Supplementary Materials for:

Sustainable Copper Mining: A Pathway to Emission Reduction Through Renewable Energy

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Table S1 Environmental impacts of each material and energy input to the ore reduction stage to produce 1 ton of copper cathode.

Impact Category	Unit	Primary crushing	Secondary crushing	Screening	conveyor
Ozone depletion	kg CFC-11 eq	1.75E-06	1.53E-06	1.06E-06	2.74E-07
Global warming	kg CO_2 eq	4.10E+01	3.58E+01	2.47E+01	6.43E+00
Smog	kg O_3 eq	2.24E+00	1.96E+00	1.35E+00	3.52E-01
Acidification	kg SO_2 eq	1.78E-01	1.56E-01	1.08E-01	2.80E-01
Eutrophication	kg N eq	1.55E-01	1.36E-01	9.38E-02	2.44E-02
Carcinogenics	CTUh	2.46E-06	2.15E-06	1.48E-06	3.86E-07
Non carcinogenics	CTUh	8.39E-06	7.34E-06	5.07E-06	1.31E-06
Respiratory effects	kg PM2.5 eq	6.06E-02	5.30E-02	3.66E-02	9.48E-03
Ecotoxicity	CTUe	3.13E+02	2.74E+02	1.89E+02	4.93E+01
Fossil fuel depletion	MJ surplus	3.10E+01	2.72E+01	1.88E+01	4.88E+00

Table S2. Environmental impacts of each material and energy input to the OAMH stage to produce one ton of copper cathode.

Impact Category	Unit	Water	Electricity	Conveyor	Sulfuric acid	Diesel
Ozone depletion	kg CFC-11 eq	7.50E-09	2.95E-06	5.50E-09	3.00E-06	1.58E-05
Global warming	kg CO_2 eq	9.86E-02	6.92E+01	1.29E-01	2.46E+01	8.88E+01
Smog	kg O_3 eq	7.10E-03	3.79E+00	7.07E-03	3.77E+00	1.80E+01
Acidification	kg SO_2 eq	3.61E-04	3.02E-01	5.61E-03	1.20E+00	6.86E-01
Eutrophication	kg N eq	2.05E-04	2.62E-01	4.88E-04	3.28E-02	1.93E-01
Carcinogenics	CTUh	5.13E-08	4.15E-06	7.74E-09	4.05E-06	1.10E-05
Non carcinogenics	CTUh	2.24E-08	1.42E-05	2.63E-08	9.90E-05	3.50E-04
Respiratory effects	kg PM2.5 eq	9.82E-05	1.02E-01	1.90E-04	1.01E-01	1.28E-01
Ecotoxicity	CTUe	2.14E+00	5.28E+02	9.88E-01	2.51E+02	1.35E+03
Fossil fuel depletion	MJ surplus	7.78E-02	5.25E+01	9.79E-02	5.34E+01	1.48E+02

Table S3. Environmental impacts of each material and energy input to the heap leaching stage to produce one ton of copper cathode.

Impact Category	Unit	Water	Electricity	Sulfuric acid
Ozone depletion	kg CFC-11 eq	7.48E-08	8.72E-06	1.77E-05
Global warming	kg CO_2 eq	9.84E-01	2.04E+02	1.45E+02
Smog	kg O_3 eq	7.08E-02	1.12E+01	2.22E+01
Acidification	kg SO_2 eq	3.60E-03	8.91E-01	7.05E+00
Eutrophication	kg N eq	2.05E-03	7.74E-01	1.93E-01
Carcinogenics	CTUh	5.12E-07	1.23E-05	2.38E-05
Non carcinogenics	CTUh	2.23E-07	4.18E-05	5.82E-04
Respiratory effects	kg PM2.5 eq	9.80E-04	3.02E-01	5.93E-01
Ecotoxicity	CTUe	2.14E+01	1.56E+03	1.47E+03
Fossil fuel depletion	MJ surplus	7.76E-01	1.55E+02	3.14E+02

Table S4 Environmental impacts of each material and energy input to the SX stage to produce one ton of copper cathode.

Impact Category	Unit	Extractant	Diluent	Electricity
Ozone depletion	kg CFC-11 eq	1.33E-07	8.00E-06	1.43E-05
Global warming	kg CO_2 eq	6.14E+00	4.31E+00	3.36E+02
Smog	kg O_3 eq	2.78E-01	4.38E-01	1.84E+01
Acidification	kg SO_2 eq	2.36E-02	4.46E-02	1.46E+00
Eutrophication	kg N eq	7.93E-03	1.13E-02	1.27E+00
Carcinogenics	CTUh	2.22E-07	5.85E-08	2.01E-05
Non carcinogenics	CTUh	3.67E-07	2.47E-07	6.87E-05
Respiratory effects	kg PM2.5 eq	4.39E-03	4.07E-03	4.96E-01
Ecotoxicity	CTUe	1.66E+01	5.26E+00	2.56E+03
Fossil fuel depletion	MJ surplus	2.84E+01	6.93E+01	2.54E+02

Table S5. Contribution of each material and energy input to the EW stage to produce one ton of copper cathode.

