Journal of Cleaner Production 487 (2025) 144635

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Water footprint of battery-grade lithium production in the Salar de Atacama, Chile

Sylvia Marinova *, Lindsey Roche, Andreas Link, Matthias Finkbeiner

Technische Universität Berlin, Chair of Sustainable Engineering, Strasse des 17. Juni, 10623, Berlin, Germany

ARTICLE INFO

Handling Editor: Panos Seferlis

Keywords:
Lithium carbonate
Lithium hydroxide
Brine
SQM
Water footprint
Water scarcity

ABSTRACT

The increasing demand for lithium, driven primarily by the electric transportation and renewable energy technologies, highlights the need to comprehensively assess the environmental implications of its production. Thus, a profound exploration of the water-related impacts caused by the life cycle of raw materials like lithium is necessary. In this context, we performed a cradle-to-gate water footprint of lithium extracted from the Salar de Atacama (SdA) operation in Chile for the production period of 2022 and 2023. Based on a Life Cycle Assessment (LCA) approach we evaluated the water inventories and explored the potential impacts of water vulnerability and scarcity by applying AWARE and WAVE + characterisation models. This resulted in a total potential impact of 442 m^3 and 5.5 m^3 world equivalents per ton of lithium product (87% lithium carbonate (Li_2CO_3) and 13% lithium hydroxide (LiOH)) for AWARE and WAVE+, respectively. The AWARE results indicate that concentrated lithium brine production significantly dominates the water footprint of lithium battery-grade products, with 326 m^3 world equivalents per ton. WAVE + results are consistent, attributing 3.81 m^3 equiv. to brine production. In the final production stages, the Li_2CO_3 production is prominent, with AWARE and WAVE + values of 59.9 m^3 and 1.01 m^3 equiv. per ton, respectively, largely due to sodium carbonate consumption and electricity generation. However, it is noteworthy that the water scarcity and vulnerability impacts remain minimal for these final production phases, which is primarily attributable to the utilisation of desalinated water. In addition, we compared the production periods of 2020–2021 and 2022–2023 finding that all measured indicators improved in 2022–2023 in the range of 9%–42%. This suggests increased efficiency of the operations in the SdA, with higher brine recovery rates and lower energy usage in certain process steps. The insights gained from this research contribute to the understanding of brine-based lithium production practices, providing a basis for exploring further mitigation strategies aimed at reducing the environmental footprint, particularly in production stages with higher water impact.

1. Introduction

In recent years, lithium has become a crucial element for various technologies and markets including lithium and lithium-ion batteries (LIBs), ceramics and glasses, nuclear fusion, pharmaceuticals, adhesives, lithium grease lubricants, etc. (Alessia et al., 2021; Zhang et al., 2021). In relation to the climate crisis and the targeted transition towards electrical mobility as well as to the development of modern technologies, lithium demand for rechargeable battery production is growing tremendously and it is forecasted to further increase. For instance, the International Energy Agency, (2023) projected the lithium demand to increase by five times from its current level by 2030 under the Stated Policies Scenario (STEPS), which reflects the energy sector's future demand based on current policies. In addition, Sverdrup (2016) developed a dynamic lithium cycle model and predicted increasing production of the metal until 2060 with a slow decline afterwards.

The steady increase in the economic importance of lithium, together with the growing demand and potential environmental and social implications related to the extracting processes, brings attention towards the material (Bobba et al., 2020; Marinova et al., 2023; Matrose et al., 2021). Hence, the existing body of literature underscores the growing need for the production of high-grade lithium and assessing its sustainability. Lithium reserves are identified mainly in the form of brine and rock ore (pegmatites), each characterised by distinct extraction challenges and environmental considerations. Hard rock deposits represent the main source of lithium (USGS, 2023). In the brine-based

* Corresponding author.
E-mail address: s.marinova@tu-berlin.de (S. Marinova).

https://doi.org/10.1016/j.jclepro.2024.144635
Received 23 July 2024; Received in revised form 27 November 2024; Accepted 30 December 2024
Available online 31 December 2024

lithium production, there are two distinct technologies used: evaporation processes (EP) and direct lithium extraction (DLE) (Halkes et al., 2024). DLE is a wider term which encompasses emerging brine extraction and concentration methods usually including electrochemical or thermal processes (Vera et al., 2023). EP is the dominant extraction method used by most of the producers, where the brine is extracted through extraction wells and pumped into a series of ponds where it undergoes concentration through solar evaporation and mineral precipitation. The final concentrated brine, rich in lithium chloride (LiCl), is transported to chemical treatment plants to produce Li_2CO_3, a crucial precursor for other lithium compounds (Khalil et al., 2022). The most significant brine-based production is linked to the lithium brine reserves concentrated in Chile, Argentina, and Bolivia also known as "The Lithium Triangle" encompassing the Salar de Atacama (SdA), Salar de Hombre Muerto, and Salar de Uyuni. Brine operations in China and the United States also contribute to a smaller extent to lithium recovery (López Steinmetz and Salvi, 2021).

The SdA basin is characterised by hyper-arid to arid climate (Boutt et al., 2016), mainly driven by the cold Humboldt Current and the Andes mountains' rain-shadow effect. The region's hydrological cycle is shaped by limited precipitation, evaporation, and groundwater recharge from surrounding mountain ranges, as well as a lack of discharge to the sea (Babidge et al., 2019; Marazuela et al., 2019). This results in the Atacama Salt Flat, which serves as the basin's natural sink. The unique ecosystems supported by groundwater are highly sensitive to anthropogenic impacts, which may have long-term effects on the water levels and biodiversity due to the region's slow hydrological response (Marazuela et al., 2020; Moran et al., 2022). When it comes to brine-based lithium production, two companies have the rights to operate in the region of the SdA: Sociedad Química y Minera (SQM) Salar S.A. and Albemarle Corporation. SQM operates within two major zones of extraction under concession granted by the Chilean government, covering about 1400 square km, with permission to extract from 820 square km and a current operation area of 394 square km, while Albemarle has one operation within a 137 square km area. SQM provided primary data for this analysis, enabling a more precise assessment of their operational impacts on the local hydrological system. In this context, the SdA basin represents one of the world's major sources of lithium and the largest battery lithium grade producer from lithium brine (Cabello, 2021). The larger extraction and production rates of SQM increase the significance of the company in the global lithium market and in recent years, attracted rather negative attention from researchers, practitioners, and NGOs (Romero et al., 2012). While some studies have found no significant impacts on the lagoons and surrounding environment to date (Guzmán et al., 2022), others have raised concerns about the potential negative impacts of brine and water extraction on the ecosystem and the rights of indigenous communities living in the proximity of the operation site (Blair et al., 2022; Lorca et al., 2022). In addition, the SdA basin is a hydrologically and hydrogeologically complex system characterised by a distinctive ecosystem and holds significant economic, cultural, and ecological importance (Guzmán et al., 2018, 2022; Moran et al., 2022). The linkage between the lithium brine extraction and the local water balance is explored in a companion paper by Link et al. (2024) while the social implications are considered by Roche et al. (2024).

There is ongoing scientific and legal debate about the nature of brine and whether it should be considered as water or mineral (López Steinmetz and Fong, 2019). For instance, according to World Health Organisation (WHO) standards for drinking water, levels of total dissolved solids (TDS) exceeding 1200 mg/l make water unsuitable for direct human consumption. In contrast, brine typically contains an estimated TDS value of around 300,000 mg/l, far surpassing the acceptable limits (World Health Organization, 2022). From a legal standpoint, in Chile, brine is not classified as water but is instead treated as a mineral or non-concessible ore (Bambach and Pulgar, 2020). There is a clear consensus, that the high mineral content of brine makes it unfit for human consumption, nevertheless, some authors argue that the water contained in brine eventually re-enters the natural water cycle once it is extracted through evaporation (Vera et al., 2023). Additionally, the brine abstraction could pose potential risks to the surrounding environment by interacting hydrodynamically with nearby systems, potentially leading to aquifer depletion, a lowering of the water table, and disruptions to the ecosystem balance (Flexer et al., 2018; Liu et al., 2019). It can also impact freshwater inflows and the overall water availability, a relationship which is not proven to be strictly linear. Consequently, changes in the water table and brine concentration, may affect evaporation rates, altering the hydrogeology, including brine circulation and the fresh water-brine interface, impacting nearby lagoons, ecosystems, and freshwater availability (Halkes et al., 2024). Previous assessments of the hydrological dynamics in the SdA basin have not conclusively demonstrated these impacts and thus lack reliable evidence for the reasoning behind the declining water storage in the area (van Pampus et al., 2023). On the contrary, some references consider the system as a closed basin, geochemically separated from lagoons and freshwater resources (Munk et al., 2016). It is important to note that no study based on hydrogeological modelling to date has successfully separated and identified the contribution of the different water table-influencing factors such as climate, companies, and human use (Moran et al., 2022).

In this context, the water footprint concept provides a useful framework for assessing water use and its impacts. Water footprint originates from the virtual water concept (water volume consumed or polluted during product manufacturing) of Allan (1993), further developed by Hoekstra (2003), and represents a multidimensional freshwater usage indicator, encompassing both direct and indirect water consumption (Berger and Finkbeiner, 2010). It assesses the volume of freshwater used to produce a product across its supply chain, including consumption and pollution, and specifies geographical and temporal aspects. According to the water footprint network, the indicator considers a blue water footprint which accounts for surface and groundwater consumption, a green water footprint referring to rainwater consumption, and a grey water footprint which quantifies pollution by assessing the volume of freshwater needed to assimilate pollutants based on existing water quality standards (Hoekstra et al., 2011). The International Standardization Organization (ISO) introduced an impact-oriented water footprint assessment approach set by the ISO 14046:2014 standard (ISO, 2016). This impact-focused method combines a water inventory with models based on Life Cycle Impact Assessment (LCIA) to quantify the regional water scarcity impacts or to establish a potential cause-effect pathway towards the effects on ecosystems, human well-being, and natural resources (Li et al., 2022; Link et al., 2021; Pierrat et al., 2023). Water scarcity, in this context, refers to the ratio of water demand to availability in a given region, often leading to stress on local water resources (Berger and Finkbeiner, 2013). Examples of impact-oriented assessment methods include water withdrawal- and water consumption-based methods using the Water Stress Index (WSI) (Pfister et al., 2009), the Available WAter REmaining (AWARE) (Boulay et al., 2018), and the Water Accounting and Vulnerability Evaluation (WAVE+) (Berger et al., 2018).

Water footprint is performed on global, local, national, urban, and industry scales. Water footprints assessment have been applied in the mining sector to primary aluminium production globally (Buxmann et al., 2016), steel production in China (Chen et al., 2022) and Iran (Nezamoleslami and Hosseinian, 2020), gold production in Colombia (Alvarez-Pugliese et al., 2021), and copper production in Chile (Peña and Huijbregts, 2014). In the context of lithium, Kelly et al. (2021) conducted a comprehensive LCA of lithium production, encompassing both Li_2CO_3 and lithium hydroxide monohydrate (LiOH•H2O) from brine extracted in the SQM's SdA operation and Australian ore sources. The assessment extends to cathode material and battery production of Li_2CO_3 and $LiOH{\bullet}H_2O$ to explore the impact of electric vehicles and their battery production. The authors used primary data and literature sources to estimate the energy, GHG emissions, and water consumption through the production cycle of lithium-ion battery cathodes and lithium-ion batteries. The blue water consumption is estimated by considering the freshwater resources incorporated in the production system and not returned to the environment. Within the study, brine is not counted as a freshwater resource due to its unsuitability for domestic and agricultural purposes. This approach aligns with the majority of existing studies, which also exclude brine from freshwater classifications (Chordia et al., 2022; Pöyry, 2020) and is consistent with state-of-the-art water footprint practices.

