Life Cycle Assessment of Lithium Carbonate Production: Comparing Sedimentary Deposits

Shayan Khakmardan[a], Wen Li[a,*], Damien Giurco[b], Robert H. Crawford[c]

[a] *Department of Mechanical Engineering, The University of Melbourne, Melbourne, VIC 3010, Australia*

[b] *Institute for Sustainable Futures, University of Technology Sydney, Ultimo, NSW 2007, Australia*

[c] *Faculty of Architecture, Building and Planning, The University of Melbourne, Melbourne, VIC 3010, Australia*

* *Corresponding author*

Abstract

Lithium sedimentary deposits which were once considered impractical to extract, have become increasingly attractive for exploiting and producing high-quality lithium compounds, due to the surge in demand for batteries and from other markets. However, potential environmental impacts are yet to be evaluated for this emerging lithium production route. Therefore, this paper presents a comparative Life Cycle Assessment study for three prominent and near-to-opening lithium clay projects globally: Sonora Mexico, Falchani Peru, and Thacker Pass USA. Specifically, this study used literature, statistical data, expert interviews, and technical reports to develop cradle-to-gate models covering the mining to refining processes. The results suggest that lithium carbonate production in the Thacker Pass project has higher impacts than the two other selected sedimentary projects. Additionally, the impact categories of the Sonora project are significantly influenced by the source of electricity. The sensitivity analysis highlights the pivotal role of a transition to clean energy sources for these emerging lithium production routes. Especially, the Thacker Pass project would benefit significantly from on-site sulfuric acid production and power generation to reduce the associated environmental impacts.

Keywords: Hectorite; Lithium Carbonate; Life Cycle Assessment; Sedimentary Deposits; Lithium Clay

1. Introduction

Lithium plays a pivotal role in shaping the future of the global transportation and energy sectors owing to its use in lithium-ion batteries (LIBs) for electric vehicles and energy storage systems [1]. In 2017, lithium consumption in LIBs accounted for only 46% of global lithium demand, but it is projected to reach 95% by 2030 [2]. Azevedo et al. suggest that the global lithium demand in 2021, equivalent to 500,000 tonnes of lithium carbonate, is expected to reach approximately 4 million tonnes by 2030, indicating an eightfold growth [3]. In the current landscape, the economic extraction of lithium is predominantly concentrated in a few regions, drawing from pegmatite and brine resources [4]. Relying just on two resource types in specific regions creates potential supply risks [1, 5].

In fact, lithium is the 25th most abundant element within the Earth's crust, dispersed among 123 distinct minerals, which can be categorised into four major groups: brines, igneous (e.g. pegmatite), sedimentary, and unconventional resources [7-9]. Apart from pegmatite and brine, sedimentary deposits such as lithium clays, hectorite, lithium-bearing tuffs and zeolites constitute a distinct portion (almost 10%) of the global lithium reserves [6]. Previously, their commercial viability has been hindered by challenges such as lower ore grades and more intricate processing methods compared to the more established pegmatites and brine sources [1, 5]. Due to the surge in demand for batteries and the dramatic upswing in lithium prices, these once-considered impractical resources have become increasingly attractive for development to produce high-quality lithium compounds.

Apart from the economic considerations, environmental concerns regarding lithium production have prompted assessments of different routes in recent years. Life cycle assessment (LCA) of lithium carbonate production from conventional resources (i.e., brine and pegmatite) have been conducted over the past decades and have reached various results as summarised in Table 1. The climate change impact of producing 1 kg of lithium carbonate in terms of greenhouse gas emissions exhibits a wide range of values in previous studies owing to the differences in study scope, completeness of the processes, modelling methods, and data sources. There are ongoing efforts to improve the accuracy and quality of LCA results for these established lithium production routes [7]. More importantly, the environmental feasibility has yet to be evaluated for emerging lithium production routes, such as sedimentary deposits. Conducting LCA for future projects, known as prospective LCA, facilitates the identification and quantification of their environmental impacts throughout their lifespan [8].

Table 1. Lithium carbonate battery grade global warming potential impact category

Region	Author	Resource	Value	Unit	Year
Chile	Schenker et al. [9]	Brine	3.4	kg CO_2eq/kg Li_2CO_3	2022
Argentina	Schenker et al. [9]	Brine	7.7	kg CO_2eq/kg Li_2CO_3	2022
Argentina	Schenker et al. [9]	Brine	7.4	kg CO_2eq/kg Li_2CO_3	2022
Argentina	Schenker et al. [9]	Brine	8.0	kg CO_2eq/kg Li_2CO_3	2022
Chile	Kelly et al. [10]	Brine	3.1	kg CO_2eq/kg Li_2CO_3	2021
Australia	Kelly et al. [10]	Pegmatite	20.4	kg CO_2eq/kg Li_2CO_3	2021
Australia	Jiang et al. [11]	Pegmatite	15.7	kg CO_2eq/kg Li_2CO_3	2020
Argentina	Jiang et al. [11]	Brine	0.3	kg CO_2eq/kg Li_2CO_3	2020
Chile	Stamp et al. [12]	Brine	2.0	kg CO_2eq/kg Li_2CO_3	2012
Chile	Ecoinvent [13, 14]	Brine	2.1	kg CO_2eq/kg Li_2CO_3	2011
Australia	Ecoinvent [13, 14]	Pegmatite	10.7	kg CO_2eq/kg Li_2CO_3	2011

Therefore, this paper presents a comparative LCA of the sedimentary deposits as emerging resources with variations in input materials to address almost all future sedimentary projects except zeolite resources, which can potentially enter the market before 2025. According to the Ganfeng and American Lithium Corp, the three most feasible sedimentary ones have been selected: Sonora (Mexico), Falchani (Peru), and Thacker Pass (USA) [15-19]. These three projects have the potential to produce around 17-20% of the current lithium carbonate equivalent capacity of the world, which shows their importance for the future market [20].

The rest of this paper is structured as follows: Section 2 focuses on the technology and the state-of-the-art of the three selected projects for the lithium extraction and lithium carbonate production from sedimentary deposits; Section 3 presents the methods and results of the comparative LCA of these projects, guided by the ISO 14044:2006 standard; Section 4 summarises the findings of this research and provides suggestions for future endeavours.

2. Sedimentary production routes and the selected projects

The process flow of the lithium carbonate production from sedimentary deposits can be generalised into three stages: mining, mineral processing (i.e., comminution and beneficiation), and purification (i.e., extraction and refining). Owing to the differences in ore grade and geological structure, the three selected projects feature different processing and purification technologies, as summarised in figure 1 and elaborated in the following subsections.

