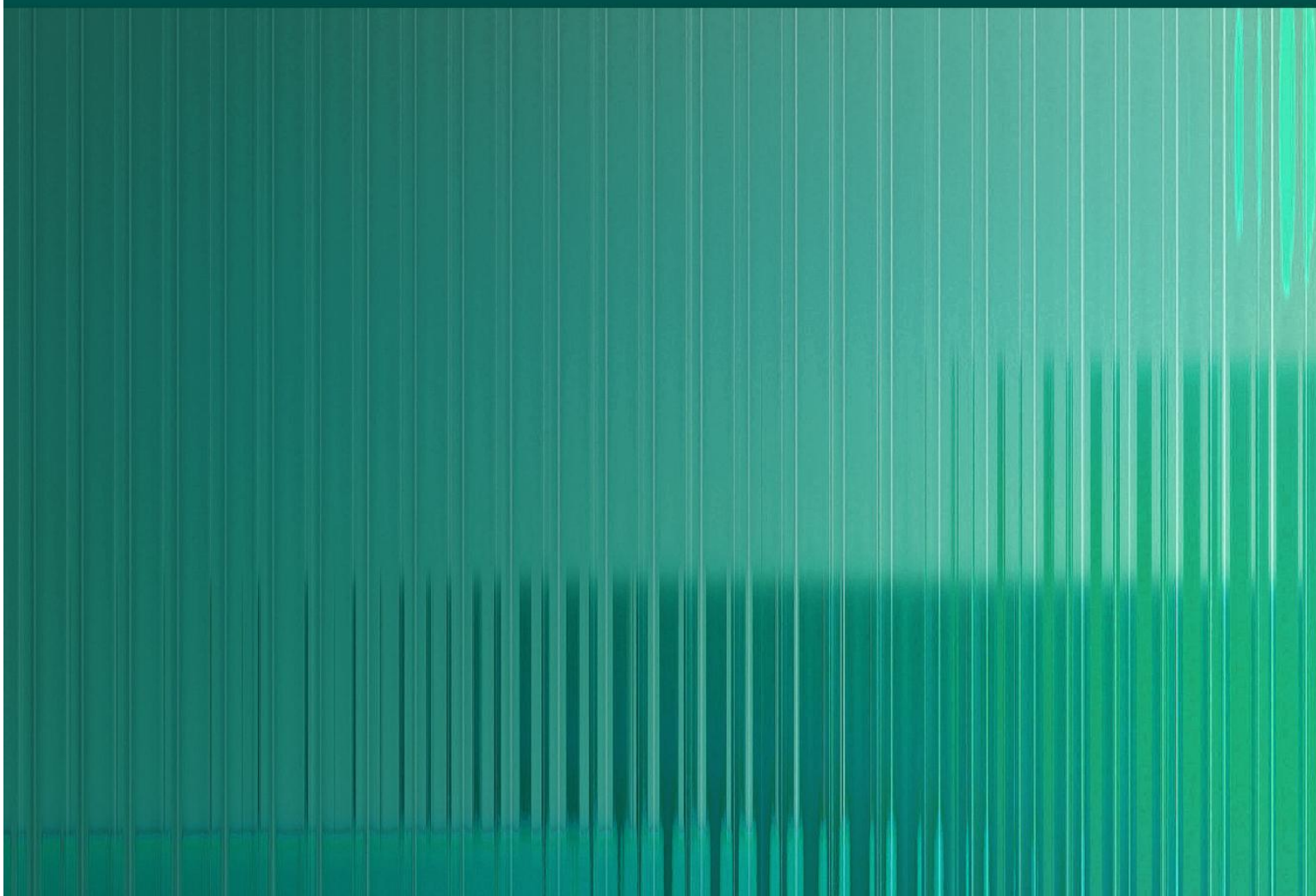
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Centro UC Energía

# Strategic Report for the Development of the Lithium Industry

## Challenges and opportunities in the LAC lithium triangle

November 24, 2025



# Strategic Report for the Development of the Lithium Industry

## Lithium, transition, and future

**Date:** 24/11/2025

**Written by**:

Mr. Videla
Director
UC Energy Center.

EULAC for Energy Transition Project.

This book offers a comprehensive overview of the lithium industry, covering topics ranging from properties, resources, and reserves to its industrial structure, costs, market behavior, and projections. The text is designed to provide a systematic overview to a wide public, preparing readers to understand technical and public policy concepts that require regional context.

The document addresses complex issues such as extraction technologies in a simple and general writing, but not less formal, focusing on both current processes for brines and Direct Lithium Extraction (DLE) technologies. It includes overviews of technological maturity, challenges, comparative analyses, and CAPEX/OPEX contrasts, as well as a global comparison of alternatives, providing useful criteria for investment decisions and project evaluation.

The book also incorporates information about the Lithium Triangle context, including a revision of the regulatory and institutional framework, and an examination of impacts that integrates economics and socio-environmental legitimacy. The latter is developed with its own conceptual basis, beyond the "social license," and is based on ethnographic evidence to situate eco-political conflicts and guide policy responses. The conclusion proposes recommendations in the technological, political, and socio-environmental areas, connecting institutional design with industrial and territorial viability.

I want to sincerely thank all the collaborators and co-authors. We all hope this document could be a source of knowledge for promoting thinking and debate to achieve a sustainable development of the lithium industry.

Sincerely,



Alvaro Videla
UC Energy Center Director
Pontificia Universidad Católica de Chile

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# 1. WHY LITHIUM?

## 1.1. Properties of lithium

Lithium is a versatile element used in various industries. In ceramics, it improves the strength and durability of products (Oruch et al., 2014). In pharmacology, it is essential for the treatment of bipolar disorders and other conditions (Malhi et al., 2017). Likewise, lithium alloys are ideal for manufacturing lightweight and resistant materials in the aerospace industry (Prasad et al., 2014). However, its main and growing application is in lithium-ion batteries (LIB).

The exceptional electrochemical properties of lithium make it the preferred material for energy storage applications. This advantageous condition can be visualized graphically in Ragone diagrams (a useful reference framework for evaluating the energy-to-power ratio of energy storage materials).

In Figure 1, lithium-ion batteries stand out due to their superior combination of energy density and power density. This combination means that LIBs can store a considerable amount of energy per unit volume and deliver this energy quickly, meeting the demands of modern devices.

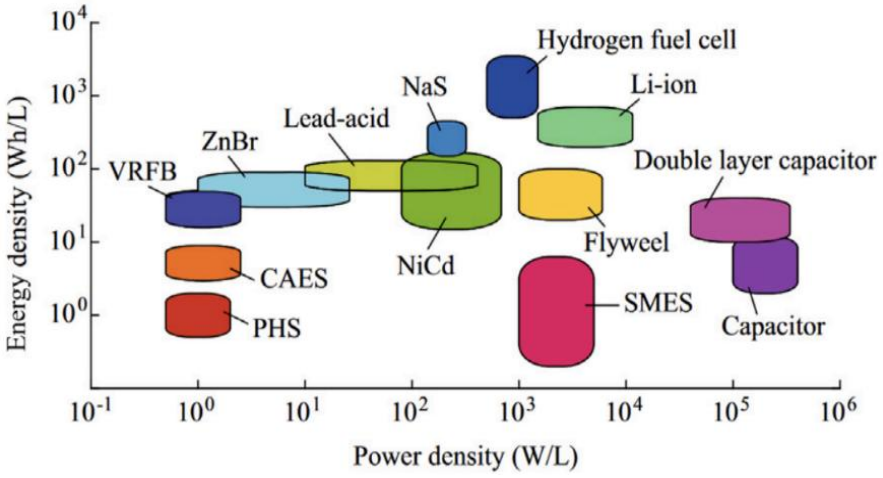



**Figure 1. The Ragone chart shows specific power density versus energy density of various storage methods**
Source: Beyers et al., 2023

In the electric vehicle (EV) industry, LIBs are crucial because high energy capacity is required for long operating ranges, and high-power density is required for rapid acceleration. These characteristics are essential for commercial viability and widespread acceptance of EVs.

In addition, lithium-ion batteries are ideal for renewable energy storage systems due to their high efficiency in charge cycles and long service life. Compared to nickel-cadmium (Ni-Cd) and nickel-

metal hydride (Ni-MH) batteries, lithium-ion batteries offer significant advantages in terms of lower weight, higher capacity, and lower memory effect (Beyers et al., 2023).

The ability of LIBs to intensify the use of renewable energies and the electrification of transport consolidates them as an indispensable strategic resource for the global energy future.

## 1.2. A critical element in the energy transition

The growing demand for lithium reflects its crucial role in the transition to a more sustainable energy economy, facilitating the use of renewable energies and the electrification of transport. These technical characteristics and their practical applicability consolidate lithium as an indispensable strategic resource for the global energy future. Greenhouse gas (GHG)-free energy sources, such as solar and wind power, have gained ground as clean alternatives. However, their main challenge lies in their intermittency, which has driven demand for efficient and reliable energy storage technologies.

In the context of this process, electromobility, together with the growth of low-emission energy sources, is leading to a transition towards a mineral-intensive paradigm. Among these critical minerals are lithium, copper, nickel, cobalt, and
rare earth elements (IEA, 2021).

The critical importance of lithium becomes even more evident when considering demand projections for the coming decades. According to the International Energy Agency, demand for lithium is expected to increase significantly, between 13 and 42 times, depending on the policy and economic development scenario adopted (IEA, 2021). In this context, ensuring a stable and sufficient supply of lithium becomes a strategic challenge for economies seeking to lead the energy transition.

In economies leading the energy transition process, growing demand for raw materials has given rise to policy strategies aimed at securing their supply. Numerous jurisdictions, including major economic powers such as the United States, the European Union, Canada, Japan, South Korea, Australia, the United Kingdom, and South Africa, have classified lithium as a critical and strategic mineral, recognizing its central role in the transition to a low-carbon economy (Cochilco, 2023). This recognition is supported by the increase in the criticality assigned to lithium by the U.S. Department of Energy for the period 2025-2035 compared to the period 2020-2025 (U.S. Department of Energy, 2023).

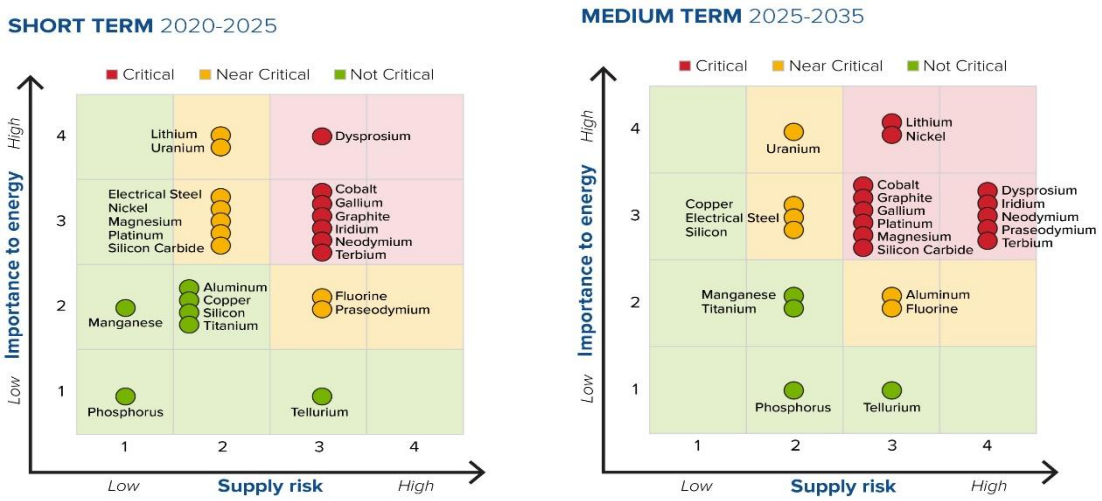



**Figure 2. List of critical minerals**
Source: U.S. Department of Energy, 2023.

In line with the criticality of lithium for countries leading the energy transition, this mineral has taken on strategic importance for countries with abundant resources, being seen as a potential driver of economic development [8]. In Latin America, countries such as Chile, Argentina, and Bolivia, which make up the Lithium Triangle, have incorporated the strategic nature of lithium into their regulatory frameworks.

## 1.3. Lithium products

Lithium is not a traditional commodity, as its market consists of chemical derivatives such as lithium carbonate ($Li_2CO_3$) and lithium hydroxide (LiOH), which vary in specifications depending on their origin and customer requirements. In particular, both hydroxide and carbonate can be categorized as technical grade and battery grade according to their degree of purity.

Lithium carbonate, generally obtained from brines, is crucial for applications in lithium phosphate (LFP) cathodes and has rigorous specifications for use in batteries. In addition, lithium carbonate is used in the electronics, ceramics, glass, and pharmaceutical industries with varying degrees of purity.

**Table 1. Comparison of specifications $Li_2CO_3$ battery grade**
Source: Prepared by the author based on Reanod International Network Technology Co, sf; Livent, 2024.

| Specifications | China Lithium | Livent | Analysis method |
|---|---|---|---|
| $Li_2CO_3$ | min. 99.5% | min. 99.5% | Titration |
| Na | max. 0.002% | max. 0.05% | AAS |
| Ca | max. 0.006% | max. 0.04% | Titration |
| $SO_4$ | max. 0.003% | max. 0.01% | Gb |

**Table 2. Comparison of specifications $Li_2CO_3$ technical grade**
Source: Prepared internally based on Xeolith, sf; Livent, 2024.

| Specifications | China Lithium | Livent |
|---|---|---|
| $Li_2CO_3$ | min. 99.0% | min. 99.3% |
| $Na_2O$ | max. 0.1% | max. 0.2% |
| CaO | max. 0.04% | max. 0.005% |
| $SO_4$ | max. 0.1% | max. 0.01% |

On the other hand, lithium hydroxide, typically produced from lithium minerals, is used in the manufacture of lubricants, as a chemical reagent, and in environmental control systems in the aerospace industry. Meanwhile, its battery-grade version is essential for LIBs due to its ability to improve the energy density and service life of batteries.

**Table 3. Comparison of $LiOH \cdot H_2O$ specifications Battery grade**
Source: Prepared by the author based on Albemarle, 2024; Livent, 2024.

| Specifications | Albemarle | Livent | Analysis method |
|---|---|---|---|
| $LiOH \cdot H_2O$ | min. 56.5% | min. 56.5% | Acidimetric titration |
| $CO_2$ | max. 0.3% | max. 0.35% | Acidimetric titration |
| Cl | max. 0.03% | max. 0.003% | Argentometric titration |
| $SO_4$ | max. 0.05% | max. 0.05% | IC |

**Table 4. Comparison of specifications $LiOH \cdot H_2O$ technical grade**
Source: Prepared internally based on Nanografi, sf; Ganfenglithium, sf.

| Specifications | Nanografi | Ganfenglithium |
|---|---|---|
| $Li_2CO_3$ | min. 99.0% | min. 99.3% |
| $Na_2O$ | max. 0.1% | max. 0.2% |
| CaO | max. 0.04% | max. 0.005% |
| $SO_4$ | max. 0.1% | max. 0.01% |

Although both derivatives are interchangeable, lithium hydroxide has the advantage of decomposing at a lower temperature, which prolongs the battery's autonomy and service life compared to lithium carbonate batteries. However, lithium carbonate is still cheaper to produce, making it more attractive in the short term, to the detriment of new technologies that allow for more direct processing and effectively increase its competitiveness in the industrial market (Bisley, 2021).

Lithium carbonate is the most important base compound among lithium salts, accounting for 60% of lithium products. Its importance lies mainly in the fact that it is easy to purify and is used for the conversion of other inorganic and organic lithium salts, such as LiCl, LiBr, $LiOH \cdot H_2O$, and other compounds. However, in recent years, there has been a gradual increase in the share of lithium hydroxide, which is mainly explained by a preference among manufacturers for NCM (nickel-lithium-cobalt-manganese) batteries, a type that tends to be hydroxide-intensive.

Lithium chloride is also marketed as a product and is mainly used for the production of metallic lithium by electrolysis of a molten mass of LiCl/KCl at 450 °C (842 °F). LiCl is also used as a flux for brazing aluminum in automotive parts. In addition, it is used as a desiccant to dry air streams.

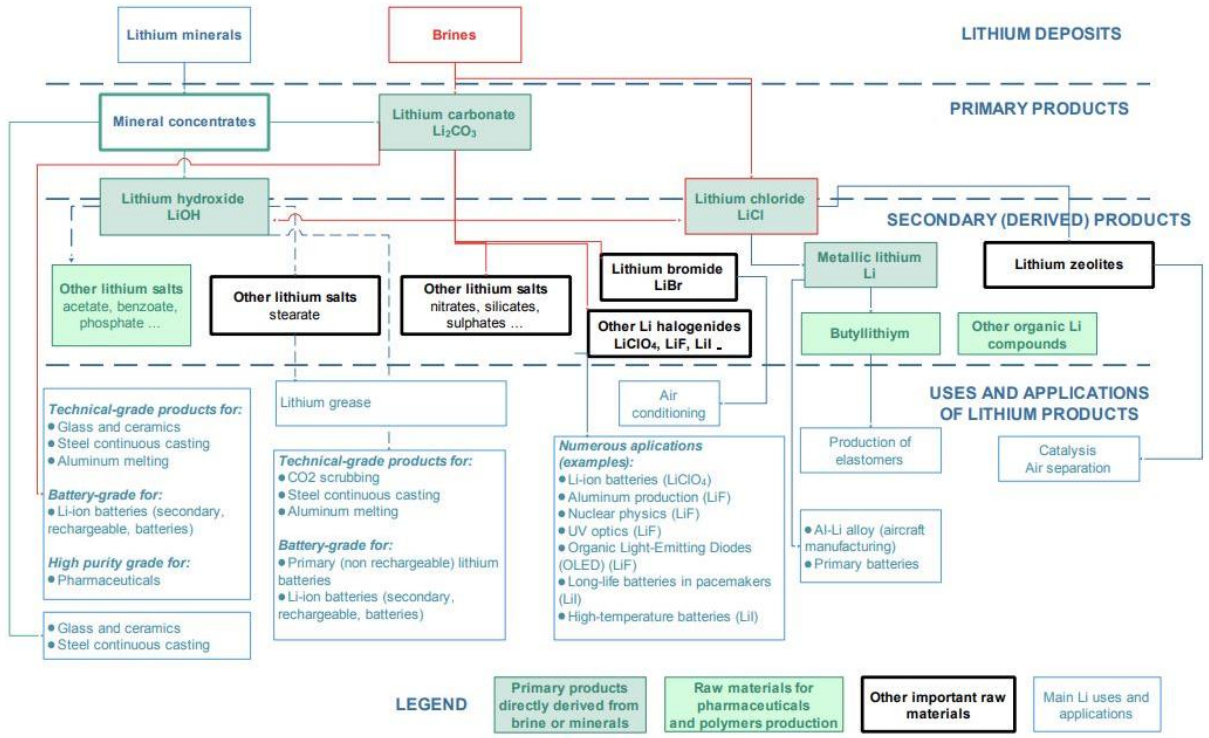



**Figure 3. Supply chains connecting lithium deposits with their applications and uses.**
Source: Christmann et al., 2015.

Lithium Carbonate Equivalent (LCE) is a standard measure used to compare different forms of lithium. The conversion of different lithium products to LCE can be seen in the following table:

**Table 5. Lithium compound conversion table.**
Source: Prepared by the authors based on Roskill, 2016.

| To convert from | Percentage of lithium | to Li | $Li_2O$ | $Li_2CO_3$ |
|---|---|---|---|---|
| **Lithium metal (Li)** | **100%** | 1,000 | 2,153 | 5,323 |
| **Lithium oxide ($Li_2O$)** | **46.4** | 0.464 | 1,000 | 2,473 |
| **Lithium hydroxide (LiOH)** | **28.9** | 0.289 | 0.624 | 1,543 |
| **Lithium carbonate ($Li_2CO_3$)** | **18.8** | 0.188 | 0.404 | 1.000 |
| **Lithium hydroxide monohydrate ($LiOH \cdot H_2O$)** | **16.5** | 0.165 | 0.356 | 0.880 |
| **Lithium chloride (LiCl)** | **16.3** | 0.163 | 0.362 | 0.871 |
| **Lithium bromide (LiBr)** | **8.0** | 0.080 | 0.172 | 0.425 |

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# 2. DESCRIPTION OF RESOURCES AND RESERVES

## 2.1. Natural sources of lithium

Despite being the 32nd most abundant element in the Earth's crust, with an average concentration of 20 parts per million (Dye, 2023), lithium is found in much lower concentrations than other elements, such as copper (60 parts per million). The main sources of lithium (Figure 4) include salt flats (60%), pegmatites and granites (27%), enriched clays (7%), geothermal brines (3%), and enriched zeolites (3%).

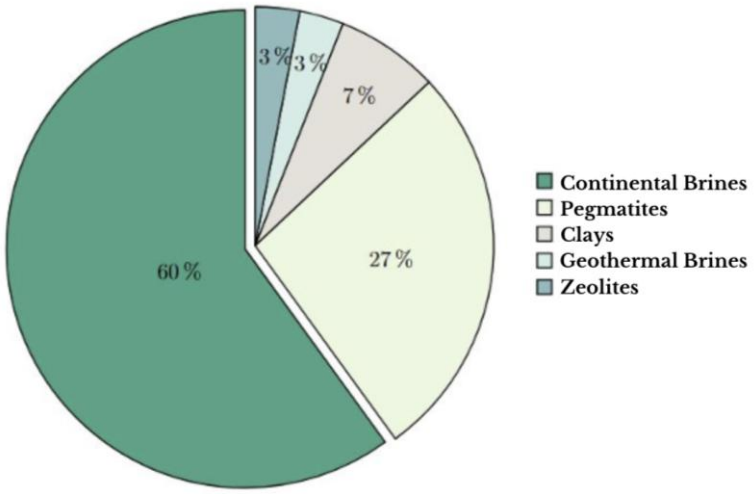



**Figure 4. Distribution of natural sources of lithium.**
Source: Cochilco, 2023.

## 2.2. Brines in continental water reservoirs

Lithium brine deposits originate from the erosion of lithologies containing lithium by meteoric waters, creating diluted lithium solutions. These deposits share a series of common characteristics (Schulz et al., 2017):

1. Arid climate.
2. Presence of a closed basin that houses a salt lake or salt flat.
3. Tectonic subsidence.
4. Associated igneous or geothermal activity.
5. Presence of lithium-bearing source rocks.

6. Existence of one or more aquifers suitable for hosting the brine deposit.
7. Sufficient time to concentrate the brine.

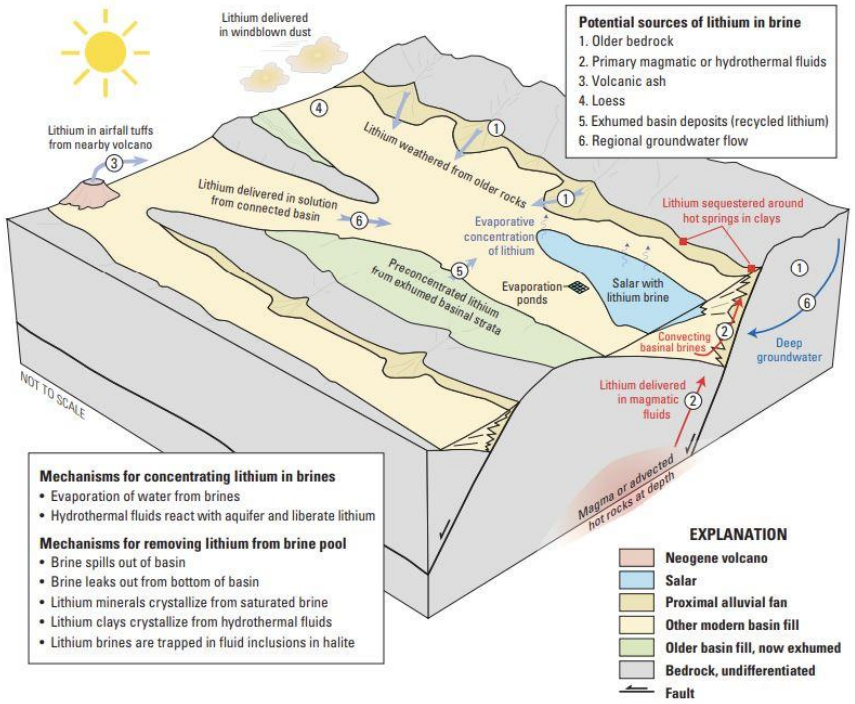



**Figure 5. Conceptual model of a lithium brine deposit.**
Source: Schulz et al., 2027.

It is essential to note that the chemical composition of brines is unique to each deposit and can even vary significantly within the same salt flat. This variability is crucial when evaluating lithium extraction methods, as other soluble ions such as magnesium, sodium, and potassium must be removed during processing.

**Table 6. Composition of continental brines in different salt flats and lagoons around the world, in wt(%).**
Source: Prepared by the authors based on Schmidt et al., 2019; Garcés, n.d.; Lebrun et al., 2002.

| Salt flats | Li | K | Mg | Ca | B | Na | Cl |
|---|---|---|---|---|---|---|---|
| Atacama (Chile) | 0.11-0.31 | 1.80-2.97 | 0.82-1.53 | 0.02-0.04 | 0.06-0.07 | 1.03-9.10 | 2.03-19.85 |
| Zhabuye (China) | 0.05-0.10 | 2.64-3.83 | 0-0.001 | 0-0.001 | 0.29-1.46 | 10.66-10.81 | 12.16-12.31 |
| Dead Man (Argentina) | 0.05-0.06 | 0.52 | 0.05-0.09 | 0.05-0.099 | 0.02-0.04 | 9.79-10.30 | 15.80-16.80 |
| Clayton Valley (USA) | 0.02-0.04 | 0.53-1.00 | 0.03-0.06 | 0.02-0.05 | 0.00-0.01 | 6.20-7.50 | 10.10-11.70 |
| Rincón (Argentina) | 0.03 | 0.62-0.66 | 0.28-0.3 | 0.04-0.06 | 0.04 | 9.46-9.79 | 15.8 |
| Uyuni (Bolivia) | 0.03-0.05 | 0.72-1.42 | 0.66-1.30 | 0.048 | 0.02 | 5.31-8.80 | 15.70-16.77 |
| Qaidam Basin (China) | 0.01-0.03 | 0.6-0.66 | 0.47-3.51 | 0.02-0.42 | 0.03-0.05 | 6.20-6.84 | 9.20-20.42 |

Brines with a high lithium concentration, a low Mg/Li ratio, and a high K (by-product) concentration are considered the most economical process. Those with lower lithium content can be exploited economically if evaporation costs or impurities are low.

The quality of the deposit will depend mainly on the concentration levels of various elements present in the brine. The lithium concentration in these typically varies between 200 and 2,000

ppm (0.02% to 0.2%). The most significant brines in terms of quality and volume are found in northern Chile (Salar de Atacama), western Bolivia (Salar de Uyuni), northern Argentina (Salar del Hombre Muerto), various salt lakes in the United States, and northeastern China (Qinghai province).

Latin America stands out for the presence of high-quality brines. The deposits in the Salar de Atacama have the highest lithium concentrations (0.11-0.31%), significantly exceeding other global deposits such as Clayton Valley (0.02-0.04%) and Qaidam Basin (0.01-0.03%).
This high concentration, together with a low Mg/Li ratio, makes processing more economical and efficient. In Argentina, the Hombre Muerto and Rincón salt flats, although they have lower lithium concentrations, have low levels of impurities that facilitate extraction.
The Salar de Uyuni (Bolivia), the largest deposit in terms of volume, faces challenges due to its high Mg/Li ratio, which increases processing costs. However, its high potassium content may offset these costs.




**Figure 6. Main salt flats within the Lithium Triangle.**
Source: Obaya et al., 2024.

## 2.3. Pegmatite rocks and granites

Pegmatites of the lithium-cesium-tantalum (LCT) family are plutonic rocks formed by late magmatic processes and concentrations of peraluminous granites. They are characterized by high concentrations of rubidium (Rb), cesium (Cs), beryllium (Be), tantalum (Ta), niobium (Nb), and tin (Sn), and significantly elevated levels of fluxing components such as lithium (Li), phosphorus (P), fluorine (F), and boron (B) (Schulz et al., 2017). These minerals are found in association with large abundances of feldspar, mica, tourmaline, apatite, and various phosphate minerals, as well as pyroxene, beryl group minerals, oxides, columbite-tantalite, and polycite.

**Table 7. The most important lithium minerals.**
Source: Prepared by the authors based on Roskill, 2016.

| Name | Formula | Maximum theoretical $Li_2O$ content (%) | Average $Li_2O$ % of minerals |
|---|---|---|---|
| **Spodumene** | $LiAlSi_2O_6$ | 8.0 | 2.9-7.7 |
| **Petalite** | $LiAl(Si_4O_{10})$ | 4.5 | 3.0-4.7 |
| **Lepidolite** | $K(Li, Al)_3(Si, Al)_4O_{10}(OH,F)_2$ | 7.7 | 3.0-4.1 |
| **Ambligonite** | $(Li, Na)Al(PO_4)(F,OH)$ | 7.4 | ... |
| **Montebrasite** | $LiAl(PO_4)(OH,F)$ | 10.2 | 7.5-9.5 |
| **Eucryptite** | $LiAlSiO_4$ | 11.8 | 4.5-6.5 |

Spodumene stands out as the mineral with the highest concentration of lithium, with an approximate content of 8% $Li_2O$. It is followed by lepidolite, a monoclinic mineral from the mica group, which is typically found associated with granitic pegmatites and contains approximately 7% $Li_2O$. Although historically, lepidolite was the most mined mineral for lithium, its high fluorine content made it less attractive compared to other lithium-bearing silicates. Petalite, on the other hand, contains less lithium than lepidolite and spodumene, with approximately 4.5% $Li_2O$ (Roskill, 2016). Most commercially mined lithium pegmatites are found near the surface, allowing open-pit mining methods to be used for extraction.



**Figure 7. Reference image of the mineral spodumene.**
Source: U.S. Department of the Interior Bureau of Land Management, 2022.

## 2.4. Lithium-enriched clays

The formation of lithium clays is mainly attributed to the decomposition of igneous rocks containing significant concentrations of lithium. This process can be driven by various factors, including hydrothermal/metasomatic alteration. Among lithium clays, the most significant are those in the smectite group, especially hectorite.

**Table 8. Main members of the smectite group.**
Source: Prepared by the authors based on Roskill, 2016.

| Name | Formula | Theoretical max. $Li_2O$ content (%) |
|---|---|---|
| **Hectorite** | $Na_{0.3}(Mg,Li)_3Si_4O_{10}(F,OH)_2$ | 1.17 |
| **Salitholite** | $(Li, Na)Al_3(AlSi_3O_{10})(OH_5)$ | 1.65 |

This type of deposit was first discovered in the 1970s, when significant concentrations of lithium were identified in clays in the town of Hector in California, giving rise to the term hectorites (Lagos, 2018).

In terms of lithium content, hectorite deposits typically contain concentrations ranging from 1.1% to 1.3% $Li_2O$. However, despite their potential value, the production of lithium carbonate or other compounds from hectorites has faced significant challenges, mainly due to the high costs associated with their processing. Consequently, these deposits were long considered economically unviable for large-scale extraction using available technologies (Zhao et al., 2023).
However, in recent years, significant advances have been made in the development of new technologies that could reconsider the exploitation of these deposits, making them economically viable.

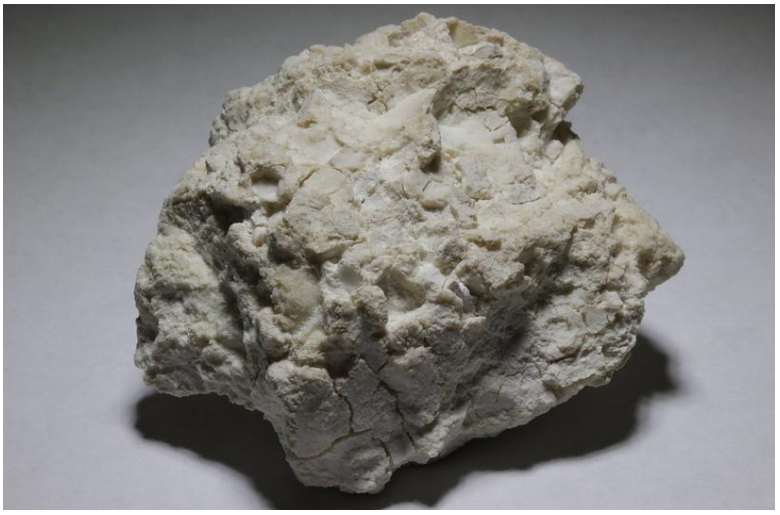


**Figure 8. Reference image of hectorite.**
Source: Mindat.org, n.d.

## 2.5. Brines in geothermal deposits

The extraction of lithium from geothermal brines has emerged as an area of significant interest due to its dual potential for renewable energy production and the extraction of critical minerals. This

process seeks to harness brines for both electricity generation and the extraction of valuable minerals such as lithium (Toba et al., 2021).

The chemical composition of geothermal brines varies depending on the geological characteristics of the region. They typically contain between 100 and 330 g/l of total dissolved solids, with lithium concentrations ranging from 20 to 1,750 mg/l (Heuberger et al., 2017).

