitivity of the double-flash carbon footprint to maritime transport distance in the two CLCD-based configurations.

Configuration	Maritime distance (km)	Sea transport emissions	Total CF	Change from baseline
eBalance	14,000	785.36	4,241.52	−7.35%
eBalance	20,000	1,121.94	4,578.11	0.00%
eBalance	26,000	1,458.53	4,914.69	+7.35%
eFootprint	14,000	452.7	5,623.79	−3.33%
eFootprint	20,000	646.72	5,817.81	0.00%
eFootprint	26,000	840.74	6,011.82	+3.33%

Note: The sensitivity analysis changes only maritime transport distance. Road transport emissions and other inventory contributions are held constant. The calculated changes represent scenario-based distance sensitivity under fixed transport datasets rather than uncertainty intervals derived from observed shipping routes. The analysis does not correct the potential vessel-class mismatch in the CLCD transport proxies.

S9. Uncertainty analysis

S9.1. Data-quality assessment

Following Section 3.5 of the main manuscript, within-configuration uncertainty is evaluated at the level of foreground–background couplings. Each plant-level material or energy flow is linked to its background unit process and scored for reliability, completeness, temporal correlation, geographical correlation, and technological correlation. The five dimensions are adapted from the pedigree-matrix framework, but the numerical scale used here is reverse-coded relative to the conventional Weidema–Wesnæs numbering: 5 represents the highest data quality or best correspondence with the studied system, whereas 1 represents the lowest.

The five scores are aggregated into a DQI and mapped to a bounded Beta distribution following the Mo and Zhang (2003) procedure. For a deterministic process contribution x, the DQI determines the relative endpoint parameter p and the Beta shape parameters α and β. In the present implementation, $\alpha=\beta$, and the distribution is scaled to the interval $[x(1-p), x(1+p)]$. Consequently, the expected value of the sampled process contribution is x, while the DQI controls the width and shape of the uncertainty distribution. Higher DQI scores therefore correspond to narrower distributions; for example, DQI = 5 uses $\alpha=\beta=5$ with p=10%, whereas DQI = 1 uses $\alpha=\beta=1$ with p=50%. Each software-database-modeling configuration is propagated through 10,000 Monte Carlo iterations. Homologous contributions use common random numbers for paired route comparison, while unmatched contributions are sampled independently. After aggregation, economic allocation factors of 98.03% for Ausmelt and 97.26% for double-flash are applied. The 95% uncertainty interval is defined by the 2.5th and 97.5th percentiles, and relative uncertainty is its half-width divided by the simulated mean. For the direct comparison of within-configuration uncertainty with inter-configuration dispersion, the coefficient of variation (CV = SD/mean) is used for both quantities so that the comparison is made on a common SD-based basis. Results are therefore conditional on the adopted DQI–Beta formulation.

Supplementary Table 19. Data-quality scores for key unit processes in the Ausmelt route

Material/energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Diesel	(4,2,5,5,5)	(4,2,5,5,5)	(3,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Detonating cord	(5,2,5,2,5)	(5,2,5,2,5)	(5,2,2,5,5)	(5,2,4,5,4)	(5,2,5,2,5)
Electrode paste	(5,2,2,4,4)	/	(5,2,2,5,5)	(5,2,2,5,5)	(5,2,5,3,4)
Electrode-paste combustion emissions	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Steel grinding balls	(5,2,2,2,5)	(5,2,2,2,5)	(5,2,2,5,5)	(5,2,4,5,5)	(5,2,2,2,5)
Central China grid electricity	(5,2,5,5,5)	(5,2,4,5,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Xanthate	(5,2,5,4,5)	(5,2,5,4,5)	(5,2,2,5,5)	(5,2,2,5,5)	(5,2,5,4,5)
Imported copper concentrate	(5,2,4,4,5)	(5,2,4,4,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,4,5)
Polyacrylamide	(5,2,5,4,5)	(5,2,5,4,5)	(5,2,5,4,5)	(5,2,5,5,5)	(5,2,5,4,5)
Polyaluminum chloride	(5,2,4,4,5)	/	(5,2,2,5,5)	(5,2,3,5,5)	(5,2,5,4,5)
Sodium hydrosulfide	(5,2,3,4,5)	(5,2,5,4,5)	(5,2,3,4,5)	(5,2,3,4,5)	(5,2,5,4,5)
Sulfuric acid	(5,2,2,3,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,4,5,5)	(5,2,5,3,5)
Calcium hydroxide	(5,2,3,3,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,3,5,5)	(5,2,5,3,5)
Sodium hydroxide	(5,2,3,4,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,4,5)
Fuel-combustion emissions	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Lime	(5,2,2,3,5)	(5,2,2,3,5)	(5,2,2,5,5)	(5,2,2,5,5)	(5,2,2,3,5)
Silica sand	(5,2,3,4,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,4,5)
Digital electronic detonator	(5,2,1,3,5)	(5,2,1,3,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,1,3,5)

