Current and Future Impacts of Lithium Carbonate from Brines: A Global Regionalized Life Cycle Assessment Model

Vanessa Schenker* and Stephan Pfister

Swiss Federal Institute of Technology Zurich, Chair of Ecological Systems Design,
Laura-Hezner-Weg 7, CH-8093 Zurich

E-mail: vanessa.schenker@ifu.baug.ethz.ch

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Abstract

Lithium (Li) is essential for decarbonization strategies, such as electric vehicles and renewable energy storage, experiencing the largest growth rates among metals required for low-carbon technologies. To meet this demand, the raw materials sector must increase current capacities and develop new ones at untapped deposits. Understanding life cycle impacts is crucial to avoid severe environmental burden shifts in the future. Although site-specific life cycle inventories exist, they do not allow for a comprehensive global assessment of the Li sector, particularly in capturing technological developments. To address this, our study presents a life cycle inventory model for brines that maintains essential site-specific parameters while providing a global perspective. We define core parameters for site-specific modeling of Li carbonate (Li_2CO_3) production and develop a systematic approach to addressing data gaps. Our model employs a class-based structure for 30 mapped processes from the literature, and quantifies environmental and technical flows. Overall, we cover 25 sites, representing 300 kilotonnes (90%) of current Li_2CO_3 production from brines and an additional 315 kilotonnes of potential future production. One key finding is that sites using direct Li extraction have 6-fold higher climate change impacts than sites using conventional technologies on average while water scarcity impacts are doubled on average. The difference is a result of the larger brine mass required to be treated due to lower Li grades. Furthermore, our model allows the implications for Li-ion battery production to be analysed. Based on our findings, we discuss decarbonization strategies for the Li sector to support a sustainable transition to a low-carbon society.

Synopsis

Life cycle impacts of lithium carbonate from brines are underestimated in literature. Our global, regionalized life cycle inventory model demonstrates increasing impacts due to technology choices and lower Li grades.

Keywords

metals, life cycle inventory, salars, geothermal brines, batteries, mining

Introduction

The demand for lithium (Li), driven by its critical role in energy storage systems, has intensified the focus on its extraction and processing[1]. Li is the metal seeing the highest growth rates of metals required for low-carbon technologies[2,3]. Worldwide capacities to extract Li-bearing brines and minerals need to significantly increase, and new sites need to be developed[4–6]. This rapid growth presents new challenges, as increasing production at existing sites and opening new sites will impose additional environmental burdens. However, the additional environmental burdens are difficult to capture and quantify because the mining sector is known for low data availability[7,8].

Currently, the bulk of Li mining is concentrated in Australia, Chile, Argentina, and

China[9], which have significant deposits of Li-bearing brines and minerals. In 2022, 43% of Li chemicals, measured in Li carbonate equivalent (LCE), were derived from continental brines located in salt lakes /salars, while the remaining 57% came from minerals[10]. Meanwhile, exploration activities have intensified globally. The 'Li triangle' in Argentina, Bolivia, and Chile has remained a focal point due to its Li-rich brines in salars[10–12]. This region is expected to be one of the main Li suppliers in the future[13,14]. Beside this, there is increasing interest in other Li-bearing deposit types, such as geothermal and oilfield brines located in North America and Europe[4,10,15].

The common products are Li carbonate (Li_2CO_3) and Li hydroxide monohydrate ($LiOH \cdot H_2O$)[16,17]. Various technologies exist to extract Li from brine and produce these chemicals[18]. Technological choices in Li_2CO_3 production from brines are influenced by site-specific conditions, particularly the unique brine chemistry[15,19]. Both Li concentration and the presence of other ions (e.g. Mg, B, Fe, Si), which can complicate processing, influence the choice of technology[16]. Furthermore, environmental conditions (e.g. the rainy season in Bolivia complicates the use of evaporation ponds) also play a crucial role[20]. Hence, the resource demand for producing Li chemicals – and thus the associated environmental impacts – can vary widely depending on the extraction technology.

Research in life cycle assessment (LCA) of Li chemical production is focused on specific sites characterized by unique geological and technological conditions[21–27]. These site-specific studies provide valuable insights into individual environmental impacts. Although Ambrose and Kendall[28] present life cycle impacts of Li chemicals on a global scale, their study lacks the granularity needed to accurately assess the diverse processing technologies and to discuss improvements from a life cycle perspective. Schenker et al.[22] present systematic and transparent guidelines to perform LCAs of Li_2CO_3 from brines and to allow comparability between sites. However, their approach is applied to only five existing and future sites. Furthermore, the sensitivity of chosen process-related parameters is not assessed in their study prohibiting any prioritization of data collection. Recognizing the high uncertainties related to input data, Schenker et al.[27] specifically address future Li_2CO_3 production from two geothermal sites by assessing a large number of scenarios with systematic variations of input data as the main focus of this study. However, the small number of assessed sites in these studies does not (1) allow to understand the relation between brine chemistry, applied technology, and the resulting life cycle impacts, and (2) cover enough sites to generalize these findings for the current and future Li_2CO_3 market. Consequently, the development of a systematic LCA model that encompasses a larger spectrum of processing technologies and addresses the inherent uncertainties is crucial for accurately evaluating the environmental impacts on a global scale.

This study introduces a novel global LCA model of existing and future Li_2CO_3 production from brine deposits, aiming to bridge identified research gaps. Our model not only facilitates a broader understanding of the life cycle impacts of the current Li production but also enables the exploration of potential environmental impacts associated with the expansion of Li mining activities in the future. By employing a parametrized and modular approach, the model accommodates a wide range of production technologies and site conditions. In total, life cycle inventories (LCI) of 25 sites across Argentina, Bolivia, Chile, China, US, and Germany are modeled and comprehensively discussed. LCIs are used to systematically assess climate change and water scarcity impacts. Additionally, we present results on reduction potentials of climate change impacts by integrating renewable energy provision. Given the critical role of Li in the Li-ion battery (LIB) sector, we thoroughly discuss the implications for LIB manufacturing. As a last point, the robustness of the model is assessed in detail.