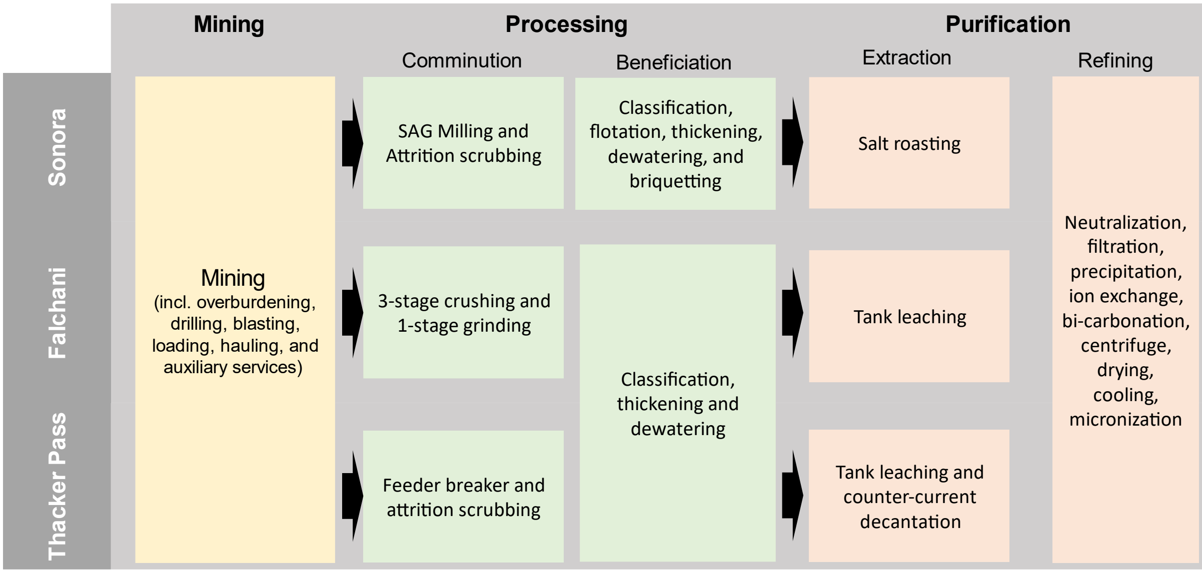


Figure 1. System flowsheet differences comparison

2.1. Sonora Project, Mexico

The Sonora lithium carbonate production project involves utilising a Hectorite deposit with an average grade of 0.35% lithium content. The mining process initiates with overburden removal, followed by drilling and blasting operations guided by the predetermined mine plans. Subsequently, hydraulic shovels and dump trucks are employed to carry out the tasks of loading and hauling, facilitating primary fragmentation resulting from the blasting in this open-pit operation. The ore is then transported to a run-of-mine (ROM) bin, while the waste materials are conveyed to a designated waste dump [21, 22].

Afterwards, the ore is directly fed into a semi-autogenous (SAG) mill, where it undergoes comminution facilitated by the introduction of grinding media. The comminuted product is subsequently passed through a vibrating screen. Due to the relative hardness and stiffness of the siliceous gangue material, it goes to the oversize fraction of the screening process and is directed to the tailings dam, while the undersize fraction proceeds to a hydrocyclone for classification of the undersized fraction, producing an overflowing stream that enters the flotation processing unit to separate calcite and an underflow stream that is recirculated within the milling plant. Following flotation, the concentrate is initially thickened by adding a flocculant reagent and subsequently filtered to obtain an acceptable moisture content. This concentrate, with an average grade of 0.65% Li, is then mixed and blended with gypsum and limestone in a pugmill. The resulting mixture is fed into a briquetting machine to produce Hectorite briquettes, which are subsequently subjected to salt roasting [21, 22].

After reaching the desired dryness level, the briquettes are introduced to a rotary kiln for salt roasting. Following salt roasting, the briquettes are processed in a ball mill, and the resulting particle size is checked using hydrocyclones. By introducing water alone, the lithium contained in the briquettes is dissolved. The addition of flocculants in thickeners then thickens the resulting slurry. Subsequently, the slurry is directed to a belt filter to separate the solid tails from the lithium-containing solution. In the subsequent step, sodium carbonate is added, and the temperature of the pregnant leach solution (PLS) is raised to approximately 80 degrees Celsius to facilitate the precipitation of calcium impurities in the form of calcium carbonate. In the next step, after rapidly cooling the solution to around 10 degrees Celsius and introducing aluminium sulphate, a crystallisation process occurs, forming Glauber's salt along with precipitated rubidium and caesium compounds. A centrifuge is employed to separate and isolate these compounds. The remaining solution undergoes three stages of ion exchange to achieve primary purification, specifically targeting the removal of fluorine, calcium, magnesium, and boron ions. pH adjustment is carried out during each ion exchange step, and specific chelating resins, both cationic and anionic, are utilised. As a result of these processes, the lithium-containing solution attains an acceptable purity level. At this stage, the primary lithium carbonate precipitates upon adding soda ash and raising the temperature to approximately 95 degrees Celsius. The precipitated lithium carbonate is subsequently filtered with the assistance of a diatomaceous filter aid and advanced to the bicarbonate step. Here, by introducing carbon dioxide and resolving the lithium carbonate as soluble lithium bicarbonate, the solution undergoes another round of ion exchange to further enhance the purity to meet battery-grade quality standards by removing trace amounts of calcium and magnesium. The production of battery-grade lithium carbonate is achieved by elevating the temperature and adding soda ash. However, before packaging, the product undergoes additional stages of drying and micronisation [21, 22].

2.2. Falchani Project, Peru

The mining process employed at Falchani exhibits notable similarities to the Sonora and is also open-pit, with major discrepancies in the mine's structural geology, mineral composition, and the waste to ore ratio. These factors contribute to the utilisation of varying quantities of consumables per tonne of extracted ore. The lithium mineralisation in this mine predominantly occurs within a lithium-rich tuff, and its average lithium content is 0.33 %. It is worth noting that lithium is present in the uranium host rock of the deposit rather than being typically found in lithium minerals such as spodumene, lepidolite, and hectorite. Therefore, the primary sources of lithium are acidic tuffs comprising alumino-silicate volcanic glass and clays formed as secondary products [23].

The processing plant at Falchani comprises several sequential stages of comminution and classification. Initially, the run-of-mine material undergoes primary crushing with a Jaw crusher. Subsequently, the crushed product is subjected to classification using vibrating screens. Then, the classified material proceeds through secondary and tertiary crushing stages using cone crushers, followed by a ball mill for the final milled product. The output from the ball mill is regulated by hydrocyclones, with the underflow from this equipment being recirculated back to the mill [23].

The processing unit's milled slurry undergoes an atmospheric sulfuric acid leaching process for approximately 24 hours to dissolve all valuable elements. Subsequently, a preconcentration step, also referred to as pre-neutralisation, takes place by introducing limestone. Certain salts and impurities precipitate by increasing the solution's pH from 0 to 4. A belt filter is then employed to separate solids from the lithium-containing solution. However, before the solids are ultimately disposed of in the tailing dam, they undergo an additional washing process to enhance the overall lithium recovery of the plant and reuse the water within the process. The lithium solution proceeds to a three-stage neutralisation process, where appropriate amounts of quicklime and aluminium sulphate are added, gradually raising the pH from 4 to 12 across these steps. Impurities, including calcium and aluminium salts and caesium and rubidium compounds, precipitate and are subsequently separated from the solution using a belt filter. The lithium solution undergoes a subsequent softening stage by adding soda ash and cooling it to around 10 degrees Celsius. Calcium impurities precipitate as calcium carbonate and are separated from the slurry using a centrifuge. The enriched lithium solution is directed to an evaporator to reduce the solution volume and increase the concentration of pregnant leach solution (PLS) for the subsequent purification step, which involves ion exchange operations. In this step, cationic and anionic chelating resins such as La-amino phosphonic and N-methylglucamine resins are used to remove trace amounts of fluorine and boron from the solution, rendering it suitable for lithium carbonate precipitation. The precipitation stage occurs in three steps, with the addition of appropriate amounts of soda ash and increasing the temperature to facilitate lithium carbonate precipitation. The resulting lithium carbonate is then separated from the solution using a centrifuge. However, further drying steps are employed to eliminate moisture from the lithium carbonate cake to achieve commercial quality. Finally, the cake is conveyed to an aero-classifier mill for micronisation and packed in one-tonne bulk bags [23].

It is worth noting that a sulfuric acid plant, located adjacent to the main plant, serves as the primary source for the necessary reagent in the project. Additionally, through the utilisation of waste heat boilers and economisers, the heat generated in the production process is converted into steam, which is then used for both electricity generation and in various sections of the plant. However, they are not considered part of the lithium carbonate production system, given the limited information for the sulfuric acid plant. As such, they are excluded from the base case of the LCA study, and their environmental impacts will be further assessed in the sensitivity analysis, section 3.5.

