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Review

Life cycle assessment and water use impacts of lithium production from salar deposits: Challenges and opportunities

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ABSTRACT

Lithium is a critical raw material for the energy transition and the salar brine deposits of South America host ~70% of global resources. However, there are concerns regarding water use, and the associated impacts, of lithium production from these deposits. Life Cycle Assessment (LCA) is becoming increasingly prevalent in the analysis of raw materials sustainability, but current methods are regarded as unsatisfactory for assessing water use impacts related to lithium production from salar deposits. This work explores the challenges and opportunities for improvement in this context. We outline how the classification and assessment of water types could be improved and identify Water Availability Assessments, groundwater specific CFs, salar-specific methodologies and multiple mid-point indicators as areas for further investigation. This will aid the development of LCA methodology and enable an improved assessment of the sustainability of lithium production from salar deposits in South America and by extension help decouple decarbonisation efforts from negative impacts.

1. Introduction

Efforts to address climate change will generate unprecedented demand for primary production of metals, even with improvements in efficiency and recycling (Giurco et al., 2019; Sovacool et al., 2020). This includes lithium, with the use of lithium chemicals (notably lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH{\cdot}H_2O$)) in battery technologies making it a key commodity for decarbonisation

From 2017 to 2022, the energy sector drove a tripling of lithium demand (IEA, 2023) and demand is predicted to increase >40x by 2040 compared to 2020 (IEA, 2021). Recycling is predicted to only have a minimal contribution to meeting short-term demand (Olivetti et al., 2017), meaning primary production will be key.

Lithium battery chemicals are currently produced from two sources: spodumene pegmatite ("hard-rock") deposits and brines contained in salars, though production routes from sedimentary, geothermal brines, oilfield brines and other types of hard rock deposits are emerging. Around 70 % of global resources are located in the salar deposits of the high Andes of South America (Flexer et al., 2018; Garcés and Alvarez, 2020; Bowell et al., 2020). This area, referred to as the "Lithium Triangle", includes parts of Argentina, Bolivia and Chile (Fig. 1), and will be key in providing the lithium required to decarbonise

However, akin to production of any battery-grade products, there are sustainability issues associated with lithium production (Ambrose and Kendall, 2020; Alessia et al., 2021). The most commonly used measure of sustainability in the mining sector is the Carbon Footprint, assessed as Global Warming Potential (GWP) in Life Cycle Assessment (LCA) (Berger et al., 2016; Mistry et al., 2016; Westfall et al., 2016; Engels et al., 2022). Production from salars typically has a lower carbon footprint than pegmatite deposits (Jiang et al., 2020; Grant et al., 2020; Kelly et al., 2021; Manjong et al., 2021; Chordia et al., 2022). However, fresh water consumption is also a common LCA impact category and one of the most important factors in resource sustainability assessments (Boulay et al., 2018; Zipper et al., 2020). This is the most significant sustainability concern of lithium production from salars, which potentially reduces water availability to local indigenous communities and sensitive ecosystems (Babidge and Bolados, 2018; Marazuela et al., 2019b; Liu and Agusdinata, 2021; Gutiérrez et al., 2022; Lorca et al., 2022).

This warrants action in its own right, but it is also causing reputational damage, not only to the lithium sector but to electrification

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(Katwala, 2018; Riofrancos, 2021; Campbell, 2022) hampering efforts to decarbonise. Lithium-producing companies are responding by obtaining accreditation with responsible mining schemes (IRMA, 2023) and commissioning LCA studies to quantify, and enable reduction of, the environmental footprint of their products.

Therefore, accurate and consistent water use impact assessment in LCA studies of lithium production from salars is required to help decouple decarbonisation efforts from negative impacts. However, this is complicated by the complexity of salars and limitations of LCA methods when applied in this context (Chordia et al., 2022; Schenker et al., 2022). This paper identifies and reviews the challenges of assessing water use impacts of lithium production from salar deposits in South America and identifies potential ways to improve methodologies and approaches. We focus on the quantitative aspects of water use, however water quality impacts also require research efforts to improve methodologies (Mikosch et al., 2021).

We describe LCA and salar systems and examine lithium production pathways and associated water usage and related impacts. Misconceptions around sustainability and the different water types are also discussed. We then examine the complexity of salars, which challenges for LCA are tied to, as well as the limitations of current LCA methods. Finally, we discuss potential improvements.

1.1. Life cycle assessment

LCA quantifies the environmental impacts of products or processes, in a quantitative manner, across multiple impact categories, for example, Ozone Depletion, Particulate Matter, and Land Use in addition to GWP and Fresh Water Use (ISO, 2006a; ISO 2006b). It is a powerful tool for assessing the sustainability of raw materials production as it can capture the direct and embodied impacts of the energy and materials required to mine, process, and refine products (Meinrenken et al., 2020; Pell et al., 2021). LCA is a key part of battery Carbon Footprint regulations (e.g. European Battery Regulations) and sustainability assessments as it enables quantitative comparisons and identification of environmental 'hotspots'; assessment of multiple impact categories also enables the avoidance of burden-shifting (Farjana et al., 2019; Pell et al., 2019).

LCA is one of the most common methods for quantifying the environmental impacts of lithium-ion batteries (LIBs) and lithium battery chemical production, including in the academic sphere. However. water use impacts are not always assessed (Notter et al., 2010; Stamp et al., 2012; Manjong et al., 2021), or are assessed without water scarcity context (Dai et al., 2019; Jiang et al., 2020). Furthermore, LCA studies tend to focus on global-scale issues, resulting in limited analysis of the raw material production stages and local & regional issues (Petavratzi et al., 2022). A small number have directly assessed water-related impacts at a lithium battery chemical scale (Kelly et al., 2021; Schomberg et al., 2021; Chordia et al., 2022; Schenker et al., 2022).

In general, current water use assessment methods in LCA are considered flawed for various reasons. These include the ability to accurately reflect local conditions (Northey et al., 2018; Kaewmai et al., 2019; Andrade et al., 2020; Sanchez-Matos et al., 2023); problems with application to mining projects (Northey et al., 2016) and groundwater impacts (Northey et al., 2018). However, salar systems are especially complex, exacerbating existing, and introducing new, issues. For these to be understood and rectified an understanding of salars systems, lithium production and its impacts is required, these are presented below.

1.2. Salar systems

Salars are some of the most complex groundwater systems in the world (Petavratzi et al., 2022), with influences from geology, climate, geochemistry, hydrology and hydrogeology (Munk et al., 2016). They often host indigenous communities and precious ecosystems (Babidge and Bolados, 2018; Gutiérrez et al., 2022; Liu and Agusdinata, 2021; Lorca et al., 2022; Marazuela et al., 2019b), including microbes (Bonelli and Dorador, 2021) Salars are typically located in arid/semi-arid basins with water inputs from precipitation, surface, ground and geothermal waters and evaporation as the main natural outflow (Rosen, 1994b; Marazuela et al., 2019a) (Fig. 2). Salars contain significant amounts of water associated with both fresh water and brine. Brines consist of water, sodium chloride and other trace elements – including lithium. The relative mass means water is the most prevalent component, lithium comprises only a small fraction of brine mass (<1 %) (Risacher and Fritz, 1991). Salars are also highly dynamic with temporal aspects ranging from hourly (rain events) to millions of years (brine and halite formation) (Marazuela et al., 2019b; Petavratzi et al., 2022).

Structurally, salars consist of the salar itself, which in a simplified manner can be divided into the nucleus and the transitional (or marginal) zone (TZ), which are contained within the wider basin watershed (Fig. 2).

Each salar differs in type and the amount of fresh water inflow (Risacher and Fritz, 1991; Godfrey et al., 2013; Boutt et al., 2016; Moran et al., 2022). The main fresh water input is surface and ground waters, which whilst small, can be significant for the salar's water balance (Garcés and Alvarez, 2020) and for maintaining the fresh/brackish surface water systems (Fig. 2). Direct rainfall is typically very low (Table 1), and rainfall recharge is limited if present at all in the nucleus and TZ. Periodic surface water flooding can also help maintain the water balance, sporadically in 'drier' salars such as Salar de Atacama (Boutt et al., 2016) and more regularly in 'wetter' salars such as Salar de Uyuni (Petavratzi et al., 2022).