Schomberg et al. (2021) performed life cycle water scarcity footprint of lithium-ion battery storage and the supply chain associated with its production. The authors explored multiple mining locations where the lithium needed to produce the battery storage is sourced. The analysis includes a life cycle inventory, afterwards characterised by a modified AWARE assessment method. Contrary to the ISO standard 14046:2014 and other authors, they consider brine as a water resource. Another study focused on brine-based lithium mining was performed by Schenker et al. (2022) who established an approach for modelling site-specific life cycle inventories (LCIs) of Li_2CO_3 production from brines when operational data is not publicly accessible. This approach was then applied to assess the environmental impacts of Li_2CO_3 production from brine operations across mining locations including Argentina, Chile, and China. The proposed method is combined with regionalised LCIA considering the climate change-related impacts, human health impacts from fine particulate matter (PM) formation, and a partly regionalised AWARE-based water scarcity footprint. The authors state that ecosystems and humans are not able to directly use brine as water and thus, they do not consider it within their analysis. Another study investigating the environmental implications associated with the production of battery-grade $LiOH{\cdot}H_2O$ from varying lithium brine and ore grades has been conducted by Chordia et al. (2022). The authors focus on all the mining and processing stages from cradle to gate and assess the current main lithium supply locations, and future lithium greenfield projects in Salar de Maricunga in Chile, Salar de Cauchari in Argentina, as well as two upcoming spodumene-based sites: Whabouchi in Canada and Central Ostrobothnia in Finland. The study evaluates the water scarcity impact of $LiOH{\cdot}H_2O$ production by using ReCiPe's water use indicators as well as the AWARE characterisation method. Additionally, Chordia et al. (2022) explored the connection between freshwater extraction and water pollution based on the USEtox method to assess freshwater ecotoxicity.

Additionally, Mousavinezhad et al. (2024) examined the impacts of DLE in Clayton Valley, Nevada and compared their results to brine- and spodumene-based lithium extraction methods. The authors applied different scenarios for power sources within LCA to explore the environmental footprint, indirect land use, and water footprint of lithium production. To assess the water footprint of the different production sources, they employed the AWARE method. For brine-based production, like Schomberg et al. (2021), the authors deviated from the ISO standard and accounted for the water content in brine. In addition, Lagos et al. (2024) evaluated the carbon footprint and water footprint inventory of lithium production within the SdA, considering primary production data from the companies operating in the region. The study does not account brine as freshwater based on the notion that its salinity does not allow for human consumption or agriculture. Another study exploring the carbon and water footprint of lithium production was performed by Mas-Fons et al. (2024). The authors used LCA to compare brine-based production in the SdA and ore-based production in Greenbushes, Australia. They compiled inventory data using a simulation module for foreground data and the Ecoinvent 3.8 database for background data. The study evaluated water consumption using the ReCiPe 2016 method and assessed water scarcity based on the AWARE method under two scenarios: considering brine as freshwater and excluding brine from freshwater consumption.

The existing body of scientific literature demonstrates that although water scarcity footprint assessments in the mining sector, particularly for lithium extraction, receive moderate attention, they are relatively underexplored. While the major lithium producers have conducted LCA studies, there is a lack of water scarcity footprint peer-reviewed studies focused on lithium mining and production from brine based on primary data sources. With the exception of Kelly et al. (2021) and Lagos et al. (2024), the majority of the literature on water-related issues attributed to lithium mining predominantly relies on publicly available and secondary data as well as often is based on assumptions that lack conclusive evidence of interconnections. This highlights the need for the evaluation of direct water consumption as well as the relevant supply chain during the lithium mining process and the potential impacts on the surrounding ecosystem, particularly in water-scarce regions like the SdA. Thus, the primary objective of this paper is to conduct a comprehensive analysis of the freshwater-related impacts associated with lithium extraction and production from brine. This is achieved by conducting a water scarcity footprint assessment of lithium production within the context of the SdA operation. Employing a cradle-to-gate life cycle assessment framework in accordance with ISO 14046:2014 standard, the analysis is based on primary data provided by SQM, in order to enhance the reliability and accuracy of the investigation. The central objectives of this study are as follows.

1. Quantify the water footprint of Li_2CO_3 and LiOH at SQM production sites and supply chain, with a focus on determining blue water use and consumption.
2. Account for the region-specific water availability, by applying an impact-oriented approach and evaluate the impact of the blue consumptive use by using AWARE and WAVE + impact assessment methods.

This study aims to reflect on the relationship between lithium mining, water usage, and water scarcity, offering insights for sustainable resource management. Its innovation lies in using primary data from a major lithium producer, enabling a more accurate assessment of water scarcity impacts. Unlike the majority of previous studies that rely on secondary data, this research fills a significant gap by focusing on water scarcity footprinting for lithium production from brine and provides a transferable methodology for similar assessments in other mining and water-scarce regions. In the subsequent sections, we look deeper into the methodology (section 2) including a description of the water footprint stages, data collection, allocation method, and sensitivity analysis, followed by the results and discussion (section 3), and conclusions (section 4) of the study.

2. Method

To identify the water footprint over the production of Li_2CO_3 and LiOH at SQM, an impact-related water footprint according to ISO 14046:2014 was performed. The approach accounts for the total volume of the freshwater used either directly or indirectly in the production of the product. In our study, we considered the blue water use and consumption. We focused on the blue water since it relates to surface and groundwater and is the most relevant for lithium production. Green water is relevant mainly for agriculture and is less suitable for arid environments with relatively limited rainfall and vegetation. Grey water is also less applicable here as the main concern is water consumption rather than the pollution of treated water (Berger and Finkbeiner, 2013).

In addition, we evaluated the consumptive water use effects (e.g., scarcity and availability), while neglecting degradative water use effects (e.g., eutrophication and acidification) (Manzardo et al., 2016). The analysis contains four main stages mirroring the life cycle assessment: definition of the goal and scope, inventory analysis, impact assessment, and interpretation. The goal and scope definition establishes the specific aim of the study, the product system boundaries, the functional unit, and the reference flow. The locations and timing of water use and data collection methods are also considered. The inventory analysis step gathers the elementary flows and associated information, while the impact assessment quantifies potential water-related effects through classification and characterisation.

2.1. Goal and scope

2.1.1. Goal

This study aimed to assess the blue water footprint associated with the production of Li_2CO_3 and LiOH from brine in the SQM's SdA and Carmen Lithium Chemical Plant facilities, to identify hotspots from the lithium production in the foreground and background systems, and to obtain a detailed water footprint using primary data for lithium. The target audience for the study was originally SQM's internal stakeholders and the main audience for this paper is the scientific community.

2.1.2. Mining area

The lithium brine is extracted in the SdA basin, situated within the Atacama Desert. The Salar is characterised as a topographical depression marked by hyperarid conditions, minimal precipitation, and an elevation of 2300 m above sea level. The region is surrounded by the Andean Cordillera to the north, south, and east and the Domeyko Range to the west. The SdA basin encompasses approximately 3000 km^2, comprising a brine-rich halite nucleus and marginal zones, predominantly characterised by halite, gypsum, and carbonate (Marazuela et al., 2018). The inflowing water very gradually transitions from low TDS to brackish and brine concentrations, which is why the zone is referred to as marginal (Marazuela et al., 2018). The basin's predominant inflow originates from the north, east, and southern recharge zones, while western recharge remains minimal (Boutt et al., 2016; Gajardo and Redón, 2019; Kelly et al., 2021; Munk et al., 2016).

2.1.3. Functional unit

The analysis involves the production of Li_2CO_3, intended for battery use, and LiOH, battery grade as well, both of which are intermediary substances with diverse applications. Thus, our study adopts a mass-based functional unit and reference flow, representing 1000 kg of battery-grade lithium product produced from brine at the Chilean factory gate (SQM, 2022). Considering the proportional shares of the total product, we determine that Li_2CO_3 (min. purity 99.2%) constitutes 87% of the functional unit, whereas LiOH (min. purity 56.5%) represents 13% of the final product.

2.1.4. System boundaries and production processes

In this assessment, a cradle-to-gate system boundary was considered. This boundary includes all the processes from brine extraction in the SdA operation to the final products leaving the Carmen Lithium Chemical Plant. The co-products (potassium chloride and potassium sulphate) were considered within the system boundaries and followed the allocation methods described below. Fig. 1 shows the system boundary defined for the water footprint. The study considers data within the temporal boundaries of 2022–2023 and performs a comparison with the period of 2020–2021, to reflect changes in resource use efficiency and environmental performance due to different production techniques.

The production of lithium involves a series of steps that lead to the recovery of lithium compounds from brine sources. The process starts with the extraction of low-concentration brine from the saline nucleus, achieved through extraction wells positioned at different depths and diverse locations within the SQM production site in the SdA. The extraction wells pump brine of different concentrations into two distinct streams: one characterised by a higher lithium concentration and the other with a lower concentration of lithium. Furthermore, due to the different lithium concentrations of the brine, two primary production pathways have been established in SQM's SdA operation: one leading to the production of LiCl and the other focused on potassium chloride (muriate of potash (MOP); KCl) and potassium sulphate (sulphate of potash (SOP); K2SO4) production.

The pumped brine flows subsequently feed into four separate evaporation pond systems with an initial average brine concentration of around 0.17% lithium. The role of the evaporation ponds is to gradually increase the concentration of lithium using solar evaporation. While the water evaporates and the lithium concentration rises, numerous salts precipitate and are subsequently removed from the pond systems. These salts find application in other production flows, such as the production of fertilisers by KCl. In the initial evaporation stage, the brine (0.17% lithium) is concentrated to approximately 0.3% lithium while halite (NaCl) is precipitated, and the brine is moved to the next system of ponds. During the next evaporation stage, the lithium concentration in the brine reaches 0.97% lithium and it is accompanied by the removal of mainly sylvinite (NaCl·KCl) and sylvite (or KCl). Further, carnallite (KCl·MgCl2·6H2O), bischofite ($MgCl_2 \cdot 6H_2O$), lithium carnallite (LiCl·MgCl2·6H2O), and boron precipitate (with concentrations between 4% and 6%) as the lithium in the brine concentrates up to 4.5–6%. KCl and carnallite are separated, with further KCl extracted from carnallite and subsequently transported to the Coya Sur production facility (beyond the system boundary). The specific location and hyperarid climate of the area contribute to the evaporation process which only relies on solar energy and the whole process lasts between 12 and 18 months (Cabello, 2021; SQM, 2021; Tran and Luong, 2015). The final dispatch pond system contains the resulting concentrated LiCl brine, which is then sent to Carmen Lithium Chemical Plant, situated close to Antofagasta city. Here, it undergoes conversion into battery-grade Li_2CO_3 and LiOH.

2.1.5. Allocation

As mentioned before, the two distinct production pathways established during the brine evaporation process result in two different types of products: KCl and LiCl. The KCl is further used in potassium sulphate (K_2SO_4) production while the LiCl is the basis to produce Li_2CO_3 and LiOH. The KCl substances have applications as agricultural fertilisers. However, there has been an increased value associated with lithium in the last few years (Bustos-Gallardo et al., 2021). According to ISO 14046, in case it is not avoidable by system expansion, one must apply allocation either by attributing to the different products based on physical characteristics (mass, volume) or economic value (Forin et al., 2020). Within the scope of our study, the allocation cannot be avoided due to the multiple co-products accompanying the production of the main products under investigation. Further, the expansion of the production system would require a large amount of additional data and modelling efforts and it might compromise the robustness of the study by increasing the uncertainty. Within our analysis, allocation based on physical relationships between co-products, such as mass or energy, was considered less suitable, as the economic allocation more accurately reflects the key drivers of the production system (International Lithium Association Ltd (ILiA), 2024). While KCl is produced in larger quantities than lithium products, the latter hold significantly higher economic value and are the primary drivers of the operation. Allocating solely based on physical characteristics might result in unequal distribution of environmental burdens and fail to accurately reflect the economic importance of the evaluated products. Additionally, economic allocation aligns better with real-world market dynamics, ensuring that the environmental impacts are distributed in a way that reflects the economic realities of the production system. By prioritising economic allocation, we provide a more representative assessment of the environmental impacts associated with lithium production within this complex system. The allocation was performed by attributing the inputs according to the internal cost distribution of the concentrated lithium-brine production processes, where 93% is attributed to LiCl and 7% to KCl. This choice of allocation follows the hierarchy proposed by Santero and Hendry (2016) to harmonise LCA methodologies for the metal and mining industry, where economic allocation is the favoured option if physical allocation fails to reflect the main purpose for the operations.