Li_2CO_3 production from brines

Various processing pathways exist to produce Li chemicals from brines[15,16,29,30]. These pathways, adapted to site-specific conditions, follow distinct patterns. Currently producing sites, such as Atacama, are characterized by the use of evaporation ponds to increase the Li concentration using solar energy. Common practice is also to add chemicals, such as quicklime

(CaO), to remove unwanted ions (e.g. Cauchari-Olaroz, Pastos Grandes). Once the brine reaches a site-specific Li concentration, it undergoes further purification with organic solvents, soda ash (Na_2CO_3), sodium hydroxide (NaOH), and/or calcium chloride ($CaCl_2$). Technical grade Li_2CO_3 is produced by adding Na_2CO_3, and if battery grade is desired, this is dissolved in water at low temperatures and re-heated to precipitate higher-purity Li_2CO_3 (battery grade). In this study, we will refer to this processing pathway as the *Conventional chemical-based technology (Type A).*

Another pathway relies on ion exchangers, as seen at Silver Peak and Olaroz. These sites use evaporation ponds and CaO to concentrate the brine, followed by precipitation of impure Li_2CO_3 with Na_2CO_3. The impure Li_2CO_3 is then dissolved in water at low temperatures, and the LiCl solution is passed through multiple ion exchangers to remove impurities. The purified brine is re-heated to precipitate battery grade Li_2CO_3[31,32]. In our study, we group sites using this technology into the group *Conventional ion exchanger technology (Type B).*

Direct Li extraction (DLE) is used for continental brines in salars (e.g. Hombre Muerto, Chaerhan) and is being considered for geothermal brines (e.g. Salton Sea and Upper Rhine Graben)[33]. DLE technologies include ion exchange resins, liquid–liquid extraction, nanofiltration, and electromembranes[15,34]. DLE technologies offer the possibility to access deposits with lower Li concentrations and/or in general, unfavorable brine chemistry. However, data on DLE are scattered and often unavailable[33]. The general DLE pathway involves pretreatment depending on brine chemistry (e.g. ion exchange, precipitation, solvent extraction, acidification), chosen DLE technology, and post-processing (further refining, volume reduction)[35]. For example, geothermal brines with high Fe and Si concentrations require specific precipitation reactions to pre-treat the brine, while continental brines need Mg and Ca removal[15,36]. Post-processing includes ion exchangers, and precipitation and volume reduction to precipitate Li_2CO_3, with the by-product freshwater, which is used for other processes[35]. When the brine is purified, technical Li_2CO_3 is precipitated, and the purity can be increased by the aforementioned processes. In our study, we will refer to sites using DLE for continental brines as *DLE technology (Type C)* and for geothermal brines as *DLE technology (Type D)* due to the different required pre- and post-treatment processes.

Methods

This study conducts a comprehensive LCA of Li_2CO_3 production from brines on a global scale, adhering to the ISO 14040 and 14044 standards for LCA[37,38]. The main goal is the development of a parametrized and modular model to quantify LCIs of Li_2CO_3 production from brines (model is provided in the appendix as a zip file), with a global scope, including future production. The functional unit is 1 kg of Li_2CO_3 at battery grade. The scope encompasses all stages from brine extraction to the final production of Li_2CO_3. Life cycle impacts of 1 kWh capacity of a LIB with an NMC cathode (NMC811 = Nickel: 80%, Manganese: 10%, Cobalt: 10% by mass) and one with an LFP cathode composed of Li, Fe, PO_4 from ecoinvent[39] are assessed when using Li_2CO_3 LCIs from this study. LCI modeling and life cycle impact assessment (LCIA) are elaborated in the following sections (more details on the modeling approach can be found in appendix A).

LCI modeling

We utilize the database from S&P Global[10], selecting active mine sites and exploration sites, particularly those with published feasibility or technical reports. We assess 25 sites in Chile, Argentina, Bolivia, China, the United States, and Germany. We integrate the reported processing sequence and input data of 5 salar-related sites (Atacama, Olaroz, Cauchari-Olaroz, Hombre Muerto (North), Chaerhan)[22] and 2 geothermal sites (Salton Sea, Upper Rhine Graben)[27] in our study.

Input data and treatment of data gaps

Figure 1 gives an overview of the presented LCA model. The selection of required parameters is based on Schenker et al.[22]. However, these data are highly scattered and often not reported, prohibiting sound assessments on a global level. Recognizing these challenges, we present a structured, hierarchical approach to data collection.

At the core of our model are critical data, such as geographic location (country, elevation, longitude, latitude) and site characteristics (deposit type – salar or geothermal, brine chemistry, technology). Based on the geographic location, the model uses a global dataset on monthly recorded temperature from the year 2019 to obtain the annual air temperature of the specific location by using the geographically closest data point[40]. If the evaporation rate is not reported in literature, the model uses the value of the closest site that reported the evaporation rate in the provided database. The elevation is used as a proxy to determine the boiling point on-site – a necessity to quantify the heating demand. The inconsistent reporting of the brine's elemental composition presents another layer of complexity. If brine chemistry is not or is only partially reported, the model's strategy is to approximate the brine chemistry by using that from the closest salt lake in our database. The brine chemistry is crucial as it significantly influences the resource demand, including energy, water, chemicals, and waste generation. As a critical component of our modeling approach, detailed information on the technology used at each site is essential, ideally at a process level. If such detailed information is not available, and only high-level descriptions of the technology are provided, the model defaults to a predefined set of processes that approximate the described technology. Other operational data (e.g. operating days, life time, well depth, etc.) are defined based on the literature.

Site-specific Li_2CO_3 production

Our model employs a class-based structure for each process allowing for dynamic execution. A graphical overview of the modular approach (Figure A1) is presented in the appendix. In total, 30 processes are included. The model enables the calculation of environmental and technical flows, including water and energy demand, chemical usage, and waste generation, tailored to the unique conditions of each site. Our model checks mapped dependencies between defined processes to prevent illogical processing sequences. Processes are modeled based on the incoming mass flow from either a previous process or the initial brine mass flow used to produce a defined amount of Li_2CO_3. Each process contains a pre-defined set of technical and environmental flows. The iterative approach to model LCI based on patents, technical reports and literature by Schenker et al.[22] is used to systematically model process-related flows. This is further expanded by parameterizing 68 process-related parameters (e.g. process temperatures, pulp concentrations) and defining ranges to account for uncertainties related to the modeling approach.

The heat demand for specific processes is calculated based on thermodynamics by using the process-specific temperature and the temperature of the incoming pulp. The heat capacity of the incoming solution as well as latent heat due to the phase changes are used to calculate the heat demand. In addition, a heat loss of 15 % is added to the modeled demand. Heat recovery is integrated in multiple processes when water and/or pulp flows are re-circulated (e.g. water generated in mechanical evaporator and reverse osmosis). Any demand for chemicals is modeled by using stoichiometric reactions (e.g. Na_2CO_3 to produce Li_2CO_3).

Chemicals are added to force a specific precipitation of wanted or unwanted ions, to wash pipes, or to adjust the pH of the brine. Chemicals, such as organic solvents or cationic resin, can be used multiple times, which is taken into account by including reported recycling rates from literature. Generated waste in these processes is either by centrifuges (as a subsequent process) or sedimentation in the presented model. Whether the waste is liquid or solid is determined by the process configuration.

Water is required to dilute chemicals, wash Li_2CO_3, desorb Li from the resin, and dissolve Li_2CO_3 to obtain a higher purity. For chemicals, the water demand is determined by the mass flows of chemicals and a defined surplus to account for incomplete chemical reactions. Water used for washing activities is defined based on the incoming mass flow.

Electricity demand is calculated by using literature values per incoming mass flow of the specific process.