Material/energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Digital detonator lead wire	(5,2,2,2,5)	(5,2,2,2,5)	(5,2,2,2,5)	(5,2,2,2,5)	(5,2,2,2,5)
Pine oil	(5,2,1,3,5)	(5,2,1,3,5)	(5,2,1,3,5)	(5,2,1,3,5)	(5,2,1,3,5)
Natural gas	(5,2,4,4,5)	(5,2,4,5,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Copper concentrate transport by sea	(3,2,3,4,5)	(3,2,3,4,5)	(3,2,2,5,5)	(3,2,5,5,5)	(3,2,5,4,5)
Copper concentrate transport by road	(3,2,3,4,5)	(3,2,4,4,5)	(3,2,2,5,5)	(3,2,5,5,5)	(3,2,5,4,5)
Hydrochloric acid	(5,2,2,3,5)	/	(5,2,2,5,5)	(5,2,4,5,5)	(5,2,5,3,5)
Raw coal	(5,2,1,5,5)	(5,2,4,5,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Conveyor belt	(5,2,3,3,5)	(5,2,3,3,5)	(5,2,3,3,5)	(5,2,3,3,5)	(5,2,3,3,5)
Explosives	(3,2,3,4,5)	(5,2,1,2,5)	(5,2,1,2,5)	(5,2,4,5,4)	(5,2,1,2,5)
Hydrogen peroxide	(5,2,2,3,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,2,3,5)
Sodium hypochlorite	(5,2,2,3,5)	(5,2,2,3,5)	(5,2,2,3,5)	(5,2,2,3,5)	(5,2,2,3,5)

Note: DQI dimension scores use a reverse-coded 1–5 scale, where 5 indicates the highest data quality or best representativeness and 1 indicates the lowest. This numerical direction is opposite to the conventional Weidema–Wesnæs pedigree numbering.

Using the DQI–Beta mapping above, 10,000 realizations were generated for each configuration. After aggregation and application of the 98.03% copper allocation factor, the Ausmelt distributions are summarized in Supplementary Table 21.

Supplementary Table 20. Data-quality scores for key unit processes in the double-flash route

Material/energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Imported copper concentrate	(5,2,4,4,5)	(5,2,4,4,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,4,5)
Copper concentrate transport by sea	(3,2,3,4,5)	(3,2,3,4,5)	(3,2,2,5,5)	(3,2,5,5,5)	(3,2,5,4,5)
Copper concentrate transport by road	(3,2,3,4,5)	(3,2,4,4,5)	(3,2,2,5,5)	(3,2,5,5,5)	(3,2,5,4,5)
Central China grid electricity	(5,2,5,5,5)	(5,2,4,5,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Processed natural gas	(5,2,4,4,5)	(5,2,4,5,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Silica sand	(5,2,3,4,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,4,5)
Limestone	(5,2,3,3,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,3,5)
Oxygen and nitrogen	(5,2,5,5,5)	(5,2,4,5,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Sodium carbonate	(5,2,3,4,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,2,5,5)
Sodium hydroxide	(5,2,3,4,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,4,5)
Natural gas	(5,2,4,4,5)	(5,2,4,5,5)	(5,2,2,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Direct natural-gas emissions	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Limestone-derived emissions	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)	(5,2,5,5,5)
Polyaluminum chloride	(5,2,4,4,5)	/	(5,2,2,5,5)	(5,2,3,5,5)	(5,2,5,4,5)
Polyacrylamide	(5,2,5,4,5)	(5,2,5,4,5)	(5,2,5,4,5)	(5,2,5,5,5)	(5,2,5,4,5)

