Supplementary Information

Conventional vs. Direct vs. Electrochemical Lithium Extraction: A Holistic TEA–LCA of Lithium Carbonate Production from Spodumene

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1- Life cycle assessment (LCA)

Table S1- Life Cycle Inventory: 1-ton LCE production through conventional method.

Input			
Properties	**Amount**	**Unit**	**Ecoinvent Unit Process (TRACI 2008)**
Materials/fuels			
Sulfuric acid	1.9	ton	Sulfuric acid {RoW}|production|APOS,U
Calcium carbonate	390	kg	Calcium carbonate, precipitated {RoW}| market for calcium carbonate, precipitated | APOS, U
Water	12.9	ton	Water, decarbonised {RoW}| market for water, decarbonised | APOS, U
Lime milk	278	kg	Lime, hydrated, packed {RoW}| market for lime, hydrated, packed | APOS, U
Soda ash	2.22	ton	Soda ash, dense {GLO}| market for | APOS, U
Sulfuric acid-Purification	250	kg	Sulfuric acid {RoW}|production|APOS,U
Electricity/heat			
National gas	11.975	GJ	Heat, district or industrial, natural gas, GLO, market group, APOS
Electricity-Extraction	10.59	GJ	Electricity, high voltage {RFC}| market for | APOS, U
Electricity-Purification	46.746	GJ	Electricity, high voltage {RFC}| market for | APOS, U
Product			
LCE	1	ton	--
Emission to air			
Carbon dioxide-Extraction	850	kg	Carbon dioxide, Undefined
Carbon dioxide-Purification	104	kg	Carbon dioxide, Undefined

Table S2- Life Cycle Inventory: 1-ton LCE production through the DLE method.

Properties	Amount	Unit	Ecoinvent Unit Process (TRACI 2008)
Input			
Materials/fuels			
Sodium hydroxide	800	kg	Neutralising agent, sodium hydroxide-equivalent {GLO}| market for | APOS, U
Lithium carbonate	150	kg	Lithium carbonate {GLO}| market for | APOS, U
Lime	520	kg	Quicklime, milled, loose {RoW}| market for quicklime, milled, loose | APOS, U
Water	103.6	ton	Water, decarbonised {RoW}| market for water, decarbonised | APOS, U
Carbon dioxide	600	kg	Carbon dioxide, liquid {RoW}| market for | APOS, U
Electricity/heat			
National gas	11.782	GJ	Heat, district or industrial, natural gas, GLO, market group, APOS
Electricity-Extraction	3.12	GJ	Electricity, high voltage {RFC}| market for | APOS, U
Electricity-Purification	19.20	GJ	Electricity, high voltage {RFC}| market for | APOS, U
Product			
LCE	1	ton	--
Emission to air			
Carbon dioxide-Extraction	670	kg	Carbon dioxide, Undefined

Table S3- Life Cycle Inventory: 1-ton LCE production through the EDL method.

Properties	Amount	Unit	Ecoinvent Unit Process (TRACI 2008)
Input			
Materials/fuels			
Soda ash	1.4	ton	Soda ash, dense {GLO}| market for | APOS, U
Lithium carbonate	5	kg	Lithium carbonate {GLO}| market for | APOS, U
Water	4.1	ton	Water, decarbonised {RoW}| market for water, decarbonised | APOS, U
Calcium hydroxide	150	kg	Lime, hydrated, packed {RoW}| market for lime, hydrated, packed | APOS, U
Hydrogen peroxide	150	kg	Hydrogen peroxide, without water, in 50% solution state {RoW}| market for hydrogen peroxide, without water, in 50% solution state | APOS, U
Sulfuric acid	1.2	ton	Sulfuric acid {RoW}| market for sulfuric acid | APOS, U
Electrode	0.05 kg Gold		Gold {GLO}| market for | APOS, U
	7.54 kg Carbon		Carbon black {GLO}| market for | APOS, U
Electricity/heat			
Electricity-Extraction	1.19	GJ	Electricity, high voltage {RFC}| market for | APOS, U
Electricity-Purification	2.06	GJ	Electricity, high voltage {RFC}| market for | APOS, U
Product			
LCE	1	ton	--

Energy: In all methods illustrated in Fig. S1, we used laboratory-scale data to estimate the specifications of equipment necessary for industrial-scale operations, including reactor dimensions and insulation materials, to determine the heating energy requirements of the chemical processes. For example, glass fiber was selected as the reactor wall insulation to reduce heat loss. The total heating energy includes (i) the energy needed to elevate the temperature of the reaction mixture and (ii) the energy lost through heat transfer across the reactor walls. Eq. S1 was applied to calculate the heating energy required for the magnets recycling process.

$$Q = \frac{mCp\Delta T + A\frac{K_a}{s}\Delta T t}{\eta_H}$$

S1

Where Cp is the specific heat capacity (J/kg.K) at room temperature, as assumed for the preliminary analysis in this study, m is the mass of the reaction mixture (kg), ΔT is the temperature difference between the target reaction temperature (K) and room temperature, and A represents the surface area of the furnace/reactor. K_a is the thermal conductivity of the insulation material, s is the insulation thickness, and t is the reaction time. The efficiency of the heating element, η_H, is assumed to be 75%. The rate of heat loss, calculated as AK_a/s, is estimated to be 3.3 W/K [1].

