

Life-Cycle Analysis of Lithium Chemical Production in the United States

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Supplementary Information

1. Literature Review

Table S1 provides the list of different LCA studies on Li-chemical production from alternative sources (sedimentary clays and low Li-content brines) in the literature. For each study, we highlight the Li-chemical produced (battery-grade Li_2CO_3 or LiOH), major objectives, and key results of each study.

Table S1: List of studies on LCA of Li-chemical production from alternative sources

Ref.	Li-chemical produced	Summary of study
1	Li_2CO_3	Objectives: <ul style="list-style-type: none">To investigate the environmental impacts of Li-chemical production for clay-based sources in the Thacker Pass project Key results: <ul style="list-style-type: none">Clay-based GHG impacts are dominated by contributions from energy sources and soda ash
2	Li_2CO_3	Objectives: <ul style="list-style-type: none">To investigate the comparative environmental impacts of membrane distillation-crystallization – a major DLE technology – over current Li-chemical production from Salar brines using ex-ante LCA (based on inventory from Chile) Key results: <ul style="list-style-type: none">DLE-based Li-chemicals showed much higher GHG emissions than that for Salar brine-based production
3	Li_2CO_3 (Results are presented per weight of lithium carbonate equivalent)	Objectives: <ul style="list-style-type: none">To determine the life-cycle environmental impacts of Li-chemical production from various sources (Salar brines, spodumene ores, and DLE-based brines) Key results: <ul style="list-style-type: none">Major impact contributors: Energy sources for Li-chemical production from baseline grid mix and materials for solar energy-based Li-chemical productionDLE exhibits minimal water footprint as it recycles and reuses water throughout Li-chemical production, unlike conventional Li-chemical production from Salar brines and spodumene ores that demands substantial water use – a major concern in water-scarce regions

		<ul style="list-style-type: none"> DLE-based production has higher indirect impacts (e.g., embodied land use) due to upstream material-related contributions
4	Li ₂ CO ₃ and LiOH	<p>Objectives:</p> <ul style="list-style-type: none"> To determine the life-cycle environmental impacts and costs of Li-chemical production from geothermal brines <p>Key results:</p> <ul style="list-style-type: none"> Major impact contributors: Soda ash (Na₂CO₃) and lime (CaO) due to CO₂ release during their production), and sorbent synthesis Geothermal brine-based Li-chemicals show a lower GHG footprint than those from Salar brines and spodumene rocks
5	Li ₂ CO ₃	<p>Objectives:</p> <ul style="list-style-type: none"> To investigate the environmental impacts of Li-chemical production from geothermal brines in the U.S. and Germany <p>Key results:</p> <ul style="list-style-type: none"> GHG impacts of Li-chemical production from geothermal brines vary significantly over a wide range Comparatively, these impacts are higher for geothermal brine-based production over that from Salar brine counterparts

2. Details on Li-Chemical Production Projects

We have previously published extensive reports on the various individual projects dealing with Li-chemical production from alternative resources (clays and low Li-content brines or LLCBs).^{6,7} Here, we provide the basic details for each project from these reports.^{6,7} Readers are encouraged to go through our reports for further information on each project (including those that are currently under exploration but do not have any production feasibility study and are thus not considered in this analysis).^{6,7} In addition, readers can also check the preliminary feasibility study reports for each of the projects for more details.⁸⁻¹²

2.1. Thacker Pass

The Thacker Pass project is considered the biggest Li resource in the United States. It is located in the McDermitt caldera in Humboldt County, NV, encompassing 42.36 km². Per the company operating the project (Lithium Americas), the resource comprises alternative layers of claystone and volcanic ash. The claystone contains two Li-containing minerals:

- a. Smectite at shallow depths (with Li-content ranging from 2,000 to 4,000 ppm); and
- b. Illite at further depths (with Li-content ranging from 4,000 to 9,000 ppm)

Overall, the resource base contains Li up to 120 m, along with other minerals such as quartz, dolomite, fluorite, and feldspar.