Impact Category	Unit	Cobalt sulfate	Guar gum	Electricity for Cu electrowinning	Electricity required for electrolyte heating and adsorption of acid mist in EW
Ozone depletion	kg CFC-11 eq	8.42E-08	2.88E-10	5.84E-05	6.49E-06
Global warming	kg CO_2 eq	5.38E-01	3.03E-03	1.37E+03	1.52E+02
Smog	kg O_3 eq	3.18E-02	2.57E-04	7.49E+01	8.32E+00
Acidification	kg SO_2 eq	5.95E-03	5.72E-05	5.96E+00	6.62E-01
Eutrophication	kg N eq	6.40E-04	2.78E-05	5.18E+00	5.76E-01
Carcinogenics	CTUh	4.00E-07	8.99E-11	8.21E-05	9.12E-06
Non carcinogenics	CTUh	5.31E-07	4.28E-10	2.80E-04	3.11E-05
Respiratory effects	kg PM2.5 eq	6.92E-04	3.92E-06	2.02E+00	2.25E-01
Ecotoxicity	CTUe	4.97E+00	3.33E-03	1.04E+04	1.16E+03
Fossil fuel depletion	MJ surplus	1.07E+00	3.59E-03	1.04E+03	1.15E+02

Table S6.1 Environmental impacts of each material and energy input to the spent ore treatment stage to produce 1 ton of copper cathode.

Impact Category	Unit	Water	Electricity	Lime	Flocculant
Ozone depletion	kg CFC-11 eq	2.17E-09	8.82E-07	6.97E-07	2.41E-08
Global warming	kg CO_2 eq	2.85E-02	2.07E+01	1.22E+01	6.81E-01
Smog	kg O_3 eq	2.05E-03	1.13E+00	1.79E-01	4.42E-02
Acidification	kg SO_2 eq	1.04E-04	9.01E-02	1.23E-02	3.11E-03
Eutrophication	kg N eq	5.93E-05	7.83E-02	2.93E-03	3.15E-03
Carcinogenics	CTUh	1.48E-08	1.24E-06	5.63E-08	4.94E-08
Non carcinogenics	CTUh	6.46E-09	4.23E-06	2.42E-07	2.59E-07
Respiratory effects	kg PM2.5 eq	2.84E-05	3.06E-02	1.78E-03	5.68E-04
Ecotoxicity	CTUe	6.19E-01	1.58E+02	7.42E+00	1.11E+01
Fossil fuel depletion	MJ surplus	2.25E-02	1.57E+01	7.13E+00	1.85E+00

Table S6.2 Environmental impacts of each material and energy input to the spent ore treatment stage to produce 1 ton of copper cathode.

Impact Category	Unit	Coagulant	Diesel	HDPE Liner
Ozone depletion	kg CFC-11 eq	1.51E-06	1.62E-05	4.03E-06
Global warming	kg CO_2 eq	6.05E+00	9.10E+01	1.04E+01
Smog	kg O_3 eq	2.54E-01	1.84E+01	5.26E-01
Acidification	kg SO_2 eq	2.01E-02	7.03E-01	4.63E-02
Eutrophication	kg N eq	3.69E-02	1.97E-01	2.35E-02
Carcinogenics	CTUh	1.38E-06	1.13E-05	5.95E-07
Non carcinogenics	CTUh	1.95E-06	3.59E-04	1.45E-06
Respiratory effects	kg PM2.5 eq	1.19E-02	1.31E-01	1.02E-02
Ecotoxicity	CTUe	1.02E+02	1.38E+03	8.79E+01
Fossil fuel depletion	MJ surplus	8.45E+00	1.52E+02	4.90E+01

Table S7.1 Environmental impact of each material and energy input to the spent solution treatment stage to produce 1 ton of copper cathode.