During the leaching stage, an agitator is required to ensure adequate mixing of chemical components, which involves energy consumption. For industrial-scale operations, agitation speed was estimated using a geometric scale-up method that maintains a constant power-to-volume ratio [2]. Cylindrical reactors or tanks were chosen for large-scale setups, with scaling based on the rotational speed observed in lab-scale experiments. The energy required for agitation was calculated using the following equation [1].

$$E = \frac{N_P \rho N^3 d^5 t}{\eta_S}$$

S2

Where E is the required energy (J), N_P is the dimensionless impeller power number derived from the theory of similarity. For this study, an axial flow impeller was assumed, with a power number of 0.79 1. ρ, represents the density of the mixture (kg/m^3), and η_S is the stirring efficiency, which is assumed to be 80%.

In this paper, an average energy consumption of 5.5 kWh/ton of dry material [1] (i.e., material with all moisture content removed) was estimated for filtration in industrial-scale operations.

Drying of solids involves the evaporation of residual moisture that remains after upstream steps such as filtration. The energy efficiency of drying varies significantly depending on the type of dryer, its configuration, and whether heat recovery is implemented. Reported efficiencies can range from as low as 30% to over 100% in systems with effective heat recovery [3].

The dryer efficiency (η_d) is defined as the ratio of the heat needed to vaporize the removed liquid to the total heat input. Only the energy required to raise the liquid temperature is explicitly considered, as other losses are accounted for within the efficiency itself. For modeling purposes, a standard efficiency of 80% is assumed based on expert estimates. Heat required for drying is calculated based on the following equation:

$$Q_d = \frac{m_{liq} Cp_{liq} (T_{boil} - T_0) + \Delta H_{vap} m_{vap}}{\eta_d} \quad \text{S3}$$

Where, m_{liq} (kg), is mass of liquid present in the wet solid before drying, Cp_{liq} (j/kg.K), is specific heat capacity of the liquid to be evaporated, T_0, reference temperature (K), T_{boil} (K), is boiling temperature of the liquid, ΔH_{vap} (j/kg), is latent heat of vaporization of the liquid at the boiling temperature, m_{vap} (kg), is mass of liquid actually evaporated during drying. Similarly, energy is required to raise the temperature of the liquid to the boiling temperature plus its enthalpy of evaporation (S3).

Equipment prices were initially estimated using the Matches [4]. These baseline costs (from 2014) were updated to 2025 prices using established cost-index inflation factors. Specifically, we adjusted each 2014 equipment cost by the ratio of the 2025 to 2014 from the CEPCI index value, following standard industry practice.

Table S4- Equipment list 1-ton LCE production from concentrated hard rock by conventional method.

Equipment list	**Number**	**Price (k$)**
Rotary kiln, CS	1	776.07
Vessel Reactor, SS316	1	415.84
Stirring heated reactor, 1000	2	193.28
Filter press, SS316	1	200.75
Stirring reactor, 800 L	2	88.68
Filtration	1	84.76
Evaporator	1	108.64
Precipitation stirring jacket reactor	1	15.56
Tank, 1000 L	2	14.70
Filter press-3	1	84.76
Carbonate removal stirring jacket reactor, 500 L SS316	1	66.26
Tank, 500 L	4	11.39
Evaporator-2	1	64.92
Filter press-3	1	73.86
Stirring heated reactor, 250 L, SS316	1	45.93
Filter pree-4	1	51.57
Dryer	1	159.60

Table S5- Equipment list 1-ton LCE production from concentrated hard rock by the DLE method.

Equipment list	**Number**	**Price (k$)**
Rotary kiln	1	576.54
Agitated reactor	2	164.62
Storage tank (4k G)	4	199.41
Filterpress-1	1	119.06
Rotary kiln, CS	1	199.16
Agitated reactor	2	215.82
Filterpress-2	1	130.81
Nanofiltration	1	108.64
Precipitation stirring jacket reactor- CO_2 bubble	2	52.30
Tank, 1000 L	2	14.70
Filterpress-3	1	73.86
Dryer	1	159.60
NaOH-recovery stirring jacket reactor	2	66.39
Filterpress-4	1	95.91

Table S6- Equipment list 1-ton LCE production from concentrated hard rock by the EDL method.

Equipment list	**Number**	**Price (k$)**
Mixing tank	1	552.2
Electrochemical reactor	2	1,676.5
Storage tank	4	199.41
Filterpress-1	1	118.21
Clarification reactor	1	103.25

Precipitation reactor	1	112.07
Filterpress-2	1	130.81
Washing tank	1	46.05
Dryer	1	159.60
Evaporator	1	66.38
Filterpress-4	1	95.91

Table S7: Factors for estimation of fixed capital investment (FCI) for plant [5].

Capital investment	**Value**
Equipment cost (EC)	Tables 3&4
Installation cost (IC)	0.70 × EC
Instrumentation	0.18× EC
Electrical	0.10×EC
Buildings	0.28×EC
Yard improvement	0.10×EC
Auxiliary facilities	0.10×EC
Other costs	
Contingency	0.05×EC

The operating labor hours per ton for each processing step (Y) were estimated based on plant capacity (X, in tons per day) using the empirical correlation shown in Equation S1.

$$\log_{10} Y = 0.783\log_{10} X + 1.384 \quad \text{S4}$$

Y: The operating labor hours per ton per processing step

X: Plant capacity, tons per day

Table S8: Assumptions for estimation of indirect OPEX [5,6].