2.2. Tonopah Lithium

American Lithium Corporation is implementing the Tonopah Lithium Claims (TLC) project over 33.43 km² in Tonopah County, NV. The resource has a weak Li bonding with clay minerals, with the company claiming to use the gravity separation method to upgrade the Li content of the resource from 1,300 ppm to 2,200 ppm.

2.3. *Ogden East and Ogden West*

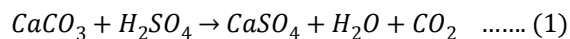
Compass Minerals has been working on developing the Li-brine resource base at Ogden in Great Salt Lake, UT. The brine is located in the northern arm of the lake and will be evaporated using a combination of solar energy and other fossil sources to produce a combination of Li-chemicals and other chemicals (mainly magnesium chloride, sulfates of potash, and other salts). While the Li-content in the ambient brine is 55-60 mg/liter, it will be treated using evaporation to increase the Li-content (up to 200-1,600 mg/liter, depending on the evaporation time) for subsequent processing via direct lithium extraction (DLE) to produce Li-chemicals.

2.4. *Smackover Arkansas and SW Arkansas*

Smackover Arkansas and South-West (SW) Arkansas are both under development by Standard Lithium Inc. The projects involve Li-chemical production from brines via the DLE route, with other co-products also being produced from these brines (bromine). The brines are located in a dominant limestone and dolomite geology formation with high calcium carbonate content and low silica and transition element contents. Standard Lithium plans to use its patented LiSTR technology for Li-chemical production via adsorption.

3. **Process Carbon Dioxide Emissions: Calculations**

In this study, clay-based projects (projects P1 and P2 in the manuscript) use sulfuric acid (H₂SO₄) as the leaching agent (see Table 1 of the manuscript).^{9,13} This is because the clay resource is basic in nature as it contains multiple alkaline elements, such as lithium (Li), magnesium (Mg), calcium (Ca), potassium (K), rubidium (Rb), and cesium (Cs).^{7,9,13} However, the company literature associated with these two projects indicates that the amount of H₂SO₄ used is more than that needed to remove these alkaline elements from the clays per chemical stoichiometry.^{9,13} Hence, the company reports indicate that limestone (CaCO₃) is added to neutralize this remaining unreacted acid.^{9,13} CaCO₃ is expected to neutralize H₂SO₄ by reacting with it to produce calcium sulfate (CaSO₄), water (H₂O), and carbon dioxide (CO₂), as shown in the reaction below (Reaction 1). This CO₂ gas is a non-combustion process emission that must be considered for a robust estimation of GHG impacts of Li-chemical production from clays.



To calculate the amount of CO₂ emitted during Li-chemical production from clays, we assume that limestone is used only to neutralize H₂SO₄ and is consumed fully in this neutralizing reaction. Per Reaction 1, one mole of CaCO₃ produces one mole of CO₂. Table S2 shows the different parameters associated with the calculation of process CO₂ emissions for the two clay-based

projects (P1 and P2). Note that the amount of CaCO₃ used in both projects is based on company literature, ^{9,13} and that both clay-based projects produce battery-grade Li₂CO₃ as output. The calculations are based on the equation given below (Equation E1).

$$CO_2 \text{ emissions} \left(\frac{MT CO_2}{MT Li_2CO_3} \right) = \text{Input qty of } CaCO_3 \times \frac{\text{Molar mass of } CO_2}{\text{Molar mass of } CaCO_3} \dots(E1)$$

Table S2: Process CO₂ emissions for clay-based projects – Calculation steps

Parameters	Sub-parameters	Variables in Equation E1	Values	Units
Molar mass	Limestone (CaCO ₃)	<i>Molar mass of CaCO₃</i>	100.09	g/mol
	Carbon dioxide (CO ₂)	<i>Molar mass of CO₂</i>	44.01	g/mol
Input quantities: CaCO ₃	For project P1	<i>Input qty of CaCO₃</i>	6.52	MT/MT Li ₂ CO ₃
	For project P2		4.16	MT/MT Li ₂ CO ₃
Output emissions: CO ₂	For project P1	<i>CO₂ emissions</i> $\left(\frac{MT CO_2}{MT Li_2CO_3} \right)$	2.87	MT/MT Li ₂ CO ₃
	For project P2		1.83	MT/MT Li ₂ CO ₃
MT: metric ton mol: mole				