Typically, evaporation is greater than recharge, and the natural trend is for the water table to gradually decline (Marazuela et al., 2019b). Evaporation is a key process for cycling fresh water through the system and concentrating brines. The evaporation rate increases as brine concentration decreases, and has an exponentially decreasing relationship with depth, once the water table is ≥0.5 m below the surface evaporation reduces significantly (Houston, 2006; Marazuela et al., 2020b).

The TZ, comprised of surface water bodies (lagunas), vegas and peatlands, is the most sensitive part of salar systems, hosting precious and delicate ecosystems (Marazuela et al., 2018; Garcés and Alvarez, 2020; Munk et al., 2021). Lagunas, key parts of ecosystem(s), are created when fresh groundwater encounters a barrier (saline wedge) and/or convection cells from the nucleus (Fig. 2) (Salas et al., 2010; Marazuela et al., 2018).

Brines are formed and concentrated in the nucleus, and typically, this is where the greatest lithium concentrations and extraction is located (Rossi et al., 2022). Large-scale convection cells, generated by the sinking of denser brine, control the hydrodynamics; this in turn affects the inflow of fresh water and the position of the brine-fresh water interface in the TZ (Rosen, 1994b; Marazuela et al., 2018). Geochemical processes can also be important in influencing brine evolution and subsequent movement (Risacher and Fritz, 2009; Marazuela et al., 2020a).

2. Lithium production and impacts

A review of the methods of lithium production, and their respective water usages, and as well as the potential impacts on salar systems is given here to highlight the nature of water usage and associated impacts.

2.1. Evaporation ponds, direct lithium extraction and water use

Each brine has a unique composition, requiring a tailored processing method (Wietelmann and Steinbild, 2014), but most follow a common framework of concentration, purification, then chemical processing.

Two types of technologies are used in the concentration and purification of brine - evaporation processes (EP) and direct lithium extraction (DLE) (Fig. 3). These can be applied separately or combined in various

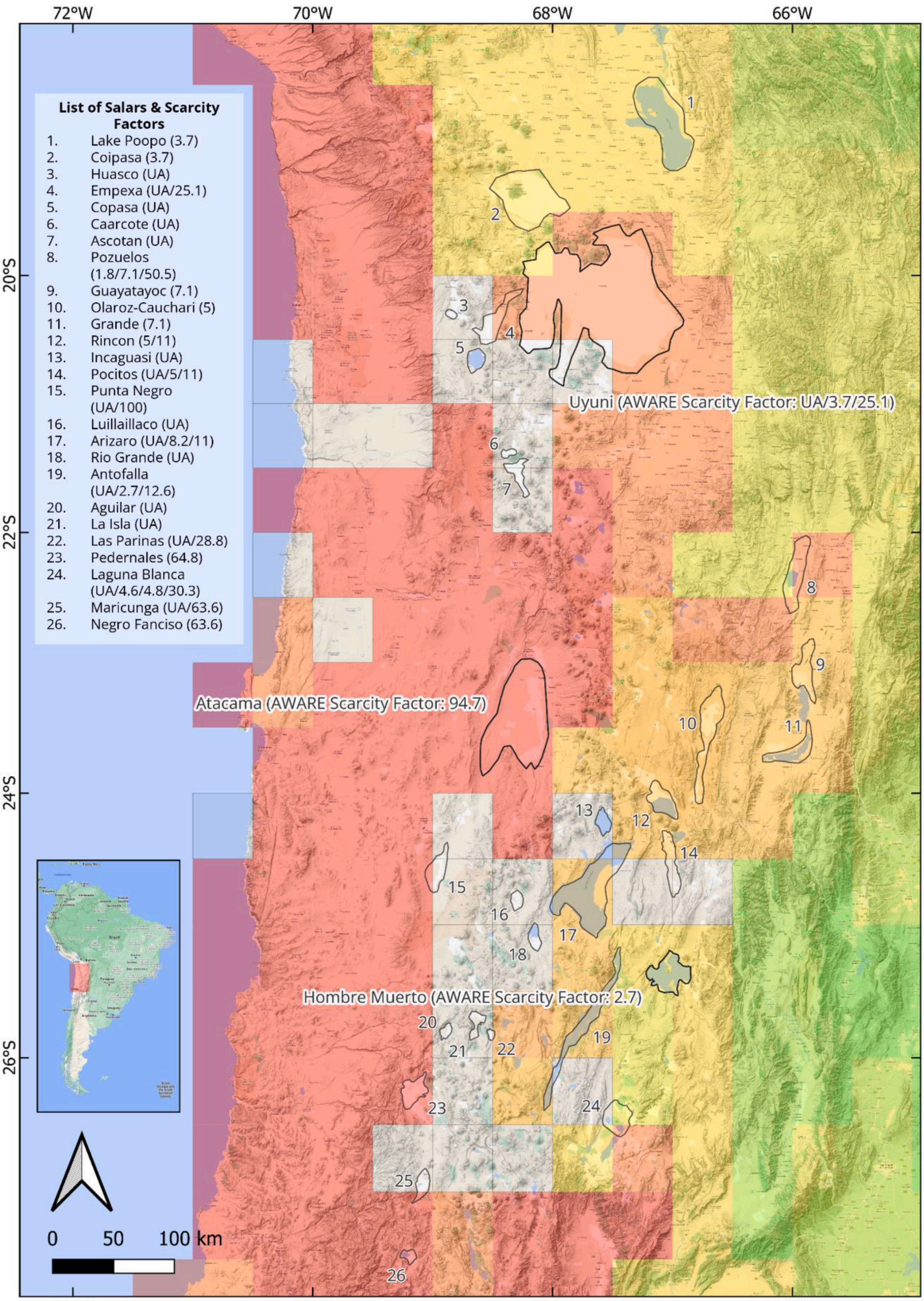

Fig. 1. Map of the Lithium Triangle of Argentina, Bolivia and Chile in South America displaying salars and their respective AWARE Fresh Water Scarcity Factors (SFs). Red corresponds to areas of high-fresh water scarcity, orange medium and green low. Grey represents areas where SFs are unavailable. Salar de Uyuni (Bolivia), Salar de Atacama (Chile) and Salar de Hombre Muerto (Argentina) are highlighted as examples of variability across the Lithium Triangle. It should be noted that a projects or products water scarcity footprint is determined by fresh water scarcity and consumption, not the areas fresh water scarcity alone. Where salars overlap multiple AWARE SFs, the SF covering the majority of the salar has been used. Image generated using data from AWARE (Boulay et al., 2018) and QGIS.