2.2. Inventory data

The study encompassed production activities in Chile, focusing on the production processes of SQM during the years 2021 and 2022. A site visit to SQM's operation in the SdA was conducted in July 2022 to identify the main process steps. The life cycle inventory was modelled in GaBi software (10.6.0.110) (Sphera Solutions GmbH, 2023). Considering the production timeline for Li_2CO_3 and LiOH, which typically lasts between 18 and 24 months, we utilised a two-year dataset for our analysis. The main input and output data consist of primary data collected and supplied by SQM including the different materials used in the products, the amount of brine extracted, the water consumed during the processes, as well as the quantities of intermediate and final products and co-products. Table 1 displays the processes and the main process flows based on the collected primary data. It is important to mention that in our analysis, we considered brine as a mineral solution that is not suitable for direct human use and is therefore not counted as freshwater consumption in the water footprint context. Only the freshwater sourced from groundwater that is used in the production process is accounted for. This choice is consistent with the majority of studies and general water footprint practice according to ISO 14046:2014, which defines freshwater as having less than 1000 mg/l of TDS. (ISO, 2016). The background data for aspects like electricity generation, transportation, and additives production were sourced from the GaBi database.

GLO = global; CL = Chile; EU-27 = European Union (twenty-seven member states); DE = Germany; RER = Europe; RSA = Rest of South America.

2.3. Water footprint assessment

2.3.1. Inventory analysis

Following the data collection, an inventory analysis was performed

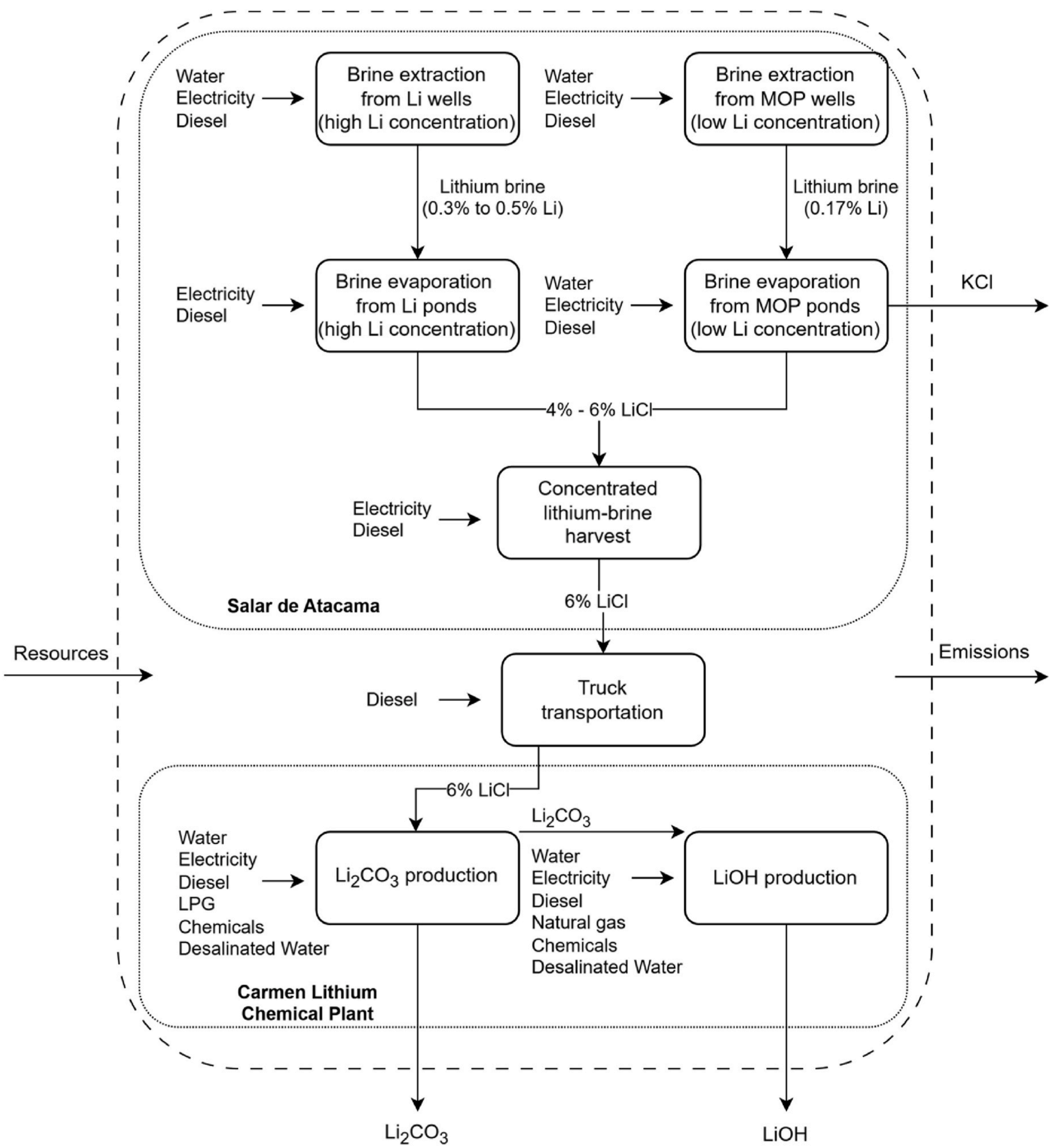

Fig. 1. System boundaries of Li_2CO_3 and LiOH production.

Table 1
Process and main elementary flows collected as primary data and the datasets used to model the inputs.

Input	Process	Flow	Geographic scope
Brine		CL: Lithium brine from lithium wells [Minerals]; CL: Lithium brine from MOP wells [Minerals]	Chile
Water		Groundwater, regionalised, CL [Water]	Chile
Desalinated water	GLO: Deionised water (reverse-osmosis/electro-deionisation, from surface water, for regionalization, Copy	Water (desalinated; deionised) [Operating materials]	Global
Quick Lime	EU-27: Quicklime	Quicklime [Minerals]	European Union
Sodium carbonate	EU-27: Soda (Na2CO3)	Soda (sodium carbonate) [Inorganic intermediate products]	European Union
Sulfuric acid	EU-27: Sulfuric acid (100% H2SO4)	Sulfuric acid (100%) [Inorganic intermediate products]	European Union
Sodium hydroxide	EU-27: Sodium hydroxide mix (50%)	Sodium hydroxide (50%; caustic soda) [Inorganic intermediate products]	European Union
Hydrochloric acid	De: Hydrochloric acid (32%)	Hydrochloric acid (30%) [Inorganic intermediate products]	Germany
Maxibags	RER: Polyethylene film (PE-LD); RER: Polyvinylidene chloride (PVdC); DE: Polypropylene Film (PP) without additives	Maxibags (PVDC + PP + PE) [Packaging]	Europe, Germany
Diesel	RSA: Diesel mix at refinery	Diesel [Refinery products]	South America
Electricity	CL: Electricity grid mix 1kV–60kV	Electricity [Electric power]	Chile
Liquefied petroleum gas	RSA: Liquefied Petroleum Gas (LPG) (70% propane, 30% butane)	Liquefied petroleum gas (LPG; 70% propane; 30% butane) [LPG, at production]	South America
Natural gas	CL: Natural gas mix	Natural gas, at consumer Chile [Natural gas, at consumer]	Chile

in accordance with ISO 14046:2014. Here we focused on the use and consumption of blue water. Specifically, blue water refers to both surface and groundwater resources, and the blue water footprint assesses the water volume that evaporates, becomes part of the product, gets transferred to a distinct catchment zone, or is returned during another timeframe (ISO, 2016). The inventory analysis provides the total volume of freshwater directly or indirectly used in the product's production.

2.3.2. Impact-oriented water footprint

The next step of our analysis quantified the water-related potential impacts by applying the impact assessment characterisation methods AWARE and WAVE+.

2.3.3. AWARE method

AWARE is a midpoint method for water scarcity footprint assessment in LCA and analyses water stress on a basin, country, and world region level. It is the consensus method recommended for evaluating the impacts of freshwater consumption by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) Life Cycle Initiative (Boulay et al., 2018). It compares human water consumption and environmental water requirements to hydrological water availability. The method is based on the quantification of the relative available water remaining per area once the demand of humans and aquatic ecosystems has been met, answering the question "What is the potential to deprive another user (human or ecosystem) when consuming water in this area?" The resulting characterisation factor (CF) ranges between 0.1 and 100 and can be used to calculate water scarcity footprints as defined in the ISO standard (ISO, 2016). It should be noted that the scale of the CF is an arbitrary choice. By using a scale up to 100, the water consumption values get numerically higher after characterisation. However, this scaling has no real meaning and therefore, it serves only as a relative comparison between the characterised results.

The lowest level of disaggregation of the AWARE CFs is the basin level. Quantitative results from the inventory analysis are multiplied with the CFs, thus transforming them into globally weighted, theoretical volumes with respect to regional conditions. These are directly proportional to the amount of water consumed (inventory) and inversely proportional to the available water remaining per unit of surface and time in a region. To calculate the AWARE CFs, the following equation is used:

$$\frac{1}{AMD} = \frac{Area}{Availability - Demand\ (HWC\ and\ EWR)} \qquad \text{(Eq. 1)}$$

where AMD stands for availability minus demand, which consists of HWC which is human water consumption and EWR which represents environmental water requirements. Water availability data is based on WaterGAP2 global model (Schmied et al., 2014) which quantifies the hydrological water availability as well as the human water consumption. The information is provided on grid cell level, offering consumption models across sectors such as agriculture, manufacturing, industry, households, and electricity generation. In our evaluation, when calculating direct water use, we incorporated the Chilean AWARE average CF of 80. In addition, we accounted for the factor derived by excluding hydropower and implementing a reduced CF in situations involving unspecified water.

2.3.4. WAVE + method

The Water accounting and vulnerability evaluation (WAVE+) encompasses multiple factors. At the inventory level, the method considers the assessment of the basin's internal evaporation recycling (BIER), which in some basins can significantly reduce evaporative water consumption through the process of prompt reprecipitation. At the impact assessment level, a vulnerability assessment is performed considering both relative freshwater scarcity through a consumption-to-availability ratio and absolute water scarcity based on aridity. Both aspects are combined into a Water Depletion Index (WDI), which is integrated into the WAVE + CF as follows:

$$\text{WAVE+} = \left(1 - \text{BIER}_{\text{runoff}}\right) \text{ x WDI} \qquad \text{(Eq. 2)}$$

The BIER quantifies the proportion of evapotranspiration that is returned to the initial basin through precipitation. This estimation is achieved using local evaporation recycling length scales obtained from the revised atmospheric moisture tracking model, WAM2-layers (Berger et al., 2018). Since the combined water depletion index (WDI) is formed by the maximum of relative and absolute water scarcity, the aridity criterion is most relevant for basins with hyper-arid to arid climates (Boutt et al., 2016) such as those in the SdA basin.