Site-specific databases & regionalization of background database

Once environmental and technical flows of Li_2CO_3 production are modeled, the model creates site-specific databases in Brightway 2.0[41]. Required flows from ecoinvent v3.9.1 are mapped in the model and can be extended in the future. The model chooses country- or region-specific datasets (e.g. electricity mix) that exist in ecoinvent v3.9.1[39] and are reported in the appendix. For the assessment of water scarcity impacts, the model regionalizes relevant water flows in the database. For example, biosphere flows, as the freshwater losses due to evaporation when storing liquid waste, are regionalized. In order to account for the re-use of water in the processing sequence, the model creates the activity of an additional reverse osmosis for water purification and re-use and regionalizes relevant biosphere flows.

Life cycle impact assessment

The selection of life cycle impacts is based on the literature highlighting their relevance regarding Li mining[21,22,24,26]. We assess climate change impacts utilizing the IPCC method assessing the global warming potential of emissions over a 100-year time horizon (GWP100a)[42] and regionalized water scarcity impacts following the AWARE methodology[43]. Site-specific characterization factors of AWARE are documented in the appendix. As highlighted by Halkes et al.[44], some salars have spatial overlaps with multiple characterization factors due to the low watershed resolution of the WaterGAP model, while for other salars, no characterization factor is available at all. Four operations are located in areas with no characterization factors. We fill these gaps by using updated AWARE characterization factors provided by Pfister and Scherer[45]. There has been a discussion on the integration of brine consumption in the AWARE methodology (e.g. Schomberg et al.[25], Halkes et al.[44]). Studies by Kelly et al.[24], Chordia et al.[21], and Schenker et al.[22] do not include the water content of the brine in their assessments when assessing water scarcity. As AWARE is designed to only assess freshwater consumption, we follow the approach defined by the UNEP-SETAC Life Cycle Initiative[43].

Local sensitivity analysis

The robustness of our model is tested by performing a local sensitivity analysis for each technology group. In total, we vary 68 parameters relevant for the 30 mapped processes in our model by defining ranges for each parameter. If possible, the range is defined on ranges reported in patents[31,46,47]. For this, one site of each technology group is used to assess the variability of life cycle impacts in relation to the process-specific parameters.

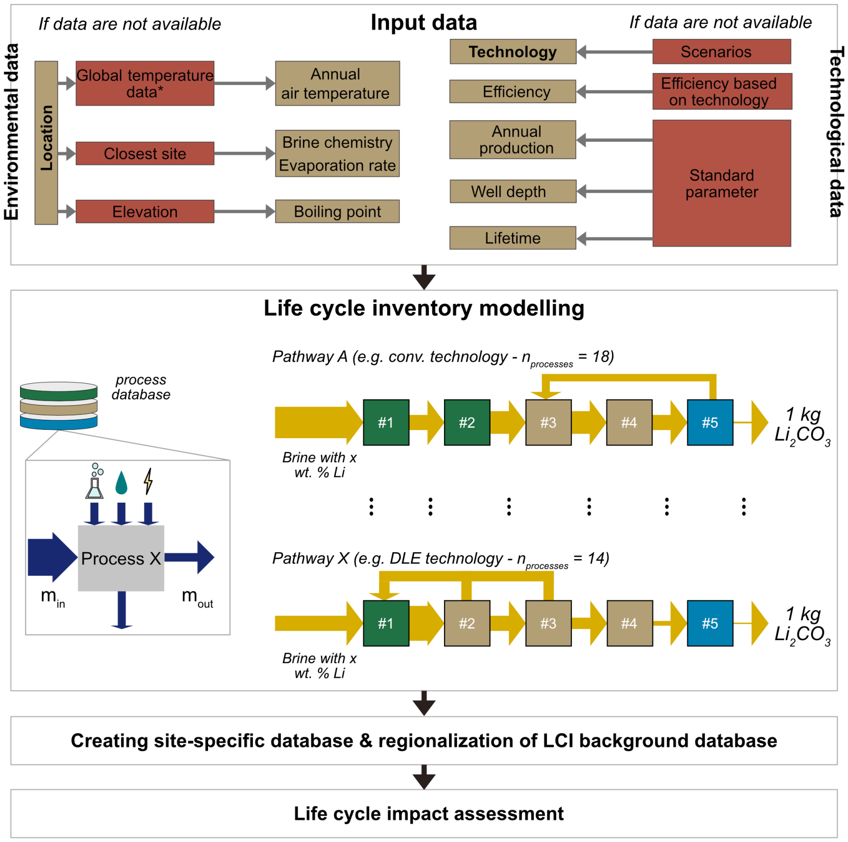

Figure 1: *Overview of the approach in this study.*

Results and discussion

LCIs

This section describes the modeled LCIs of 25 sites based on the availability of technical reports, patents, and/or literature (Figure 2). We cover 300 kilotonnes (kt) of current LCE production representing 90 % of the LCE production in 2022[10] and additional 315 kt of future LCE production from brines. Notably, the capacity of future production in this study is based on announcements and thus, faces high uncertainties. Missing production capacity of 8 exploration sites were filled by assuming a mid-size operation (10 000 t Li_2CO_3/year). The sites are divided into four groups based on the reported technology used on-site. The resource demand of each site to produce 1 kg of Li_2CO_3 at battery grade is summarized in

Table 1. Required input data and LCI of each site can be found in the appendix (Table B.2 and B.11).