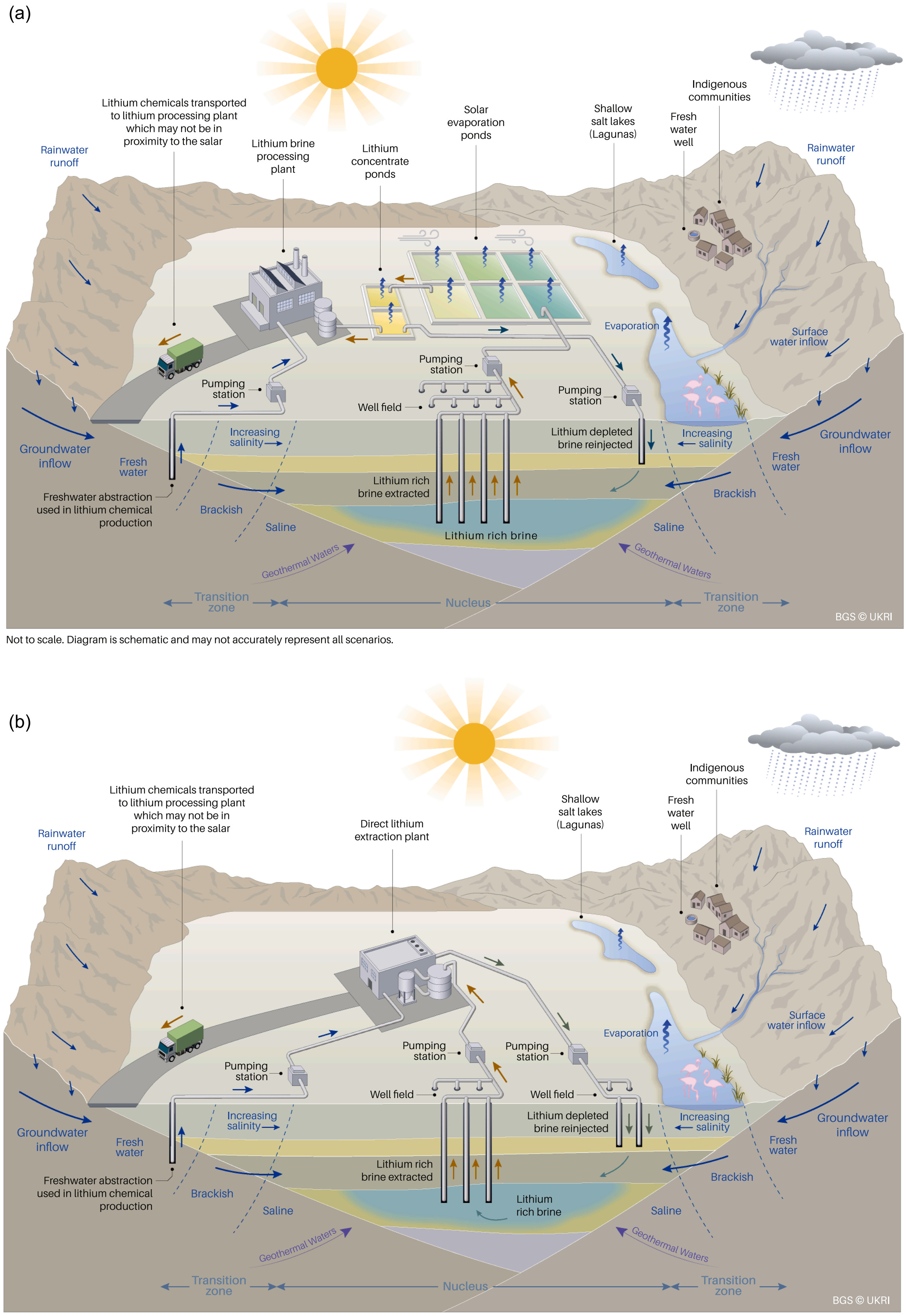

Fig. 2. Schematic block diagram of a salar illustrating brine extraction and concentration with a) evaporation ponds and b) direct lithium extraction (DLE). Hydrogeological and other salar features are also displayed. Diagram is not to scale and is schematic, so may not accurately reflect all scenarios. Position and nature of extraction and reinjection is indicative and may not accurately reflect actual practices.

Table 1
Comparison table of Salar de Uyuni, Salar de Atacama and Salar de Hombre Muerto (Modified from (Al-Jawad et al., 2024)).

Salar	Region/ Country	Summary of Extraction	Operator(s)	AWARE Fresh Water Scarcity Factor*	Technology	Li (mg/l)[a]	Total Dissolved Solids (TDS) (g/l)[a]	Rainfall (mm/yr)[b]	Evapotranspiration (ET) (mm/yr)[c]	Pan area (km2)[c]	Basin area (km2)[d]	Elevation (m.a.s.l)[e]
Uyuni	Potosi, Bolivia	Exploited for KCl for the last few years by YLB. Li output is ~200 tpa.	YLB	25.1	Evap. (for KCl production). DLE under consideration.	715	123	337.02	831.61	12,617.9	47,350.8	3660
Atacama	Antofagasta, Chile	Initially exploited for KCl since 1986 by Abermarle and subsequently SQM. Li output is ~16 ktpa.	Albermarle and SQM	94.7	Evap. (DLE being considered)	1000	181	96.74	1031.75	3522.41	15,658.9	2304
Hombre Muerto	Salta/ Catamarca, Argentina	Exploited for KCl since 1997 by FMC now LIVENT. Li output is ~6 ktpa but with further exploration.	Livent (Fenix)**	2.7	DLE and Evap.	628	167	219.76	805.75	732.72	3888.2	3967

* The 'Annual non-agri' indicator of water scarcity was used. Where more than one AWARE Scarcity Factor area overlaps on the salar area the one covering the majority of the salar has been used.
** Other projects at various stages include: Galaxy Resources - Sal de Vida; POSCO - Sal del Oro ; Galan Lithium - Candelas; Galan Lithium - Hombre Muerto Oeste ; Sino Lithium Materials and Lithium South Development - Hombre Muerto Norte.
a (López Steinmetz and Salvi, 2021).
b (Muñoz-Sabater et al., 2021).
c (Al-Jawad et al., 2024).
d (Lehner et al., 2008).
e (Farr et al., 2007).

orders, with further chemical processing to produce lithium battery chemicals. Typically, Li_2CO_3 is produced first, and converted to LiOH·H2O if required (Flexer et al., 2018; Garcés and Alvarez, 2020; Kelly et al., 2021; Chordia et al., 2022). Processing can take place at the salar,or off-site. The varying brine consumption, water loss through evaporation and fresh water consumption of EP and DLE are presented in Table 2 and Fig. 3, though comparison is complicated by differences in units and approaches between studies.

2.1.1. Evaporation processes

During EP, solar and wind-driven evaporation progressively concentrates the brine in a succession of evaporative ponds (Fig. 2). Different intermediate salts may be harvested as they precipitate and impurities removed (Swain, 2017; Flexer et al., 2018; Garcés and Alvarez, 2020). Fresh Water is also consumed in the process (Kelly et al., 2021). EP have a lithium recovery rate of 30–50 %. While 85–95 % of water contained within the brines is lost through evaporation (Flexer et al., 2018).

2.1.2. DLE

DLE is a blanket term used to refer to several different technologies that actively concentrate lithium (Tabelin et al., 2021; Vera et al., 2023). DLE processes have higher lithium extraction efficiency, potentially up to 90 %, and a significantly reduced surface footprint compared to EP (Fuentealba et al., 2023).

There is a degree of uncertainty around the fresh water requirements of DLE as it has yet to be widely deployed at a commercial scale on a range of brine compositions. Vera et al. (2023) found in a quarter of articles they analysed that fresh water requirements of DLE were >500 m^3 per tonne of Li_2CO_3, an order of magnitude greater than EP. Though similar or lower fresh water consumptions for EP were found in ~40 % of reports with the remaining articles not reporting fresh water consumption values (Fuentealba et al., 2023). This could be related to the use of different elution solutions e.g. acid in place of water.

Furthermore, at Hombre Muerto the overall water use, for a hybrid EP and DLE scheme, is reported as 71 m^3 per tonne of Li_2CO_3, 200 % and 50 % higher than volumes used at Salar de Atacama and Salar de Olaroz, respectively (Vera et al., 2023). Though it is worth noting that at Hombre Muerto, DLE processes only a fraction of the extracted brine. Fuentealba et al. (2023) state that, considering this, and that fresh water consumption of the EP at Hombre Muerto could be similar to Atacama and Olaroz, the fresh water requirement of the DLE process could be twice that of EP.

Overall, DLE techniques are considered to require more fresh water, while EP consume more brine (Fig. 3). However, introduction of water recycling could reduce the requirements and footprint of DLE processes. There is currently no clear advantage to one of these technologies in terms of an overall impact on a salars hydrogeology or availability of water to communities and ecosystems. This will not only be influenced by the technology used, but lithium concentration and impurities in brines,local hydrogeology and climatic conditions.