2.3. Thacker Pass Project, USA

The mining process at Thacker Pass bears similarities to the Sonora and Falchani cases, with differences primarily observed in the geological structure of the mine and the waste-to-ore ratio. These variations impact the consumption of consumables per tonne of ore extracted. At Thacker Pass, the lithium mineralisation occurs within the sedimentary sequence of a caldera lake situated above the intra-caldera Tuff; The average lithium grade of the deposit is 0.32%. The Thacker Pass deposit comprises two clay minerals: smectite and illite. Smectite clay contains approximately 2,000 – 4,000 ppm lithium, whereas illite clay exhibits a higher lithium content ranging from 4,000 to 9,000 ppm. The sedimentary sequence intermittently consists of claystone layers, volcanic ash, and basaltic lavas. Consequently, this leads to implementing a direct leaching process for lithium extraction from the ore [24, 25].

The Thacker Pass processing plant comprises four primary steps: comminution, attrition scrubbing, classification, and solid-liquid separation. In order to achieve this, the run-of-mine material undergoes a tooth-rolled crushing process, followed by attrition scrubbing to separate and liberate the silicified gangue materials from the remaining slurry. Vibrating screens control this operation, with coarse materials larger than 25mm directed to the tailing dam. The underflow of the screened product is then subjected to dewatering hydrocyclones, followed by passage through a high-rate thickener. This thickener increases the solid-to-liquid ratio from 20% to approximately 55%, facilitating easier conveying from the beneficiation plant [24, 25].

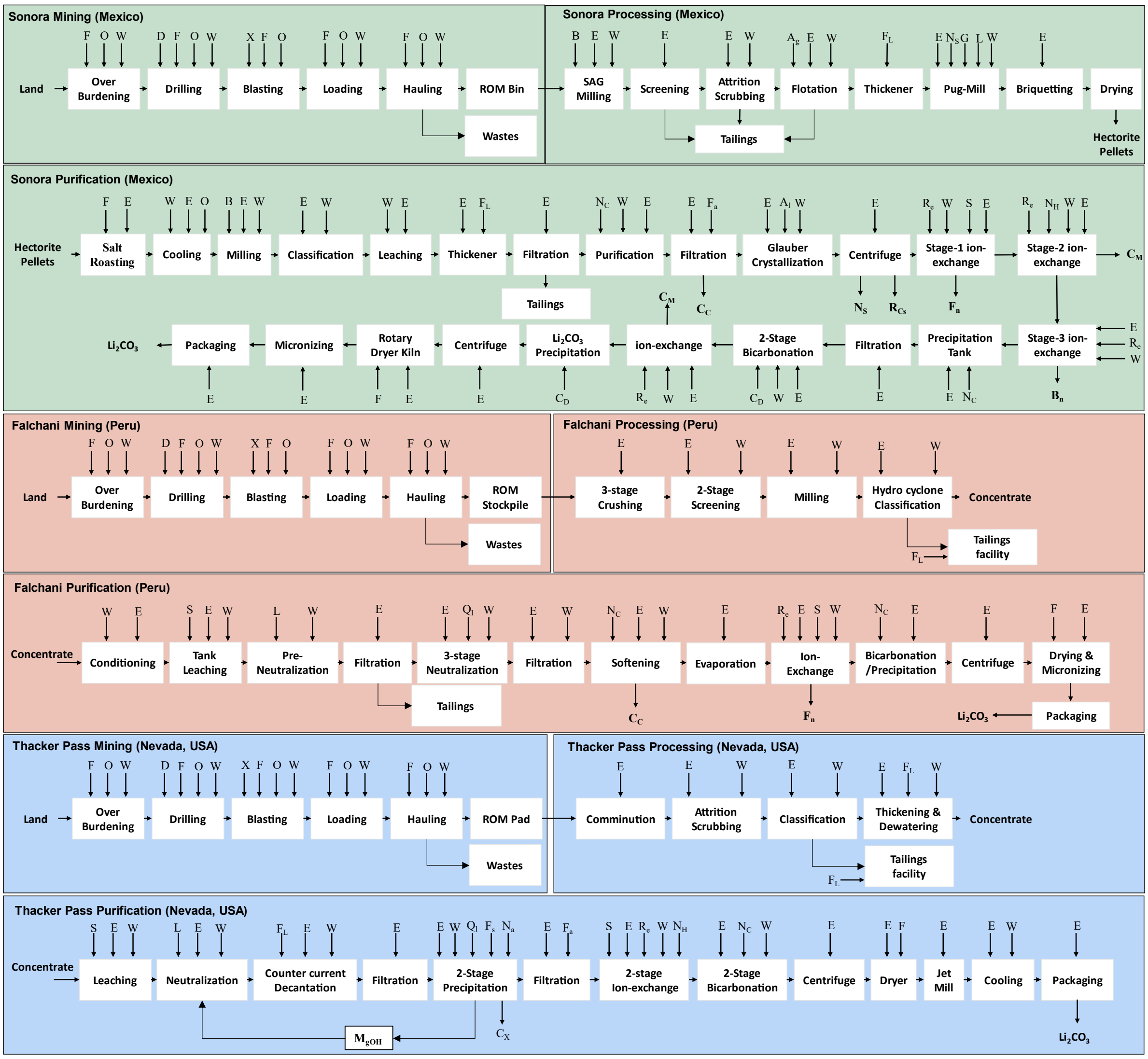
The cake is transported to the sulfuric acid leach plant, where it undergoes leaching at temperatures of 75-90 degrees Celsius for 1 hour. This process facilitates the transfer of lithium ions into the solution. Subsequently, a two-stage neutralisation process is implemented, with the first stage lasting approximately 1.5 hours. During this stage, limestone is added to increase the pH from 0 to 4, resulting in the precipitation of iron and aluminium compounds. The second stage, which takes approximately 1 hour, involves the utilisation of recycled magnesium hydroxide from downstream steps to raise the pH to around 6.5. This pH adjustment is necessary for the precipitation of calcium borate, gypsum, metal hydroxides, and residual clay compounds. The resulting slurry is then subjected to thickening using a high-density thickener to achieve a solid content of approximately 33%. Following thickening, the slurry is cooled and fed into a frame filter press to separate the solid and liquid phases. The liquid phase, which contains impurities such as magnesium, potassium, sodium cations, and lithium, requires purification. In a three-stage crystallisation process, evaporators are employed to precipitate magnesium sulphate hexahydrate from the solution. Subsequently, the precipitate is separated from the aqueous phase by increasing the pH to around 11 using quicklime. The solution is then mixed with soda ash, aided by ferric sulphate, to precipitate calcium carbonate. Filtration is performed, and the solution undergoes further purification through a two-stage ion exchange operation utilising cationic and anionic chelating resins to remove trace amounts of magnesium, calcium, and boron. Sodium hydroxide and hydrochloric acid are utilised during resin stripping and conditioning. In the final stages, the purified solution undergoes a three-stage carbonation process. Soda ash is added, and the temperature increases, leading to primary lithium carbonate formation. However, this lithium carbonate is redissolved by injecting carbon dioxide into the system, forming lithium bicarbonate. This process is carried out to produce lithium carbonate of battery grade, effectively reducing the presence of trace impurities by filtering out insoluble materials. The lithium carbonate is then produced during the final crystallisation step. The produced lithium carbonate is subsequently subjected to further processing. Initially, it undergoes centrifugation, followed by filtration and drying. The resulting lithium carbonate is then fed into a jet mill to reduce the particle size from 30 to 130 microns to approximately 5 to 8 microns. The final product is packaged in small bags weighing 25kg and bulk bags weighing 1000 kg for distribution in the market [24, 25]. Similar to the Falchani project, a sulfuric acid plant is also considered to produce the reagent and generate electricity. To keep the consistency of this LCA study, the environmental impacts of the sulfuric acid plant will be first excluded from the baseline model but tested in the sensitivity analysis in section 3.5.