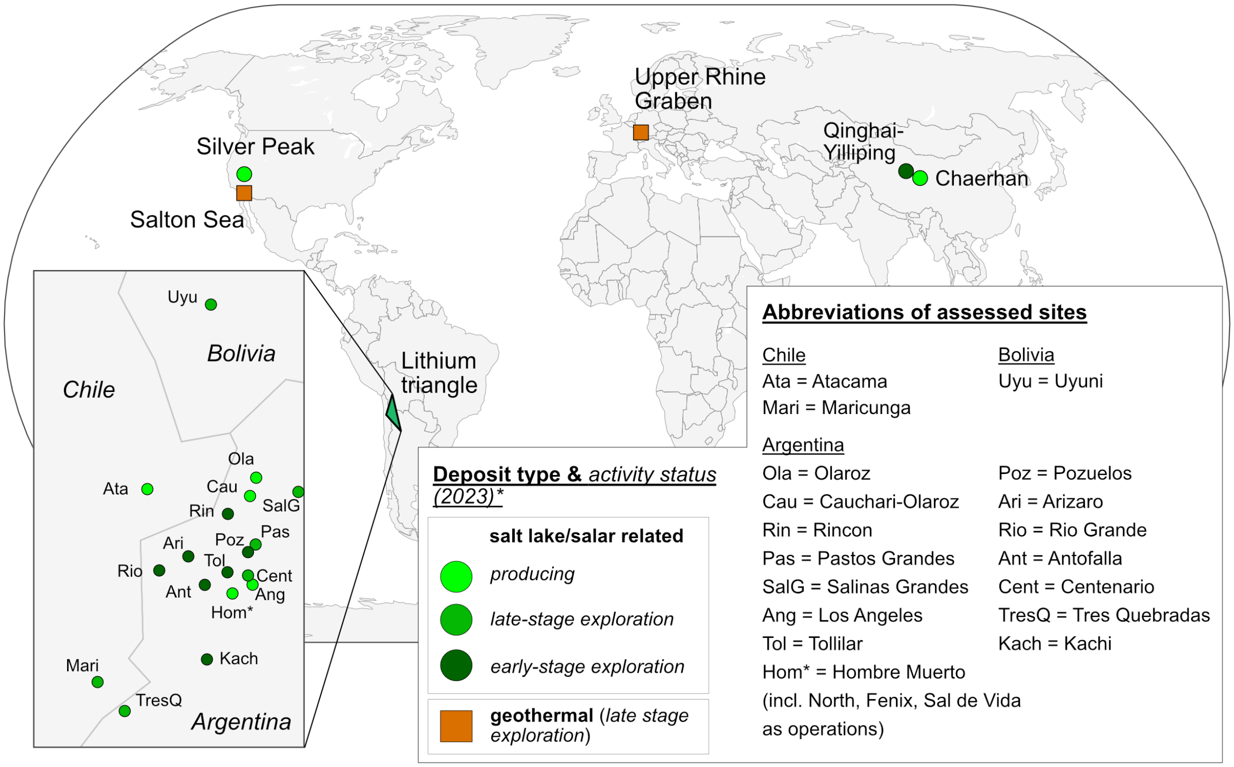

Figure 2: *Global map of assessed Li sites from either salt lakes/salars or geothermal brines. Data, summarized in Table B.2, are taken from S&P Global*[10].

Conventional chemical-based technology – Type A

Seven of the 25 sites reported a chemical-based procedure to produce Li chemicals. As seen in Table 1, the Li concentrations of the brine vary between 0.04 and 0.15 wt.% Li with Atacama having the highest Li concentration used in this study. Thermal energy demand varies between 13 and 49 MJ/kg Li_2CO_3, and power demand varies between 1.1 and 2.5 kWh/kg Li_2CO_3. The freshwater demand ranges between 0.04 and 0.2 m^3/kg Li_2CO_3. The chemical demand (i.e. Na_2CO_3, CaO, $CaCl_2$) is highly variable as it is determined by the brine chemistry (Table 1) but also by the reported purification processes. For example, Pastos Grandes has the highest CaO demand with 6.2 kg/kg Li_2CO_3, while the lowest is reported to be 0.02 kg/kg Li_2CO_3 at Atacama. The main reason is that the brine from Pastos Grandes has the lowest Li concentration and a relatively high impurity concentration compared to the other brines. In contrast, Na_2CO_3 is relatively similar across the sites due to the main demand coming from the Li_2CO_3 precipitation, which is not affected by the brine chemistry.

Conventional ion exchanger technology – Type B

Two of the 25 sites currently produce Li chemicals using ion exchangers to purify brine in their processing facilities. The Li concentration used in the model is 0.02 wt.% Li at Silver Peak and 0.06 wt.% Li at Olaroz.

The heating demand is estimated to be 8 MJ/kg Li_2CO_3 at Silver Peak and 9 MJ/kg Li_2CO_3 at Olaroz. Power consumption is 1.2 kWh/kg Li_2CO_3 at Silver Peak and 1.4 kWh/kg Li_2CO_3 at Olaroz. Water demand is higher compared to other technologies, with 0.07 m^3/kg Li_2CO_3 at Silver Peak and 0.13 m^3/kg Li_2CO_3 at Olaroz, due to extensive water use during the regeneration of ion exchangers to purify the LiCl solution. CaO consumption is estimated at 0.36 kg/kg Li_2CO_3 at Silver Peak and 3.7 kg/kg Li_2CO_3 at Olaroz. The discrepancy is explained by the overall smaller mass of Mg that needs to be removed in the brine of Silver Peak. Additionally, 1.9 kg Na_2CO_3/kg Li_2CO_3 is required at both sites to precipitate impure Li_2CO_3.

DLE technology – Type C

Fourteen sites report the installation of the DLE technology. Most assessed sites are located in Argentina, with Uyuni in Bolivia and Chaerhan and Yiliping in China as exceptions. The Li concentration varies between 0.02 and 0.07 wt.% Li, with a notable tendency to lower Li grades than in the two conventional technology groups. The heat demand ranges between 241 and 656 MJ/kg Li_2CO_3, which is much more than the Types A and B. The highest energy demand is modeled for the operation at Pozuelos and results from the relatively low Li grade compared to the other sites. Power demand ranges between 3.9 and 10 kWh/kg Li_2CO_3, while water demand ranges between 0.21 and 0.34 m^3/kg Li_2CO_3. Water and electricity demand are also much higher than for Type A and B production. In the presented study, the pre-treatment processes consist of Mg removal by Na_2CO_3 and acidification of the brine, which then goes into the Li-ion selective adsorption process. Na_2CO_3 demand varies between 1.9 and 38 kg/kg Li_2CO_3, with Uyuni having the highest Na_2CO_3 demand. This is a result of the elevated Mg concentration in the brine compared to other brine sites. The lowest hydrochloric acid (HCl) demand for acidification is modeled for Fenix with 2.5 kg/kg Li_2CO_3. The highest demand is modeled for Arizaro with 19 kg/kg Li_2CO_3 due to the elevated impurity (especially SO_4) concentration of the brine compared to sites, such as Fenix.

DLE technology – Type D

DLE is reported to be used for Li extraction from geothermal brines at Salton Sea in the USA and Upper Rhine Graben in Germany. The Li concentration in the geothermal brine is 0.19 wt.% at Upper Rhine Graben and 0.18 wt.% at Salton Sea. As aforementioned, processing sequence and input data are primarily sourced from Schenker et al.[27] and integrated into the model to extend it to potential future geothermal sites. The energy requirements are 172 MJ/kg Li_2CO_3 at Salton Sea and 179 MJ/kg Li_2CO_3 at Upper Rhine Graben. Power demand is similar for both sites, at 14 kWh/kg Li_2CO_3, as is water demand, at 0.36 m^3/kg Li_2CO_3. While heat demand is lower than for Type C sites, water consumption and electricity demand are higher due to more pumping of brine/process water and the lower adsorbent capacity reported in literature compared to Type C sites. CaO consumption differs, with 2.4 kg/kg Li_2CO_3 needed at Salton Sea and 0.1 kg/kg Li_2CO_3 at Upper Rhine Graben. Additionally, limestone demands are 3.7 kg/kg Li_2CO_3 at Salton Sea and 0.4 kg/kg Li_2CO_3 at Upper Rhine Graben. HCl use for acidifying the brine is estimated at 2.1 kg/kg Li_2CO_3 at Salton Sea and 1.5 kg/kg Li_2CO_3 at Upper Rhine Graben. The main reason for the higher demand of chemicals is the increased impurity content in Salton Sea's brine compared to that from Upper Rhine Graben[27].

Comparison with the literature

Table B.5 summarizes literature LCIs of Li_2CO_3 production from specific sites and the most relevant findings when comparing them with our obtained results are discussed.