Impact Category	Unit	Lime	Electricity	sodium sulfide	Ferric Chloride	Sodium carbonate	Extractant
Ozone depletion	kg CFC-11 eq	3.32E-07	3.37E-06	5.45E-08	1.51E-08	6.04E-09	1.03E-09
Global warming	kg CO_2 eq	5.81E+00	4.27E+01	9.45E-01	3.21E-02	9.79E-02	4.73E-02
Smog	kg O_3 eq	8.51E-02	3.39E+00	6.85E-02	2.34E-03	6.16E-03	2.14E-03
Acidification	kg SO_2 eq	5.86E-03	2.66E-01	5.88E-03	1.94E-04	4.17E-04	1.82E-04
Eutrophication	kg N eq	1.39E-03	4.53E-02	3.91E-03	1.44E-04	4.82E-04	6.11E-05
Carcinogenics	CTUh	2.68E-08	2.44E-06	9.73E-08	6.96E-09	8.99E-09	1.71E-09
Non carcinogenics	CTUh	1.15E-07	1.37E-05	4.91E-07	2.28E-08	2.78E-08	2.83E-09
Respiratory effects	kg PM2.5 eq	8.46E-04	5.47E-02	8.54E-04	4.85E-05	7.62E-05	3.38E-05
Ecotoxicity	CTUe	3.53E+00	6.71E+01	2.45E+01	1.64E+00	1.83E+00	1.28E-01
Fossil fuel depletion	MJ surplus	3.39E+00	3.98E+01	7.20E-01	2.71E-02	1.16E-01	2.19E-01

Table S7.2 Environmental impact of each material and energy input to the spent solution treatment stage to produce 1 ton of copper cathode.

Impact Category	Unit	Diluent	Coagulant	Flocculant	Filter aids	Iron Scrap	Diesel	$MgSO_4$
Ozone depletion	kg CFC-11 eq	6.15E-08	7.95E-08	1.61E-09	5.44E-11	3.21E-06	1.62E-06	9.42E-07
Global warming	kg CO_2 eq	3.32E-02	3.18E-01	4.54E-02	3.02E-04	3.95E+01	9.10E+00	6.88E+00
Smog	kg O_3 eq	3.37E-03	1.34E-02	2.94E-03	8.49E-05	2.62E+00	1.84E+00	6.60E-01
Acidification	kg SO_2 eq	3.43E-04	1.06E-03	2.07E-04	3.84E-06	2.37E-01	7.03E-02	4.26E-02
Eutrophication	kg N eq	8.66E-05	1.94E-03	2.10E-04	6.75E-07	1.93E-01	1.97E-02	2.29E-02
Carcinogenics	CTUh	4.50E-10	7.25E-08	3.29E-09	2.60E-11	2.95E-05	1.13E-06	6.66E-07
Non carcinogenics	CTUh	1.90E-09	1.03E-07	1.73E-08	5.84E-11	1.25E-04	3.59E-05	9.83E-06
Respiratory effects	kg PM2.5 eq	3.13E-05	6.24E-04	3.79E-05	4.79E-07	5.50E-02	1.31E-02	8.36E-03
Ecotoxicity	CTUe	4.04E-02	5.35E+00	7.38E-01	3.13E-03	7.12E+03	1.38E+02	3.40E+02
Fossil fuel depletion	MJ surplus	5.33E-01	4.45E-01	1.23E-01	4.98E-04	3.95E+01	1.52E+01	1.04E+01

Table S8.1 The absolute values of each stage to the whole process to produce 1 ton of copper cathode.

Impact Category	Unit	Total	Size reduction	Feed preparation	Leaching
Ozone depletion	kg CFC-11 eq	2.40E-04	4.61E-06	2.18E-05	3.64E-05
Global warming	kg CO_2 eq	3.39E+03	1.08E+02	1.83E+02	5.83E+02
Smog	kg O_3 eq	2.49E+02	5.91E+00	2.55E+01	4.62E+01
Acidification	kg SO_2 eq	2.37E+01	7.22E-01	2.19E+00	8.96E+00
Eutrophication	kg N eq	1.16E+01	4.09E-01	4.88E-01	1.85E+00
Carcinogenics	CTUh	2.70E-04	6.48E-06	1.93E-05	5.06E-05
Non carcinogenics	CTUh	2.61E-03	2.21E-05	4.63E-04	6.72E-04
Respiratory effects	kg PM2.5 eq	5.31E+00	1.60E-01	3.32E-01	1.24E+00
Ecotoxicity	CTUe	3.59E+04	8.24E+02	2.13E+03	4.84E+03
Fossil fuel depletion	MJ surplus	3.69E+03	8.18E+01	2.54E+02	6.47E+02

Table S8.2 The absolute values of each stage to the whole process to produce 1 ton of copper cathode.