3 Methodology and Data Collection

This comparative LCA follows ISO14044:2006, which consists of four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation of results [26]. This study utilises a cradle-to-gate approach for the LCA modelling constructed using the OpenLCA software. The life cycle inventory (LCI) data were primarily obtained from technical reports of the project owners, supplemented with theoretical estimations and the EcoInvent database [27, 28].

3.1. Goal and System Boundary Definition

As previously explained, the primary goal of this study is to assess the environmental impacts of different lithium extraction methods from sedimentary deposits in the countries of Mexico, Peru, and the United States. Thus, the functional unit of this study is the production of 1 metric tonne of lithium carbonate (Li_2CO_3) with a grade suitable for lithium-ion battery production. The system boundary is set from cradle to gate, including mining, transportation, comminution, processing, metallurgical, chemical, and purification processes associated with lithium extraction and lithium carbonate production. The overall process flows, input-outputs and system boundaries of the three case studies are illustrated in Figure 2. Possible by-products of these projects are excluded from the analysis in this study; thus, no allocation has been performed.



Inputs:

A_g – Flotation reagents (collector, frother, depressant)
A_l – Alum sulfate
B – Grinding media
B_n – Boron
C_C – Calcium carbonate
C_M – Calcium and Magnesium
C_D – Carbon Dioxide
D – Drill bits
E – Electric energy
F – Fossil energy (fuel, gas, coal)
F_a – Filtration aid (Diatomaceous earth)
F_n – Fluorine
F_L – Flocculant
F_s – Iron sulfate

G – Gypsum
L – Limestone
N_a – Ammonia
N_C – Sodium Carbonate
N_H – Sodium Hydroxide
N_S - Sodium Sulfate
O – Lubricants (motor oil, grease)
Q_l – Quicklime
R_e – Ion-exchange resins
S – Sulfuric acid
W – Water
X – Explosives (Charge, Booster, Cord, etc)

Outputs:

B_n – Boron
C_C – Calcium carbonate
C_M – Calcium and Magnesium
C_X- Calcium compounds
F_n – Fluorine
Li_2CO_3 – Lithium carbonate
M_{gOH} – Magnesium hydroxide compounds
N_S- Sodium Sulfate
R_{Cs}– Rubidium/Cesium salts
T – Tailings

Figure 2. System boundaries and process flows of the three selected projects

3.2. Life cycle inventory (LCI)

Analysis of the main inputs and outputs of the system was conducted by utilising publicly available resources, including company technical and economic assessment reports of all three projects and statistics from the geological organisations of the United States and Britain [20-25, 29]. Also, papers, books, and patents are used to estimate some of the inputs and outputs. Their exact amount wasn't mentioned in the technical reports [10, 11, 30-36]. To simulate the mining sector parametrically, the inventory of the mining sector was recalculated using handbook formulas published by the Society for Mining Engineering (SME) in the United States and basic design information and parameters from the project's technical reports [35, 37-59]. All data was ultimately entered into the main model using the EcoInvent 3.7.1 and OzLCI2019 databases as background data. These values are presented in Table 2 and adjusted to reference flows for producing one metric tonne of battery-grade lithium carbonate. Overall, the model inputs include various forms of energy consumption, minerals and chemicals, water, explosives, mining consumables, and system outputs specifically focused on mining waste, final products, and processing and chemical tailings.

Table 2. Inputs and outputs of main processes

Title	Sonora	Falchani	Thacker Pass	Unit	Source
Mining Inputs					
Water	11.07	65.19	12.93	$10^3 \cdot g$	Calculation [39-41, 47, 56]
Fuel	193.82	229.65	225.65	$10^3 \cdot g$	Calculation [39-41, 47, 56]
Lubricant (motor oil)	1.45	1.46	1.69	$10^3 \cdot g$	Calculation [41, 49, 56]
Ammonium nitrate	77.52	134.22	106.71	$10^3 \cdot g$	Calculation [37-40, 57]
Explosive fuel	4.65	8.10	6.40	$10^3 \cdot g$	Calculation [37-40, 57]
TNT	30.45	42.18	35.57	g	Calculation [37-40, 57]
Nonel	11.07	46.02	12.93	g	Calculation [38, 40]
Drill bits	94.13	134.22	171.38	g	Calculation [43-49]
Processing and Purification Inputs					
Water	54.29	87.47	151.91	$10^6 \cdot g$	Technical report [21-25]
Electricity	21020.00	4842.80	20029.55	kWh	Technical report [21-25]
Sulfuric acid	0.97	25.10	31.25	$10^6 \cdot g$	Technical report [21-25]
Soda ash	2.35	1.78	3.71	$10^6 \cdot g$	Technical report [21-25]
Limestone	4.00	12.42	6.52	$10^6 \cdot g$	Technical report [21-25]
Sodium hydroxide	0.25	0.00	0.11	$10^6 \cdot g$	Technical report [21-25]
Quicklime	0.00	5.58	2.10	$10^6 \cdot g$	Technical report [21-25]
Flocculant	2.34	5.10	70.00	$10^3 \cdot g$	Technical report [21-25]
Heavy Fuel Oil	0.00	2.28	0.00	$10^3 \cdot g$	Technical report [21-25]
CNJ	89999.17	0.00	0.00	$10^6 \cdot J$	Technical report [21-25]
Propane	0.00	0.00	20.00	$10^3 \cdot g$	Technical report [21-25]
Potable water	0.00	0.00	0.83	$10^6 \cdot g$	Technical report [21-25]
Grinding Media	0.26	27.3	0.00	$10^3 \cdot g$	Technical report [21-25]
Unleaded Gasoline	0.00	0.00	3.92	$10^3 \cdot g$	Technical report [21-25]
Diesel	0.00	4120.35	0.00	$10^3 \cdot g$	Technical report [21-25]
Ammonia	0.00	0.00	5.00	$10^3 \cdot g$	Technical report [21-25]
Iron Sulphate	0.00	0.00	10.00	$10^3 \cdot g$	Technical report [21-25]
Aluminium Sulphate	400.00	0.00	0.00	$10^3 \cdot g$	Technical report [21-25]
Hydrochloric Acid	0.00	0.00	20.00	$10^3 \cdot g$	Technical report [21-25]
Gypsum	9.48	0.00	0.00	$10^6 \cdot g$	Technical report [21-25]
Diatomaceous aid	229.34	193.51	249.36	$10^3 \cdot g$	Approximation [11]
Sodium Hypochlorite	54.29	87.50	151.91	g	Approximation [35]
CO_2 liquid	191.12	161.30	207.80	$10^3 \cdot g$	Approximation [11]
Cationic IX resin	0.01	0.01	0.02	g	Calculation [59]
Anionic IX resin	31.83	26.86	34.61	g	Calculation [59]
Lubricant (grease)	0.16	0.07	0.27	g	Approximation [52, 58]
Flotation Collector	1.00	0.00	0.00	$10^3 \cdot g$	Approximation [36, 60]

Outputs					
Lithium Carbonate	**1.00**	**1.00**	**1.00**	10^6·g	**Technical report**
Mine Wastes	213.71	320.1	256.7	10^6·g	Mass balance calculation [21-25]
Processing Tailings	62.14	62.4	65.7	10^6·g	Mass balance calculation [21-25]

3.3. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment analysis was conducted using the midpoint assessment of ReCiPe 2016 and the normalisation method based on the World 2010 on the selected case studies [27, 28]. Figure 3 depicts the comparative level of all impact categories for these three projects. In general, the Thacker Pass project in the USA has the highest values in 13 impact categories (e.g., freshwater ecotoxicity, global warming, mineral resource scarcity), the Falchani project shows the highest impact in 4 categories (e.g. terrestrial ecotoxicity), and Sonora project only tops in one impact category (i.e., stratospheric ozone depletion).
The comprehensive analysis of selected impact assessment methodologies, such as ReCiPe 2016 (midpoint E, H, I) - World 2010, USETox, IPCC 2013, ILCD 2011, EPD 2018, IMPACT2002+, TRACI 2.1, CML-IA baseline 2000 world, CML-IA non-baseline 2000 world, Greenhouse Gas Protocol, and EDIP 2003, is detailed in the supplementary material document (SI-1) through a series of tables showcasing the absolute values of each impact category.