When considering the overall sustainability benefits of DLE compared to EP, the increased energy requirements and energy source, as well as the embodied environmental footprint of the DLE plant and process, expected to be higher compared to the relatively straightforward EP method, need to be considered.

2.1.3. Reinjection

Post-concentration lithium-depleted brine may be returned to the salar through reinjection (Fig. 2 and 3), for EP this can return around 15–20 % of the depleted brine (Fuentealba et al., 2023). Given the higher extraction efficiency, it would be expected that DLE presents a higher, albeit <100 % return (Flexer et al., 2018), of processed brine to be available for reinjection.

Reinjection is currently utilised in the Salar de Atacama (Marazuela et al., 2020b; Petavratzi et al., 2022) and proposed elsewhere

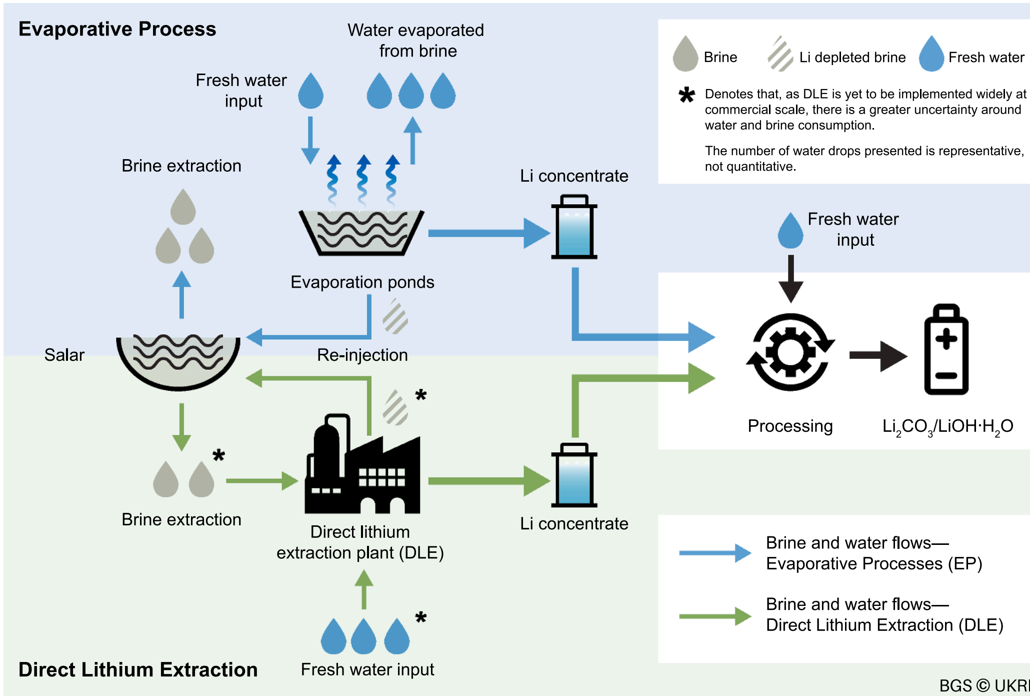

Fig. 3. Schematic diagram showing the differing lithium production pathways and brine/water usages per unit of lithium battery chemical production from salars using Evaporation Processes and DLE based on data in Table 2. It is important to note that EP and DLE can be used in conjunction in a variety of orders as well as separately. The number of drops is representative of the quantity that is thought to be used, it is not quantitative.

(Bloomberg, 2023). Benefits of reinjection include returning solutes, including remaining lithium, to the salar, potentially helping to maintain the chemical properties of the brine and system. Furthermore, the impacts of brine abstraction could be partially mitigated by injecting depleted brine between the wellfield and sensitive locations (lagunas), reducing water/brine table drawdown and subsequent effects.

2.2. Brine and fresh water related impacts

Brine and fresh water-related impacts can be divided into those relating to:

1) brine abstraction
   a) causing indirect drawdown of fresh water
   b) affecting the geochemistry of the system
2) fresh water abstraction
   a) causing direct drawdown of fresh water
   b) affecting the geochemistry of the system
3) brine reinjection
   a) reducing the indirect drawdown of fresh water
   b) affecting the geochemistry of the system

All of the above can individually and collectively affect water availability and impacts will be unique to each salar and project, with the hydrogeology, hydrology, geomorphology, geology, elevation and technology used all influencing how impacts materialise (Flexer et al., 2018; Pell et al., 2021; Munk et al., 2021).

Brine abstraction affects the inflow of fresh water from salar margins and/or depth, and therefore potentially fresh water availability in the wider system (Fig. 2); but there is no linear relationship between brine abstraction and decreases in water storage (Marazuela et al., 2019b). Fluctuations in the water table and brine concentration, influenced by reinjection as well as abstraction, can affect the evaporation rate (Houston, 2006; Marazuela et al., 2019b, 2020b). In turn, this could impact the salars hydrogeology, especially brine circulation, fresh water inflow, the position of the brine-fresh water interface (Rosen, 1994b; Marazuela et al., 2020b) and subsequently lagunas, ecosystems and fresh water availability to communities.

Operations also often have separate fresh water supplies, with the potential to directly reduce groundwater levels, impacting availability to ecosystems and communities as well as introducing salinity into fresh parts of the system (Fig. 2) (Herrera et al., 2016; Petavratzi et al., 2022). Fresh Water abstraction is thought to have a direct and larger impact than brine abstraction on wetlands, lagunas and fresh water resources (Moran et al., 2022). However, it should be noted that in some areas the fresh water may not be suitable for human consumption without further treatment (Concha et al., 2010; Flexer et al., 2018).

Reinjection could cause undesirable impacts. Depleted brines are likely to be of a different chemical composition to raw brine, especially those from DLE due to the leaching of active materials and/or chemical treatments (Vera et al., 2023). This may alter the geochemistry of the salar system; there are also concerns reinjection could cause dilution and/or disruption to the stratigraphic structure (Flexer et al., 2018).

2.3. Sustainability of fresh water, brine and lithium in salars

There are some areas of ambiguity when discussing sustainability in this context. Whilst the region is arid/semi-arid, salars do receive significant fresh water inflows (Rossi et al., 2022), meaning sustainable fresh water abstraction is theoretically possible depending on the contemporary recharge vs. withdrawal rate. This requires thorough assessment on a case-by-case basis.

Despite its salinity, on a mass balance scale, water constitutes the majority (~80 %) of brine. Given the likely, but unconstrained depth of aquifers (due to limited detailed assessments) this 'contained' water could constitute a substantial volume. However, this is difficult to assess and may have limited recharge so could be seen as being 'mined' by abstraction. As for brines, whilst they are continually created, this requires 100,000–1000,000's of years, they are not recharged on 'human' timescales. Brine creation was also influenced by differing climatic conditions in the past.

Lithium battery chemical production causes a net reduction of

Table 2
Summary table of brine and water usages of evaporative ponds and DLE processing pathways.

