MSc Program
Environmental Technology & International Affairs

Attaining Sustainability in Lithium Supply Chains - An Assessment of Challenges and Opportunities for Application of Direct Lithium Extraction on Brine Deposits

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 29.05.2024

Affidavit

I, **LUKA ŠOLIĆ, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ATTAINING SUSTAINABILITY IN LITHIUM SUPPLY CHAINS - AN ASSESSMENT OF CHALLENGES AND OPPORTUNITIES FOR APPLICATION OF DIRECT LITHIUM EXTRACTION ON BRINE DEPOSITS", 85 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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ABSTRACT

In the collective effort toward the decarbonization of anthropogenic activities and the attainment of a carbon-free society, critical minerals are recognized to be of significant importance in the transition process. As one of the critical minerals pivotal for the electrification of the transportation sector and making a constituent part of battery energy storage systems, lithium holds a major role in the transition process. Consequently, the demand for lithium in the upcoming decades is expected to increase, raising questions on how to source the mineral in a sustainable manner. One set of technologies, direct lithium extraction, emerges as a promising answer. To find out the technologies' prospect, the paper considers two research questions: (I) How does the adoption of direct lithium extraction on brine deposits impact the environmental sustainability of lithium supply chains*?*, and (II) What are the challenges associated with integrating direct lithium extraction into existing lithium supply chains, and how can these challenges be overcome? With the means of an extensive literature review and invaluable input from interview partners, the answers to research questions are formulated through two parts of the paper. The first part deals with the working principles of both the prospective technologies and the currently commercially exercised method of the evaporitic technology. Subsequently, the paper compares between the technologies' environmental footprints. The second part addresses the challenges direct lithium extraction technologies face on the path of commercialization, where the obstacles recognized are divided into three categories: economic, policy and geopolitical, and technical aspects. Following the assessment, the ensuing conclusions are made: first, the implementation of direct lithium technologies can provide sensibly greater sustainability of the lithium supply chains if brine water reinjection, fresh water recovery and reuse, and appropriate waste management are conducted; second, to facilitate the technologies' proliferation and to attract investments, it is proposed that lithium is established as a commodity in commodity markets, applicable stringent water-related regulations established, and national policies endorsing the technologies set up. Notwithstanding direct lithium extraction's potential, further research and development are necessary since not all technologies are equally environmentally sustainable or mature for commercial application.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

BESS	Battery Energy Storage Systems
CAPEX	Capital Expenditure
CFD	Contract for Difference
DLE	Direct Lithium Extraction
DOE	U.S. Department of Energy
EU	European Union
EVs	Electric Vehicles
GHG	Greenhouse Gas
IEA	International Energy Agency
IRR	Internal Rate of Return
LiAl-LDH	Lithium-Aluminum Layered Double Hydroxide
LIS	Lithium-ion Sieve
OPEX	Operating Expenditure
PLC	Public Limited Company
PPP	Public-Private Partnership
PSMCDI	Permselective Exchange Membrane Capacitive Deionization
PVC	Polyvinyl Chloride
TBP	Tributyl Phosphate
TRL	Technology Readiness Level
US	United States
USD	United States Dollar

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1. INTRODUCTION

In the pursuit of mitigating anthropogenic climate change and adhering to the 2015 *Paris Agreement*, many actors ranging from national governments, sub-national municipalities, a variety of institutions and the private sector pledged to take action in the agenda of achieving the ambitious goal of net-zero greenhouse gas (GHG) emissions by 2050 (UN, n.d.)

To reach the ambitious goal where GHG emissions are to be evaded, and/or reduced and offset over a sustained period, countries and other apposite stakeholders have to proliferate technologies that act as replacements for and are independent of fossil-based energy sources, such as renewable sources of energy, electric vehicles (EVs), battery energy storage systems (BESS) and carbon dioxide removal technologies among others (Frankhauser et al., 2022; IEA, 2021a: 30).

However, in the course of ongoing efforts towards the attainment of Net-Zero 2050 and its inherent process of the clean energy transition, the director of the International Energy Agency (IEA) Fatih Birol (2021) critically put it:

> *"Today's supply and investment plans for many critical minerals fall well short of what is needed to support an accelerated deployment of solar panels, wind turbines and electric vehicles. Many minerals come from a small number of producers. (…) the long lead times to bring new mineral production on stream, the declining resource quality in some areas and various environmental and social impacts all raise concerns around reliable and sustainable supplies of minerals to support the energy transition.*
>
> *These hazards are real, but they are surmountable. The response from policy makers and companies will determine whether critical minerals remain a vital enabler for clean energy transitions or become a bottleneck in the process."*
> (Birol, 2021).

The statement noticeably articulates the down to earth actuality of challenges the global society as a collective is undergoing in the progress of decarbonizing anthropogenic activities. One challenge that can be identified from the statement is ensuring that supply chains provide sufficient and timely quantities of necessitated raw materials for the process of clean energy transition wherever demanded. Another challenge is related to the previous one and concerns the attainment of sustainability and dependability in sourcing the relevant raw materials.

Lithium, as one of the minerals that play a critical role in the clean energy transition, does not fall short of these challenges, where one means of extracting lithium, direct lithium extraction (DLE), emerges as a potential solution to overcome them.

1.1. Lithium's Relevance

Lithium plays an indispensable constituent role in lithium-ion batteries; a type of battery that is used in a variety of cutting-edge technologies, and performs an elemental part in EVs and BESS (Khan et al., 2023). For the reason of its fundamental role in technologies that are a constituent part of the green energy transition, and the EU's ambition of achieving climate neutrality by 2050 under the framework of the 2020 *European Green Deal*, the EU recognized the necessity of scaling up the production and hence securing lithium supplies to avoid its shortages in the long term. Lithium, therefore, has not only been identified as an important material by the EU but also, it was recognized as both a critical raw material, which indicates that material holds high economic value to the EU; and as a strategic raw material, which denotes that material plays a vital role in developing fossil-free technologies and in facilitating the green energy transition (European Commission, 2020: 19; European Commission, 2023: 1, 20, 46).

In addition to the EU, the United States (US) through the report prepared by the White House (2021: 86, 89) acknowledged the battery market as one of the most important markets to its national interest. To secure the national battery manufacturing industry, domestic extraction of lithium, which would abide by applicable environmental standards, is suggested to be prioritized. This would in return result in a more strengthened lithium supply chain and a more secured national battery production. Furthermore, the report proceeds with accentuating the essentiality of batteries based on lithium as a "*critical enabling technology for success in the next generation clean energy marketplace and for achieving vital economic, energy, national security, and climate* *priorities"* (White House, 2021: 89). What is noteworthy in this accentuation is the recognition that lithium-ion batteries are acknowledged as technology of significant importance to the US economy, energy and thereupon national security.

Consequently, the U.S. Department of Energy (DOE) (2023: 106) proclaimed lithium as a critical mineral due to its high importance to energy and its high susceptibility to supply risk (Figure 1.1.), whereby critical mineral is defined as an element or a substance that "*(i) has a high risk of a supply chain disruption; and (ii) serves an essential function in 1 or more energy technologies, including technologies that produce, transmit, store, and conserve energy"* (*Consolidated Appropriations Act 2021*).

Figure 1. 1: Criticality matrix for critical minerals for the time period 2025 – 2035 (Source: U.S Department of Energy, 2023)

The EU and the US are not the only international actors that recognize the strategic importance of lithium. According to two separate reports compiled by the IEA (2022a: 27; 2023a: 109), China was the leading lithium-ion battery producer in the world with a share of 65% of global production in 2021, and held 60% of all lithium processing activities in 2022, respectively, thus holding a considerable control over the lithium supply chain. Perceiving the gravity lithium carries for the battery sector, China has been investing substantial financial and infrastructure resources in the upstream and midstream segments of lithium supply chains so as to reinforce it for domestic production of lithium-ion batteries and thus minimize potential disruptions in the supply chain. Moreover, both the Bolivian Ministry of Hydrocarbons and Energy (2023) and the Chilean Ministry of Economy, Development and Tourism (2023) disclose that China is investing considerably in lithium production activities, concluding partnerships with their respective governments and bringing its companies to their countries, henceforth making its presence felt in South American countries rich in lithium reserves.

Thence, the influence of geopolitics on sourcing lithium, where the question of the production of lithium in a sustainable way is additionally stressed, is not to be disregarded in the analysis of the lithium supply chain.

1.2. Lithium's Global Reserves and Demand

The question of lithium reserves is not a matter of major concern. According to data from the U.S. Geological Survey (2024: 111), total global reserves of lithium as of 2024 are estimated at 105 million tons. Out of this amount, 56 million tons or roughly 53% of all lithium reserves are concentrated in the Lithium Triangle in the form of continental brines. The Lithium Triangle, a region in South America that extends through parts of Argentina, Bolivia and Chile, is therefore the region with the most abundant reserves of lithium resource on the planet, which concurrently happens to be one of the driest places in the world (Ahmad, 2020; Gramling, 2019). This actuality plays an important role in the discussion of the sustainability of lithium production since the current practice of mineral production in the region is highly water intensive (Vera et al., 2023)

The estimations of lithium demand for the coming decades, on the other hand, is a matter that has to be put under greater examination considering that the magnitude of demand influences how much effort in producing lithium is needed and, accordingly, its supply. Making confident estimations for lithium demand by the mid-century, however, is no easy endeavor. Distinctive sources forecast different projections of lithium demand for 2050, with some providing approximations with greater uncertainties while others give predictions within narrower ranges, as listed below in Table 1.

Table 1: Comparison of forecasted lithium demand on a global level for 2050 between different authors

Source of data	Projected Demand [kt/year]*	Remarks
(Speirs et al., 2014)	184 – 989	Despite the reasonability in argumentation that the paper is outdated, the observable sizeable uncertainty in the forecast of the future lithium demand, as the paper states, stems from several factors: (i) potency of trend in future sales of EVs; (ii) battery capacity of future EVs; and (iii) the amount of lithium necessitated per each battery
(Xu et al., 2020)	620 – 1,600	The range is between scenarios of stated policies and sustainable development, respectively**
(World Bank, 2020: 103)	415	The report states that the demand greatly depends on the existing policies, market circumstances and other factors that can alter the level of certain

		technology's application and consequently the material demand
(IEA, 2020: 122)	1,250 – 1,550	The range is between sustainable development and faster innovation scenarios, respectively***
(Carrara et al., 2023: 191)	804 – 1,100	The range is between low demand and high demand scenarios, respectively****

Notes: * kt/year denotes kiloton per year

**The stated policies scenario considers policies that are currently set in place, whereas the sustainable development scenario includes additional actions needed to be in compliance with the Paris Agreement. Additionally, the latter scenario envisions that 30% of all vehicle sales in 2030 will be EVs.

***Both of these scenarios are arguably optimistic in reaching net zero in this century. The sustainable development scenario accounts for the expansion of existing and developing technologies that are expected to achieve net zero by 2070; the faster innovation scenario, in comparison, envisions the achievement of net zero by 2050 with the proliferation of existing technologies and technologies currently under research that are needed and/or hold the potential to contribute to the accelerated achievement of the goal.

****The low demand scenario considers a slower deployment of emerging fossil-free technologies, resulting in overall lower demand for minerals; the high demand scenario, on the other hand, foresees the swifter implementation of such technologies, corresponding to their greater material intensity and leading to higher demand for minerals.

Regardless of what the most accurate prediction will turn out to be in the future, all projections confidently express an expected notable increase in demand for lithium in the upcoming years to the year 2050, except for the lower range in the paper by Speirs et al. (2014). However, it should be noted that the lower range of lithium demand in the respective paper was estimated at the time when, in 2014, there were 320,000 EVs sold globally, which is 44 times less compared to 2023 when slightly over 14,000,000 EVs were sold worldwide (Irle, 2024), and when EVs had not yet fully established themselves in the market of one the world's largest economies (Block, Harrison and Brooker, 2015). The positive trend in sales of EVs is evident and is forecasted to cumulatively increase to approximately 250 million vehicles by 2030 (IEA, 2023b: 109).

A similar can be discerned for BESS, a technology that is highly reliant on lithium-ion batteries (Hesse et al., 2017), and whose positive trend and growth forecast by BloombergNEF (2022) to a total global capacity of slightly over 400 GW can be observed underneath in Figure 1.2.

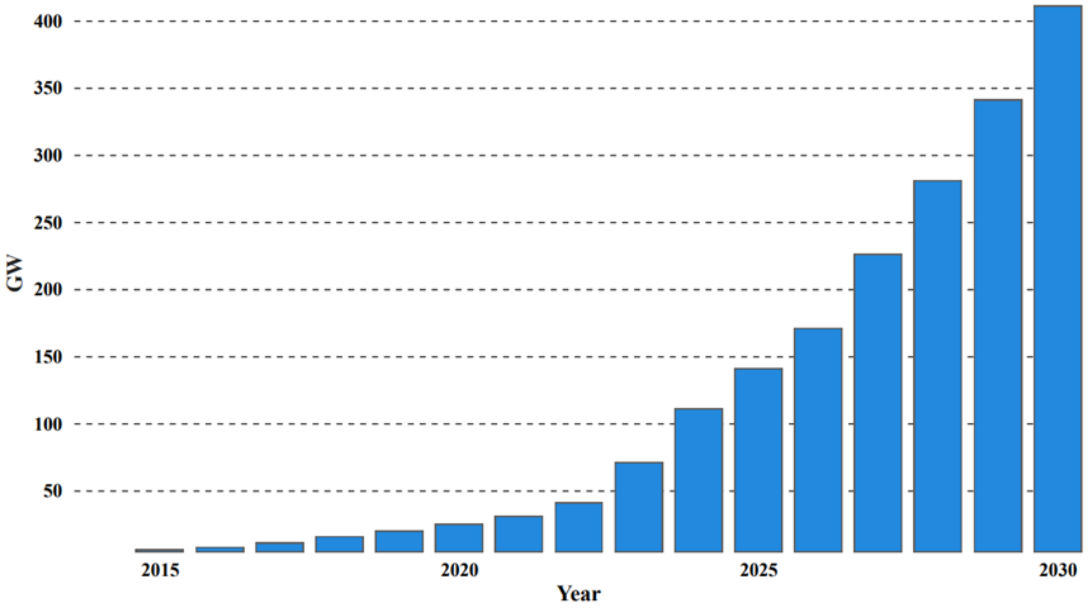


Figure 1. 2: Forecast of aggregate worldwide installation capacity of battery energy storage systems, 2015 – 2030 (Adapted from source: BloombergNEF, 2022)

This provides enough encouragement to confidently take a stance that demand for lithium will continue to increase if the markets for EVs and BESS continue to expand at a rate observed in the latest years.

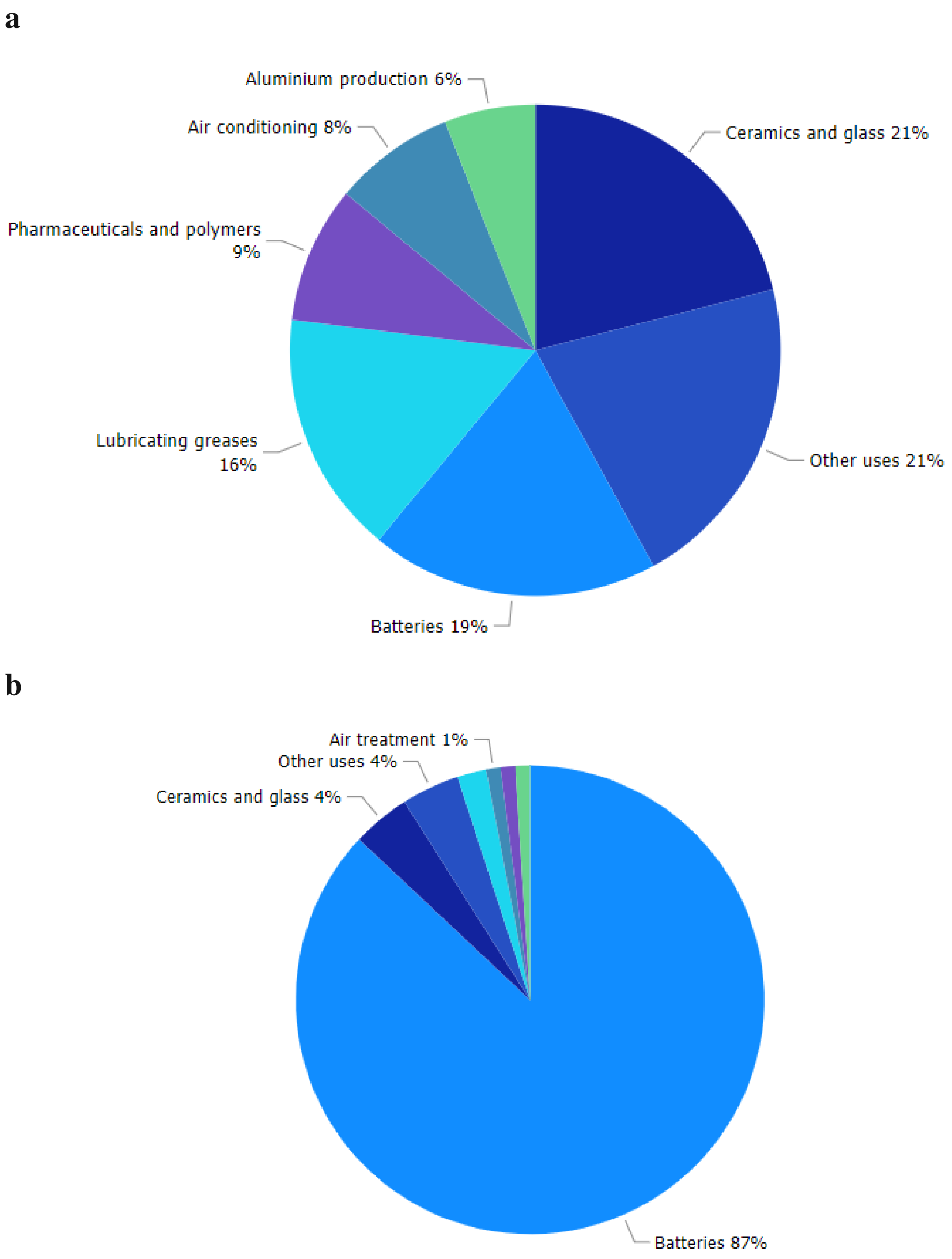
1.3. Historical Background of Lithium Applications

Lithium was not always a mineral of great significance to state economies and national securities. Since the discovery of its existence by Arfwedson and Berzelius in Sweden until the late 2000s, lithium in great part was not used for batteries but for a variety of different applications as displayed in Figure 1.3.