In 2021, a study was conducted to assess the feasibility of extracting lithium from geothermal brines in the US and its impact on the supply chain. The results indicated that these brines could contribute significantly to the lithium supply, potentially offsetting between 4% and 8% of the total lithium in the United States. In addition, the study showed that extracting lithium from geothermal brines could be economically viable by leveraging existing geothermal facilities to reduce production costs (Chesnutt et al., 2023).

Despite the high theoretical potential, industrial-scale lithium extraction from geothermal brines has not yet been widely implemented. This is due to the need to develop selective extraction methods that can deal with relatively low lithium concentrations, high temperatures, and the presence of other minerals in the brines, such as iron, manganese, silica, zinc, lead, and magnesium (Lagos, 2023).

## 2.6. Lithium-enriched zeolites

The only known lithium zeolite deposit is located in a system of Neogene basins in Eastern Europe, specifically in the Balkan region (Schulz et al., 2023). This deposit was first identified in 2004 in the Jadar basin (Serbia), giving rise to the name of the mineral, jadarite.

Jadarite is a sodium-lithium borosilicate mineral found both in massive form, with a layer more than 7 meters thick, and in nodules within a fine-grained carbonate matrix. Its unique geology stems from its deposition as a stratiform sedimentary deposit in a lacustrine environment, interbedded with clay, limestone, and shales (Szlugaj et al., 2023). This particular geology gives jadarite a soft to medium hardness, making it significantly easier and more cost-effective to mine and process compared to hard rock lithium spodumene.
In terms of lithium content, this deposit typically has average concentrations of around 1.8% $Li_2O$ (British Geological Survey, 2016).

Rio Tinto planned to start operations in 2025. However, significant concerns arose about the potential impact of the mine on local communities in the Jadar Valley.
For this reason, the Serbian government made the decision to cancel the licenses related to
The company's proposed project (Rio Tinto Lithium, 2022).

## 2.7. Secondary sources of lithium

In addition to natural sources of lithium, this mineral can be obtained from non-purely natural sources such as recycling, oil wells, and tailings.

### 2.7.1. Recycling of LIBs

Recycling LIBs using conventional methods is inefficient, costly, and complicated (Swain et al., 2007), resulting in approximately 95% of LIBs worldwide ending up in landfills instead of being properly recycled. Pyro, hydro, and biohydrometallurgical methods are the most appropriate for

large-scale recycling, although they face challenges such as process complexity, pollution generation, and low economic efficiency due to high costs (Bae & Kim, 2021). These methods can generate toxic components and gaseous emissions that affect the environment, including acidic wastewater that contaminates water bodies, as well as emissions of gases such as $CO_2$, SOx, NOx, HF, and other atmospheric pollutants (Rautela et al., 2023).
On the other hand, techniques such as the repair and reuse of electrode materials can improve the efficiency and sustainability of recycling by conserving resources and reducing the environmental impact associated with the extraction and refining of new materials. Innovative methods such as bioleaching, which use microorganisms or benign chemicals, offer the possibility of reducing or eliminating the production of toxic components and gaseous emissions during the recycling process (Li et al., 2023).

### 2.7.2. Oil wells

As for lithium production from oil wells, these deposits are usually found at depths greater than 1 km, unlike brine aquifers. Furthermore, unless they are located in arid regions, recovering lithium from these wells in a cost-effective and rapid manner, as is done with brines through solar evaporation, is not feasible, making their exploitation difficult in the medium term (Cochilco, 2023).

### 2.7.3. Production from tailings

Finally, in the case of tailings utilization, AMG has established a plant at its Mibra operation to recover spodumene from tailings from its tantalum operations, reaching an estimated production of approximately 6,000 tons of lithium carbonate equivalent (LCE) in 2020 (Cochilco, 2023). Apart from Mibra, Bravura Holdings is expected to develop a similar operation in the Kamativi tailings by 2025, which is the only initiative of this type planned for the next decade (Hinostroza, 2024).

## 2.8. Geographical location of lithium deposits

Natural sources of this resource are distributed across more than 85 deposits around the world, concentrated mainly in four prominent areas (Shaw, 2021). The first and most recognized is the so-called "Lithium Triangle," made up of Bolivia, Argentina, and Chile. This region is known for its abundance of lithium in the form of continental brine, making it one of the most important areas for the extraction of this resource worldwide.
In the United States, lithium is found in various forms, including continental brine, clays, and geothermal brines. Australia, meanwhile, stands out for its abundance of lithium in the form of hard rock minerals, such as pegmatites and granites, making it another important center for lithium extraction and production worldwide. China, meanwhile, has a mixed presence of lithium in the form of continental brine and pegmatites, consolidating its position as another key player in the global lithium market.
It should be noted that there are also lithium resources distributed throughout Europe and Africa, predominantly in the form of spodumene and granites. However, these represent a smaller proportion compared to the areas mentioned above.

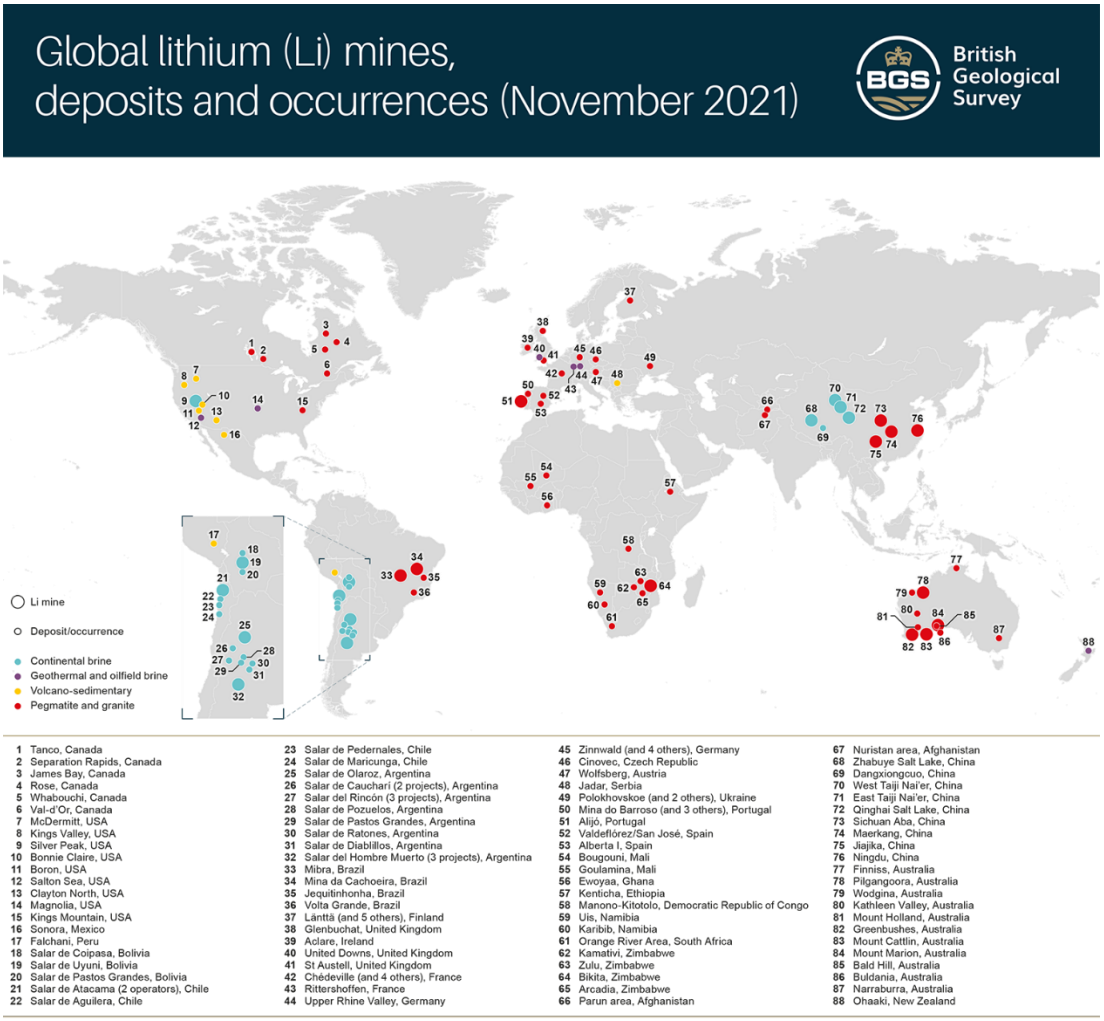



**Figure 9. Geographic location of lithium deposits.**
Source: Shaw, 2021.

According to data from the United States Geological Survey (USGS, 2024), global lithium resources currently amount to 105 million tons. Of this total, more than 50% is concentrated in the Lithium Triangle, a strategic region covering Bolivia, Argentina, and Chile. These countries, together with the United States, Australia, and China, account for more than 80% of global resources (Figure 10), shaping a geopolitical landscape of great relevance to the industry.

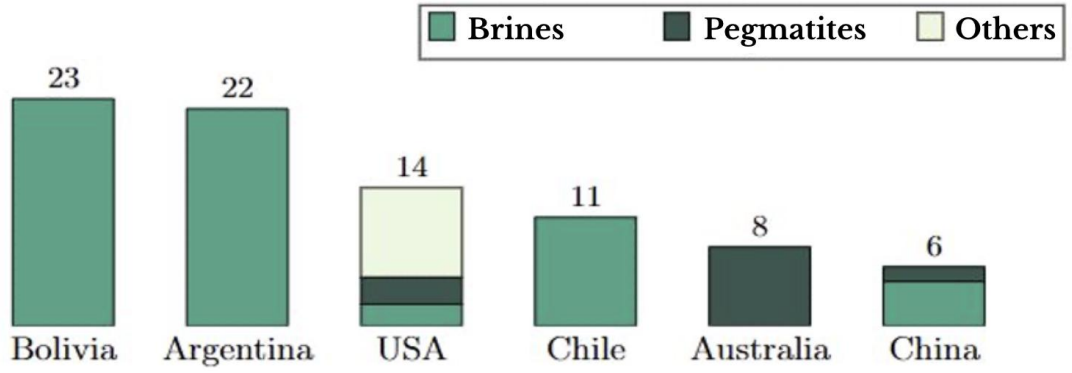



**Figure 10. Distribution of lithium resources worldwide (M tons of metallic lithium).**
Source: Prepared by the authors based on U.S. Geological Survey, 2024.

When considering mineral reserves, i.e., the fraction of identified resources that can be economically extracted with available technology, the outlook varies significantly for some countries in the region. This change is due to various factors, such as economic and market conditions, financing, extraction methods, and legal, environmental, and social conditions.
These aspects condition the viability of exploiting the resource, beyond the geological knowledge of the deposit.

In this scenario, Chile stands out as having the largest lithium reserves, with approximately 9.3 million tons, representing 33% of global reserves. Australia has around 6.2 million tons, equivalent to 22% of total reserves, followed by Argentina with 3.6 million tons, representing 13% of global reserves. China and the United States contribute 11% and 4%, respectively. This latest update from the USGS shows that the five countries mentioned above account for more than 95% of global lithium reserves.

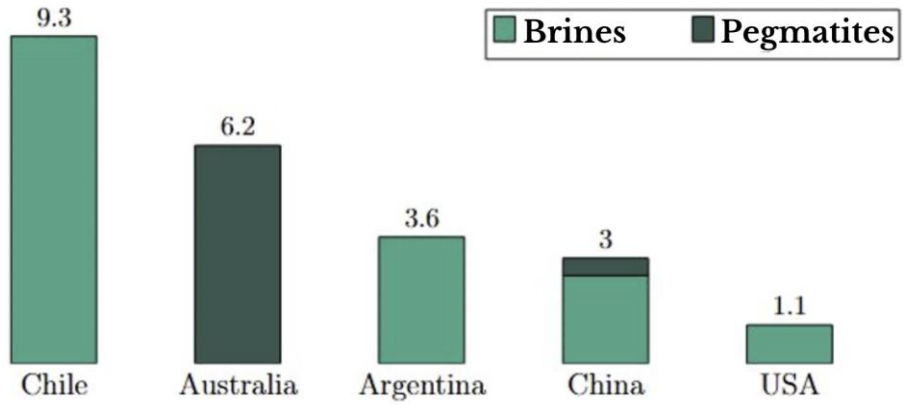



**Figure 11. Distribution of global lithium reserves (M tons of lithium metal).**
Source: Prepared by the author based on the U.S. Geological Survey, 2024.

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# 3. INDUSTRY STRUCTURE

## 3.1. Main participating countries

Lithium production is mainly concentrated in four countries: Australia, Chile, China, and Argentina, which accounted for more than 93% of global production in 2023. Australia leads with more than 46% of the market share, followed by Chile (24%), China (18%), and Argentina (5%). The relative share of each country in global lithium production has varied over the years. Between 2000 and 2010, Chile had an average share of 39% in global production, while Australia stood at around 23%. China had a share of 15% and Argentina close to 9%. In the period between 2010 and 2015, the leadership changed, with Chile's share falling to 36% and Australia's rising to 38%. Between 2015 and 2023, there was a notable increase in demand and, consequently, in prices, widening the gap between the two countries. In 2018, Australia reached a peak of 62% of global production, while Chile stood at 18%.

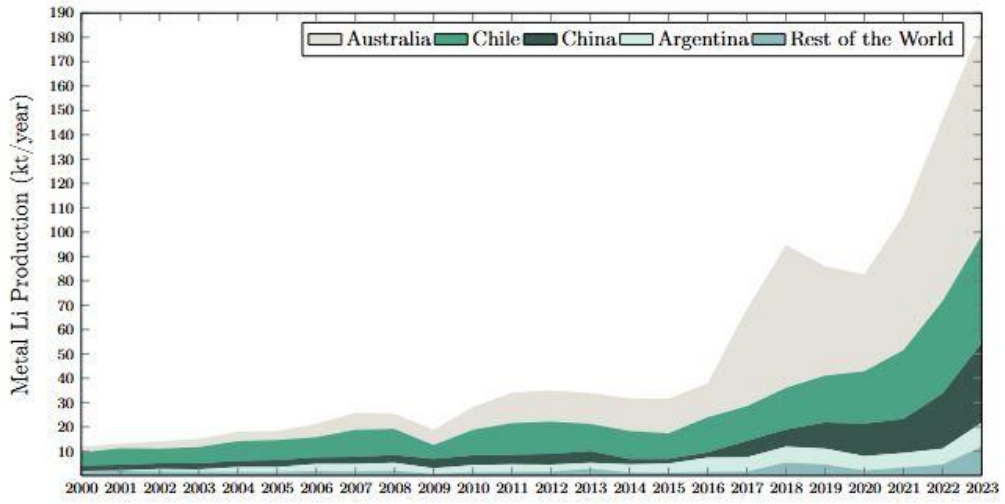



**Figure 12. Metallic Lithium Production [KTon] (2000-2023).**
Source: Prepared internally based on U.S. Geological Survey, 2024.

The rapid growth in Australia's share can be explained by the addition of five new spodumene production projects, which have a relatively short production time compared to lithium extraction from brines using evaporation ponds. In addition, spodumene can be processed directly to produce lithium hydroxide, without first having to go through the carbonate stage, as is the case with brine deposits. Although lithium carbonate is currently still in greater demand than hydroxide, in recent years, there has been a gradual increase in the share of lithium hydroxide, mainly due to manufacturers' preference for NCM (nickel-lithium-cobalt-manganese) batteries, a type that tends to be hydroxide-intensive.

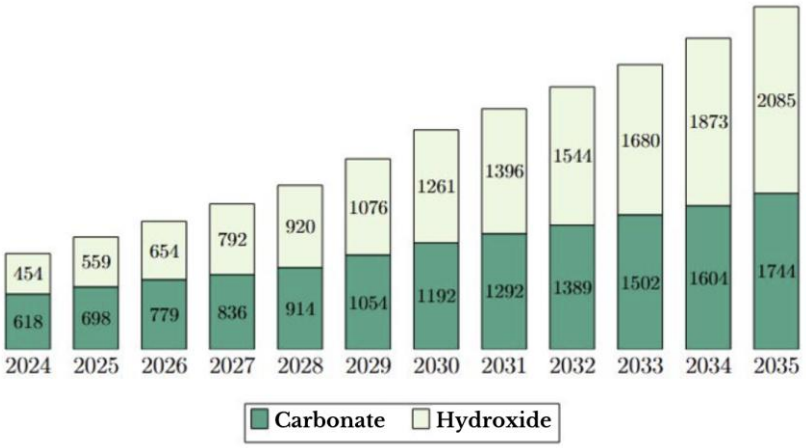



**Figure 13. Projected lithium demand by type of compound (kt LCE), 2024-2035.**
Source: Prepared by the authors based on Cochilco, 2023.

In Latin America, the trend has been marked by the performance of Chile and Argentina. Between 2000 and 2008, the lithium triangle's share of global production was over 50%, peaking at 55.8% in 2005. In 2016, the lithium triangle again contributed more than half of global production (52.9%), partly supported by the increase recorded in Argentina following the start-up of the Olaroz project, the second operation in the country. However, in 2017, Australia significantly increased its production capacity, affecting the Lithium Triangle's share (Roskill, 2016).

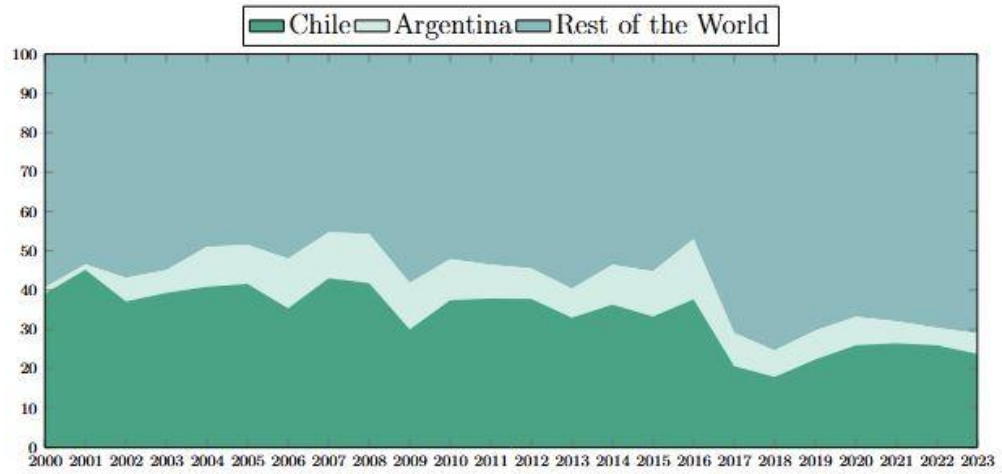



**Figure 14. Share of Metallic Lithium Production [%] (2000-2023).**
Source: Prepared by the author based on the U.S. Geological Survey, 2024.

It is important to note that a significant advantage of extracting lithium from brines is that it requires fewer inputs. Unlike lithium production from spodumene, which involves extraction, crushing, grinding, flotation, heating, and leaching with sulfuric acid, the treatment of brines is mainly chemical in nature (evaporation and precipitation). Depending on evaporation rates and impurities present in the reservoir (such as magnesium and calcium), processing lithium from brines tends to be less expensive (Roskill, 2016). From this perspective, production from the lithium triangle provides cheaper lithium carbonate with a smaller water and carbon footprint.

## 3.2. Main participating companies

The market share of companies in lithium extraction can be analyzed using two approaches: considering the companies responsible for direct operations (operating companies) and evaluating the corporate holdings that influence both operations and other entities.

When analyzing market share based on operational control, Talison, the operator of the Australian Greenbushes mine, leads with a 27% market share. It is followed by SQM with 20%, which could become the leader with the start of operations at the Mt Holland project in Australia. Other companies with smaller shares include Mineral Resources with 9%, Pilbara with 8%, and Albemarle with 7% (Cochilco, 2023).

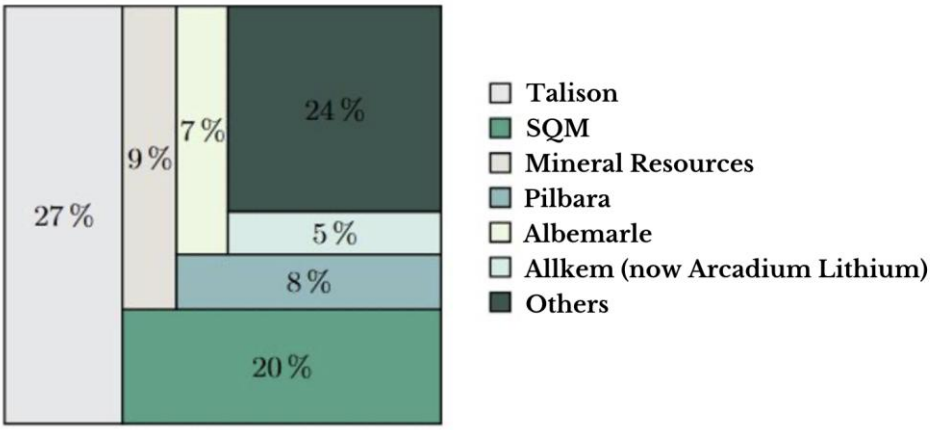



**Figure 15. LCE production by operational control (2021).**
Source: Prepared by the authors based on Cochilco, 2023.

However, evaluating the market solely from the perspective of direct operators does not fully reflect the industry's power structure. Many companies participate in mining projects through joint ownership agreements and strategic stakes, allowing them to influence production without directly operating the mines. From this perspective, Albemarle ranks as the largest lithium producer in corporate terms, due to its 51% control of Greenbushes and its operation in the Salar de Atacama. In this scheme, SQM ranks with a 15% share, followed by Tianqi with 12% (Cochilco, 2023).

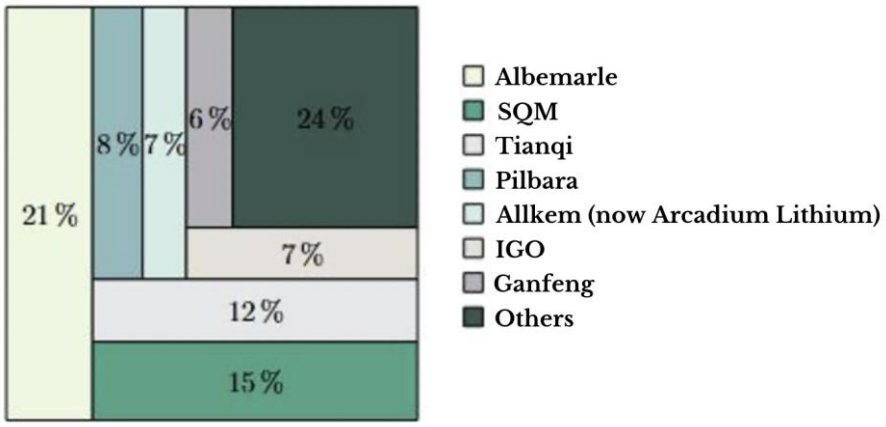



**Figure 16. LCE production by corporate share (2021).**
Source: Prepared by the authors based on Cochilco, 2023.

This approach provides a better understanding of the power dynamics in the lithium industry and the impact that new *greenfield* projects will have on the market structure. As new operations develop, such as the Belo Lithium project in Brazil (recently announced by Pilbara) or the

advancement of strategic projects in Argentina, such as Mariana or Pozuelos-Pastos Grandes (both by Ganfeng), the distribution of market share could change significantly in the coming years.

To understand the competitiveness of the companies that account for 75% of global Lithium Carbonate Equivalent (LCE) production, eight key financial indicators have been selected to assess their performance in terms of size, profitability, valuation, and risk (Table 9).

- **Market Cap (MUSD):** This is the total market value of a company, calculated as the price of its shares multiplied by the total number of shares outstanding. It reflects the size and relevance of the company in the industry.

- **EV (Enterprise Value, MUSD):** Represents the total value of the company, including its market capitalization and net debt. It is used to assess the actual cost of acquiring the company.

- **EV/EBITDA Est 2025:** Indicates how many times the enterprise value (EV) covers the estimated EBITDA for 2025. A high multiple suggests growth expectations, while a low multiple may indicate an attractive valuation or financial problems.

- **Beta (5Y Monthly):** Measures the volatility of the stock relative to the market. A value greater than 1 implies that the stock is more volatile than the market, while a value less than 1 indicates lower relative risk.

- **P/E Ratio 2025:** Relates the stock price to projected earnings per share for 2025. A high value suggests high growth expectations, while a low value may indicate an undervalued stock or one with lower growth potential.

- **P/Book (Price to Book Value):** Compares the market price of the stock to its book value. A value greater than 1 suggests that the market values the company above its book value, which may be due to growth expectations or valuable intangibles.

- **Return on Common Equity (ROCE):** Measures how efficiently the company uses shareholders' capital to generate profits. A high ROCE indicates good profitability and operational efficiency.

- **Operating Margin:** Represents the percentage of revenue that remains as operating profit after deducting operating costs. A high margin indicates greater efficiency and operating profitability.

**Table 9. Comparison of financial indicators for the most relevant companies in the industry.**
Source: Prepared by the author based on Bloomberg, 09/12/2024.

| Indicators | Albemarle<br>ALB US | SQM<br>SQM US | Tianqi<br>002466 CH | Pilbara<br>PLS AU | Arcadium<br>ALTM US | IGO<br>IGO AU | Ganfeng<br>002460 CH |
|---|---|---|---|---|---|---|---|
| Operations | Chile<br>Australia<br>USA | Chile<br>Australia | Chile<br>Australia<br>China | Australia | Australia<br>Argentina<br>Canada | Australia | Australia<br>Argentina<br>China<br>Mexico |
| Market Cap (MUSD) | 10,358 | 10,675 | 6,185 | 5,816 | 2,646 | 2,783 | 6,972 |
| EV (MUSD) | 14,755 | 13,082 | 8,082 | 5,117 | 3,780 | 2,469 | 11,103 |
| EV/EBITDA FY 2025 Est 12/31/2025 (MUSD) | 10.11 | 5.63 | 5.88 | 23.71 | 7.90 | 14.98 | 14.67 |
| Beta (5Y Monthly) | 1.57 | 1.06 | 0.93 | 1.64 | 1.63 | 0.76 | 0.75 |
| P/E FY 2025 Est 12/31/2025 | 25.06 | 8.39 | 15.54 | 21.18 | 12.06 | 16.46 | 19.04 |
| P/Book Est 12/31/2025 | 1.03 | 1.86 | 0.92 | 2.42 | 0.48 | 1.32 | 1.09 |
| Return on Common Equity 2023 (%) | 18.09 | 38.60 | 14.08 | 102.14 | NA | 15.20 | 10.94 |
| Operating Margin 2023 (%) | 2.62 | 38.09 | 81.96 | 79.03 | 17.14 | -87.91 | 8.34 |

Among the companies analyzed, SQM and Pilbara stand out for their high profitability. SQM has an operating margin of 38.09% and a ROCE of 38.6%, reflecting its competitive cost advantage thanks to its access to the highly concentrated brines of the Salar de Atacama. Pilbara, on the other hand, shows even more impressive figures, with an operating margin of 79.03% and an ROCE of 102.14%, demonstrating its extraordinary efficiency in lithium production in Australia.

In terms of market capitalization, Albemarle leads with an enterprise value of $14.7 billion, confirming its dominance in the industry. Its high P/E ratio (25.06x) indicates that the market has high growth expectations for the company, backed by its expansion and presence in the most important lithium production projects (Salar de Atacama and Greenbushes) and its long-term supply contracts with battery manufacturers. In contrast, SQM has a P/E ratio of 8.39x, indicating that it is being valued more conservatively, probably due to regulatory uncertainties in Chile and its recent agreement with Codelco for the joint exploitation of the Salar de Atacama.

On the other hand, Chinese companies Ganfeng and Tianqi have a strong presence in the lithium value chain, with access to strategic resources and vertical integration that allows them to control the production and distribution of the material. Ganfeng, in particular, has been expanding its lithium refining and processing capacity, giving it a competitive advantage in the production of high-value-added products (Bloomberg, 2024).

Finally, some companies face more significant challenges in terms of profitability and market perception. IGO, with negative operating margins, and Arcadium Lithium, with a market valuation that could reflect investors' expectations to see tangible results from the merger before assigning it greater value, appear to be the companies with the most structural problems within the group. Uncertainty about their future puts them at risk, which could make them less attractive to investors compared to their more established peers.

To perform a comparative exercise between companies at different stages of their investment cycle, we propose using the Blended Forward Price/Earnings Per Share (BF P/E) indicator, which measures the relationship between the share price and projected future earnings, adjusting the company's valuation based on growth expectations. This indicator allows us to understand whether

a company is trading at a premium or discount compared to its historical average and other companies in the sector.

Albemarle has a BF P/E of 37.19x, which is high compared to its competitors, indicating that the market has strong expectations for its future growth. Its current premium of 57% is well above its historical average of 19%, suggesting that investors are willing to pay more for each dollar of future earnings. This optimism may be related to its geographic diversification, leadership in the sector, and capacity for expansion in the lithium value chain.

For its part, SQM has a BF P/E ratio of 11.71x, significantly lower than Albemarle and Pilbara. In addition, its current premium is negative at -51%, meaning that the market is valuing it below its historical average of -8%. This indicates that investors have doubts about its future growth potential or that the stock is undervalued. This valuation may be contingent upon the review of the lithium production agreement in the Salar de Atacama between SQM and Codelco. Although negotiations between the two mining giants began in May 2023 and the final agreement was signed on the last day of May 2024, several steps remain before the agreement can be finalized. Specifically, it requires free competition authorization from at least seven other jurisdictions: the General Authority for Competition of the Kingdom of Saudi Arabia; the Administrative Council for Economic Defense of Brazil; the State Administration for Market Regulation of the People's Republic of China; the Fair Trade Commission of Korea; the European Commission; the Fair Trade Commission of Taiwan; and the Fair Trade Commission of Japan. This could explain why, despite having one of the highest operating margins in the industry (38.09%), its low multiple suggests that the market anticipates regulatory challenges or a reduction in its margins due to the volatility of lithium prices (Bloomberg, 2024).

On the other hand, we see that Tianqi is at an intermediate level with a BF P/E of 27.64x. Its current premium is 16%, although historically it has had a premium of 51%, indicating that the market has lowered its expectations for this company. This difference of -35% from its historical average suggests that Tianqi faces uncertainty in its business model or in its ability to generate consistent profits over time, which would be explained by the reduction of its stake in SQM (currently owning 22%) as a result of the alliance with Codelco, which will have a majority stake in the Salar de Atacama.

One notable player is Pilbara, which has the highest BF P/E in the sector at 51.79x and a current premium of 118%, indicating that investors have extremely high expectations for its future growth. This is reflected in the 95% difference from its historical average, meaning that the market has significantly revalued the company compared to its track record. Given that Pilbara has an operating margin of 79.03% and a ROCE of 102.14%, this valuation could be justified if the company maintains its efficiency and expansion. However, this high multiple also implies a risk of market correction if it fails to meet expectations (Bloomberg, 2024).

In the case of Arcadium Lithium, it has a BF P/E of 12.59x, which positions it as a low-valuation company compared to the sector. Its current premium of -47% shows that the market does not yet assign a premium valuation to the company, possibly due to uncertainty about the integration of the merger and its ability to generate synergies. Given that the company has a robust portfolio of assets and projects, this valuation could represent an opportunity if it manages to consolidate its business and improve its profitability (Bloomberg, 2024).

On the other hand, IGO has a BF P/E of 22.37x and a premium of -6%, indicating that the market is valuing it more stably compared to its historical average. However, its negative operating margin of -87.91% suggests that it faces significant challenges in terms of profitability. If it fails to improve its operational efficiency, it could face difficulties in justifying its current valuation multiple.

Finally, Ganfeng has a BF P/E of 21.83x, and although it has historically traded at a premium of 75%, it is currently at -8%, indicating that the market has significantly reduced its expectations for the company. With a difference of -83% from its historical average, Ganfeng appears to be experiencing a valuation correction, possibly due to changes in its operating structure, production costs, or uncertainty in the materialization of its pipeline projects due to fluctuations in the price of ore.

**Table 10. Comparison of the most relevant companies in the industry in terms of BF P/E.**
Source: Prepared internally based on Bloomberg data, 09/12/2024.

| | Metrics | Albemarle ALB US | SQM SQM US | Tianqi 002466 CH | Pilbara PLS AU | Arcadium ALTM US | IGO IGO AU | Ganfeng 002460 CH |
|---|---|---|---|---|---|---|---|---|
| Current | Blended Forward Price/Earnings Per Share (BF P/E) | 37.19x | 11.71x | 27.64x | 51.79x | 12.59x | 22.37x | 21.83x |
| Current vs. 5Y Average Historical Premium (BF P/E) | Prem | 57 | -51% | 16 | 118 | -47 | -6 | -8% |
| | Hist Avg | 19 | -8 | 51 | 23 | NA | -12 | 75 |
| | Diff | 38 | -43% | -35 | 95 | NA | 18 | -83 |
| | # SD | 1.5 | -2.0 | -0.4 | 1.5 | NA | 0.4 | -0.9 |
| 5Y Historical Premium Range (BF P/E) | Low | -43 | -56 | -42 | -63 | -52 | -50 | -40 |
| | Current | 57% | -51% | 16 | 118 | -47 | -6 | -8% |
| | Hist Avg | 19 | -8 | 51 | 23 | NA | -12 | 75 |
| | High | 77 | 39 | 375 | 252 | 71 | 25 | 368 |

To compare the financial results with analysts' recommendations, three graphs are presented that illustrate the growth outlook for the companies evaluated. First, Figure 17 shows the relationship between Bloomberg's estimate of the EV/EBITDA ratio (Enterprise Value to EBITDA), a key indicator that measures how much investors are willing to pay for each dollar of EBITDA generated by the company, and the consensus recommendation of analysts, which is measured on a scale from 1 (sell recommendation) to 5 (buy recommendation), with values close to 3 indicating "hold."