Material/energy	SimaPro	GaBi	eBalance	eFootprint	OpenLCA
Sodium hydrosulfide	(5,2,3,4,5)	(5,2,5,4,5)	(5,2,3,4,5)	(5,2,3,4,5)	(5,2,5,4,5)
Calcium hydroxide	(5,2,3,3,5)	(5,2,4,3,3)	(5,2,2,5,5)	(5,2,3,5,5)	(5,2,5,3,5)
Hypochlorite reagent	(5,2,2,3,5)	(5,2,2,3,5)	(5,2,2,3,5)	(5,2,2,3,5)	(5,2,2,3,5)

Note: DQI dimension scores use a reverse-coded 1–5 scale, where 5 indicates the highest data quality or best representativeness and 1 indicates the lowest. This numerical direction is opposite to the conventional Weidema–Wesnæs pedigree numbering.

Using the same DQI–Beta procedure, 10,000 realizations were generated for each configuration. After aggregation and application of the 97.26% copper allocation factor, the double-flash distributions are summarized in Supplementary Table 22.

S9.2. Route-specific Monte Carlo results

Supplementary Table 21. Monte Carlo uncertainty results for the Ausmelt case across the five software-database-modeling configurations

Configuration	Mean total emissions	Standard deviation of total emissions	Coefficient of variation (CV, %)	Minimum total emissions	Maximum total emissions	2.5% percentile	97.5% percentile	95% interval-based relative uncertainty (%)
eFootprint	6,148	214	3.48	5,484	6,761	5,740	6,551	6.60%
eBalance	5,851	202	3.44	5,166	6,620	5,457	6,241	6.70%

Configuration	Mean total emissions	Standard deviation of total emissions	Coefficient of variation (CV, %)	Minimum total emissions	Maximum total emissions	2.5% percentile	97.5% percentile	95% interval-based relative uncertainty (%)
OpenLCA	6,938	274	3.95	6,038	7,767	6,416	7,465	7.56%
SimaPro	7,129	245	3.44	6,283	7,963	6,655	7,594	6.58%
GaBi	6,601	234	3.54	5,841	7,384	6,148	7,050	6.83%

Note: Relative uncertainty is the half-width of the 95% uncertainty interval (2.5th–97.5th percentiles) divided by the simulated mean. All statistics use N = 10,000 realizations after economic allocation to cathode copper.

Supplementary Table 22. Monte Carlo uncertainty results for the double-flash case across the five software-database-modeling configurations

Configuration	Mean total emissions	Standard deviation of total emissions	Coefficient of variation (CV, %)	Minimum total emissions	Maximum total emissions	2.5% percentile	97.5% percentile	95% interval-based relative uncertainty (%)
eFootprint	5,820	307	5.27	4,932	6,673	5,241	6,393	9.90%
eBalance	4,579	320	7.00	3,566	5,544	3,955	5,196	13.56%
OpenLCA	6,195	314	5.06	5,311	7,106	5,605	6,786	9.53%

Configuration	Mean total emissions	Standard deviation of total emissions	Coefficient of variation (CV, %)	Minimum total emissions	Maximum total emissions	2.5% percentile	97.5% percentile	95% interval-based relative uncertainty (%)
SimaPro	6,278	320	5.10	5,317	7,237	5,673	6,887	9.67%
GaBi	5,694	303	5.32	4,890	6,492	5,113	6,256	10.04%

Note: Relative uncertainty is the half-width of the 95% uncertainty interval (2.5th–97.5th percentiles) divided by the simulated mean. All statistics use N = 10,000 realizations after economic allocation to cathode copper.