As early as 1847, thirty years after humanity's familiarity with the element, lithium served medical purposes. At first, it was used for treating gout-related arthritis issues, but it started receiving application in psychiatric practices for treating mania, anxiety-related disorders and hypnosis induction in the 1870s, and for bipolar disorder in the following century (Shorter, 2009).

Several decades later, in the mid-20th century, scientists started working on developing the first lithium-based battery. In the early stages, researchers conceptualized a rechargeable lithium metal battery in which lithium substance was placed in the negatively charged electrode of a battery that is an anode and metal sulfide in a positively charged electrode that is a cathode. However, these batteries were characterized by short cell life, low power and low safety due to their susceptibility to fire and explosion caused by the noteworthy likelihood of short circuits and lithium's reactivity. Eager to improve the imperfections of lithium metal batteries, scientists substituted metal sulfide in the cathode with lithium-cobalt oxide. The result was a more powerful battery of greater capacity that was safer, but nonetheless still susceptible to catching fire. After years of research and efforts invested to refine batteries and overcome safety concerns, scientists eventually came up with the first commercially viable lithium-ion battery in 1985. Instead of using lithium substances, they placed the carbon-based substance of petroleum coke's origin in the anode. The outcome was a more durable and as equally powerful battery with greater energy density and improved safety. It was not until 1991 when such lithium-ion batteries were first commercialized and the electronics industry revolutionized (Royal Swedish Academy of Sciences, 2019).

It was with the growing prevalence of electronic devices, and an urgency in addressing anthropogenic climate change with the simultaneous emergence of new technologies that battery research, development and production expanded and lithium received ever greater significance. That being the case, nowadays there are numerous types of lithium-based batteries developed and commercially used, each with different characteristics in performance, safety, life span, power and cost. The most popular types range from lithium cobalt oxide ($LiCoO_2$), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA) and lithium titanium oxide (LTO) (Miao et al., 2019).



a) Illustrated data for 2007; b) illustrated data for 2024

Figure 1. 3: Comparison of percentage of lithium consumption per end-use between 2007 and 2024 (Adapted from sources: U.S. Geological Survey, 2007: 96; U.S. Geological Survey, 2024: 110)

1.4. Lithium's Chemical and Physical Profile

What makes lithium such a desired mineral in battery production is its unique elemental properties. It is the lightest metal, it has the lowest density among solid elements and appears in nature in the form of two stable isotopes: lithium-6 and lithium-7, the latter one being more prevalent among the two. It belongs to the group of alkali metals and like the rest of its group, it is highly reactive. In the reaction with air, it gives two principal products: with oxygen, it gives lithium oxide ($4Li_{(s)} + O_{2(g)} \rightarrow 2Li_2O_{(s)}$) and with nitrogen lithium nitride ($6Li_{(s)} + N_{2(g)} \rightarrow 2Li_3N_{(s)}$); and in the reaction with water, it gives lithium hydroxide and hydrogen ($2Li_{(s)} + 2H_2O_{(l)} \rightarrow 2LiOH_{(aq)} + H_{2(g)}$). Because of its high reactivity with air and water, lithium cannot be found in an elemental form in the environment but rather it can exclusively be found as a constituent part in a compound, bound to one or more distinctive elements (Lazouski et al., 2019; LibreTexts, 2023a).

As electrons in a battery flow between anode and cathode, a substance between two electrically charged poles should preferably be a substance that easily gives up on its electron, i.e. it should have a high negative electrochemical potential and simultaneously be a strong reducing agent. Since lithium is the strongest reducing agent among all the elements as it, among other factors, has only one single valence electron in its outer shell that renders its configuration rather unstable, it gives up on its electron from the outer electron shell without much obstruction, hence making it a good element to be used in batteries (LibreTexts, 2023b; Royal Swedish Academy of Sciences, 2019).

What additionally makes lithium suitable for utilization in batteries are its properties of high nominal cell voltage and high theoretical specific capacity or specific energy that contribute to the attainment of high energy density within a battery, which is either expressed through volumetric energy density, defined as how much energy a system can store per unit of volume (watt-hour per liter [Wh/l]), or more commonly through gravimetric energy density, defined as how much energy a system can store per unit of mass (watt-hour per kilogram [Wh/kg]) (Battery University, 2022; Burke and Schweitzer, 2019: 4).

The latest efforts in lithium-ion battery development yielded batteries with gravimetric energy density of up to slightly over 700 Wh/kg with further attempts being made to come up with lithium-based batteries that would have energy densities exceeding 1,000 Wh/kg. Despite the progress made in battery research in the past thirty years as illustrated below in Figure 1.4, among the more advanced lithium-ion batteries that have been put to commercialized use in EVs are batteries with a gravimetric energy density of 300 Wh/kg (Gao et al., 2022; Li et al., 2023).

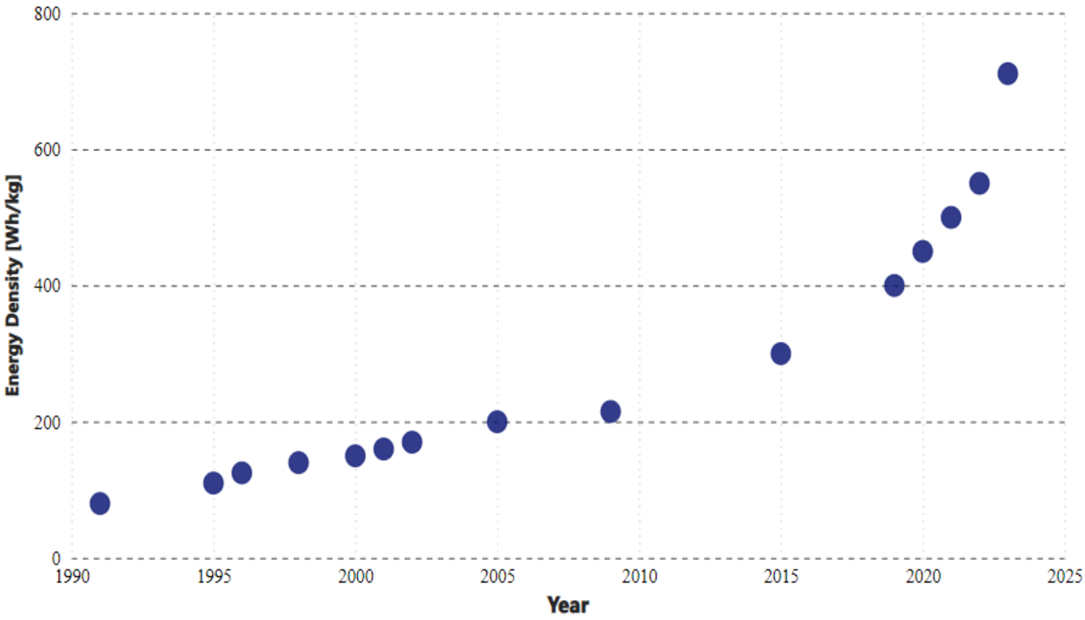


Figure 1. 4: Development of lithium-ion batteries in terms of energy density, 1991 – 2024 (Adapted from source: Li et al., 2023)

Notwithstanding the achieved improvements in lithium-ion batteries, other kinds of batteries that do not ineluctably rely on lithium are being developed, such as sodium-ion battery which exerts itself as a practicable replacement to lithium-ion batteries or the least as an addition to the battery market. In comparison, the state of the art sodium-ion batteries are relatively heavier and larger than lithium-ion batteries per the same amount of energy stored resulting ultimately in potentially greater weight of an EV, more space needed and shorter range an EV can cover. This is because of the closely related sodium-ion battery's lower energy density which varies in the range from 75 to slightly below 160 Wh/kg. Concurrently though, sodium-ion batteries are cheaper, safer in terms of flammability and retain greater security from disruptions in supply chains due to the greater abundance and availability of sodium in the environment (Abraham, 2020; Yu et al., 2023).

Where it cannot be ignored that sodium-ion batteries could be a viable complement for its application in low-range EVs that might be suitable, for example, for urban areas, it is likely that due to their superior chemistry, lithium-ion batteries will remain a preferable battery in the production of EVs and BESS.

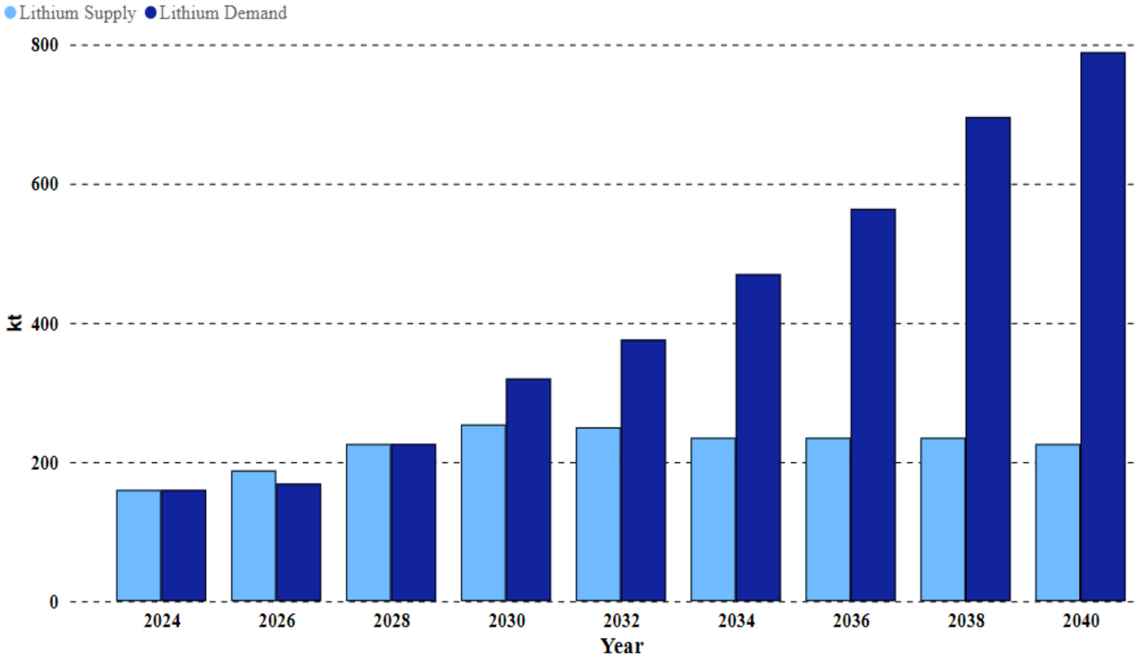
1.5. Lithium Extraction Methods

Lithium is largely found in two forms in the environment that are subject to commercialized extraction: hard-rock, which is the source of just about 60% of all lithium produced; and brines, which account for nearly 40% of global lithium production (Benchmark Mineral Intelligence, 2023a). Where lithium from hard-rock is sourced for the most part from spodumene ores (Tadesse et al., 2019); lithium in brines, or essentially in the water of high salt concentration, is found in one of its three distinct types: continental brines, which are reservoirs most commonly found beneath the arid regions of South America; geothermal brines, which are located at depths of several kilometers and can reach temperatures higher than 180 degrees Celsius, but is lowered to a temperature range of between 60 – 80 degrees Celsius after energy recovery; and oilfield brines, which are found alongside some oil and gas deposits (Vera et al., 2023).

Two main approaches to commercialized extraction of lithium from the aforementioned sources are presently exercised worldwide: one is the mining of lithium-containing ores, where heavy mining machinery is necessitated and is for the most part practiced in Australia; the other involves extraction of lithium from brines with an application of evaporation method which is in the large part carried out in the Lithium Triangle (Benchmark Mineral Intelligence, 2023a).

Both of these approaches yield some negative impacts on the environment, ranging from somewhat analogously deteriorated air quality due to higher concentrations of nitrogen oxide and particulate matter (PM 1, PM 2.5 and PM 10) that are released from hard-rock mining activities (Rodrigues, Antao and Rodrigues, 2019), to a threat of decline in number of endemic (Flexer, Baspineiro and Galli, 2018) and non-endemic living organisms (Kanuda, 2020) that is caused by lithium production which utilizes evaporation method on continental brines.

Several reports from different international organizations (Gielen and Lyons, 2022; IEA, 2021b), a price reporting agency (Benchmark Mineral Intelligence, 2023b), a consulting company (McKinsey & Company, 2022) and research papers (Blair et al., 2023; Liu, Agusdinata and Myint, 2019) address and concur on additional concerns regarding lithium. These include further environmental considerations that stem from the practiced approaches to lithium production, particularly the stress exerted on water resources (Blair et al., 2023; IEA, 2021b: 142; Liu, Agusdinata and Myint, 2019); and/or the looming probability of shortage in lithium supply that is expected by 2030 due to its insufficient production relative to demand as illustrated below in Figure 1.5 (Gielen and Lyons, 2022: 12 – 13; IEA, 2021b: 119; McKinsey & Company, 2022).



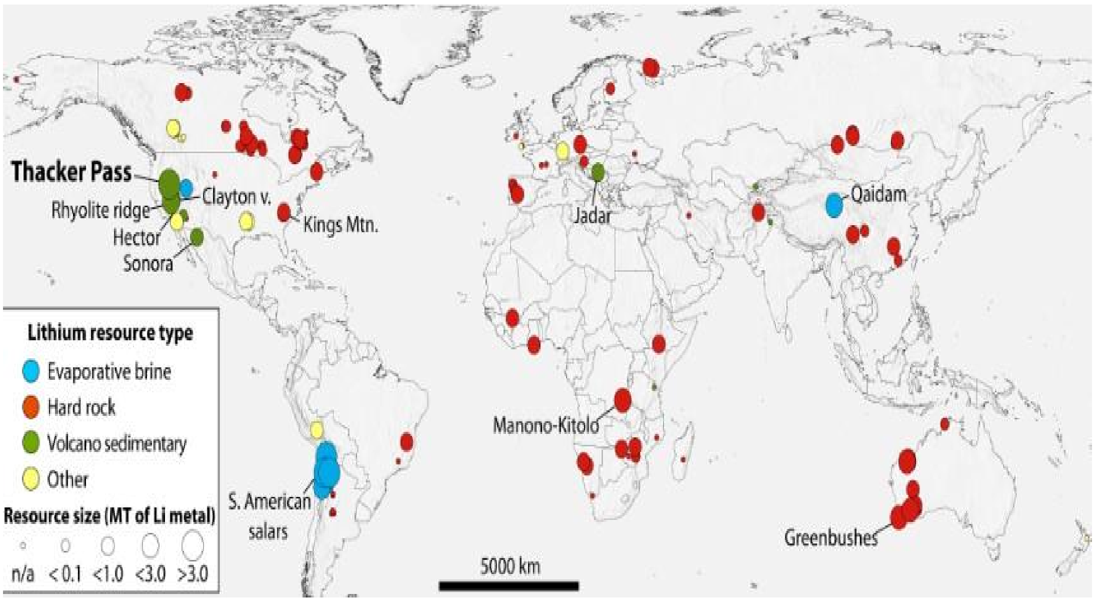
Note: primary and secondary sources of lithium supply are accounted for, which indicate that lithium is produced from both extraction activities from the environment and from the recycling of lithium-ion batteries, respectively

Figure 1. 5: Forecast of global lithium supply-demand relation, 2024 – 2040 (Adapted from source: Joint Research Center, 2022)

As a result, there has been a growing interest in the third means of lithium extraction which has not yet been scaled up in the great part of the world, but with its implementation, foremost, on continental and geothermal brines it could possibly fill in the anticipated gap in lithium supply chains and complement the existing methods of lithium extraction – direct lithium extraction (DLE) (McKinsey & Company, 2022).

DLE encompasses a number of different technologies whose operations are based on particular physiochemical processes, such as adsorption, ion exchange, solvent extraction, electromembrane and electrochemical processes that selectively extract lithium ions from the remaining salts appearing in brine water. With the selective extraction of lithium ions from other minerals, which consequently delivers purer product with fewer mineral impurities, presumably less demand for total water consumption, faster extraction and less need for land area, DLE signifies the potential for a comparatively more sustainable means of lithium production compared to the hard-rock mining and evaporation method (Warren, 2021: 3 – 4). Among the aforementioned means of lithium extraction, IEA (2021b: 169), as one of the most renowned organizations on energy-relevant matters, also recognizes DLE as an emerging technology that could cover a considerable portion of future lithium supply needs.

Following the data on the reserves and distribution of lithium in the world, as can be denoted below in Figure 1.6, the Lithium Triangle carries the potential as a region where the proliferation of more environmentally sound lithium production projects with the large-scale application of DLE technologies in the forthcoming years could be exercised.



Notes: evaporative brine in this instance is synonymous with continental brine; the Lithium Triangle is an area indicated by the blue circles in South America

Figure 1. 6: Global distribution of lithium by type (Source: Benson, Coble and Dilles, 2023)

1.6. Research Questions and Aim of the Study

Following from what has been stated in the insofar paper – the awareness of the cruciality and vulnerability of lithium supply chains among some of the leading economic powers in the world, consensus on the forecasted increase in lithium demand mainly because of the production of batteries for EVs and BESS, and the potentiality of emerging DLE technologies to source lithium from brine deposits in a relatively sustainable way – the following two research questions are derived:

(I) *How does the adoption of direct lithium extraction on brine deposits impact the environmental sustainability of lithium supply chains?*

(II) *What are the challenges associated with integrating direct lithium extraction into existing lithium supply chains, and how can these challenges be overcome?*

In order for society to collectively achieve the set ambitious goal of net zero carbon emissions, and for countries to ensure an uninterrupted flow of raw materials, it is pivotal that lithium supply chains are both secured and managed in as sustainable manner as feasible. To that end, the aim of the present study is twofold: (i) to enhance understanding of whether DLE technologies could effectively contribute to filling out the forecasted lithium demand in a more environmentally considerate manner, as opposed to the commonly practiced means of lithium extraction; and (ii) to conduct an overarching analysis which is set to provide with the greater conception of challenges and opportunities associated with ventures of large-scale utilization of DLE technologies on continental and geothermal brines.

By following these two aims and answering the research questions, the present paper seeks to contribute to project developers on future lithium extraction projects with recommendations and/or better understanding of DLE aimed at attaining more sustainable lithium supply chains.

2. METHODOLOGY

The following text lays down the structure of the research segment of the paper and the means of data gathering that inherently describe how the answers to the aforementioned research questions are obtained.