In this context, Pilbara Minerals and Ganfeng Lithium have the highest EV/EBITDA values (30.39x and 31.81x, respectively), suggesting that the market has significantly high expectations for their growth potential. However, their consensus recommendation is relatively low, with values of approximately 3.5 and 3.7, indicating that some analysts may consider their valuations to be overly optimistic or that the risk associated with these companies is higher. On the other hand, Albemarle and SQM have more moderate EV/EBITDA values (13.08x and 8.89x), but with a higher analyst consensus (4.3 and 4.4), suggesting that they are perceived as more stable investments within the sector. Tianqi Lithium and Arcadium Lithium have low EV/EBITDA values (9.93x and 10.28x, respectively), which may indicate that the market perceives them as less dynamic in terms of expansion or that their business models present less uncertainty in the long term.

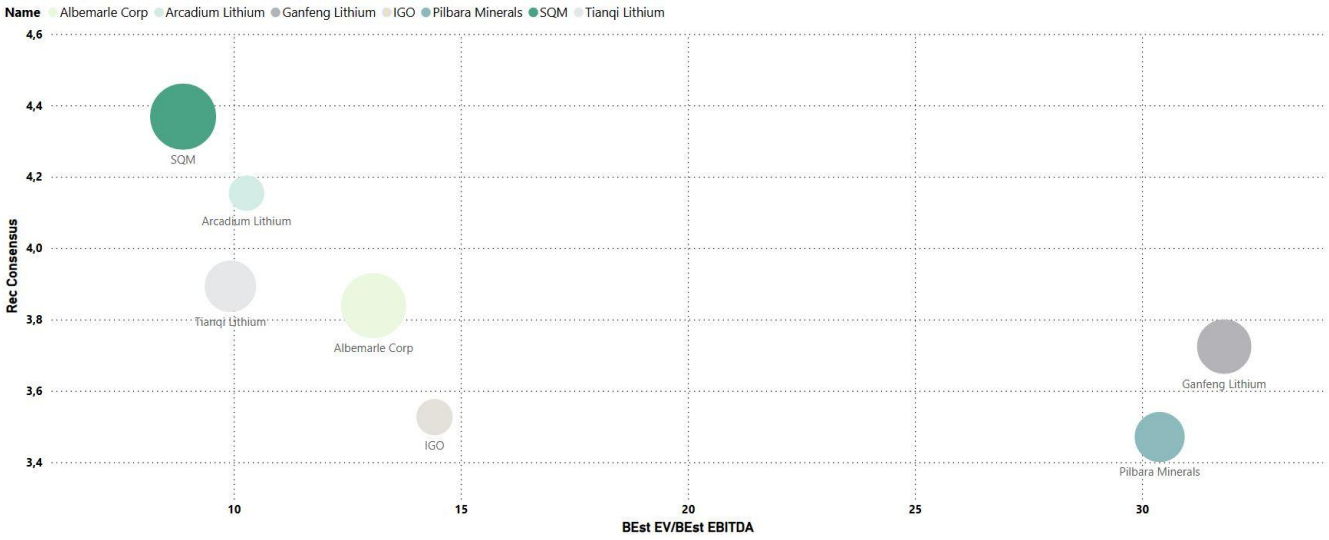



**Figure 17. Rec Consensus vs B est EV/B est EBITDA (Bubble size by Market Cap)**
Source: Prepared by the author based on Bloomberg data, 09/12/2024.

Secondly, Figure 18 shows the relationship between the P/Book ratio and the consensus of analysts' recommendations. In this graph, Pilbara Minerals stands out with a P/Book of 2.42, which implies that investors highly value its assets in relation to their book value. This reflects optimism about its future profitability and the possibility that its assets will generate higher income streams. In contrast, Albemarle and SQM have more moderate values of 1.03, indicating that their valuations are more aligned with their tangible assets, reflecting less speculation. The case of Arcadium Lithium is striking, with an extremely low P/B ratio (0.48), indicating that the market is valuing it below the book value of its assets. This situation may be related to the uncertainty following the merger between Allkem and Livent, suggesting that investors have not yet fully reflected the company's potential value in its share price. Tianqi and Ganfeng also show relatively low P/B ratios (0.92 and 1.09), which may suggest that their assets are being undervalued or that the market anticipates challenges in converting those assets into sustainable income.

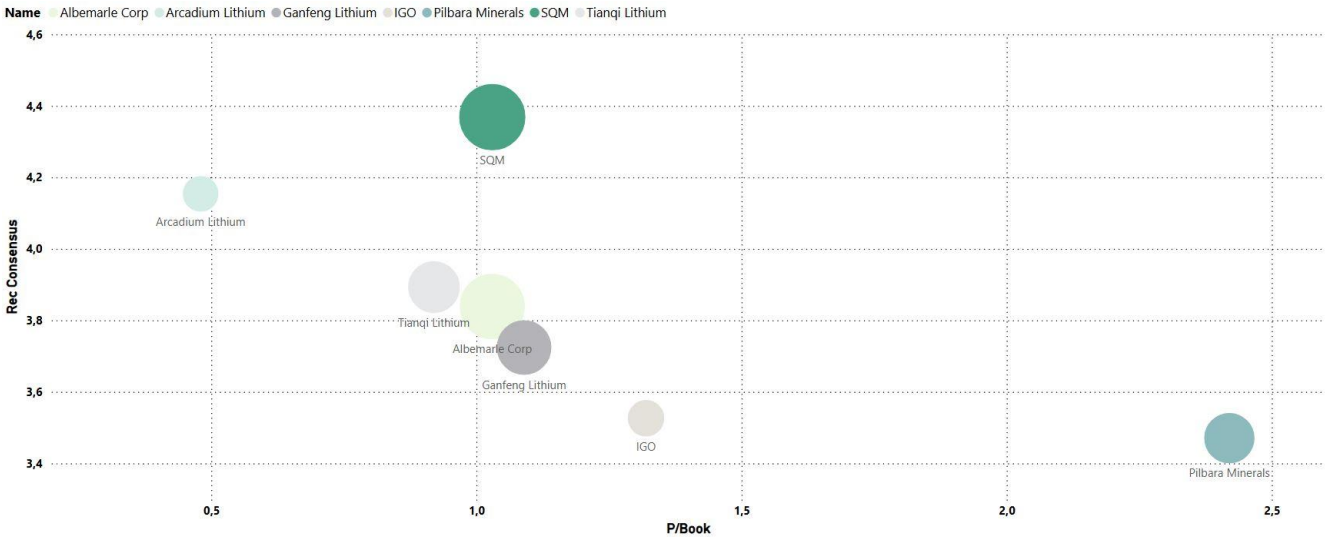



**Figure 18. Consensus vs. P/Book (Bubble size by Market Cap)**
Source: Prepared by the author based on Bloomberg, 09/12/2024.

Finally, Figure 19 shows the relationship between the P/Sales ratio and the consensus of analysts' recommendations, which is fundamental for analyzing the market's perception of a company's ability to generate revenue.

Pilbara Minerals again stands out with the highest value (6.91), indicating that investors are willing to pay a significant premium on its current revenues, reflecting aggressive growth expectations. This high valuation could be supported by its strong operating margin and competitive position in the lithium industry, although it also implies greater risk if projected revenues do not materialize.

IGO also has a high P/Sales ratio (5.04), suggesting that the market has relatively optimistic expectations about its ability to generate revenue. On the other hand, SQM, Tianqi, and Albemarle have lower P/Sales ratios (1.38 to 2.05), suggesting that they are being valued more conservatively based on their current revenues. In the case of Arcadium Lithium (P/Sales of 1.91), the low valuation could be due to uncertainty surrounding the integration of the merger and the consolidated revenue structure.

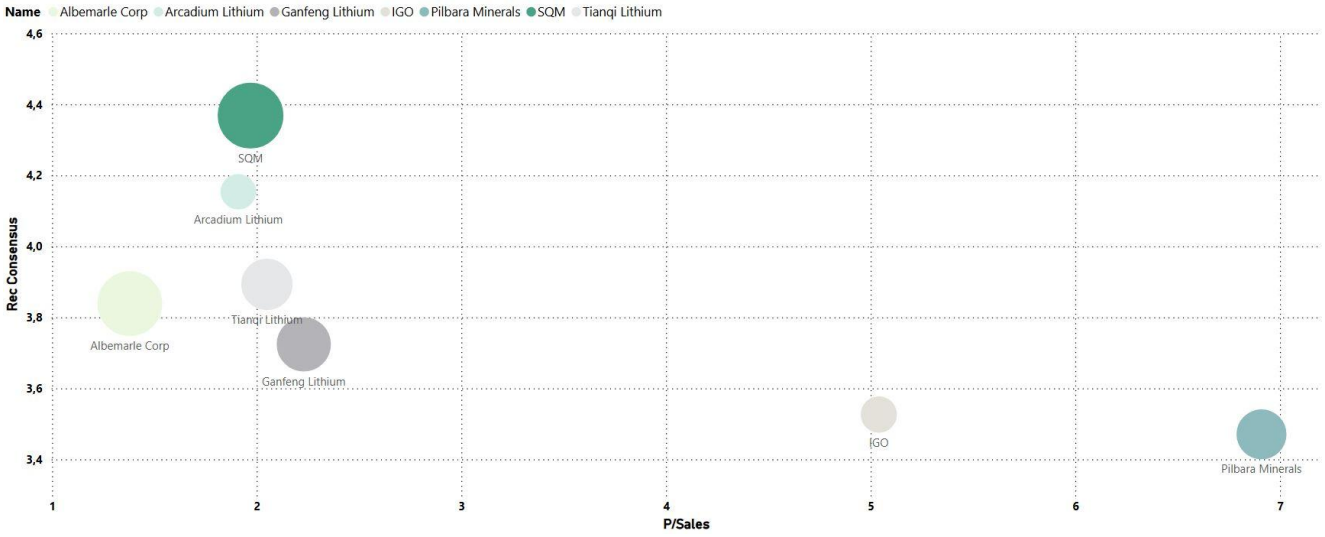



**Figure 19. Rec Consensus vs P/Sales (Bubble size by Market Cap)**
Source: Prepared internally based on Bloomberg data, 09/12/2024.

Based on this assessment, we can see that Pilbara Minerals is the company with the highest growth expectations in the industry, reflected in its high EV/EBITDA and P/S ratios, although its relatively low consensus recommendation suggests that some analysts have doubts about the sustainability of its current valuation. In contrast, Albemarle and SQM are positioned as more balanced options, with reasonable valuations and a favorable consensus among analysts, indicating that they are perceived as safer investments within the sector.

Arcadium Lithium appears to be significantly undervalued in terms of P/Book and P/Sales, which could represent an investment opportunity if it manages to consolidate its business model after the merger. Ganfeng and Tianqi, meanwhile, show more conservative valuation metrics, suggesting that the market has more moderate expectations for their growth.

Finally, IGO faces a mixed outlook, with a lower consensus recommendation and high valuation multiples, which could indicate that some analysts perceive risks in its financial and operational performance.

In summary, the data shows clear segmentation in the lithium industry. Pilbara and Ganfeng are in the category of companies with higher valuations and high expectations. In the case of Pilbara, a

$400 million investment was recently announced to mine lithium in Brazil, specifically in the Belo Lithium operations. Ganfeng has five projects in Argentina (Mariana, Pozuelos-Pastos Grandes, Incahuasi, Caucharí-Olaroz, and Sal de la Puna), which the market appears to assess as having a considerable risk of execution if certain projections that condition the price of the mineral are not met.

Albemarle and SQM represent safer options, with more stable valuations and analyst support, a situation explained by their high market capitalization and presence in the Salar de Atacama, one of the most economical LCE production projects in the world.

Arcadium Lithium is the most interesting case in terms of undervaluation, which could represent an investment opportunity if it manages to improve its post-merger integration. Finally, IGO appears to be in a more uncertain position, with a high valuation but without solid support in terms of analyst recommendations.

The key to determining which company has the best combination of current value and growth potential, considering the balance between risk and return, will be contingent on external factors such as lithium prices, environmental regulations, and advances in new extraction technologies, primarily operations that extract lithium from brine.

## 3.3. Current technology for extracting lithium from brine

The history of lithium extraction from brine began in 1966 after the first industrial method of producing concentrated lithium salts came into effect in Silver Peak, Nevada, USA. This method included a process of extracting brine and storing it in water evaporation ponds in order to precipitate the less soluble salts and concentrate the brine in lithium. This lithium extraction technology was brought to Chile in the 1980s, becoming the conventional method of lithium exploitation mainly due to its high efficiency in terms of operating costs (Azócar, 2023).

The conventional method of extracting lithium from brines for the production of lithium carbonate involves three consecutive steps: extraction of brines by pumping from the Salt Lake or corresponding lagoon, evaporation ponds for water and precipitation of contaminating salts, and finally a purification and carbonation process to obtain a commercial product (Figure 20). The extraction of brine from salt flats and/or lagoons involves the installation of a significant number of pumping stations from which the brine is extracted, thereby reducing the level of brine stored in the salt flat. This brine is transported through pipes to low-lying, large evaporation ponds where the water is evaporated by solar radiation. As the water evaporates, the concentration of ions in the brine increases, and the less soluble salts begin to precipitate, leaving the remaining salts in the brine. Once the brine has reached a high lithium concentration, it is sent to an industrial process where the lithium is precipitated in pure form as carbonate ($Li_2CO_3$).




**Figure 20. General diagram of the conventional method for extracting lithium from brines**
Source: Prepared by the authors.

In the case of the Salar de Atacama, the extracted brine contains a low initial concentration of lithium, close to 0.2% by weight, along with high concentrations of other elements such as sodium, magnesium, boron, and potassium. The evaporation pond system is designed to harness solar

energy and facilitate both the concentration of lithium and the precipitation of unwanted salts, such as sodium chloride (NaCl), potassium chloride (KCl), and magnesium chloride ($MgCl_2$). Figure 21 shows how halite would precipitate in the first pond, reducing the presence of sodium in the brine; in the second pond, sylvinite precipitates, reducing the sodium and potassium content in the brine; in the third pond, potassium carnalite precipitates; in the fourth pond, bischofite; and finally, lithium carnalite.

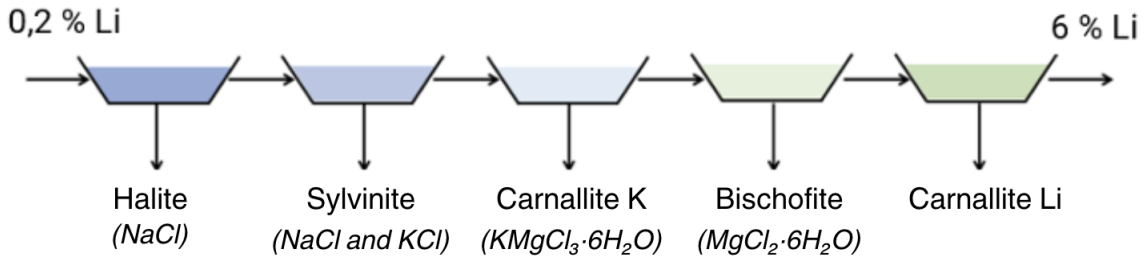



**Figure 21. Schematic diagram of evaporation ponds**
Source: Lee. M, 2020.

Throughout a continuous process lasting between 14 and 18 months, the concentration of lithium in the brine gradually increases from an initial 0.2% to approximately 6%, representing a lithium concentration factor of 30 times (6/0.2), which is achieved through the evaporation of water and the precipitation of other contaminating elements.

The precipitation of other elements in the brine is based on the different solubilities of the salts present, which allows for fractional crystallization. In this process, the less soluble salts precipitate first, separating from the solution, while lithium chloride, being more soluble, remains in solution as the evaporation process progresses. Effective lithium recovery in this part of the process reaches approximately 55% (Lee, 2020), given that part of the lithium is lost due to coprecipitation with other salts, in addition to losses due to impregnation and carryover of lithium in the precipitated solids.

As shown in Figure 22, once the solution has been concentrated in lithium, the concentrated brine undergoes a solvent extraction process at a low pH regulated with hydrochloric acid (HCl) to remove boron. This step is crucial as boron can contaminate subsequent lithium precipitation processes. The boron-free brine is then treated with calcium hydroxide ($Ca(OH)_2$) and sodium carbonate ($Na_2CO_3$). This precipitates the remaining magnesium and calcium in the form of magnesium hydroxide ($Mg(OH)_2$), magnesium carbonate ($MgCO_3$), and calcium carbonate ($CaCO_3$), which are removed from the process as waste solids. The resulting solution, which mainly contains lithium chloride with traces of impurities, undergoes further purification using ion exchange columns to remove $Ca^{+2}$ and $Mg^{+2}$ from the solution, leaving only traces of them in the solution. The final lithium chloride solution has a minimum impurity content and is ready to precipitate lithium carbonate without impurities.

The purified brine is finally treated with sodium carbonate ($Na_2CO_3$) and heated to 80 °C to precipitate lithium carbonate ($Li_2CO_3$), which is separated from the lithium-depleted solution, rich in chloride and sodium carbonate, known as the mother liquor. This purification process, which takes place in the chemical plant using concentrated brine from the ponds, has an efficiency of around 90%, meaning that most of the lithium present in the brine is recovered in the form of lithium carbonate.

Subsequently, the precipitated lithium carbonate is filtered to separate it from the remaining liquid, washing it if necessary to remove impurities such as residual sodium and potassium salts. This washing process must ensure that the lithium carbonate has the necessary purity to qualify as battery-grade lithium carbonate, or for other industrial and technological applications. Finally, the purified lithium carbonate is dried and prepared for commercialization.

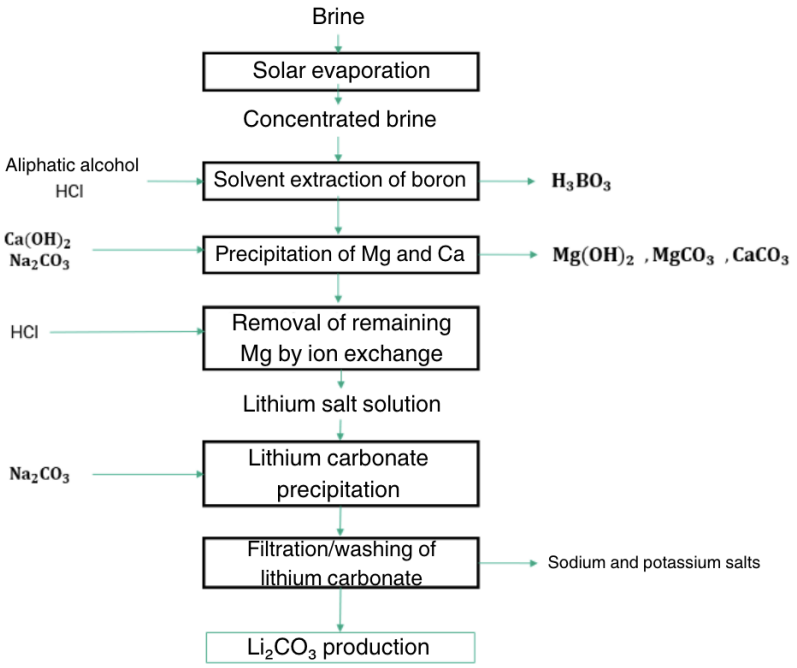



**Figure 22. Diagram of the lithium extraction process from brines**
Source: Prepared by the authors based on Pankaj et al., 2016

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# 4. INDUSTRY COST STRUCTURE

The cost structure of lithium producers is a key aspect that varies depending on the type of operation, the final product, the raw material, and the geographical location of the projects. Currently, there are two main sources of lithium with dominant extraction methods in each case: the conversion of rock minerals, such as spodumene, with Australia as the main producer, and solar evaporation of brines, traditionally used in salt flats such as those in Chile and Argentina, with the main objective of producing lithium carbonate.

Lithium production costs differ significantly between these two main extraction methods, which are aimed at obtaining the two main products demanded by the market: lithium carbonate and lithium hydroxide. Brine extraction focuses predominantly on the production of lithium carbonate, while rock mineral conversion is geared towards the production of lithium hydroxide.

In general, brine-based operations have lower operating costs than mineral conversion plants if the end product is lithium carbonate, because the solar evaporation process requires less energy and reagents (Cochilco, 2023). However, there are variations in costs between different producers, influenced by factors such as the quality of the brines and the specific conditions of each salt flat.

An illustrative case is the lithium extraction project in the Atacama Desert, operated by SQM, which ranks as the lowest operating cost on the lithium carbonate cost curve.
This is due to the favorable conditions of the Atacama salt flat, which include a high lithium content and a low content of impurities such as magnesium and sulfate, significantly reducing the need for costly inputs and services during the extraction and purification process. Figure 23 shows the cost curve for lithium brine projects in Latin America for the year 2028, expressed in terms of USD/t of LCE FOB, before applying royalties.

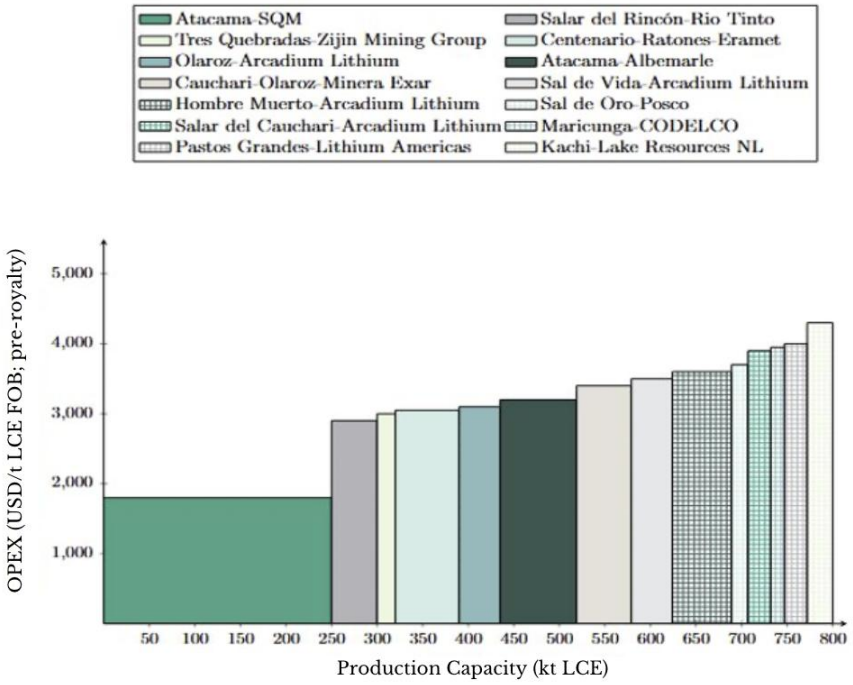



**Figure 23. Cost curve for lithium brine projects in Latin America for 2028.**
Source: Prepared by the authors based on Wood Mackenzie, Data compiled by Goldman Sachs Global Investment Research, 2023.

Based on this curve, a model was developed that takes as a reference the lowest operating cost, corresponding to the brine project in Atacama (SQM). This model allows the operating cost of new lithium extraction projects from brine to be estimated using three key variables: the concentration of lithium in the brine, the content of impurities (magnesium and sulfate), and the projected level of lithium carbonate production.

$$Base\ Cost = Lowest\ cost\ brine\ project \quad (1)$$

$$Ratio_{Lithium} = \frac{Lithium\ concentration\ of\ the\ lowest\ cost\ project}{Lithium\ concentration\ of\ project\ i}\ \forall i \in Brine\ projects\ without\ DLE \quad (2)$$

$$Ratio_{Magnesium} = \frac{Magnesium\ concentration\ of\ project\ i}{Magnesium\ concentration\ of\ the\ lowest\ cost\ project}\ \forall i \in Brine\ projects\ without\ DLE \quad (3)$$

$$Ratio_{Sulfate} = \frac{Sulfate\ concentration\ of\ project\ i}{Sulfate\ concentration\ of\ the\ lowest\ cost\ project}\ \forall i \in Brine\ projects\ without\ DLE \quad (4)$$

$$Ratio_{Calcium} = \frac{Calcium\ concentration\ of\ ptoject\ i}{Calcium\ concentration\ of\ the\ lowest\ cost\ project}\ \forall i \in Brine\ projects\ without\ DLE \quad (5)$$

$$Ratio_{Capacity} = \frac{Production\ capacity\ of\ the\ new\ project}{Production\ capacity\ of\ the\ lowest\ cost\ project} \quad (6)$$

$$Project\ Cost_{Brine} = Base\ Cost \cdot Ratio_{Lithium}{}^{\alpha} \cdot Ratio_{Magensium}{}^{\beta} \cdot Ratio_{Sulfate}{}^{\gamma} \cdot Ratio_{Calcium}{}^{\varepsilon} \cdot Ratio_{Capacity}{}^{\theta} \quad (7)$$

The model is built on the premise that a project with a lower lithium concentration or higher impurity content than the reference project (Atacama-SQM) will incur higher input costs to obtain the final lithium carbonate product. Likewise, it is expected that a project with lower production capacity will not be able to benefit from economies of scale, which increases its unit input cost.

**Table 11. Comparison of the chemical composition of lithium brine projects in Latin America for 2028.**
Source: Prepared by the authors based on the respective technical feasibility or pre-feasibility reports for each project.

| Projects | Li concentration Mg/L | Mg/Li ratio | $SO_4$/Li ratio | Ca/Li ratio | Country |
|---|---|---|---|---|---|
| Atacama (SQM) | 2,205 | 6.15 | 10.13 | 0.21 | Chile |
| Tres Quebradas | 637 | 2.27 | 0.35 | 34.91 | Argentina |
| Olaroz | 641 | 2.29 | 23.02 | 0.62 | Argentina |
| Atacama (ALB) | 1,959 | 6.15 | 10.13 | 0.21 | Chile |
| Cauchari-Olaroz | 585 | 2.40 | 28.50 | 0.65 | Argentina |
| Sal de Vida | 747 | 2.81 | 7.82 | 1.32 | Argentina |
| Caucharí Salt Flat | 476 | 2.60 | 36.97 | 0.65 | Argentina |
| Maricunga | 953 | 6.53 | 0.63 | 11.47 | Chile |
| Pastos Grandes | 427 | 6.20 | 19.30 | 2.10 | Argentina |

To determine the optimal parameters (Alpha, Beta, and Gamma) of the proposed model, the Nelder-Mead optimization method was used, whose objective is to minimize the mean square error between the observed operating costs and those estimated by the model. The results obtained indicate that the optimal parameters are as follows:

- $\alpha$= 4.21315598016993
- $\beta$ = 0.732189384554769
- $\gamma$ = -2.0086999666414
- $\varepsilon$ = -2.09458745466221
- $\theta$ = 0.00344228396638044

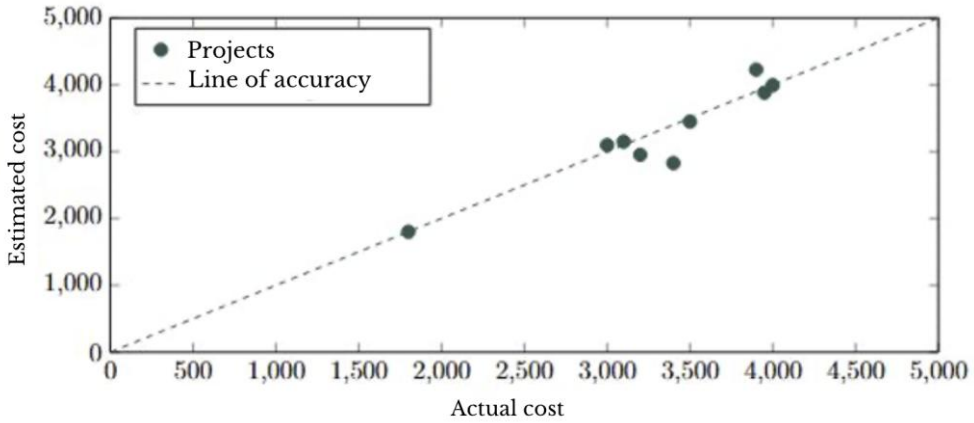



**Figure 24. Comparison of actual costs vs. model estimates (USD/t LCE FOB; pre-royalty)**
Source: Own elaboration

With these values, the proposed model is an effective tool for positioning new lithium brine projects on the cost curve, considering variations in lithium concentration, impurity content, and production capacity. This analysis is crucial for strategic decision-making in the planning and development of new lithium projects in the lithium triangle region.

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# 5. INDUSTRY BEHAVIOR

## 5.1. Supply and demand

Climate change has been recognized as a global challenge since the adoption of the United Nations Framework Convention on Climate Change in 1994, which acknowledged the need to reduce greenhouse gas emissions in order to mitigate their effects through the application of new technologies that are economically and socially beneficial. This recognition has prompted the adoption of significant measures at the international level, such as the Kyoto Protocol (1997) and the Paris Agreement (2015), which seek to reduce emissions and promote the use of clean technologies. These agreements have created a favorable environment for the transition to renewable energy sources and electromobility. Since then, the demand for lithium for battery manufacturing has grown steadily.

In this context, the market, which was characterized by an oversupply of lithium in 2010 with an average price of USD 5,000/ton $Li_2CO_3$, began a process known as the "lithium boom." This milestone in the market encouraged the expansion of global supply, leading to a more than proportional increase in global production of the mineral (Argentine Ministry of Economy, 2023).

In the following years, the price of battery-grade lithium carbonate rose sharply, reaching a peak of $16,000/ton $Li_2CO_3$ in 2018. This was due, on the one hand, to the growing demand for electronic devices and their increasing complexity, which translated into a greater need for longer-lasting batteries; and on the other hand, to the surge in interest in hybrid and electric cars, which require a large supply of lithium-containing batteries. As a result, demand for lithium for batteries, which accounted for approximately 30% of total demand, increased to represent 50% of global demand for the mineral.

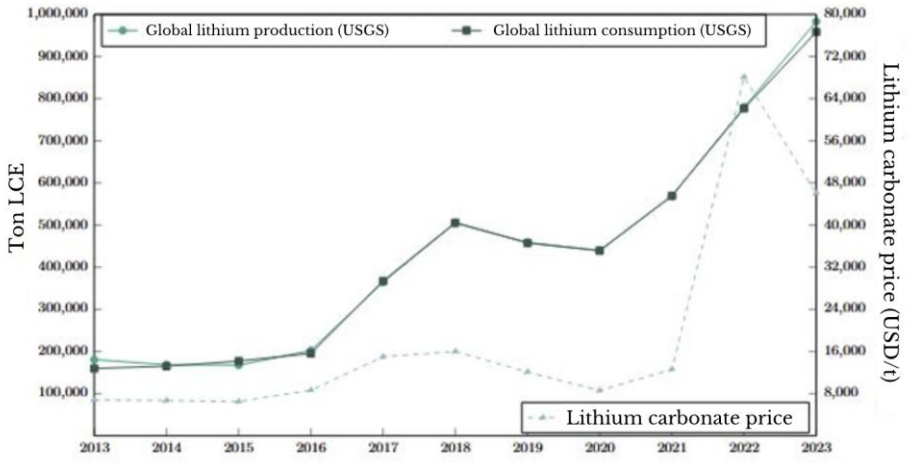



**Figure 25. Global lithium production and consumption curves, and the evolution of the average price of lithium carbonate between 2013 and 2023**
Source: Prepared by the authors based on U.S. Geological Survey, 2024; Statista, 2024.

This demand has been a key catalyst for the increase in global lithium production, as more countries have committed to electromobility and carbon emission reduction. As expected, the "lithium boom" encouraged the launch of several major projects, especially in Australia, where some were reactivated, and expansion plans were implemented, leading to large production volumes.

The impact of the COVID-19 pandemic temporarily slowed demand and prices for lithium due to global economic uncertainty and reduced production and sales of electronic devices and electric vehicles. The slowdown in the supply chains of industrial and consumer goods on which lithium demand relies, such as electric vehicles and electronic goods, coupled with the global economic downturn, naturally led to lower expectations for growth in lithium demand. However, the market rebounded in 2021, with demand for batteries accounting for 60% of global lithium consumption (Argentine Ministry of Economy, 2021).