Cost category	**Cost estimation method**
Maintenance	0.03×FCI
Depreciation	Modified Accelerated Cost Recovery System (MACRS)
Insurance	0.03×Total Capital Cost (CAPEX)

Table S9- Chemicals and utility costs required to supply per ton/day or kWh/day production of 1-ton LCE through the conventional method from concentrated hard rock [7,8].

Item	Qty.	Unit price ($/per unit)	Total price ($)
Acid, Sulfuric, 96%	2.12 t	327 ($/t)	703.0
Water	12.9 m^3	1 ($/m3)	12.9
Calcium carbonate	0.42 t	225 ($/t)	94.5
Lime milk	0.278 t	220 ($/t)	61.1
Soda ash	1.63 t	229	373.5
Natural Gas	311 m^3	0.381 $/m3	118.4
Electricity	6377.6 kWh	0.1 ($/kWh)	637.7

Table S10- Chemicals and utility costs required to supply per ton/day or kWh/day production of 1-ton LCE through the DLE method from concentrated hard rock [7,8].

Item	Qty.	Unit price ($/per unit)	Total price ($)
NaOH	0.8 t	400 ($/t)	320
Water	98.4 m^3	1 ($/m3)	98.4
Lime	0.52 t	385 ($/t)	200.2
Filter	68 m^2	0.15 ($/$m^2$)	10.3
LCE	0.015 t	14000 ($/t)	210
CO_2	0.6 t	305 ($/t)	183
Natural Gas	308 m^3	0.381 $/m3	117.3
Electricity	4534.9 kWh	0.1 ($/kWh)	453.4

Table S11- Chemicals and utility costs required to supply per ton/day or kWh/day production of 1-ton LCE through the EDL method from concentrated hard rock [7,8].

Item	Qty.	Unit price ($/per unit)	Total price ($)
H_2SO_4	1.2 t	327 ($/t)	392.4
Water	4.0 m^3	1 ($/$m^3$)	4
Soda ash	1.43 m^2	229 ($/t)	10.3
LCE	0.015 t	14000 ($/t)	420
Electrode-makeup	5 kg	180 ($/kg)	900
H2O2	0.1 t	900 $/t	90
Electricity	3266.4 kWh	0.1 ($/kWh)	326.6

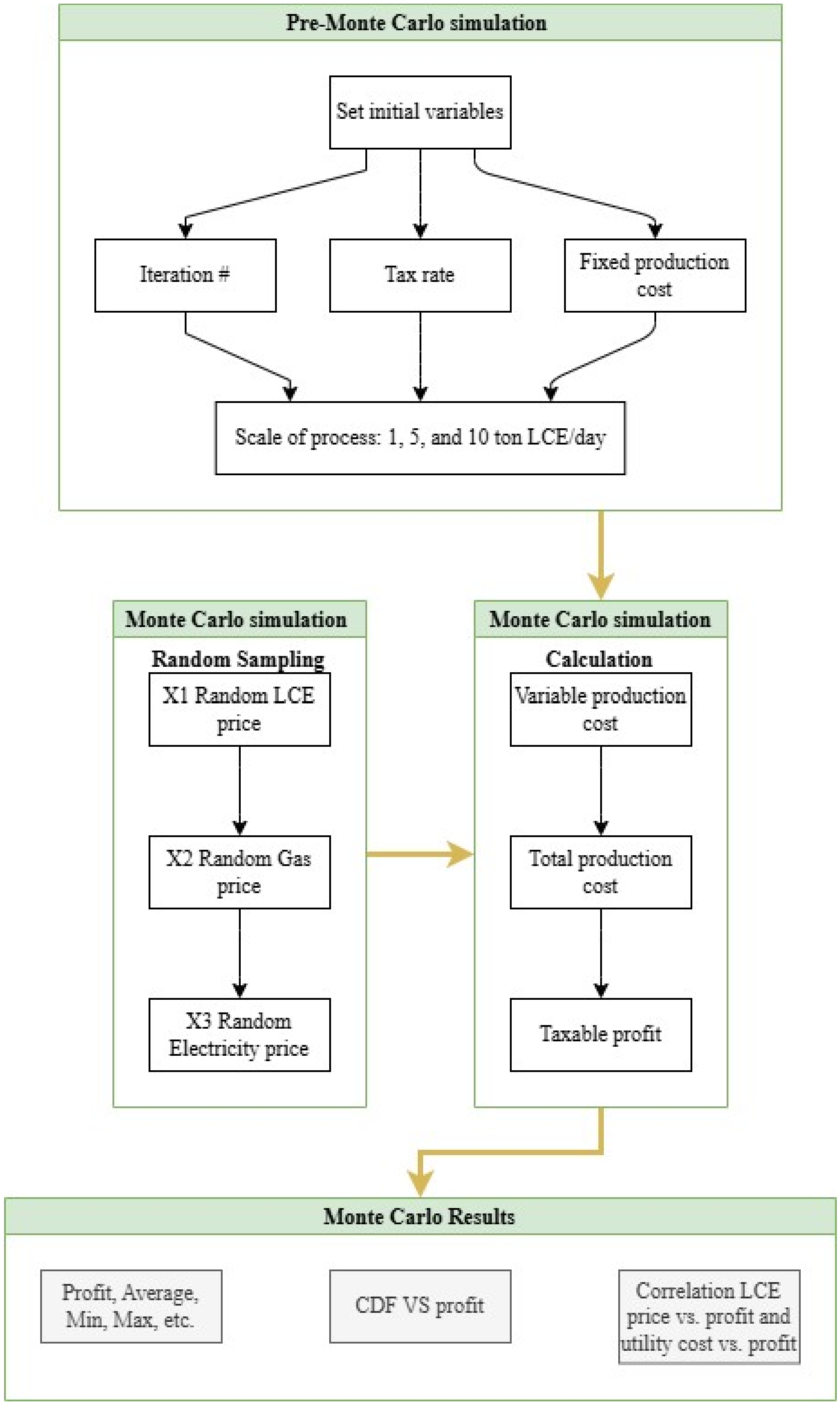


Fig. S1. Schematic workflow of the Monte Carlo simulation process.