2.1. Research Structure

The research aspect of the paper is broken down into two parts. The first part examines the state of the art of contemporary methods of lithium extraction; the widely practiced method of brine evaporation, as well as the DLE method which has not yet taken its full swing in commercial production. The aim of the first part is to grasp the understanding of what these approaches are, what they consist of, how they work from the technical aspect of view and what their impacts on the environment are. This is continued and finalized with the critical comparison of the considered lithium extraction methods on the sustainability of the approaches following the relevant selected environmental parameters.

The second part of the research intends to scrutinize how to pave the path and accelerate the commercial implementation of DLE technologies on continental and geothermal brines. This comprehends the consideration of both the challenges and possible inconspicuous opportunities encountering DLE utilization. To recognize the challenges and opportunities as well come up with pragmatic solutions, insights into the implementation and development of DLE projects are gathered through interviews held with the respective representatives of the lithium industry.

Following these two sections of the research, the research questions are expected to be provided with complete answers and an overarching study concluded, which could eventually serve as a starting point for further examination to be carried out by the public and/or private sectors.

2.2. Data Compilation

For both parts of the research literature review as a secondary source of information is extensively used to aggregate the state of the art findings. Throughout the research, various research and review papers, and other kinds of written sources are carefully examined: on concerns of brine and fresh water consumption – Bustos-Gallardo, Bridge and Prieto (2021), Cerda et al. (2021), Ejeian et al. (2021), Garcia et al. (2023), Jerez, Garces and Torres (2021), Marazuela et al. (2019) and Marchegiani, Hellgren and Gomez (2019); on brine evaporation approach – Agusdinata et al. (2018), Baspineiro, Franco and Flexer (2020), Bustos-Gallardo, Bridge and Prieto (2021) and Meshram, Pandey and Mankhand (2024); on different DLE technologies – Battistel et al. (2020), Joo, Lee and Yoon (2020), Li et al. (2019), Nguyen and Lee (2018), Weng et al. (2020), Xiong et al. (2022), Xu et al. (2021) and Xu et al. (2016); economic, policy and geopolitics, and technical concerns regarding lithium – Garcia et al. (2023), MacDonald (2023), Molen (2022), Williams, C. (2024) and Williams, G. (2024). These papers comprise the fundamental secondary source of information and do not exclusively pertain to the sub-topics previously mentioned. Among the mentioned papers, the sources that provide with comprehensive understanding of the topics, for which they are oftentimes used in the forthcoming chapters, are papers by Boroumand and Razmjou (2024), Flexer, Baspineiro and Galli (2018), Murphy and Haji (2022), Stringfellow and Dobson (2021), Vera et al. (2023) and Warren (2021). Additional sources include documents and online publications from consultancy companies, governments, international organizations and private companies that contain supplemental or relevant specific data.

Besides the literature review, interviews with the DLE developers and/or private companies that are in the process of commercial implementation of DLE provide with invaluable primary source of information that aids in better comprehension of how DLE works and/or in the recognition of hindrances behind the large-scale application of such technologies from the first-hand and practical aspect of view. With that, interviews to a great extent contribute to both parts of the research segments of the paper and consequently contribute to the formulation of answers to the research questions.

The interviews conducted were with:

- Nick Baxter: Mr. Baxter serves as the Head of Communications and Environmental, Social and Governance (ESG) in CleanTech Lithium, PLC. CleanTech Lithium is a British registered company established in 2017 with an ambition to produce lithium from continental brines that would utilize DLE. Currently, the company has four ongoing projects in total that are either in the feasibility study phase or exploration phase in Argentina and Chile. The interview was held on the 29th of February 2024.

- Fabien Burdet: Mr. Burdet acts as a Chief Technology Officer (CTO) at Eramet, a French mining company established in 1880. The company is spread worldwide and is involved in mining several metals, including lithium in Argentina and expectably in Chile. The lithium project in Argentina that utilizes DLE commenced with the production of lithium for commercial purposes in the current year of 2024. Furthermore, Mr. Burdet has conceptualized 8 physiochemical inventions for which he holds intellectual property in the form of patents, some of which are applied as part of DLE in the company's relevant lithium project. The interview was held on the 4th of April 2024.

- Xitong Liu: Mr. Liu obtained a Ph.D. from the Johns Hopkins University in Environmental Health Engineering and currently holds the position of an Assistant Professor at the Department of Civil and Environmental Engineering at the George Washington University. He has published over 40 papers largely on extraction of critical minerals and water treatment. As a leader of a team, Mr. Liu came up with a DLE technology based on an electrochemical process for which, alongside his team, he received recognition from the DOE. Subsequently, Mr. Liu co-founded a company named Ellexco which proposes to extract lithium from geothermal brines using the invented DLE technology. The interview was held on the 25th of April 2024.

- Richard Thompson: Mr. Thompson is a project manager in Cornish Lithium, PLC. Cornish Lithium is a British company founded in 2016 set to produce lithium in the Cornwall region, in the United Kingdom. The company aims to extract lithium from hard-rock ores and from geothermal brines using DLE technology. Furthermore, Mr. Thompson leads a team on exploring the opportunities and feasibility of implementing DLE technology on deposits of geothermal brine in Cornwall. The interview was held on the 3rd of May 2024.

Besides the information conveyed in the interviews, some interviewees provided additional sources of publicly available information published by their respective companies on the lithium and DLE related subject.

3. METHODS FOR LITHIUM EXTRACTION FROM UNDERGROUND BRINE DEPOSITS

The present chapter provides state of the art knowledge of different methods of lithium extraction from brine deposits, namely brine evaporation and utilization of DLE technologies. The focal point is placed on the technical principles these approaches are based on, including prerequisite conditions and the environmental impacts that arise from their application.

3.1. Evaporitic Technology

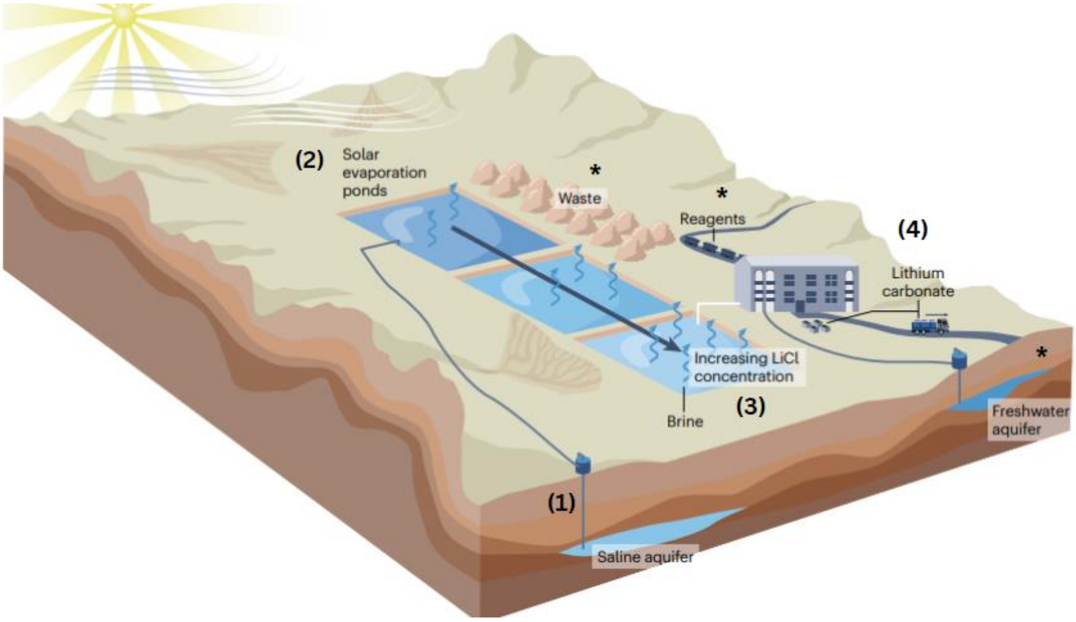
The evaporation method also commonly referred to in the literature as evaporitic technology, is at present the principal method of lithium extraction from continental brines in the Lithium Triangle. The important factors to consider in approaching this kind of method are threefold: what the environmental evaporation conditions are, what the mineral content of brine is and what the mineral concentration of the targeted mineral within brine is (Bustos-Gallardo, Bridge and Prieto, 2021).

Concerning ambient evaporation conditions, the Lithium Triangle makes an ideal region for this kind of method as it provides perfect conditions for the evaporation of mineral-rich water given that the region is one of the driest places on the planet, has very low annual precipitation, low air humidity, frequent winds and high solar irradiation at a high altitude that together contribute to a high evaporation rate (Bustos-Gallardo, Bridge and Prieto, 2021).

In such conditions, the process of the evaporitic technology works in such a way, in its essence, that, after drilling to a saline aquifer has taken place, lithium-containing brine is pumped out from underground reservoirs into a series of ponds at the surface, where brine water is left to evaporate and lithium ions in the form of a lithium chloride (LiCl) compound gradually concentrated; as illustrated in Figure 3.1 underneath. However, the process is not as straightforward as superficially described. Once brine water containing between usually 400 and 1500 mg/kg of lithium is brought to the surface into brine ponds, which are shallow but cover great surface area, a series of mineral removal processes take place. Beforehand, however, to prevent the brine treated with chemicals from leaching into soil, the basin of the ponds is covered with polyvinyl chloride (PVC) liner. The risk that PVC liner could rupture and consequently cause the brine and the chemicals to leach into the environment is existent nonetheless (Agusdinata et al., 2018). Notwithstanding the risk, compounds spontaneously precipitate during the first 9 months of the evaporation, such as sylvanite, sodium chloride and carnallite. The rest of the minerals that cannot spontaneously precipitate are removed with further chemical treatment, i.e. with the addition of reagents. Most notably, borates are removed using liquid-liquid extraction, magnesium is precipitated by the addition of calcium oxide (CaO), that is lime, and calcium with the addition of sodium oxalate ($Na_2C_2O_4$) (Baspineiro, Franco and Flexer, 2020; Bustos-Gallardo, Bridge and Prieto, 2021; Flexer, Baspineiro and Galli, 2018; Meshram, Pandey and Mankhand, 2014). The rest of the salts such as bromine, calcium, potassium and the remainder are removed using various chemicals, if not spontaneously precipitated during the evaporation activity. All these removed salts from brine are considered as waste, except perhaps for magnesium and calcium which are occasionally put to practical use in road maintenance. The total amount of removed salts, that is waste, is not insignificant; per 1 ton of lithium extracted, up to 612 tons of waste is generated which if it is not managed, is left next to the ponds to amass (Flexer, Baspineiro and Galli, 2018).

Among the salts found in the brine, magnesium turns out to be of particular issue in lithium extraction. As magnesium and lithium ions share some similarities in chemical properties, in the course of precipitation of lithium carbonate (Li_2CO_3), magnesium carbonate ($MgCO_3$) precipitates as well, leading to a lower purity of the end product. To avoid impurities in the final product, the aforementioned lime is added to the brine to precipitate magnesium at conditions of value of over 9 on the pH scale. However, this leads to precipitation of magnesium hydroxide ($Mg(OH)_2$), which while precipitating takes up more lithium-containing brine water. This consequently leads to a lower lithium yield of approximately 70%, or even as low as 50% lithium extracted, depending on the magnesium content in the brine. Therefore, it is essential to know the chemical composition of brine, in particular the magnesium and lithium ratio, for if magnesium concentration is too high in comparison to lithium, the lithium extraction utilizing evaporitic technology with lime as a precipitant to sequester magnesium might be rendered as economically not practical (Flexer, Baspineiro and Galli, 2018).

The evaporation process of lithium-containing brine water in ponds is not in stagnation, but rather it cascades through a series of ponds, from blue-colored ponds with lower concentrations of lithium to yellow-colored ponds with higher concentrations of lithium until a desired concentration of lithium has been reached. Once over 90% of the brine has evaporated, minerals in the brine are removed either through spontaneous precipitation or with an addition of chemicals, and saline water reaches a concentration of lithium of over 6000 mg/kg, brine is sent to the lithium carbonate plant where lithium in the form of lithium chloride from the brine is precipitated into lithium carbonate by adding soda ash, that is sodium carbonate (Na_2CO_3) in the following reaction: $2LiCl(aq) + Na_2CO_3(aq) \rightarrow 2NaCl(aq) + Li_2CO_3(s)$. With the concluded precipitation of lithium carbonate after between 10 and 24 months, the lithium extraction process is finished (Baspineiro, Franco and Flexer, 2020).



Notes: saline aquifer and underground brine deposit are used synonymously
(1) drilling and extraction of brine water; (2) evaporation of brine water, the commencement of precipitation of undesired salts; (3) during the evaporation process, brine cascades through evaporation ponds where further disposal of unwanted salts takes place and the concentration of lithium increases; (4) after the final purification from the remainder of salts in the lithium carbonate plant, lithium carbonate is precipitated
*waste is a variety of removed salts from brine; reagents are chemicals used for precipitating and removing unwanted salts from brine; freshwater aquifer is the source of fresh water that is used in various parts of the evaporation method for different purposes

Figure 3. 1: An illustration of the evaporation method of lithium extraction from continental brines (Adapted from source: Vera et al., 2023)

In various parts of the process of precipitating and removing non-lithium minerals, fresh water from freshwater aquifers is added to the brine. Its function is versatile: to dissolve lime and sodium carbonate, to scrub off organic solvents used in liquid-liquid extraction and to wash formed lithium carbonate crystals, hence placing additional stress on water resources from the environment (Flexer, Baspineiro and Galli, 2018; Vera et al., 2023).

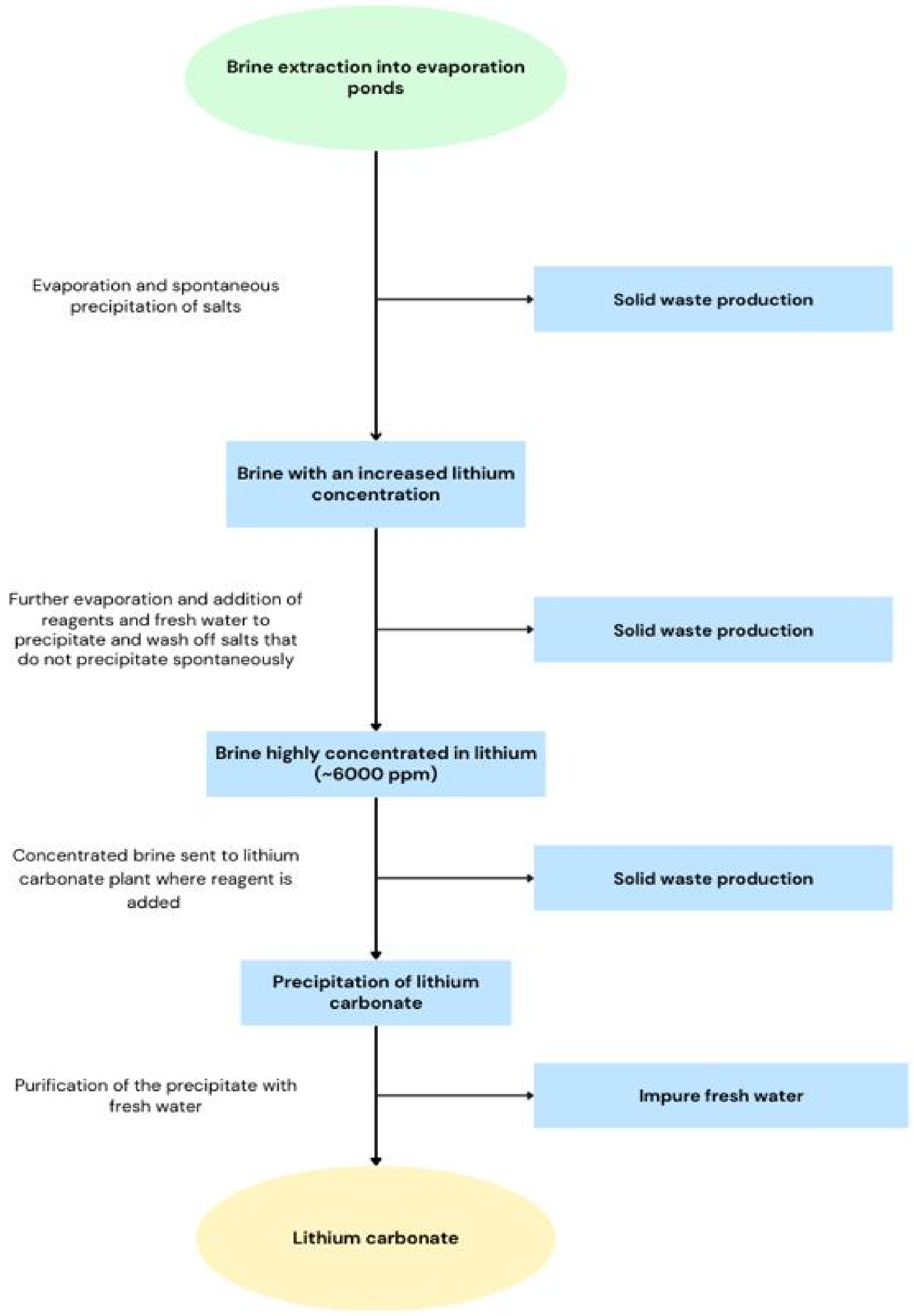


Figure 3. 2: Flowchart for lithium production by the evaporitic technology (Own work)

Evaporitic technology is a long process of lithium production that throughout the operation produces solid and aqueous waste. Bearing in mind that the brine water evaporates in the course of the operation of this extraction approach, this process is not considered environmentally friendly; particularly if fresh water is not recovered, and if solid waste is left to amass next to the evaporation ponds, similarly as tailings from hard-rock mining.