S9.3. Paired comparison and inter-configuration dispersion

For paired comparison, Ausmelt-minus-double-flash differences were calculated iteration by iteration. Homologous foreground–background contributions used common random numbers so shared uncertainties varied coherently between cases; unmatched contributions were sampled independently. Supplementary Table 23 summarizes the paired results, and none of the five 95% paired uncertainty intervals includes zero.

Supplementary Table 23. Paired Ausmelt-minus-double-flash Monte Carlo differences (N = 10,000)

Configuration	Mean difference(kg CO_2e/t Cu)	2.5th percentile	97.5th percentile	Paired correlation	95% UI excludes zero
eFootprint	327.6	86.3	564.7	0.947	Yes

eBalance	1,271.5	863.2	1,678.3	0.762	Yes
OpenLCA	742.1	429.3	1,062.7	0.853	Yes
SimaPro	851.1	464.4	1,244.3	0.779	Yes
GaBi	907.5	568.4	1,249.9	0.819	Yes

Across the five configuration means, the sample standard deviation is 533.3 kg CO_2e/t Cu for Ausmelt and 680.0 kg CO_2e/t Cu for double-flash, corresponding to inter-configuration coefficients of variation (CVs) of 8.16% and 11.90%, respectively. For a like-for-like SD-based comparison, the within-configuration Monte Carlo distributions have CVs of 3.44%–3.95% for Ausmelt and 5.06%–7.00% for double-flash, calculated as the standard deviation divided by the simulated mean using Tables S21 and S22. The inter-configuration CV is therefore approximately 2.1–2.4 times the within-configuration CV for Ausmelt and 1.7–2.4 times that for double-flash. Thus, inter-configuration dispersion exceeds within-configuration parameter uncertainty for both observed production systems. Because only five configurations are examined (n = 5) and the configurations are not statistically independent, these statistics and ratios are descriptive of the implementations considered rather than estimates of an underlying population distribution of structural uncertainty.

S10. Electricity-related mitigation scenarios and regional sensitivity analysis

S10.1. Electricity-scenario and baseline-factor sensitivity calculations

The electricity-scenario analysis uses the observed 2025 double-flash demand of 1,523.553998 kWh/t Cu. Process-efficiency trajectories and directly weighted year-specific electricity carbon-footprint factors are reported in Tables 4 and 5 of the main text. The directly weighted 2025

factor is 0.536430 kg CO_2e/kWh. For each baseline-factor case, the complete trajectory is rebased so that its 2025 value equals the selected baseline. The official 2024 national-average factor of 0.5777 kg CO_2e/kWh is used in the primary analysis, while 0.550 and 0.914 kg CO_2e/kWh are retained as alternative baseline cases.

Electricity demand under efficiency case s in year t was calculated as:

$I_{s,t} = I_{2025} \times (1 - r_s)^{(t - 2025)}$

For baseline case b, the year-specific electricity factor was rebased as:

EF(rebased, t, b) = EF(weighted, t) × EF(b) / 0.536430

The three counterfactual cases were calculated as follows:

CF(grid, t, b) = I(2025) × EF(rebased, t, b) × 0.972648

CF(efficiency, s, t, b) = I(s, t) × EF(b)× 0.972648

CF(combined, s, t, b) = I(s, t) × EF(rebased, t, b) × 0.972648

The percentage reduction relative to calibration baseline b was calculated as:

Reduction(s, t, b) = [1 − CF(scenario, s, t, b) ÷ (I(2025) × EF(b) × 0.972648)] × 100%

where I(2025) = 1,523.553998 kWh/t Cu; r(s) = 0.010, 0.011, or 0.012 for the conservative, moderate, and accelerated cases; EF(weighted, t) is the generation-weighted year-specific factor derived from the generation shares and technology-specific factors in Table 5; EF(b) is the selected 2025 calibration baseline; and EF(rebased, t, b) is the year-specific factor obtained by proportionally adjusting the complete trajectory so that its 2025 value equals EF(b).