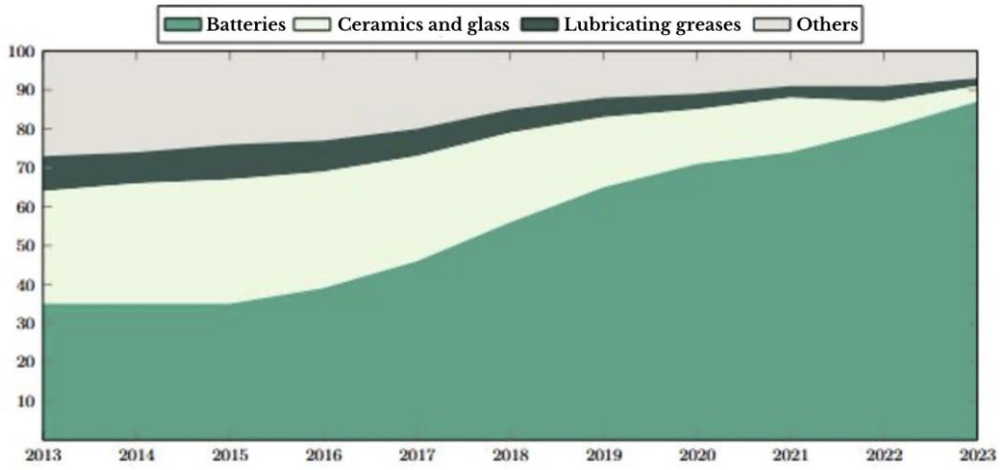



**Figure 26. Proportion of lithium consumption by use [%] (2013-2023)**
Source: Prepared by the authors based on U.S. Geological Survey, 2024.

The global lithium market was valued at USD 4.6 billion in 2021 and is expected to grow at a compound annual growth rate (CAGR) of 13.5% during the period 2023-2028 (Reportlinker, 2022). It should be noted that this recent rapid growth is based on a palpable increase in demand in the face of a projected supply shortage, especially towards the end of the decade. This resurgence drove up the price of lithium carbonate, reaching an all-time high of nearly $68,000/ton $Li_2CO_3$ in 2022.

In 2023, the market began to show signs of stabilization, with an average price of $46,000/ton of $Li_2CO_3$, due to expectations of new projects and expansions in production in countries such as Australia and Chile (Ministry of Economy of Argentina, 2023). On the other hand, the impact of the elimination of subsidies in China in January 2023 has put downward pressure on EV demand in that region, thereby accelerating the decline in international prices for lithium compounds. This adjustment reflects the dynamics of supply and demand in a market that remains highly sensitive to changes in demand for electric vehicles and other lithium-dependent technologies.

Currently, between 65-67% of lithium demand is associated with the manufacture of electric vehicles (EVs), a market that has experienced significant growth in recent years. The latest data from the International Energy Agency (IEA) indicates significant growth in electric vehicle sales, from 6.6 million units in 2021 to 10.2 million in 2022, representing an increase of 55%. By 2023, sales reached 13.8 million units, an additional increase of 35%. This continued growth, averaging

3.6 million additional EVs per year, underscores the rapid penetration of EVs in the automotive market (International Energy Agency, 2024).

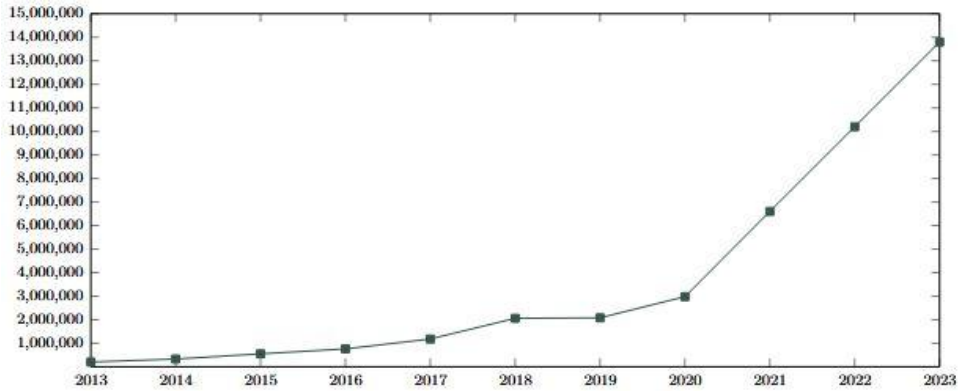



**Figure 27. Number of new electric vehicles sold worldwide, 2010 to 2023 (electric vehicles include fully electric and plug-in hybrids)**
Source: Prepared by the authors based on the International Energy Agency, 2024.

China has emerged as the undisputed leader in the adoption of electric vehicles, accounting for 60% of global sales in 2022. In this country, EV sales increased by 100% compared to the previous year. In contrast, growth in North America was 55%, while in Europe, a traditionally strong market, growth was more modest, reaching only 18% (Argentine Ministry of Economy, 2023). This disparity in EV market penetration between regions is due to a combination of factors, including varying levels of political support, business activity, consumer preferences and awareness, driving patterns, and cultural specificities (International Energy Agency, 2023).

In major EV markets such as China, Europe, and the United States, the initial adoption of these vehicles was driven by government policies designed to encourage demand. These policies include direct economic incentives for buyers, such as subsidies and discounts on EV purchases, zero-emission mandates, and tax regulations that penalize internal combustion engine (ICE) vehicles. China, in particular, also implemented direct incentives for automakers, which catalyzed its leadership in EV production and adoption.

In addition to consumer incentives, governments in these key markets have increased their EV adoption targets and have begun to address other parts of the supply chain, such as vehicle and battery manufacturing, and support for the extraction and processing of critical minerals such as lithium. In 2022, combined global government and consumer spending on electric vehicles exceeded $400 billion, reflecting the magnitude of the commitment to the energy transition (International Energy Agency, 2023).

Electrification mandates and bans on internal combustion engines, with target dates ranging from 2025 to 2050, are central to the transition to sustainable mobility. These mandates, ranging from 100% electrified sales to a total ban on internal combustion engine vehicles, are aligned with global commitments to reduce greenhouse gas emissions.

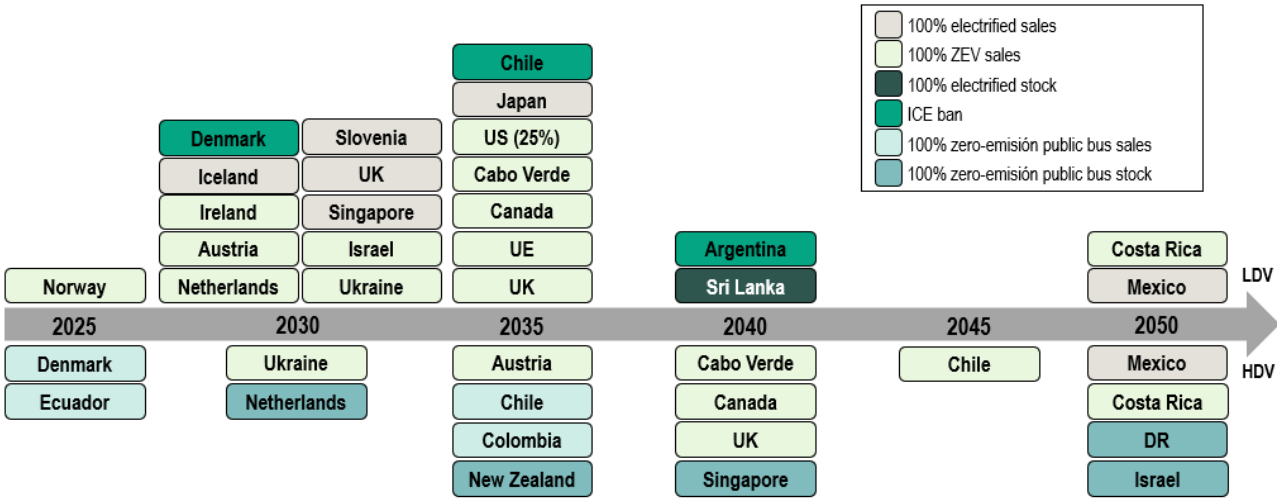



**Figure 28. Global mandates on zero-emission vehicles and bans on internal combustion engines**
Source: Prepared by the authors based on the International Energy Agency, 2024.

The growing demand for EVs has had a direct impact on the lithium industry, as the lithium requirement for electric vehicles is such that it is estimated that for every million EVs, around 40-50 thousand tons of LCE are consumed (Argentine Ministry of Economy, 2023). Projections suggest that by 2030, between 77% and 80% of global lithium demand will be for the manufacture of batteries for electric vehicles, a significant increase from the current 65-67%. This increase is closely linked to the global expansion of electrification policies, and lithium demand projections are highly sensitive to compliance with the deadlines set out in international climate and energy agreements (International Energy Agency, 2023).

## 5.2. Market restructuring

The lithium market has undergone profound changes since 2013, driven by the boom in demand for LIBs for electronic devices and, more recently, for EV production. Below is a detailed analysis of the expansion and launch of lithium production projects in Australia, Argentina, and Chile, highlighting the key factors that have influenced the development of the industry in each period.

### 5.2.1. Turning point in the Lithium Market: 2013-2015

In 2014, the lithium market began to show signs of expansion, driven mainly by accelerated growth in demand for LIBs, used in portable electronic devices such as smartphones, laptops, and digital cameras. However, the EV boom was still in its early stages, with limited impact on global lithium demand.

Global demand for lithium in 2013 was mainly focused on industrial consumption and the production of batteries for consumer electronics. The main competitors in the lithium market were SQM in Chile, Albemarle, and FMC (now Arcadium Lithium) in the US. The price of lithium carbonate was around $6,000-7,000 per ton, considerably lower than the prices that would be seen in the following years.

In terms of production projects, the Salar de Atacama in Chile remained one of the world's main sources of lithium, with SQM and Albemarle as key operators.

Installed capacity in Chile was approximately 60,000 tons per year of lithium carbonate equivalent (LCE). In Australia, production was led by Talison at its Greenbushes project, with an installed capacity of around 70,000 tons per year of LCE.

### 5.2.2. The rise of electric vehicles: 2016-2017

The lithium market underwent a significant change between 2016 and 2017, with the increase in EV adoption. This period marked the beginning of a sustained increase in demand for lithium, driven by global emission reduction targets and the transition to more sustainable mobility.

Australia began to add and expand projects that were key to meeting growing demand. In 2017, the Mount Marion and Wodgina projects, funded by Mineral Resources (Australia)-Ganfeng Lithium (China) and Mineral Resources (Australia)-Albemarle (USA) respectively, were inaugurated. In addition, Talison began the expansion of Greenbushes, positioning Australia with an installed capacity of approximately 220,000 tons per year of LCE.

In Chile, both SQM and Albemarle began expansion projects in the Salar de Atacama. SQM, for example, increased its capacity to 70,000 tons per year of LCE, strengthening the country's position in the global lithium market, while Albemarle announced an increase in capacity to 80,000 tons per year of LCE starting in 2019.

Argentina, for its part, began to gain ground on the global lithium scene with the inauguration of the Sales de Jujuy project in 2016, with a capacity of 17,500 tons per year of LCE. Operated by Orocobre (now Arcadium Lithium), this project marked the beginning of the systematic exploitation of the country's salt flats.

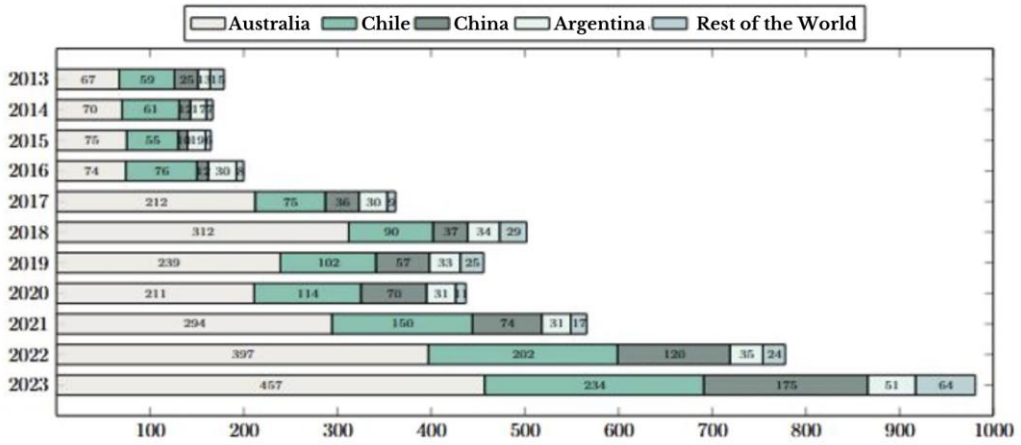



**Figure 29. Evolution of KTon LCE Production between 2013-2023**
Source: Prepared internally based on U.S. Geological Survey, 2024.

### 5.2.3. Acceleration of global projects: 2018-2019

With demand for lithium constantly growing, mainly due to the production of batteries for electric vehicles, key countries began to accelerate the development of new projects and the expansion of existing ones.

In Australia, production capacity expanded significantly. Wodgina rapidly increased its production capacity to 100,000 tons per year in 2018. Likewise, Pilgangoora and Bald Hill, financed by Pilbara

Minerals (Australia) and Mineral Resources (Australia) respectively, began operations in 2018, consolidating Australia as the world's largest lithium producer.

Argentina, for its part, saw the acceleration of projects such as Cauchari-Olaroz, developed by Lithium Americas (Canada) and Ganfeng (China), which in 2018 began construction of its plant with a capacity of 40,000 tons per year of LCE. This project was crucial in positioning Argentina as an emerging player in the lithium industry.

Chile was facing growing regulatory and environmental challenges that prompted CORFO to renegotiate contracts with private companies operating in the Salar de Atacama (SQM, Albemarle), with the aim of increasing royalty collection based on the price of lithium. Meanwhile, Albemarle reached an installed capacity of 80,000 tons per year, and the first CEOL was granted for a new project to be developed by CODELCO in the Salar de Maricunga.

During this period, the price of LCE reached record highs, averaging USD 16,000 per ton in 2018, due to strong demand from the electric vehicle market. However, at the end of 2019, the price began to moderate slightly, settling at around US$12,000-14,000 per ton due to an adjustment between supply and demand.

### 5.2.4. Consolidation and new challenges: 2020-2024

During this period, the lithium market consolidated its position as one of the strategic sectors for the global energy transition, with demand skyrocketing due to the exponential growth in electric vehicle production.

Australia continued to lead the expansion of lithium production. In 2020, Bald Hill reached a capacity of 155,000 tons per year of LCE, while Greenbushes completed another phase of expansion, increasing its capacity to 160,000 tons per year of LCE. In addition, Finniss, financed by Core Lithium (Australia), began operations. This exceptional progress in projects led to Australia accounting for nearly 46% of the lithium supply in 2023.

In Argentina, Cauchari-Olaroz began operations and recently the Centenario-Ratones project in 2024, with a capacity of 24,000 tons per year of LCE, marking a new milestone in the country's production capacity thanks to DLE technologies.

In Chile, expansion continued, but at a more moderate pace due to growing social pressure and regulatory challenges. By 2023, SQM and Albemarle had reached capacities of 140,000 and 85,000 tons per year of LCE, respectively, but international competition and legal restrictions prevented further expansion. Since 2020, the price of LCE has experienced significant volatility.

It should be noted that, starting in 2021, some projects in Argentina and Chile began to integrate DLE technologies in pilot phases. This technology, which is more efficient and has a lower environmental impact, became a viable option for increasing lithium production in brines in deposits with high impurity content.

The industry has grown exponentially over the last decade, from 20 operations to 80 today. The evolution of the price of LCE during these years reflects market dynamics, with periods of rapid growth and adjustments, highlighting the importance of sound policies and a favorable regulatory environment to capitalize on the growing demand for lithium.

The lithium market experienced a significant boom in 2022, when lithium carbonate prices averaged $68,000 per ton of LCE. This milestone sparked interest from new players in the industry and led

to a series of restructurings that materialized in 2024. In January of that year, the Australian company Allkem and the US company Livent merged to form Arcadium Lithium. Recently, in October 2024, Rio Tinto acquired Arcadium Lithium in a transaction valued at $67 billion, positioning the transnational company strongly in the growing lithium industry.

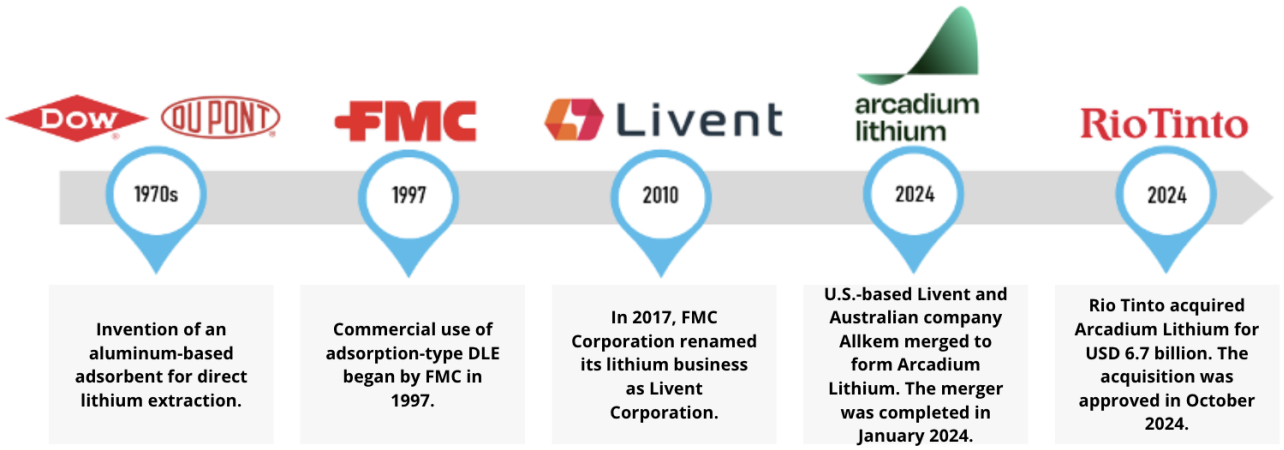



**Figure 30. Origin and evolution of direct lithium extraction technologies**
Source: Own elaboration.

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# 6. FUTURE PROJECTIONS

## 6.1. Supply and demand

The lithium industry has undergone an unprecedented transformation over the last decade, positioning itself as a key strategic resource for the transition to a low-carbon economy. The rise of energy storage systems, particularly lithium-ion batteries, has redefined the global market structure. As discussed in previous sections, the battery industry, especially for electric vehicles, currently represents the main source of demand for lithium, accounting for approximately 60% of global consumption proportionally (Argentine Ministry of Economy, 2023).

The widespread adoption of EVs, the development of stationary storage solutions, and the expansion of the portable electronic device market have driven a trend of sustained growth. According to estimates by various industry analysts, demand for lithium for batteries is projected to grow at a compound annual growth rate (CAGR) of between 20% and 30% during this decade. This implies an estimated global demand of between 2.1 and 2.5 million tons of lithium carbonate equivalent by 2030, more than double the approximately 1.0 million tons demanded in 2023 (Cochilco, 2023).

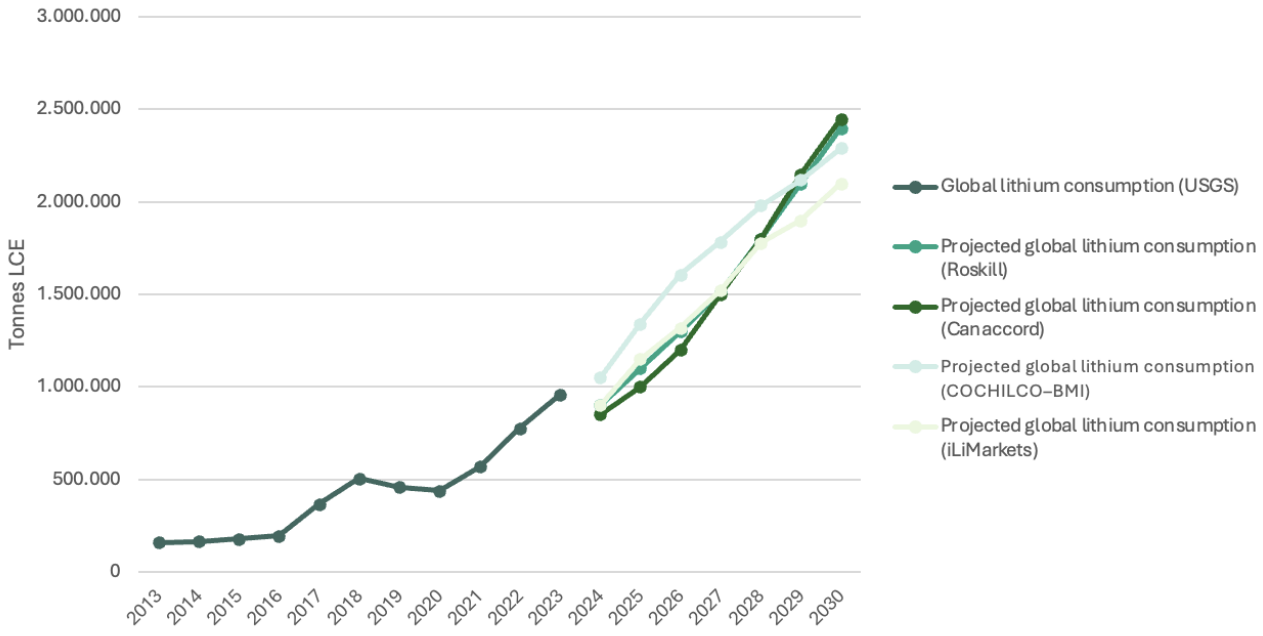



**Figure 31. Global lithium consumption curve between 2013 and 2030**
Source: Prepared by the authors based on USGS, 2024; Cochilco, 2023; Jiménez & Sáez, 2022; Roskill, 2021; Canacord, 2021.

In terms of supply, although there is consensus regarding sustained growth toward 2030, estimates show a high degree of dispersion among sources. A key element in this expansion is the dynamism of Argentina, which has gained greater prominence thanks to the approval of new projects, including the use of direct lithium extraction technologies, and a more favorable investment environment. Even so, Australia would remain the world's leading producer, largely due to its robust infrastructure and established market for lithium extraction from rock ore.

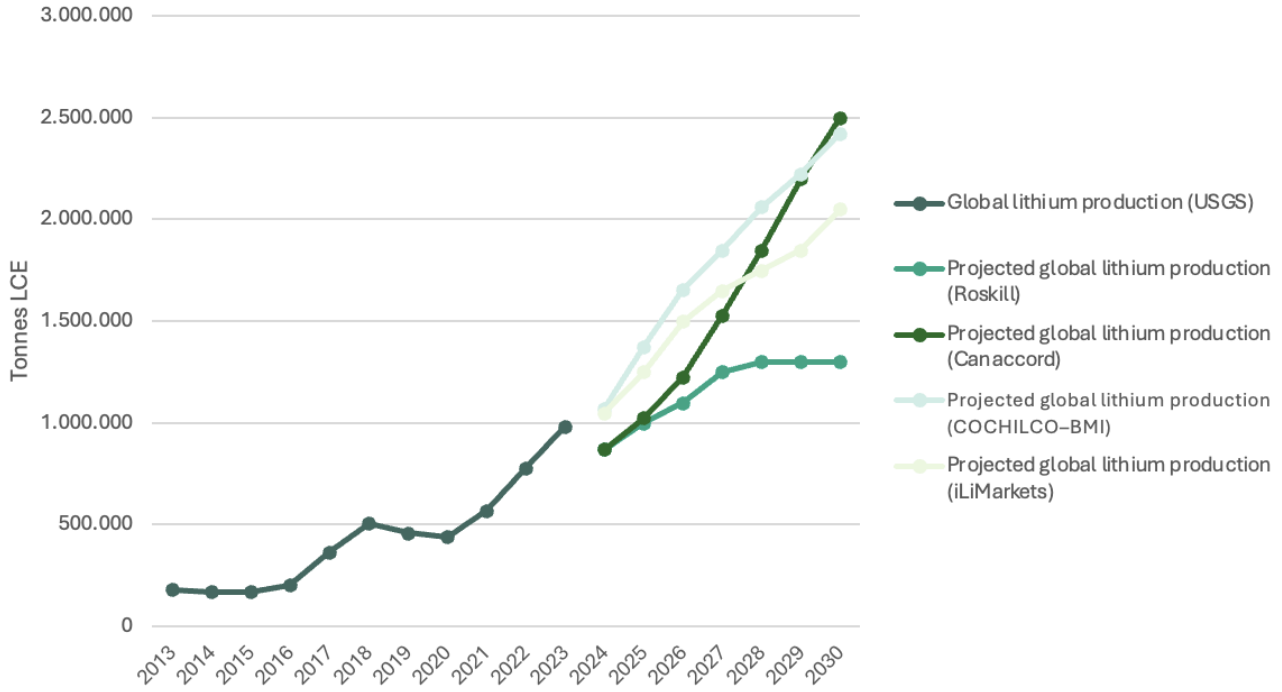



**Figure 32. Global lithium production curve between 2013 and 2030**
Source: Prepared by the authors based on USGS, 2024; Cochilco, 2023; Jiménez & Sáez, 2022; Roskill, 2021; Canacord, 2021.

A direct comparison between supply and demand projections reveals significant divergences. For example, Roskill (2021) anticipated a severe structural deficit of around 1.0 million tons LCE by 2030. In contrast, Cochilco (2023) projects a slight surplus of approximately 130,000 tons in the same year. For its part, iLiMarkets proposes an intermediate scenario, with a projected deficit of 50,000 tonnes LCE in 2030, where market equilibrium critically depends on the successful implementation of new projects and the degree of adoption of DLE technologies.

The long-term projections made by Cochilco (2023) anticipate a turning point around 2031, when a scenario of growing structural deficit would begin to take shape. By 2035, the gap between supply and demand could reach 975,000 tons LCE. This gap will depend critically on both the materialization of projects currently in the pipeline and the pace of adoption of electric vehicles and other storage systems.

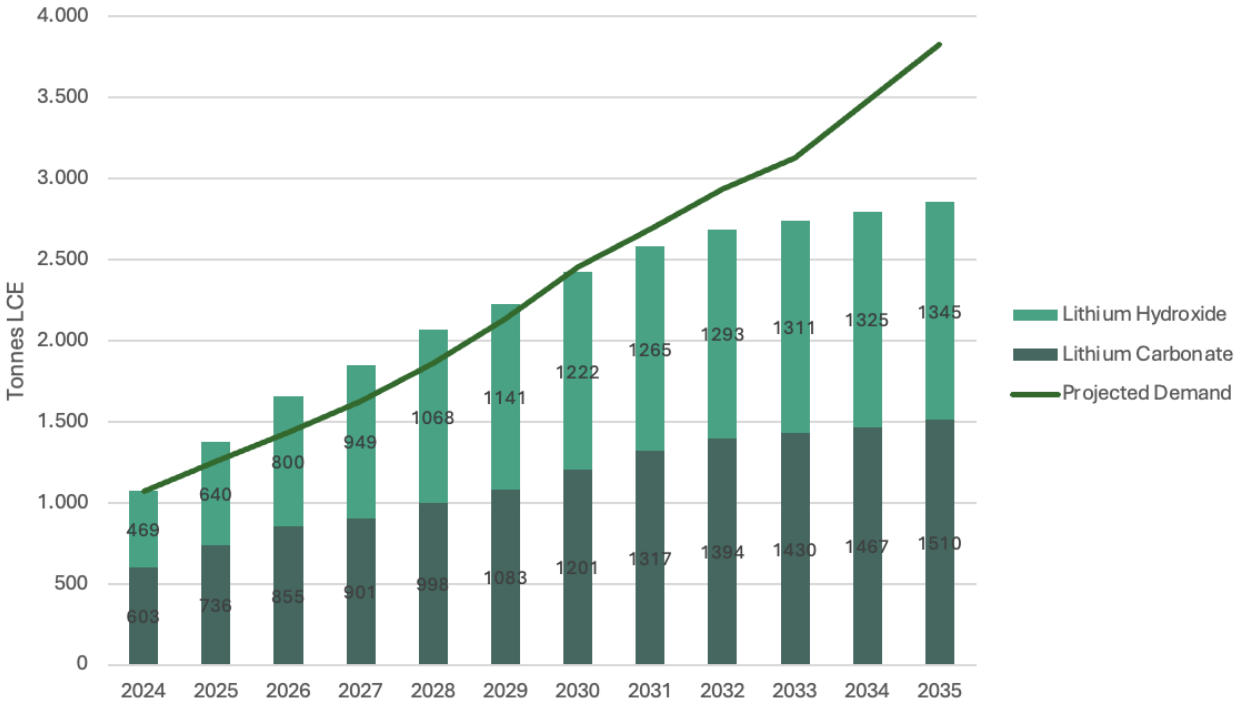



**Figure 33. Projected supply by lithium compound and aggregate demand (kt LCE), 2024-2035**
Source: Prepared by the authors based on Cochilco, 2023.

Given that the lithium industry is still in a consolidation phase, projections are subject to a considerable degree of uncertainty. In this regard, the main risks to consider include:

- **Demand**: The adoption of EVs is subject to public policies (subsidies, emissions regulations), charging infrastructure development, and lithium price trends.
- **Supply**: Obstacles such as delays in environmental permits, social opposition, technical challenges, and financial risks can delay or cancel projects.
- **Technology**: While DLE promises to accelerate production and reduce environmental impact, its implementation on an industrial scale is still limited.

Separating the product categories, it can be seen that both lithium carbonate and lithium hydroxide will face growing deficits in the next decade. However, the projected deficit for hydroxide is significantly higher. This compound, used especially in high-energy battery cells such as NMC (nickel-manganese-cobalt), has key technical advantages: it decomposes at lower temperatures, extending the life and range of batteries (Bisley, 2021).

Despite its benefits, hydroxide is more expensive to produce, and many operations require converting carbonate into hydroxide, adding pressure on supply. According to Cochilco (2023), it is estimated that by 2035, the hydroxide deficit will reach 726,000 tons, which is higher than the entire lithium production in 2021. The carbonate deficit, on the other hand, would be around 234,000 tons, for a combined deficit of close to 960,000 tons LCE.

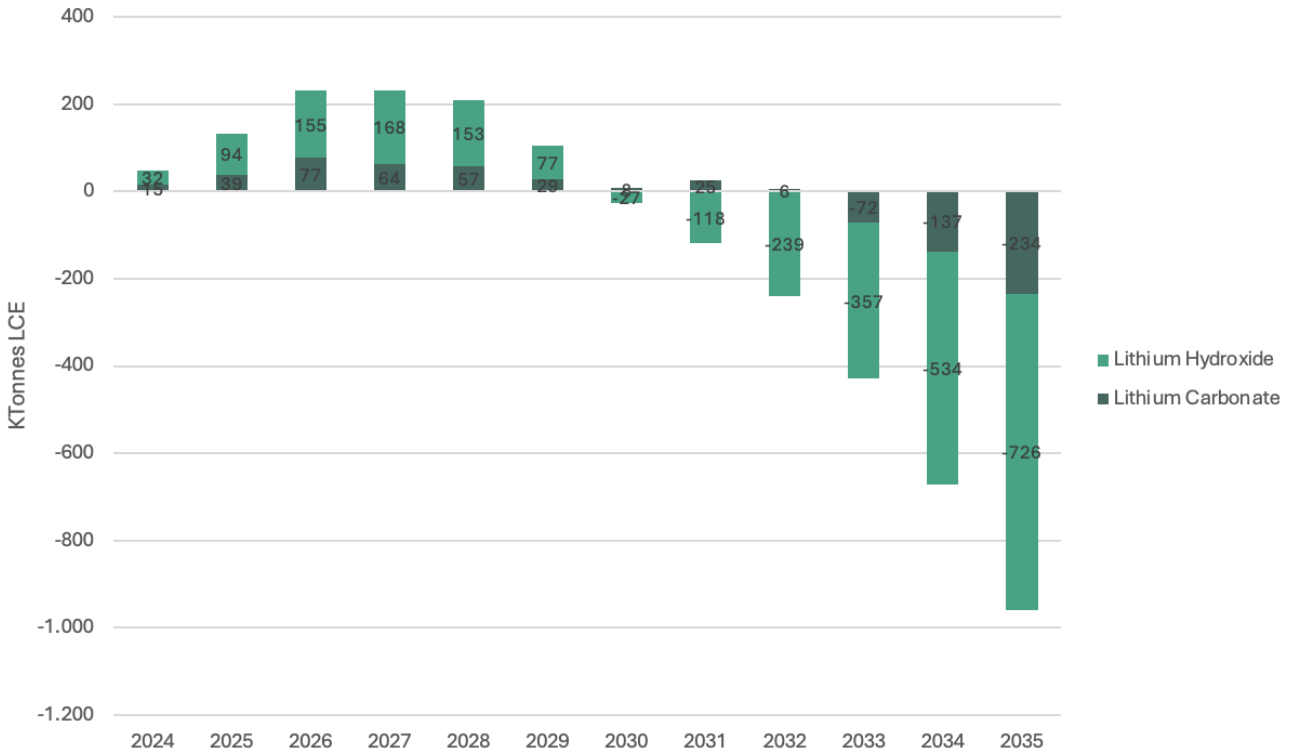



**Figure 34. Projected balance of lithium carbonate and hydroxide (kt LCE), 2024-2035**
Source: Prepared by the authors based on Cochilco, 2023.