3.2. Direct Lithium Extraction

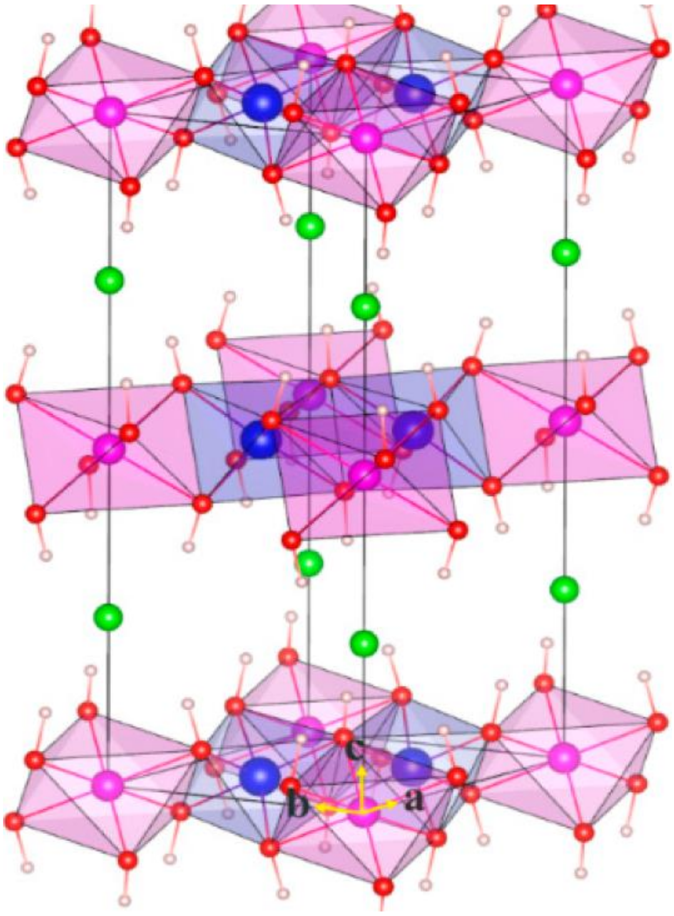
DLE does not correspond to one technology, but several distinct technologies differentiated by particular physiochemical processes upon which lithium separation from brine is grounded. Two advantages of DLE over evaporitic technology are that DLE can be applied to brines with a somewhat lower content of minerals, and secondly, it does not depend on ambient conditions. Consequently, the implementation of DLE is not limited to certain climates but rather it can be applied in a greater geographic span and on different types of brines, for example on geothermal in addition to continental type.

There are five such processes actively being developed for a prospective commercial application in lithium extraction from continental and/or geothermal brines. However, as it is a cluster of technologies that is under intensive research and development in several countries, there are many different variations within DLE technologies themselves, each being tested and based on different chemical compounds utilized within the processes. Due to a high number of different variations, the following text will not deal with an exhaustive list of developed patents but rather it will focus on the principles of how these processes in their essence work.

3.2.1. Adsorption Extraction

With the conducted extensive research, adsorption DLE provides the most assurance among developers of lithium production in being a reliable, fast and feasible means of lithium extraction between DLE technologies. There are currently over 25 ongoing projects conducting feasibility and pilot studies on the practical viability of this DLE, which corresponds to approximately half of all active DLE projects, with two more projects being in a phase of successful practical implementation of the technology. Eramet, as one of the companies applying the adsorption DLE, is the latest company that started the production of lithium in the first quarter of the current year (Burdet, personal communication, 2024; Deloitte, 2023; Eramet, 2024; Murphy and Haji, 2022).

The adsorption process functions in a way that an adsorbent with high adsorption capacity and affinity towards lithium adsorbs lithium ions onto its structure, leaving other salts non-adsorbed in the brine. Aluminum-based materials have been demonstrated to have high adsorption capacity and affinity towards lithium, where lithium-aluminum layered double hydroxide (LiAl-LDH) (Figure 3.3), with the formula $m\text{LiCl}\cdot 2\text{Al(OH)}_3\cdot n\text{H}_2\text{O}$, has been put to use in a successful commercial production of lithium from continental brines. In the first step of the process, the adsorbent adsorbs lithium and chloride ions onto its octahedral structure. In the subsequent step, with the addition of an eluent, lithium precipitates with chloride forming LiCl solution whence further processing takes place (Boroumand and Razmjou, 2024; Murphy and Haji, 2022).



Notes: blue is aluminum, green is chloride, purple is lithium, red is oxygen, white is hydrogen

Figure 3. 3: A lithium-aluminum layered double hydroxide structural model (Adapted from source: Zhang et al., 2019)

Once the LiAl-LDH adsorbs lithium onto its structure, it has to be desorbed. This part of the process comes in two steps and requires a significant amount of eluent. In the first step, the adsorbent is washed with a saline solution, preferably with the solution of LiCl or other lithium salt, to remove any impurities, that is, any undesired ions that have adsorbed onto the adsorbent. In the second step, once the unwanted ions had been washed off, the adsorbent is washed with warm pure fresh water that strips off lithium and chloride ions into the eluent. Counting both steps, the desorption process consumes five times more fresh water compared to some alternative DLE technologies (Bouroumand and Razmjou, 2024; Boualleg, Burdet and Oudart, 2023; Flexer, Baspineiro and Galli, 2018). To avoid high production of wastewater, the eluent is recovered and reused in further desorption processes. Next to water recovery, adsorption technology does not utilize a great deal of reagents and does not produce a significant amount of waste (Baxter, personal communication, 2024; Boroumand and Razmjou, 2024; Burdet, personal communication, 2024).

There are several aspects to consider in an estimation of whether this DLE is economically viable. In their paper, Boroumand and Razmjou (2024) identify three important factors that should be examined: salinity, temperature and lithium content of the brine.

In a medium with a limited amount of water molecules, ions of different elements mutually compete for hydration. If there is a medium with high salinity content, that is with a high content of other salts besides lithium in brine, lithium forms a single hydration layer around its ion, whereas other salts are more successful in forming two layers. This is important for the adsorption process as, having one hydration layer, lithium will be preferred to be adsorbed onto a material in comparison to salts that have a double hydration layer (Figure 3.2) (Boroumand and Razmjou, 2024). Without high salinity content and greater competition amongst alkali ions, lithium would form a double hydration layer more easily and would thus not be adsorbed on an adsorbent as efficiently.

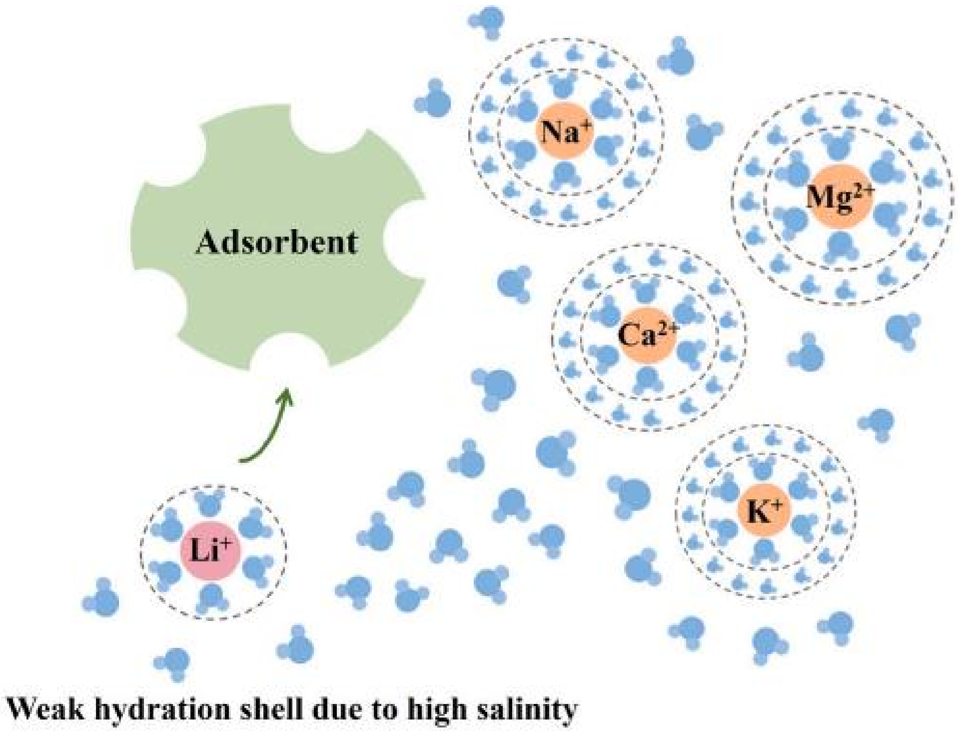
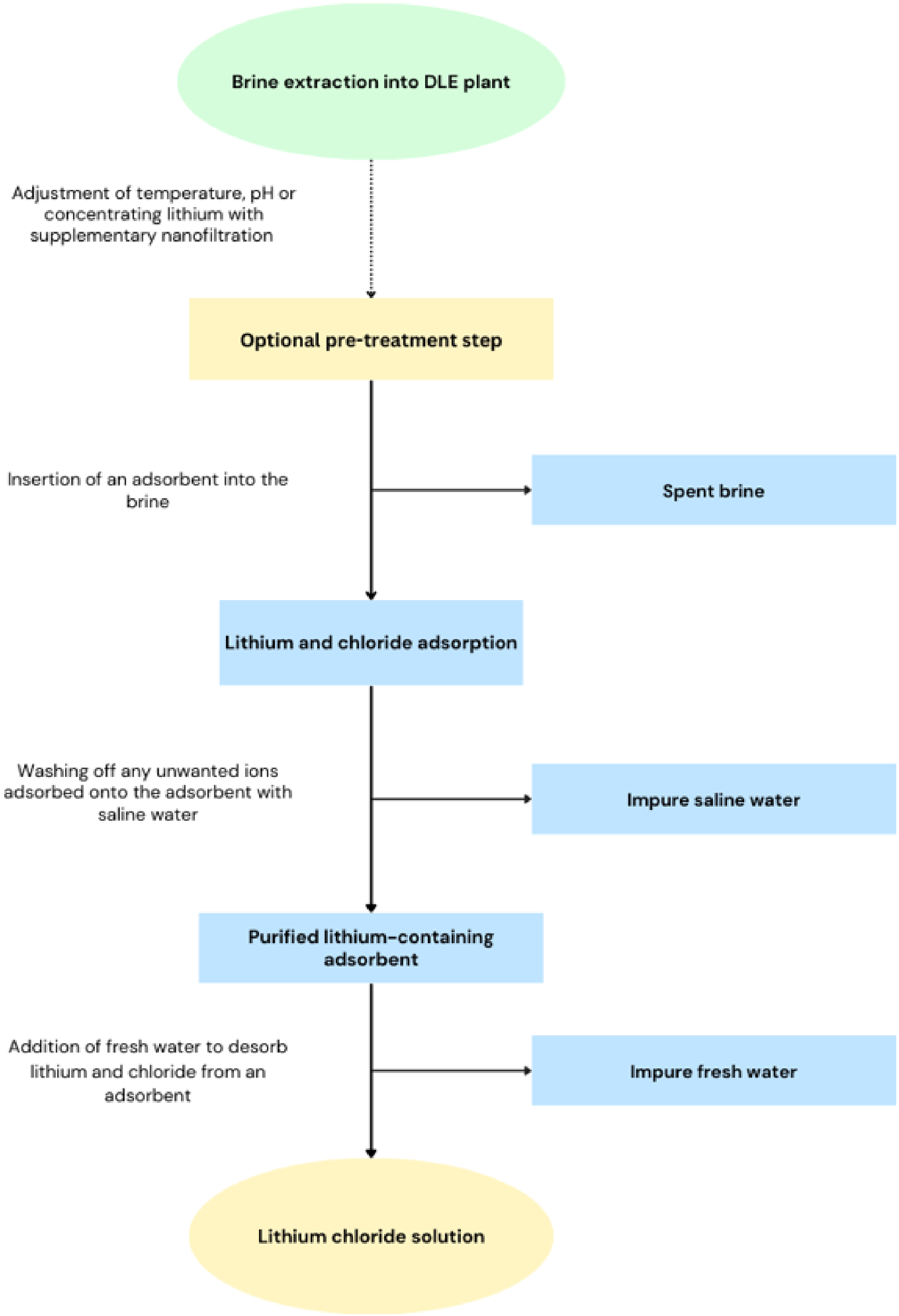


Figure 3. 4: Lithium adsorption onto an adsorbent material (Adapted from source: Boroumand and Razmjou, 2024)

Temperature is another important factor for efficient lithium adsorption. Since the lithium adsorption process is an endothermic process, a higher temperature corresponds to more efficient lithium adsorption. For the reason that one of the characteristics of continental brines is that they do not have a high temperature of brine waters as geothermal brines do, the matter of temperature for the extraction operation should be of consideration when approaching the relevant DLE. The optimal temperature range for the process has been evaluated to be between 40 and 95 degrees Celsius, whereby a process with an increase in temperature by 70 degrees Celsius might lead to an increase in lithium yield by 55% (Boroumand and Razmjou, 2024; Vera et al., 2023). Although this would increase the efficiency of the lithium extraction process, heating the brine would simultaneously elevate the costs of operating the DLE. Notwithstanding, heating the brine might not be necessary for a high lithium yield, as Burdet (2024) indicated in personal communication. Eramet, as Burdet (2024) continued, does not operate with brine at a high temperature, but at a relatively low temperature of 20 degrees Celsius with lithium adsorption efficiency of $\geq 90\%$.

The final factor that should be considered is lithium concentration in a brine. Higher lithium content in a brine elevates the lithium adsorption efficiency, increasing the lithium extraction per each adsorption operation. To increase the concentration of lithium in brine, the pH of the brine can be changed with the addition of reagents (Boroumand and Razmjou, 2024). If lithium concentration in brine is below 100 mg/L, utilization of adsorption DLE might be deemed as not economically viable as the costs of production could outweigh the value of lithium extracted (Boroumand and Razmjou, 2024).



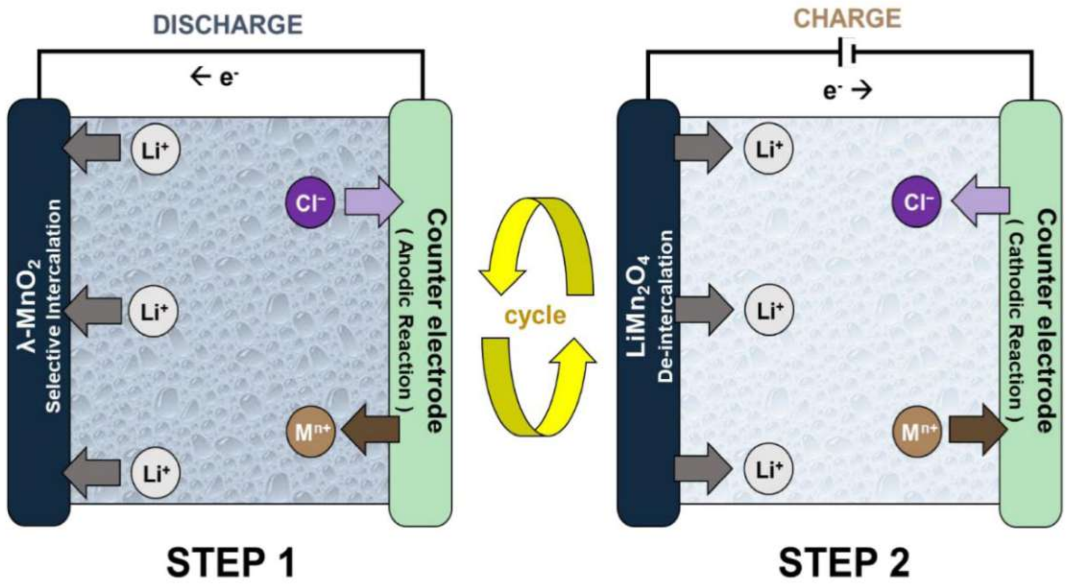
Note: the pre-treatment step affects final energy demand and waste production

Figure 3. 5: Flowchart for lithium production by adsorption DLE (Own work)

Overall, the adsorption DLE represents a good potential for large-scale lithium extraction in an environmentally considerate manner, as it requires no acids or reagents in the process, except the saline solution for the washing step. There are, however, several points to address – how saline eluent is treated after the uptake of unwanted ions, what the rate of fresh water recovery to consumption is, and what the final cost of the process is.

3.2.2. Electrochemical Extraction

There are currently many efforts being invested in research on electrochemical processes that are based on different configurations; configurations that vary from carbon-based capacitive deionization, redox-mediated capacitive deionization, electrolysis, electrodialysis to electrochemical ion pumping (Xiong et al., 2022). Regardless of the diversity of configurations applied within the electrochemical operations, the fundamentals of the most propitious lithium extraction using electrochemical DLE are such that with the process of selective electrochemical intercalation, lithium is spontaneously intercalated into the active electrode material and hence removed from other salts in the brine. Concurrently, chloride is attracted to the counter electrode. Once the ions are sequestered, by replacing brine water with fresh water recovery solution, and with the application of current, lithium and chloride are released into the recovery solution. Although the recovery solution after the current application contains lithium, it is low in its concentration. Therefore, to increase the concentration of lithium in the recovery solution, the described process is repeated in numerous cycles until the desired higher concentration is reached (Figure 3.6) (Joo, Lee and Yoon, 2020; Vera et al., 2023).



Note: the medium in the step one is brine water whereas the medium in the step two is fresh water

Figure 3. 6: An electrochemical process of lithium extraction from brine (Source: Joo, Lee and Yoon, 2020)

The selectivity is feasible due to lithium's very small ionic radius and because of the utilization of intercalation material that can intercalate only so small ions between its structures, whereby lithium manganese oxide ($LiMn_2O_4$) emerges as a material that showcases high intercalation selectivity towards lithium ions (Figure 3.7) (Xiong et al., 2022). Moreover, with the application of the right voltage, with the fast movement of small lithium ions, with the control over the brine conditions and subsequently working around lithium's electrochemical potential, the extraction of the aimed ion is enhanced. As a result of the electrochemical process, up to 90% of lithium can selectively be separated from other salts (Liu, personal communication, 2024).