Evaporative ponds Brine/water in brine consumption *Value*	*Unit*	*Per unit/Narrative*	*Location*	*Study/Source*
0.06667	kg	Raw brine per kg of LCE	Salar de Atacama, Salar de Hombre Muerto, Salar de Uyuni	Schomberg et al., 2021
4.19	kg	Concentrated brine per kg of LCE	Salar de Atacama	Schomberg et al., 2021
23,400,000	m3	Annually abstracted brine used to produce lithium (60 % of total brine extraction)	Salar de Atacama	Kelly et al., 2021
24.1	t	Raw brine per t of concentrated brine	"	"
96.4	"	Raw brine per t Li2CO3	"	Kelly et al., 2021 and own calculations*
101.22	"	Raw brine per t LiOH*H2O	"	"
788	m3	Water in brine per t LiOH*H2O	Salar de Cauchari	Chordia et al., 2022
693	"	"	Salar de Atacama	"
450	"	"	Salar de Maricunga	"
654.05	t	Raw brine per t of Li2CO3	Salar de Cauchari	Chordia et al., 2022 and own calculations*
485.645	"	Water in brine per t of Li2CO3	"	"
403.92	"	Raw brine per t of Li2CO3	Salar de Maricunga	"
297.792	"	Water in brine per t of Li2CO3	"	"
Water loss from brine through evaporation				
130	kg	kilogram of Li2CO3	Salar de Atacama	Stamp et al., 2012
620	kg	kilogram of Li2CO3	Salar de Uyuni	"
500,000	L	Water in brine per tonne of Li2CO3	–	Flexer et al., 2018
40.5089	kg	Per kg of concentrated brine	Salar de Atacama	Schomberg et al., 2021
98.215	kg	Per kg of concentrated brine	Salar de Hombre Muerto	Schomberg et al., 2021
163.6605	kg	Per kg of concentrated brine	Salar de Uyuni	Schomberg et al., 2021
20,710,344	"	Quantity of water contained within the annually abstracted brine used to produce lithium	Salar de Atacama	Calculated from Kelly et al., 2021**
17,000,000	m3	Quantity of water evaporated, representing 81.93 %, of water used to produce lithium annually	"	Kelly et al., 2021 (percentage calculated)
200 - 1400	m3	water lost from brines per ton of Li contained in the extracted brine	Chile	Cerda et al., 2021
500,000 - 1000,000	L	Brine water per tonne of Li2CO3***	–	Marconi et al., 2022
451.14	t	Evaporated water per t of Li2CO3	Salar de Cauchari	Chordia et al., 2022 and own calculations*
282.744	"	Evaporated water per t of Li2CO3	Salar de Maricunga	"
100 - 800	m3	Water in brine per tonne of Li2CO3	–	Vera et al., 2023
Fresh Water consumption				
0.414	m3	Per kg of concentrated brine	Salar de Atacama	Schomberg et al., 2021
0.0991	m3	Per kg of concentrated brine	Salar de Hombre Muerto	Schomberg et al., 2021
0.1646	m3	Per kg of concentrated brine	Salar de Uyuni	Schomberg et al., 2021
2.40 - 5.94	m3	Tonne of concentrated brine	Salar de Atacama	Kelly et al., 2021
10.9	"	Tonne of LiOH*H2O - Facility level allocation (mass)****	"	"
26.3	"	Tonne of LiOH*H2O - Facility level allocation (economic)	"	"
16.7	"	Tonne of LiOH*H2O - Product level allocation	"	"
10.7	"	Tonne of LiOH*H2O - Process level allocation	"	"
80,000 - 140,000	L	Tonne Li2CO3	–	Marconi et al., 2022
307	m3	Tonne LiOH*H2O	Salar de Cauchari	Chordia et al., 2022
71	"	"	Salar de Atacama	"
326	"	"	Salar de Maricunga	"
38	kg	1 kg Li2CO3	Salar de Atacama	Schenker et al., 2022
219	"	1 kg Li2CO3	Salar de Olaroz	"
46	"	1 kg Li2CO3	Salar de Cauchari-Olaroz	"
43	"	1 kg Li2CO3	Salar de Hombre Muerto*****	"
22.5	m3	Tonne Li2CO3	Salar de Atacama	Vera et al., 2023

(*continued on next page*)

Table 2 (*continued*)

Value	*Unit*	*Per unit/Narrative*	*Location*	*Study/Source*
Evaporative ponds				
Brine/water in brine consumption				
50	"	Tonne Li2CO3	Salar de Olaroz	"
Direct lithium extraction				
Brine consumption				
383	m3	Tonne Li2CO3 - 700 ppm brine (70 % recovery)		Vera et al., 2023
2684	"	Tonne Li2CO3 - 100 ppm (70 % recovery)		"
587.1	"	Estimated minimum volume of brine required per tonne Li2CO3******	Salar de Uyuni	"
119.7	"	Estimated minimum volume of brine required per tonne Li2CO3	Salar de Atacama	"
329.6	"	Estimated minimum volume of brine required per tonne Li2CO3	Salar de Olaroz	"
208.7	"	Estimated minimum volume of brine required per tonne Li2CO3	Salar de Hombre Muerto*****	"
Fresh Water consumption				
474	kg	1 kg Li2CO3	Chaerhan*******	Schenker et al., 2022
>500	m3	Tonne Li2CO3	–	Vera et al., 2023
71	m3	Tonne Li2CO3	Hombre Muerto*****	"

* Calculated as the quantity of raw brine (t) required per t of concentrated brine multiplied by the quantity of concentrated brine (t) required per t of battery chemical (Li2CO3 or LiOH*H2O).
** Calculated as 88.46 % of the amount of brine used to produce lithium annually. 88.46 % was derived from the given amount of water within brine in Kelly et al., 2021.
*** Unclear if referring to water within brine or brine.
**** Per Kelly et al. (2021) fresh water is not consumed in converting concentrated brine to Li2CO3 but 0.5m3 is required to convert a tonne of Li2CO3 to a tonne of LiOH.
***** According to Fuentealba et al. (2023) at Hombre Muerto DLE processes a fraction of brine and considering this and that fresh water consumption of the evaporation ponds could be similar to Atacama and Olaroz the fresh water requirement of the DLE process could be twice of the conventional method.
****** Assuming a recovery efficiency of 100 % and brine density of 1.2 g *l* − 1.
******* The Chaerhan operation is located in China but is included here for comparison.

lithium within the salar. Whilst this may represent a small percentage year-on-year, nonetheless a reduction occurs meaning lithium is not sustainably produced per the true definition. Though this is true for conventional mining as well. Overall, it should be noted that discussions on the sustainability of lithium production revolve around responsible production with minimal negative and maximum positive impacts.

3. LCA water use impact assessment methodology

Consequences of fresh water use can be assessed as an impact category within LCA or as a stand-alone Water Footprint (WF) (ISO 14046). The most common method is the Available WAter REmaining (AWARE) method, which produces a water scarcity footprint (WSF). AWARE, based on the WaterGap 2.2 global hydrological model (Müller Schmied et al., 2014), quantifies the relative amount of fresh water remaining after the demands of aquatic ecosystems and anthropogenic activities are met. It aims to assess the extent to which fresh water users (humans and ecosystems) are at risk of fresh water scarcity or deprivation due to operational fresh water consumption (Boulay et al., 2018).

Geographic variations in fresh water availability are accounted for through spatially explicit characterisation factors (AWARE Scarcity Factors (SFs)) (Fig. 1) (Boulay et al., 2018). Data for fresh water availability is sourced from WaterGAP 2.2 (Müller Schmied et al., 2014), human demand data (represented by human consumption) from Flörke et al. (2013) and ecosystem demand data from Pastor et al. (2014).

AWARE SFs are calculated as the water Availability Minus Demand (AMD) (demand being of humans and aquatic ecosystems) relative to the area over the timespan of a month (m^3m^{-2} $month^{-1)}$. This is normalised against the world average, so the final value is relative to the global average (Boulay et al., 2018).

The AMD value is then inverted to create a factor that is the inverse of fresh water remaining. This value is limited to a range of 0.1–100, where 1 is the world average. These final values are AWARE SFs (also known as Characterisation Factors; CFs). As an example, a SF of 50 represents a region with 50x less available fresh water remaining per area per month than the world average (Boulay et al., 2018).

AWARE is a midpoint indicator, assessing the potential of a project or operation to deprive humans and ecosystems of fresh water, rather than an assessment of 'materialised' (i.e. end-point) impacts. It is also important to note that with AWARE the WSF results are determined by fresh water scarcity and consumption, not solely the fresh water scarcity of the operational area.

4. Salar complexity and LCA limitations

4.1. Salar complexity & variability

The complexity of salar systems requires attention so that the numerous interacting features of these systems and related LCA limitations can be better understood. While there are similarities between salars in the Lithium Triangle, there are also significant differences (Al-Jawad et al., 2024), as displayed in Table 1. There are also differences between salar nuclei (Fornari et al., 2001; Godfrey et al., 2013; Marazuela et al., 2019a), laguna size, density and their connection to the groundwater system (Godfrey et al., 2013; Boutt et al., 2016; Rossi et al., 2022). The heterogeneity of salar systems affects how abstraction and reinjection will be transmitted to environmentally sensitive receptors and their vulnerability to environmental harm.