2.4. Interpretation

The results of the water footprint were interpreted in accordance with ISO 14046:2006. The processes with the main contribution to the water footprint were identified and analysed to assess the hotspots in terms of water-related impacts. Further, we performed completeness and consistency checks and data validation by comparing our outcomes to the available literature on the production of lithium products from brine sources. In addition, we conducted a performance tracking where we examined the data from 2020 to 2021 and 2022 to 2023, focusing on the percentage changes in water-related impacts. This analysis assesses the potential improvements in water usage and its environmental effects over the two periods. Finally, a sensitivity analysis was performed. We conducted the sensitivity analysis by applying a theoretical worst-case scenario applying the maximum CF for one of the impact assessment methods: The regionalised AWARE CF of the groundwater was increased to the maximum possible value of 100 to evaluate the influence of the direct water use within the production system. By setting the factor to its highest value, we can assess the assumption of maximal water scarcity on the final result. The sensitivity analysis focuses only on the AWARE CF, as the WAVE + factor is already adjusted nearly to its maximum value. This adjustment is made because hyper-arid regions are assigned the highest possible impact. Furthermore, as a second sensitivity analysis, we implemented physical allocation (based on mass) in addition to the standard price allocation scenario. Here, the energy, materials, and water inputs specific to the concentrated lithium-brine production pathway were allocated to the mass of the products. This approach ensures that burdens are distributed in proportion to the mass shares of the total output. Within the physical allocation, 32% of the burdens were attributed to the lithium products and the remaining 68% to KCl.

3. Results and discussion

3.1. Life cycle inventory

Table 2 displays a summary of the overall unallocated input quantities required for the production of 1000 kg of Li_2CO_3 and LiOH. The table shows that approximately 217 m^3 brine is extracted in order to produce 1000 kg of lithium products. During the concentrated lithium brine production, 4.5 m^3 of groundwater was used while the Li_2CO_3 production and LiOH production process steps require 7.5 m^3 desalinated water. Other material inputs consist of quick lime, sodium carbonate, sulfuric acid, sodium hydroxide, hydrochloric acid and diatomite. Diesel, electricity, liquefied petroleum gas and natural gas are the main energy inputs. Electricity and diesel are the main energy sources used throughout all of the production processes with 2674 MJ of electricity and 1557 MJ of diesel used for the production of 1000 kg Li_2CO_3 and LiOH. Liquefied petroleum gas is mostly used during the Li_2CO_3 production step (251 MJ) while natural gas represents an additional energy source used during the LiOH production.

Table 2
Unallocated input data summary per 1000 kg of Li_2CO_3 and LiOH.

Flow	Input	Unit
Materials		
Brine	217	m^3
Water	4.5	m^3
Desalinated water	7.5	m^3
Quick Lime	0.16	kg
Sodium carbonate	1872	kg
Sulfuric acid	23.2	kg
Sodium hydroxide	0.03	kg
Hydrochloric acid	51	kg
Diatomite	0.03	kg
Energy		
Diesel	1557	MJ
Electricity	2674	MJ
Liquefied petroleum gas	251	MJ
Natural gas	4948	MJ

3.2. Water footprint impact assessment

Fig. 2 provides the aggregated absolute numbers of water use and consumption as well as the water use impact assessed. The results demonstrate that for all of the processes, the blue water use with a total of 107 t per lithium product is greater compared to the blue water consumption (18.7 t per lithium product) due to the fact that the use depicts the total amount of water entering the product system. In contrast, water consumption encompasses not only the water entering the system but also water returned to the environment (ISO, 2016).

The AWARE and WAVE + results are comparable, with the WAVE + values showing a slight elevation. It is important to note that the AWARE results are displayed as m^3 world equiv./100 due to the difference in the scaling of WAVE+ and AWARE CFs. As previously discussed, AWARE is scaled between 0 and 100, while WAVE + scores range from 0 to 1. To put them graphically in the same order of magnitude, we divided the AWARE scores by 100. This is due to the nature of the different indicators and water volumes: while water use and consumption focus on quantities, the AWARE and WAVE + results characterise the implications in terms of water scarcity and vulnerability.

Fig. 3 illustrates the different contributions of the main production system processes to the overall water footprint of Li_2CO_3 and LiOH. The figure displays the relative shares of each production stage while using AWARE and WAVE + characterisation methods, respectively. It is worth mentioning that the processes indicated as “Concentrated lithium production from Li ponds” and “Concentrated lithium production from MOP ponds” refer to extraction and subsequent evaporation of brine with differing levels of lithium concentration. In this context, "MOP" stands for muriate of potash, which is another term for potassium chloride (KCl) being part of the KCl production pathway. Specifically, the former process handles brine with a higher lithium concentration, while the latter deals with brine with a lower concentration of lithium. The stages characterised with the lowest contribution to the water footprint are the processes of lithium brine harvesting and truck transportation. These processes do not require direct water use and are characterised by a low amount of diesel usage and no electricity use. Furthermore, next to the Li_2CO_3 production stage, the concentrated lithium production from MOP ponds is the stage requiring the largest quantities of water within the studied system. This is due to the groundwater pumped into the evaporation ponds together with the brine at the beginning of the pumping process which is used to prevent salt crust from forming in the pipes.

In addition, Fig. 3 shows that the highest AWARE and WAVE + values are attributed to the production of concentrated brine process steps, particularly for the ponds with a higher lithium concentration (MOP), which have a calculated AWARE value of 326 m^3 world equiv. per ton of Li_2CO_3 and LiOH. In comparison, the Li_2CO_3 production process at the Carmen Lithium Chemical Plant equals 59.9 m^3 world equiv. per ton of Li_2CO_3 and LiOH. The AWARE values attributed to the concentrated brine production could be explained, on the one hand, by the relatively high groundwater usage accompanying these processes when compared to some of the other production phases: for the studied period of 2 years, a total of approx. 1,296,003.5 m^3 or 3.6 m^3 groundwater per ton of Li_2CO_3 and LiOH is used during the concentrated lithium brine production from MOP while around 192,121.96 m^3 in total or 0.5 m^3 desalinated water is needed during the LiOH production process. On the other hand, the region is characterised by low water availability, implying a higher impact in terms of water scarcity with a rather heightened AWARE factor (CF = 80). Thus, multiplying the AWARE CF with the water quantities results in elevated values. In addition, the actual Li_2CO_3 and LiOH production processes require lower water quantities, which are supplied from a desalination plant situated near the SQM production facility in Antofagasta City. However, in the context of Li_2CO_3 and LiOH production, blue water use shows a much larger contribution here, as is the case when considering consumption or impact-based results. As previously highlighted, this is due

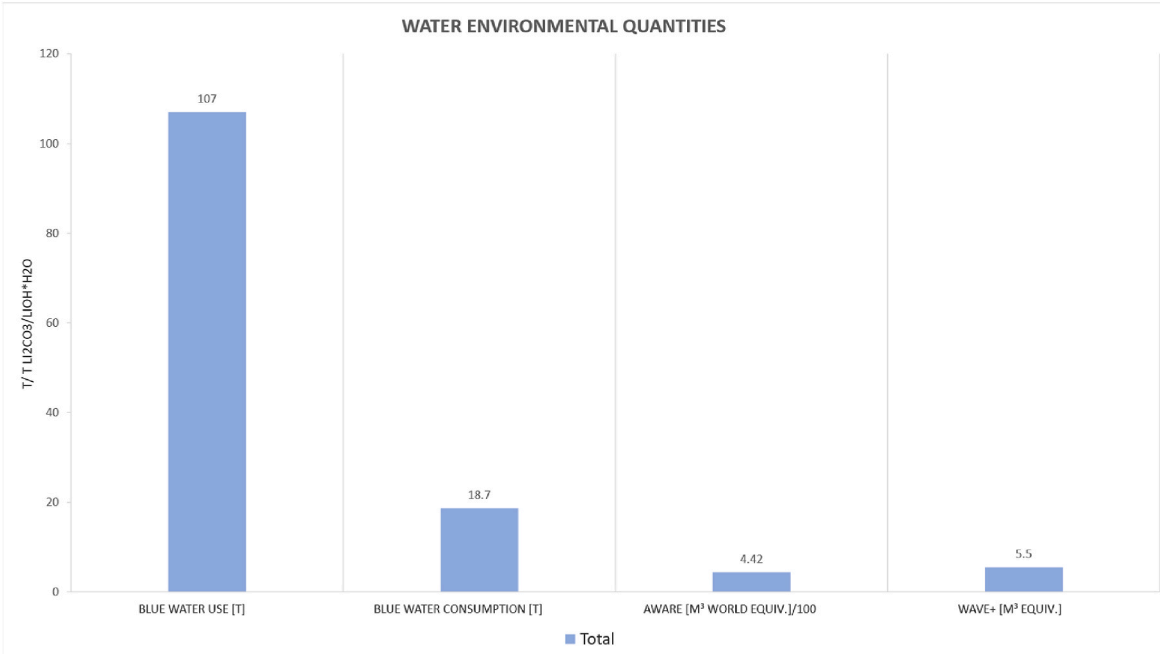

Fig. 2. Aggregated absolute contributions to the water footprint of the Li_2CO_3 and LiOH production processes.

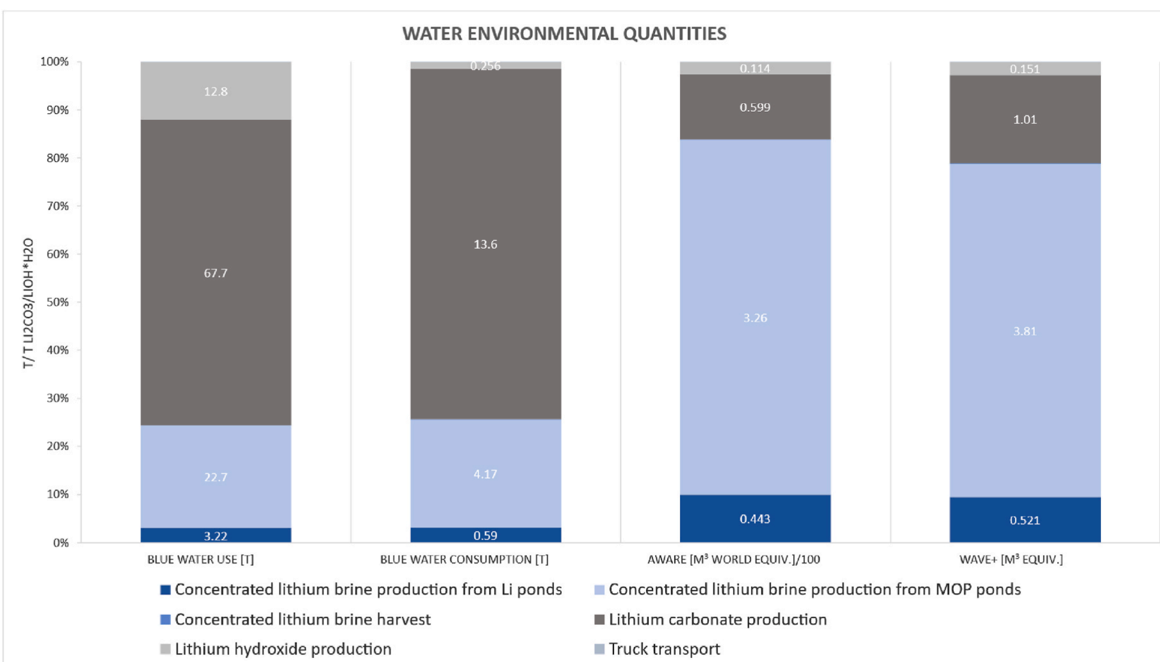

Fig. 3. Relative water inventory and impact-related shares to the water footprint of the main Li_2CO_3 and LiOH production processes.

to the use of desalinated water which is not accounted as a freshwater resource by the AWARE and WAVE + methods (Berger et al., 2018; Boulay et al., 2018).