LCA Results

Table S12- Impact categories associated with the conventional method, evaluated per 1 ton of LCE produced.

TRACI	Unit	Natural gas-Calcination	Sulfuric acid	Water	Direct Emission	Calcium Carbonate-Water leaching	Lime milk	Sulfuric acid	Direct Emission	Sodium carbonate-Total	Electricity-Total
Ozone depletion	kg CFC-11 eq	1.46E-04	2.87E-05	1.07E-07	0.00E+00	1.58E-05	1.74E-05	2.36E-06	0.00E+00	1.67E-04	5.0E-04
Global warming	kg CO2 eq	9.22E+02	1.98E+02	1.04E+00	8.50E+02	1.52E+02	2.67E+02	2.80E+01	1.04E+02	2.71E+03	8.2E+03
Smog	kg O3 eq	1.47E+01	1.62E+01	6.64E-02	0.00E+00	1.30E+01	6.13E+00	1.73E+00	0.00E+00	1.70E+02	2.3E+02
Acidification	kg SO2 eq	8.88E-01	1.56E+01	5.22E-03	0.00E+00	9.02E-01	3.74E-01	2.09E+00	0.00E+00	1.16E+01	2.7E+01
Eutrophication	kg N eq	2.45E-01	8.35E-01	3.14E-02	0.00E+00	3.64E-01	1.50E-01	1.09E-01	0.00E+00	1.33E+01	3.2E+01
Carcinogenics	CTUh	1.66E-05	4.57E-05	7.40E-07	0.00E+00	2.22E-05	2.70E-06	7.88E-06	0.00E+00	2.49E-04	5.0E-04
Non carcinogenics	CTUh	2.54E-05	7.28E-04	1.52E-06	0.00E+00	6.36E-05	9.48E-06	1.67E-05	0.00E+00	7.68E-04	1.5E-03
Respiratory effects	kg PM2.5 eq	1.13E-01	1.02E+00	7.72E-04	0.00E+00	1.36E-01	5.45E-02	1.46E-01	0.00E+00	2.11E+00	8.2E+00
Ecotoxicity	CTUe	1.96E+03	1.27E+04	2.33E+01	0.00E+00	4.55E+03	3.54E+02	1.57E+03	0.00E+00	5.07E+04	4.5E+04
Fossil fuel depletion	MJ surplus	2.40E+03	7.66E+02	1.47E+00	0.00E+00	2.56E+02	1.76E+02	1.81E+02	0.00E+00	3.21E+03	7.2E+03

Table S13- Impact categories associated with the DLE method, evaluated per 1 ton of LCE produced.

TRACI	Unit	NaOH	Natural gas-total	Direct Emission	Water	Lime	LCE	CO_2 Reactor	Electricity-Total
Ozone depletion	kg CFC-11 eq	5.6E-04	1.43E-04	0.00E+00	8.62E-07	9.5E-02	1.35E-04	1.94E-05	2.0E-04
Global warming	kg CO2 eq	9.4E+02	9.07E+02	6.70E+02	8.39E+00	6.0E+02	1.13E+03	4.94E+02	3.2E+03
Smog	kg O3 eq	6.2E+01	1.45E+01	0.00E+00	5.34E-01	9.2E+00	1.01E+02	7.14E+01	9.1E+01
Acidification	kg SO2 eq	5.1E+00	8.74E-01	0.00E+00	4.19E-02	6.3E-01	8.77E+00	1.43E+00	1.0E+01
Eutrophication	kg N eq	3.7E+00	2.41E-01	0.00E+00	2.53E-01	1.8E-01	1.24E+01	1.15E+00	1.2E+01
Carcinogenics	CTUh	9.7E-05	1.63E-05	0.00E+00	5.94E-06	4.8E-06	1.08E-04	4.73E-05	2.0E-04
Non carcinogenics	CTUh	3.4E-04	2.50E-05	0.00E+00	1.22E-05	3.3E-05	5.47E-04	1.08E-04	5.9E-04
Respiratory effects	kg PM2.5 eq	1.3E+00	1.11E-01	0.00E+00	6.20E-03	9.5E-02	1.45E+00	3.86E-01	3.2E+00
Ecotoxicity	CTUe	1.8E+04	1.93E+03	0.00E+00	1.87E+02	1.1E+03	2.83E+04	8.10E+03	1.8E+04
Fossil fuel depletion	MJ surplus	7.4E+02	2.36E+03	0.00E+00	1.18E+01	3.5E+02	1.35E+03	4.03E+02	2.8E+03

Table S14- Impact categories associated with the EDL method, evaluated per 1 ton of LCE produced.