Impact Category	Unit	SX	EW	Spent ore treatment	Spent Solution treatment
Ozone depletion	kg CFC-11 eq	2.86E-05	6.50E-05	2.34E-05	9.70E-06
Global warming	kg CO_2 eq	4.89E+02	1.52E+03	1.41E+02	1.06E+02
Smog	kg O_3 eq	2.69E+01	8.32E+01	2.06E+01	8.70E+00
Acidification	kg SO_2 eq	2.15E+00	6.63E+00	8.75E-01	6.30E-01
Eutrophication	kg N eq	1.83E+00	5.76E+00	3.42E-01	2.89E-01
Carcinogenics	CTUh	2.90E-05	9.16E-05	1.46E-05	3.39E-05
Non carcinogenics	CTUh	9.86E-05	3.12E-04	3.67E-04	1.85E-04
Respiratory effects	kg PM2.5 eq	7.17E-01	2.25E+00	1.86E-01	1.34E-01
Ecotoxicity	CTUe	3.68E+03	1.16E+04	1.75E+03	7.70E+03
Fossil fuel depletion	MJ surplus	4.61E+02	1.15E+03	2.34E+02	1.10E+02

Table S9 LUI for wind turbines and solar PV

Primary Energy Sources	Required land (m^2)	LUI m^2/(ton/year)
Solar PV	200,000	17.5
Wind turbine	700,000	61.4

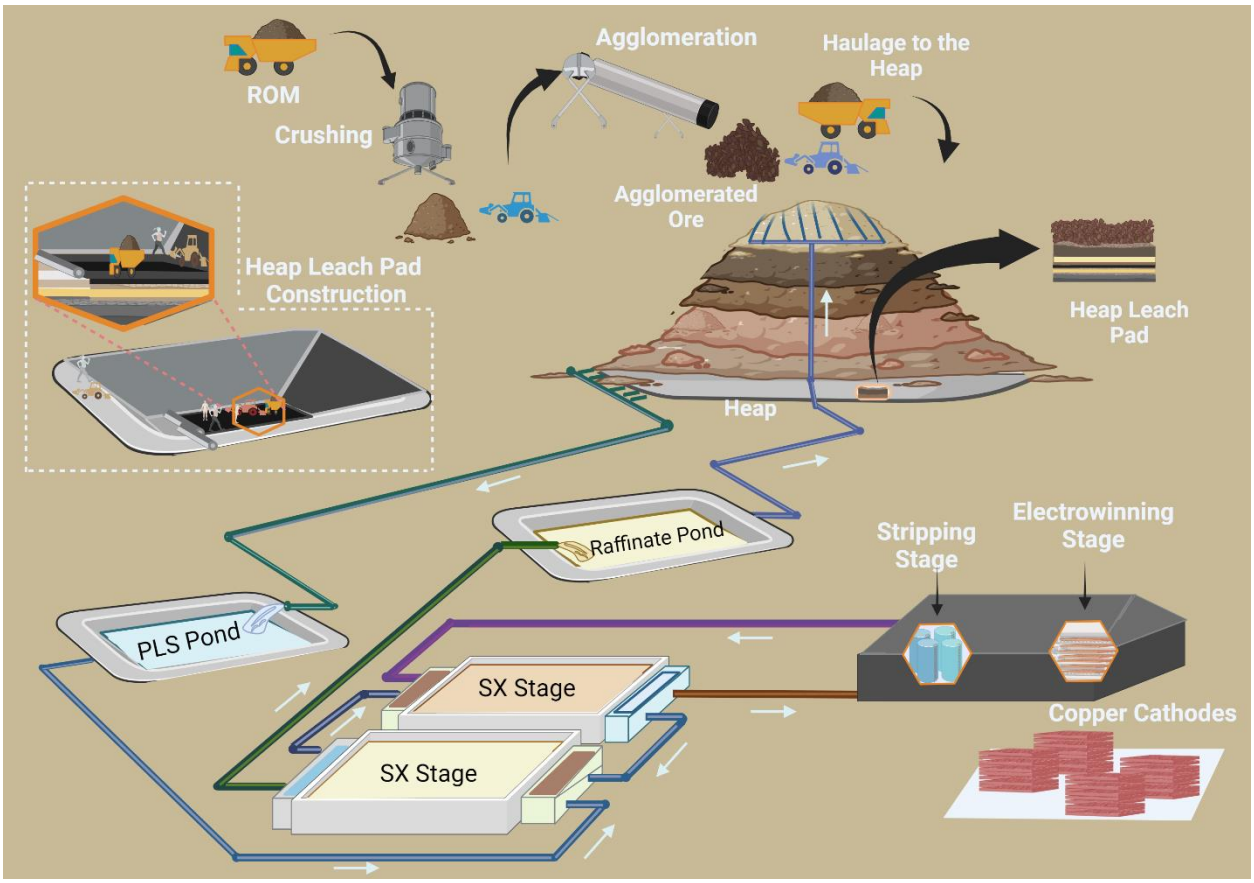

Fig. S1. The schematic flow diagram of this study. ("Created with BioRender.com.")