Unlike clay-based projects, brine-based projects do not use limestone (CaCO₃). Also, for all projects, soda ash (Na₂CO₃) is used in the softening and concentration steps of low Li-content brine (LLCB)-based projects and in the Li₂CO₃ production step for clay-based projects (see Figure 2(a-b) in the manuscript). The reactions in these steps do not involve the generation of any CO₂ as process emissions. Thus, the sole process CO₂ emissions associated with Li-chemical production from conventional sources are those calculated and provided in Table S2 here.

4. NERC Regions: A Description

The North American Electric Reliability Corporation (NERC) is a non-profit international regulatory authority responsible for safe, reliable, and secure electricity transmission from the centers of production to those of distribution (for final supply). ¹⁴ NERC is the sole transmission authority across the entire United States, Canada, and the northern part of Baja California province in Mexico. NERC serves nearly 400 million users across North America and is the Electric Reliability Organization (ERO) for the continent. ¹⁴ NERC comprises six regional entities of similar size and complexity ¹⁴:

- a. Midwest Reliability Organization (MRO)
- b. Northeast Power Coordinating Council (NPCC)

- c. Reliability First (RF)
- d. SERC Reliability Corporation (SERC)
- e. Texas Reliability Entity (TRE); and
- f. Western Electricity Coordinating Council (WECC)

Figure S1 shows the regions serviced by each of the six entities constituting NERC. ¹⁴

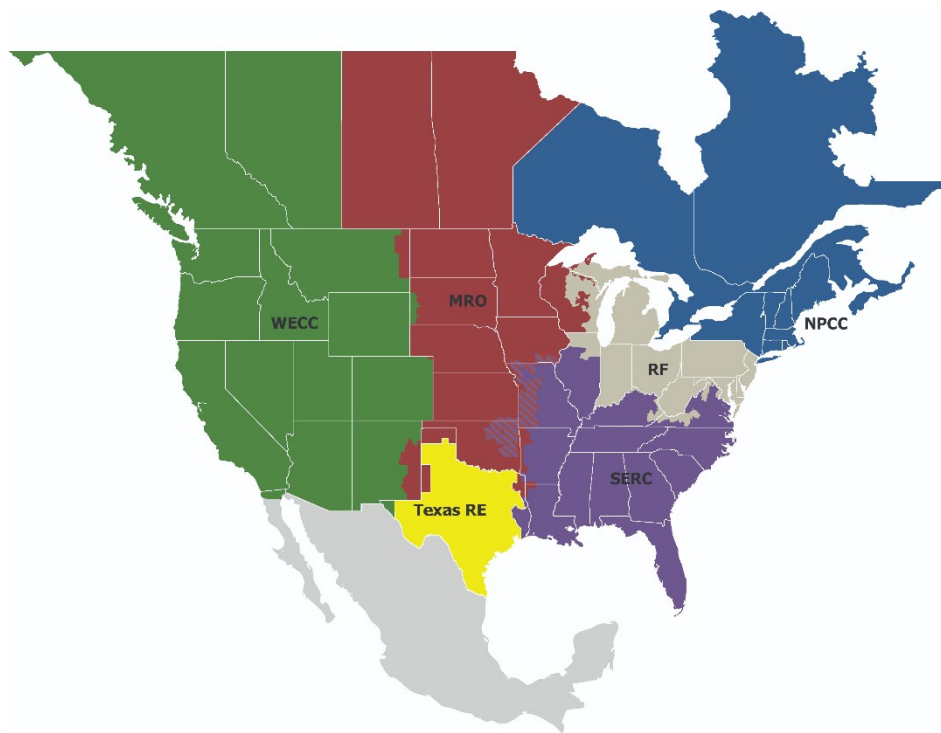


Figure S1: A map showing different regional entities that comprise the NERC

However, these entities have been created at different times, and the GREET model uses an older mix of entities constituting the NERC, ¹⁵ as shown in Figure S2, that was used till 2019, based on data from the U.S. Environmental Protection Agency (EPA). In this share, the entities comprising NERC include:

- a. Alaska Systems Coordinating Council (ASCC)
- b. Florida Reliability Coordinating Council (FRCC)
- c. Hawaii Interisland Cable Company (HICC)
- d. Midwest Reliability Organization (MRO)
- e. Northeast Power Coordinating Council (NPCC)
- f. Reliability First Corporation (RFC)
- g. SERC Reliability Corporation (SERC)
- h. Southwest Power Pool (SPP)
- i. Texas Reliability Entity (TRE)

j. Western Electricity Coordinating Council (WECC)

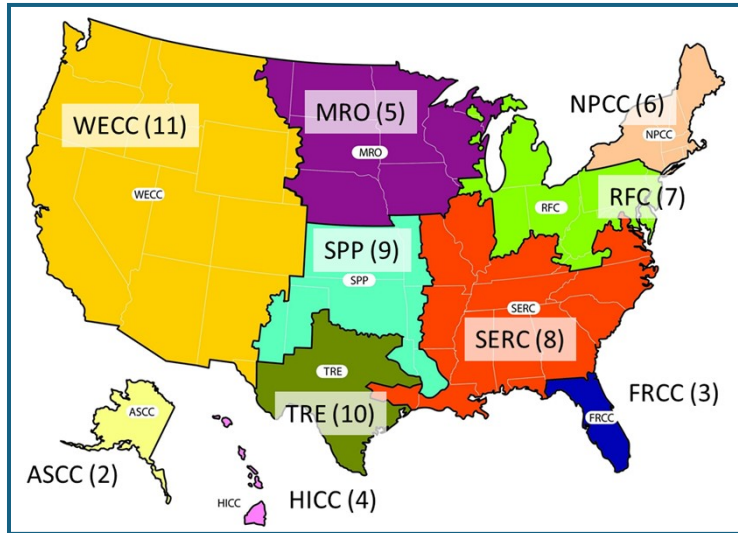


Figure S2: A map of regional entities comprising the NERC per GREET ¹⁵

To avoid any complications, we use the GREET-based NERC classification for the regions serviced by different NERC entities. Table S3 shows the electric grid mix for these different entities per the GREET model, ¹⁵ while Table S4 shows the NERC region that corresponds to the locations of different projects studied in this analysis. This corresponding NERC region is assumed to supply all the electricity needs met through external electricity supply for the concerned project.

Table S3: Electric grid mix of different NERC regions

Energy source	NERC Regional Entities (Share (%) of different energy sources in electric grid)									
	ASCC	FRCC	HICC	MRO	NPCC	RFC	SERC	SPP	TRE	WECC
Coal	11.4	10.4	11.8	36.6	0.7	18.3	25.5	26.2	13.9	15.9
Natural gas	46.7	71.3	0.0	30.9	50.5	43.9	34.9	23.8	44.5	30.7
Oil	13.7	0.2	67.0	0.2	0.2	0.1	0.2	0.1	0.1	0.1
Nuclear	0.0	12.5	0.0	14.2	23.6	31.1	31.6	5.7	10.1	7.9
Hydro	25.6	0.8	1.3	1.4	16.0	1.3	4.6	5.5	0.2	22.9
Biomass	0.6	0.2	3.1	0.2	1.1	0.1	0.4	0.0	0.0	0.4
Solar PV	0.0	4.2	5.5	0.9	2.0	1.2	2.8	0.3	4.7	8.6
Wind	2.0	0.0	7.2	15.3	4.0	3.5	0.0	38.4	26.4	11.1
Geothermal	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1
Others	0.0	0.6	2.2	0.3	1.9	0.4	0.1	0.1	0.0	0.3