Numerous salar features need to be considered in understanding the environmental impacts of lithium production, including the quantity and nature of inflows, the surface water features (lagunas), the nature and properties of the aquifer and the longevity and characteristics of abstraction. The complexity of salar systems, and therefore the potential impacts of lithium production is currently difficult to fully capture and reflect with current LCA practices. Potential ways forward are discussed in Sections 5 and 6.

Table 3
Summary table of three studies on the water use impacts of lithium battery chemical production from salar deposits using LCA.

Study	Functional unit of study*	Location	Water impacts assessment method	Results	
Kelly et al., 2021	1 tonne Li2CO3/LiOH·H2O	Salar de Atacama & Antofagasta (Chile)	Water Consumption	*Li2CO3*	
				Facility Level (Mass)	15.5 m3/tonne
				Facility Level (Value)	32.8 m3/tonne
				Product Level	22.9 m3/tonne
				Process Level	16.4 m3/tonne
				LiOH H2O	
				Facility Level (Mass)	31 m3/tonne
				Facility Level (Value)	50 m3/tonne
				Product Level	39 m3/tonne
				Process Level	32 m3/tonne
Chordia et al., 2022	1 tonne LiOH·H2O	Salar de Atacama (Chile)***	ReCiPe	*Li2CO3***	76.2 m3/t
		Salar de Cauchari (Argentina)			235.44 m3/t
		Salar de Maricunga (Chile)			321.33 m3/t
		Salar de Atacama (Chile)***		*LiOH H2O*	80.2 m3/t
		Salar de Cauchari (Argentina)			244.1 m3/t
		Salar de Maricunga (Chile)			327.22 m3/t
			AWARE ****	*Li2CO3***	4199.59 m3/t
		Salar de Atacama (Chile)***			10,301.21 m3/t
		Salar de Cauchari (Argentina)			18,176.96 m3/t
		Salar de Maricunga (Chile)			
				LiOH·H2O	4370.89 m3/t
		Salar de Atacama (Chile)***			10,673.1 m3/t
		Salar de Cauchari (Argentina)			18,429.4 m3/t
		Salar de Maricunga (Chile)			
Schenker et al., 2022	1 kg Li2CO3	Salar de Atacama (Chile)	AWARE	*Li2CO3*	4.77 m3 world eq/kg
		Salar de Olaroz (Argentina)			1.73 m3 world eq/kg
		Salar de Cauchari-Olaroz (Argentina)			1.62 m3 world eq/kg
		Salar del Hombre Muerto (North) (Argentina)			1.36 m3 world eq/kg
		Chaerhan salt lake (China)			35.25 m3 world eq/kg

[*] Studies also examined how variations in the impact of Li battery chemical production affects the impacts of Li-Ion battery production.
[**] Calculated based on data available in SI 5.3.2.
[***] Data from Ecoinvent and Kelly et al., 2021 is presented for Atacama, data from Kelly et al., 2021 has been presented here due to it being a primary source.
[****] Units are those reported (m3/t) as opposed to those used in the reporting of AWARE results (m3 world eq/kg).

4.2. Limitations and complications of LCA methodology

4.2.1. Water use assessment methodology

AWARE is valuable for assessing and comparing projects in a global context, but underlying models have a limited resolution so may not accurately reflect local fresh water scarcity and impacts (Northey et al., 2018; Kaewmai et al., 2019; Andrade et al., 2020; Sanchez-Matos et al., 2023). This, for reasons explored earlier, is especially problematic in complex salar systems.

Additionally, data for human-associated fresh water demand (Flörke et al., 2013) is based on models from 2010, so is now over a decade behind population growth, industrialisation and associated increased demand. Also, not all kinds of human consumption (e.g. mining) are considered in the hydrological model, this may lead to AWARE SFs being underestimated by up to 100 % in some basins (Schomberg et al., 2021). Furthermore, anthropogenic activities may consume more fresh water than just the activities accounted for, and ecosystems may consume more fresh water if it was available to them (Boulay et al., 2018).

Northey et al. (2016) highlighted limitations when applying AWARE to 'traditional' (i.e., non-salar-based) mining projects a) availability of mine site water use data; b) availability of inventory data for mining supply chains; c) uncertainty of post-closure impacts; d) accounting for cumulative impacts and extreme events. These are also applicable to salar-based mining projects.

There are also limitations specific to applying AWARE to salar-based projects. AWARE is not designed to assess potential impacts of groundwater depletion and is underdeveloped regarding this (Northey et al., 2018). Furthermore, WaterGAP is calibrated to estimate discharge from major river systems (Alcamo et al., 2003; Müller Schmied et al., 2014). This means that while the renewable part of groundwater is considered, fossil groundwater is omitted. Fossil groundwater can constitute an important part of the modern water balance in salars, such as Salar de Atacama (Moran et al., 2022).

Furthermore, fresh water demands of ecosystems were proxied using the requirements of fresh water ecosystems. The demands of terrestrial and groundwater-dependant ecosystems, such as those found in salars, were not included. This was due to the ambiguous link between blue water consumption and terrestrial ecosystems; however, this is not considered ambiguous regarding groundwater table lowering or wetlands lowering (van Zelm et al., 2011; Verones et al., 2013; Boulay et al., 2018). Meaning the fresh water demands of ecosystems surrounding salars are unlikely to be accurately reflected in AWARE SFs.

Uncertainty with AWARE data varies significantly and tends to be more substantial in regions of higher scarcity (Boulay et al., 2021), common in the Lithium Triangle (Fig. 1). There are areas, containing salars of economic interest, where AWARE SFs are unavailable and/or salars overlap differing SFs (Fig. 1). Without SFs it is not possible to calculate a WSF, meaning the important context of fresh water scarcity is omitted. Salars geographically overlapping multiple SFs is problematic as it introduces subjectivity into the choice of SF, which can significantly influence results (Schenker et al., 2022).

4.2.2. Allocating impacts to co-products

As many salar brines are rich in multiple solutes in addition to lithium, co-production is common e.g. potash (Table 1). This can complicate LCAs, as the elementary flows and impacts must be assigned to the multiple products through multi-output allocation. This is amongst the most sensitive aspects of LCA given its potentially significant influence on results (Cherubini et al., 2011).

Kelly et al. (2021) had access to detailed data from SQM for their Salar de Atacama operations, enabling them to utilise multiple allocation approaches, process-, product- and facility-level (including mass and economic value allocation), and examine the effect on results of the production of concentrated brine. The variance in results between allocation methods of Kelly et al. (2021) (Table 3) demonstrates how these choices can impact LCA results, not only of the studied product (concentrated brine in this case) but also follow-on products i.e. lithium battery chemicals and batteries.

4.2.3. Differing LCA approaches

The use of LCA for assessing water-related impacts of lithium battery chemicals production from salars is an emerging technique, with only a few publicly available studies at the point of writing (Kelly et al., 2021; Schomberg et al., 2021; Chordia et al., 2022; Schenker et al., 2022). The approach and results of these studies are summarised in Table 3. Comparison between studies is difficult due to a lack of consistency in functional units, system boundaries, background methodology and approaches in the classification of brine.

Schomberg et al. (2021) created a new spatially explicit WSF methodology for LIBs, based on the AWARE method, and compared the change in fresh water availability using the safe operating space outlined by the Sustainable Development Goals. The evaporation of water molecules within brine was treated as fresh water consumption. They found that a 2 MWh LIB resulted in a 33.155 regionally weighted m^3 WSF, with highest contributions from Chilean lithium, but WSF results at a lithium battery chemical scale were not presented and as such are not present in Table 3.