Regarding type A, our modeled heat demand for Atacama (18 MJ/kg Li_2CO_3) is higher than the ecoinvent v3.9.1 value (2.9 MJ/kg Li_2CO_3), as our study includes processes to obtain a battery grade in contrast to ecoinvent[39]. Kelly et al.[24] include fewer chemicals when using company data from Atacama – only Na_2CO_3 is explicitly mentioned, and the value reported is similar to ours. Freshwater is estimated to be 0.024 m^3/kg Li_2CO_3, which is half of our modeled value. The aggregation of company data, observed in ecoinvent[39] and Kelly et al.[24], prohibits any analysis on these differences. Mas-Fons et al.[26] used a process-simulation tool showing higher energy (power and heat) (11.1 kWh/kg Li_2CO_3) than our value (6.2 kWh/kg Li_2CO_3). This observation is in accordance with Parvatker and Eckelman[48] that process calculation has the tendency to underestimate process-specific electricity demand compared to process-simulation tools. Schomberg et al.[25] report additional LCIs for Hombre Muerto, Uyuni, and Silver Peak by using linear adaptions of the LCI[39] based on the Li concentration of the brine. However, this approach does not take into account any technological differences among these sites, such as the use of quicklime at Silver Peak for Mg removal[49]. Consequently, our site-specific LCIs converge from those provided by Schomberg et al.[25].

Mousavinezhad et al.[50] use aggregated industry data from the Clayton Valley site employing DLE technology (type C). Even though we do not include Clayton Valley in our study due to restricted data availability, we still compare our data with this study, as it is one of the few studies regarding life cycle impacts of DLE. Mousavinezhad et al.[50] report an energy demand (sum of heat and power: 59 kWh/kg Li_2CO_3) which is half compared to ours (e.g. range of summed heat and power: 102 - 188 kWh/kg Li_2CO_3). The lack of transparency regarding process-related data (i.e., process temperature to heat up the raw brine) prohibits a detailed comparison with our study to understand the process-related differences in energy demand. Their water use is optimistic, assuming full recycling of water, while our model accounts for freshwater withdrawals in a more conservative manner. More specifically, our model sends 90 % of process water back after Li_2CO_3 precipitation and discards the rest as liquid waste - which still is a rather optimistic assumption. Furthermore, our study includes Mg- and Ca-removal by Na_2CO_3 while Mousavinezhad et al.[50] reports acidification as the only required pre-treatment process at Clayton Valley, explaining the lower Na_2CO_3 demand (1.53 kg/kg Li_2CO_3) in their study compared to our range (1.9 - 38 kg/kg Li_2CO_3. Li_2CO_3 from Chaerhan is first assessed in Schenker et al.[22]. Our study has a higher heat demand (465 MJ/kg Li_2CO_3) than the one (298 MJ/kg Li_2CO_3) by Schenker et al.[22] due to the increased operating temperature (80 °C) in the DLE column than the one (10 °C) reported by Schenker et al.[22]. The increased temperature in the DLE column is often reported in more recent literature and thus, used in our study[33,35,51].

In the context of Li_2CO_3 production from a geothermal brine at Salton Sea, Huang et al.[52] only assess the DLE process without any pre-treatment, leading to a substantial lower and/or non-existing resource demand compared to our obtained one. One major difference to the modeling approach by Schenker et al.[27] is that the heat demand is reduced from 230 MJ/kg Li_2CO_3 to 179 MJ/kg Li_2CO_3 in the case of Salton Sea. This results from the enhanced re-circulation of process water after Li_2CO_3 is precipitated on our model as the heated water can be used to reduce freshwater and energy demand for the adsorption column. In the specific context of water use, re-circulation and purification strategies result in an overall water demand (357 kg/kg Li_2CO_3) modeled by Schenker et al.[27] which is comparable with the reported range (200 - 600 kg/kg Li_2CO_3) from companies operating at Salton Sea[53]. However, information on the processing technology including pre- and post-purification processes from these companies are absent impeding a further comparison with our study.

Table 1: Material and energy demand per kg of Li_2CO_3 (battery grade). Impurity concentration signed with a $*$ means that there was no information on the impurity concentration and a proxy was used. The column "other" presents the sum of other chemicals used on-site.

Site	**Technology**	**Li**	**Impurity**	**Heat**	**Power**	**Process water**	**CaO**	**H_2SO_4**	**Na_2CO_3**	**HCl**	**NaOH**	**Resin**	**Other**	**Waste**
Units		*wt.%*	*wt.%*	*MJ*	*kWh*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*
Atacama	A	0.15	2.7	18	1.1	47	0.03	0.03	2.0	0.06	—	0.03	0.06	112
Tres Quebradas	A	0.10	4.4	24	1.7	53	—	0.04	1.9	0.11	—	0.06	0.12	174
Maricunga	A	0.09	1.8	49	1.6	200	0.2	0.13	2.5	0.13	—	0.06	0.81	132
Sal de Vida	A	0.08	1.1	13	1.1	33	0.4	0.00	1.9	0.00	—	0.00	0.00	27
Hombre Muerto North	A	0.07	1.1	48	1.3	61	3.4	0.05	1.9	0.28	—	0.08	0.69	261
Cauchari-Olaroz	A	0.05	0.9	24	1.2	56	2.7	0.00	1.9	0.19	—	0.08	0.36	226
Pastos Grandes	A	0.04	0.3	18	2.5	85	6.2	0.08	1.9	0.16	—	0.09	0.20	167
Olaroz	B	0.06	1.8	9	1.2	128	3.7	0.11	1.9	0.03	—	0.02	—	113
Silver Peak	B	0.02	0.7	8	1.4	67	0.3	0.00	1.9	0.03	—	0.02	—	93
Uyuni	C	0.07	3.5	241	3.9	336	—	0.04	37.6	3.96	0.5	0.04	—	101
Fenix	C	0.07	1.1	352	4.2	247	—	0.08	9.7	2.51	0.4	0.04	—	124
Rio Grande	C	0.03	1.3	388	4.2	261	—	0.08	13.0	6.77	0.5	0.04	—	124
Centenario	C	0.03	1.2	387	4.3	265	—	0.09	12.7	4.05	0.5	0.04	—	130
Rincon	C	0.03	1.6	430	4.4	269	—	0.10	12.7	8.88	0.5	0.04	—	134
Tolillar	C	0.03	0.2	442	5.4	269	—	0.11	11.3	3.74	0.5	0.04	—	139
Arizaro	C	0.03	3.1	457	4.5	324	—	0.11	25.0	19.55	0.5	0.04	—	139
Antofalla	C	0.03	0.8	446	4.5	252	—	0.11	6.6	5.42	0.5	0.04	—	141
Salinas Grandes	C	0.02	0.4	524	4.6	272	—	0.13	9.4	3.14	0.5	0.04	—	150
Kachi	C	0.02	*	546	6.1	304	—	0.14	15.5	4.31	0.5	0.04	—	158
Los Angeles	C	0.02	1.0	561	4.8	281	—	0.15	9.0	7.36	0.5	0.04	—	161
Pozuelos	C	0.02	1.1	656	5.0	328	—	0.17	17.9	11.29	0.5	0.04	—	172
Chaerhan	C	0.02	*	465	10.0	212	—	0.13	1.9	0.19	0.5	0.09	—	80
Qinghai Yiliping	C	0.02	*	444	10.0	212	—	0.13	1.9	0.19	0.5	0.09	—	80
Upper Rhine Graben	D	0.02	0.5	179	14.0	356	0.05	—	1.9	1.46	1.0	0.28	0.38	23
Salton Sea	D	0.02	2.6	172	13.8	357	2.4	—	1.9	2.05	1.0	0.28	3.72	37

Life cycle impacts of Li_2CO_3 from brines

Climate change and water scarcity impacts of 1 kg of Li_2CO_3 at battery grade from 25 sites grouped by the technology groups are shown in Figure 3 (see also Table B.6). Figure 3 not only shows site-specific life cycle impacts but also sets our findings in the current and future brine-related Li_2CO_3 market. We present results on the energy provision level by using renewable energy. As a last point, we discuss our findings in the context of LIB production and the overall raw material sector.