The results calculated based on WAVE + demonstrate similar results compared to AWARE with 1.01 m^3 equiv./tonne lithium product for Li_2CO_3 production and 0.186 m^3 equiv./tonne lithium product for LiOH production processes. The reason for the slightly elevated WAVE + value compared to AWARE is the different calculation methods, underlying principles, and corresponding variables each approach includes. WAVE+ is characterised by a broader perspective and it focuses not only on relative water scarcity but also considers the absolute water shortage, resulting in the potential for higher calculated impact values. This is valid for particularly arid regions such as the SdA basin (Berger et al., 2018). Given that the concentrated lithium-brine production from MOP ponds displays the highest impact characterised by AWARE (Fig. 3), we look closer into the different sub-processes displayed in Fig. 4. The results show that the dominant AWARE contribution arises from the stage of concentrated lithium brine production within the ponds, the most water-intensive process (no brine was accounted for within these processes, solely groundwater). Meanwhile, electricity production is the process displaying the largest blue water use. This pattern could be attributed to the nature of the electricity production and the fact that

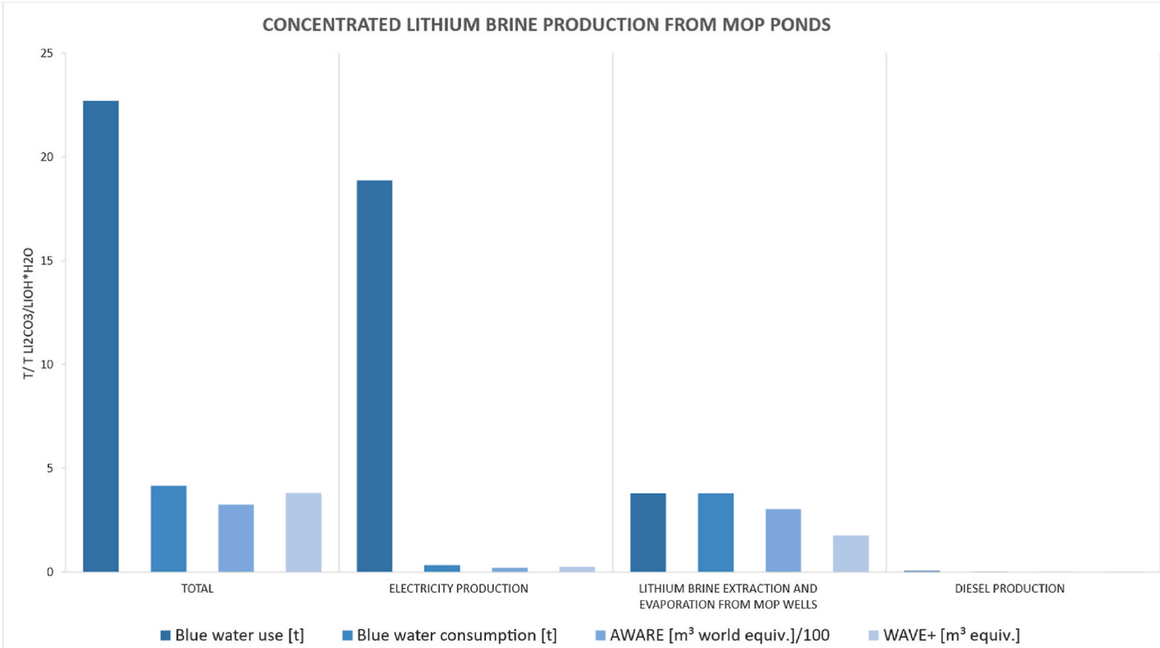

Fig. 4. Contributor processes to the concentrated brine production from MOP ponds.

even though we consider the Chilean grid mix, which is country-specific, a certain amount of the electricity is more likely produced and imported from neighbouring countries. The data set for the Chilean grid mix has 37% of electricity from coal and 17% from natural gas. Thermal power generation (including coal and natural gas) requires freshwater inputs for the cooling system which can explain its overall contribution to blue water use.

Further, Fig. 5 provides further insights into the Li_2CO_3 production phase in the Carmen Chemical Plant's water footprint and the relative contribution of the different sub-processes. As Fig. 2 shows, the Li_2CO_3 production is characterised by the highest blue water use and consumption. Once again, this is due to the electricity, as well as the soda production as the latter displays the highest contribution within all of the processes and across all of the indicators. The results do not come as a surprise given the fact that sodium carbonate production through the most common Solvay process requires large volumes of water (Speight, 2017).

3.3. Sensitivity analysis of selected aspects

3.3.1. AWARE factor

Fig. 6 displays the outcomes derived from the sensitivity analysis of the water footprint. Within the sensitivity analysis, instead of using the average Chilean CF (CF 80), we calculated the AWARE-based water

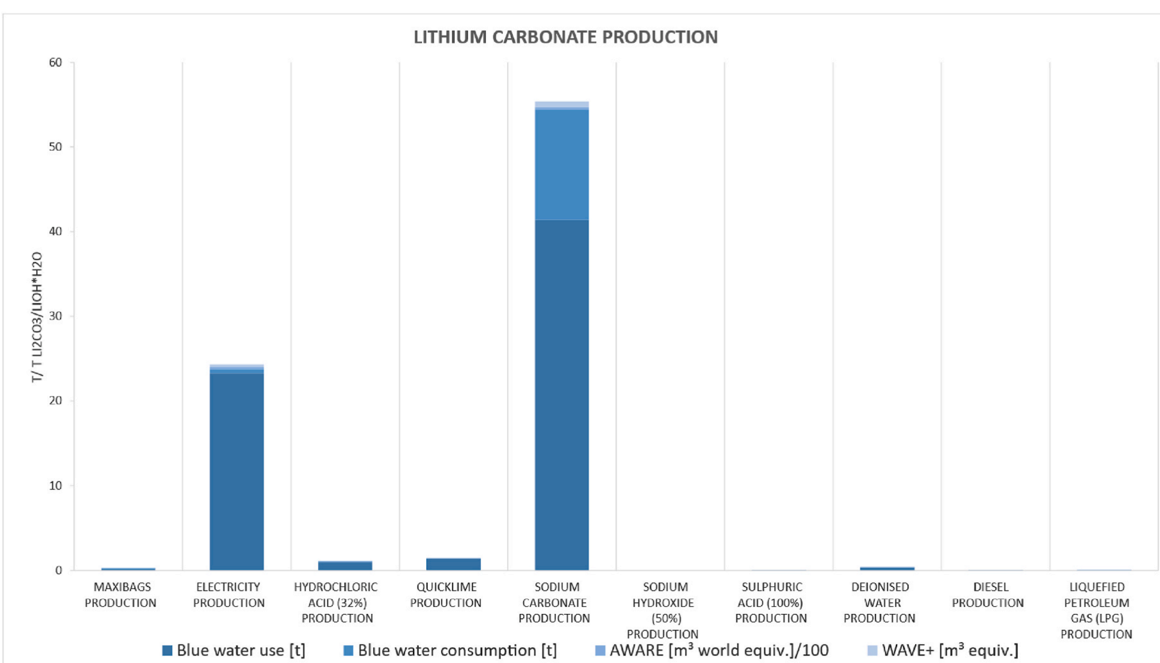

Fig. 5. Contributor processes to the Li_2CO_3 water footprint.

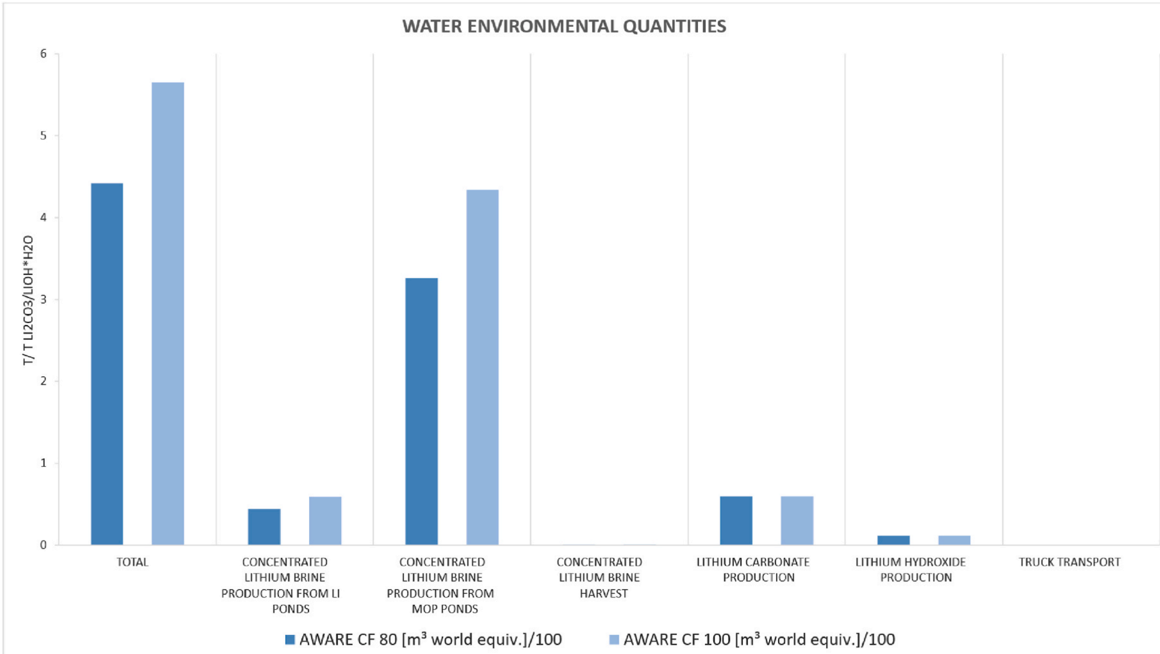

Fig. 6. Total contribution from Li_2CO_3 and LiOH production, calculated based on AWARE CF of 100.

scarcity footprint based on a factor of 100, which assumes the highest level of scarcity. This was done to assess the potential impact under a worst-case water scarcity scenario. The values for concentrated lithium brine production rose by approximately 20%, however, the values calculated with the average Chilean AWARE factor remain unchanged for the Li_2CO_3 and LiOH production. This is explained by the fact that the initial stages are largely dependent on direct water consumption in the affected region. Later processing of Li_2CO_3 and LiOH, on the other hand, involves water consumption that is largely attributable to background processes, such as electricity and additive production, that are not affected by the change in the CF.

3.3.2. Allocation

As previously described, in addition to the economic value allocation, we performed physical allocation which involves dividing the impacts according to the mass shares of the input and output flows. The economic allocation attributes the water-related impacts to the different processes based on the economic value of the products (Kelly et al., 2021). Fig. 7 shows the results of the applied allocation per 1 tonne Li_2CO_3/LiOH considering the blue water consumption. In addition, Fig. 8 presents the allocation difference between mass and price water scarcity impacts calculated based on the AWARE method.