TRACI	Unit	Soda ash	Water	Lime hydrate	LCE	Sulfuric acid	Hydrogen peroxide	Electrode	Electricity-Total
Ozone depletion	kg CFC-11 eq	1.1E-04	3.4E-08	9.4E-06	4.5E-06	2.3E-05	1.9E-05	2.7E-04	1.0E-04
Global warming	kg CO2 eq	1.7E+03	3.3E-01	1.4E+02	3.8E+01	1.9E+02	2.2E+02	4.0E+03	1.7E+03
Smog	kg O3 eq	1.1E+02	2.1E-02	3.3E+00	3.4E+00	2.9E+01	1.1E+01	2.0E+02	4.8E+01
Acidification	kg SO2 eq	7.4E+00	1.7E-03	2.0E-01	2.9E-01	9.3E+00	8.7E-01	2.4E+01	5.5E+00
Eutrophication	kg N eq	8.6E+00	1.0E-02	8.1E-02	4.1E-01	2.7E+00	6.8E-01	1.9E+01	6.6E+00
Carcinogenics	CTUh	1.6E-04	2.4E-07	1.5E-06	3.6E-06	7.2E-05	5.9E-05	4.0E-04	1.0E-04
Non carcinogenics	CTUh	4.9E-04	4.8E-07	5.1E-06	1.8E-05	1.3E-03	7.2E-05	2.2E-03	3.1E-04
Respiratory effects	kg PM2.5 eq	1.4E+00	2.5E-04	2.9E-02	4.8E-02	7.8E-01	2.0E-01	4.1E+00	1.7E+00
Ecotoxicity	CTUe	3.3E+04	7.4E+00	1.9E+02	9.4E+02	8.3E+04	4.4E+03	1.3E+05	9.2E+03
Fossil fuel depletion	MJ surplus	2.1E+03	4.7E-01	9.5E+01	4.5E+01	4.1E+02	3.5E+02	4.4E+03	1.5E+03

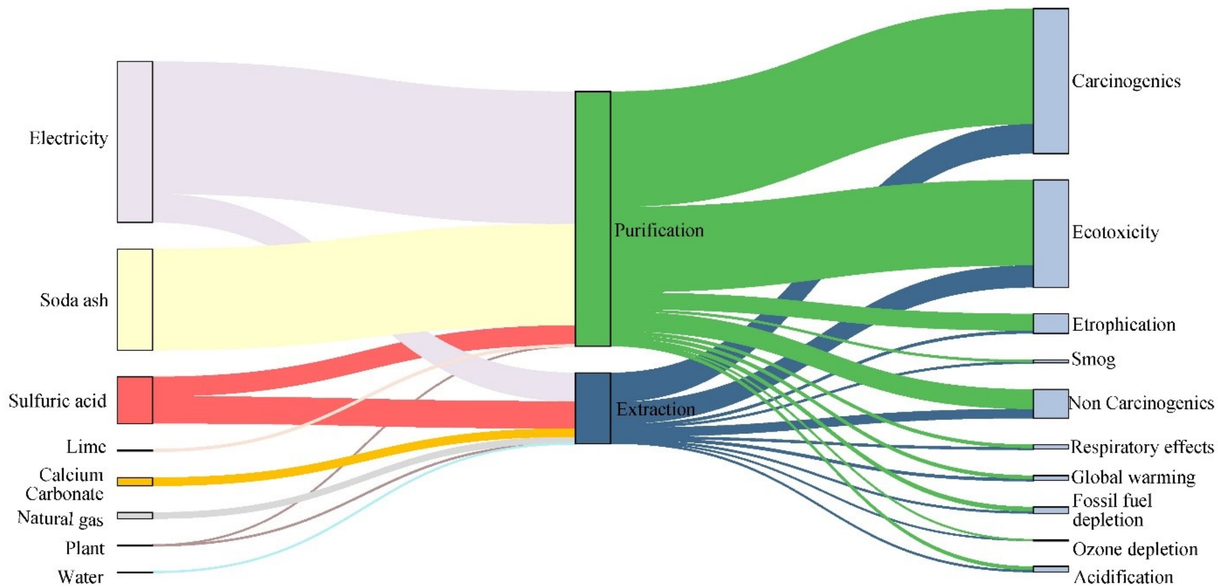


Fig S2. Normalized LCA results based on TRACI impact categories for 1-ton LCE production from the conventional method from hard rock.