Table S4: NERC regions for different projects studied in this analysis

Project Code	Project and Location	NERC region corresponding to the
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(in this study)		project's location
P1	Thacker Pass, NV	WECC
P2	Tonopah Lithium, NV	WECC
P3	Ogden East, UT	WECC
P4	Smackover Arkansas, AR	SERC
P5	Ogden West, UT	WECC
P6	South-West Arkansas, AR	SERC

5. Material Composition of Lithium-Ion Batteries

Table S5 shows the bill-of-materials or material composition of all the cathode chemistries considered for lithium-ion batteries (LIBs) in this analysis (discussed in the manuscript) per the GREET model.

Table S5: Material composition of LIBs with different cathode chemistries

Materials	Cathode Chemistry (Values in %)				
	NMC111	LFP	NMC622	NMC811	NMC532
Cathode	28.00	27.80	26.55	25.02	26.76
Graphite/Carbon	15.80	14.32	16.65	17.51	16.46
Binder	0.89	0.86	0.88	0.87	0.88
Copper	8.10	9.77	7.91	7.74	7.94
Aluminum Sheet (Automotive)	12.03	12.63	12.11	12.20	12.10
Electrolyte: LiPF ₆	1.05	1.20	1.04	1.03	1.04
Electrolyte: Ethylene Carbonate	2.92	3.35	2.90	2.89	2.90
Electrolyte: Dimethyl Carbonate	2.92	3.35	2.90	2.89	2.90
Plastic: Polypropylene	1.70	1.98	1.67	1.64	1.68
Plastic: Polymer	0.02	0.03	0.02	0.02	0.02
Plastic: Polyethylene Terephthalate	0.26	0.28	0.27	0.27	0.26
Steel	16.10	14.83	16.61	17.13	16.59
Stainless Steel	6.51	6.23	6.67	6.83	6.66
Rubber	0.01	0.01	0.01	0.01	0.01
Thermal Insulation	0.36	0.33	0.37	0.38	0.37
Coolant: Glycol	2.26	2.17	2.32	2.38	2.31
Electronic Parts	1.07	0.86	1.12	1.19	1.12
Battery weight (kg)	438.2	537.5	416.0	394.2	421.1

6. Life-Cycle Impacts of Lithium-Ion Batteries: Contribution from Li-Chemicals

Figure S3 shows the life-cycle GHG impacts of Li-ion batteries when sourcing Li-chemicals from both conventional (Salar brines and spodumene ores) and alternative sources (clays and LLCBs)

of Li-chemical production. Additionally, Table S6 provides the baseline life-cycle GHG impacts of different Li-ion batteries upon using Li-chemicals from conventional resources.