This scenario suggests that it will be necessary to increase production from both brine and rock ore, as well as to promote the conversion of carbonate to hydroxide, which could put upward pressure on the prices of both products. This pressure, in turn, could accelerate investment decisions in projects and expansions.

## 6.2. Direct lithium extraction (DLE) technologies

DLE technologies are a set of solutions that seek to enable the extraction of lithium from brines without the need to evaporate the water, while allowing the re-injection of brine devoid of lithium back into the salt flat, thus minimizing the impact on surrounding ecosystems.
DLE technologies include technologies based on adsorption, ion exchange, solvent extraction, membranes, electro-membranes, and electrodialysis methods, among others, which offer an alternative to the conventional method by allowing selective lithium extraction without the need for evaporation, but still requiring pumping and purification processes, as shown in Figure 35.

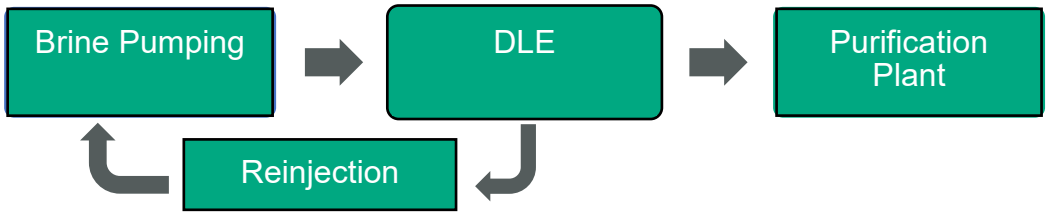



**Figure 35. General diagram of the DLE method for brine treatment**
Source: Own elaboration.

The first alternative technologies to the conventional method of evaporating lithium brines date back to the 1970s. In that year, Dow Chemical developed aluminum-based adsorbent technology that would later enable lithium to be extracted from brines, laying the foundations for the development of other techniques. This technology was transferred to FMC, which in 1997 implemented the first commercial use of adsorption technology in the Fénix project in the Salar del Hombre Muerto in Argentina. Years later, in 2017, FMC reorganized its lithium business under the name Livent Corporation.

The operation in the Salar del Hombre Muerto in Argentina represented the first successful integration of DLE technology on a commercial scale, bringing the innovation ecosystem in DLE technologies to the forefront and transforming it into a dynamic and highly diverse ecosystem. In the last five years, more than 40 startups (Figure 36) have developed new solutions based on different technologies, which are at varying stages of development. Most of these companies have a presence or express interest in positioning themselves in Chile, Argentina, or Bolivia, operating pilot plants or in advanced stages of construction, underscoring the rapid growth of the sector in the region. (Bunel, 2024).

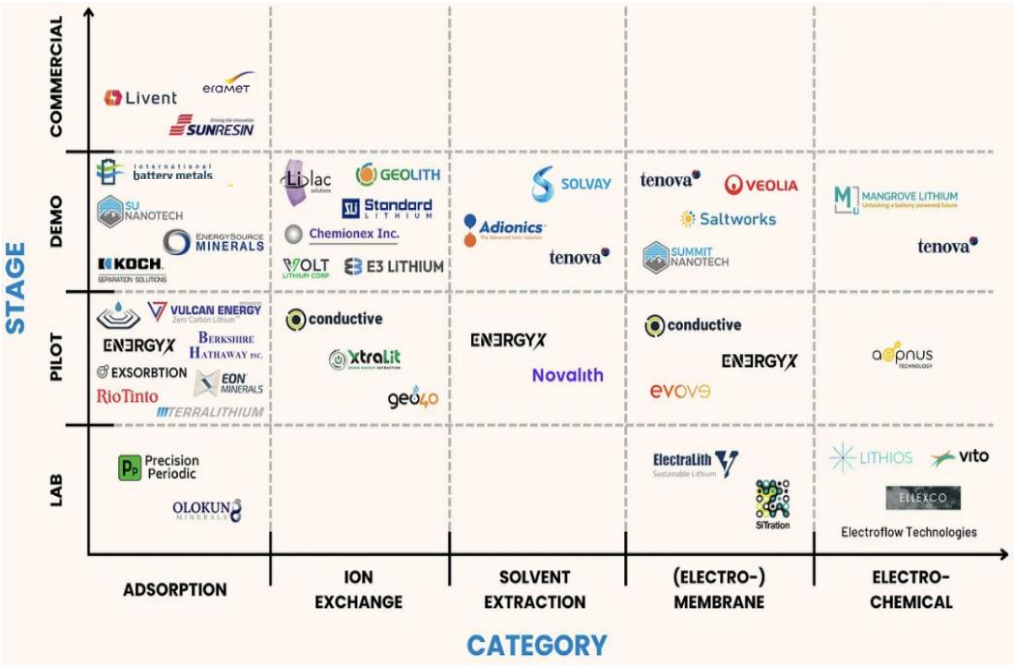



**Figure 36. Non-exhaustive inventory of DLE technology providers by category and maturity status**
Source: Extantia, 2024.

Although direct lithium extraction has been used for more than two decades by Livent (now Rio Tinto) in the Salar del Hombre Muerto (Catamarca, Argentina), it is only in the last decade that significant technological innovations have emerged for processing lithium in an unconventional way. The first technological developments were driven by interest in exploiting geothermal brines in the United States. However, at that time, lithium carbonate prices did not justify the investments required to implement new technologies.

There are various technological approaches via DLE for the extraction and recovery of lithium from brines (Figure 37). Among the most developed are adsorption, ion exchange, solvent extraction, membrane separation, and electrochemical methodologies.

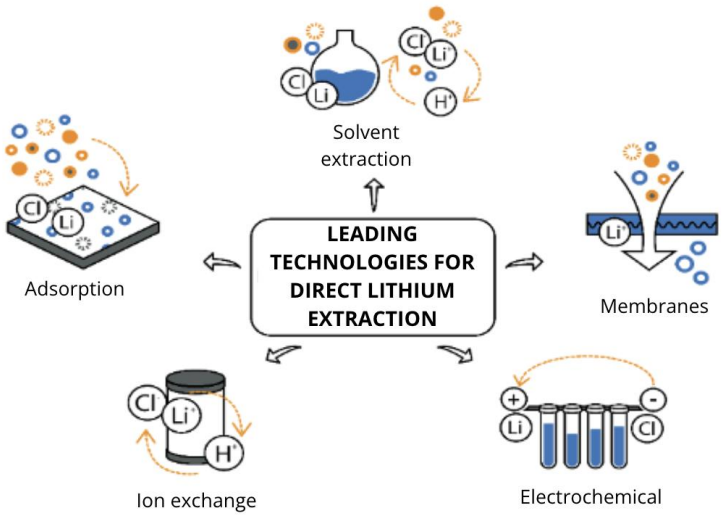



**Figure 37. Main DLE technologies**
Source: Prepared by the authors based on Extantia, 2024.

### 6.2.1. Adsorption technologies

In the late 1970s, Dow Chemical developed an inorganic adsorbent based on aluminum hydroxide (Figure 38) with the aim of capturing lithium from enriched brines in the Smackover region of Arkansas. Dr. John Burba, an expert in chemistry and physics, led the development of this technology, which was later implemented by FMC (now Rio Tinto) in the Salar del Hombre Muerto (Argentina) in 1997. (International Battery Metals, n.d.).

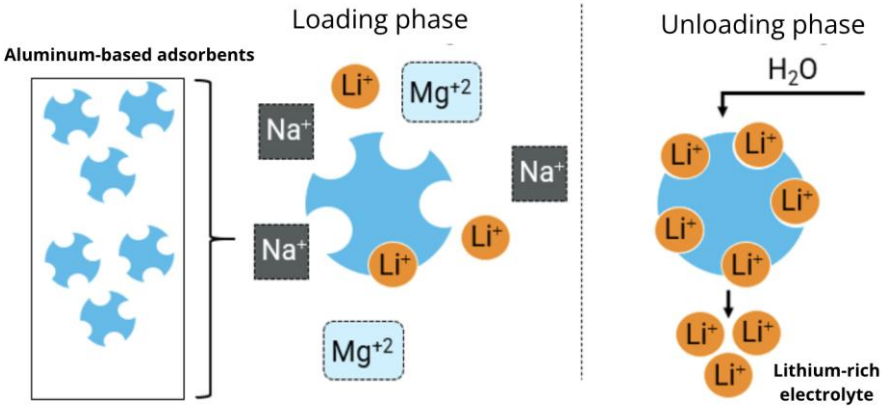



**Figure 38. Adsorption mechanism for lithium recovery using aluminum-based adsorbents**
Source: Prepared by the author based on Boroumand & Razmjou, 2024.

Direct lithium extraction (DLE) technology based on adsorption is based on the physical adhesion of lithium ions to the surface of solid particles composed of aluminum-based adsorbent materials. This process is reversible, as it does not involve an exchange of electrons. Research has shown that aluminum hydroxide-based adsorbents have high selectivity for lithium, making them particularly effective for this purpose. Lithium ions are lodged in the octahedral voids of the crystalline layers of aluminum hydroxides, such as gibbsite, bayerite, and nordstrandite. These hydroxides can form intercalation matrices with lithium, while amorphous aluminum hydroxides react with lithium chloride at high temperatures to form the crystalline compound $LiCl{\cdot}2Al(OH)_3$.

Aluminum-lithium double hydroxides have also proven to be effective for lithium recovery from geothermal brines, standing out as a versatile solution for different types of brines (Bunel, 2024). This technology improves its efficiency in brines as the lithium concentration increases and both salinity and temperature rise, factors that facilitate lithium intercalation (Vera et al., 2018).

Despite its advantages, this technology has not yet been applied industrially with depleted brine reinjection, as this could dilute the lithium concentrations in the feed brine, affecting the long-term performance of the project.

#### 6.2.1.1. Arcadium Lithium Process

At Salar del Hombre Muerto, the Phoenix Project, operated by Arcadium Lithium (now Rio Tinto), has been in operation since 1997. This project represents an example of commercial-scale DLE. The process, described in an FMC patent from February 1997, consists of circulating brine through columns filled with hydrated polycrystalline alumina (PHAl). This is prepared by reacting alumina with lithium hydroxide, subsequently neutralized with dilute hydrochloric acid in a sodium bicarbonate carrier solution. The resulting crystallization of lithium chloride-aluminum hydroxide (LiCl-Al(OH)3), from which the lithium is removed by washing with water, leaves the PHAl with the ability to adsorb lithium chloride in strongly ionic solutions. As a result, when the brines pass through the columns, the lithium dissolved in the brine solution is adsorbed onto the surface of the PHAl. Once saturated with lithium, the columns are removed, and the lithium is extracted from the PHAl by washing it again with water (Figure 39). To ensure that all the lithium has been recovered, the columns are washed with a saturated sodium chloride solution, a process that also restores the PHAl's initial capacity to adsorb lithium from the brine solution (Roskill, 2016).

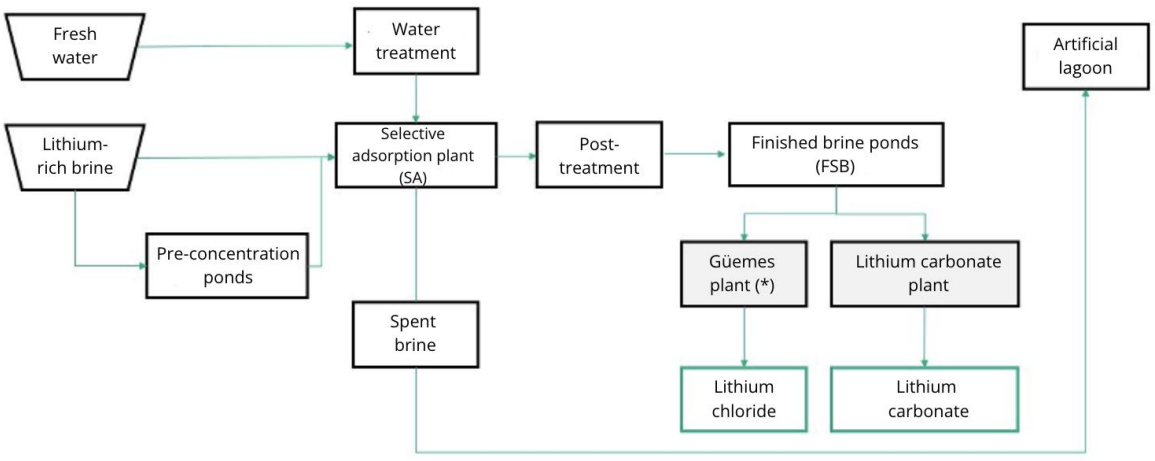



**Figure 39. Diagram of the Arcadium Lithium process in the Fenix project (Argentina)**
Source: Prepared by the authors based on Arcadium Lithium, 2023.

The lithium solution obtained is pumped into solar evaporation ponds to increase its concentration before being processed again, using a process similar to the conventional method described above. A major challenge associated with this technology is the high use of fresh water, which reaches 71 $m^3$ per ton of $Li_2CO_3$. This is 200% and 50% more than the unit volume used in the Salar de Atacama and Salar de Olaroz, respectively, highlighting that DLE technology may not necessarily require less water than the conventional process.

### 6.2.1.2. Eramet process

Eramet has recently positioned itself as the leader in DLE-related patents, having developed a versatile technology for various brines, especially those rich in divalent ions such as calcium and magnesium. Its process includes a nanofiltration stage to remove calcium and magnesium before the DLE stage (Figure 40), as well as recycling 60% of the water used by employing reverse osmosis to concentrate the LiCl and NaCl solution, followed by forced evaporation to achieve the optimal lithium chloride concentrations necessary for carbonation. Both effluents (water recovered from reverse osmosis and forced evaporation) are combined and constitute part of the water used to remove LiCl from the adsorbent (Eramet, 2023).

With regard to reinjection, Eramet has opted to send all spent lithium brine to solar evaporation ponds while it evaluates the feasibility of reinjection.

Production at the Centenario project in Argentina began in mid-2024 and is expected to have an OPEX of approximately USD 5,000/t LCE, with an annual capacity of 24,000 tons of lithium carbonate.

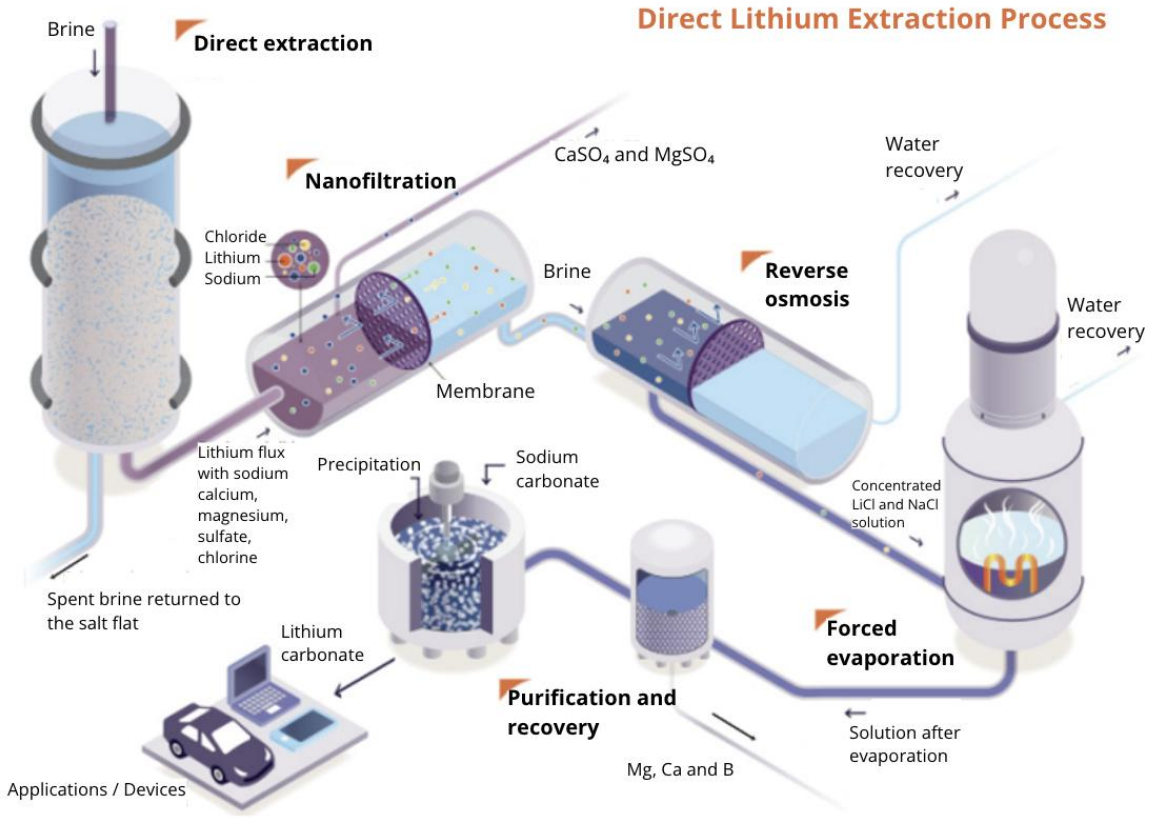



**Figure 40. Diagram of Eramet's process at the Centenario-Ratones project (Argentina)**
Source: Eramet, 2024.

### 6.2.2. Ion Exchange Technologies

Ion exchange technology dates back to the mid-1930s, when Adams and Holmes discovered the exchange properties of certain materials synthesized from formaldehyde and phenol. This breakthrough spurred the development of ion exchange resins, which are now widely used in various industries such as water treatment and precious metal extraction. The versatility of these resins was quickly recognized, resulting in their application in areas such as the Manhattan Project (1942), where synthetic ion exchangers played a crucial role in the production of plutonium (Lucy, 2003).

Currently, organic polymers capable of selectively extracting lithium in the presence of other metal ions have been developed. These polymers are designed with specifically structured exchange sites to exchange cations (e.g., $H^+$) in the resin for $Li^+$ ions in solution. This property is achieved through chemical synthesis processes that allow the inclusion of reactive or chelating sites in specifically sized structures through an ion imprinting process to allow the selective entry of lithium, leaving out competing ions (Figure 41).

Ion exchange resins, mostly based on manganese oxides (LMO) and titanium oxides (LTO), have a high affinity for the $Li^+$ ion. During the exchange process, these resins, packed in columns, selectively capture lithium, replacing a cation such as $H^+$. Subsequently, an acid solution or fresh water is used to desorb the $Li^+$ cations and generate a concentrated LiCl solution. However, acid elution causes significant losses of manganese and titanium, degrading the material over time and decreasing its efficiency. To mitigate this problem, LMO doping with aluminum has been investigated, which would improve cyclic stability and reduce manganese dissolution. Titanium-based adsorbents, on the other hand, do not undergo significant dissolution, allowing for greater stability, although their durability remains a challenge due to high operating costs (Farahbakhsh et al., 2024).
Unlike physical adsorption technologies (without ion exchange), this method would not be affected by the dilution of reinjected brine as it maintains its performance even at low lithium concentrations (concentrations of approximately 10 mg/L).

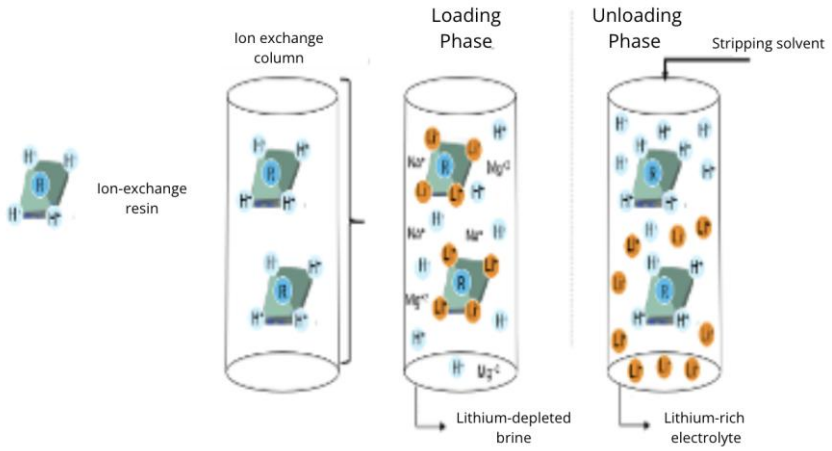



**Figure 41. Ion exchange mechanism for lithium recovery**
Source: Prepared by the authors based on Yang et al., 2024.

### 6.2.2.1. Lilac Solutions process

Lilac Solutions, founded in 2016 by David Snydacker, has proposed new ion exchange technologies derived from doctoral research at Northwestern University, USA. Lilac's ion exchange microspheres and continuous brine processing system allow for the efficient concentration of lithium solutions from low-concentration brines, generating lithium chloride and a lithium-depleted brine that can be returned to the salt flat (Figure 42). The optimization of these technologies has improved the stability and performance of ion exchange microspheres (Lilac Solutions, 2023).

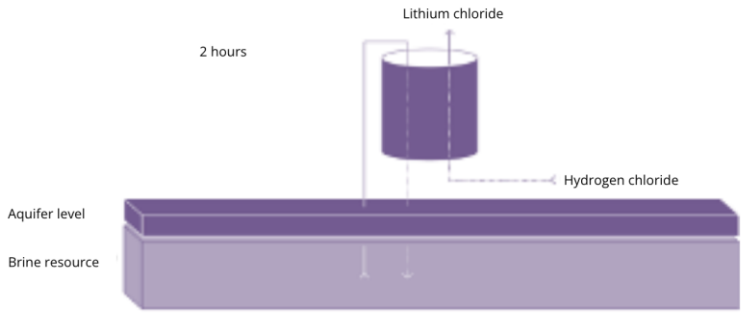



**Figure 42. Lilac Solutions process diagram**
Source: Lilac Solutions, 2023.

Among the challenges that Lilac has solved in its technology is the development of $Li_2Mn_2O_5$ particles coated with a protective layer of $SiO_2$ to prevent the dissolution and degradation of the materials, which would significantly extend the useful life of the microspheres. The microspheres have an average diameter of 3 to 5 microns, and the coating thickness is approximately 10 nanometers.

Lilac's technology was recently selected as the DLE technology provider by Lake Resources for its Kachi project in Argentina, with pilot plant operations commencing in late 2020. In April 2023, Lilac announced that the Kachi plant had processed more than 5.2 million liters of brine and generated more than 200,000 liters of concentrated LiCl product, with a lithium recovery rate of 80% and a high impurity rejection rate (99.9%), successfully producing 2,500 kg of LCE (Lilac Solutions, 2023). Although fresh water consumption was 20 tons of water per ton of $Li_2CO_3$, the company is exploring solutions to reduce water consumption through reverse osmosis and forced evaporation.

### 6.2.3. Solvent Extraction Technologies

Solvent extraction is an established industrial process that, together with distillation, constitutes one of the two most important industrial separation procedures in the world. The first commercially successful liquid-liquid extraction operation was developed for the petroleum industry in 1909, when the Edeleanu process was used to remove aromatic hydrocarbons from kerosene using liquid sulfur dioxide as a solvent. Since then, many other processes have been developed based on the same principle in the petroleum, chemical, metallurgical, nuclear, pharmaceutical, and food processing industries (Thornton, 2008).

In the context of lithium extraction, this technology is particularly attractive due to its simplicity, ease of control, low cost, high efficiency, and selectivity. This positions it as a promising method

for recovering lithium ions from brines with a high Mg/Li ratio, such as those found in salt lakes in China (Zhou et al., 2020).

In this method, an organic liquid phase, composed of a solvent and an extractant, is mixed with an aqueous phase loaded with lithium. Both phases are immiscible, so after mixing, they separate, as occurs with water and oil. During agitation or mixing, contact occurs between the two phases, and the lithium associates with the extractant to form specific $Li^+$ complexes that are retained within the organic phase. While the complexes formed by $Li^+$ pass into the organic phase, most of the impurities remain in the aqueous phase (Figure 43). Then, at rest, both phases separate, resulting in an organic phase loaded with lithium and an aqueous phase with a residual concentration of lithium. This loading process can be repeated as many times as desired until a residual lithium concentration in the brine is reached, determined by the contact stages used. Once the organic loading stage is complete, $Li^+$ is extracted or discharged from the organic phase by contacting the organic phase with a clean acid solution, exchanging $Li^+$ for $H^+$, ultimately resulting in a lithium-rich aqueous phase and a discharged organic phase that can be recycled for reuse (Shi, 2017). The extraction process is driven by cation exchange, while the regeneration of the organic phase depends on acid-base neutralization (Mashtalir et al., 2018).

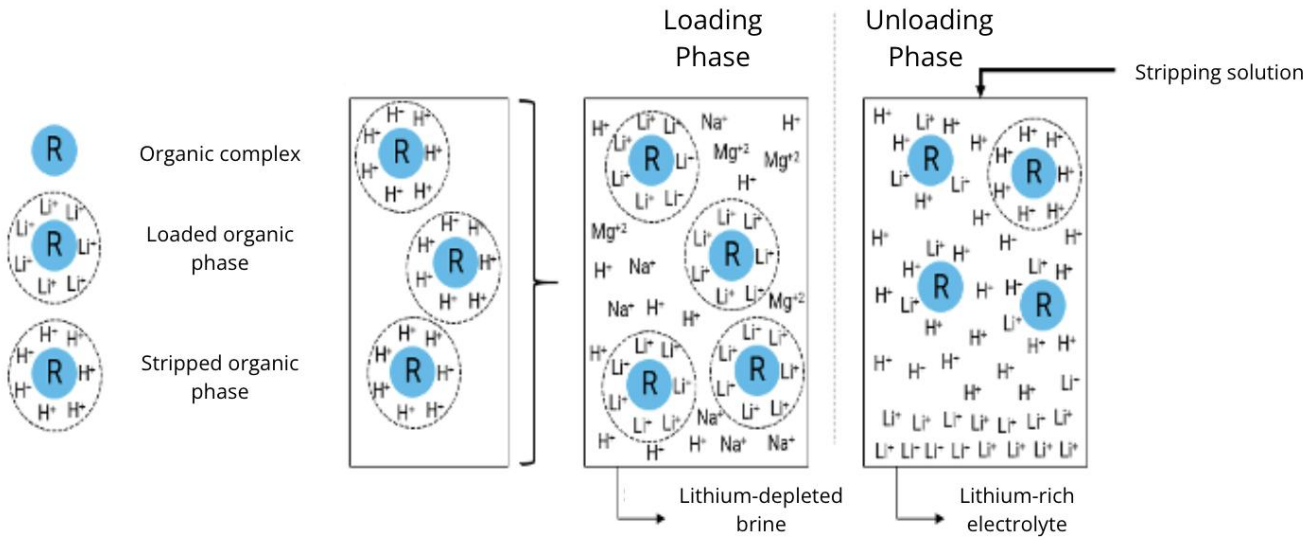



**Figure 43. Solvent extraction mechanism for lithium recovery**
Source: Prepared by the authors based on Fuentealba et al., 2023.

An important advantage of this method is its ability to concentrate lithium without the need for prior concentration stages. However, as with other DLE methods, it generates waste and presents environmental sustainability challenges due to the use of organic compounds and corrosive additives, which limit the possibility of reinjecting the treated brine into the salt lake itself unless there is an additional treatment stage to ensure that there would be no contamination by carryover. The problem with reinjection and the high cost of extractants and solvents remains an obstacle to its application in brines with low Li+ concentrations (Vera et al., 2018; Bunel, 2024).

In terms of water consumption, this process requires approximately 1 $m^3$ of fresh water per ton of lithium carbonate produced. While this consumption is significant, it is lower than the water losses via evaporation associated with the conventional method of lithium extraction from brines.

#### 6.2.3.1. Adionics process

Adionics is a French company that, after initially focusing on water desalination, applied its technology to the lithium extraction sector in 2017. The technology developed by Adionics uses a fluid called Flionex, which is a mixture of a dense organic solvent and molecular extractants capable of selectively coordinating cations and anions. This process allows for the efficient extraction of lithium from brines of various concentrations using a modular and adaptable system (Smolyakov et al., 2018).

The main advantages of Adionics technology include:

- Lithium recovery of up to 99%.
- High selectivity: $Mg^{+2}$, $B^{+3}$, $K^{+}$, $SO_4^{2-}$ ions are not extracted.
- LiCl purity up to 99%.
- Lower water consumption.
- Process that does not require additional chemical reagents.

Flionex technology allows lithium to be extracted from brines without significant changes in pH or the use of corrosive solvents, reducing acid consumption and environmental impact. The cationic extractants used belong to the calixarene family, organic compounds that allow high selectivity in lithium extraction (Bunel, 2024).

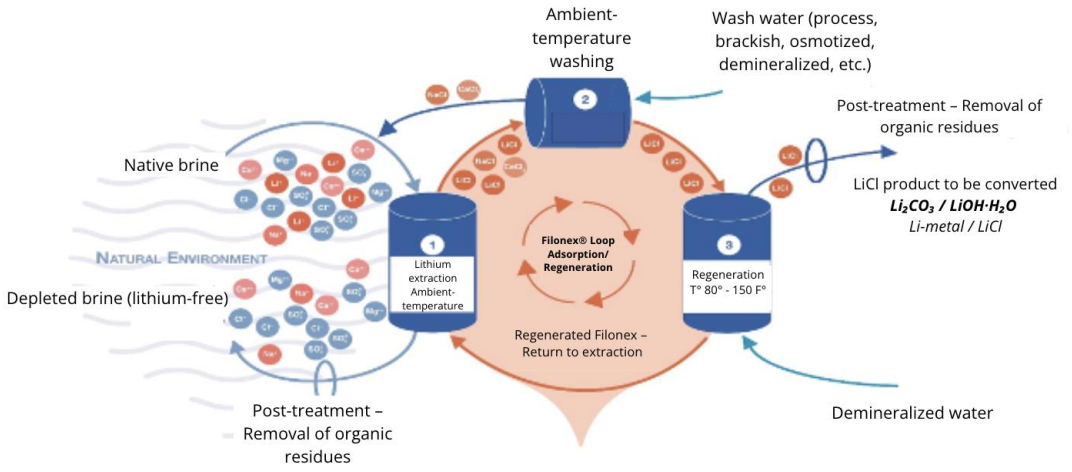



**Figure 44. Diagram of the Adionics process**
Source: Adionics, 2022.

### 6.2.4. Membranes and Electro Membranes

A membrane is a system with a thickness significantly smaller than its surface area, which, when placed between two liquid phases, allows the selective transfer of matter or energy. Membrane separation processes can be classified according to the driving force (pressure or electrical potential), the type of membrane, its configuration, or the separation mechanisms involved. The main membrane separation technologies include electrodialysis (1955), reverse osmosis (1960), and nanofiltration (1990), which are mainly used in seawater treatment and desalination processes (Solis et al., 2016).

A key feature of membrane technologies is the relationship between pore size and the pressure required for separation (Figure 45).

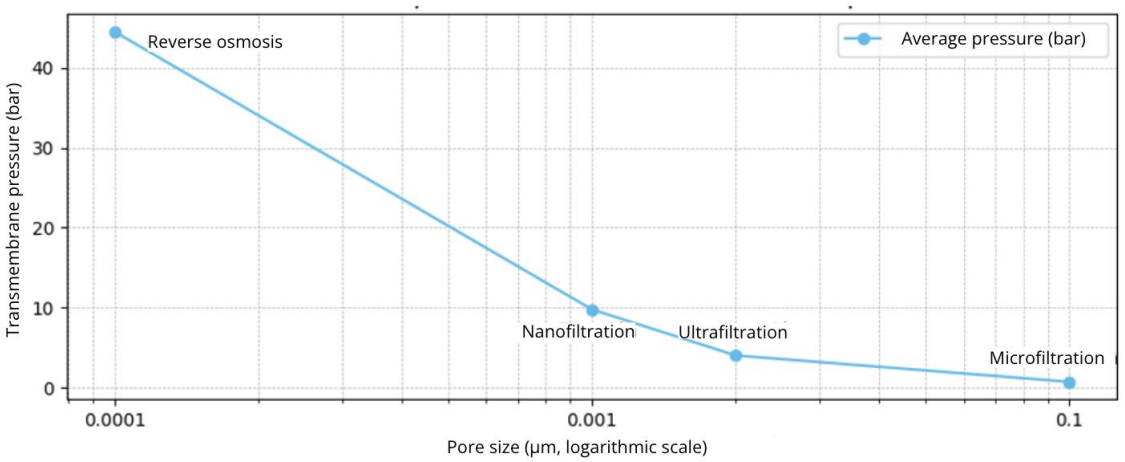



**Figure 45. Pressure required as a function of particle size for membrane technologies**
Source: Prepared internally based on DuPont, 2024.

Pore size determines the membrane's ability to retain particles, from sediments to dissolved molecules. For example, technologies such as microfiltration work at low pressures and are ideal for retaining coarse particles, such as sediments and bacteria, while ultrafiltration, with pore sizes in the range of 0.002–0.1 microns, requires moderate pressures (2–10 bar) and is commonly used to retain macromolecules such as proteins and colloids.

On the other hand, nanofiltration and reverse osmosis technologies, which have pore sizes smaller than 0.001 microns, are capable of retaining dissolved solutes, including ions and low molecular weight organic molecules. These membranes operate at significantly higher pressures: typically, 4-30 bar for nanofiltration and up to 70 bar for reverse osmosis in seawater desalination applications.