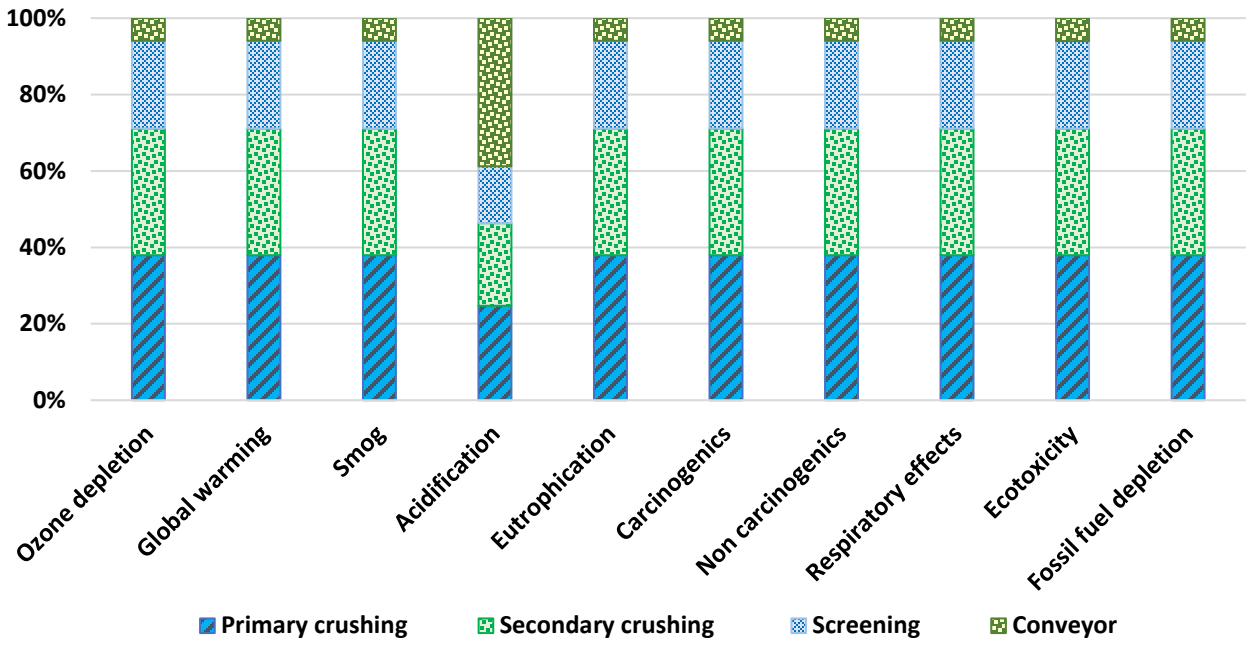

Fig. S2 Contribution of energy and material flows in the ore size reduction stage to produce one ton of copper cathode using TRACI.

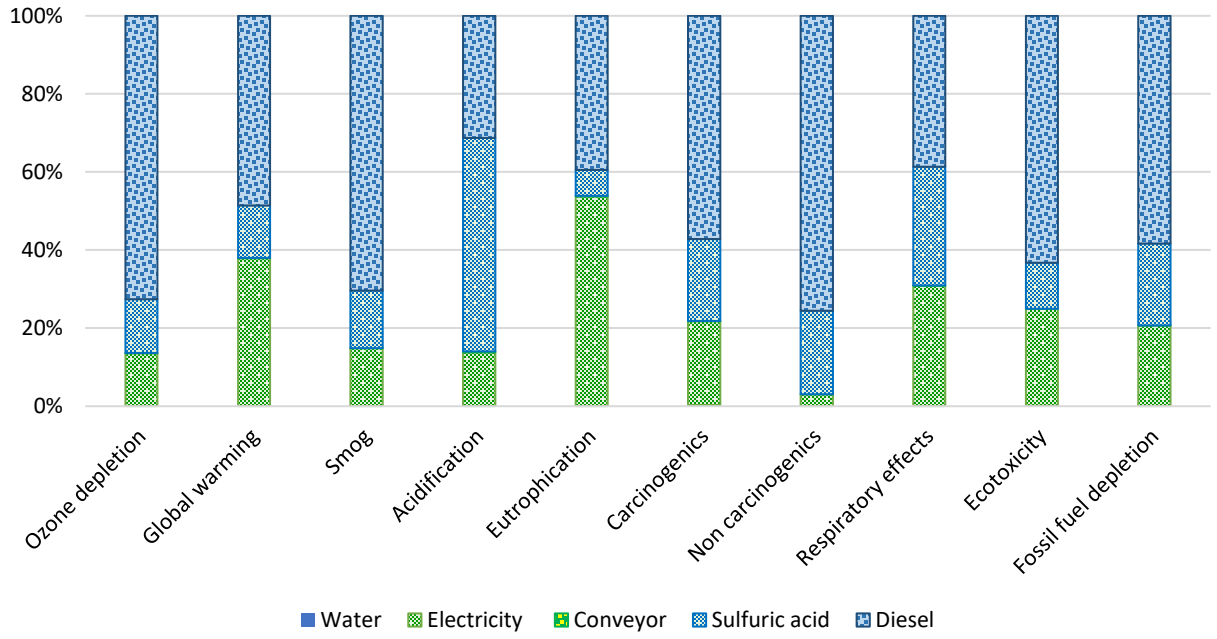

Fig. S3. Contribution of process energy and material flows in the OAMH stage for obtaining one ton of copper cathode using TRACI.