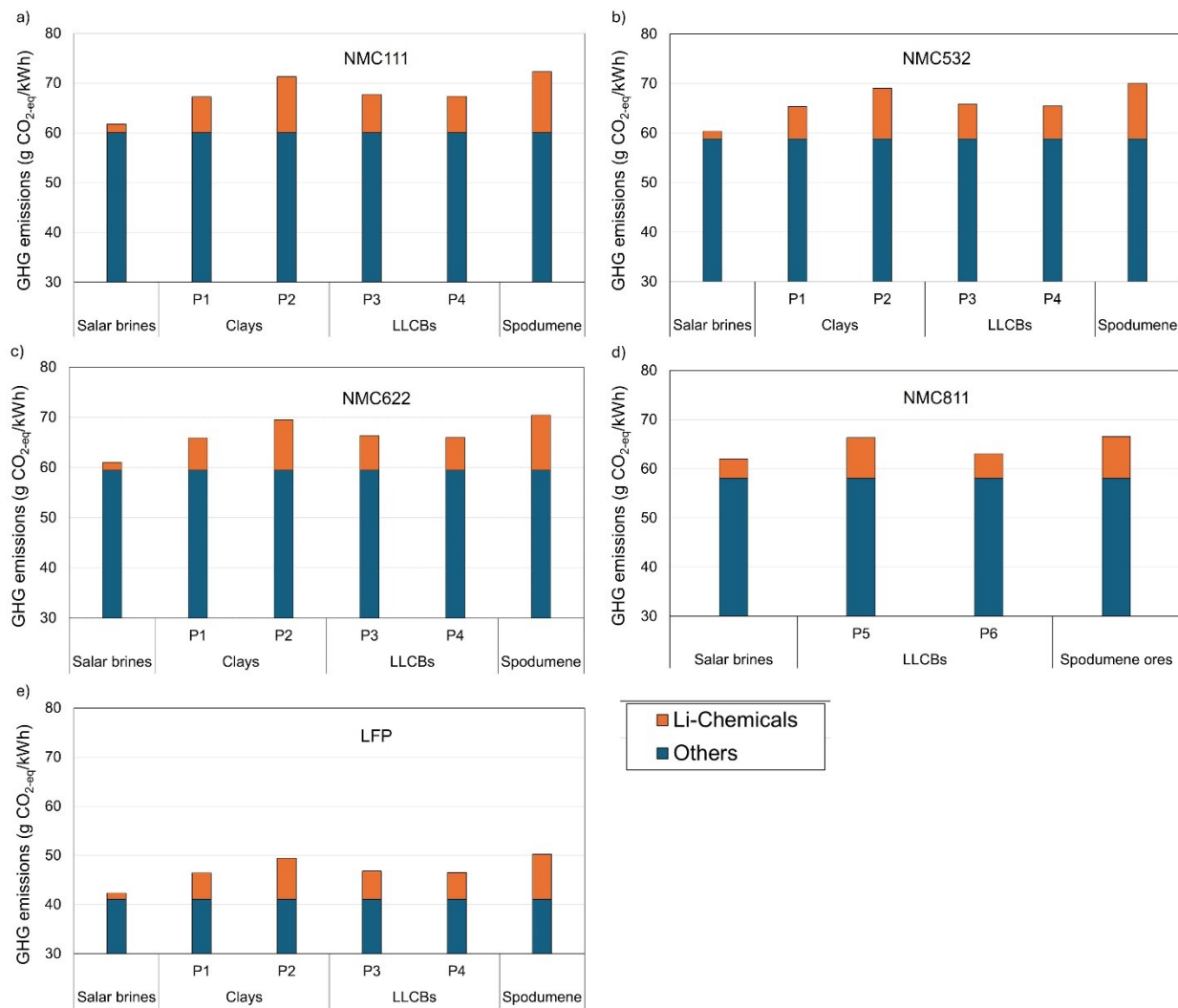


Figure S3: Life-cycle GHG impacts of LIBs based on Li-chemical sourcing from conventional and alternative production sources: (a) NMC111; (b) NMC532; (c) NMC622; (d) NMC811; and (e) LFP

Table S6: Life-cycle GHG impacts of LIBs based on Li-chemical sourcing from conventional sources (Salar brines and spodumene ores)

LIB Chemistry (Cathode)	GHG Impacts (g CO _{2-eq} /kWh)	
	Salar brines	Spodumene ores
NMC111	62	72
NMC532	60	70

NMC622	61	70
NMC811	62	67
LFP	42	50

7. Carbon Capture & Storage: Details for This Analysis

The GREET model considers the use of carbon capture and sequestration (CCS) technologies to capture CO₂ generated during the fermentation process in corn ethanol plants.^{15,16} The CO₂ generated from this process is highly pure and does not require any additional energy to be purified further; it is directly captured and sequestered (with compression) under the CCS process. About 97-98% of the fermentation CO₂ can be captured/sequestered, with the process consuming ~175-200 kWh/US short ton of CO₂ input.¹⁷ GREET assumes the CO₂ capture efficiency rate of 97.5% and an associated electricity consumption of 180 kWh/metric ton CO₂.^{15,16}