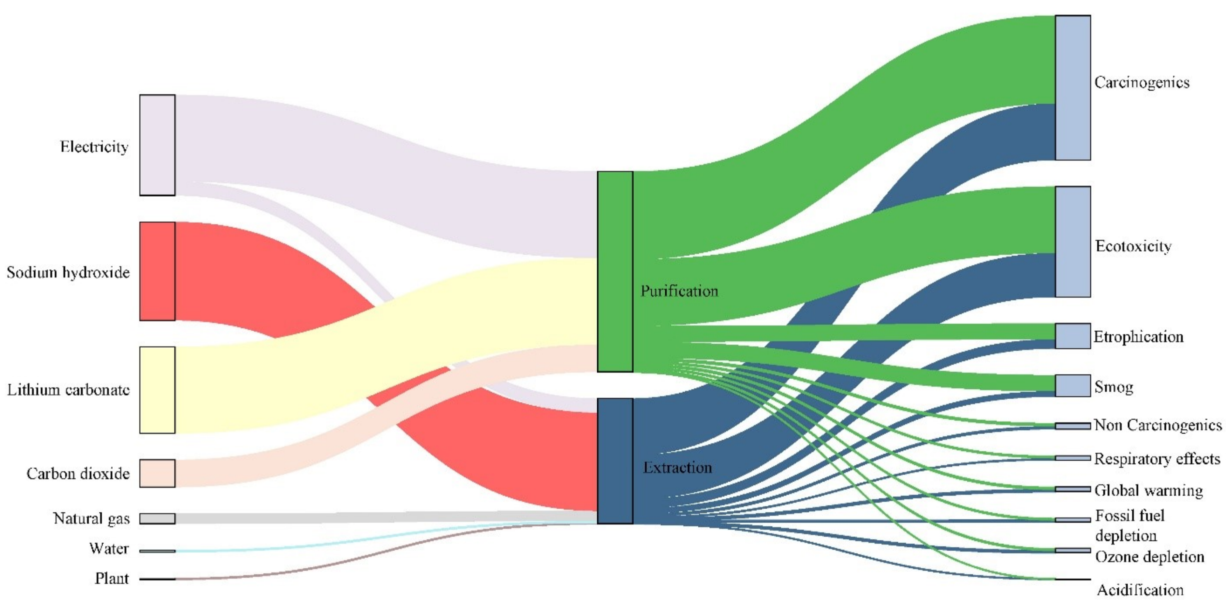


Fig S3. Normalized LCA results based on TRACI impact categories for 1-ton LCE production from the DLE method from hard rock.

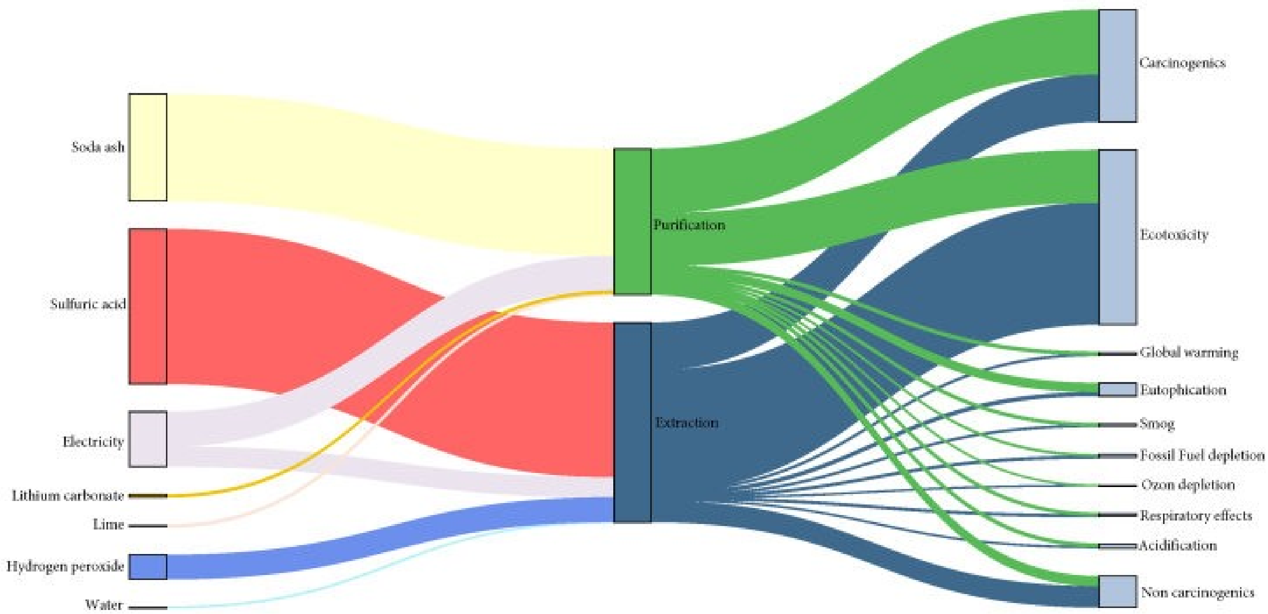


Fig S4. Normalized LCA results based on TRACI impact categories for 1-ton LCE production from the EDL method from hard rock.

TEA Results:

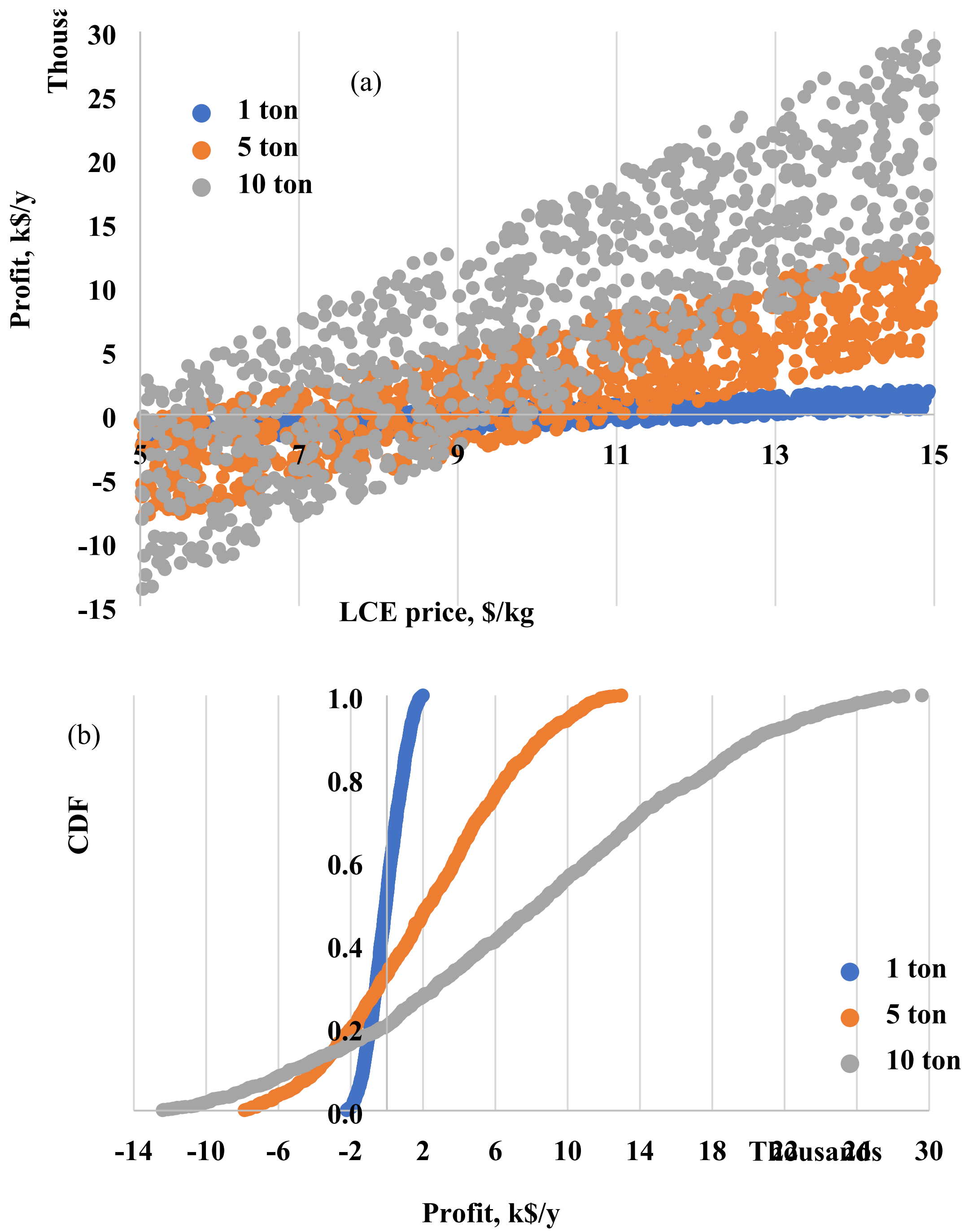


Fig. S5. Profit vs. LCE price for different production scales (a), and CDFs of annual profit for 1, 5, and 10 tons/day LCE production for the conventional method.