Supplementary Table 24. Sensitivity of absolute electricity-related emissions to the calibrated 2025 electricity carbon-footprint factor

Baseline factor(kg CO_2e/kWh)	Scaling factor	Baseline emissions(kg CO_2e/t Cu)	2030 combined emissions (kg CO_2e/t Cu)	2060 combined emissions (kg CO_2e/t Cu)	Allocated oxygen-efficiency reduction (kg CO_2e/t Cu)
0.550	1.025297	815.035	653.009–659.645	28.849–30.965	101.719
0.5777	1.076935	856.083	685.897–692.867	30.302–32.525	106.842
0.914	1.703857	1,354.440	1,085.182–1,096.210	47.942–51.458	169.038

Note: For each baseline-factor case, the complete year-specific electricity-factor trajectory was rebased using EF(rebased, t, b) = EF(weighted, t) × EF(b) / 0.536430. Reported emission ranges span the conservative, moderate, and accelerated process-efficiency cases. Because each trajectory is consistently matched to its corresponding 2025 baseline, the combined percentage reductions are identical across the three baseline cases: 19.065%–19.880% in 2030 and 96.201%–96.460% in 2060. The baseline factor affects absolute emissions and absolute oxygen-efficiency benefits but is not itself treated as mitigation.

S10.2. Oxygen-production efficiency improvement

The oxygen-efficiency calculation uses a purchased-electricity-equivalent oxygen demand of 1,000.76 Nm^3/t Cu. This value is obtained by applying the 0.976 purchased-electricity factor to the physical oxygen demand of 1,025.37 Nm^3/t Cu:

1025.37 × 0.976 = 1000.76 Nm^3/t Cu

The factor 0.976 is the share of electricity purchased from the grid and is distinct from the economic-allocation fraction 0.972648 used below.

The observed electricity intensity of 0.65 kWh/Nm³ is compared with a pressure-matched commercial benchmark of 0.46 kWh/Nm³.

The electricity saving is a physical quantity and is therefore not allocated. When the associated avoided emissions are reported as a reduction in the cathode-copper carbon footprint, they are multiplied by the double-flash copper economic-allocation fraction of 0.972648 (97.26%).

Electricity saving = 1000.76 × (0.65 − 0.46) = 190.144 kWh/t Cu

$\Delta CF0.550 = 190.144 \times 0.550 \times 0.972648 = 101.719$ kg CO_2e/t Cu

$\Delta CF0.5777 = 190.144 \times 0.5777 \times 0.972648 = 106.842$ kg CO_2e/t Cu

$\Delta CF0.914 = 190.144 \times 0.914 \times 0.972648 = 169.038$ kg CO_2e/t Cu

For a future year t, the avoided emissions allocated to cathode copper are calculated as:

$\Delta CFt = 190.144 \times EF(rebased, t, b) \times 0.972648$

The avoided carbon footprint from oxygen-efficiency improvement therefore declines with the rebased year-specific electricity factor and is not added directly to reductions attributed to future grid decarbonization.

S10.3. Provincial electricity-factor calculation and consistency checks

The provincial carbon-footprint sensitivity analysis was conducted using the double-flash SimaPro–ecoinvent 3.10 configuration as the reference model. The province-specific electricity carbon-footprint factors were calculated from the projected 2025 installed-capacity composition reported by Zhuo et al.and the technology-specific life-cycle electricity carbon-footprint factors in the official 2024 Chinese dataset.

Seven generation technologies were included: coal, natural gas, nuclear, hydropower, wind, solar photovoltaic, and biomass.

For each province p, the installed-capacity share of generation technology j was calculated as:

$$w(p,j) = C(p,j) / \Sigma C(p,j)$$

where C(p,j) represents the installed capacity of technology j in province p. Shares were normalized such that their sum equals unity for each province.