We assume the use of this CCS technology for the capture and sequestration of process CO₂ emissions generated via chemical reactions during the life-cycle of Li-chemical production. These reactions include:

- a. Neutralization reaction during Li₂CO₃ production from clays;
- b. Production of lime (CaO) from limestone (CaCO₃); and
- c. Production of sodium carbonate (Na₂CO₃) from sodium bicarbonate (NaHCO₃)

Process CO₂ emissions for these chemical reactions are either obtained from the GREET model (CaO and Na₂CO₃) or, alternatively, computed using the GREET model (for clay-based Li₂CO₃ production). Since these emissions are generated only from chemical reactions and no other process emissions of other gases are generated during these reactions (apart from CO₂), we assume that the CO₂ generated from these reactions is highly pure and does not need further purification process. Hence, we assume that the CCS used for ethanol fermentation is applicable for these three chemical reactions, with only compression, capture, and sequestration processes used without any purification process.

8. Sensitivity Analysis: A Summation

Figure S4 shows the life-cycle impacts of Li-chemical production under both baseline and the combination of all alternative scenarios covered under sensitivity analysis (i.e., use of renewables-based electricity and the use of CCS for all process emissions in Li₂CO₃, CaO, and Na₂CO₃ production).

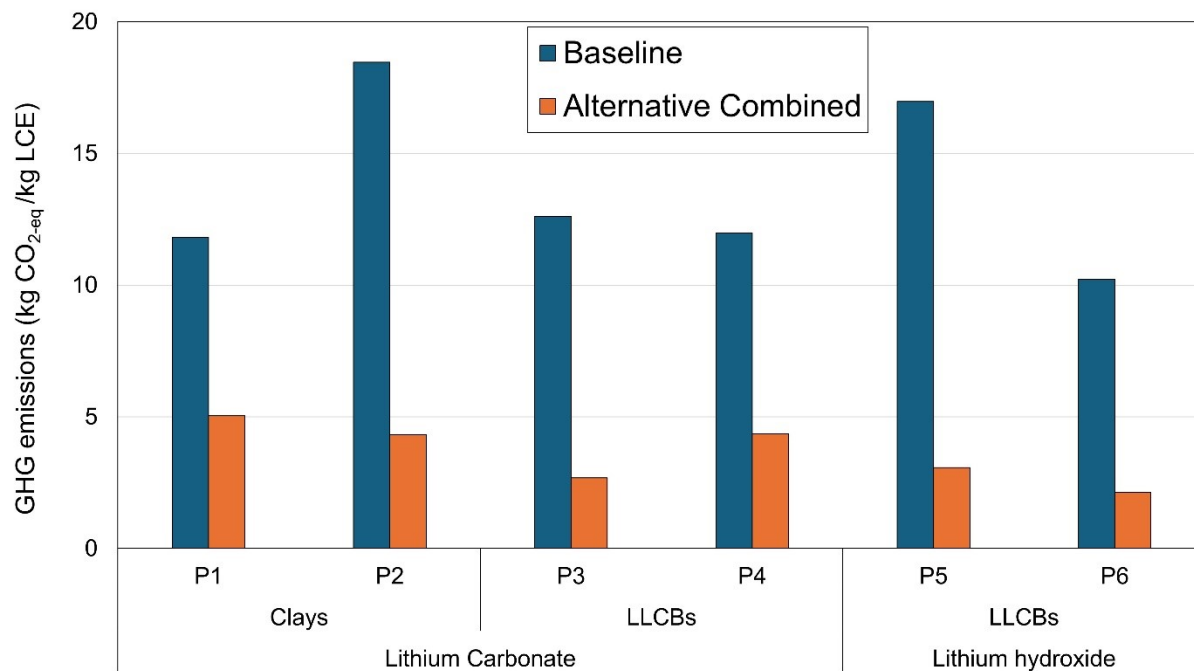


Figure S4: Life-cycle GHG impacts of Li-chemical production: A comparison of baseline and the combination of all alternative scenarios covered in the sensitivity analyses

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