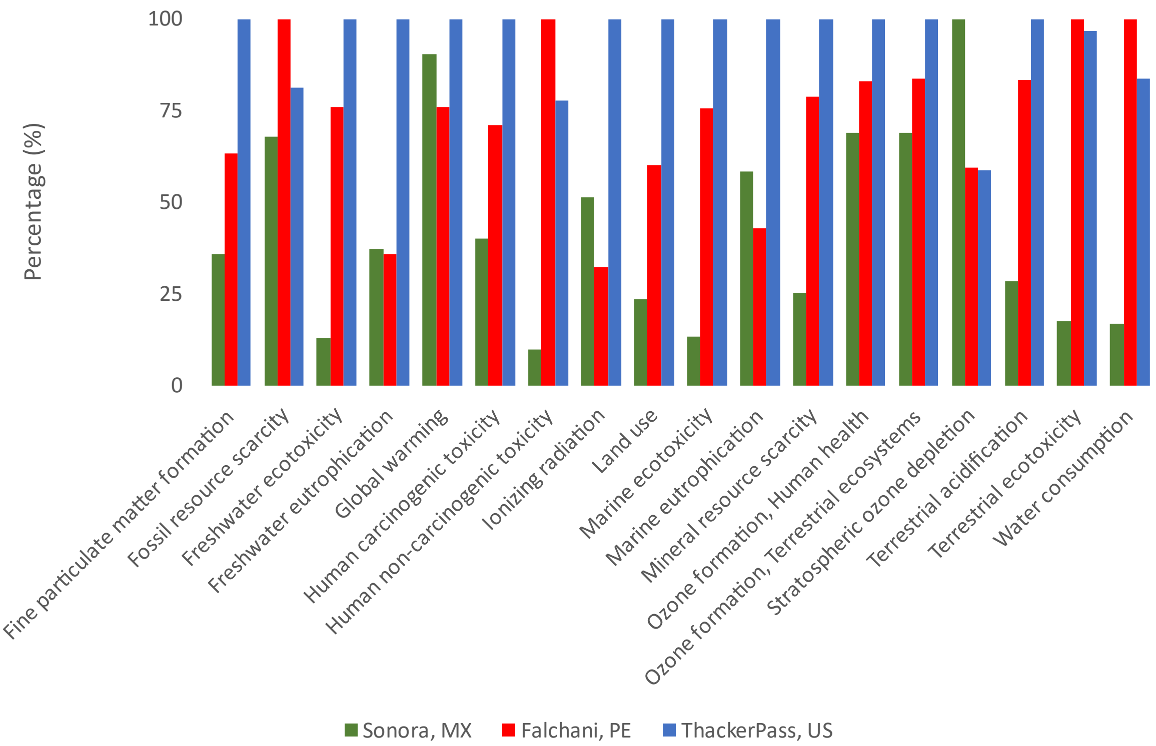


Figure 3. Comparative level of all impact categories for Sonora, Falchani and Thacker Pass

3.4. Hot spot analysis

Fine Particulate Matter Formation

The future lithium carbonate production at Thacker Pass emits nearly 2.8 times kilograms of PM2.5 equivalent compared to Sonora and almost 1.6 times as the Falchani product. In the context of Thacker Pass, where 100.1 kg PM2.5 eq are generated per 1 tonne of lithium carbonate battery grade, a significant portion, 63.1%, arises from the use of sulfuric acid for the direct leaching of the ore. This high sulfuric acid consumption could be attributed to the elevated levels of calcium and magnesium present in the ore input. Additionally, 28.1% of the impact results from electricity usage, while 6.4% can be attributed to soda ash consumption. The remaining inputs and outputs contribute only 2.4% to the formation of fine particulate matter in the final product of this project. In the Falchani project, which shares minor differences in extraction and purification technology with the Thacker Pass project, 79.8% of the environmental impact arises from sulfuric acid consumption, 9.8% from diesel consumption, and 8.3% from soda ash and quicklime consumption combined. The remaining inputs and outputs contribute a mere 2.2% to the overall impact. On the other hand, in the case of Sonora lithium carbonate, the primary contributor to fine particulate matter is electricity usage, accounting for 70.4% of the impact. This is followed by soda ash at 11.3%, sulfuric acid at 5.5%, and the remaining inputs and outputs of the system contributing 12.8% to the overall impact.

Fossil Fuel Scarcity

The Falchani lithium carbonate production demonstrates approximately 1.4 times impact in terms of fossil fuel scarcity compared to Sonora and about 1.2 times as Thacker Pass. Within the scope of Falchani, where 9516.6 kg oil equivalent is used per tonne of lithium carbonate, the primary contributor, accounting for 53.2% of the impact, is diesel consumption. Following this, 28.9% of the impact can be attributed to sulfuric acid consumption, while 12.4% results from the combined usage of quicklime and soda ash. Regarding Thacker Pass, 44.3% of the impact comes from sulfuric acid usage, while electricity contributes 30.4%, soda ash 15.3%, and diesel only 3.4%. In the Sonora project, electricity is the largest contributor at 59.2%, followed by natural gas at 20.0%, soda ash at 11.6%, and diesel at 3.0%.

Fresh Water Ecotoxicity

The Thacker Pass future lithium carbonate production exhibits approximately 7.6 times kilograms of 1,4-DCB (1,4-Dichlorobenzene) eq compared to Sonora and roughly as 1.3 times as the Falchani product within freshwater ecotoxicity. Among the 4868.5 kg of 1,4-DCB eq produced per 1 tonne of lithium carbonate battery grade at Thacker Pass, a substantial 86.3% is attributed to the use of sulfuric acid in the process, while 7.2% is linked to electricity usage and 5.5% to soda ash consumption. In the Falchani project, the predominant factor driving the impact is sulfuric acid consumption, accounting for 91.0%. This is trailed by 3.9% from soda ash and 3.1% from the combination of other inputs and outputs. However, in the context of the Sonora project, the three primary contributors to this impact category are electricity at 37.3%, soda ash at 26.6%, and sulfuric acid at 20.3%.

Freshwater Eutrophication

Thacker Pass has almost 2.8 times kg P eq compared to Falchani and almost 2.7 times as Sonora in terms of freshwater eutrophication. Within the scope of Thacker Pass, where 16.4 kg P eq are generated per 1 tonne of lithium carbonate, 53.8% is attributed to electricity consumption, and 35.7% to the use of sulfuric acid. For Sonora case, the highest contributor is electricity at 74.1%, followed by soda ash at 14.8%. In comparison, as for the Falchani project, 79.7% of the impact stems from sulfuric acid consumption and 11.6% from soda ash consumption.