Kelly et al. (2021) reported on direct fresh water and brine consumption only, rather than producing a WSF with AWARE. The water component of brine was not treated as fresh water consumption because "it cannot be used directly for human activities and is differentiated from fresh water consumption in water resource analysis". Fresh Water pumped from groundwater outside of the salar was included to compensate for brine evaporation.

Chordia et al. (2022) utilised the AWARE method as well as the ReCiPe method (Table 3). They also used the water content of brine to estimate the amount of water (contained within brine) extracted per tonne of $LiOH \cdot H2O$.Compared to fresh water use, they found the brine volumes to be significantly higher (Table 3).

Schenker et al. (2022) found that impacts at Salar de Atacama mainly originate (81 %) from the direct use of fresh water at the processing plant. The Chaerhan Salt Lake in China was also studied and is included here for comparison and as an example of the potentially higher fresh water consumption of DLE (Table 3).

These studies have used a variety of methods and approaches, most notably there is a lack of consensus on the methodology for the assessment of brine, also highlighted by Schomberg and Bringezu, 2023. Some studies agree with accounting for brine evaporation within WF methods (AWARE) (Schomberg et al., 2021; Chordia et al., 2022; Schomberg and Bringezu, 2023), while others state that brine should not be counted as water consumption (Kelly et al., 2021; Schenker et al., 2022), akin to indstry approaches (Albermarle 2022).The treatment of brines in LCA assessments is discussed further in Section 5.2.

5. Discussion

5.1. Impacts and uncertainty

Hydrogeological understanding of salars, and by extension how ecosystems and communities may be impacted by abstraction, is limited (Moran et al., 2022). Determining impacts is difficult given the aridity of the region, system complexity, variation of climate conditions and the system's response potentially taking years or even decades to materialise (Rossi et al., 2022). Further details on salar features and their relation to environmental impacts are presented in S1.

At the Salar de Atacama, the most studied, the nature and extent of impacts is debated. Some studies have linked lithium production to changes in the dynamics of the water table, groundwater depletion and as impacting ecosystems (Marazuela et al., 2019b, 2020b; Garcés and Alvarez, 2020; Liu and Agusdinata, 2021). However, Moran et al. (2022) established lithium production corresponds to only 8 % of total fresh water abstraction in the basin and that total water storage has increased significantly over the past decade; going on to state that the claim lithium production in the Salar de Atacama affects surface water ecosystems is not scientifically supported.

Salar variability (Table 1) means it is difficult to generalise one salar's behaviour from another with Atacama existing as an end-member of complex and variable systems (Al-Jawad et al., 2024). Given the complexity of salars, it is important to develop a well-founded understanding of the system behaviour and interaction between the salar nucleus and any environmental features e.g. lagunas.

Salar systems are sensitive to both climatic and anthropogenic influences (Rosen, 1994a). Anthropogenic derived impacts can only be accurately understood and attributed after accounting for the influence of natural variations (Moran et al., 2022). Impacts should also be considered in the wider context of other water uses within the basin, such as tourism and agriculture (Gössling et al., 2012). In the Salar de Atacama watershed, copper mining and agriculture are the largest fresh water consumers, with the greatest groundwater storage losses occurring where these users are concentrated (Moran et al., 2022).

Uncertainty surrounding the impacts of lithium production complicates prioritising areas for LCA development. Further work is needed for the link between abstraction and the response of the system to be better established (Petavratzi et al., 2022), this in turn will help inform development of LCA.

5.2. Classification and assessment of water types

Classification and assessment of brine in LCA is one of the most controversial topics in the literature, with studies using different approaches (Kelly et al., 2021; Schomberg et al., 2021; Chordia et al., 2022; Schenker et al., 2022). Schomberg and Bringezu, 2023 set out "if brine water evaporation should be assessed at all, and if so, how" as a key question for the research space.

Debate focuses on the 'value' and nature of brines. Flexer et al. (2018)defines fresh water as water with Total Dissolved Solids (TDS) below 10 g L^{-1}. Brines tend to have TDS values at least an order of magnitude higher than fresh water (Table 1). Due to their salinity brines are unsuitable for drinking or irrigation (Flexer et al., 2018) and are not directly used by aquatic ecosystems or humans as a water source. Consequently, brine would not be considered as fresh water and therefore not assessed by the AWARE method (Boulay et al., 2018; Schenker et al., 2022).

While most LCIA methods are designed to assess fresh water, which is a fit-for-purpose approach in most scenarios, in salar environments this is not sufficient to accurately capture all water related impacts. As brine is in hydrodynamic relation with the salar system (Marazuela et al., 2019a) and its abstraction is thought to influence fresh water availability (Garcés and Alvarez, 2020; Marazuela et al., 2020b; Liu and Agusdinata, 2021) its abstraction, and associated impacts should be assessed. Ideally, the impacts of both brine abstraction on fresh water and water loss through evaporation from brine would be considered. However, brine-related impacts should not be treated as equivalent to fresh water consumption as the water contained within brine is not available for anthropogenic uses, though it may support other organisms and ecosystems (Cubillos et al., 2018).

Classifying and assessing brine is a unique situation that requires a pragmatic approach drawing upon existing guidance and frameworks/methods where applicable. ISO 14046 provides principles, requirements and guidelines for conducting WF assessments based on LCA principles (ISO, 2014). Under ISO 14046 fresh water is defined as typically <1000 mg/L of TDS and being generally acceptable for withdrawal and conventional treatment to produce potable water. Broadly, fresh water present around salars and/or in the TZwould be expected to meet this definition and therefore treated as such in assessments. "Brackish" is defined as containing less TDS than seawater (TDS 1000 – 30,000 mg/L) but exceeding normally acceptable standards for municipal, domestic or irrigation uses. Despite higher TDS than seawater, under these definitions brine could be classified as brackish waters in assessments. This is partly for potential applicability in Water Availability Footprints (5.3).

Within AWARE, in order not to be classed as consumption, water has to be returned to the same watershed and be of the same quality. It could be argued due to the difference in geochemical properties reinjected brine would still count as consumptive water use. However, further data on quantities and the geochemical properties is needed.

It may also be necessary, in addition to assessing brine and fresh water, that other types of industrial water and its usage(s) be assessed. This could cover water that does not fall into the classification of fresh water or brine, e.g. water used within processing plants, that may be treated wastewater and/or partly recycled.

5.3. ISO14046 and Water availability footprints

AWARE is a WSF under ISO 14046, while ISO 14046 was not developed with salars in mind, rather than proposing specific methods, it defines criteria which must be fulfilled (Berger et al., 2016). It provides useful information and guidance which can aid the development of a consensus approach and improved methodologies.

ISO 14046 states that water issues are local in character and related to specific drainage basins and precipitation, hydrological and geographic factors and climatic, ecosystemic and socio-economic conditions. Assessments conducted under ISO 14046 should consider these local factors, including temporal aspects and utilise characterisation factors (CFs) derived from models which account for local differences in water scarcity. AWARE does meet this guidance, but only to an extent. There is scope for improvement of models and CFs regarding the consideration of local, and regional factors as well as those relating to salar complexity. Though this is not without issue itself, see Section 5.4.

The ISO 14046 definition of water use includes any withdrawal, or release of other anthropogenic activities within the basin impacting water flows and/or quality including in-stream uses. Water consumption is defined as water removed from, but not returned to, the same basin including due to evaporation and/or integration into a product or release into a different basin or sea. Changes in evaporation caused by land-use changes are also considered water consumption (ISO, 2014). Based on these definitions brine abstraction and reinjection would be considered as water use impacts and water lost through brine evaporation and changes in evaporation rate considered as water consumption.

WSFs are one type of WF, an alternative is Water Availability Footprints (WAF). WAFs include temporal and quality aspects (which can influence the availability of water) as well as the potential to assess pressure on other types of water in addition to fresh water, they can also comprise one or several impact categories (ISO, 2014). This may allow the assessment of brine and fresh water as distinct water types, in addition to other features such as water quality, but within one methodolgical framework. Due to these features and potential, we suggest exploring WAFs as a technique for potential application to lithium production from salars. However, further work will be needed to address issues with water quality assessment aspects (Mikosch et al., 2021).