Both figures display higher impacts from the processes when the

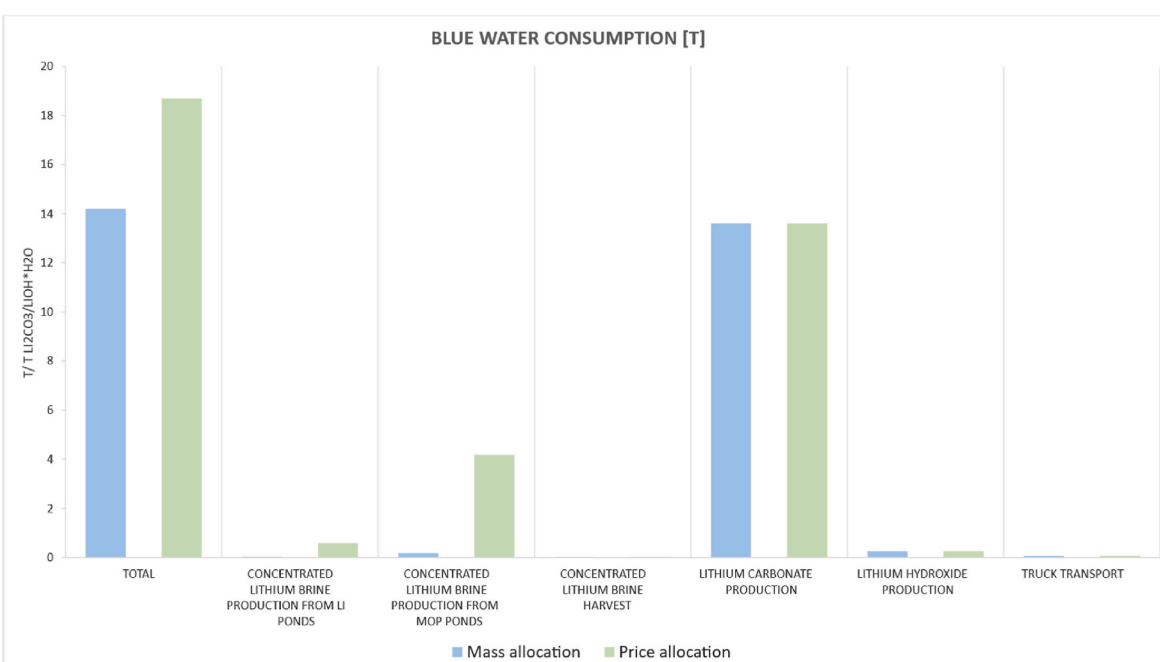

Fig. 7. Mass and price allocation of blue water consumption within Li_2CO_3 and LiOH life cycle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

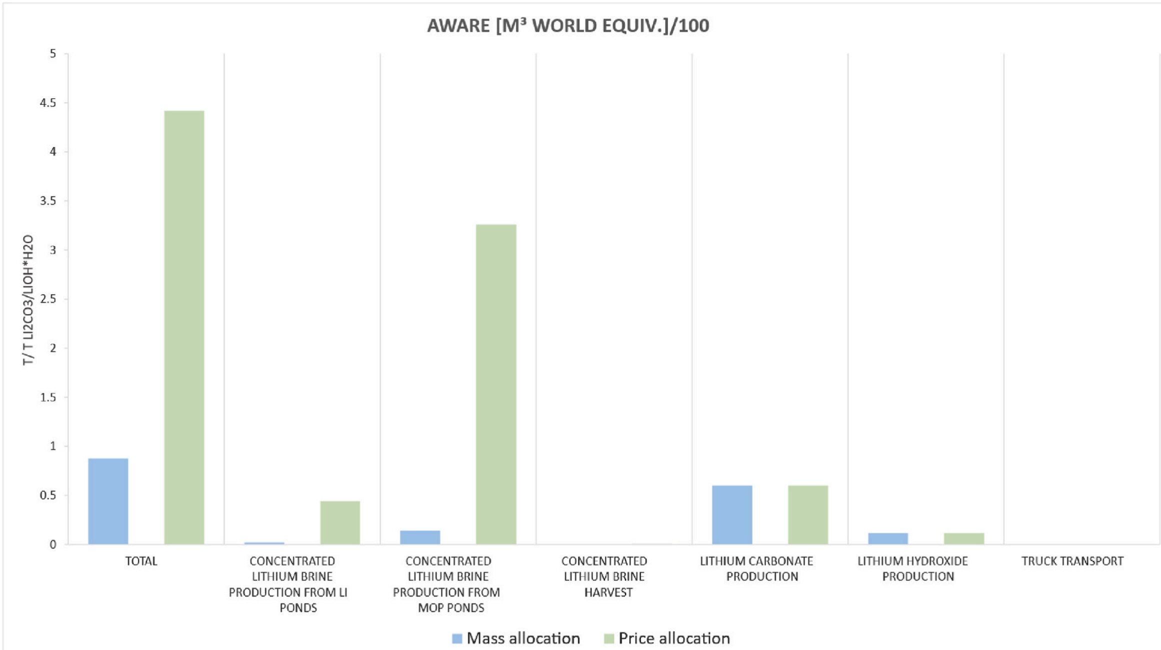

Fig. 8. Mass and price allocation of AWARE results within Li_2CO_3 and LiOH life cycle.

indicators are calculated based on the economic value. Although the company produces a larger amount of KCl compared to Li_2CO_3 and LiOH, the economic value of the lithium products is considerably higher. Thus, these results underline the importance of considering a product's economic value as often they represent the main driver for production. As the figures show, the Li_2CO_3 and LiOH production processes are characterised by equal values with both types of allocation. This is because allocation was only applied to the initial production phases: concentrated brine production and harvesting as the co-products are obtained along these steps.

3.4. Performance tracking (2020–2021 vs 2022–2023)

Table 3 displays the difference in the aggregated absolute numbers of water use, water consumption and water-related impacts for the periods of 2020–2021 and 2022–2023. The results show that for all measured indicators, the values for 2022–2023 are lower compared to 2020–2021. This improvement is due to increased efficiency in company operations in the SdA region, resulting in higher brine recovery rates and reduced electricity and diesel usage for several process steps. However, the evaporation of lithium ponds and the concentrated lithium brine harvest steps are associated with higher diesel usage for the period of 2022–2023. Lithium carbonate production shows a slight increase in blue water consumption (from 13 t to 14 t of water per Li product) due to the higher amounts of chemicals and energy required, proportional to the increased amount of concentrated brine input.

The largest difference observed between the study periods is a 42% reduction in the AWARE value, while the smallest difference (9%) is in blue water consumption. The relatively small difference in the blue water consumption could be attributed to the increased use of chemicals, which is associated with higher energy consumption for their production. Meanwhile, the improvement associated with the AWARE water scarcity factor is explained by the lower overall energy consumption within the SdA basin. The increased use of chemicals and their production impacts do not significantly affect the AWARE result, as water use and consumption do not occur in a water-scarce region like the SdA.

In addition, Fig. 9 presents the differences between the price and mass allocation for the two studied periods. The figure displays the total blue water consumption as well as the production of concentrated brine from lithium and MOP ponds processes due to the relatively small contribution of the rest of the process steps. The results show that the price-mass allocation differences are lower for 2022–2023 compared to the previous two years. The lower price-mass allocation ratio observed in 2022–2023 suggests a more balanced economic distribution per unit of mass. This change is primarily due to the higher volume of the final product in this period. The increased production volume dilutes the cost per unit mass, resulting in a lower ratio. In addition, the lower allocation ratios suggest that the cost per unit of mass is reduced, likely due to economies of scale and enhanced production processes. This performance tracking proves useful to inform future strategies for optimising production performance and minimising costs as well as water-related environmental impacts in relation to mass output. Additionally, it provides a basis for comparing trade-offs between impacts originating from different sources. For instance, while improving water use efficiency can reduce the overall water footprint, it may require increased chemical use, which could have other environmental implications. Balancing these trade-offs is important for long-term lithium resource

Table 3
Comparison between the aggregated water footprint of Li_2CO_3 and LiOH production for 2020–2022 and 2022–2023.

Total environmental quantities	2020–2021	2022–2023	Percentage reduction
Blue water use t per t Li_2CO_3/LiOH	132	107	−19%
Blue water consumption t per t Li_2CO_3/LiOH	21	19	−9%
AWARE m^3 world equiv./100 per t Li_2CO_3/LiOH	7	4	−42%
WAVE + m^3 world equiv. per t Li_2CO_3/LiOH	8	6	−25%

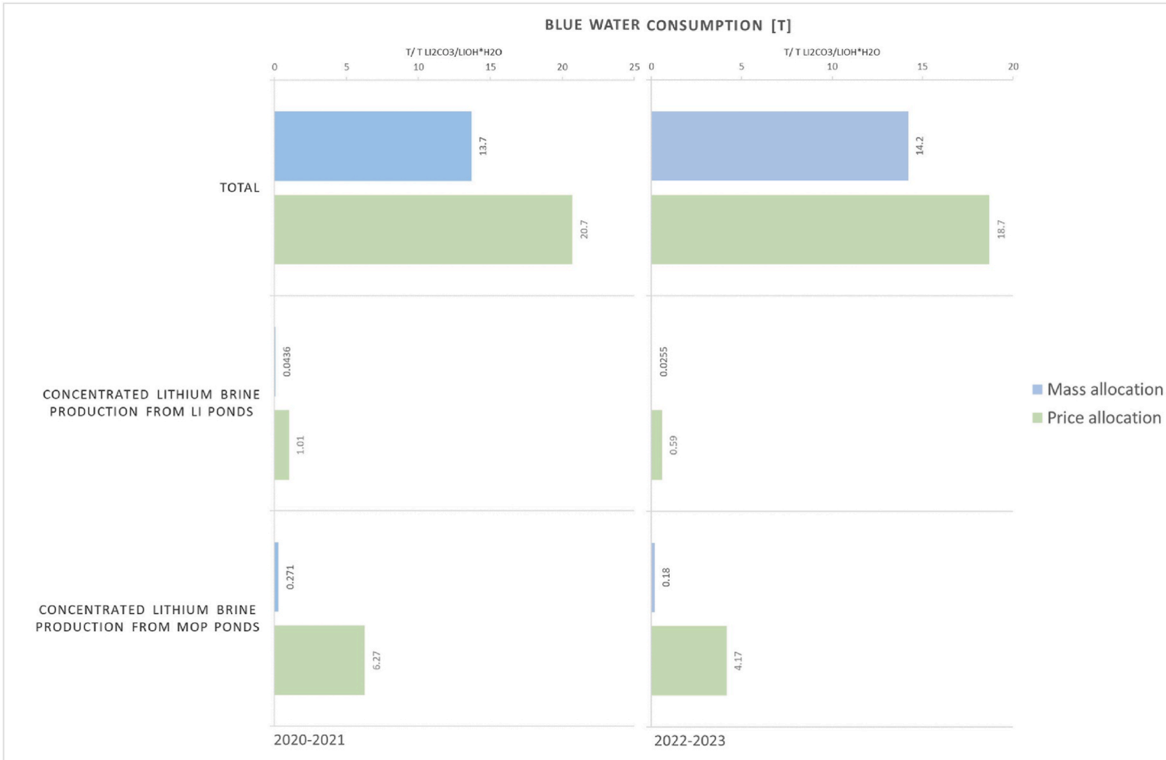

Fig. 9. Comparison between mass and price allocation of blue water consumption within Li_2CO_3 and LiOH life cycle for 2020–2021 and 2022–2023. Two process steps are highlighted next to the total blue water consumption for the whole life cycle of lithium production due to the relatively small contribution to the rest of the processes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

management.

Based on these results, several key policy recommendations in the direction of sustainable resource management and production practices can be made. First, investment in research to assess the hydrological, social, and environmental impacts and their interconnections in regions like the SdA, as well as the consequent development of water-efficient technologies and alternative extraction methods, should be encouraged. Along with that, it is important to implement robust monitoring and reporting requirements for water usage and the related impacts, accompanied by enhanced transparency. It is also important to develop policies that prioritise economic allocation frameworks when performing water footprints for products with high economic importance, such as lithium, to ensure environmental impacts are accurately represented in relation to market values.

3.5. Model validation

Within the existing literature, assessments of the water footprint associated with lithium production have been conducted using different methods, often in combination with LCAs of lithium-ion batteries. Our results are overall consistent with the observations of Schenker et al. (2022) and Kelly et al. (2021). The results calculated in this study demonstrate lower AWARE values (0.44 m^3 world equiv. per kg of Li_2CO_3/LiOH) compared to Schenker et al. (2022) who reported 4.77 m^3 world equiv. per kg Li_2CO_3. While the authors do not account for brine as a freshwater due to its inability to be directly used by the ecosystem, they report that the majority of the water scarcity impact originates from the freshwater use in the processing plant. In contrast, our study considers desalinated water as the only water source throughout the chemical plant process. In addition, Schenker et al. (2022), report that the AWARE CF attributed to the foreground processes in the SdA region, due to its aridity, is considerably higher (CF 94.7). The authors mention that the background data for water is not regionally characterised and was evaluated with the relatively high global average AWARE CF. This potentially leads to an overestimation of background water scarcity values in certain instances, e.g., electricity production. This also demonstrates the importance and added value of using first-hand primary data, as was the case in our work. An additional reason for the elevated water-related impact compared to our results might be the higher amount of quick lime and sodium hydroxide inputs reported by Schenker et al. (2022), which are an order of magnitude greater than those in our study.