Conventional chemical-based technology – Type A

Type A sites have the lowest average climate change impact of 7.8 kg CO_2eq/kg Li_2CO_3. The range is between 2.8 and 12.8 kg CO_2eq/kg Li_2CO_3. Figure 4 highlights that the impacts mainly originate from chemicals used in evaporation ponds, purification, and Li_2CO_3 precipitation. At sites like Cauchari-Olaroz, CaO usage in evaporation ponds is a major contributor due to its heat demand and CO_2 release during production[22,54]. For water scarcity impacts, conventional technology sites average 5.8 m^3world-eq/kg Li_2CO_3, with a range from 0.8 to 16.2 m^3world-eq/kg Li_2CO_3. These impacts also stem from the chemicals used in evaporation ponds, purification, and Li_2CO_3 precipitation. The use of CaO further amplifies water scarcity impacts due to water losses during chemical production, such as the dehydration of $NaHCO_3$ to produce Na_2CO_3, which releases H_2O into the atmosphere[55].

Conventional ion exchanger technology – Type B

Type B sites reveal climate change impacts comparable with Type A (Olaroz: 7.6 kg CO_2eq/kg Li_2CO_3; Silver Peak: 3.6 kg CO_2eq/kg Li_2CO_3). Water scarcity impacts are 1.3 m^3world-eq/kg Li_2CO_3 at Olaroz and 3.2 m^3world-eq/kg Li_2CO_3 at Silver Peak. These impacts are mainly due to CaO use in evaporation ponds and ion exchangers. Silver Peak uses less CaO than Olaroz because of the smaller amount of Mg which needs to be removed from the brine. Even though the overall water demand is lower at Silver Peak, it still reveals higher water scarcity impacts than Olaroz due a characterization factor of 95 m^3world-eq/m^3 at Silver Peak.

DLE technology – Types C & D

Type C & D sites have higher climate change impacts than the other types, while water scarcity impacts do not show this trend. Li_2CO_3 production averages 49 kg CO_2eq/kg Li_2CO_3 from continental brines and 30 kg CO_2eq/kg Li_2CO_3 from geothermal brines, ranging from 36 to 70 kg CO_2eq/kg Li_2CO_3, with higher impacts at lower Li concentrations. Water scarcity impacts average 2.2 m^3world-eq/kg Li_2CO_3 from geothermal brines and 10 m^3world-eq/kg Li_2CO_3 from continental brines, ranging from 4.8 to 22 m^3world-eq/kg Li_2CO_3. DLE technologies are characterized by high energy demand, particularly from natural gas, leading to elevated climate change impacts. The use of chemicals like Na_2CO_3 and HCl in pre-treatment also contributes significantly to both climate change and water scarcity impacts (e.g. Uyuni). The combination of a high characterization factor (100 m^3world-eq/m^3) and using DLE leads to substantial water scarcity impacts of up to 17 m^3world-eq/kg Li_2CO_3 at Yiliping.

Uncertainties appear due to the wide range of possible DLE technologies[15]. The variability of DLE technologies is difficult to capture due to the unavailability of publicly available data, an issue also emphasized by Vera et al.[33]. One limitation of our study is that only one type of DLE is assessed. We use the DLE technology with the highest Technology Readiness Level[33,56] because other technologies are less well covered in literature. The model only contains one type of adsorbent, which strongly affects the adsorption capacity, water demand for desorption and the lifetime of the resin[33]. Furthermore, the model assumes a constant adsorption capacity, which in reality would decrease over time[51]. Required pre-treatment processes are often not reported, while they are dominating impacts in most cases. Hence, more data on the pre-treatment as well as on the DLE process itself need to be reported by the mining companies to allow better LCA.