Global Warming

Thacker Pass exhibits almost 30% more kilograms of CO_2 eq compared to Falchani and nearly 10% more than the Sonora product for global warming. Within the Thacker Pass project, which generates 22512.8 kg CO_2 eq per 1 tonne of lithium carbonate, the contributions are distributed as follows: 38.1% from electricity usage, 25.3% from sulfuric acid usage, 21.1% from soda ash consumption, 10.8% from quicklime consumption, and the remaining inputs and outputs contribute 4.7% to this impact category. In the Sonora case, the largest contributor is electricity at 61.1%, followed by natural gas at 17.0%, and soda ash at 14.7%. The rest of the inputs and outputs in this system account for 7.1% of this impact category. In the Falchani project, the impact contributions are as follows: 37.7% from quicklime consumption, 26.8% from sulfuric acid consumption, 13.3% from soda ash consumption, 12.5% from diesel consumption, and 9.8% from the remaining inputs and outputs.

Human Carcinogenic Toxicity

Thacker Pass has almost 2.5 times kilograms of 1,4-DCB eq compared to Sonora and almost 40% more than Falchani products for human carcinogenic toxicity. Within the context of Thacker Pass, where 2250.5 kg of 1,4-DCB eq are produced per 1 tonne of lithium carbonate, 53.1% arises from sulfuric acid consumption, 26.3% from electricity usage, and 16.7% from soda ash consumption. In the Falchani case, the primary contributor is sulfuric acid at 67.4%, followed by soda ash at 12.6%, and diesel at 8.9%. For the Sonora project, 41.1% of the impact stems from electricity consumption, 26.3% from soda ash consumption, and 16.0% from aluminium sulphate consumption.

Human Non-Carcinogenic Toxicity

In contrast to the previous category, the Falchani has over tenfold kilograms of 1,4-DCB eq compared to Sonora, and 30% more than Thacker Pass for this impact category. Within the context of Falchani, where 95880.2 kg of 1,4-DCB eq is generated per 1 tonne of lithium carbonate, a substantial 92.8% originates from sulfuric acid consumption. Similarly, 84.6% is attributed to sulfuric acid consumption for Thacker Pass. For the Sonora project, the primary contributor is electricity consumption at 42.2%, followed by soda ash at 22.8% and sulfuric acid at 20.6%.

Ionisation Radiation

Like most categories, Thacker Pass demonstrates over 3.1 times kBq Co-60 eq impact compared to Falchani and approximately 90% more than Sonora in ionisation radiation. Within the Thacker Pass project, which produces 1962.1 kBq Co-60 eq per 1 tonne of lithium carbonate, the impact contributions are distributed as follows: 64.6% from electricity consumption, 20.8% from sulfuric acid, 11.3% from soda ash, and the remaining inputs and outputs contribute 3.2% to this impact category. For the Sonora case, the largest contributor is electricity at 76.7%, followed by soda ash at 13.9%. In the Falchani project, the impact contributions are as follows: 51.3% from sulfuric acid, 22.0% from diesel, and 16.6% from soda ash. However, it's important to note that the Falchani deposit is situated on uranium-bearing host rocks, but due to a lack of access to appropriate data, this aspect is not included in this impact category.

Land Use

Similarly, Thacker Pass demonstrates over fourfold m^2a crop eq compared to Sonora and about 70% more than Falchani in land use. Within Thacker Pass, which generates 619.9 m^2a crop eq per 1 tonne of lithium carbonate, the impact is distributed as follows: 51.0% from sulfuric acid, 29.6% from electricity, and 15.8% from soda ash. For Sonora's case, the primary contributors are soda ash at 42.2%, followed by electricity, oleic acid, sulfuric acid, and aluminium sulphate, contributing 18.1%, 8.9%, 6.7%, and 6.5%, respectively. For the Falchani project, 68.1% of the impact is associated with sulfuric acid consumption, 12.6% with soda ash, and 7.0% with diesel.

Marine Ecotoxicity

Again, Thacker Pass reveals nearly 7.5 times kilograms of 1,4-DCB eq compared to Sonora and approximately 30% more than Falchani for marine ecotoxicity. Within Thacker Pass, which generates 6,274.8 kg of 1,4-DCB eq per 1 tonne of lithium carbonate, the impact distribution is as follows: 86.0% from sulfuric acid, 7.3% from electricity, and 5.5% from soda ash. In the Sonora case, the main contributors are electricity at 38.2%, followed by soda ash at 26.1%, and sulfuric acid at 19.9%. In the Falchani project, the impact is predominantly due to sulfuric acid consumption (91.3%).

Marine Eutrophication

Once more, Thacker Pass demonstrates almost 2.3 times kilograms of N eq compared to Falchani and nearly 70% more than Sonora. Within Thacker Pass, generating 4.4 kg of N eq per 1 tonne of lithium carbonate, 75.7% is attributed to soda ash consumption, while 13.4% arises from electricity usage. For Sonora, the primary contributor is soda ash at 82.0%, followed by electricity usage at 14.6%. In the Falchani project, the main impact contributions are as follows: 84.1% from soda ash and 10.0% from sulfuric acid.

Mineral Resource Scarcity

In a similar trend, Thacker Pass exhibits almost 30% more kilograms of Cu eq compared to Falchani but nearly four times as much as Sonora in mineral resource scarcity. Within Thacker Pass, generating 256.1 kg of Cu eq per 1 tonne of lithium carbonate, 88.9% is attributed to sulfuric acid consumption and 6.5% to soda ash usage. In the Sonora case, the primary contributor is gypsum at 41.8%, followed by soda ash at 16.4%, aluminium sulphate at 15.6%, and sulfuric acid at 10.9%. In the Falchani project, the impact is predominantly associated with sulfuric acid, accounting for 90.5%.

Ozone Formation Human Health

Thacker Pass has almost 20% more kilograms of NOx eq compared to Falchani and nearly 50% more than Sonora for ozone formation human health. Within Thacker Pass, where 53.5 kg of NOx eq are generated per 1 tonne of lithium carbonate, the impact distribution is as follows: 54.3% from sulfuric acid, 21.0% from electricity, and 17.3% from soda ash. In the Sonora case, the primary contributor is electricity at 61.3%, followed by soda ash at 15.9%, and natural gas at 9.3%. In the Falchani project, the impact contributions are as follows: 52.5% from sulfuric acid, 21.0% from diesel, 9.9% from soda ash, and 9.5% from quicklime. The results for Ozone formation in terrestrial ecosystems share almost an identical trend.

Stratospheric Ozone Depletion

Unlike other categories, Sonora exhibits almost 70% more kilograms of CFC11 eq compared to Falchani and Thacker Pass for stratospheric ozone depletion. Within Sonora, where 0.02 kg CFC11 eq are produced per 1 tonne of lithium carbonate, 74.3% results from electricity usage, 12.7% from ammonium nitrate consumption, and the remaining inputs and outputs contribute 13.0% to this impact category. In the Thacker Pass case, the primary contributor is ammonium nitrate at 34.5%, followed by electricity at 27.6% and sulfuric acid at 22.4%. In the Falchani project, the impact contributions are as follows: 36.9% from ammonium nitrate consumption, 29.6% from diesel consumption, 17.8% from sulfuric acid consumption, and 15.7% for the rest of the inputs and outputs.

Terrestrial Acidification

Thacker Pass exhibits nearly 20% more kilograms of SO_2 eq compared to Falchani and almost 2.5 times more than Sonora in terms of terrestrial acidification. Within Thacker Pass, which generates 238.2 kg SO_2 eq per 1 tonne of lithium carbonate, the impact distribution is as follows: 85.7% from sulfuric acid, 6.1% from soda ash, and 5.5% from electricity. In the Sonora case, the main contributors are electricity at 62.6%, followed by soda ash at 13.7%, and sulfuric acid at 9.4%. In the Falchani project, the impact is primarily sourced from sulfuric acid consumption, accounting for 82.6%, with an additional 9.2% from diesel consumption.