In a similar study, using primary data from SQM, Kelly et al. (2021) report on an inventory level a total freshwater consumption of 15.5–32.8 m^3/tonne Li_2CO_3 for the production of Li_2CO_3 process, which is close to our inventory result of 24.3 m^3/tonne Li_2CO_3/LiOH. Additionally, the authors obtained a value of 2.95–7.30 m^3/tonne lithium for freshwater consumption attributed to the lithium concentration production stage, which aligns with the results of our study which attributes the value of 4.5 m^3/tonne Li_2CO_3/LiOH. Comparing the results to the studies performed by Schomberg et al. (2021), Chordia et al. (2022), Mas-Fons et al. (2024) and Mousavinezhad et al. (2024) does not make sense because the studies treated brine as water which leads to a significant inflation of the water inventories considered in their analysis. In addition, Lagos et al. (2024) explore the water footprint of lithium products only on inventory level for the year 2020 which makes the comparison not meaningful due to temporal, methodological, and contextual differences in the studies.

3.6. Limitations and outlook

There are certain limitations related to LCA-based water footprint evaluation and the utilisation of primary data. Temporal variability resulting from data collection during specific periods might overlook seasonal variations. In addition, changes in the production methods might be neglected.

Furthermore, the absence of consideration for changes in production processes highlights the need to conduct regular water footprint assessments with up-to-date and comprehensive life cycle stages. This is evident from the differences observed when comparing the water footprint for the production periods of 2020–2021 and 2022–2023. Additionally, while the ISO 14046 standard for water footprinting provides an internationally agreed framework, it cannot ensure complete methodological consistency. As a consequence, the uncertainty of water footprint studies is on a similar level than LCA studies in general. Another limitation is the absence of a strict classification framework for saline and brine waters in water footprinting, which could improve the accuracy and comparability of water assessments across studies.

In terms of data availability, site-specific primary data was only available for the foreground system and could not be applied to other locations or contexts. For instance, the water use associated with electricity generation shows variability across various LCA databases, influenced by the chosen electricity mix and technical system boundaries. This variation originates from differences in the chosen technical system boundaries and the selection of representative energy generation technologies used to model real-world scenarios (Chordia et al., 2021). In order to select the electricity generation dataset that best reflects the water impacts of the region of the product system under study, it is important to weigh the strengths and weaknesses of the data used, the assumptions made, and the calculation methods.

Furthermore, the water footprint assessment might benefit from further application of more watershed-specific CFs. Both the AWARE and WAVE + methods have certain limitations in this context. Neither method accounts for different water types or qualities, nor do they treat brine as a distinct category. In addition, without adapting these methods to specific cases, water availability may be inaccurately calculated, leading to potential under- or overestimation. Furthermore, while AWARE reduces availability by considering the water needs of river systems, a full assessment of different ecosystem needs beyond this (e.g. considering the water needs of lake or terrestrial ecosystems) is not yet available for either method. Northey et al. (2016) highlighted in this context, for instance, that AWARE does not fully reflect the freshwater demands for ecosystems. Future methods and CFs could be applied more precisely to better capture the situation in the SdA basin which is very unique and generalisation might lead to a distortion of the results. Given the hydrological situation in the region and the presence of so-called fossil groundwater, research might be focused on quantifying these types of groundwater and developing an accounting method within the water footprint framework (Baspineiro et al., 2020).

Additionally, further analysis should go beyond the SdA operation context, incorporating a comparative approach across different salt flats and production systems around the world. This could include a deeper focus on technologies targeting brine reduction within the DLE framework, a process currently being explored by companies like SQM (Reuters, 2024). The primary water footprint data for conventional treatment processes in SQM's SdA operation provides a valuable benchmark for evaluating emerging technologies, such as DLE, which may entail additional freshwater demands but at the same time has the potential to decrease the amount of brine required per Li product (Fuentealba et al., 2023; Halkes et al., 2024). A comparative analysis of the new and conventional methods alongside with the potential trade-offs could be a key strategy for establishing a sustainable roadmap for lithium extraction.

4. Conclusion

This study emphasises the significance of properly assessing environmental impacts related to lithium extraction by performing a water footprint of Li_2CO_3 and LiOH. We focused our assessment on the cradle-to-gate life cycle of the lithium products – from lithium brine extraction to battery grade Li_2CO_3 and LiOH within the production site in the SdA and Carmen Lithium Chemical Plant using primary data. The inventory results demonstrate that producing 1000 kg of lithium products requires the extraction of 217 m^3 of brine, using 4.5 m^3 of groundwater at the SdA operation site and 7.5 m^3 of desalinated water for the Li_2CO_3 and LiOH production processes. Additionally, the total blue water use was estimated at 107 m^3 per lithium product, while blue water consumption was 18.7 m^3 per lithium product. Our research shows that the concentrated lithium brine production mainly contributes to the water footprint of lithium battery grade products among the operations requiring direct water use due to the direct water consumption during the process stage and the use of relatively high scarcity impact CFs. When it comes to the Li_2CO_3 and LiOH final processing, Li_2CO_3 stands out with 59.9 m^3 world equiv. for the AWARE-based assessment and 1.01 for the WAVE + factor due to the indirect impact of sodium carbonate and electricity production. The impact of water scarcity and vulnerability of these phases is negligible since they utilise desalinated water. The comparison between the production periods of 2020–2021 and 2022–2023 demonstrated improvement in all of the measured indicators for 2022–2023 in the range of 9%–42% due to the increased performance efficiency of the operations in the SdA basin. Identifying these hotspots across the life cycle and supply chain contributes towards the understanding and improvement of the operation. Thus, we believe that our results underscore the significance of assessing water footprints with a holistic approach, particularly in regions facing severe water scarcity.

CRediT authorship contribution statement

Sylvia Marinova: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lindsey Roche:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas Link:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthias Finkbeiner:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Funding

Funding for this study was provided by Sociedad Química y Minera de Chile (SQM)

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors report financial support for the study was provided by Sociedad Química y Minera de Chile.

Acknowledgements

We would like to thank Veronica Gautier, Sebastian Franco, Stefan Debruyne, Denise Kirschner, Francisca Rios, Valentin Barrera and others for their support and information provided.

Data availability

The data that has been used is confidential.

References

Alessia, A., Alessandro, B., Maria, V.G., Carlos, V.A., Francesca, B., 2021. Challenges for sustainable lithium supply: a critical review. J. Clean. Prod. 300, 126954. https://doi.org/10.1016/j.jclepro.2021.126954.

Allan, J.A., 1993. Fortunately there are substitutes for water: otherwise our hydro-political futures would be impossible. In: Priorities Water Resour. Alloc. Manag. Overseas Dev. Adm., pp. 13–26.

Alvarez-Pugliese, C.E., Machuca-Martínez, F., Perez-Rincon, M., 2021. Water footprint in gold extraction: a case-study in Suarez, Cauca, Colombia. Heliyon 7, e07949. https://doi.org/10.1016/j.heliyon.2021.e07949.

Babidge, S., Kalazich, F., Prieto, M., Yager, K., 2019. "That's the problem with that lake; it changes sides": mapping extraction and ecological exhaustion in the Atacama. J. Polit. Ecol. 26. https://doi.org/10.2458/V26I1.23169.

Bambach, J.P., Pulgar, M.P., 2020. Mining in Chile: overview [WWW Document]. Thomson Reuters Pract. Law. URL. https://uk.practicallaw.thomsonreuters.com/w-020-5636?transitionType=Default&contextData=(sc.Default)&firstPage=true.

Baspineiro, C.F., Franco, J., Flexer, V., 2020. Potential water recovery during lithium mining from high salinity brines. Sci. Total Environ. 720, 137523. https://doi.org/10.1016/j.scitotenv.2020.137523.

Berger, M., Eisner, S., Van Der Ent, R., Flörke, M., Link, A., Poligkeit, J., Bach, V., Finkbeiner, M., 2018. Enhancing the water accounting and vulnerability evaluation model: WAVE+. Environ. Sci. Technol. 52, 10757–10766. https://doi.org/10.1021/acs.est.7b05164.

Berger, M., Finkbeiner, M., 2013. Methodological challenges in volumetric and impact-oriented water footprints. J. Ind. Ecol. 17, 79–89. https://doi.org/10.1111/j.1530-9290.2012.00495.x.

Berger, M., Finkbeiner, M., 2010. Water footprinting: how to address water use in life cycle assessment? Sustainability 2, 919–944. https://doi.org/10.3390/su2040919.

Blair, J.J.A., Balcázar, R.M., Barandiarán, J., Barbara, S., Maxwell, A., 2022. Exhausted: how we can stop lithium mining from depleting water resources. Draining Wetlands, and Harming Communities in South America Authors.

Bobba, S., Carrara, S., Huisman, J., Mathieux, F., Pavel, C., 2020. Critical Raw Materials for Strategic Technologies and Sectors in the EU - a Foresight Study. European Commission. https://doi.org/10.2873/58081.

Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int. J. Life Cycle Assess. 23, 368–378. https://doi.org/10.1007/s11367-017-1333-8.

Boutt, D.F., Hynek, S.A., Munk, L.A., Corenthal, L.G., 2016. Rapid recharge of fresh water to the halite-hosted brine aquifer of Salar de Atacama, Chile. Hydrol. Process. 30, 4720–4740. https://doi.org/10.1002/hyp.10994.

Bustos-Gallardo, B., Bridge, G., Prieto, M., 2021. Harvesting Lithium: water, brine and the industrial dynamics of production in the Salar de Atacama. Geoforum 119, 177–189. https://doi.org/10.1016/j.geoforum.2021.01.001.

Buxmann, K., Koehler, A., Thylmann, D., 2016. Water scarcity footprint of primary aluminium. Int. J. Life Cycle Assess. 21, 1605–1615. https://doi.org/10.1007/s11367-015-0997-1.

Cabello, J., 2021. Lithium brine production, reserves, resources and exploration in Chile: an updated review. Ore Geol. Rev. 128. https://doi.org/10.1016/j.oregeorev.2020.103883.

Chen, W., Zhang, Q., Wang, C., Li, Z., Geng, Y., Hong, J., Cheng, Y., 2022. Environmental sustainability challenges of China's steel production: impact-oriented water, carbon and fossil energy footprints assessment. Ecol. Indicat. 136, 108660. https://doi.org/10.1016/j.ecolind.2022.108660.

Chordia, M., Nordelöf, A., Ellingsen, L.A.W., 2021. Environmental life cycle implications of upscaling lithium-ion battery production. Int. J. Life Cycle Assess. 26, 2024–2039. https://doi.org/10.1007/s11367-021-01976-0.

Chordia, M., Wickerts, S., Nordelöf, A., Arvidsson, R., 2022. Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene. Resour. Conserv. Recycl. 187. https://doi.org/10.1016/j.resconrec.2022.106634.

Flexer, V., Baspineiro, C.F., Galli, C.I., 2018. Lithium recovery from brines: a vital raw material for green energies with a potential environmental impact in its mining and processing. Sci. Total Environ. 639, 1188–1204. https://doi.org/10.1016/j.scitotenv.2018.05.223.

Forin, S., Mikosch, N., Berger, M., Finkbeiner, M., 2020. Organizational water footprint: a methodological guidance. Int. J. Life Cycle Assess. 25, 403–422. https://doi.org/10.1007/s11367-019-01670-2.

Fuentealba, D., Flores-Fernández, C., Troncoso, E., Estay, H., 2023. Technological tendencies for lithium production from salt lake brines: progress and research gaps to move towards more sustainable processes. Res. Pol. 83. https://doi.org/10.1016/j.resourpol.2023.103572.

Gajardo, G., Redón, S., 2019. Andean hypersaline lakes in the Atacama Desert, northern Chile: between lithium exploitation and unique biodiversity conservation. Conserv. Sci. Pract. 1, 1–8. https://doi.org/10.1111/csp2.94.