Understanding this relationship is essential for selecting the appropriate membrane technology according to process requirements.

### 6.2.4.1. Electrodialysis (ED) Technology

Electro-membrane systems, also known as electrodialysis (ED) systems, use an electric current to move ions through selective membranes, allowing Li+ to be separated from other cations present in brines, such as $Na^+$, $K^+$, $Mg^{2+}$, and $Ca^{2+}$(Figure 46).

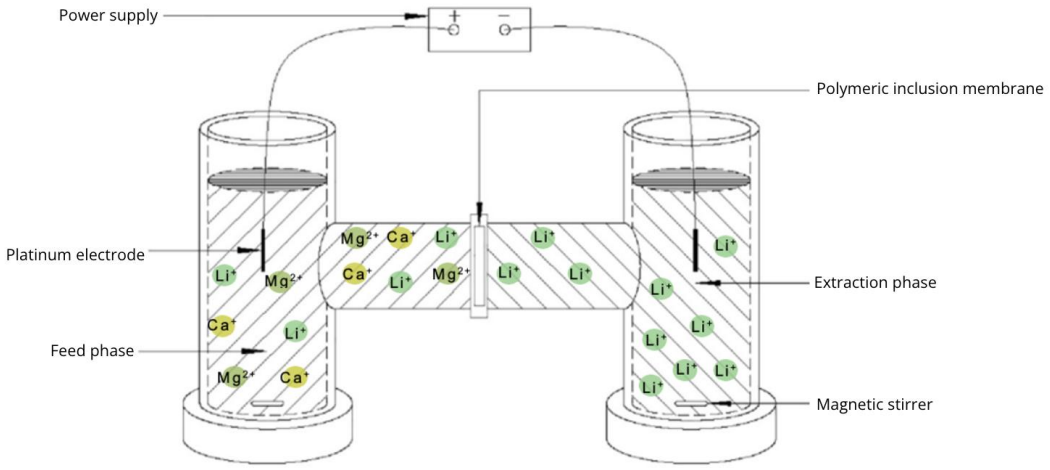



**Figure 46. Electro-membrane mechanism for lithium recovery**
Source: Meng et al., 2021.

Although electrodialysis offers advantages such as continuous processes and relatively simple controls, its implementation on an industrial scale faces technical challenges such as fouling or clogging of the membranes, caused by the trapping of salts on the surface and deterioration of the membrane. Although it has a low carbon footprint if the source of electrical energy is green, its use is hampered by high capital expenditure and operating costs (Vera et al., 2018).

### 6.2.4.2. Reverse Osmosis (RO) Technology

Reverse osmosis is a process of separating salts in solutions based on the removal of water using membranes with pores between 5 and 15 Å, mainly used for desalination (Figure 47). Although reverse osmosis requires high energy consumption due to the high pressures applied, its filtration and solution concentration capacity are highly efficient, excelling in pretreatment and water recovery processes (Solis et al., 2016). This technology alone does not allow for the production of purified lithium products, but it would allow for an increase in ion concentration in the initial stages of brine preparation without evaporating water.

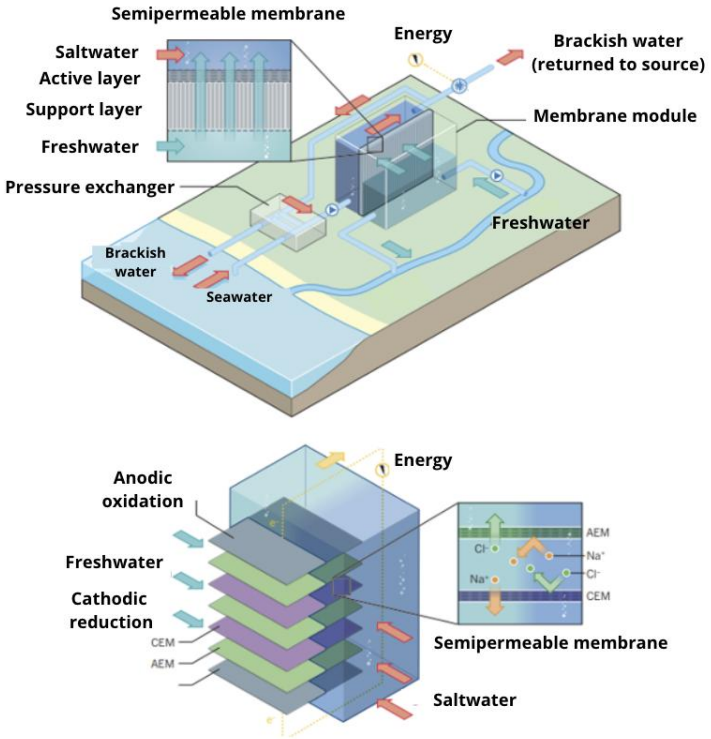



**Figure 47. Reverse osmosis mechanism for sustainable energy generation from seawater**
Source: Logan & Elimelech, 2012.

### 6.2.4.3. Nanofiltration (NF) technology

Nanofiltration is a membrane separation process that uses pores smaller than 0.001 µm (1 nm), allowing the selective separation of ions according to their size (Figure 48). Developed as an alternative to reverse osmosis, nanofiltration operates at lower pressures, reducing energy costs, and is used for the precise separation of lithium ions in complex solutions. Its development has accelerated in recent decades, improving membrane characteristics and expanding its industrial applications (Solis et al., 2016).

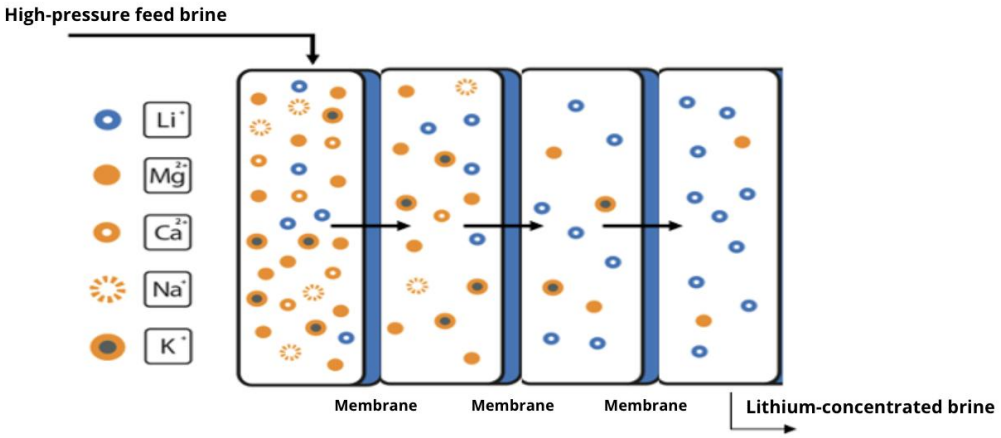



**Figure 48. Nanofiltration mechanism for lithium recovery**
Source: Prepared by the authors based on Meng et al., 2024.

### 6.2.4.4. ElectraLith process

ElectraLith, a spin-off company from Monash University (Australia), has developed a patented direct lithium extraction and refining (DLE-R) process based on electro-membrane technologies, capable of producing battery-grade lithium hydroxide without the use of water or chemicals, and with minimal energy consumption.
ElectraLith's DLE-R technology is characterized by its modularity and flexibility, applying to various sources of lithium, including low-concentration brines such as geothermal and oil field brines (ElectraLith, n.d.).

The ElectraLith process consists of two stages (Figure 49):

- **DLE stage**: Uses patented membranes for electrodialysis, extracting lithium in the form of lithium chloride (LiCl) without requiring the use of water or chemicals. This process can handle high-concentration brines, such as those with less than 60 ppm of lithium, and is highly effective in removing contaminants.
- **R stage**: The treated brine is returned to the aquifer, minimizing environmental impact without generating additional waste.

To validate the technology, ElectraLith conducted a proof of concept where it produced battery-grade lithium hydroxide from various lithium sources (salt flats brines, geothermal brines from oil fields) and geographical areas (USA, Argentina) with minimal water consumption and without the use of chemicals. This proof of concept included the production of lithium hydroxide with a purity of 99.9% from brine with less than 60 ppm of lithium (IP Group, 2024).

Backed by Rio Tinto, IP Group, and Monash Investment Holdings, ElectraLith's DLE-R technology has become an important emerging technology for extracting and refining lithium.

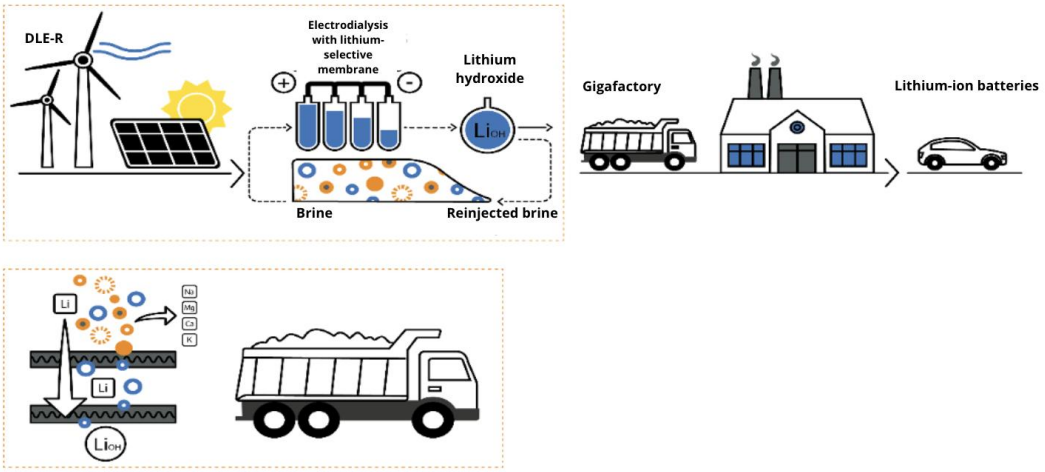



**Figure 49. ElectraLith process diagram**
Source: Prepared by the author based on ElectraLith, n.d.

### 6.2.5. Electrochemical Separation Technologies

The electrochemical separation of metal ions was first described in 1903 by French scientist M.A. Hollard, who used this method to separate nickel from zinc using an amalgamated zinc anode and a platinum cathode. Since then, numerous studies have been published on the electrochemical separation of various metal ions (Clarke & Wooten, 1939).
The basic principle of this method involves applying an external electrical potential that induces the migration of ions in an electrolyte (in this case, lithium-enriched brine) toward an electrode containing adsorbent materials specifically designed for their capture (Kim et al., 2019).

Currently, the electrode materials used in this process are classified into two main categories: i) lithium iron phosphate ($LiFePO_4$ or LFP) and ii) lithium manganese oxide ($LiMnO_2$ or LMO) (Battistel et al., 2020). Among these, $LiFePO_4$ stands out for its one-dimensional internal channel, which facilitates the insertion of $Li^+$. In addition, it has significant advantages such as structural stability, high reversibility, lower toxicity, and competitive costs.

This technology is particularly interesting for extraction from brines with a high Mg/Li ratio and low $Li^+$ concentrations, due to its environmental sustainability and proven ability to offer high levels of recovery, cycle efficiency, scalability, reversibility, and selectivity (Srimuk et al., 2020).

Compared to other DLE alternatives, such as ion exchange technology, electrochemical separation does not present problems related to adsorbent dissolution and does not require the use of additional chemical reagents, such as acids or bases. However, the presence of other cations contained in lithium brine can negatively affect the selectivity and efficiency of the process, underscoring the need to develop materials with high specificity for $Li^+$ (Bunel, 2024).

Once $Li^+$ is captured, it is released from the electrode material using a clean recovery solution, which commonly requires fresh water. This process generates a diluted LiCl solution (Figure 50), which can be concentrated in subsequent stages to meet the specifications of the final product. This approach is emerging as a sustainable and competitive alternative for lithium extraction, especially when combined with renewable energy sources, thus minimizing its environmental impact (Calvo, 2019).

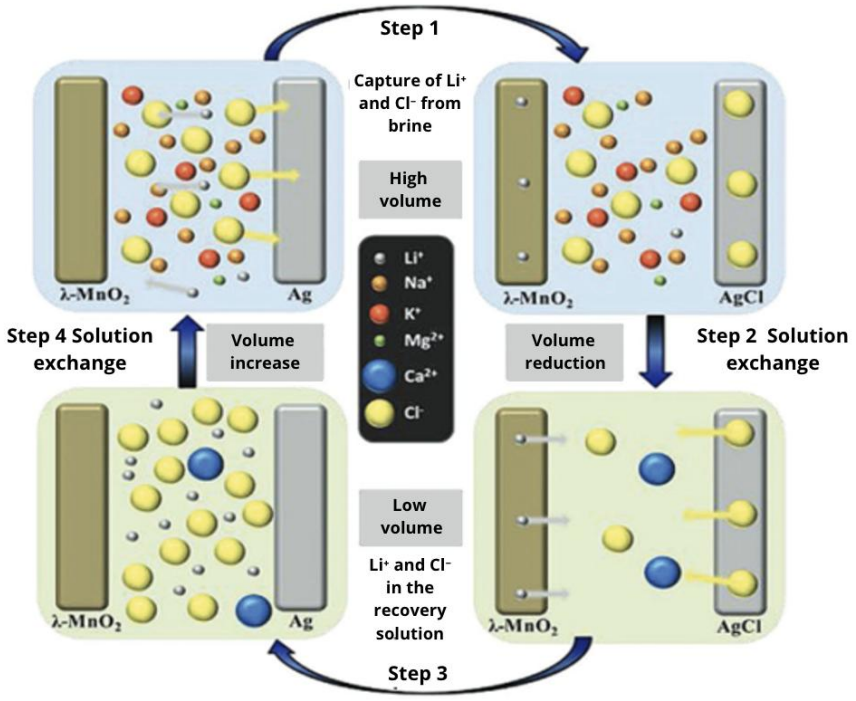



**Figure 50. Lithium recovery from brines using λ-$MnO_2$as the $Li^+$capture electrode and $Ag^+$as the $Cl^-$capture electrode**
Source: Battistel et al., 2020.

### 6.2.5.1. Mangrove Lithium Process

Mangrove Lithium is a Canadian company based in Vancouver that has developed an innovative proposal for the production of lithium hydroxide and carbonate using various feed sources, such as brines, hard rocks, clays, and recycled batteries. The technology of this platform is also marketed for the conversion of waste brines into chemicals and desalinated water (Mangrove Lithium, 2022).

Mangrove's modular solution implements a patented electrochemical process called Clear-Li that enables the direct conversion of lithium chloride and lithium sulfate into lithium hydroxide (Figure 51). This lithium refining process also generates fungible by-products, which increases the return on investment and strengthens the financial viability of the project. These by-products, such as HCl and $H_2SO_4$ in the case of lithium chloride and lithium sulfate, respectively, can be reused in the extraction phase of the lithium production process, thereby improving sustainability through a closed-loop extraction system (Mangrove, n.d.).

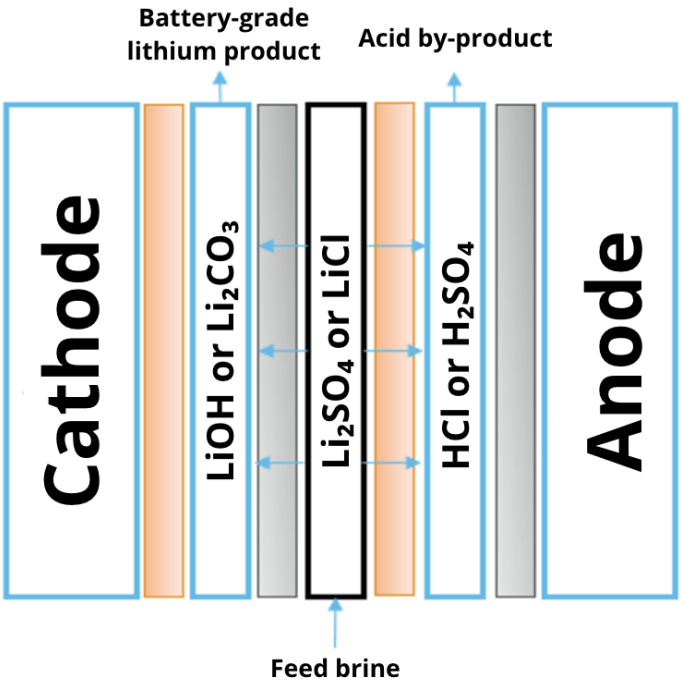



**Figure 51. Mangrove Lithium process diagram**
Source: Prepared by the author based on Mangrove Lithium, n.d.

## 6.3. Summary of direct lithium extraction (DLE) technologies

The number and characteristics of DLE technologies currently available and under development are extensive. Below is a comparative analysis of the various technologies to facilitate the identification of opportunities and advantages. This information allows for the identification of the technical and economic attributes of each method, highlighting their strengths in terms of efficiency, selectivity, and adaptability to different operating conditions. It also facilitates the assessment of challenges such as the need for pretreatment, environmental impact, investment and operating costs, as well as water requirements and dependence on critical reagents. Table 12 presents a summary of the advantages and disadvantages of the main DLE technologies: adsorption, ion exchange, solvent extraction, electro-membranes, and electrochemical separation.

### 6.3.1. Advantages and disadvantages of DLE technologies

**Table 12. Advantages and disadvantages of DLE technologies**
Source: Prepared by the authors based on Goldman Sachs, 2023; International Lithium Association, 2024; Farahbakhsh et al., 2024; and others, 2023.

| Technology | Advantages | Disadvantages |
|---|---|---|
| | • High selectivity<br>• Adaptability<br>• Global marketing | • Loss due to dissolution<br>• Risk of adsorbent wear |

| | | |
|---|---|---|
| **Adsorption** | • No chemical reagents required<br>• Can achieve over 90% recovery<br>• Low waste<br>• Low energy consumption<br>• Low-medium environmental impact<br>• Not affected by weather conditions<br>• Technology in commercial use for over 20 years | • Temperature-dependent process (>50 °C)<br>• Requires post-treatment and purification stages<br>• Requires monitoring and control of interference from other metals during lithium extraction and adsorbent stability over time |
| **Ion exchange** | • High selectivity<br>• Low-medium initial investment<br>• High separation efficiency<br>• High theoretical lithium absorption capacity<br>• Relatively low water consumption<br>• Not affected by climatic conditions<br>• Suitable for low lithium concentration<br>• High recovery rate<br>• Can achieve over 90% recovery | • High acid and base requirements<br>• Safety risk in acid supply<br>• Risk of adsorbent degradation at low pH over the long term |
| **Solvent extraction** | • Low dependence on post-treatment stages<br>• Well-established technology for separating metals from aqueous solutions<br>• High selectivity<br>• Not affected by weather conditions<br>• Low energy consumption | • Requires additives and corrosive solvents<br>• Risk of residual brine contamination<br>• High waste production<br>• Potentially higher capital cost |

| | | |
|---|---|---|
| | • Can achieve over 90% recovery | • Intensive pretreatment required for brines with high Ca/Li and Mg/Li mass ratios<br>• Production costs would be too high when the Mg/Li ratio is too high |
| **Electro Membranes** | • No contact between feed and outlet solutions<br>• Continuous process<br>• Generates low levels of impurities<br>• Not affected by weather conditions<br>• Does not require chemical reagents | • *Fouling* problems<br>• High CAPEX and OPEX<br>• Requires pretreatment and posttreatment<br>• Risk of membrane degradation |
| **Electrochemical separation** | • Good response in terms of high Mg/Li ratio<br>• Low environmental impact<br>• No chemical reagents required<br>• Can achieve over 90% recovery<br>• High selectivity<br>• Low energy consumption | • Still to be demonstrated on a pilot and large scale<br>• High OPEX<br>• Risk of electrode degradation |

## 6.4. Comparison of projects with DLE technologies based on CAPEX and OPEX

In general, technology providers present preliminary indicators on $CO_2$ emissions, energy consumption, water consumption, and chemical reagent consumption in their corporate reports that cannot be verified. Furthermore, the lack of detailed information and the confidentiality of data obtained from pilot plants make it difficult to directly compare these technologies.

Although no technical-economic analysis of the different DLE technologies has been carried out due to insufficient publicly available information, there is a relevant study developed by the National Renewable Energy Laboratory (NREL) in 2021, which compares DLE processes for geothermal brines, evaporites, and oil fields.

Table 13 compares key data from selected projects, highlighting production costs (CAPEX and OPEX), internal rate of return (IRR), and the particular characteristics of each project. This information, although limited, points to the importance of having pilot-scale data to refine profitability and sustainability models for lithium extraction.

The study shows that the production costs of DLE technologies, regardless of the type of brine, converge at around $4,000 per ton of LCE produced, with projected prices averaging $13,000 per ton of lithium carbonate.

**Table 13. Economic comparison between different DLE projects**
Source: Prepared by the authors based on Warren, 2021.

| Company | SRI International | Vulcan Energy Resources | Standard Lithium | E3 Metals Corp | Anson Resources | Pure Energy Minerals | Lake Resources |
|---|---|---|---|---|---|---|---|
| **Project name** | Salton Sea | Upper Rhine Valley | Lanxess Smackover | Clearwater | Paradox Phase 3 | Clayton Valley | Kachi |
| **Location** | California, USA | SW Germany | Arkansas, USA | Alberta, Canada | Utah, USA | Nevada, USA | Catamarca, Argentina |
| **Document** | DOE, CEC reports | PFS | PEA | PEA | PEA | PEA | PFS |
| **Type of brine** | Geothermal | Geothermal | Evaporite | Oil fields | Evaporite | Evaporite | Salt flats |
| **Resources (tonnes LCE)** | Information not available | 15,850,000 | 3,140,000 | 2,200,000 | 192,000 | 217,700 | 1,010,000 |
| **Lithium concentration (mg/l)** | 400 | 181 | 168 | 74.6 | 100-500 | 65-221 | 289 |
| **Production (t/year)** | 20,000 | 40,000 | 20,900 | 20,000 | 15,000 | 11,500 | 25,500 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Production cost (USD/t)** | 3,845 | 3,217 | 4,319 | 3,656 | 4,545 | 3,217 | 4,178 |
| **CAPEX (USD 1,000)** | 52,300 | 1,287,600 | 437,162 | 602,000 | 120,000 | 358,601 | 544,000 |
| **OPEX (USD 1,000/year)** | 76,900 | 128,688 | 90,259 | 73,200 | 68,180 | 36,516 | 106,539 |
| **Estimated price (US$/t)** | 12,000 | 14,925 | 13,550 | 15,160 | 13,000 | 12,267 | 11,000 |
| **IRR (before taxes %)** | 268 | 31 | 41.8 | 32 | 106 | 24 | 25 |
| **Type of technology** | Ion exchange | Adsorption | Ion exchange | Ion exchange | Ion exchange | Solvent extraction | Ion exchange |
| **Lithium recovery** | 90 | 90 | 90 | 90% | 75 | 90 | 83.2% |
| **Product** | $Li_2CO_3$ | $LiOH{\cdot}H_2O$ | $Li_2CO_3$ | $LiOH{\cdot}H_2O$ | $Li_2CO_3$ | $LiOH{\cdot}H_2O$ | $Li_2CO_3$ |

## 6.5. Global comparison of DLE technologies

The comparative evaluation of direct lithium extraction technologies requires cross-cutting indicators that allow their performance to be classified according to three fundamental objectives:

- **Selective lithium Extraction**: DLE technologies must be designed to selectively capture lithium ions from brines, considering that in most brines the concentration of lithium represents less than 1% of total dissolved solids, compared to other much more concentrated ionic species such as sodium, potassium, and magnesium.

- **Reinjection of treated brine**: DLE technologies make sense compared to conventional technology insofar as they allow the processed brine to be returned to the salt flat, which would greatly preserve the water balance and minimize environmental disturbance.

- **Environmental impact**: DLE technologies require less operating area and potentially less fresh water than evaporation ponds, which helps reduce the impact on local ecosystems.

Table 14 presents a comparison of the characteristics of each DEL method, and Table 15 presents a comprehensive comparison of lithium extraction methods, covering both conventional approaches and DLE technologies. This analysis identifies the strengths and weaknesses of each technology using key metrics that evaluate its technical performance, environmental sustainability, and economic viability. It should be noted that the scoring is based on the average results of projects associated with each technology. The parameters analyzed are listed in Table 14.

**Table 14. Comparison of the characteristics of each DLE method**
Source: Prepared by the authors based on Goldman Sachs, 2023; International Lithium Association, 2024; Farahbakhsh et al., 2024; and others, 2023.
.

| Indicator | ★ | ★★ | ★★★ |
|---|---|---|---|
| **Production time** | Production on a monthly scale. | Production on a daily basis. | Production in hours. |
| **Lithium Recovery Rate** | 40-50% recovery. | 60-80% recovery. | 60-80% recovery. |
| **Production Costs** | More than $6,000 USD per ton of LCE. | Between $4,000 and $6,000 USD per ton of LCE. | Less than $4,000 USD per ton of LCE. |
| **$Li^+/Na^+$selectivity** | Low selectivity, with high dependence on subsequent processes. | Moderate selectivity, but still requires additional steps to achieve commercial purity levels. | High selectivity, minimizing the need for subsequent treatments to achieve commercial purity levels. |
| **$Li^+/Mg^{2+}$selectivity** | Low selectivity, with high dependence on subsequent processes. | Moderate selectivity, but still requires additional steps to achieve commercial purity levels. | High selectivity, minimizing the need for further treatment to achieve commercial purity levels. |
| **Water use (includes losses due to water evaporation)** | Consumption greater than 100 $m^3$ of water per ton of LCE. | Consumption between 70 and 100 $m^3$ of water per ton of LCE. | Consumption of less than 70 $m^3$ of water per ton of LCE. |
| **Land use** | More than 1,200 $m^2$ per ton of LCE. | Between 300 and 1,200 $m^2$ per ton of LCE. | Less than 300 $m^2$ per ton of LCE. |
| **Energy Use** | More than 210,000 MJ per ton of LCE. | Between 33,000 and 210,000 MJ per ton of LCE. | Less than 33,000 MJ per ton of LCE. |
| **Feasibility of Brine Reinjection** | Contamination by external agents in residual brine. | No external contamination, but sensitive to dilution. | No external contamination and no impact on recovery after reinjection. |

**Table 15. General comparison between lithium extraction methods**
Source: Prepared by the authors based on Goldman Sachs, 2023; International Lithium Association, 2024; Farahbakhsh et al., 2024; and others, 2023.

| Parameters | Conventional method | Adsorption | Ion exchange | Solvent extraction | Electro-membranes | Electrochemical separation |
|---|---|---|---|---|---|---|
| Shorter production time | ★☆☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| Lithium recovery rates | ★☆☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| Lower production costs | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ | ★☆☆ |
| Li vs Na selectivity | ★☆☆ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★★☆ |
| Li vs Mg selectivity | ★☆☆ | ★★☆ | ★★★ | ★★☆ | ★★☆ | ★★☆ |
| Lower water use | ★★☆ | ★★☆ | ★★★ | ★★★ | ★★★ | ★★★ |
| Lower land use | ★☆☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| Lower energy consumption | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| Feasibility of brine reinjection | ★★☆ | ★★☆ | ★★★ | ★☆☆ | ★★★ | ★★★ |
| Shorter production time | ★☆☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |

| | | | | | | |
|---|---|---|---|---|---|---|
| Lithium recovery rates | ★☆☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| Lower production costs | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ | ★☆☆ |
| Li vs Na selectivity | ★☆☆ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★★☆ |
| Li vs Mg selectivity | ★☆☆ | ★★☆ | ★★★ | ★★☆ | ★★☆ | ★★☆ |
| Lower water use | ★★☆ | ★★☆ | ★★★ | ★★★ | ★★★ | ★★★ |
| Lower land use | ★☆☆ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| Lower energy consumption | ★★★ | ★★☆ | ★★☆ | ★★☆ | ★★☆ | ★☆☆ |
| Feasibility of brine reinjection | ★★☆ | ★★☆ | ★★★ | ★☆☆ | ★★★ | ★★★ |

The choice of the most suitable DLE technology for lithium extraction in a salt lake will depend on a comprehensive assessment of these factors, including aspects such as brine quality, operating costs, extraction efficiency, and environmental and operational constraints.

Technologies such as adsorption and ion exchange stand out for their high selectivity and adaptability, but face challenges related to material degradation and the need for specific pretreatments for brine in order to prepare it before processing. Solvent extraction, despite its good performance in terms of energy efficiency and selectivity, continues to face obstacles due to the presence of organic additives in the residual brine, hindering the goal of reinjection.

Electro-membrane and electrochemical separation technologies offer a promising alternative due to their selectivity and low environmental impact, although their high costs and the need for constant maintenance of their components remain key areas for improvement.

In the next decade, technological development and innovation in materials will be fundamental to overcoming the limitations. These solutions must seek a balance between operational efficiency, environmental sustainability, and economic viability in the production of lithium from brines. Today, there is no certainty as to which of these technologies will dominate the lithium industry in the future, and in the coming years, we will surely see significant efforts to find solutions tailored to each project, where each of these technologies will have to be evaluated in terms of the aspects reviewed above.

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# 7. LITHIUM TRIANGLE

## 7.1. Characteristic aspects of the areas where resources and demand are located

### 7.1.1. Salar de Atacama

The Salar de Atacama is one of the endorheic basins located in the Antofagasta region of Chile, at the foot of the Domeyko Mountain Range. This salt flat, located in the world's driest desert, covers approximately 3,100 km², measuring 100 km long by 80 km wide, and is located at an elevation of 2,300 meters above sea level (masl) (Valdivielso et al., 2022). Its importance lies not only in its mineral wealth but also in its unique ecosystems and its interaction with local communities (Torres et al., 2024).

The climate of the Salar de Atacama is extremely arid, with annual rainfall not exceeding 160 mm, concentrated mainly in the months of January and February during the "Altiplano winter." The average annual temperature reaches 14 °C, with marked seasonal differences (Valdivielso et al., 2022):

- **Warm months**: In January and February, average temperatures are around 19.9 °C and 19.6 °C, with highs of 23 °C and lows of 16 °C.
- **Cold months**: In June and July, temperatures drop to an average of 9.2 °C, with lows of 6 °C and highs of 15 °C.

In addition, the salt flat is notable for its intense solar radiation. In summer, values reach up to 1,600 W/m² at midday, while in winter they reach 970 W/m². These conditions make it an ideal region for solar energy projects (Kampf et al., 2005).

The salt flat is home to significant biodiversity, including more than 70 species of fauna, many of which depend on the wetlands of its hydrological system (SQM, n.d.). In particular, the Soncor lagoons, part of the Los Flamencos National Reserve and protected as a Ramsar site since 1996, are home to three emblematic species of flamingos:

- Andean flamingo (Phoenicoparrus andinus).
- James's flamingo (Phoenicoparrus jamesi).
- Chilean flamingo (Phoenicopterus chilensis).

Other species include reptiles such as Liolaemus constanzae, small mammals such as Abrothrix andinus, and the culpeo fox (Lycalopex culpaeus). The flora, although adapted to the desert environment, is key to the survival of these species (SERNAGEOMIN, n.d.).

The salt flat and its surroundings have been home to ancient cultures such as the Atacameños and Chinchorros, who managed to adapt to the extreme conditions of the desert. Today, Atacameño communities maintain a presence in nearby towns such as Toconao and Peine, where they actively

participate in initiatives to protect ecosystems and manage natural resources (Pre-Hispanic Ethnic Groups of Northern Chile, n.d.).

The Salar de Atacama can be accessed from the nearby cities of Calama (160 km to the northwest) and Antofagasta (230 km to the west). From Calama, the main route is Route R-23 (220 km), while from Antofagasta, Route B-385 (272 km) or Route B-355 are used, which connect to towns such as Toconao and Peine (WSP, 2022).

In terms of port infrastructure, SQM's commercial products, such as lithium carbonate, are mainly transported to the port of Tocopilla (located 370 km from the Salar de Atacama). Alternatively, the port of Mejillones, 310 km from the Salar de Atacama, is used (WSP, 2022). In the case of Albemarle, commercial products are transported to the port of Antofagasta, 20 km from the "La Negra" treatment plant (SRK Consulting, 2022).




**Figure 52. Main ports in northern Chile**
Source: CAMPORT, 2023.

### 7.1.2. Maricunga Salt Flat

Located in the Atacama region, in the Altiplano of northern Chile, the Maricunga Salt Flat is part of a 2,195 km² hydrographic basin and covers an area of approximately 142.2 km². The core of the salt flat is at an average altitude of 3,750 meters above sea level (masl), within a range that varies between 3,738 and 6,749 masl, making it one of the highest salt flats in the lithium triangle (Worley, 2022).

Maricunga's climate is typical of cold, high-altitude deserts, with low humidity, strong temperature fluctuations, and irregular rainfall. Rainfall is concentrated in the form of summer storms between December and March, and snowfall from May to September. The average maximum temperature in January is 18.8 °C, while the overall average between October and March is 9.1 °C. During the winter, precipitation reaches 72 mm, falling to about 1 mm in summer (CIREN Institutional Observatory, n.d.).