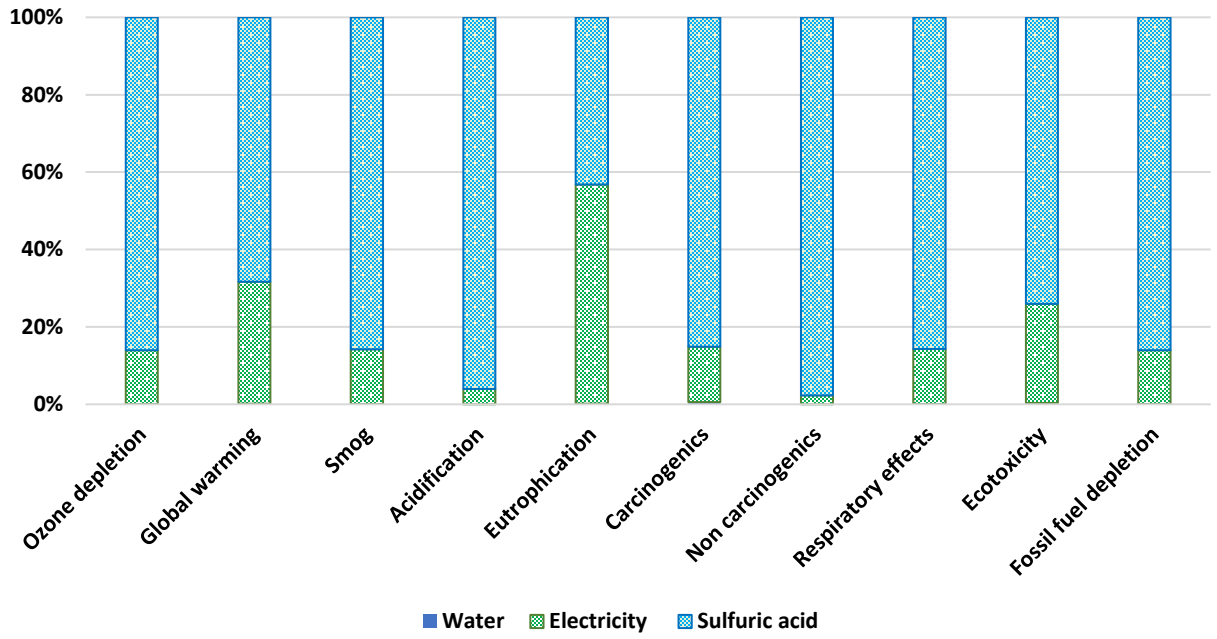

Fig. S4. Contribution of process energy and material flows in the heap leaching stage for obtaining one ton of copper cathode using TRACI.