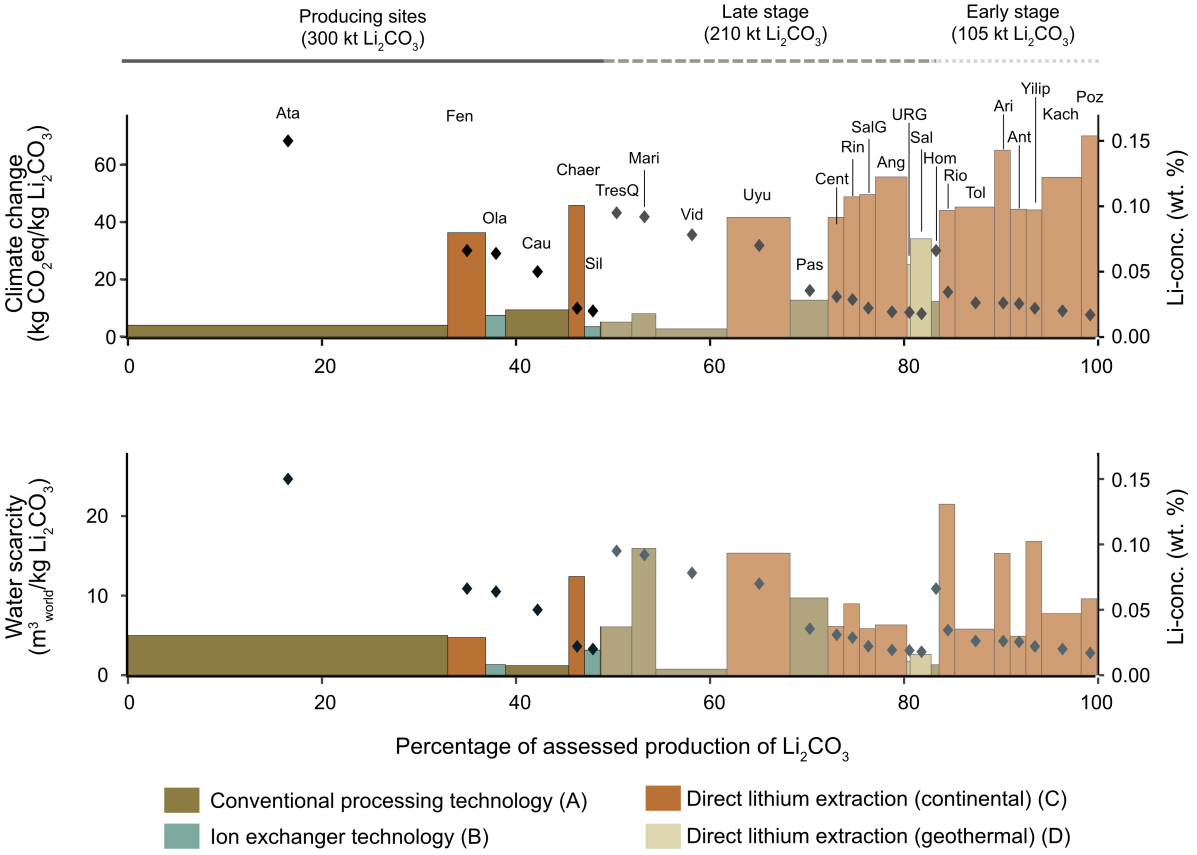

Figure 3: *Climate change and water scarcity impacts of 1 kg* Li_2CO_3 *from continental and geothermal brines (left Y-axis). Reported production in kilotonnes (kt) is plotted on the x-axis and expressed in percentage of the total assessed production mass of* Li_2CO_3*. Diamonds show Li concentrations in weight percent (right Y-axis)*

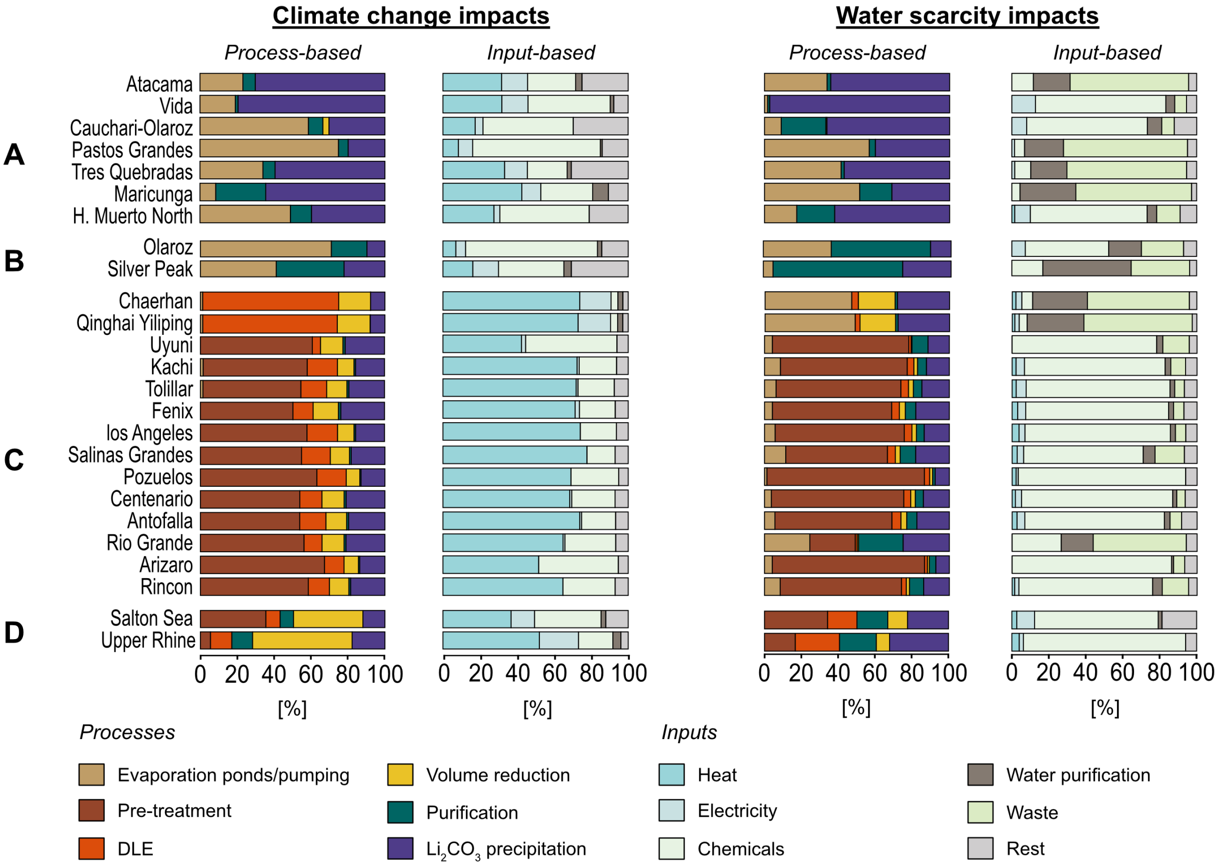

Figure 4: *Process- and input-related contributional analysis of climate change and water scarcity impacts of 1 kg of Li_2CO_3 at battery grade of the investigated sites.*

Comparison with the literature

We find that our observed range for type A (2.8–12.8 kg CO_2eq/kg Li_2CO_3) is similar to the range reported in the literature (2.1–15.1 kg CO_2eq/kg Li_2CO_3) (Table B.5). Studies on the Atacama report impacts ranging between 2.1 and 4.9 kg CO_2eq/kg Li_2CO_3 while this study reveals climate change impacts of 4.1 kg CO_2eq/kg Li_2CO_3. All studies identify Na_2CO_3 as the main contributor to these emissions. Notably, Lagos et al.[57] suggest that the ecoinvent dataset underestimates GHG emissions, reporting 1.6 kg CO_2eq/kg Na_2CO_3 in GREET compared to 0.44 kg CO_2eq/kg Na_2CO_3 in ecoinvent. Using the GREET database, soda ash is the only contributor of climate change impacts and other chemicals become less relevant[57]. However, required chemicals, such as HCl or CaO, also rely on generic data leading to an mis-estimation of climate change impacts[58] which requires sound assessment in the future.

For DLE technologies at Clayton Valley, Mousavinezhad et al.[50] report climate change impacts between 17.3 and 22 kg CO_2eq/kg Li_2CO_3. These results are lower than the average of the Type C sites (49 kg CO_2eq/kg Li_2CO_3) due to lower heating demand assumptions. Their energy demand from industry is towards the lower end of the range reported by Vera et al.[33], which, on the other hand, is primarily based on lab-scale data. The opaque LCI prohibits any detailed evaluation regarding technical differences, such as process temperature, and their implications from a life cycle perspective. Schenker et al.[22] report 31.6 kg CO_2eq/kg Li_2CO_3 for Chaerhan, which is lower than our 46 kg CO_2eq/kg Li_2CO_3, due to higher operating temperature in our model.

Regarding Type D sites, the reported value[27] is 25 % lower than 34 kg CO_2eq/kg Li_2CO_3 modeled in this study. The difference in climate change impacts is explained by the changes in the heating demand due to enhanced re-circulation of heated process water in our presented LCA model. A study by Huang et al.[52] underestimated climate change impacts (2.1 kg CO_2eq/kg Li_2CO_3) due to missing pre-treatment processes which are described in literature[15,59].