Solar radiation in the SIMCO SpA project area located in the Salar is high due to its altitude and clear skies. The annual average is 298 W/m², with maximums exceeding 1,000 W/m² around midday.

Combined with temperatures that rarely exceed 7.5 °C, these conditions favor high natural evaporation, which is relevant for brine concentration processes (Garces, 2020).

The flora of the Salar consists mainly of herbaceous scrub and shrubs adapted to the altitude, with 29 species identified, 20% of which are endemic. The vegetation is concentrated on the edges of the salt flat and in nearby wetlands, such as the Santa Rosa lagoon, a Ramsar site integrated into the Nevado Tres Cruces National Park (Worley, 2022).

In terms of fauna, three species of flamingos inhabit its saline wetlands, in addition to vicuñas, guanacos, foxes, and vizcachas, which depend on the high Andean grasslands and wetlands for their survival. The salt flat is located within a fragile ecological environment that is highly sensitive to human intervention (Worley, 2022).

From a cultural point of view, the Maricunga Salt Flat is part of the ancestral territory of indigenous Collas communities, such as Pai Ote, which still maintain a presence and cultural links with the environment. The spiritual and territorial connection with the Santa Rosa lagoon and the national park reinforces its socio-environmental value (Gutiérrez, 2023).

Access to the salt flat is from the city of Copiapó, 160 km to the southwest, via the CH-31 international highway. This road is paved for 75% of the route, with the remainder being a section of gravel in good condition. The main port facilities associated with projects in the salt flat are the port of Caldera, about 80 km west of Copiapó, and the port of Chañaral, 250 km from the salt flat, both with capacity for bulk cargo and fuel (Worley, 2022).

### 7.1.3. Salar de Olaroz

The Salar de Olaroz is located in the Puna region, northwest of the province of Jujuy, Argentina. This elevated Andean plateau has an average altitude of 3,700 meters above sea level, while the salt flat is located between 3,900 and 3,950 meters above sea level (Alonso, 2017). The salt flat extends for about 40 km from north to south and 10 to 15 km from east to west (Allkem, 2023), and is part of an extensive saline basin shared with the Cauchari salt flat. Its privileged location within the Olaroz-Cauchari Provincial Flora and Fauna Reserve reinforces its environmental and strategic value.

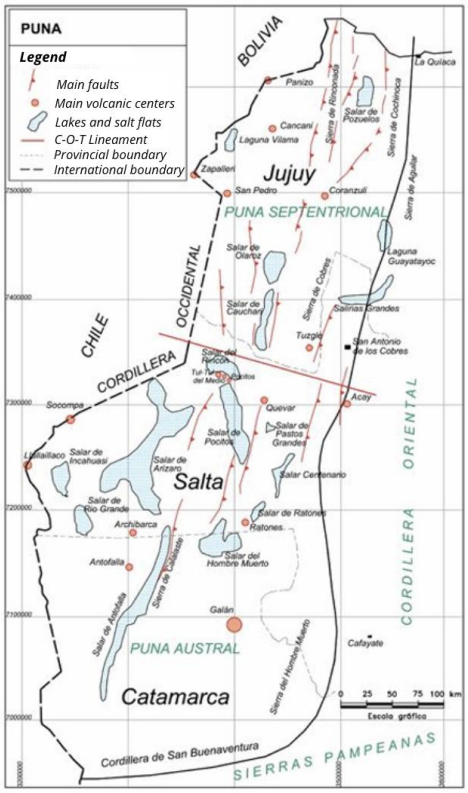



**Figure 53. Major geological features of the Argentine Puna and main salt flats**
Source: Alonso, 2017.

The climate is cold and dry, typical of high mountains, with average annual temperatures of 6.3 °C, extreme winter temperatures that can drop between -25 °C and -30 °C, and summer highs of up to 25 °C. Rainfall is scarce, with an annual average of 49.5 mm, concentrated in brief summer storms between December and March. The rest of the year remains practically dry. Interannual variability is influenced by ENSO events (Allkem, 2023).

Solar radiation is high, with an annual average of 660 W/m². During the summer, peaks of up to 755 W/m² are reached, while in winter the values drop to a minimum of 390 W/m² in June. Data dispersion is greater in the summer months. This is due to the effect of cloud cover, which appears to be greater in summer and spring (Lithium Americas, 2020).

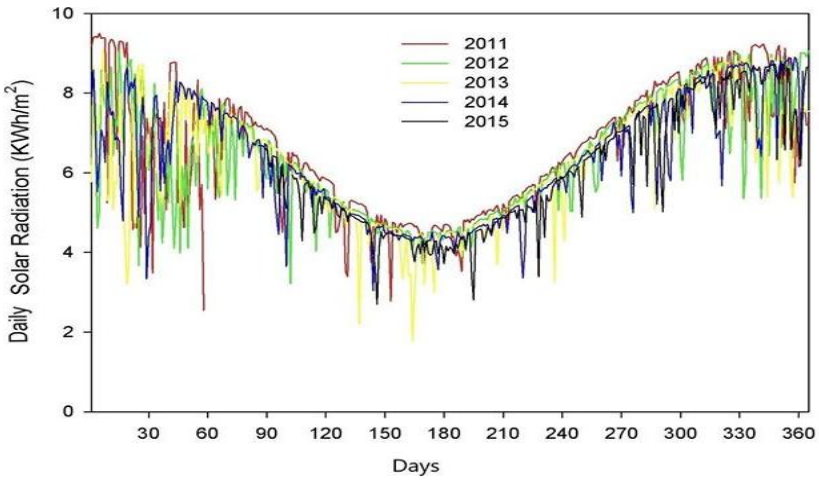



**Figure 54. Solar radiation for the period 2011-2015**
Source: Lithium Americas, 2020.

The flora of the salt flat is dominated by xerophytic species adapted to salinity, winds, and extreme radiation. Low-lying woody herbaceous plants, grasses, and cushion species predominate. The core of the salt flat lacks vegetation, which is concentrated on its margins, meadows, and peladales. Vegetation units have been identified as yareta shrub steppes, Sporobolus and Festuca herbaceous steppes, and sterile areas with high salinity (Allkem, 2023).

The fauna includes 49 identified species, with five resident mammals, 40 bird species, and some reptiles and amphibians. Notable species include the vicuña (Vicugna vicugna) and the llama (Lama glama), along with predators such as foxes (Lycalopex) that hunt rodents such as the tuco-tuco (Ctenomys opimus). In the wetlands and edges of the salt flat, species such as the Puna rail, the lesser rail, and the oquencho can be observed. Thanks to conservation initiatives, the vicuña has been classified as a species of "Least Concern" by the Union for Conservation of Nature since 2008 (Lithium Americas, 2020).

The communities that settle in these localities of the Argentine Puna are recognized as descendants of pre-Hispanic peoples, claiming their pre-existence in the territories that later became national states. In the case of Susques, there are ten indigenous communities: El Toro Rosario de Susques, Huancar, Pórtico de los Andes, Olaroz Chico, Del Valle de Piscuno, Termas de Tuzgle, Los Manantiales de Pastos Chicos, Catua, Paso de Jama, and Coranzulí (Pragier, 2021).

Road access to the Olaroz Salt Flat is from San Salvador de Jujuy, following National Route 9 to Purmamarca, and then National Route 52 through the Jama Pass. This fully paved highway crosses the border with Chile and connects to the ports of Antofagasta (570 km) and Mejillones (600 km), facilitating the export of products such as lithium carbonate. To access the salt flat directly, take gravel road 70, which runs along the western edge of the salt flat, allowing access to the project's mining facilities (Allkem, 2023).

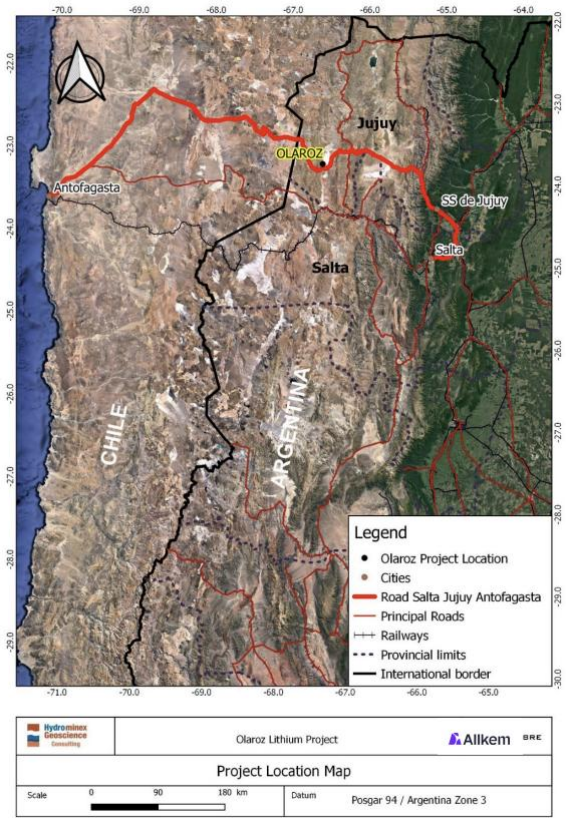



**Figure 55. Accessibility of the Olaroz project**
Source: Allkem, 2023.

### 7.1.4. Salar del Hombre Muerto

Located in the northwest of the province of Catamarca, on the border with Salta, the Salar del Hombre Muerto covers approximately 588 km² in a high mountain environment at 4,000 meters above sea level. This evaporite basin sits on geological formations dating from the Precambrian to the Cenozoic era and contains brines rich in lithium, potassium, sodium, boron, cesium, rubidium, and bromine, making it one of the most important salt flats in the lithium triangle (Vinante and Alonso, 2006).

The climate is desert and high mountain, with an average annual temperature of 5 °C and extremes ranging from -30 °C at night in winter to 27 °C during the day in summer. The daily temperature range can reach 35 °C, and the winds are persistent, with gusts exceeding 120 km/h. Average annual precipitation is approximately 100 mm, concentrated in the summer months (December to March), mainly in the form of convective storms. The higher areas of the salt flat may receive light snowfall during the winter (Livent, 2023).

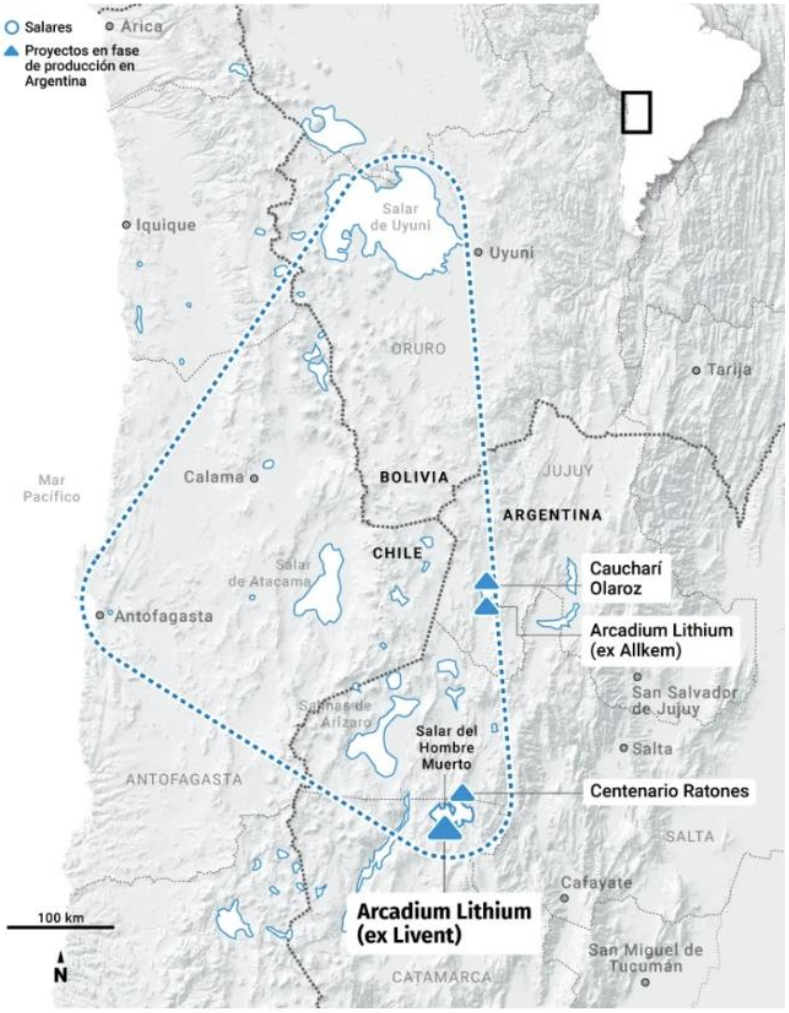



**Figure 56. Geographic location of the main salt flats within the lithium triangle**
Source: Ruido, 2024.

Direct solar radiation reaches maximum values of up to 1,200 W/m², with an annual average of approximately 530 W/m², which, together with the dry and cold conditions, favors a high evaporation rate, essential for lithium concentration processes.

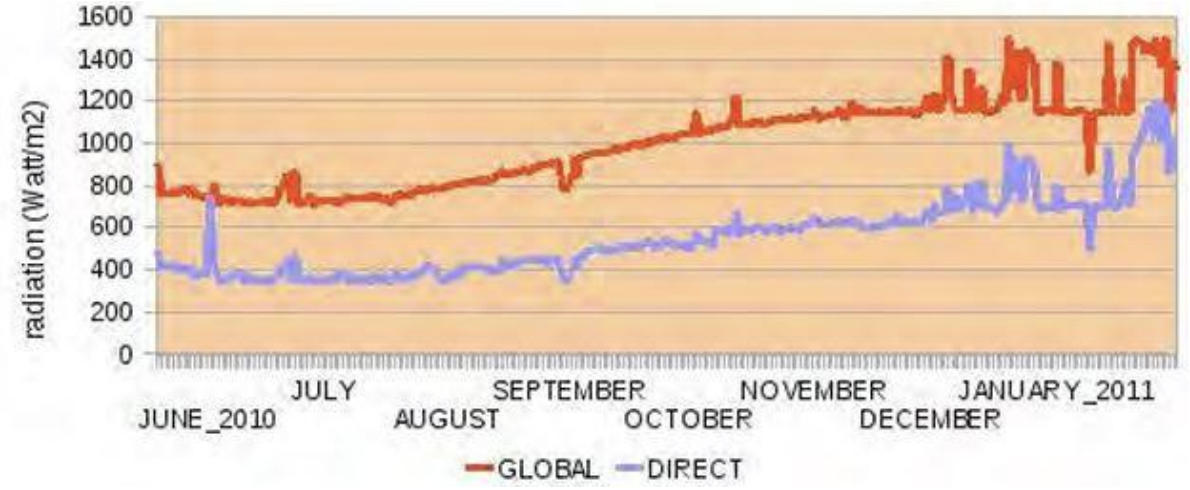



**Figure 57. Maximum solar radiation measured between May 2010 and January 2011 in Salar del Hombre Muerto**
Source: Lithium Americas, 2011.

In terms of flora, vegetation is sparse and adapted to extreme aridity. It is concentrated in meadows and riparian corridors, where grasses and phreatophytes predominate. Twenty-eight species belonging to 12 botanical families have been identified, including Asteraceae, Cactaceae, and Chenopodiaceae. Of particular note is the copana cactus (Maihueniopsis glomerata), classified as "Least Concern" in conservation (Lithium South, 2023).

The local fauna is adapted to the hostile environment of the highlands. Notable mammals include the vicuña (Vicugna vicugna), the culpeo fox (Lycalopex culpaeus), the vizcacha (Lagidium viscacia), and the tuco-tuco (Ctenomys opimus). Semi-wild donkeys have also been recorded. In terms of birdlife, 15 species of birds have been identified, including the mountain finch, the collared dove, the puna miner, the mountain caracara, and the gray hawk. In addition, an endemic reptile has been recorded: the Liolaemus poecilochromus lizard (Lithium South, 2023).

The salt flat is part of the ancestral territory of the Atacameños del Altiplano indigenous community, and there are archaeological remains in the surrounding area (AIDA Americas, 2024). The nearest town is La Redonda, 25 km away, inhabited by llama and sheep herders. The most important municipality in the area is Antofagasta de la Sierra, 100 km south of the salt flat, which has basic services, an airstrip, and regional connectivity (Livent, 2023).

Access to the salt flat can be gained from the city of Salta (380 km to the northeast), using National Route 51 and Provincial Routes 27 and 17; or from Catamarca (650 km to the south), via National Route 40 and Provincial Route 43. For exports, the salt flat is connected to the port of Antofagasta (Chile), 675 km away, via an international road corridor that includes Argentine provincial routes and the Pan-American Highway North 5 in Chile (Livent, 2023).

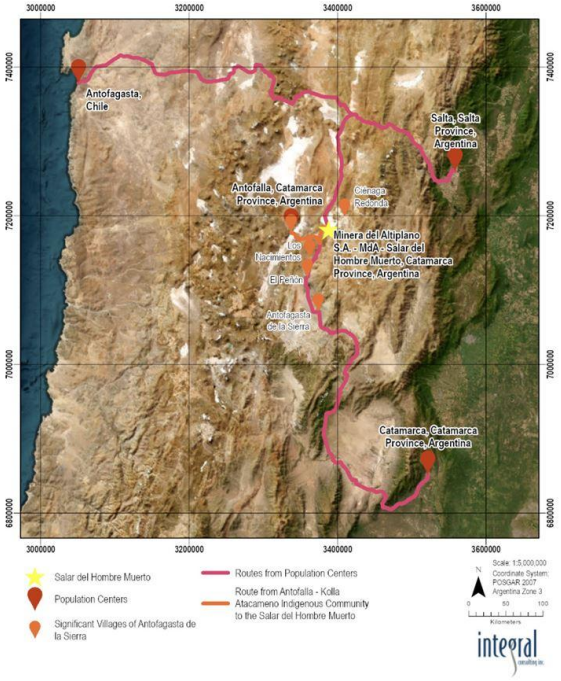



**Figure 58. Accessibility of Salar del Hombre Muerto**
Source: Livent, 2023.

### 7.1.5. Salar de Uyuni

Located in the province of Daniel Campos, in southwestern Bolivia, the Salar de Uyuni is the largest salt flat in the world, with an area of 10,500 km² and an average altitude of 3,656 meters above sea level (Schmidt et al., 2011). Formed by alternating layers of halite and lacustrine clay sediments, its upper layer can reach up to 11 meters in thickness, storing brines rich in sodium chloride, potassium, lithium, boron, sulfate, and magnesium, which gives it enormous potential as a strategic source of lithium globally (Woong An et al., 2012).

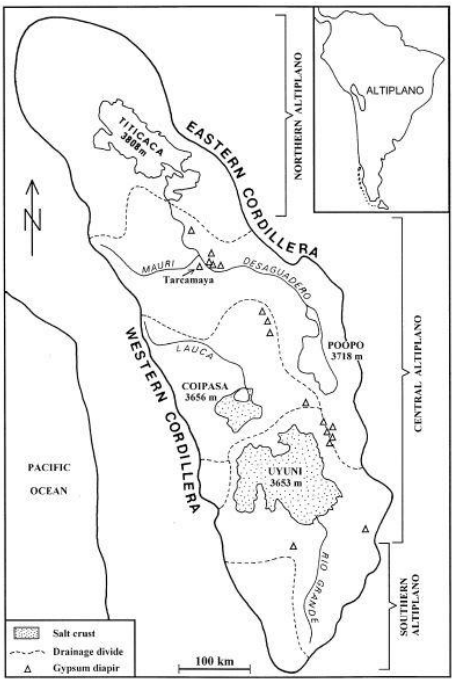



**Figure 59. Extent and altitude of the Salar de Uyuni**
Source: Risacher and Fritz, 2000.

The climate is marked by two distinct seasons:

- Wet season (December to March): rainfall between 200 and 250 mm/year, with average temperatures of 10.7 °C, highs of 19 °C, and lows close to 0 °C (Mondaca, 2021).

- Dry season (April to November): very low rainfall (1–2.5 mm/month), average temperatures of 6.3 °C, with highs of 18 °C and lows of up to -4 °C (Climate data, 2021).

Solar radiation is intense throughout the year. During the dry season (May–November), averages reach 777 W/m², with peaks exceeding 1,000 W/m², while in the wet season, radiation fluctuates between 500 and 920 W/m² (Global Solar Atlas, n.d.).

The flora consists of species adapted to the altitude and aridity: giant cacti (Echinopsis atacamensis, E. tarijensis), shrubs such as thola (Baccharis dracunculifolia), pilaya, queñua, and quinoa plants in the surrounding areas. These species play a vital role in the stability of the Andean ecosystem.



**Figure 60. Giant cacti on Incahuasi Island in the center of the Salar de Uyuni**
Source: Vulkaner, n.d.

In terms of fauna, the salt flat is an important breeding habitat for three species of South American flamingos: the Andean flamingo, the Chilean flamingo, and James's flamingo, the latter being the rarest. In addition, more than 80 species of birds have been recorded, including the horned coot, the Andean goose, and the Andean mountain starling. On the mainland, the Andean fox (culpeo) and colonies of vizcachas on inland islands such as Incahuasi stand out (Vulkaner, n.d.).



**Figure 61. Incahuasi Island in the center of the Salar de Uyuni**
Source: Vulkaner, n.d.

From a sociocultural perspective, the salt flat is located between three indigenous territories recognized since 1949:

- To the north, the Aymara province of Daniel Campos.
- To the south, the Quechua-speaking province of Nor Lípez.
- To the east, the predominantly Quechua province of Antonio Quijarro.

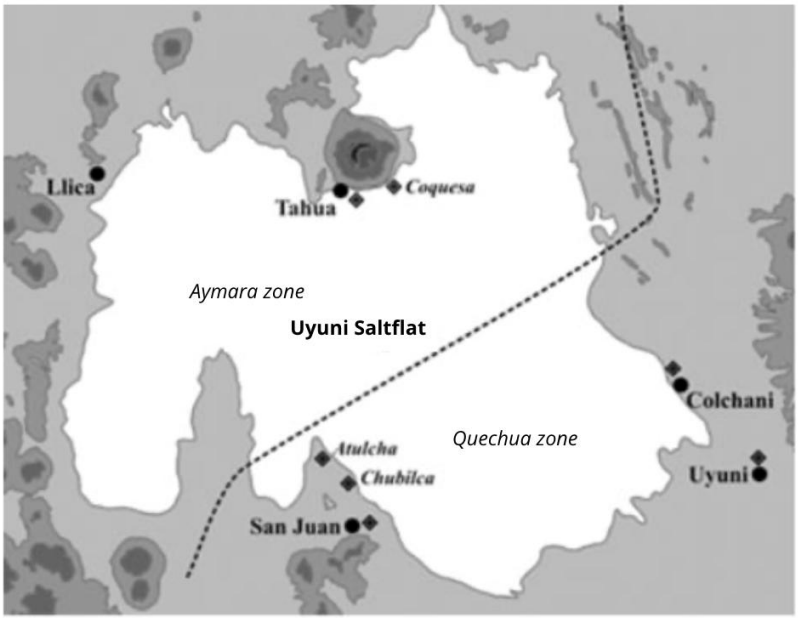



**Figure 62. Sociocultural distribution of the Salar de Uyuni**
Source: Cruz, 2009.

The city of Uyuni (20,000 inhabitants), located on the edge of the salt flat, acts as a logistical hub, with Joya Andina Airport, accommodation, basic services, and land connections. Around the salt flat are communities such as Colchani (dedicated to artisanal salt production), San Juan (famous for its 17th-century church and pre-Hispanic ruins), Tahua, and Coquesa, both located on the slopes of the Tunupa volcano and known for their natural and cultural heritage.

In terms of accessibility, Bolivia has planned the development of the Lithium Corridor, which connects Uyuni with the Chilean border at Hito 60 (300 km). However, the sections between Uyuni and the border are not yet paved. On the Chilean side, there are 224 km of road to the port of Iquique, of which 200 km are high-standard paved roads built by the Doña Inés de Collahuasi mining company, while the remaining 24 km between Tenencia Ujina and the border still require improvements. Once completed, the entire stretch from Uyuni to Iquique will provide a direct connection between the world's largest salt flat and the Pacific ports, enabling its logistical integration into international markets (Orostica, 2022).




**Figure 63. Bioceanic corridors project**
Source: Oróstica, 2022.

## 7.2. Upcoming projects

The so-called Lithium Triangle, made up of Argentina, Bolivia, and Chile, accounts for more than 50% of the world's lithium resources contained in brines. In recent years, this region has seen an intensification of exploration and project development, consolidating its position as one of the main strategic hubs for the global energy transition.

Table 16 presents a detailed inventory of the most advanced projects in this region, with the aim of providing an integrated overview of the current status of the most relevant initiatives in the lithium industry. The projects considered cover various stages of development, from preliminary studies (PEA/PFS) through construction and pilot testing to early commercial phases.

This information gathering allows us to quantify the expected installed capacity by 2030, identify the estimated contributions by country, and highlight technological trends, common challenges, and emerging opportunities.

The information presented was compiled from multiple publicly available sources, including official websites of operating companies and parent companies, technical reports, and financial updates published under international standards (such as NI 43-101 and JORC). Data traceability and reliability were prioritized to ensure an accurate representation of the current and future landscape in the region.

**Table 16. List of advanced projects in Argentina, Chile, and Bolivia**
Source: Prepared internally based on Goldman Sachs, 2023; International Lithium Association, 2024; Farahbakhsh et al., 2024; and others, 2023.

| Company | Project | Project country | Status | Type Technology | Estimated average annual production |
|---|---|---|---|---|---|
| Ganfeng Lithium Co. Ltd. (46.66%)<br>Lithium Argentina (44.84%)<br>Jujuy Energy and Mining (8.5%) | Cauchari - Olaroz | Argentina | In Operation | Conventional | Stage 1: 40,000 t/yr LCE, Stage 2: expansion of at least 20,000 t/yr LCE |
| Eramet | Centenario-Ratones | Argentina | In operation | DLE (Adsorption) | 24,000 t/yr LCE |
| Rio Tinto | Fenix (Hombre Muerto) | Argentina | In Operation | DLE (Adsorption) | 32,000 t/yr LCE |
| Ganfeng Lithium | Mariana | Argentina | In Operation | Conventional | 20,000 t/yr LiCl |
| Rio Tinto (66.5%)<br>Toyota Tsusho (25%)<br>Jujuy Energy and Mining (8.5%) | Olaroz | Argentina | In operation | Conventional | 43,000 t/yr LCE |
| POSCO | Gold Salt | Argentina | In Operation | Conventional | 48,000 t/yr LCE |

| | | | | | |
|---|---|---|---|---|---|
| **Galan Lithium Limited** | Hombre Muerto Oeste | Argentina | Under Construction | Conventional | 12,000 t/year LCE \| HMW Phase 2 commercial-scale mining permit granted for up to 21,000 t LCE |
| **Argosy Minerals** | Rincón | Argentina | Under construction | Conventional | 10,000 t/yr LCE |
| **Revotech Asia Ltd. (46%)**<br>**Tibet Summit Resources Co. (45%)**<br>**Leading Resources Global Ltd. (9%)** | Los Angeles Salt | Argentina | Under Construction | Conventional | 20,000 t/yr LCE |
| **Rio Tinto** | Sal de Vida | Argentina | Under construction | Conventional | Stage 1: 15,000 t/yr LCE, Stage 2: 45,000 t/yr LCE |
| **Zijin Mining Company** | Tres Quebradas | Argentina | Under Construction | Conventional | Stage 1: 20,000 t/yr LCE, Stage 2: 30,000 t/yr LCE |
| **Lake Resources (75%)**<br>**Lilac Solutions Inc. (25%)** | Kachi | Argentina | Feasibility | DLE (Ion Exchange) | 50,000 t/yr. LCE |
| **Lithium Argentina (85%)**<br>**Ganfeng Lithium Group (15%)** | Pastos Grandes | Argentina | Feasibility | Conventional | 24,000 t/yr. LCE |
| **Ganfeng Lithium** | Pozuelos (PPG) | Argentina | Feasibility | Conventional | 25,000 t/yr LCE |

| | | | | | |
|---|---|---|---|---|---|
| Rio Tinto | Salar del Rincón | Argentina | Feasibility | Conventional | 60,000 t/yr LCE |
| Lithium Chile Inc. (80%)<br>SMG S.R.L. (20%) | Arizaro | Argentina | Pre-feasibility | DLE (No information) | 25,000 t/yr LCE |
| Austroid Corp. | Caucharí | Argentina | Pre-feasibility | DLE (No information) | 40,000 t/yr. LCE |
| Rio Tinto | Caucharí Salt Flat | Argentina | Pre-feasibility | Conventional | 25,000 t/yr LCE |
| Galan Lithium Limited | Candelas | Argentina | Preliminary Economic Assessments | Conventional | 14,000 t/yr |
| Lithium South Development Corp. (70%)<br>Sino Lithium Materials Pty Ltd (30%) | Hombre Muerto Norte | Argentina | Preliminary Economic Assessments | Conventional | 15,600 t/yr LCE |
| Alpha Lithium Corporation | Tolillar Salt Flat | Argentina | Preliminary Economic Assessments | DLE (No information) | 25,000 t/yr LCE |
| Albemarle | Atacama | Chile | In operation | Conventional | 80,000 t/yr LCE |
| Codelco (50% +1)<br>SQM (50% -1) | Atacama | Chile | In operation | Conventional | 260,000 t/yr LCE |
| Codelco (50.01%)<br>Rio Tinto (49.99%) | Paloma (stages 1 and 2) | Chile | Under construction | DLE (No information) | 40,000 t/yr LCE |

| | | | | | |
|---|---|---|---|---|---|
| **ENAMI (51%)**<br>**Rio Tinto (49%)** | High Andean Salt Flats | Chile | Preliminary Economic Assessments | DLE (No information) | 50,000 t/yr LCE |
| **YLB - CATL, BRUMP, and CMOC (CBC)** | Salar de Uyuni | Bolivia | Agreement | DLE (Adsorption) | 25,000 t/yr LCE |
| **YLB - Uranium One Group** | Salar de Uyuni | Bolivia | Agreement | DLE (No information) | 14,000 t/yr LCE |
| **YLB - CATL, BRUMP, and CMOC (CBC)** | Salar de Coipasa | Bolivia | Agreement | DLE (Adsorption) | 25,000 t/yr LCE |

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# 8. REGULATORY AND INSTITUTIONAL FRAMEWORK

## 8.1. The triangle and three models: Argentina, Bolivia, and Chile face the opportunity presented by lithium

Over the last two decades, South American countries with abundant lithium resources have deployed various strategies to take advantage of the opportunities offered by their endowment of this mineral. These actions are part of a broader trend associated with the resurgence of natural resource nationalism, which took hold following the commodity price boom that began in 2003. During this period, many countries with abundant natural resources took advantage of this favorable context to increase the economic rents derived from the exploitation of these resources and, in some cases, to promote productive and technological linkages related to extractive activities (Dietsche, 2014; Gudynas, 2016; Haslam & Heidrich, 2016).

Although resource-rich countries face a common international context, the strategies adopted differ significantly. This shows that external conditions alone are not sufficient to explain the nature and scope of the actions taken. Institutional legacies (Johnson et al., 2024; Lee, 2025), the capacities and resources of the state apparatus (Orihuela & Serrano, 2024), as well as the social imaginaries that shape expectations and consensus around the role of lithium in national development (Barandiarán, 2019; Kohl & Farthing, 2012).

The experience of the countries in the lithium triangle—Argentina, Bolivia, and Chile—which account for more than half of the world's lithium resources, is a clear example of this. Policy strategies have not only been very heterogeneous but have also varied over time (Obaya, 2022), generating processes of convergence and divergence within the region. The differences between strategies are reflected in various dimensions, such as the role of the state vis-à-vis the private sector, the type of policies implemented, the level of coordination between them, the volume of resources allocated, etc.

This chapter presents the strategies implemented by Argentina, Bolivia, and Chile to promote economic development processes linked to the lithium industry. To understand the nature and scope of these strategies, two complementary dimensions are addressed. The first corresponds to the regulatory framework governing lithium mining. This is a central element that determines the rights and obligations of the various actors involved, as well as the conditions for access to and use of the resource. The regulatory framework ultimately defines the limits and possibilities of the "policy space" available to governments. The second dimension of analysis focuses on productive and technological policies aimed at developing local capacities, both in extraction activities and in the intermediate and downstream segments of the lithium battery value chain. The chapter concludes with some reflections on the opportunities and challenges facing lithium policy in enhancing the contribution of this sector to the economic development of the countries in the region.

### 8.1.1. Argentina: federalism and openness

The regulatory framework for lithium mining in Argentina is structured around three pillars: the National Constitution, the Mining Code, and the Mining Investment Law. This regulatory framework was established between 1993 and 1997, in the context of the structural reforms promoted in those years, commonly associated with the so-called Washington Consensus. Essentially, these reforms sought to reduce the role of the state in economic activity by privatizing public companies, opening the country to foreign investment, and dismantling the complex web of regulations that governed much of the economy. While many of these reforms underwent a profound reversal after the economic crisis that erupted in December 2001, in the case of mining, they have remained almost unchanged to this day.