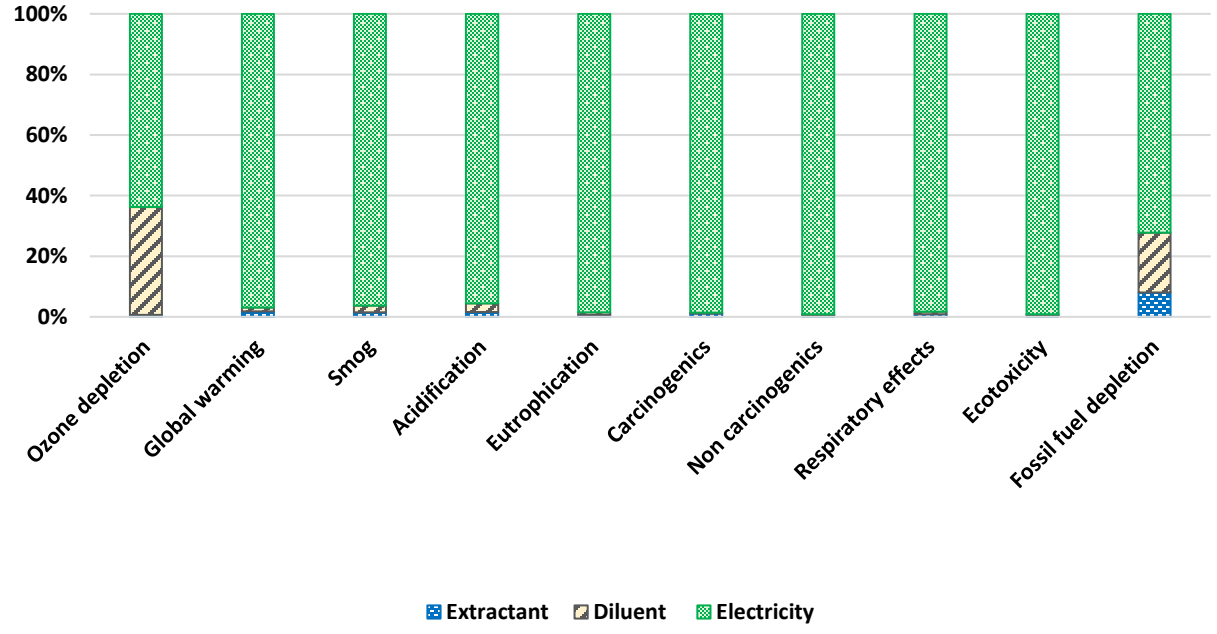

Fig. S5 Contribution of process energy and material flows in the SX stage for obtaining one ton of copper cathode using TRACI.

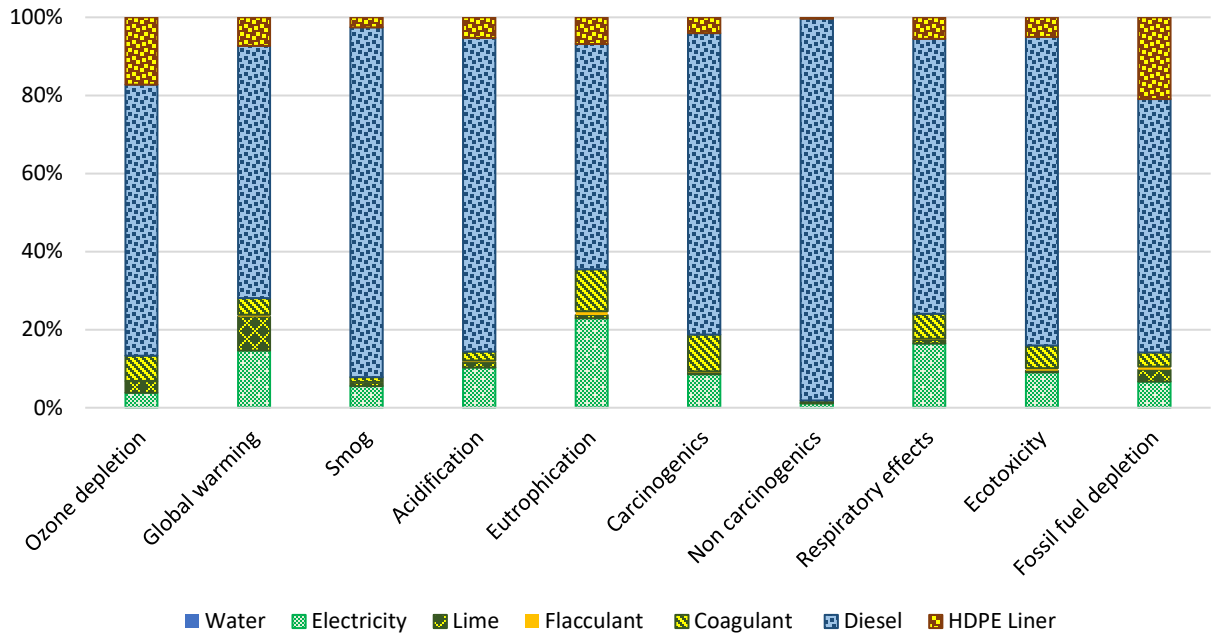

Fig. S6 Contribution of process energy and material flows in the spent ore treatment stage for obtaining one ton of copper cathode using TRACI.