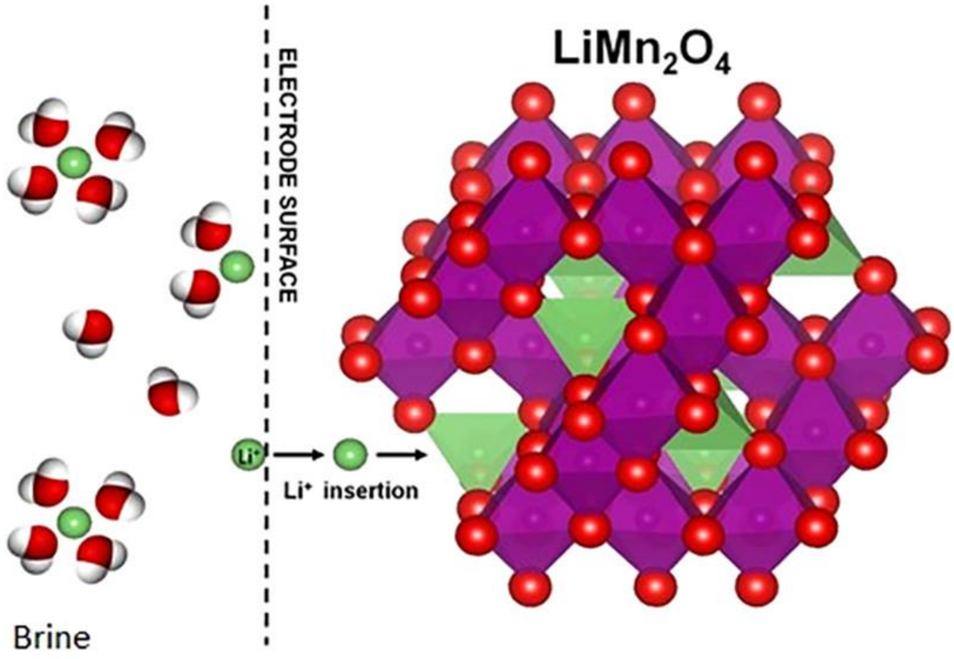


Figure 3. 7: Intercalation of lithium ions into the crystalline structure of lithium manganese oxide (Source: Calvo, 2021)

The electrochemical process is different from other methods insomuch that it utilizes electricity to recover lithium from materials containing lithium. However, since it requires electricity, the process might lead to higher energy consumption (Murphy and Haji, 2022). This would not present much problem if the DLE were applied to geothermal brines as the heat energy from this type of brine could be used for electricity generation. For continental brines in the Lithium Triangle, electricity generation is more of a challenge due to the remoteness of lithium excavation sites from national electricity grids. Nevertheless, since the excavation sites are located in highly insolated arid areas, the installation of solar panels presents a viable option (Liu, personal communication, 2024).

Moreover, Flexer, Baspineiro and Galli (2018) state that the process might necessitate a not insignificant amount of material: for 1 mole of lithium extracted, which is equivalent to 6.94 grams of lithium, between 150 and 181 grams of input material for the electrodes are required. This is a factor that would certainly affect the costs of the DLE's implementation, along with the energy cost if sustainable means of energy provision are not secured. In order for the costs not to exceed the value of lithium extracted, the electrode materials should be able to operate for a certain number of cycles, i.e. how many times electrodes can fulfill the operations of lithium intercalation and de-intercalation in the process of lithium extraction from brine before wearing off. Otherwise, this technology would be depicted as economically not viable (Battistel et al., 2020). Besides the material demand, there are two more challenges associated with this DLE, at least in regards to geothermal brine: one is sensitivity to temperatures and another one is silica content. Electrochemical DLE can operate at a temperature of 80 degrees Celsius, but there is no certainty whether it would be feasible to operate the technology over a sustained period at temperatures of over 100 degrees Celsius. In regards to silica, various DLE technologies have run into a challenge on how to remove it from brine in as economically sensible way as possible. This question remains a matter to be resolved, but the current confidence is in profound brine pre-treatment processes where silica, in addition to other suspended solids and transition metals, would be removed (Liu, personal communication, 2024).

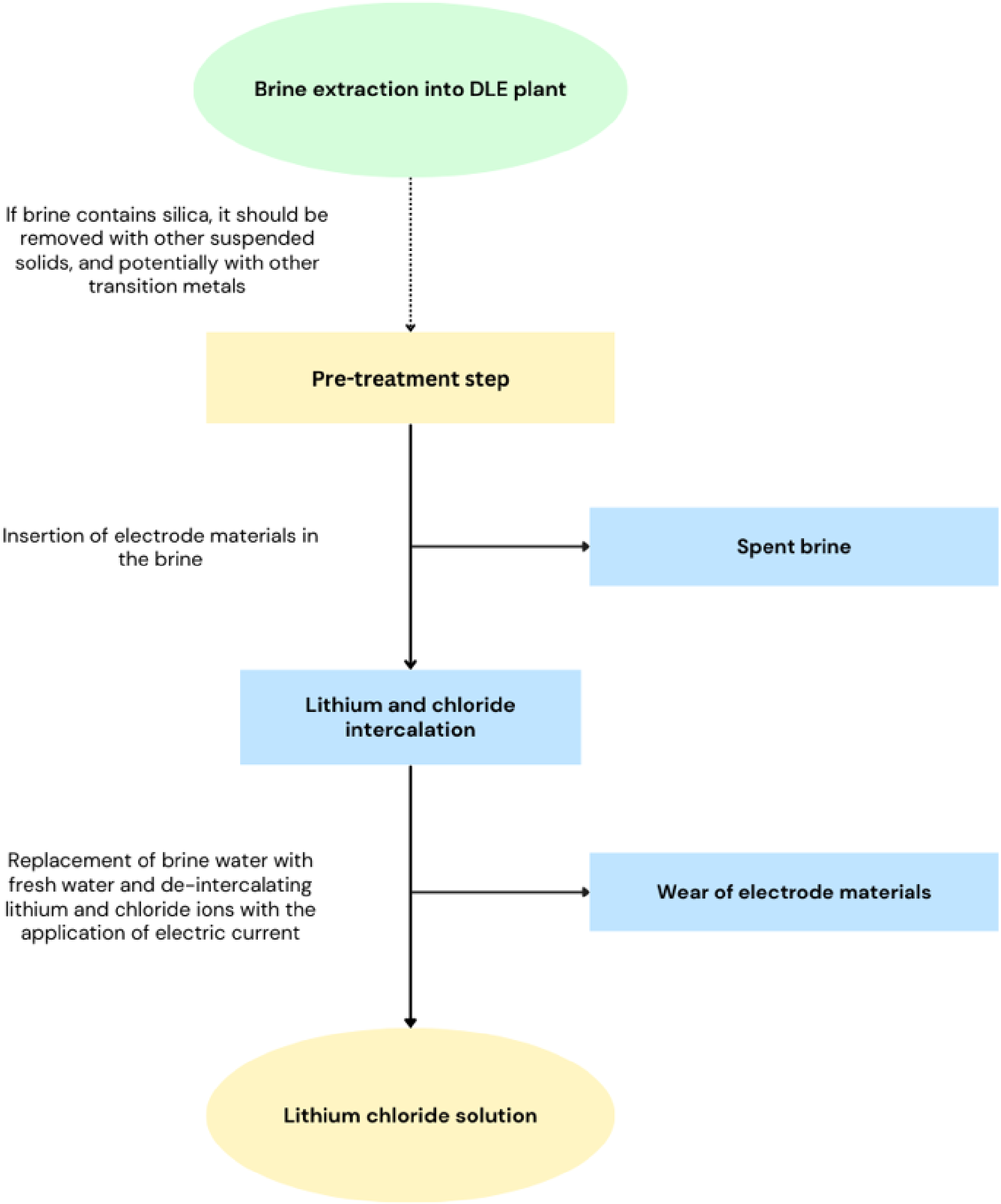
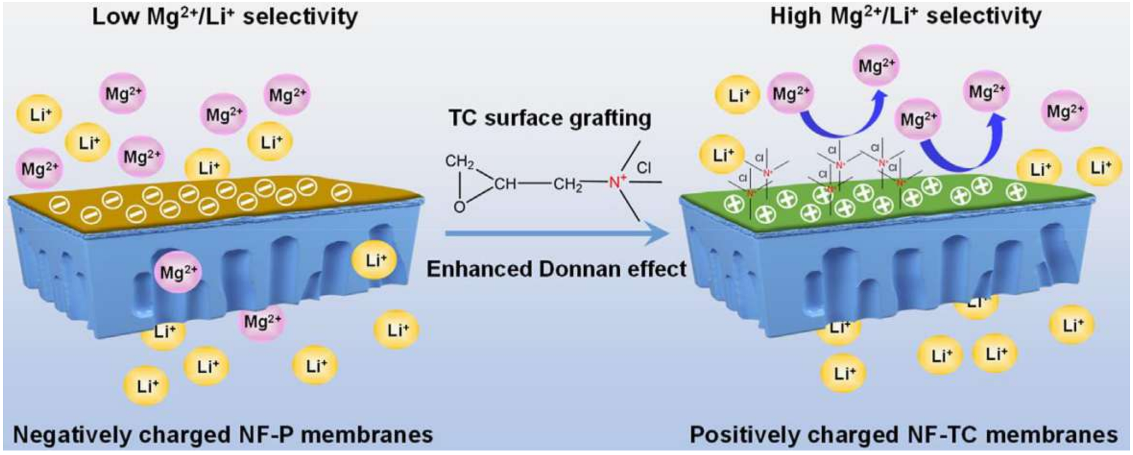


Figure 3. 8: Flowchart for lithium production by electrochemical DLE (Own work)

Conclusively, the electrochemical process of lithium extraction arises as a potentially viable and sustainable technology if the costs of the process do not outweigh the value of the extracted lithium. However, at present more research and development are needed to come up with the optimal configuration of materials and to test the viability of the technology's practical implementation on continental and/or geothermal brines.

3.2.3. Electromembrane Extraction

Electromembrane extraction utilizes lithium's small ionic radius and electrochemical properties to separate and extract the targeted metal from the rest of the salts in the brine. Two essential elements make up the most developed technology within the respective DLE method: the first one is the usage of nanofiltration that filters through, to a great extent, monovalent ions and, to a low extent, bivalent ions, which is enough to come up with impure residue. The challenge at this step is to separate lithium ions from magnesium ions due to the similarity in their ionic radii. This is where the second element of the technology comes out as important. To increase the permeability and separation of lithium from magnesium, the Donnan exclusion effect is exploited. As lithium and magnesium ions both share positive charges, with magnesium being more positive, they can be separated on the difference in the positivity of their charges. Therefore, by making nanopores moderately electropositive, magnesium ions are repulsed and lithium ions are made comparatively more permeable, as illustrated in Figure 3.9 beneath. In addition to the moderate electropositivity of the membrane, by changing the pH of the solution to a low value, the separation between magnesium and lithium ions might be additionally enhanced but is not deemed as essential (Li et al., 2019; Xu et al., 2021).



Notes: NF-P is nanofiltration utilizing phosphate as a material in the membrane; TC is trimethylsilyl chloride; NF-TC is nanofiltration utilizing trimethylsilyl chloride as a material in the membrane

Figure 3. 9: An illustration of the separation of lithium from magnesium in brine (Source: Zhao et al., 2023)

Another electromembrane technology that is being developed and which results in a low environmental footprint is permselective exchange membrane capacitive deionization (PSMCDI). With the establishment of the electric field, cations from the brine go toward the negatively charged electrode and anions go toward the positively charged electrode where they are adsorbed. However, to repel unwanted ions from getting to the electrodes, permeability-selective monovalent exchange membranes are inserted in front of them. Upon the removal of the remainder of the salts and with the change in electric current, lithium ions and chloride ions are released into fresh water and subsequently recovered (Figure 3.10) (Li et al., 2019). Noticing from the previously stated, without the addition of reagents, the PSMCDI technology concurrently utilizes elements of different technologies: adsorption for capturing targeted ions, electrochemistry for inducing the movement of ions and membrane components for selectively enabling passage of ions to electrodes.

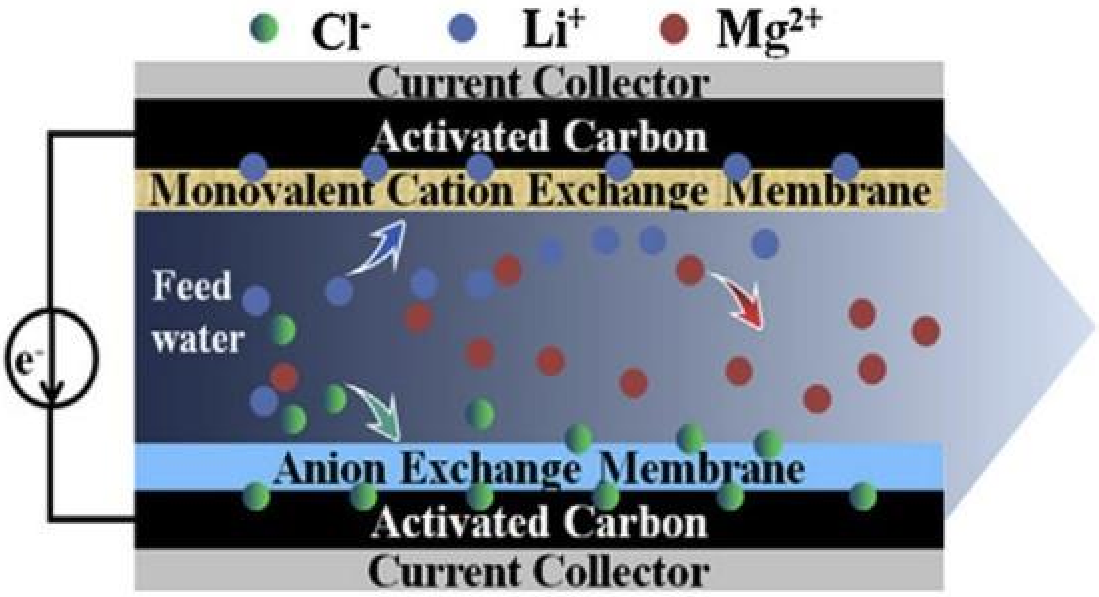


Figure 3. 10: Lithium extraction with permselective exchange membrane capacitive deionization technology (Adapted from source: Li et al., 2019)

Electromembrane method does not necessarily have to be used on its own. In personal communication, Burdet (2024) and Thompson (2024) stated that to increase the concentration of lithium from brine and to recover fresh water from the saline medium, nanofiltration and/or reverse osmosis can be utilized as a pre-extraction part of the process. However, economic concerns regarding the supplementary application of pure membranes on geothermal brines are raised due to the complexity and concentration of salt content in such brines, which might render the entire process sensitively more expensive (Stringfellow and Dobson, 2021).

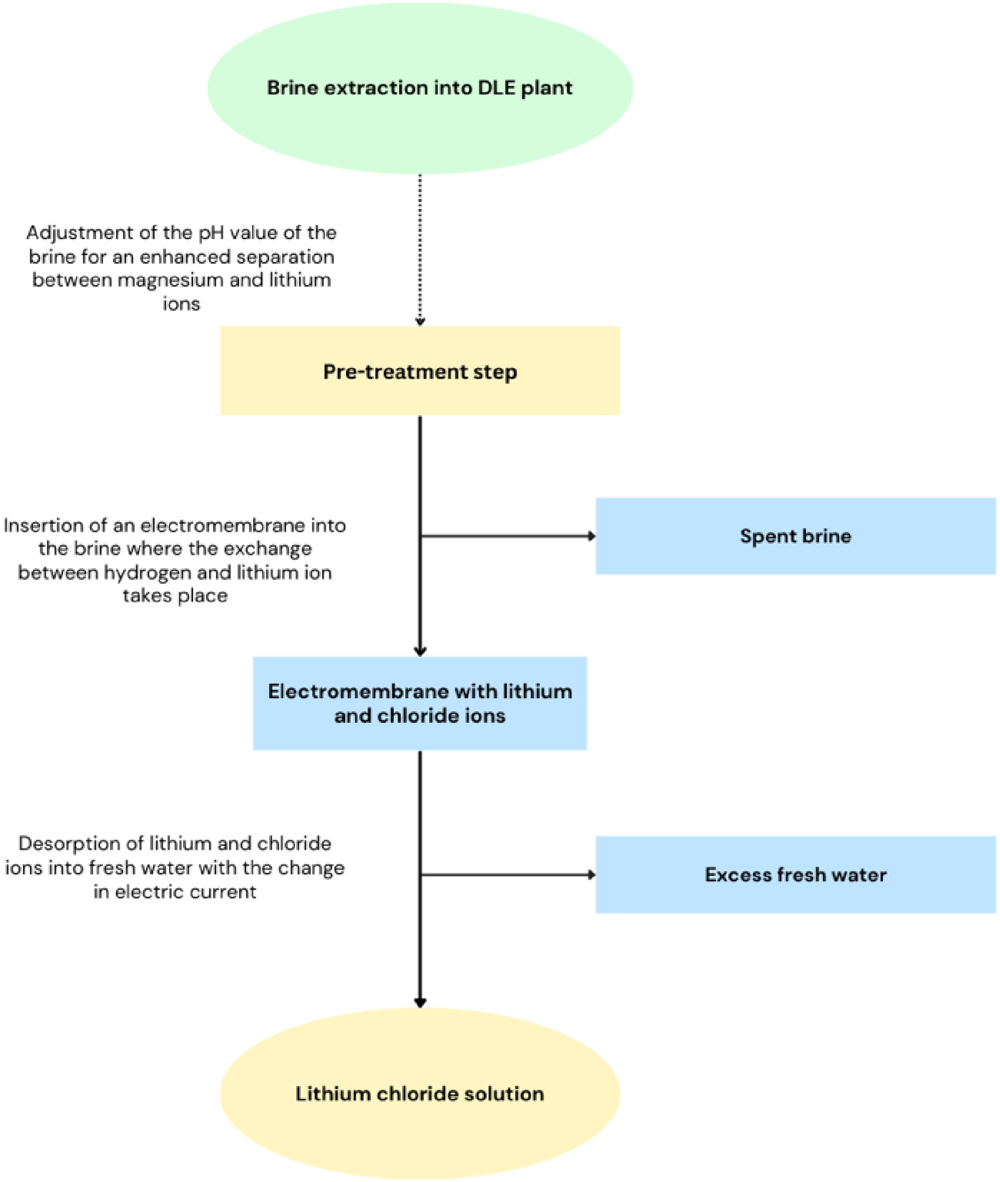


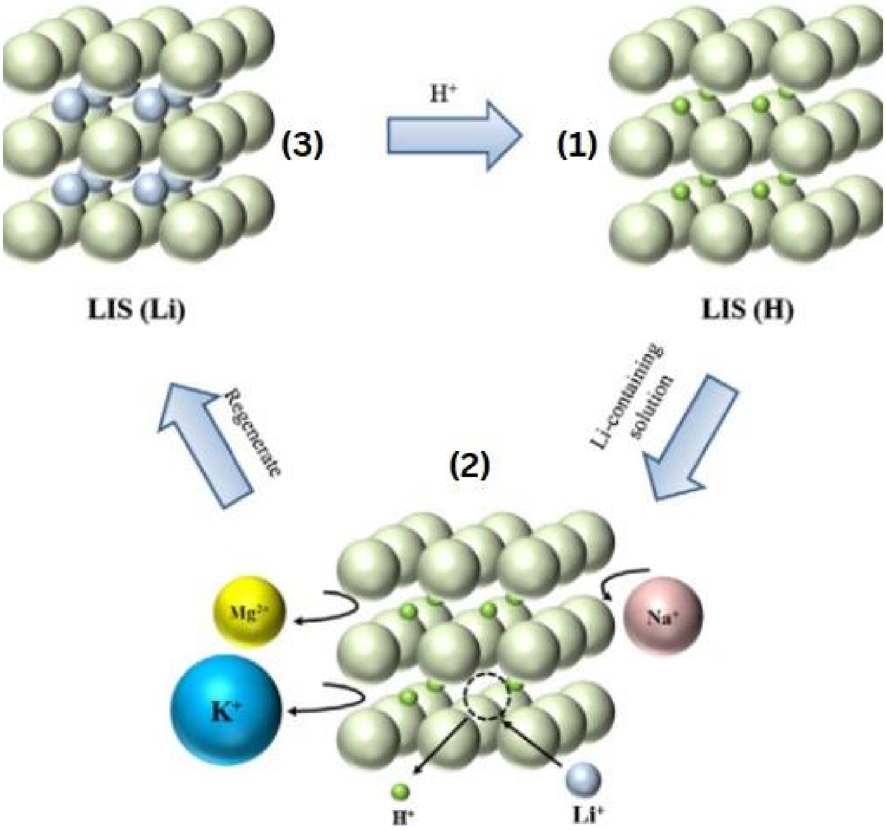
Figure 3. 11: Flowchart for lithium production by electromembrane DLE (Own work)

Concerning the environmental footprint, for the reason that the technology does not necessitate usage or addition of reagents and does not produce waste, except perhaps the spent brine, which without much complication can be reintroduced to the underground brine deposit, electromembrane extraction technology does not inflict notable negative repercussions on the environment. One of the biggest issues encountered with the present technology is frequent fouling of its membranes, leading to a significant gradual decrease in lithium selectivity, and ultimately, its extraction. Notwithstanding electromembrane's potentiality in lithium extraction and low environmental footprint, further research and development of the technology is necessary to be conducted as the technology is not yet mature for application in large-scale lithium production, and technical and economic viability is uncertain (Li et al., 2019; Murhpy and Haji, 2022; Vera et al., 2023).