Terrestrial Ecotoxicity

In contrast, Falchani exhibits nearly 5.7 times kilograms of 1,4-DCB eq compared to Sonora and approximately 10% more than Thacker Pass in terms of terrestrial ecotoxicity. Within Falchani, which generates 153,618.0 kg of 1,4-DCB eq per 1 tonne of lithium carbonate, 80.8% of the contribution stems from sulfuric acid usage. For Thacker Pass, the major contributor is sulfuric acid at 87.0%. In the Sonora project, the distribution is as follows: 45.3% from electricity, 23.7% from soda ash, and 15.0% from sulfuric acid.

Water Consumption

Similar to the above category, Falchani demonstrates nearly six times more cubic meters (m^3) compared to Sonora and about 20% more than Thacker Pass in terms of water consumption. Within Falchani, which uses 1,011.6 m^3 per 1 tonne of lithium carbonate, the contributions are as follows: 44.3% from electricity, 41.8% from sulfuric acid, and 8.7% from water. In the case of Thacker Pass, the distribution is 62.1% from sulfuric acid, 18.1% from water, and 10.1% from soda ash. For the Sonora project, the contributions are divided as follows: 31.9% from water, 31.6% from soda ash, 13.9% from electricity, and 9.5% from sulfuric acid.

3.5 Sensitivity Analysis

Considering the industries' heightened awareness of climate change and carbon footprint, a sensitivity analysis was performed with a specific focus on global warming. Table 3 offers a comparison among various impact assessment methods for all three selected cases. While there are slight variations in absolute values, the consistent trend among Sonora, Falchani, and Thacker Pass remains unchanged. Irrespective of the method, Thacker Pass consistently yields the highest impact in terms of global warming potentials.

Table 3. Comparison of selected impact categories with other LCIA methods for the case studies per tonne Li_2CO_3

Impact Category	*LCIA method*	*Unit*	*Sonora*	*Falchani*	*Thacker Pass*
Global warming					
	ReCiPe'2016 mid H	kg CO_2 eq	20381.7	17101.3	22512.0

	ReCiPe'2016 mid E	kg CO_2 eq	18658.9	15760.8	20437.1
	ReCiPe'2016 mid I	kg CO_2 eq	22407.3	18916.2	25415.7
GWP100a	EPD 2018	kg CO_2 eq	20051.8	16840.8	22102.4
	IMPACT	kg CO_2 eq	19044.3	16090.7	20874
Climate change	ILCD 2011	kg CO_2 eq	19900.9	16612.5	21840.3
climate change - GTP 100a	IPCC 2013	kg CO_2 eq	18980.2	15993	20673.6
climate change - GTP 20a	IPCC 2013	kg CO_2 eq	21790.1	18602.6	24627
climate change - GWP 100a	IPCC 2013	kg CO_2 eq	20080.9	17017.8	22206.3
climate change - GWP 20a	IPCC 2013	kg CO_2 eq	22485.5	19328.2	25668.5
Global warming 100a	EDIP 2003	kg CO_2 eq	19895.1	16677.2	21830.8
	BEES+	kg CO_2 eq	19732	16561.3	21619.5
Fossil CO_2 eq	Greenhouse Gas Protocol	kg CO_2 eq	20065.3	16830.8	22092.2
GWP100a	CML base 2000	kg CO_2 eq	20051.8	16840.8	22102.4

As evident from the hotspot analysis, electricity emerges as the most impactful among the input factors within the process systems of the Sonora and Thacker Pass projects. The next significant factors were natural gas and sodium carbonate for Sonora and sulfuric acid and soda ash for Thacker Pass, while diesel and electricity consumptions within the Falchani project only account for 12.5% and 6.3% of total greenhouse gas emissions. Although chemicals and consumable materials are also major contributors, their values seem challenging to adjust from a chemical perspective and based on existing empirical tests. On the other hand, there are ongoing initiatives and efforts to increase renewable energy penetration globally. For example, the share of renewable sourced electricity in the USA has risen from around 9% in 2005 to more than 22% in 2022 [61]. Therefore, it is worth examining the sensitivity of the impact results in different future energy scenarios, as constructed below:

- **Base:** electricity generation based on Mexican, Peruvian, and Western Electricity Coordinating Council (WECC) grid mix, which is the base case scenario for each model.
- **Re100:** electricity generation with 100% renewable energies.
- **D2U:** electricity from used diesel generators with 25% efficiency instead of grid.
- **D2N:** electricity from new diesel generators with 45% efficiency.

As depicted in Figure 4, the utilisation of entirely renewable electricity sources showcases a substantial decrease in the global warming potential of the Sonora project in Mexico. This reduction is remarkable, as it brings the potential impact to less than half of the original value. Like the US, Mexico's electricity grid has witnessed a notable evolution in terms of renewable energy integration, which has risen from a mere 15.5% in 2001 to a more substantial 22.3% as of 2022 [60]. Even a shift to onsite diesel-generated electricity, especially with the implementation of efficient new generators, would lead to considerable reductions in greenhouse gas emissions. This change would greatly enhance the environmental competitiveness of the Sonora project in comparison to the other two projects.

In contrast, the transition to a solar and wind-based renewable energy mix does not result in a significant reduction in global warming potentials for the Falchani project in Peru (less than 5%). This outcome is primarily attributed to Peru's energy mix, which still prominently relies on hydropower as a prevailing cleaner source. This trend is also expected due to the minor role of electricity in this impact category within the base scenario. Notably, this contribution might potentially be underestimated when juxtaposed with the energy requirements of other projects, where the energy demand is considerably higher (e.g. exceeding 20MWh for other projects as opposed to Falchani's 4.8 MWh).

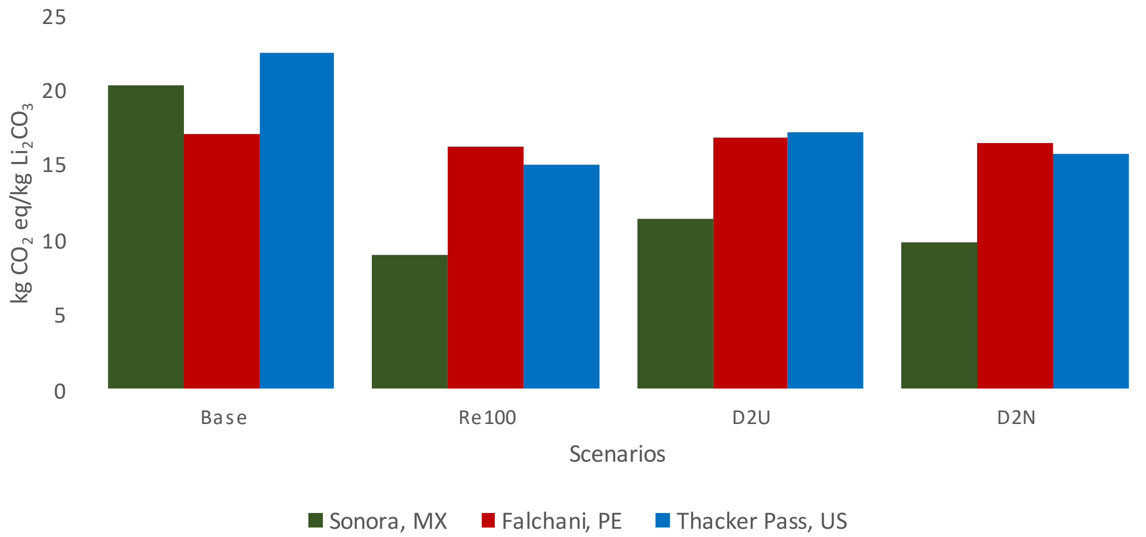


Figure 4. Sensitivity Analysis on different scenarios for Sonora, Falchani and Thacker Pass projects

In the base scenario, the Thacker Pass project in the United States emerges as the most concerning among its counterparts. This disparity can be attributed partially to the discrepancies in lithium-bearing minerals and subsequent lithium carbonate production methods employed across these projects. Additionally, the composition of electricity in the US grid plays a significant role. As depicted in Figure 4, a complete transition to renewable electricity sources has the potential to yield a substantial 33% reduction in global warming potentials. An equivalent reduction can be achieved by transitioning to power the facility using efficient diesel generators. This adjustment would place the Thacker Pass project on par with the Falchani project in terms of carbon footprint. These findings underscore the potential for significant impact mitigation by establishing a solar farm and other onsite energy generation adjacent to the facility.