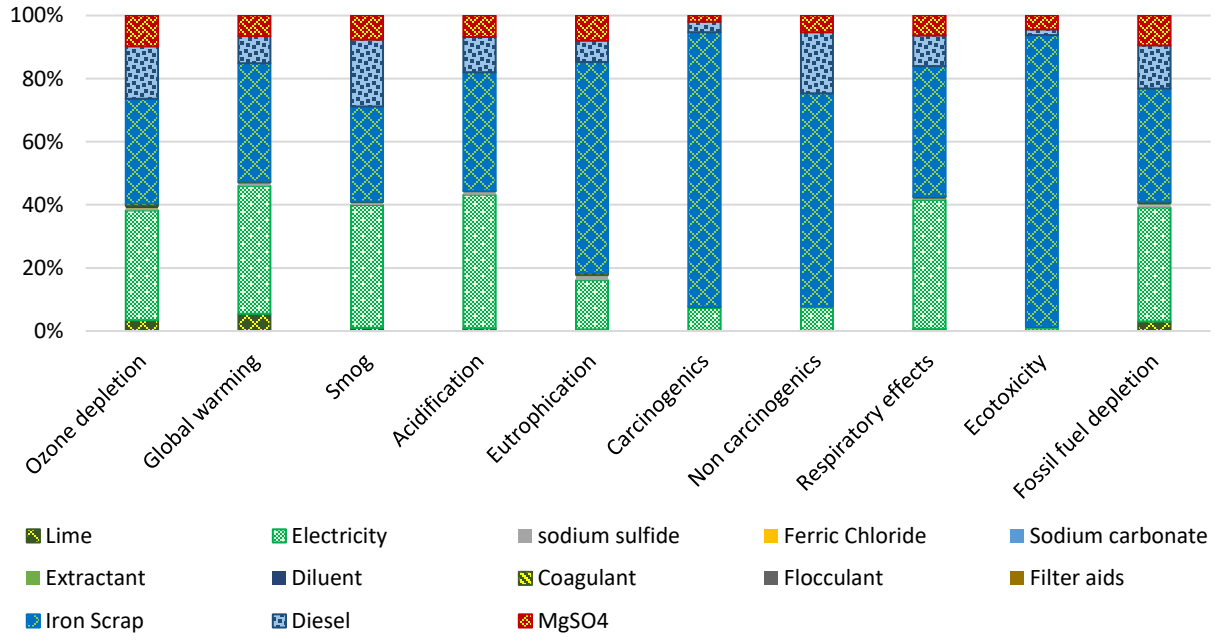

Fig. S7 Contribution of process energy and material flows in the spent solution treatment stage for obtaining one ton of copper cathode using TRACI.

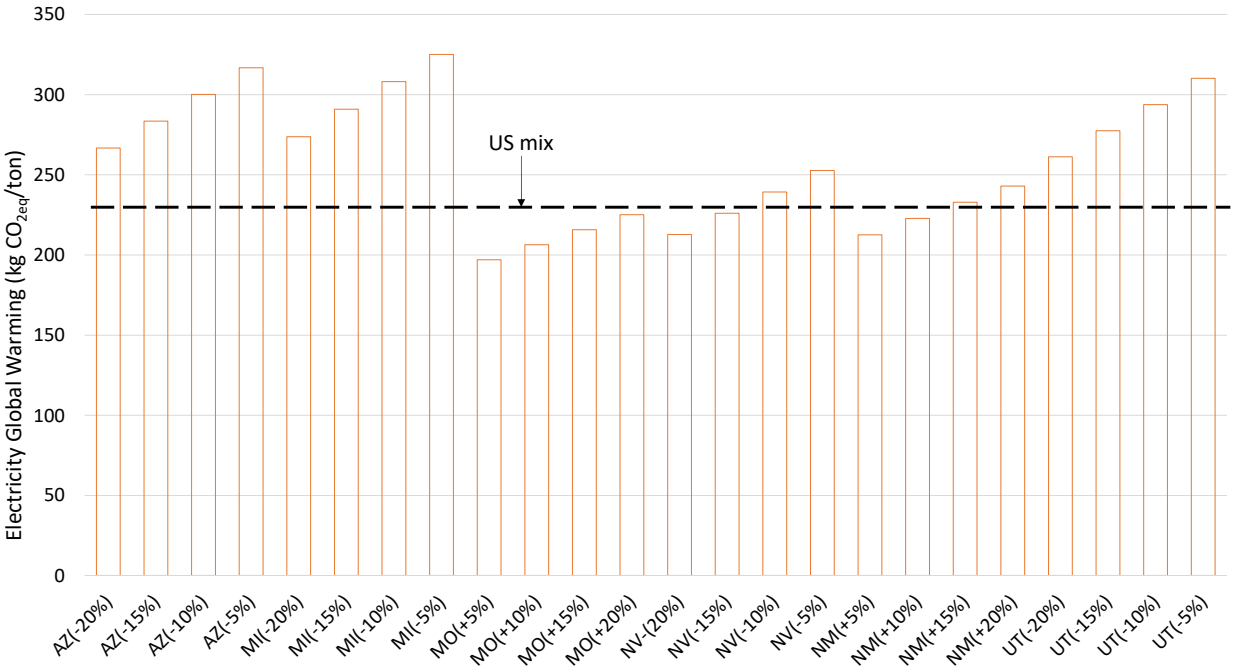

Fig. S8 State-by-state sensitivity of GHG emissions from electricity contribution: best efficiency scenario for fossil-based States (Coal > 50%) vs. worst efficiency scenario for renewable-based St**ates (Coal < 50%)**