The provincial electricity carbon-footprint factor was calculated as:

$$EF(p) = \Sigma [w(p,j) \times EF(j)]$$

where EF(j) denotes the technology-specific life-cycle electricity carbon-footprint factor.

To maintain consistency with the revised SimaPro baseline, the provincial copper carbon footprint was calculated as:

$$CF(p) = CF(0) + I \times \alpha \times [EF(p) - EF(0)]$$

where:

$CF(0) = 6{,}274.8$ kg CO_2e/t Cu, the reference SimaPro carbon footprint;

$I = 1{,}523.553998$ kWh/t Cu, the explicitly modeled purchased-electricity-equivalent demand;

$\alpha = 0.972648$, the copper economic-allocation fraction;

$EF(0) = 0.914$ kg CO_2e/kWh, the reference ecoinvent 3.10 electricity factor.

The fixed residual contribution is therefore:

$$CF(residual) = CF(0) - I \times \alpha \times EF(0)$$

$CF(residual) = 4{,}920.36$ kg CO_2e/t Cu.

The fixed residual contribution includes all unchanged background emissions, including electricity-related emissions embedded in upstream processes. Therefore, the calculated lower bound applies only to the explicitly modeled electricity demand and does not represent the elimination of all electricity-related emissions throughout the entire supply chain.

The original provincial installed-capacity data were reprocessed without relying on previously tabulated electricity-share percentages. The resulting shares were checked to ensure that they summed to unity within each province.

The recalculated electricity carbon-footprint factors range from 0.01836 to 0.61599 kg CO_2e/kWh, corresponding to refined-copper carbon footprints of 4,947.6–5,833.2 kg CO_2e/t Cu. All 31 provincial scenarios satisfy the lower-bound consistency condition:

$CF(p) \geq 4{,}920.36$ kg CO_2e/t Cu.

The analysis changes only the electricity factor associated with the explicitly modeled electricity demand. Concentrate production, transportation, fuel use, auxiliary materials, and economic allocation are retained from the reference model. The provincial factors are capacity-weighted proxies, not measured consumption-based grid factors. Provincial differences in capacity utilization, electricity imports and exports, and electricity delivery were not explicitly modeled. Consequently, these results are intended for comparative screening rather than prediction of actual province-specific production footprints.

Supplementary Table 25. Provincial installed-capacity-weighted electricity carbon-footprint factors and recalculated cradle-to-gate carbon footprints of refined copper under the double-flash reference model

Province	Electricity EF (kg CO_2e/kWh)	Copper CF (kg CO_2e/t Cu)
Anhui	0.58324	5,784.70
Beijing	0.42805	5,554.70
Chongqing	0.46328	5,606.90
Fujian	0.36467	5,460.80
Gansu	0.38437	5,490.00
Guangdong	0.44118	5,574.10
Guangxi	0.31984	5,394.30
Guizhou	0.43601	5,566.50
Hainan	0.38961	5,497.70
Hebei	0.44509	5,579.90
Heilongjiang	0.31711	5,390.30
Henan	0.562	5,753.20
Hubei	0.33814	5,421.40
Hunan	0.39896	5,511.60
Inner Mongolia	0.2777	5,331.90
Jiangsu	0.52635	5,700.30
Jiangxi	0.4918	5,649.10
Jilin	0.23899	5,274.50
Liaoning	0.5074	5,672.30
Ningxia	0.49782	5,658.10
Qinghai	0.11502	5,090.80
Shaanxi	0.59394	5,800.50

Shandong	0.56714	5,760.80
Shanghai	0.61128	5,826.20
Shanxi	0.56044	5,750.90
Sichuan	0.03407	4,970.90
Tianjin	0.61599	5,833.20
Tibet	0.08151	5,041.20
Xinjiang	0.53885	5,718.90
Yunnan	0.01836	4,947.60
Zhejiang	0.4819	5,634.50