5.4. Modification of the AWARE methodology

Studies have been conducted that modify AWARE input data, and sometimes calculations, to better reflect local conditions and potential impacts (Ansorge and Beránková, 2017; Kaewmai et al., 2019; Andrade et al., 2020; Sanchez-Matos et al., 2023).

Andrade et al. (2020) used the Brazilian national database and hydrographic delimitations from the National Water Agency to generate regionalised AWARE CFs (AWARE BR CFs). They found WaterGAP overestimated fresh water availability, and underestimated demand in different basins, and the use of AWARE BR CFs led to improved, but often very different WSF results. For example, in the São Francisco region, the AWARE CF increased from 2.6 to 37.7 for AWARE BR CF.

Kaewmai et al. (2019) calculated CFs from data in the Chao Phraya watershed in Thailand. As well as modifying the input data, AWARE was modified to assess the individual fresh water scarcity of each type of water user based on the priority of order (domestic, environmental, livestock, agricultural, and industrial). They found the mean difference between AWARE CFs and their local CFs to be statistically significant.

More recently, Sanchez-Matos et al. (2023) developed regionalised CFs for the hyper-arid Peruvian coast. They found significant differences between the updated and original CFs, both geographically and temporally. In a new approach they proposed specific water scarcity CFs for groundwater, which could be used to monitor the overexploitation of these sources (Sanchez-Matos et al., 2023).

Modification and localisation of AWARE is an interesting but imperfect approach that could be applied in the Lithium Triangle. The primary issues is that it can result in a loss of compatibility and comparability, a core aspect of LCA, with differing collection methods, processing/calculations, scales and uncertainty between locally derived vs global data. Furthermore, relying on data from various sources across the Lithium Triangle is potentially problematic due to differences in availability and equivalency. Additionally, prioritisation of users (Kaewmai et al., 2019), which could provide valuable insights, is not without issue as it introduces subjectivity. Introducing governance mechanisms for the creation of regionalised SFs may go some way to addressing the issues of creating regionalised methods and data (Section 5.4), however it is unlikely to fully resolve them e.g. a loss of compatibility and comparability, variability of salars etc.

Ultimately, modification could allow for valuable accuracy improvements while still potentially allowing a comparison between lithium production pathways within South America.

5.5. Social impacts

Social impacts are of particular concern (Lorca et al., 2022) and lithium production in the Lithium Triangle has been considered to constitute a form of green extractivism replicating historical inequalities between the Northern and Southern hemispheres (Jerez et al., 2021). Community members' access to pumping wells may be restricted and their utilisation of ecological services and social values (cultural attachment to water, recreation and aesthetic values) provided by water impacted (Liu and Agusdinata, 2021; Lorca et al., 2022). Social Life Cycle Assessment (S-LCA) is a developing tool that could be used to assess some of these social impacts, but these areas and ecosystems have intrinsic intangible values, difficult to capture with quantitative assessments, requiring consideration in the wider scope of sustainability assessments.

5.6. Applicability of LCA

LCA's primary purpose is the objective comparison of production across supply chains, regions and life cycle stages. This requires generic methods applicable in all contexts, resulting in limited suitability for local assessments. When assessing the sustainability of lithium production from salar deposits, LCA results and, in particular, water scarcity insights, should be considered in tandem with other techniques and methods; at a project and watershed scale, such as social and environmental and hydrogeological impact assessments. However, LCA is a valuable and powerful tool for the assessment of raw material sustainability that will continue to grow in use and suitability; as such its limitations should be improved wherever possible.

6. Conclusions

6.1. Challenges and limitations

The AWARE method is one of the most suitable for assessing the fresh water use impacts of lithium production, however utilising it to assess the water-related impacts of lithium production from salar deposits is challenging due to:

- Salar complexity, variability and presence of multiple water types (brine and fresh water)
- Variable extraction technologies (Evaporative Processes and DLE) and associated water usages; meaning brine and fresh water consumption and reinjection can vary considerably
- Lack of publicly available data on brine and fresh water consumption and reinjection
- Impact uncertainty, derived from hydrogeological uncertainty More specifically, current LCA methodologies are limited regarding:

- Underlying data and methodology issues with AWARE
- Not accounting for the utilisation of various water types and differing mechanisms of water consumption and impacts
- Lack of consensus approach on the classification and assessment of brine usage and associated impacts
- Consideration of reinjection, both as a return flow of water to the salar and potential impacts.
- General limitations concerning mining projects, after Northey et al. (2016)
  a) availability of mine site water use data;
  b) inventory data for mining supply chains;
  c) uncertainty of post-closure impacts;
  d) accounting for cumulative impacts and extreme events.
- Specific limitations regarding application to salar systems
  a) Freshater availability potentially miscalculated and underestimated
  b) The fresh water demands of ecosystems not being accurately reflected
  c) Availability & resolution of AWARE SFs

6.2. Improvements of existing methods

Reporting of water consumption alone should be avoided where possible; the AWARE method is preferable, as even with limitations, it allows water usage to be assessed with consideration of regional scarcity and in a global context.

In some cases, an intermediate product (e.g. concentrated brine) is transported from the salar for further processing. In this situation, fresh water usage of 'off-salar' processing should be assessed using the SF of where processing takes place, or the area water is sourced from. Furthermore, multi-output allocation assumptions should be stated, even if allocation is not required or undertaken.

6.3. Development of future methods

Improvements in the underlying data and methods of AWARE represent one of the most significant opportunities. Within the Lithium Triangle there are areas where AWARE SFs are unavailable and/or salars overlap different SFs (Fig. 1). This is problematic as the SF can have a significant influence on results (Schenker et al., 2022). Resolving this unavailability should be a priority. Where salars overlap multiple AWARE SFs (Fig. 1), the SFs could be aggregated with weighting applied to the area of salar coverage to produce a unique salar SF. AWARE 2.0 may go some way or fully resolve these and underlying issues but at the time of writing is yet to be released.

The generation of AWARE SFs more specific to the Lithium Triangle could be undertaken, however this is not without issues (Section 5.4) and may not be a pragmatic way forward, depending on the data availability and equivalency across the region. The creation of SFs specific to groundwater, after Sanchez-Matos et al., 2023, could also be investigated further.

Future efforts should work towards further investigation and development of WAFs, in line with guidance set out in ISO 14046. This could allow consideration of differing water types (brines and fresh water) as well as water quality impacts This may require the development of characterisation models and impact categories specific to salar systems. Akin to the development of region specific SFs, this will impact the ability to compare results to lithium production from other deposit types. Some of the system complexity of salars may need to be omitted, or simplified, to maintain comparability. However, decent comparability between projects within the Lithium Triangle would still be possible and WAF methods could be applied to other, i.e. 'hard rock', production routes to maintain a good degree of comparability.

Another potential development is the introduction of multiple mid-point indicators, potentially within the framework of WAFs, for different water types, i.e. fresh water, brine and water contained with brine. Akin to the multiple impacts areas assessed within the LANCA impact category framework. This would require a consensus approach to define these categories and the associated methodologies. However, aggregation of any potential separate mid-point indicators should be avoided due to its subjectivity.

Future improvements in hydrogeological understanding and data availability will help inform the development of LCA methods. Governance mechanisms are a potential way to improve data availability and disclosure.

The authors welcome a collaborative and constructive discussion on the ideas raised and progress towards improved LCA methodologies, helping to decouple decarbonisation from negative impacts.

CRediT authorship contribution statement

Rowan T. Halkes: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Andrew Hughes:** Conceptualization, Funding acquisition, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Frances Wall:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Evi Petavratzi:** Conceptualization, Funding acquisition, Methodology, Visualization, Writing – review & editing. **Robert Pell:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Jordan J. Lindsay:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available within the data tables presented within this paper.

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Supplementary materials

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