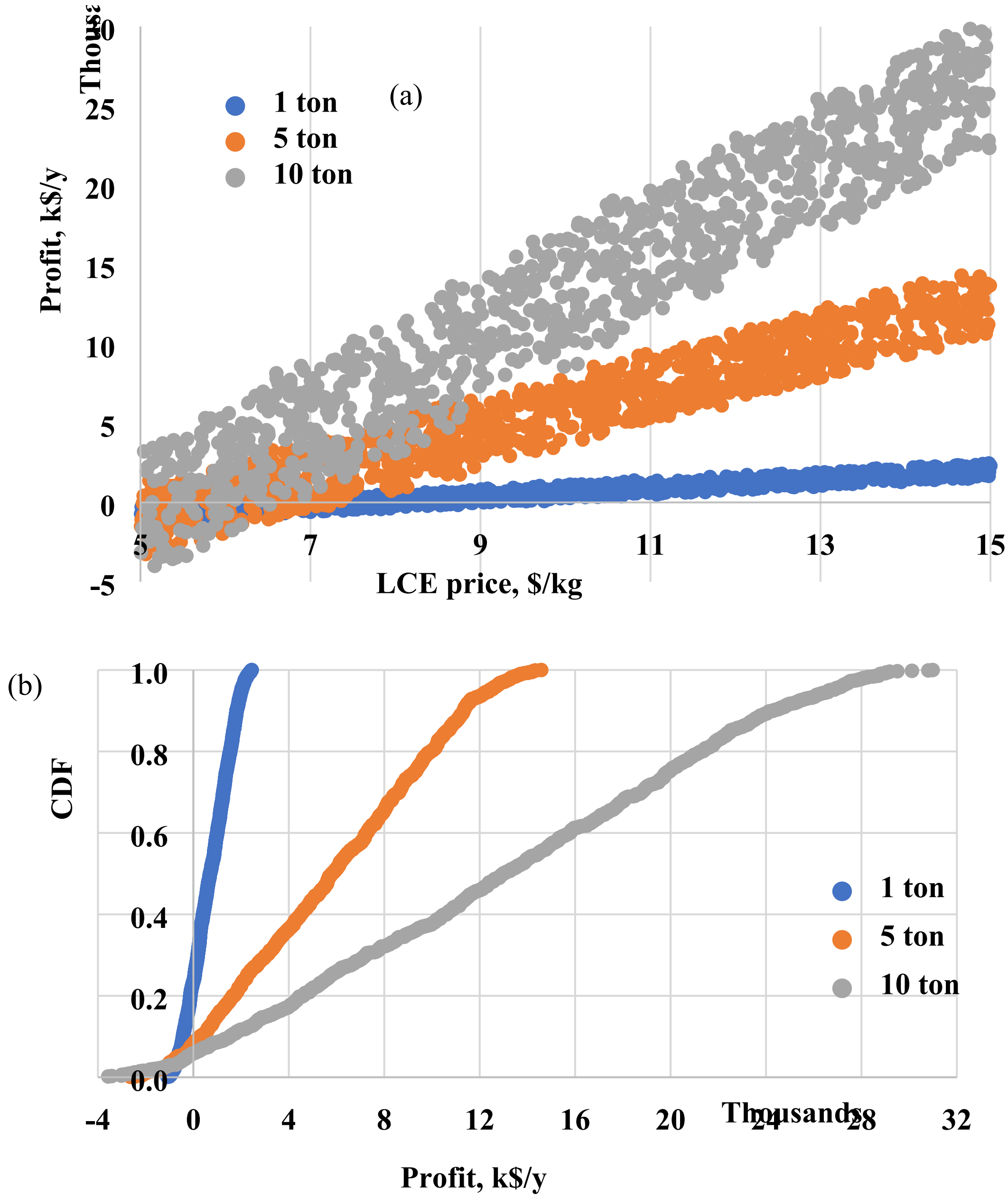
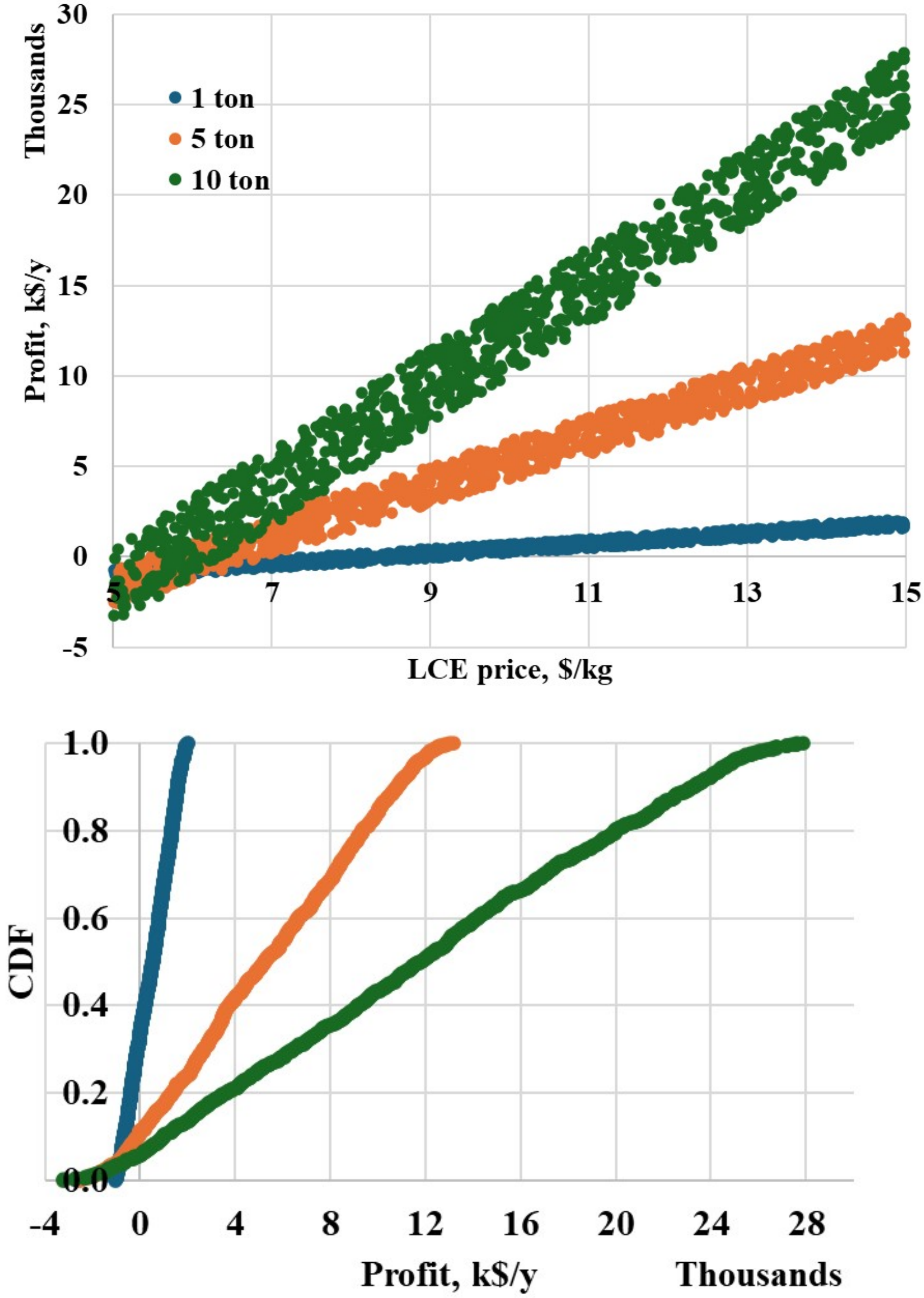


Fig. S6. Profit vs. LCE price for different production scales (a), and CDFs of annual profit for 1, 5, and 10 tons/day LCE production for the DLE method.

(a)



(b)

Fig. S7. Profit vs. LCE price for different production scales (a), and CDFs of annual profit for 1, 5, and 10 tons/day LCE production for the EDL method.

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