As mentioned in Section 2, acid plants play a crucial role in providing the necessary sulfuric acid not only for the convenience of acid handling and transportation but also for electricity generation for both the Falchani and Thacker Pass projects. Owing to the limited information about the sulfuric acid plants, the input and output for the sulfuric acid production are modelled using the background data provided by EcoInvent. Thus, the energy required for the on-site production of sulfuric acid is already counted. Importantly, the electricity generated from the waste heat of sulfuric acid production at Thacker Pass is estimated to be 705.5 GWh per year, according to [23]. Therefore, the input electricity for lithium production can be offset, reducing from 20029.55 kWh/t to 3995.45 kWh/t. Based on [22], the acid plant co-generation is expected to produce a net surplus of power and be self-sufficient for lithium carbonate production; thus, the electricity input is adjusted to 0 kWh/t for this case. Figure 5 presents the comparison of mid-point assessment results between sulfuric acid co-generated electricity with base grid-mix case scenarios for both the Falchani and Thacker Pass projects. Specifically, for global warming potential, the value for the Thacker Pass project decreases from 22.51 kg CO_2 eq/kg Li_2CO_3 to 15.64 kg CO_2 eq., which means around 31% reduction in carbon dioxide equivalent per functional unit of lithium carbonate battery grade. This reduction for Falchani is just 6% due to the lower contribution of electricity in the base case scenario.

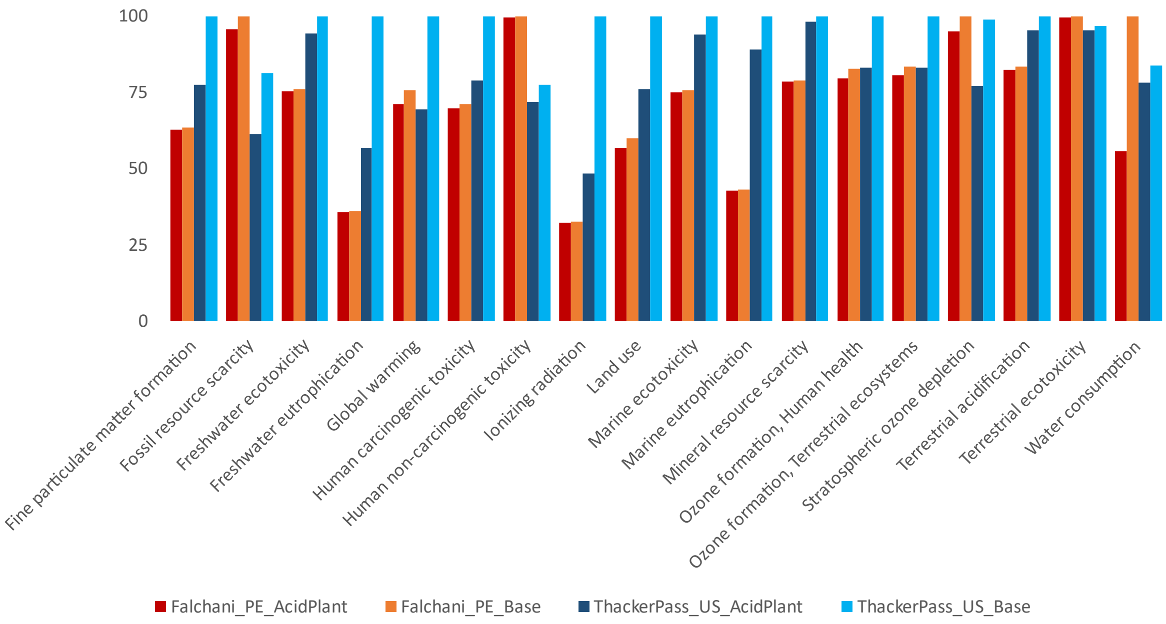


Figure 5. Sensitivity Analysis on acid plant scenarios for Falchani and Thacker Pass projects

4. Conclusion

Given the growing economic and technological viability of extracting lithium from sedimentary deposits, we explored the environmental performance of three promising projects: Sonora (Mexico), Falchani (Peru), and Thacker Pass (USA). By analysing their distinct process flowcharts, a comparative cradle-to-gate LCA model was developed. The results indicated that the Thacker Pass project exhibits greater potential environmental impacts when compared with the other two projects in the context of most impact categories (13 out of 18, including global warming potential). Furthermore, a sensitivity analysis underscored the importance of linking these emerging lithium carbonate production pathways to clean energy sources in order to reduce their carbon footprint.

Additionally, in contrast to prior LCA investigations which focused on established production routes, the greenhouse gas emissions associated with the sedimentary route (ranging from 15.8 to 25.7 kg CO_2eq/kg Li_2CO_3, as seen in Table 3) align within a comparable range to the pegmatite route (10.7 to 20.4 kg CO_2eq/kg Li_2CO_3, as presented in Table 1). While the sedimentary deposits exhibit lower-grade characteristics compared to pegmatite (e.g., 0.63% versus 1.21% Li_2O content), the energy-intensive comminution processes, which constitute a significant portion of energy consumption in a processing plant (ranging from 55% to 75%), have been omitted from the process. This omission is attributed to the higher work bond index required for milling pegmatites (e.g., 20 kWh/t input) and its associated wastes. However, it is worth mentioning that by using renewable energy to supply power for pegmatite routes, the global warming impact can be mitigated immensely. In addition, the planned sulfuric acid co-generated electricity can result in a significant reduction of carbon footprint, especially for the Thacker Pass project.

Despite our best efforts to gather pertinent life cycle inventory data for this study, theoretical estimations and assumptions were inevitable, given that these projects are not yet operational. The hotspot analysis revealed that primary contributors encompass energy consumption (e.g., electricity, natural gas, and diesel), along with chemical and consumable materials (e.g., sulfuric acid, soda ash, and quicklime). To comprehensively model these flows, further efforts are required, supported by primary data. Similar efforts are equally essential for well-established routes, given the substantial disparities uncovered in comparison to existing LCA studies, as listed in Table 1. As indicated by the sensitivity study (see Section 3.5), the adoption of renewable energy technologies and other energy efficiency measures will notably mitigate the environmental ramifications from a climate change perspective. Monitoring of electrification and the integration of renewable energy across all lithium production pathways becomes paramount, thereby underscoring the necessity for prospective LCA studies and subsequent updates. Another limitation of this study is the absence of consideration for possible radioactivity in the Falchani Uranium-Lithium deposit, followed by direct pollutants and emissions of blasting operation stemming from the lack of access to proper data. Therefore, it is recommended that additional endeavours be undertaken to address this aspect.

In conclusion, this study has contributed to advancing the discourse on enhancing transparency and accuracy within the future trajectory of lithium carbonate production from sedimentary clays. Further analysis using operational data would strengthen transparency and responsible mining practices. Finally, the findings of this study offer valuable insights for engineers seeking to benchmark various technologies through a sustainability lens, facilitating the selection and implementation of environmentally friendly alternatives for the processing of complex resources in the evolving landscape of the mining industry.

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