3.2.4. Ion Exchange Extraction

The method of ion exchange extraction shares some similarities with electrochemical and adsorption approaches. Similarly to electrochemical technology, some configurations of ion exchange method utilize the same lithium manganese oxide material, but are not based on electricity for desorption; and similarly to the adsorption process, this method is grounded on the adsorption principle for capturing lithium ions, although through the exchange of ions.

As the name of the method gives away, lithium ions are exchanged with other cation ions in an appropriate material, in an ion exchange resin or lithium-ion sieve (LIS) as it is commonly referred to in the literature. Given that the ion exchange can take place between cations of similar ionic radii, lithium is exchanged with hydrogen ions (Figure 3.12) in either lithium manganese oxide or lithium titanium oxide ion sieve that showcase high lithium selectivity, where the presence of other ions do not hinder the lithium uptake process (Stringfellow and Dobson, 2021). Once lithium ions are exchanged with hydrogen ions in a material, lithium is desorbed using a strong acid. The commonly used acid is hydrochloric (HCl) whereby in the reaction between the adsorbing material and the acid, lithium ions are stripped off and replaced with hydrogen ions to a configuration as in the initial resin, while LiCl is formed as a product in the solution (Flexer, Baspineiro and Galli, 2018; Xu et al., 2016).



Notes: (1) lithium-ion sieve containing hydrogen ions; (2) with the introduction of lithium-containing brine, hydrogen ions are exchanged with lithium ions; (3) lithium-ion sieve containing lithium ions

Figure 3. 12: Ion exchange between lithium and hydrogen cations in a lithium-ion sieve (Adapted from source: Xu et al., 2016)

To ensure the optimal rate of lithium extraction, the pH value of the solution is adjusted beforehand, thus requiring a pre-processing step. For manganese oxide materials the solution is adjusted to a high basic value of 10 or 11 on the pH scale, and for titanium oxide materials to a slightly acidic value of 6.5 (Flexer, Baspineiro and Galli, 2018; Stringfellow and Dobson, 2021; Weng et al., 2020).

In such a process, manganese-based materials dissolve in the solution provoking two challenges: firstly, regular replacement of the material is needed due to the manganese's dissolution, which consequently elevates the costs of the present method; and secondly, it presents an environmental concern due to the water pollution stemming from difficulties in removing manganese from water medium. Titanium oxides, on the other hand, demonstrate greater endurance and stability in the acid treatment, in addition to the recognition that they have a less negative environmental impact due to lower water pollution compared to manganese oxides (Murphy and Haji, 2022; Stringfellow and Dobson, 2021; Weng et al., 2020; Xu et al, 2016).

Another environmental concern this method brings up is the question of how the used solution and subsequent waste are managed. As lithium ions are exchanged with hydrogen ions between LIS and brine, brine is left with a higher concentration of hydrogen ions, lowering spent brine's pH value and/or changing the chemistry of the medium, leaving a question of what to do with the spent brine (Boroumand and Razmjou, 2024; Flexer, Baspineiro and Galli, 2018).

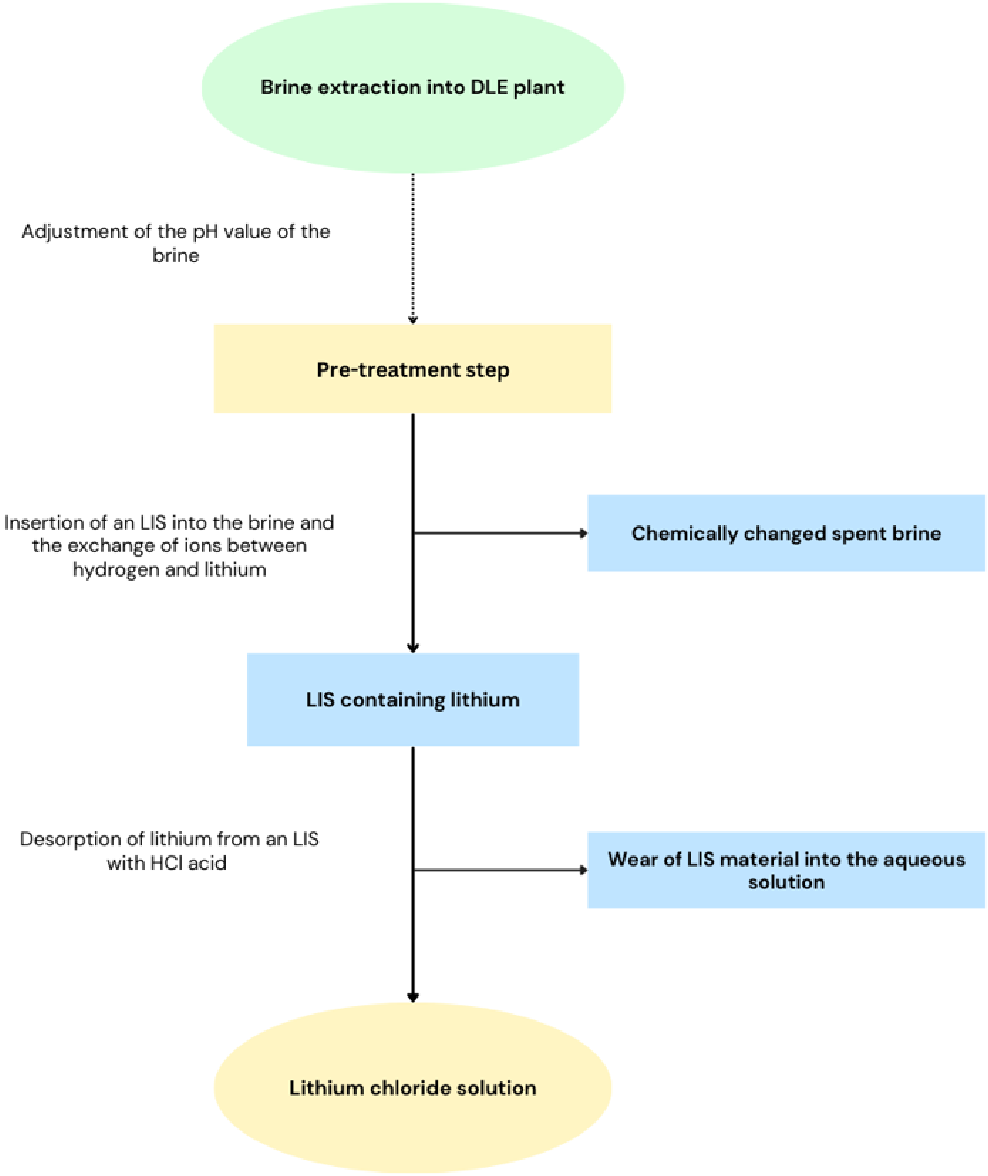


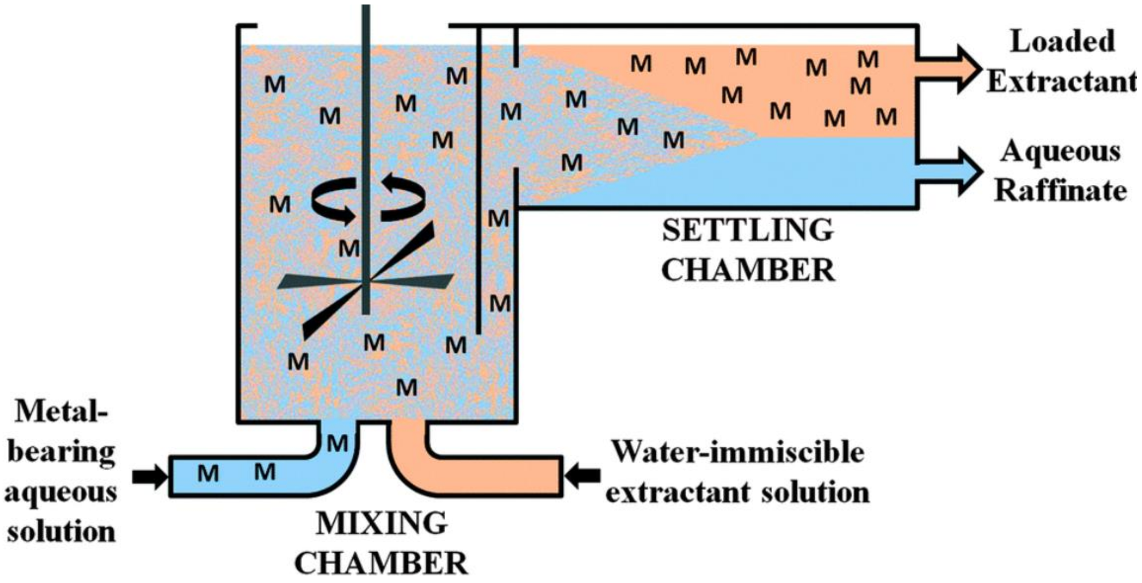
Figure 3. 13: Flowchart for lithium production by ion exchange DLE (Own work)

Despite the potentiality of producing lithium of high purity with the ion exchange method, the dependency on the usage of strong acids to recover lithium, dissolution of material in acids and usage of reagents for adjusting pH values of brine solutions raise questions on how environmentally friendly this method is. Furthermore, due to the change in the chemical composition of brine in the course of lithium extraction, the effect of the reintroduction of brine into brine reservoirs is not well known. Conclusively, in comparison to other DLE technologies, the present DLE leaves with an unresolved and potentially greater environmental footprint, apart from water usage.

3.2.5. Solvent Extraction

Solvent or liquid-liquid extraction is different from other DLE technologies insomuch as it utilizes organic solvents in the extraction process, which is carried out in two steps and is more complex compared to other methods of lithium extraction.

In the first step, with the addition of alkaline earth metal chlorides, namely magnesium chloride ($MgCl_2$), the concentration of chloride ions eventually increases along with the acidity of the brine. This part is important for the formation of tetrachloroferrate ion ($FeCl_4^-$), which is critical for lithium extraction in the second step of the process. In the second step, an organic phase is created with the addition of an organic immiscible or slightly miscible compound that acts as a diluent, such as methyl isobutyl ketone ($C_6H_{12}O$) (MIBK) or kerosene ($C_{12}H_{26} - C_{15}H_{32}$) which are mixed with tributyl phosphate ($C_{12}H_{27}O_4P$) (TBP) and ferric chloride ($FeCl_3$) that act as extracting and co-extracting reagents, respectively. The purpose of the diluent is to dilute lithium from the brine into the organic phase whereas the purpose of extracting reagents is to capture lithium from the newly lithium-enriched organic medium. To be able to extract lithium from the solution, $FeCl_3$ has to be first transformed into $FeCl_4^-$, which occurs due to an increased concentration of chloride ions from the first step. Afterward, newly formed $FeCl_4^-$ with TBP form into $HFeCl_4 \cdot 2TBP$ from which point, similarly as in the ion exchange DLE, ion exchange between hydrogen ion in the extractant and lithium ion in the solution takes place. To recover lithium from the newly formed $LiFeCL_4 \cdot 2TBP$, a 6-mole HCl acid is applied and another ion exchange is conducted forming the initial lithium extractant and LiCl solution (Murphy and Haji, 2022; Nguyen and Lee, 2018; Stringfellow and Dobson, 2021).



Notes: metal-bearing aqueous solution is lithium-containing brine; M denotes a relevant metal, which is, in this case, lithium; water-immiscible extractant solution is an organic solvent used in the solvent extraction process; loaded extractant is an extractant loaded with lithium; aqueous raffinate is spent brine

Figure 3. 14: An illustration of the fundamentals of the solvent extraction process (Source: Wilson et al., 2013)

However, at the beginning of the second process and apart from lithium, diluent dissolves other alkali and alkaline salts, and efficiently extracts magnesium and sodium ions onto TBP due to its wider selectivity towards salt ions, besides lithium ions. Therefore, to increase the purity of the process, the rest of the salts are scrubbed and stripped off with additional reagents before lithium recovery takes place, which is done with either 0.5-mole HCl, HCl and NaCl, or HCl and $MgCl_2$. Only afterward does the previously mentioned lithium recovery with a 6-mole HCl solution occur (Murphy and Haji, 2022; Nguyen and Lee, 2018; Stringfellow and Dobson, 2021).

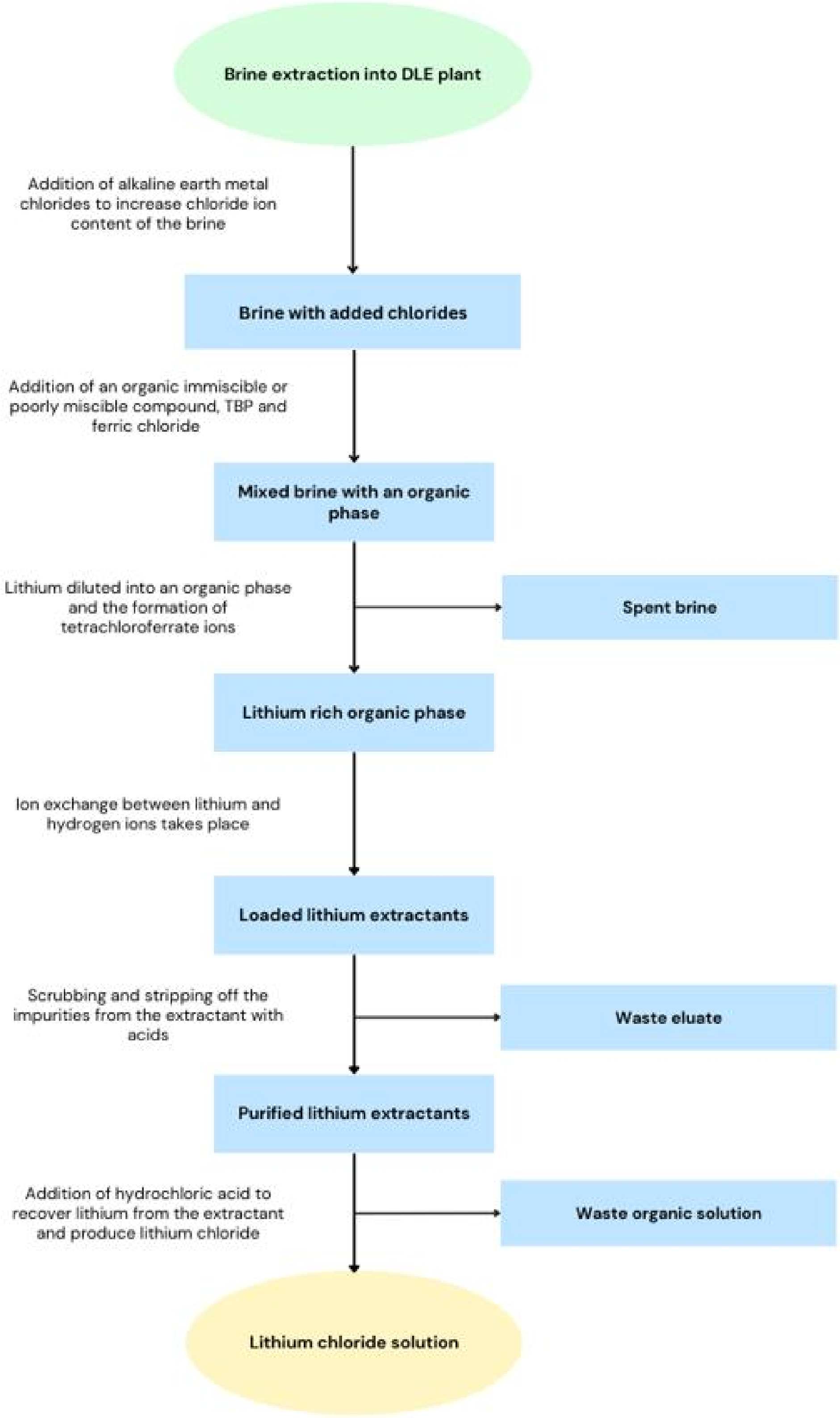


Figure 3. 15: Flowchart for lithium production by solvent extraction DLE (Own work)

Among the DLE technologies, this method raises the most skepticism. As Flexer, Baspineiro and Galli (2018) argue, the implementation of this kind of DLE on large-scale lithium production is not optimal if environmental implications are considered. Namely, the process produces a significant amount of organic solution that has to be managed at the end of its use, and the materials used as solvents are susceptible to corrosion in the lithium extraction process, making the waste solution more difficult to manage and the process challenging for the large-scale operation. Moreover, Murphy and Haji (2022) address additional concerns about the harmful waste produced during the removal of unwanted salts from a lithium extractant in an acidic eluate; and Thompson (2024) stated in personal communication that some companies might be deterred from this method due to the risk of hydrocarbon-containing solutions' spillage into the environment

Therefore, before the right equipment resistant to corrosion suitable for long-term practical application of the technology has not been fully developed and the question of appropriate waste management sorted, the present means of lithium extraction seems not to be optimal among DLE technologies.