Life cycle impacts from a market perspective

Using market data from 2023[10] indicates that the average climate impact of currently producing sites is 18 kg CO_2eq/kg Li_2CO_3, while the average climate change impact of late-stage exploration sites when implementing the reported technology is 30 kg CO_2eq/kg Li_2CO_3 (+70%). Regarding early-stage exploration sites, the average of climate change impacts increases up to 48 kg CO_2eq/kg Li_2CO_3 (+162%). This strong trend of increasing impacts is less observed for water scarcity impacts. We find that the average of producing sites is 4.7 m^3world-eq/kg Li_2CO_3, while late-stage and early-stage sites exhibit an average of 7.3 and 11 m^3world-eq/kg Li_2CO_3, respectively.

Decarbonized energy provision

Continental brines are located in regions with a high solar irradiation, making them optimal locations to use solar energy when producing Li_2CO_3[60]. Changing the energy provision to photovoltaic and Cu-plate collectors on-site enables a significant reduction potential of climate change impacts (Table B.8). Type A sites show a reduction potential of between −19% and −62%. B Type sites have a reduction potential of −11% at Olaroz and −39% at Silver Peak. The reduction potential is even more pronounced for Type C sites due to their energy-intensive processes. The reduction of climate change impacts varies between −48% at Uyuni and −90% at Chaerhan and Yiliping. The high variability of reduction potentials comes from the use of chemicals (e.g. Na_2CO_3, CaO, sulfuric acid) which mainly contribute to the overall climate impacts and hence are not reduced by on-site measures of alternative energy supply. Our findings emphasize the need for site-specific data when developing any decarbonization strategies, as the main drivers for impacts differ substantially between sites. The integration of renewable energies in the mining sector is only one of various levers[61]. Prospective assessments on global decarbonization strategies of entire sectors (e.g. chemicals) are needed to capture the reduced climate change impacts of any Li chemical production and to highlight any benefits and trade-offs.

LIB production

The raw material sector is one of the most significant contributors to greenhouse gas emissions of a produced LIB[62,63]. However, using generic and highly aggregated LCI data can obscure the range of climate change impacts of an LIB[64,65]. For NMC811 batteries, climate change impacts vary between 75.6 kg CO_2eq/kWh and 109.6 kg CO_2eq/kWh of battery capacity, when using site-specific LCIs obtained in this study. Climate change impacts of LFP batteries vary between 90.7 and 151.2 kg CO_2eq/kWh of battery capacity. For both battery types, impacts increase when using Li from early stage sites compared to currently active mine sites. Early-stage exploration sites require sound assessment at the appropriate time as they can substantially increase the impacts of a battery. When comparing these results with existing ecoinvent datasets, we find that impacts increase up to + 139 % for NMC batteries and + 157 % for LFP batteries. The stronger effect in LFP batteries has also been observed by Peiseler et al.[64]. The New Battery Regulation by the European Union[66] defines the reporting of greenhouse gas emissions over the life cycle stages of a battery and aims to reduce the overall carbon footprint of batteries. Our study underlines the need to obtain detailed LCI on process level[67] when estimating climate change impacts of batteries in the future.

Robustness of the model

Figure A7 emphasizes that for each technology group a specific subset of variables requires special focus for improved assessment in the future as they influence the magnitude of life cycle impacts. A compilation of the most relevant parameters affecting processes that contribute >5 % to the impacts can be found in Figure A7 while Table B.10 presents results of the entire range of assessed parameters. For technology groups A and B, heat loss and chemicals (Na_2CO_3 and CaO) are the most sensitive parameters to climate change impacts while chemicals and washing water have generally highest sensitivities for water scarcity impacts within the ranges considered. For C and D sites, heat- and DLE-related parameters are highly sensitive for climate change impacts and adsorption water respectively ion exchanger water are sensitive for water scarcity. Additionally, the brine chemistry highly influences the outcome of life cycle impacts[27]. Thus, chemical analyses of South American salt lakes[68] are used and reveal the substantial variability of impacts at different sites (Figures A4 to A6). Hence, future LCA should include the variability of the brine chemistry, if related data becomes available.

Implications for Li and other battery metals

As the demand for Li will increase over the coming years, it is inevitable to ramp up current production and to open new sites. There is a need to understand the magnitude and the influential site-specific factors of life cycle impacts. Our study shows that the life cycle impacts of Li_2CO_3 and their causes vary among the 25 assessed sites. Currently producing sites have lower life cycle impacts than exploration sites. The variability results from the combination of brine chemistry and applied technology, which implies the need for a holistic approach when assessing life cycle impacts.

The increase of life cycle impacts of the assessed market is primarily caused by the widespread implementation of DLE technologies at new sites, which often features lower Li grades than existing operations. Although DLE technologies have the potential to access previously unreachable Li deposits[33], they come with uncertainties due to limited technological data. Existing sites also face these uncertainties when planning to integrate DLE technologies, with potentially higher impacts than the technology currently used. Future research should focus on addressing these uncertainties and closing these data gaps. Moreover, DLE technologies promise higher recovery rates than conventional technologies, which could alter resource accessibility (e.g. Dewulf et al.[69]). It is crucial to carefully evaluate these potential benefits and trade-offs.

If counter-actions are not developed, life cycle impacts of the Li_2CO_3 market might increase in the future. Our study emphasizes the significant potential of decarbonized energy provision, which can reduce climate change impacts. The variability of reduction potentials, however, underscores the need for site-specific decarbonization strategies.

The future development of the Li market will be shaped by changes in production capacities, electricity mixes, and background supply chains. Technological advancements must be accounted for – especially in such a rapidly developing sector. This includes assessing prospective market development and considering mid-term and long-term perspectives, as was shown for cobalt by van der Meide et al.[70]. Additionally, future research should focus on assessing Li extraction from both primary (e.g. clays and pegmatites) and secondary resources. In particular, Li extraction from secondary resources is still in its infancy and requires scientific assessments for its sustainable development.

Beyond Li, the environmental impacts of other metals required for renewable energy technologies need to be thoroughly assessed in the future (e.g. as demonstrated for the case of copper by Adrianto et al.[71]). This necessity is underscored by recent political measures such as the European Union's Battery Regulation and the Critical Raw Materials Act, which aim to ensure the sustainable and responsible sourcing of essential materials. These regulations mandate stringent environmental standards and transparency in supply chains, further highlighting the importance of comprehensive and transparent data from the mining sector.

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Supporting Information Available

The supporting information of this manuscript contains the following files free of charge:

- Appendix A: PDF file presenting overall model structure to perform a regionalized life cycle assessment and tables on required input data, detailed process description and used sources, further results on brine chemistry and local sensitivity analysis
- Appendix B: Excel file containing raw data on used AWARE characterization factors, input data for the model, results on resource demand, provision of site-specific life cycle inventories
- Appendix C: Github link to the model to perform a global regionalized life cycle assessment of Li_2CO_3 from brines

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