Guzmán, J., Retamal, C., Faúndez, P., Joaquín Jara, J., 2022. Evolution of the Surface Area of Critical Lagoon Systems in the Salar de Atacama. Nat. Resour. Res. 31, 2571–2588. https://doi.org/10.1007/s11053-022-10070-7.

Guzmán, J.I., Faúndez, P., Jara, J.J., Retamal, C., 2018. Role of lithium mining on the water stress of the salar de atacama basin. J. Clean. Prod. https://doi.org/10.31223/X54S5G.

Halkes, R.T., Hughes, A., Wall, F., Petavratzi, E., Pell, R., Lindsay, J.J., 2024. Life cycle assessment and water use impacts of lithium production from salar deposits: challenges and opportunities. Resour. Conserv. Recycl. 207, 107554. https://doi.org/10.1016/j.resconrec.2024.107554.

Hoekstra, A., 2003. Virtual water trade: proceedings of the international expert meeting on virtual water trade. Value ofWater Research Report Series No. 12. https://doi.org/10.4337/9781785369131.00016.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual. Earthscan. https://doi.org/10.1080/0969160x.2011.593864.

International Energy Agency, 2023. World Energy Outlook, vol. 2023, pp. 23–28.

International Lithium Association Ltd (ILiA), 2024. Determining the Product Carbon Footprint of Lithium Products 1–52.

ISO, 2016. Environmental Management – Water Footprint – Principles, Requirements and Guidelines. ISO 14046:2014).

Kelly, J.C., Wang, M., Dai, Q., Winjobi, O., 2021. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. Resour. Conserv. Recycl. 174, 105762. https://doi.org/10.1016/j.resconrec.2021.105762.

Lagos, G., Cifuentes, L., Peters, D., Castro, L., Valdés, J.M., 2024. Carbon footprint and water inventory of the production of lithium in the Atacama Salt Flat, Chile. Environ. Challenges 16. https://doi.org/10.1016/j.envc.2024.100962.

Li, X., Zhu, L., Dong, Y., Chen, B., Li, Q., Wang, X., Zhang, Y., Wang, L., 2022. Water footprint assessment of wool products with a low-water footprint baseline. Sustain. Prod. Consum. 34, 310–317. https://doi.org/10.1016/j.spc.2022.09.023.

Link, A., Berger, M., Van Der Ent, R., Eisner, S., Finkbeiner, M., 2021. Considering the fate of evaporated water across basin boundaries - implications for water footprinting. Environ. Sci. Technol. 55, 10231–10242. https://doi.org/10.1021/acs.est.0c04526.

Link, A., Marinova, S., Roche, L., Coroama, V., Hinkers, L., Borchardt, D., Finkbeiner, M., 2024. (under review). Water and lithium mining in the Salar de Atacama - current accounting practices and framework development for water footprinting. Appl. Water Sci.

Liu, W., Agusdinata, D.B., Myint, S.W., 2019. Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile. Int. J. Appl. Earth Obs. Geoinf. 80, 145–156. https://doi.org/10.1016/j.jag.2019.04.016.

López Steinmetz, R.L., Fong, S.B., 2019. Water legislation in the context of lithium mining in Argentina. Res. Pol. 64. https://doi.org/10.1016/j.resourpol.2019.101510.

López Steinmetz, R.L., Salvi, S., 2021. Brine grades in Andean salars: when basin size matters A review of the Lithium Triangle. Earth Sci. Rev. 217. https://doi.org/10.1016/j.earscirev.2021.103615.

Lorca, M., Olivera Andrade, M., Escosteguy, M., Köppel, J., Scoville-Simonds, M., Hufty, M., 2022. Mining indigenous territories: Consensus, tensions and ambivalences in the Salar de Atacama. Extr. Ind. Soc. 9. https://doi.org/10.1016/j.exis.2022.101047.

Manzardo, A., Mazzi, A., Loss, A., Butler, M., Williamson, A., Scipioni, A., 2016. Lessons learned from the application of different water footprint approaches to compare different food packaging alternatives. J. Clean. Prod. 112, 4657–4666. https://doi.org/10.1016/j.jclepro.2015.08.019.

Marazuela, M.A., Ayora, C., Vázquez-Suñé, E., Olivella, S., García-Gil, A., 2020. Hydrogeological constraints for the genesis of the extreme lithium enrichment in the Salar de Atacama (NE Chile): A thermohaline flow modelling approach. Sci. Total Environ. 739, 139959. https://doi.org/10.1016/j.scitotenv.2020.139959.

Marazuela, M.A., Vázquez-Suñé, E., Ayora, C., García-Gil, A., Palma, T., 2019. Hydrodynamics of salt flat basins: The Salar de Atacama example. Sci. Total Environ. 651, 668–683. https://doi.org/10.1016/j.scitotenv.2018.09.190.

Marazuela, M.A., Vázquez-Suñé, E., Custodio, E., Palma, T., García-Gil, A., Ayora, C., 2018. 3D mapping, hydrodynamics and modelling of the freshwater-brine mixing zone in salt flats similar to the Salar de Atacama (Chile). J. Hydrol. 561, 223–235. https://doi.org/10.1016/j.jhydrol.2018.04.010.

Marinova, S., Bach, V., Yokoi, R., Motoshita, M., Islam, K., Finkbeiner, M., 2023. Country-level criticality assessment of abiotic resource use in Japan - application of the SCARCE method. J. Clean. Prod. 412, 137355. https://doi.org/10.1016/j.jclepro.2023.137355.

Mas-Fons, A., Horta Arduin, R., Loubet, P., Pereira, T., Parvez, A.M., Sonnemann, G., 2024. Carbon and water footprint of battery-grade lithium from brine and spodumene: a simulation-based LCA. J. Clean. Prod. 452, 142108. https://doi.org/10.1016/j.jclepro.2024.142108.

Matrose, N.A., Obikese, K., Belay, Z.A., Caleb, O.J., 2021. Criticality assessment of metal resources in China. iScience 24, 102524. https://doi.org/10.1016/j.isci.2021.102524.

Moran, B.J., Boutt, D.F., McKnight, S.V., Jenckes, J., Munk, L.A., Corkran, D., Kirshen, A., 2022. Relic groundwater and prolonged drought confound interpretations of water sustainability and lithium extraction in arid lands. Earth's Future 10, 1–24. https://doi.org/10.1029/2021EF002555.

Mousavinezhad, S., Nili, S., Fahimi, A., Vahidi, E., 2024. Environmental impact assessment of direct lithium extraction from brine resources: global warming potential, land use, water consumption, and charting sustainable scenarios. Resour. Conserv. Recycl. 205, 107583. https://doi.org/10.1016/j.resconrec.2024.107583.

Munk, L.A., Hynek, S.A., Bradley, D.C., Boutt, D., Labay, K., Jochens, H., 2016. Lithium brines: a global perspective. Rare earth crit. Elem. Ore Depos. 18, 339–365.

Nezamoleslami, R., Hosseinian, S.M., 2020. An improved water footprint model of steel production concerning virtual water of personnel: the case of Iran. J. Environ. Manag. 260, 110065. https://doi.org/10.1016/j.jenvman.2020.110065.

Northey, S.A., Mudd, G.M., Saarivuori, E., Wessman-Jääskeläinen, H., Haque, N., 2016. Water footprinting and mining: where are the limitations and opportunities? J. Clean. Prod. 135, 1098–1116. https://doi.org/10.1016/j.jclepro.2016.07.024.

Peña, C.A., Huijbregts, M.A.J., 2014. The blue water footprint of primary copper production in Northern Chile. J. Ind. Ecol. 18, 49–58. https://doi.org/10.1111/jiec.12036.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43, 4098–4104. https://doi.org/10.1021/es802423e.

Pierrat, É., Laurent, A., Dorber, M., Rygaard, M., Verones, F., Hauschild, M., 2023. Advancing water footprint assessments: combining the impacts of water pollution and scarcity. Sci. Total Environ. 870. https://doi.org/10.1016/j.scitotenv.2023.161910.

Pöyry, 2020. Life Cycle Assessment (LCA) for Lithium Products.

Reuters, 2024. Chile's SQM plans to choose lithium extraction technology by next year [WWW Document]. URL. https://www.reuters.com/markets/commodities/chiles-sqm-plans-choose-lithium-extraction-technology-by-next-year-2024-06-27/.

Roche, L., Link, A., Marinova, S., Coroama, V., Finkbeiner, M., 2024. S-LCA of Lithium Mining in Chile and its Potential Impacts on Water and the Local Community (accepted).

Romero, H., Méndez, M., Smith, P., 2012. Mining development and environmental injustice in the atacama desert of Northern Chile. Environ. Justice 5, 70–76. https://doi.org/10.1089/env.2011.0017.

Santero, N., Hendry, J., 2016. Harmonization of LCA methodologies for the metal and mining industry. Int. J. Life Cycle Assess. 21, 1543–1553. https://doi.org/10.1007/s11367-015-1022-4.

Schenker, V., Oberschelp, C., Pfister, S., 2022. Regionalized life cycle assessment of present and future lithium production for Li-ion batteries. Resour. Conserv. Recycl. 187, 106611. https://doi.org/10.1016/j.resconrec.2022.106611.

Schmied, H.M., Eisner, S., Franz, D., Wattenbach, M., Portmann, F.T., Flörke, M., Döll, P., 2014. Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. Hydrol. Earth Syst. Sci. 18, 3511–3538. https://doi.org/10.5194/hess-18-3511-2014.

Schomberg, A.C., Bringezu, S., Flörke, M., 2021. Extended life cycle assessment reveals the spatially-explicit water scarcity footprint of a lithium-ion battery storage. Commun. Earth Environ 2, 1–10. https://doi.org/10.1038/s43247-020-00080-9.

Speight, D.J.G., 2017. Environmental inorganic Chemistry for engineers. https://doi.org/10.1016/B978-0-12-849891-0.00003-5.

Sphera Solutions GmbH, 2023. GaBi software system and database for life cycle engineering [WWW Document]. Sphera Solut. GmbH, Leinfelden-Echterdingen. URL. https://gabi.sphera.com/international/index/.

SQM, 2022. Lthium hydroxide [WWW Document]. Lithium Hydroxide. URL. https://www.sqmlithium.com/en/hidroxido-de-litio/.

SQM, 2021. Sociedad Química Y Minera: Sustainability Report 2021.

Sverdrup, H.U., 2016. Modelling global extraction, supply, price and depletion of the extractable geological resources with the LITHIUM model. Resour. Conserv. Recycl. 114, 112–129. https://doi.org/10.1016/j.resconrec.2016.07.002.

Tran, T., Luong, V.T., 2015. Lithium Production Processes, Lithium Process Chemistry: Resources, Extraction, Batteries, and Recycling. Elsevier Inc. https://doi.org/10.1016/B978-0-12-801417-2.00003-7.

USGS, 2023. Mineral Commodity Summaries 2023.

van Pampus, M., Hogenboom, B., Hoorn, C., Seijmonsbergen, A.C., 2023. Uncertainties in the debate on the environmental impact of lithium brine extraction in the Salar de Atacama, Chile. Evol. Earth 1, 100024. https://doi.org/10.1016/j.eve.2023.100024.

Vera, M.L., Torres, W.R., Galli, C.I., Chagnes, A., Flexer, V., 2023. Environmental impact of direct lithium extraction from brines. Nat. Rev. Earth Environ. 4, 149–165. https://doi.org/10.1038/s43017-022-00387-5.

World Health Organization, 2022. Strong Systems and Sound Investments: Evidence on and Key Insights into Accelerating Progress on Sanitation, Drinking-Water and Hygiene. UN-water Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS) 2022 Report. Geneva.

Zhang, Y., Sun, W., Xu, R., Wang, L., Tang, H., 2021. Lithium extraction from water lithium resources through green electrochemical-battery approaches: a comprehensive review. J. Clean. Prod. 285, 124905. https://doi.org/10.1016/j.jclepro.2020.124905.