4. ENVIRONMENTAL IMPLICATIONS OF LITHIUM EXTRACTION TECHNOLOGIES

Following the overview of DLE and evaporitic technologies, the upcoming part of the paper aims to provide deeper scrutiny of their environmental implications.

Attempts to make comparisons between the respective technologies have already been conducted by several authors, specifically by Darcy Partners (2023), Deloitte (2023) and Goldman Sachs (2023). However, the comparisons either omit the elaboration on the criteria used, or address the consumption of fresh water as a separate parameter in the comparison, which should be considered on its own next to the consumption of brine water to objectively highlight positive and less positive aspects between individual technologies.

4.1. Water Resources

Before the comparison between the technologies is undertaken, further disputes concerning water resources should be discussed. In the evaluation of the environmental impacts of brine extraction processes, it has been argued whether brine should be considered as a dynamic water medium or static mineral medium since brine is an underground body of water with a high concentration of mineral content. The answer to this dispute is significant for the matters of what to include in the assessment of the total water footprint from lithium extraction activities, and for determining the application of appropriate environmental regulations on activities thereof (Garcia et al., 2023; Jerez, Garces and Torres, 2021).

To counter-argue and refute any suggestions that brine should not be accounted for the total water footprint of brine extraction operations for the reason of brine's inappropriateness for human consumption or for usage in the agriculture industry, papers by Ejeian et al. (2021) and Vera et al. (2023) argue that brine should in effect be considered in the evaluation of total water footprint from extraction activities, in addition to the consumption of fresh water. The two argumentations are: firstly, as Vera et al. (2023) state:

> *"However, we suggest that brine must be considered, as the brine volume that is pumped will directly determine the amount of fresh water that naturally flows from outside the brine aquifer, is mixed with brine and thus is no longer considered fresh water or can be used as such."*
> Vera et al., (2023).

As more brine water is extracted from underground reservoirs, underground freshwater from the surroundings substitutes the missing volume of brine in a certain proportion through the enhanced underground movement of water via permeability and porosity of soils (Figure 3.16) (Marazuela et al., 2019). The uptake of freshwater from the environment is thus indirectly influenced by the brine extraction, causing the two water bodies to mix, rendering fresh water undrinkable, and the brine to dilute. If the brine is therefore not considered a water medium, then regulations regulating the consumption of water resources, and water rights themselves might be ineffective, allowing for extraction activities to extract an unbounded amount of brine, consequently jeopardizing and depleting the reserves of both brine and freshwater in the area (Bustos-Gallardo, Bridge and Prieto, 2021; Ejeian et al., 2021; Marchegiani, Hellgren and Gomez, 2019: 36; Vera et al., 2023). However, as Flexer, Baspineiro and Galli (2018) and Vera et al., (2023) annotate, there is a lack of research conducted and data available on the hydrogeology of the Lithium Triangle to fully understand the process and interconnection between the brine extraction and freshwater depletion. Therefore, this aspect of the indirect uptake of freshwater remains not fully understood and resolved, and thus cannot be accurately evaluated nor considered in the final assessment of water footprint in the present paper.

The second argumentation is that over 90% of negative Gibbs free energy of formation within brines stems from water molecules, not minerals, indicating that the stability of the energy state and the formation of products, i.e. solid salts in brine highly depend on water, rather than that solid salts form spontaneously. Moreover, in regards to physiochemical and thermodynamic characteristics, the similarity in structures between brine water molecules and fresh water molecules is high (Garcia et al., 2023; Ejeian et al., 2021).

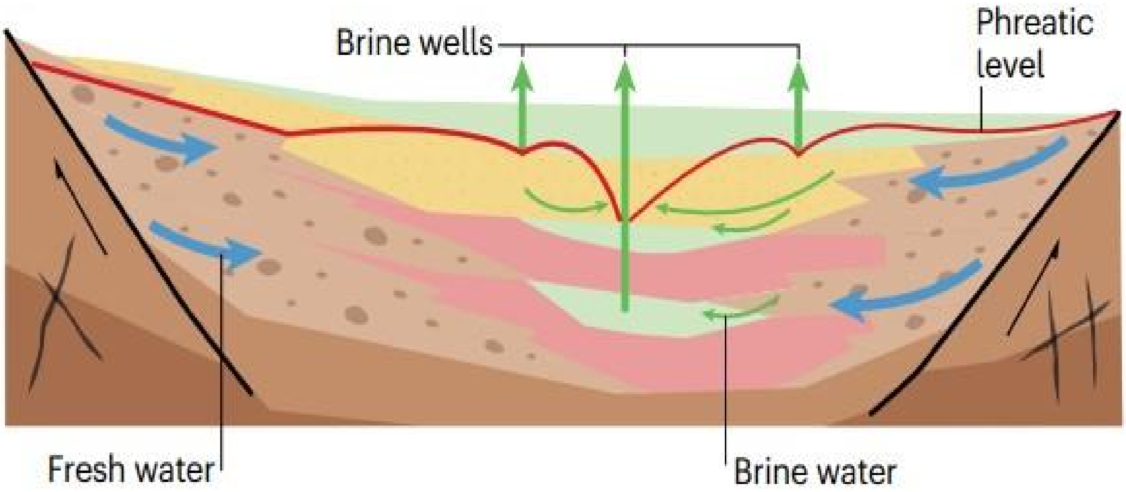


Figure 4. 1: Induced freshwater movement towards brine reservoirs from brine extraction activities (Source: Vera et al., 2023)

Having the matter laid out, there are three water flow paths that should be considered for the total impact of lithium-containing brine extraction activities on water resources: brine water which is extracted and subsequently evaporated or returned to the underground reservoir, fresh water that is used for different purposes in various parts of the lithium extraction process, and freshwater that is drawn into brine reservoir and consequently mixed with brine water, which, as it was previously stated, remains an open question.

4.2. Comparison between Different Technologies

Several environmental parameters are considered in an attempt to make a comparison between the relevant technologies: brine water withdrawal, fresh water consumption, need for land area, waste concern and electricity demand; and one non-environmental parameter, duration of the lithium extraction process. The assessment criteria for ranges taken in the comparison are explained in the subsequent text.

Data is derived from the following sources: Baspineiro, Franco and Flexer (2020), Desert Research Institute (2023: 9), IEA (2022b), Earthworks (2023: 25), Flexer, Baspineiro and Galli (2018), Lawrence Berkeley National Laboratory (2023: 92-93) and Vera et al. (2023). The comparison is a compilation and approximation made following the state of the art knowledge and information from the aforementioned sources.

If the rate of fresh water recovery and reuse, and reintroduction of spent brine into underground reservoirs are taken into account, the table for the first two parameters would be somewhat different as outlined in Table 3, as opposed to Table 2 where no recovery, reuse and reinjection are included. Water purification and brine reinjection would undoubtedly increase the electricity demand of the operation plants and subsequently, the operation expenditures (OPEX) as well as capital expenditures (CAPEX) if carried out.

4.2.1. Brine water

The amount of brine water extracted will vary due to the different concentrations of lithium from different brine deposits, with more brine being needed for the evaporitic technology due to its lower lithium recovery of 40 – 60%, compared to over 90% with DLE (Goldman Sachs, 2023; Murphy and Haji, 2022).

Furthermore, it is important to emphasize the difference that brine water with the mixture of fresh water in the evaporation ponds in the evaporitic technology is lost in the course of evaporation to the amount of up to 95% of total water used, whereas in DLE technologies, brine is envisioned to be reintroduced into the brine reservoir at the end of lithium extraction, gauging the final footprint regardless of brine water withdrawal (Baxter, personal communication 2024; Burdet, personal communication, 2024; Cerda et al., 2021).

The criteria taken in the comparison are as follows: Brine water withdrawal

Low	Up to 900 m^3
Medium	Between 900 and 1,800 m^3
High	Over 1,800 m^3

Note: The unit is in cubic meters of brine water per ton of lithium extracted

4.2.2. Fresh water

Similarly to brine water, the amount of fresh water used in either the evaporitic or DLE technologies differs based on the characteristics of brine and the specific configurations opted for within the technology used, and whether the pretreatment step is undertaken or not.

The lack of exact quantified data, and subsequently lack of certainty in making the comparison on fresh water consumption for the individual DLE technologies has been criticized as something that should be compiled and made publicly accessible, as there is an insufficiency thereof (Vera et al., 2023).

Nevertheless, looking at the available data on fresh water usage among different lithium extraction technologies, DLE technologies can be seen as less environmentally friendly compared to the evaporitic technology due to their higher fresh water consumption. However, even if fresh water consumption might turn out to be higher in DLE technologies than in the evaporation approach, rather than being lost via the evaporation, water is susceptible to being recovered, which is hence deliberated not to be lost or released as untreated wastewater. With the post-extraction fresh water treatment, the amount of fresh water that can be recovered ranges between 75 and 95 %, making DLE technologies in the end not as net water intense if water treatment is employed (Baxter, personal communication 2024; Cerda et al., 2021).

The criteria taken in the comparison are as follows: Fresh water consumption

Low	Up to 50 m^3
Medium	Between 50 and 250 m^3
High	Over 250 m^3

Note: The unit is in cubic meters of fresh water per ton of lithium extracted

4.2.3. Land use

One of the characteristics of the evaporitic technology is the exposure of evaporation ponds to ambient conditions. As evaporation ponds are constructed to cover shallow but large surfaces, they necessitate extensive areas of land, whereas DLE technologies require approximately 95% less area, principally for DLE plant (Deloitte, 2023; Flexer, Baspineiro and Galli, 2018).

The criteria taken in the comparison are as follows: Land requirement for the implementation of a technology

Low	Up to 200 m^2
Medium	Between 200 and 1,200 m^2
High	Over 1,200 m^2

4.2.4. Waste production

Different technologies produce different waste and different amount of waste, depending on the reagents and materials used in the processes. In the place where DLE technologies do not produce the amount of as the evaporitic technology does, some DLE variants generate waste that presents detriment to the environment, if it is not properly managed.

The criteria taken in the comparison are as follows: Concerns with waste produced

Low	No environmental concerns with waste and no challenges in waste management
Medium	Some environmental concerns with waste and some challenges in waste management
High	Major environmental concerns with waste and challenges in waste management

4.2.5. Electricity

While both the evaporitic technology and DLE technologies require electricity for pumping out brine from underground reservoirs, the evaporitic technology throughout the lithium extraction operation largely depends on the solar energy, whereas DLE technologies rely on electricity to run the processes and DLE plants themselves, which account for 60% of total electricity demand in DLE projects. The demand for the production of electricity is therefore higher with DLE, approximately double to that of the evaporitic technology, making electricity one of the largest sources of costs in OPEX. (Deloitte, 2023; Lithium Americas, 2019; Standard Lithium, 2021; Warren, 2021: 13 – 14).

This, however, does not necessarily have to be the case. When it comes to geothermal brines, heat energy from the relevant medium can be harvested as a renewable source of energy and used in heat exchange (Warren, 2021: 1, 14). Regarding continental brines, installing solar panels in highly insolated Lithium Triangle is an option that would to a great extent resolve the matter of power supply in a sustainable way, reduce OPEX but increase CAPEX (Vera et al., 2023).

The criteria taken in the comparison are as follows: Electricity dependence

Low	No electricity is required in the extraction process
Medium	Electricity is required, but is not the main driver in the extraction process
High	Electricity is the main driver in the extraction process

4.2.6. Process duration

As it had been stated in the previous chapter, the lithium extraction process following the evaporitic technology lasts up to two years, making the relevant approach a relatively slow segment of lithium supply chain. DLE technologies, on the other hand, require up to seven days to conclude lithium extraction process, many of which require even less time, on an intraday level (Haji and Murphy, 2022). This gives DLE technologies a competitive edge over the evaporitic technology in a sense that lithium producers can be more responsive to the changes in demand in the lithium market by acting timely, adequately and adjusting the production, providing therefore greater security in terms of disruptions within the lithium supply chain.

The criteria taken in the comparison are as follows: Duration of lithium extraction process

Low	Up to 7 days
Medium	Between 7 and 300 days
High	Over 300 days

Table 2: Comparison between DLE and evaporitic technologies without fresh water purification and reuse, and brine reinjection

Technology / Parameter	Evaporitic Technology	Direct Lithium Extraction				
		Adsorption	Electrochemical	Electromembrane	Ion Exchange	Solvent Extraction
Brine water	High	Medium	Medium	Medium	Medium	Medium
Fresh water*	Medium	High	High	High	Medium	Medium
Land area	High	Low	Low	Low	Low	Low
Waste	High	Low	Low	Low	Medium	High
Electricity	Medium	High	High	High	High	High
Process duration	High	Low	Low	Low	Low	Low

Note: *the loss of fresh water from freshwater reservoirs that occurs due to the brine extraction activities is not accounted for due to the lack of sufficient research conducted on the matter and the following unavailability of quantified data

Table 3: Comparison between DLE and evaporitic technologies with fresh water purification and reuse, and brine reinjection

Technology / **Parameter**	**Evaporitic Technology**	**Direct Lithium Extraction**				
		Adsorption	Electrochemical	Electromembrane	Ion Exchange	Solvent Extraction
Brine water	High	Low	Low	Low	Low	Low
Fresh water*	Medium	Low	Low	Low	Low	Low
Land area	High	Low	Low	Low	Low	Low
Waste	High	Low	Low	Low	Medium	High
Electricity	Medium	Increase	Increase	Increase	Increase	Increase
Process duration	High	Low	Low	Low	Low	Low

Note: *the loss of fresh water from freshwater reservoirs that occurs due to the brine extraction activities is not accounted for due to the lack of sufficient research conducted on the matter and the following unavailability of quantified data

5. SCALING UP THE IMPLEMENTATION OF DIRECT LITHIUM EXTRACTION TECHNOLOGIES

Following the comparison between the evaporitic method with different DLE technologies, the present chapter sets to provide an understanding of which hindrances lie on the path of scaling up the lithium production operations using DLE, and what their potential mitigations might be. Interviews held with innovators developing DLE technologies and with lithium project developers working with DLE aid substantially in comprehending these challenges. Several different but connected aspects in acknowledging the challenges were considered: economic, policy and geopolitical, and technical challenges.

5.1. Economic Aspect

With the reinjection of brine into underground reservoirs, water recovery, negligible land requirements, lower waste production and faster extraction process, DLE showcases significant advantages over the evaporitic technology. To expect the proliferation of DLE technologies, however, costs of technologies' processes should not outweigh the value of lithium extracted, and should preferably be lower than that of the evaporitic technology. To get a better sense of the costs, sources of CAPEX and OPEX of three DLE projects from three different countries are compared: CleanTech Lithium's *Francisco Basin* project in Chile, Lake Resources' *Kachi* project in Argentina and Standard Lithium's *Lanxess Smackover* project in the US; and one project developing the evaporitic technology – Lithium America's Cauchari-Olaroz project in Argentina.

Understandably, several factors will affect the total cost of a technology's implementation, namely brine's unique properties, whether the pre-treatment step is carried out, what technology configuration is used and what efforts for post-lithium extraction waste are needed. Notwithstanding individual technologies' characteristics, the percentage of major constitutes of total costs for 3,700 – 4,700 tons of lithium per year projects are listed in Table 4.

Table 4: Costs of DLE and evaporitic projects

Company	CleanTech Lithium		Lake Resources		Standard Lithium		Lithium Americas	
Project	Francisco Basin		Kachi		Lanxess Smackover		Cauchari-Olaroz	
Country	Chile		Argentina		US		Argentina	
DLE	Adsorption		Ion exchange		Ion exchange		Evaporitic technology	
Annual production [t/year]	3,760		4,700		3,929		4,700**	
Project duration	12 years		25 years		25 years		40 years	
CAPEX (USD)	Direct costs	72%	Direct costs	69%	Direct costs	n.d.	Direct costs	78%
	Indirect costs	8%	Indirect costs	19%	Indirect costs	n.d.	Indirect costs	9%
	Contingency	20%	Contingency	12%	Contingency	25%	Contingency	13%

	Total CAPEX	**449,964,000**	**Total CAPEX**	**1,376,670,000**	**Total CAPEX**	**437,162,000**	**Total CAPEX**	**425,000,000**
		DLE technology accounts for 44% of total CAPEX		DLE technology accounts for 31% of total CAPEX		DLE technology accounts for 62% of total CAPEX		N/A
OPEX (USD)	Electricity	31%	Electricity	41%	Electricity	10%	Electricity	7%
	Reagents	29%	Reagents	37%	Reagents*	72%	Reagents	40%
	Total OPEX [USD/ton of lithium]	**19,370**	**Total OPEX** [USD/ton of lithium]	**32,170**	**Total OPEX** [USD/ton of lithium]	**22,876**	**Total OPEX** [USD/ton of lithium]	**13,273**

Notes: the data are compiled from CleanTech Lithium (2023), Lake Resources (2023), Lithium Americas (2019) and Standard Lithium (2023); *infrastructure costs are accounted for as well; **the final project is planned for the production of 9,400 tons of lithium per year

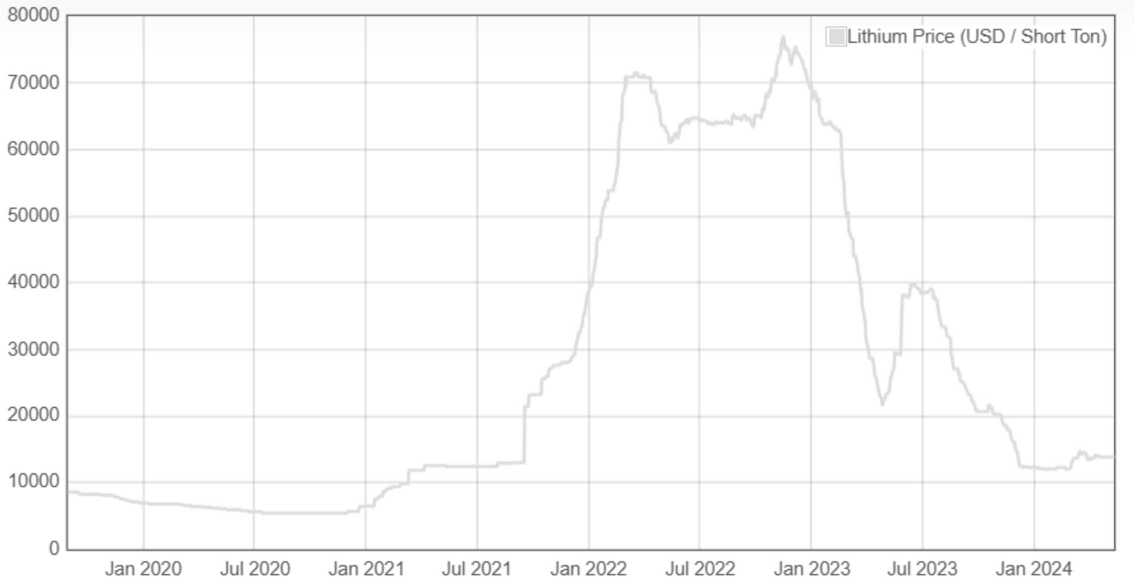
Interpreting the above table, the greatest part of the total cost of the implementation of DLE technologies falls on the DLE technologies themselves, which concurrently make the central distinction from the evaporitic technology, and whose cost differ between different DLE developers. Following the DLE technologies that exceed 30% of CAPEX, the usage of reagents, such as sodium carbonate in the production of lithium carbonate, constitutes a bulk portion of OPEX. If a technology necessitates the use of additional reagents in the extraction process, in particular ion exchange and solvent extraction technologies, OPEX rises sensitively. Next to reagents, electricity makes up another considerable portion of OPEX costs, making up to 41% of OPEX costs and being up to six times larger than in the evaporitic technology. Together with reagents, electricity makes up a large majority of up to roughly 80 % of OPEX costs in DLE projects, whereas in the evaporitic technology, combined they make up around half of OPEX.

The range of the total costs depends on the size of the projects being developed, i.e., on the expected annual lithium production. CAPEX for DLE projects generally varies from USD 200,000,000 up to USD 1.5 billion, and for the evaporitic technology it ranges between USD 250,000,000 and USD 425,000,000. On the other hand, OPEX among both methods is commonly between USD 13,000 and USD 25,000 per ton of lithium. (Boroumand and Razmjou, 2024; Flexer, Baspineiro and Galli, 2018; Goldman Sachs, 2023; Lithium Americas, 2019; Warren, 2021: 12 – 14, 19 – 21; Williams, C., 2024). Looking at Table 4 and taking 3,700 – 4,700 tons of lithium produced per year as a benchmark, DLE projects exceed USD 430,000,000, whereas compared to USD 425,000,000 for the evaporation method, it is more probable that DLE projects turn out to be more expensive between the two. This is for the reason that it is not simple to develop a technology that selectively extracts lithium from the brine and leaves the remainder of the medium as intact as possible (Stringfellow and Dobson, 2021: 13). Having an observable potentially higher total cost of DLE projects, the questions remain on how to increase the interest of investors for the more expensive DLE projects and whether the costs of DLE projects can be decreased.

Regarding the electricity costs for DLE projects on continental brines and given that they are located in remote arid and highly insolated areas, an installation of solar panels jointly with the utilization of BESS might lower OPEX. Granted, however, this would simultaneously increase CAPEX. To that end, considering the projects in Table 4 with their long-term average period of 20 years of project duration, and with average electricity constituting 27% of OPEX which on average amounts to USD 25,000 per ton of lithium annually, the costs of electricity at the end of the project's lifetime of average 4,000 tons of lithium per year can be expected to exceed USD 500,000,000. Considering the established trajectory of a decrease in prices of solar panels, and the forecasted decrease of BESS prices, the installation of two technologies could lower the overall costs of projects in the long term and hence be recommendable.

High costs of reagents could be evaded if DLE technologies that are not necessarily reagent intensive, such as adsorption, electrochemical and electromembrane technologies, are given greater favorability as opposed to ion exchange and solvent extraction technologies. In addition to this, with the non-reagent intensive technologies, the matter of relatively more challenging waste management and subsequent costs thereof would be evaded (Burdet, personal communication, 2024). It should be given that in spite of this, this does not necessarily imply that non-reagent technologies are inexpensive. As Garcia et al. (2023) state, electrochemical and electromembrane technologies have cost-efficiency challenges of their own rendering them not necessarily more economically viable than reagent-intensive technologies. As the remaining DLE technology, adsorption might be the optimal choice for the implementation as a non-reagent intensive technology, especially as it has already been proved in the production of lithium.

DLE projects provide positive economic forecasts: a payback period of within five years from the start of the commercial production and between 20 and 44 % of the post-tax internal rate of return (IRR), indicating that the projects are expected to yield a not inconsiderable profit after taxes. Nevertheless, this does not imply that there are no strains in accruing investments for project development. As Baxter (personal communication, 2024) addressed, finding investors is one of the biggest challenges in developing and scaling up DLE projects. The reason behind this is the risk of investing in lithium production projects caused by the uncertainty and unpredictability of lithium prices in the volatile global markets. At the beginning of 2021, prices of lithium carbonate were around USD 8,000 per ton of lithium carbonate. At the end of the following 2022, the prices surged almost tenfold to over USD 70,000 per ton of lithium carbonate. From that point, in less than five months, prices fell by over 70% to approximately USD 20,000. As of May 2024, prices swing between USD 13,000 and USD 16,000 per ton of lithium carbonate (Figure 5.1) (Daily Metal Price, 2024; Williams, G., 2024). The volatility of battery-grade lithium prices thereof is evident, producing not the most positive sentiment among investors to invest in the capital-demanding lithium industry, which can be designated as still being in its infancy, particularly as far as it is concerned the DLE technologies as opposed to well-established evaporitic technology that provides greater assurance in its practical viability (Baxter, personal communication, 2024; Liu, personal communication, 2024). Furthermore, as Warren (2021: 10) specifies in the report, prices of lithium carbonate below USD 11,000 per ton would not be economically viable or favorable as far as both OPEX and low IRR are concerned, and thus lithium projects would not be recommended for pursuing. Following Warren's evaluation and observing the volatility of lithium prices rendering lithium prices unpredictable, it is clear why some investors might be skeptical about and disincentivized from investing in CAPEX-intensive DLE projects.



Notes: lithium is regarded in the form of lithium carbonate compound

Figure 5. 1: Historical chart of changes in lithium prices, 2020 – 2024 (Source: Daily Metal Price, 2024)

From the viewpoint of a company that is developing DLE projects in Chile, Baxter (personal communication, 2024) proposes several activities that could be undertaken to increase the stability of lithium prices and secure funding for the realization of lithium projects. In order to restore certainty, reduce volatility in lithium prices and increase predictability that would induce investments, lithium should be established as a commodity that would be traded identically as some precious and base metals; for example, just the same as copper and silver are traded at present in the global markets. That is to say, unlike copper, lithium is currently not traded through common market mechanisms, such as futures trading in which parties previously agree to buy and sell an asset at a previously determined date in the future at a certain price; options trading in which parties similar to futures trading agree to trade an asset at a future date at a certain price, but where the buyer is not required to buy an asset but rather it retains the right to buy it; or contract for difference (CFD) trading in which a trader can either take a buy or sell position according to the trader's expectation on whether the price of an asset will rise or fall. Futures and options trading can affect lithium prices and provide greater price stability due to the assurance of future price levels, whereas CFD trading does not affect the price change. Further activity that can be done, if a company is a publically listed company, it should not to be listed only in one market, but in several. This would more likely attract a greater pool of investors as opposed to being publically listed only in one market, if, understandably, all exchange market's requirements would be met and associated fees settled. The third activity that can be undertaken is to have closer communication and cooperation with the competent authorities, and foremost national government, to obtain operating agreements and acquire eligibility to seek funding from national banks, and funding and support from the respective government.

5.2. Policy and Geopolitical Aspect

As it was discussed in the previous chapter, the discussion whether brine should be regulated as a mineral or water medium is of great importance for brine's management, and ultimately, the protection of the environment. In their paper, Garcia et al. (2023) highlight that brine is thus far considered and regulated as a mineral, not water medium, hence making water-regulating regulations not fully applicable, and brine extraction and management supportive of not the most environmentally considerate lithium extraction operations. For that reason, the topic of reevaluation of brine's classification and its recognition as a water medium is an area that should be tackled by the pertinent policymakers. By changing the status of brine from mineral to water medium, and by having more stringent water management policies established and/or adhered to, companies and, thence, lithium project developers might be deterred from opting for the evaporitic technology. In view of the technologies which have appropriate post-extraction water treatment, they could be considered as a more environmentally friendly and a more sustainable set of technologies for lithium extraction, and DLE technologies would likely catch greater interest for investments and subsequently scaled up, as opposed to alternative means of lithium extraction that gradually deplete brine reservoirs.

To endorse the proliferation of DLE technologies, further policies that incentivize their utilization over the evaporitic technology should be put in place. Recognizing the role of lithium in the global transition towards a decarbonized world, Chile adopted the 2023 *National Lithium Strategy* (from this point forward: "the strategy"); a strategy and a set of policies that endorse a sustainable national lithium industry with a public-private partnership (PPP) format. The strategy recognized DLE technologies as a priority in the prospective lithium projects: "*Promoting such technologies is important for ensuring environmentally sustainable production. As such, their implementation in existing lithium mining operations and new projects should be an obligatory requirement*" (Government of Chile, 2023: 10). Interpreting the second sentence from the quotation, the strategy aims to have the implementation of DLE technologies as a compulsory obligation in all future lithium extraction projects. With great certainty, this will facilitate large-scale implementation of the respective technologies within the country. Furthermore, the strategy aims to establish an institutional framework that will promote the usage of renewable sources of energy for the expected high electricity consumption, and minimize loss of freshwater in the lithium extraction operations (Government of Chile, 2023: 14). Having these elements included within the strategy, and having a PPP as an arrangement on cooperation between the public and private sector, scaling up of DLE projects could be made easier. Taking these elements into account, project developers that intend to use DLE technologies in their projects welcome the strategy and its policies. Reflecting on the strategic turn made by the Chilean government, Baxter (personal communication, 2024) approved that the strategy is expected to have a positive effect in the realization of CleanTech Lithium's DLE projects in Chile. If similar strategies are adopted in other lithium-rich brine countries that are expecting to develop or are interested in developing lithium extraction projects, such as Argentina and Bolivia, a more sustainable upstream lithium supply chain could be achieved.

Not only policies but also the geopolitical situation determines which technologies and which actors get to develop lithium extraction projects in foreign countries. Bolivia, being one of the countries richest in lithium resources with over 21 million tons of lithium, is interested in and keen on exploiting its abundant reserves. Since the country lacks adequate infrastructure, economic potency and know-how knowledge, however, it depends on foreign investments and companies that would see the projects through. As numerous countries want to secure sources of lithium for their industries, several countries express interest in developing these projects, among which China and the US stand out as the most determined ones. EnergyX, an American DLE developing company, attempted to get into Bolivia and realize projects with their DLE but got banned from the bidding. Chinese companies, on the other hand, following the sympathy of former Bolivian president Morales and strong trading relations between the two countries, invested substantial funds in Bolivia and got the upper hand in developing the lithium projects. Nevertheless, due to political instability following the succession of president Morales in Bolivia, Chinese projects came to a temporary stall before subsequent continuation with lithium project's actualization (MacDonald, 2023; Molen, 2022).

What is noteworthy is that international relations, relations between the countries' leaders and national political stability determine which country's technologies might be favored and whether project realization is likely to stumble upon problems and consequently come to a standstill due to intranational political situation. By taking geopolitical and political factors into account, the risks and concerns related to not getting access to compete in competitive bidding for grant of lithium extraction rights, acquiring all the necessary legal permits for developing a project, and the likelihood of unsuccessful project realization could be assessed and subsequently avoided.

5.3. Technical Aspect

DLE has proved to be an effective set of technologies through numerous testing in various pilot projects. Nevertheless, however, not all DLE technologies are yet mature for industrial application. In the light of technology readiness level (TRL), a type of assessment that evaluates technology's maturity according to the progress of technology's conceptualized and practical workability, the potential for each of DLE's scalability can be assumed.

Following the TRL grading system where TRL 1 corresponds to the lowest level of maturity denoted by the understanding of basic principles, and where TRL 9 corresponds to the highest level of maturity defined by a successful commercialized implementation of a technology, a DLE that demonstrates the highest TRL is adsorption technology that is currently in a successful phase of commercial lithium production. Ion exchange follows behind by being in pre-commercial phase and is soon expected to be put to use in the production of lithium, climbing high on TRL, between 7 and 9. For the reason that these technologies are well researched, the most developed among the DLE technologies and do not represent a high risk for the environment with the included water treatment in the operation, all three lithium project developing companies with whom interviews were held, specifically CleanTech Lithium, Cornish Lithium and Eramet, are interested in or are employing one of the two DLE technologies (Baxter, personal communication, 2024; Burdet, personal communication, 2024; Thompson, personal communication, 2024). The remaining three DLE technologies, that is electrochemical, electromembrane and solvent extraction, are not as developed as the aforementioned technologies and score between 3 and 7 on TRL (Boroumand and Razmjou, 2024; Deloitte, 2023). Garcia et al. (2023) convey that the reasons behind low TRL for electrochemical technology are that the technology's overall cost-efficiency, more efficient electricity usage and dependence on low cost electricity have not yet been resolved. Notwithstanding, active efforts are being invested in improving the technology and finding optimal workable configurations to overcome the observed technology's downsides (Liu, personal communication, 2024). Garcia et al. (2023) continue that electromembrane technology tends to have a greater number of complications, among others, including frequent membrane fouling and overall cost-efficiency concerns, similar to the previously mentioned DLE. Furthermore, the authors conclude that environmental concerns and lithium extraction efficiency of solvent extraction render the technology not the highest on TRL. In addition, Liu (personal communication, 2024) accentuated that with the idea of adopting cleaner and greener DLE technologies, solvent extraction may pose sustainability challenges due to the usage of chemicals and the production of secondary contamination.

Optimal materials and configurations within some DLE technologies and DLE developers have therefore not yet been developed to reliability, without major issues and in economically viable or preferable way extract lithium in the long term. For that reason, it is not unlikely that DLE technologies related to electrochemical, electromembrane and solvent extraction approaches will require further research and development, and not yet be applied for commercialized large-scale lithium extraction purposes. Ion exchange remains to be proven in commercialized production, but if shown successful, together with adsorption it could expedite the proliferation of DLE technologies in the soon future.

6. CONCLUSION

With the expected positive trajectory of lithium demand in the upcoming years up to 2050 under consideration, a matter was raised on how to source the resource from brines in a sustainable way that would concurrently be practicable and economically reasonable. To find out the possibilities of attaining a more sustainable lithium production, two research questions concerning not widely employed DLE technologies were posed and throughout the paper pursued to be given answers to.

The final part of the paper, therefore, aims to provide answers to research questions, whereby the answers formulated derive from the literature review conducted and the interviews held with representatives of the lithium industry. The questions and the answers are as follows:

How does the adoption of direct lithium extraction on brine deposits impact the environmental sustainability of lithium supply chains?

Comparing DLE technologies with the evaporitic technology, different conclusions and accentuations can be given. As it can be read in the third and the fourth chapters of the present paper, the evaporitic technology is a less sustainable means of lithium extraction from brine medium as compared to DLE. This is principally because of greater water consumption and subsequent water loss, and concerns related to waste generated throughout the process of the technology. DLE technologies, on the other hand, on average have lower total water consumption and lower waste concerns. Notwithstanding, however, it is important to accentuate that different DLE technologies yield different impacts on the environment.

The environmental concerns pertained to solvent extraction, mainly due to the production of harmful waste, render the technology not optimal among the cluster of technologies. With regard to the rest of DLE technologies, if no substantial efforts in water treatment and waste management are invested, negative environmental impacts are lesser or not higher than those of the evaporitic technology. If post-extraction fresh water treatment and appropriate waste management were established, the majority of DLE technologies conclusively present to be a more sustainable means of lithium extraction, mainly due to the reasons that less environmentally detrimental waste is generated, brine water is not evaporated but returned to the original underground reservoir, and fresh water that is used throughout the extraction process is aimed to be recovered and reused, rather than lost.

The adoption of DLE technologies in lithium extraction from brine deposits, in particular adsorption, would therefore contribute to greater sustainability in upstream lithium supply chains.

What are the challenges associated with integrating direct lithium extraction into existing lithium supply chains, and how can these challenges be overcome?

For the most part, the fifth chapter addressed the challenges, and their plausible solutions and opportunities in regard to the commercial application of DLE and the consequent incorporation of the technologies into lithium supply chains.

The challenges addressed are threefold: economic, policy-level and geopolitical, and technical. As a major barrier of an economic nature, uncertainty of the movement of lithium prices in volatile global markets presents a challenge on how to attract investments for not well-known DLE technologies in a not fully developed lithium industry. To overcome these challenges, the uppermost effort that is proposed to be taken is to establish lithium as a commodity that would be traded similarly as copper is presently being traded, which would expectedly bring greater stability and predictability of lithium prices, and hence provide more confidence among the investors in investing in lithium projects. Other two workable solutions are the development of closer ties and cooperation with the competent government, and/or being listed in more than one market, as far as it is concerned PLCs.

The second group of challenges pertains to policy and geopolitics. If there is a lack of national programs supportive of attaining more sustainable lithium industries, and if relations between the lithium-rich country and a country from which a project developing company or DLE developing company come are not in the closest of relations, non-DLE projects might still be preferred over DLE, and existing DLE projects halted. Concerning the national programs, it might be recommended for lithium-rich countries to follow the Chilean example and look up to its strategy related to its national lithium industry.

The final set of challenges is linked to the technical aspect of DLE technologies. The principal obstruction on the path of integrating DLE into lithium supply chains is the immaturity of some of the technologies, specifically electrochemical, electromembrane and solvent extraction. For these technologies to reach a high level of advancement, further research and development will be needed, making these technologies likely not employable in the imminent future. Notwithstanding, with current efforts invested in improving the technology, which depends on finding the right configuration within a technology and making it economically viable, there is a positive sentiment that electrochemical DLE could be an additional sustainable solution for commercial application in the foreseeable future so much so as it necessitates no reagents and produces no harmful waste. The remaining two technologies, that is adsorption and ion exchange, are being or are soon going to be implemented in the commercial production of lithium.

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LIST OF TABLES

LIST OF FIGURES