The 1994 National Constitution establishes the federal nature of mining in Argentina, in line with the country's political organization. This is a distinctive feature within the lithium triangle, since in neighboring countries the administration of the resource has been centralized by the national government. In Article 124, the Constitution establishes that the provinces have original ownership of the natural resources existing in their territory. Among their various functions, the provinces are responsible for the administration of concessions, the regulation of salt flat exploitation, the implementation of consultation and social participation processes, and the monitoring of mining operations. However, it is important to note that this does not imply that the provinces are solely responsible for mining policy, as there are certain areas in which powers are shared with the national government (Obaya et al., 2024).

The second distinctive feature of Argentina's mining regulatory framework is its openness to private investment and the treatment of lithium as an ordinary mineral resource. As will be seen below, private investment in the mining industry is restricted in Bolivia and Chile due to the strategic nature of lithium in the legislation of those countries. The Argentine Mining Code of 1993 allows individuals or legal entities to acquire ownership of mining holdings through concessions granted by the competent authority. For its part, the **Mining** Investment Law **of 1997 seeks to encourage private investment by offering tax stability for a period of 30 years and benefits that reduce investment costs, especially during the first years of activity.** These benefits include the deduction of prospecting and exploration expenses, accelerated depreciation of investments, and tax exemptions for the importation of capital goods, equipment, and specific inputs. In addition, the law establishes a 3% limit on provincial royalties, calculated on the value at the mine mouth (Jorratt, 2022).

This regulatory framework has been effective in multiplying the number of mining concessions, currently held mainly by foreign private companies (Secretariat of Mining, 2024). This can be seen in the number of lithium projects under development in Argentina, compared to its neighboring countries. However, this has not immediately translated into accelerated progress of projects toward the production phase. For several years, concessions remained at a low level of investment. Their development process began to gradually get underway in 2022.

In August 2024, the Executive Branch of the Nation regulated the Large Investment Incentive Regime (RIGI), following its approval by the National Congress, through Decree 749/2024. This regime, intended for investments exceeding USD 200 million in strategic sectors, including mining, offers benefits that go beyond the Mining Investment Law, providing legal certainty, stability, and incentives for a period of 30 years.

The tax benefits offered by the RIGI include a reduction in the income tax rate from 35% to 25%, the elimination of import duties on capital goods, parts, and inputs, and exemption from export

duties after three years of adherence to the regime. In addition, the obligation to settle foreign exchange earnings from exports in the single exchange market is progressively reduced: to 80% after two years, to 60% after three years, and to 0% from the fourth year onwards. In the lithium sector, the first company with an approved project was Rio Tinto, which plans to invest USD 2.7 billion to begin operations in 2028 in the province of Salta[1].

In contrast to the federal nature of the mining governance regime, the main production and technology policies related to lithium have been promoted mainly by the national government. However, the resources invested have been relatively low, and the actions have not been articulated in a consistent plan. The role of the provinces in the field of industrial policy has been limited. This is largely due to the budgetary constraints faced by subnational governments, especially in areas rich in lithium resources (Obaya et al., 2024).

Between 2010 and 2023, the main focus of promotion has been on science and technology policy. Three instruments stand out in this area. First, the financing of science and technology activities through the salaries of researchers and the stipends of doctoral and postdoctoral fellows from the National Scientific and Technical Research Council (CONICET). In their analysis of the period 2011-2021, Freytes et al. (2022) surveyed a total of 236 researchers and fellows with publications on lithium-related topics, of whom 52% specialize in topics related to batteries and their components.

CONICET has also played an important role in the creation of the Center for Research and Development in Advanced Materials and Energy Storage in Jujuy (CIDMEJU), created in 2017 and based in Palpalá. From an institutional point of view, the center has a triple affiliation, as, together with CONICET, the National University of Jujuy and the government of the province of Jujuy also participate. CIDMEJU's research work focuses on three topics: lithium extraction, batteries, and battery and solar panel recycling. Currently, there are seven researchers, eight technicians, four postdoctoral fellows, and four doctoral fellows working there[2].

The second instrument is managed by the National Agency for the Promotion of Research, Technological Development, and Innovation (Agencia I+D+i), a decentralized national agency that operates under the Ministry of Science, Technology, and Innovation[3]. Between 2012 and 2021, this agency funded 48 projects through various lines of funding, for a total of approximately USD 5.7 million (Freytes et al., 2022).

Finally, the UniLIB project, led by the technology company Y-TEC[4] and the Institute for Theoretical and Applied Physical-Chemical Research (INIFTA)—a center of CONICET and the University of La Plata—is noteworthy. The initiative, launched in 2021, aims to operate a small-scale plant for the manufacture of lithium cells and batteries, with a capacity of 13 MWh per year, and involved an investment of USD 7 million (UNIDO, 2024). This size is equivalent to 1,000 batteries for the stationary storage of renewable energy or 50 for electric buses[5]. The supply of lithium carbonate for the plant's operation, which is low volume due to its scale, would come from lithium companies operating in the country.

[1] See econojournal.com.ar/2025/05/the-government-approved-the-first-rigi-for-a-mining-project-rio-tinto-will-invest-us$2.7-billion-in-salta-for-lithium-production
[2] Source: https://cidmeju.unju.edu.ar/quienes-somos.php.
[3] The Agency was restructured in July 2025 through Decree 447/2025, which modified its structure and functions.
[4] Y-TEC is a technology-based company formed by YPF and the National Scientific and Technical Research Council of Argentina (CONICET).
[5] For more information, see https://www.argentina.gob.ar/noticias/llegaron-las-maquinas-para-la-primera-planta-argentina-de-desarrollo-de-baterias-de-litio

The main objective of the project is to disaggregate the technology package for the design and manufacture of lithium-ion battery cells and to train qualified human resources in this field[6]. The project envisages sources of demand driven by the public sector, including purchases by the Ministry of Defense for military applications and acquisitions by the Renewable Energy Project in Rural Markets in the Province of Buenos Aires. In addition, the possibility of establishing agreements with local companies engaged in the production of electric vehicles and buses is being evaluated (UNIDO, 2024).

As noted, these instruments were developed mainly between 2010s and 2023. Beginning in 2024, funding for science and technology policy, as well as other industrial policy instruments, was virtually eliminated. The projects, therefore, rely heavily on external sources of financing.

The provinces focused on maximizing the hiring of local personnel and suppliers in the development of lithium mining. The main mechanism for achieving this objective has been minimum local content regulations. This requirement has been formalized in Salta (Provincial Law No. 8164) and Catamarca (Resolution of the State Secretariat of Mining No. 498/14), which establish minimum levels of participation by local suppliers and labor at around 60-70% (Obaya et al., 2024).

For several years, the province of Jujuy has taken a more active approach to promoting the development of local technological capabilities related to lithium mining. In 2011, the province declared lithium a resource of strategic interest through Decree-Agreement No. 7592, considering it a "generator of socio-economic development." Within this framework, it created the public institution Jujuy Energía y Minería Sociedad del Estado (JEMSE). This company has an 8.5% stake in Sales de Jujuy (currently alongside Rio Tinto and Toyota Tsusho), which has been producing lithium compounds since 2015, and Minera Exar (alongside Lithium Argentina and Ganfeng), which began production in 2023. This stake gives JEMSE the right to priority sales of 5% of the lithium carbonate produced by the companies. Through this instrument, JEMSE sought to attract private companies to process the lithium compounds produced in the province of Jujuy. However, the company failed to make progress on any of the announced projects.

This result can be explained by several factors. The quota offered represented too small a volume, and no preferential price was offered. Furthermore, the conditions of the productive fabric of the province of Jujuy are less favorable than those of other more industrially developed provinces, where lithium processing could be carried out under more favorable conditions (Obaya et al., 2021).

In 2022, the provinces of Catamarca, Salta, and Jujuy formed the Lithium Mining Region. The decision was interpreted as a way of reaffirming their control over mining resources in the face of a series of projects to modify the regulatory framework in the National Congress, and was discussed in the public arena, which sought greater state intervention in the sector. Formally, the Region aims to improve the competitiveness of the sector and promote the development of the resource-rich geographical area[7]. From a governance perspective, the region is led by the Regional Lithium Committee, made up of the highest-level mining authority in each of the provinces (ministers of Mining or Production). In addition, national authorities from the areas of the Interior, Productive Development, Science, Technology, and Innovation were invited[8]. The committee aims to coordinate requirements between the provinces and the nation throughout the lithium value chain.

[6] For more information, see https://periferia.com.ar/innovacion/unlp-avanza-la-puesta-en-marcha-de-la-primera-planta-de-baterias-de-litio/
[7] For more information, see https://www.salta.gob.ar/prensa/noticias/salta-jujuy-y-catamarca-dejaron-oficialmente-conformado-el-comite-regional-del-litio-82187
[8] For more information, see https://www4.hcdn.gob.ar/dependencias/dsecretaria/Periodo2023/PDF2023/TP2023/2372-D-2023.pdf

Among the measures adopted by the Region, it was agreed to create a support system aimed at prioritizing the hiring of local suppliers, with the objective of boosting employment in areas directly linked to the activity. This scheme establishes an order of priority that favors, first, suppliers from the province where the project is being developed; second, suppliers from the Lithium Mining Region; and, finally, other suppliers of national origin[9].

### 8.1.2. Bolivia: state nationalism

The Bolivian strategy can be characterized as the antithesis of the Argentine case (Obaya, 2022). Its origin lies in a nationalist policy that, since the beginning of Evo Morales' government in 2006, has promoted a strategic vision for the country's natural resources. In the case of lithium, the policy was based on a state monopoly on the exploitation of evaporative resources, which excluded the participation of private companies in this segment of the value chain (Nacif, 2012; Olivera, 2017). However, as will be discussed below, this nationalist stance began to soften in 2019, allowing, under certain conditions, the participation of foreign companies in the extractive sector.

The background to Bolivia's lithium strategy dates back to 2007. As part of an agenda to nationalize natural resources, the Regional Federation of Rural Workers of Southwestern Potosí (FRUTCAS) presented President Morales with a proposal for the state to take over the industrialization of Uyuni's evaporative resources, without the participation of transnational companies. That same year, Law No. 3,720 restored to the Bolivian Mining Corporation (COMIBOL) exclusive authority over the exploration, exploitation, industrialization, commercialization, and administration of fiscal mining reserves.

Since then, a regulatory framework has been developed that positions the state as a central actor in the development of the sector. In 2008, Supreme Decree No. 29,496 declared "the industrialization of the Salar de Uyuni a national priority for the productive, economic, and social development of the Department of Potosí" (art. 1). Within this framework, COMIBOL was allocated an initial budget of $5.7 million, which was to be executed by the National Directorate of Evaporative Resources (DNRE), established through COMIBOL Resolution No. 3,801. This entity would assume responsibility for the exploration, exploitation, industrialization, and commercialization of the salt flat's resources.

The strategic role of natural resources in the Morales government's vision of development was consolidated with the enactment of the new Political Constitution of the State (CPE) in 2009. The Constitution explicitly recognizes the strategic nature of evaporative resources and establishes state control over their management. Article 348, paragraph II, declares natural resources to be "strategic and of public interest for the development of the country." Article 349, paragraph I, affirms that the Bolivian people are the "direct, indivisible, and imprescriptible" owners of these resources, delegating their administration to the state in accordance with the collective interest. Likewise, Article 350 grants the national State authority over all fiscal reserves, while Article 351, paragraph I, confers upon it "control and direction over the exploration, exploitation, industrialization, transportation, and commercialization of strategic natural resources." Finally, Article 369, paragraph II, grants strategic status to evaporative resources in brines and provides for the cancellation, within one year, of all mining concessions—for metallic, non-metallic, evaporative, salt flat, and sulfur minerals—granted in fiscal reserves.

In 2010, the National Strategy for the Industrialization of Evaporative Resources (hereinafter, the Strategy) was presented, which was consolidated as the programmatic axis of state policy for the

[9] For more information, see https://regionnortegrande.com.ar/noa-mesa-del-litio-articula-por-el-empleo-y-la-contratacion-de-proveedores-locales/

development of the lithium industry. That same year, the DNRE was elevated to the rank of National Evaporite Resources Management (GNRE), assuming responsibility for implementing and managing the Strategy.

The Strategy aimed to comprehensively develop the value chain of lithium and other evaporative resources, covering the extraction, industrialization, and commercialization of lithium, cathode materials, and lithium-ion batteries. The project included the construction of industrial plants for lithium carbonate (and also potassium salts), based on processes previously developed on a pilot scale by the national government. In parallel, and following the same logic of moving from pilot plants to industrial production, the strategy aimed to develop the manufacture of electrodes and lithium-ion batteries. However, in these more advanced links of the value chain, the possibility of incorporating private partners—including foreign companies—was envisaged, provided that the Bolivian state retained a majority stake in the projects.

From a programmatic point of view, the Strategy proposed a plan to be developed in three phases, extending until 2016 and financed by the Central Bank of Bolivia (Table 17).

**Table 17. Phases of the National Strategy for the Industrialization of Evaporative Resources in Bolivia.**
Source: Obaya (2019), based on GNRE (2011).

| Phase | Description | State investment (in millions of dollars) | Financing | Estimated year of production | Technology |
|---|---|---|---|---|---|
| 1 | Research and pilot plants. Research and technological development process for salt flat exploitation. Construction and commissioning of pilot plants for potassium salts (potassium chloride and potassium sulfates) and lithium carbonate. | 10 | 100% Bolivian state | 2012 | Bolivian |
| 2 | Industrial plants. Construction and commissioning of industrial plants for lithium carbonate (30,000 t/year) and potassium salts (700,000 t/year). | 485[a] | 100% Bolivian state | 2016 | Bolivian |
| 3 | Lithium industrialization. Production of cathode materials, electrolytes, and lithium-ion batteries. | 400 | 100% Bolivian state | 2014 | Partners for technology transfer |

[a] According to GNRE (2010), the distribution of investment would be: USD$255 million for the potassium chloride plant, USD$174 million for the lithium carbonate plant, and USD$56 million for infrastructure works.

The implementation of the plan faced significant delays. In 2017, the government created the strategic public company Yacimientos de Litio Bolivianos (YLB). This measure, which had been on the government's agenda since the failed attempt to create a public company in 2010, was intended to prioritize the national strategy and provide it with a management team with greater autonomy, less constrained by the bureaucratic procedures of COMIBOL (Montenegro Bravo, 2018).

The creation of YLB marked a turning point in Bolivia's strategy. Starting in 2017, the company began negotiations with international companies interested in becoming strategic partners. To participate, they had to meet four requirements: i) agree to sign a partnership agreement guaranteeing the state a majority stake (51%); ii) have proven experience and cutting-edge technology for the installation and operation of the planned plants, as well as any additional ones that might be proposed; iii) ensure a market for products manufactured in Bolivia, particularly lithium-ion batteries; and iv) commit to processing the waste generated (Montenegro Bravo, 2018).

After a process of negotiations, in April 2018, YLB chose the German company ACI Systems as its partner. In December 2018, Supreme Decree No. 3738 established the YLB-ACI joint venture, which would be mandated to produce lithium salts. However, shortly thereafter, this partnership was dissolved by President Evo Morales in response to growing protests and demands in the region, led by the Potosí Civic Committee (COMCIPO)[10].

Without foreign partners, the Strategy launched in 2010 entered a phase of stagnation, which deepened during the government that took power after the coup against Evo Morales. With the government of Luis Arce, which took office in November 2020, a new approach to policy was introduced. In parallel with the development of the Strategy, a new line of work was opened, focusing on the production of lithium compounds using direct extraction technologies (EDL). These methods allow lithium to be separated from other ions present in brines, such as magnesium or sodium, with the aim of reducing—or even eliminating—the need for the traditional evaporation process. Direct extraction includes various techniques, including the use of ion exchange resins, electrochemical pumping systems, and nanofiltration processes (Bunel, 2024).

To advance in this area, in 2021, the government issued a call for international companies interested in conducting pilot tests of EDL technologies in the country's salt flats. Of the twenty companies that applied, in January 2023, it selected the Chinese consortium CBC, made up of Contemporary Amperex Technology Co., Limited (CATL), Guangdong Brunp Recycling Technology Co., and CMOC Group Limited. The agreement signed with this consortium provides for the installation of two industrial plants in the Coipasa and Uyuni salt flats, with an individual production capacity of 25,000 tons per year of battery-grade lithium carbonate, and a joint investment of more than $1 billion[11].

In June 2023, two additional agreements were signed with the Russian company Uranium One Group and the Chinese company Citic Guoan. The processing plants, which would be located in Uyuni and Pastos Grandes, represent a total investment of $1.4 billion and are projected to reach a combined annual production of 50,000 tons of lithium carbonate[12].

In January 2024, YLB launched a new international tender to develop lithium projects in seven salt flats using EDL technologies. In May, 21 companies were selected to advance to the next phase of the process, in which they must demonstrate their financial capacity to carry out the projects[13]. In September 2024, YLB signed a contract with Uranium One Group for the development of a direct lithium extraction plant with an annual production capacity of 14,000 tons. The works, which are expected to take 30 months, will begin once the contract is approved by the Bolivian legislature[14] [15].

[10] The arguments put forward by regional leaders opposed to the joint venture were that the distribution of profits was unfavorable to the Department of Potosí and, more broadly, contrary to the national interest. A more detailed analysis of these arguments can be found in Fundación Solón (2019).
[11] For more information, see https://www.ylb.gob.bo/resources/img/31012023.pdf.
[12] Sourcehttps://www.mhe.gob.bo/2023/06/29/bolivia-da-el-segundo-paso-trascendental-en-su-politica-de-industrializacion-del-litio-con-la-firma-2-convenios-con-los-gigantes-de-esta-industria-en-el-mundo-citic-goan-lider-en-el-manejo-de-tecno/
[13] For more information, see https://www.ylb.gob.bo/node/85
[14] For more information, see https://www.ylb.gob.bo/node/113
[15] For more information, see https://www.ylb.gob.bo/node/114

It is important to note that, to date, none of the agreements signed have been approved by Congress, which is an essential condition for the projects to go ahead. As in the past with the signing of the joint venture with ACI Systems, various civic organizations in the Potosí region have expressed their rejection of the new agreements, questioning the real benefits they would bring to the region.

### 8.1.3. Chile: towards a public-private model

Chile offers a case that falls between Argentina's liberal model and Bolivia's nationalist statism. As in the latter, lithium is considered a strategic resource in Chile that cannot be concessioned. However, the rationale for this measure differs from that adopted in Bolivia, as it was based on the classification of lithium as a material of nuclear interest in 1965. The declaration not to allow the concession of lithium was adopted in 1979 through Decree Law No. 2,886. Since then, a regulatory framework has been developed, including the Political Constitution of the Republic (1980) and the Mining Code (1983), which establishes that lithium exploration and exploitation can only be carried out through the following modalities: directly by the State, through state-owned companies, or through administrative concessions and special operating contracts granted to private actors (Lagos, 2018; Poveda, 2020)[16].

There is one exception in this regulatory framework that has been key to the development of the Chilean lithium industry: mining properties that had been established, or were in the process of being established, before 1979 were excluded from the non-concessionary regime. Among these properties were the holdings of the Corporation for the Promotion of Production (CORFO) in the Atacama salt flat[17]. It was precisely on the basis of the contracts signed by CORFO between 1988 and 1995 that the operations currently active in the country were developed, under the management of the companies SQM and Albemarle. Until the early 2010s, Chile was the world's leading lithium producer. This position was clearly taken over by Australia in 2017, when a large number of lithium operations in rock deposits came into production.

In this context, in 2014, then-President Michelle Bachelet created the National Lithium Commission (CNL), composed of 18 high-level experts from the public and private sectors and chaired by the Minister of Mining. Chile's relative delay contrasts with the scenario of growing global demand for lithium. The National Lithium Commission (CNL) was mandated to identify the opportunities offered by this mineral to diversify Chile's productive matrix, strengthen its position in the international market, and promote the generation of added value through the development of productive chains. This analysis had to consider both the opportunities and the tensions and externalities associated with mining activity, particularly its relationship with other natural resources and its impact on communities, with the aim of promoting a sustainable development model.

After months of work, in 2015, the CNL formulated a set of recommendations aimed at strengthening the role of the State in lithium governance and promoting the sustainable development of the salt flats. First, it highlighted the need to create a specialized institutional framework for the management and supervision of the salt flats, which would allow the State to reduce information asymmetries with companies and build technical and regulatory capacities. It also proposed that the state participate directly in lithium exploitation through CODELCO, ENAMI,

[16] The pillars of this regulatory framework are the 1980 Constitution of the Republic of Chile (CPR), the 1982 Organic Constitutional Law on Mining Concessions (Law No. 18,097), and the 1983 Mining Code (Law No. 18,248).
[17] Other holdings that met the same conditions include those of the National Copper Corporation (CODELCO) in the Pedernales and Marincunga salt flats, and those of the National Mining Company (ENAMI) in the Aguilar, Infieles, and Cototos salt flats.

or a new state-owned company, taking advantage of CORFO's mining assets and enabling public-private partnership schemes.

The CNL also recommended adopting the concept of shared value in relations with communities, guaranteeing their right to receive benefits and compensation for the impacts of projects. In addition, it raised the need for active policies to promote research, technological development, and the exploitation of synergies between lithium and the country's solar potential.

Finally, as an immediate measure, the CNL recommended reviewing the current contracts with SQM and Rockwood (now Albemarle), with the aim of giving the State a more prominent role, including as a partner in operations, and advised against renewing them under the existing terms. Although the CNL document served as input for the negotiation process, its content was not fully incorporated into the decisions taken.

The new contracts defined the pillars of Chile's lithium strategy. On the one hand, they authorized a significant expansion of production quotas, which led to a 143% increase in the volume of lithium carbonate produced between 2018 and 2022[18]. On the other hand, clauses were established to improve the capacity to capture the economic income from the activity and productive and technological policies, and a new form of relationship with the operating companies was established (Poveda, 2020).

One of the most significant changes was the introduction of a quota of up to 25% of the companies' production capacity, which must be allocated, at a preferential price, to those companies interested in processing these compounds within the national territory (Irarrazaval & Carrasco, 2023). This quota is allocated through international tenders.

To date, three tenders have been held. The first, completed in 2018, offered a quota of more than 24,000 tons of lithium hydroxide produced by Albemarle. However, the three selected companies—Sichuan Fulin Industrial Group (China), Samsung SDI and Posco (South Korean consortium), and Molymet (Chile)—subsequently withdrew from their projects. Various sources attribute this decision to Albemarle's inability to guarantee the committed volumes and to discrepancies in the setting of the preferential price.

The second tender, corresponding to SQM's quota, took place in 2020 and resulted in the selection of a project by the Chilean company Nanotec, focused on the production of lithium nanoparticles and nanoparticle additives, essential inputs for battery manufacturing. However, the product is still in the development phase and has not yet entered the market. This suggests that, at least in the short term, the effective demand for lithium compounds for value-added projects remains below the available quota (Obaya & Céspedes, 2021).

The third tender was opened in August 2022. In April 2023, CORFO awarded the Chinese company BYD a quota of 11,244 tons per year of battery-grade lithium carbonate. BYD plans to build a plant in the Antofagasta region to produce lithium iron phosphate (LFP) cathodes with a capacity of 50,000 tons per year. The estimated investment amounts to $290 million and is expected to generate 500 jobs.

That same year, CORFO allocated an equivalent quota to the Chinese company Yongqing Technology Co. Ltd. This company announced the installation of a plant with the capacity to produce 120,000 tons of LFP cathode material per year, which would also begin operating in 2025. The project involves an investment of $233 million and the creation of 688 jobs when it reaches its maximum production capacity.

[18] Source: USGS.

In May 2025, it became public knowledge that both companies would face obstacles that would lead them to give up their allocated quotas. In the case of Yongqing, problems were identified in its corporate structure that prevented it from being incorporated as a joint-stock company in China. The company attempted to transfer the award to another firm, Eternal Tsingshan Group, which was not contemplated in the original terms of the process. For its part, BYD has not formally renounced its quota, but neither has it shown concrete progress in the execution of the project, attributing uncertainties to the lack of definition of the Chilean government's lithium strategy.

In line with the CNL's recommendations, the new contracts also incorporated financing mechanisms aimed at strengthening research and development (R&D) capabilities in areas related to the energy transition. In the case of Albemarle, a contribution was established that will increase progressively from $6 million to $12.4 million per year. For its part, SQM must contribute an initial amount of $10.7 million, which will gradually increase to $18.9 million per year. The funds raised were channeled, through international tenders, to the creation and financing of research centers.

Within this framework, the Circular Economy Technology Center and the Sustainable Electromobility Acceleration Center were created, the characteristics of which are detailed in Table 18. In April 2023, CORFO awarded the creation of the Clean Technologies Institute to a consortium led by Corporación Alta Ley, which brings together 11 Chilean universities. This project involves a total investment of US$193 million[19].

**Table 18. Phases of the National Strategy for the Industrialization of Evaporative Resources in Chile.**
Source: Obaya (2019), based on GNRE (2011).

| Year of award | Name of center | Leaders and concession members | Financing | Objectives |
|---|---|---|---|---|
| **2019** | Circular Economy Technology Center (CTEC) | Innovation center for the Circular Economy in Iquique. Members: Arturo Prat University, Antofagasta University, Atacama University, Catholic University of the North, University of Chile, University of Santiago, University of Tarapacá, Pontifical Catholic University ( ), HUB APTA, and KNOW HUB. | US$21.5 million over a period of 10 years, with funds coming from the contract with Albemarle (US$10 million), the regional government of Tarapacá (US$4.9 million), the private sector, the Pontificia Universidad Católica de Chile, and study centers (US$6.6 million). | Create an institutional framework that facilitates innovation and commercial scaling of companies and ventures focused on the circular economy. Focus areas: solar energy, lithium salts, lithium batteries and energy storage, and metallic and non-metallic mining. |
| **2020** | Center for Sustainable Electromobility Acceleration (CASE) | University of Chile. Members: Energy Sustainability Agency, Mario Molina Center, University of Santiago, Metropolitan Technological University, Austral | US$7 million over a period of five years, with funds from the contract with Albemarle (but capped at 80% of the total cost of the proposal) and | To create and scale up technology providers and users of services related to electromobility. To increase electric charge distribution systems; more sustainable self-generation of electricity; the |

[19] The bidding process initially concluded in 2021 with the award of the project to the Associated Universities Inc. consortium. However, the award was the subject of complaints of alleged irregularities, which led to a judicial review of the process. In July 2022, the Supreme Court overturned the award and ordered CORFO to make a new decision. The final resolution was adopted in April 2023.

| | | | | |
|---|---|---|---|---|
| | | University of Chile, and Ernst & Young. | contributions from the successful bidder (up to 20%). It has the support of the Ministries of Energy and Transport & Telecommunications . | development of technical and professional capacities, and to contribute to the increase in national demand for technological developments that use copper and lithium. |
| **2023** | Institute of Clean Technologies (ITL) | Association for the Development of the Institute of Clean Technologies (ASDIT). Members: Antofagasta Industrial Association AG, Antofagasta Minerals S.A., Colbún S.A., Alta Ley Corporation, Atamos Tec Corporation, CODELCO, Enérgica City SpA, Fraunhofer Chile Research Foundation, Leitat Chile Foundation, The University of Nottingham Chile Foundation, Hydrox SpA, Minera Escondida, University of Chile, Pontifical Catholic University of Valparaiso, Psinet Chile SpA, Adolfo Ibáñez University, Catholic University of the North, University of Antofagasta, Pontifical Catholic University of Chile, University of Concepción, University of Santiago de Chile, University of Talca, University of Tarapacá, Federico Santa María Technical University | US$125 million from R&D contributions under the contract between CORFO and SQM for the exploitation of the Salar de Atacama. | Promote a portfolio of research and technological development (R&TD) projects, public goods, training initiatives, attraction, development, and scaling of new companies, open innovation initiatives, and alliances with other national and global companies. |

With President Boric's arrival in power, some of the guidelines included in the CNL report are being revisited, thus ushering in a new era in Chilean lithium policy. In April 2023, the National Lithium Strategy was presented, defining the main strategic guidelines for the coming years[20]. First, the strategy proposes the creation of the Strategic Committee for Lithium and Salt Flats, led by CORFO, with the participation of the Ministries of Mining, Economy, Development and Tourism, Finance, Foreign Affairs, Environment, Science, Technology, and Innovation.

[20] For more information, see https://www.gob.cl/litioporchile/

The Strategy contemplates the creation of the National Lithium Company, a state-owned company whose constitution must be approved by Congress. This new entity would play an active role in the production of lithium compounds through partnerships with private companies and would assume responsibility for promoting the development of value chains linked to the mineral. In this collaborative scheme, the private sector is expected to contribute capital, technological innovation capabilities, and access to international market networks.

Until the creation of this company, which requires congressional approval, CODELCO will be responsible for implementing the productive aspects of the Strategy. In this context, through its subsidiary Minera Talar, it signed a partnership agreement with SQM for the joint exploitation of the Salar de Atacama. The agreement defines the stages of work, distributes roles and responsibilities between both parties, and establishes the conditions of the public-private partnership for the production of refined lithium, with an expected operating horizon until 2060[21].

The agreement creates a joint venture in which CODELCO, representing the State, will hold a majority stake, equivalent to 50% plus one share. The implementation of the project will be divided into two phases. The first, between 2025 and 2030, will be under the administration of SQM and envisages a total production of 300,000 tons of lithium carbonate equivalent (LCE), representing an average of 60,000 tons per year. The second phase, which will run from 2031 to 2060, will be managed by CODELCO. During this period, annual production is expected to increase to between 280,000 and 300,000 tons of LCE. This increase will be possible thanks to the optimization of production processes and the incorporation of new technologies, without the need to increase brine extraction levels or continental water consumption.

At the time of writing this chapter, the agreement is in the process of being approved. In April 2025, the Chilean Nuclear Energy Commission (CCHEN) authorized SQM to increase its production quota for lithium carbonate and its equivalent (LCE) by 300,000 tons during the current term of the contract with CORFO, without requiring increased brine extraction. [22]This authorization is in addition to the one recently granted by the National Economic Prosecutor's Office (FNE) to Codelco, as well as previous approvals granted by the competition authorities of Brazil, South Korea, Japan, Saudi Arabia, and the European Union. To complete the process, an indigenous consultation and approval by the Chinese competition authority, the only one pending among the main jurisdictions, are still required.

Another central pillar of the Strategy is the expansion of Chile's lithium frontier beyond the Atacama Salt Flat, incorporating new salt flats in the national territory into the development of the industry. Specific criteria for state participation have been defined for this expansion stage. In projects located in the Atacama and Maricunga salt flats, the state, through CODELCO, must maintain a majority stake in public-private partnerships. Likewise, CODELCO will be in charge of leading the projects in the Pedernales salt flat, while the National Mining Company (ENAMI) will take the lead in the initiatives in the Grande, Los Infieles, La Isla, and Aguilar salt flats. In all cases, private companies participating in these developments must sign a CEOL.

As part of the Strategy, the Public Institute of Technology and Research on Lithium and Salt Flats was created in 2025, with headquarters in the Antofagasta and Atacama regions. Among its main functions is the development of applied research and technologies associated with both extraction processes and new ways of using lithium. In turn, the Institute will play a central role in the environmental monitoring of salt flats through the development of publicly accessible ecosystem baselines and the strengthening of scientific models that allow for understanding and minimizing

[21] For more information, see https://acuerdocodelcosqm.cl/asociacion-codelco-sqm/
[22] See https://www.emol.com/noticias/Economia/2025/06/30/1170783/acuerdo-codelco-sqm.html
https://www.bnamericas.com/es/analisis/acuerdo-de-codelco-y-sqm-por-el-litio-bajo-presion-al-acercarse-las-elecciones-en-chile

the impacts of mining activity on these fragile territories. This organization also has the mission of promoting synergies between lithium and other strategic resources, such as the solar potential of northern Chile, exploring opportunities for productive diversification and energy transition. Its funding comes, in part, from contributions from private companies operating in the sector, guaranteeing resources for its operation and research programs in the medium and long term. In addition, the Institute incorporates a social and territorial dimension, promoting the active participation of local communities and indigenous peoples in defining guidelines and generating knowledge. Citizen science and the concept of shared value are integrated as pillars for articulating productive development with the well-being of the inhabitants of the affected areas.

### 8.1.4. Final reflections: in search of a development strategy

The energy transition opens a window of opportunity for countries rich in critical minerals. However, it also poses significant challenges: how can we take advantage of these opportunities to build local capacities and avoid the vulnerability presented by boom and bust cycles? As the history of Latin American countries clearly shows, these cycles tend to accompany the processes of valorization of certain raw materials driven by global technological changes.

Although these external factors offer similar enabling conditions for countries with significant resource endowments, national responses have been very different. The case of the lithium triangle provides a privileged laboratory for analyzing these strategies. Throughout this chapter, we have presented not only the pillars of the different paths taken by Argentina, Bolivia, and Chile, but also their evolution over time.

The orientation and type of instruments used vary from more liberal approaches, as in the case of Argentina, to the nationalist statism that characterized the first stage of Bolivia's strategy. Each of these models proposes different balances between the state and the market, different types of industrial and technological policies—whether horizontal or sectoral—diverse risk distribution schemes—assumed mainly by the private sector or by the public sector—and a different conception of the scope that policy should have focusing on the mining segment or moving toward other links in the value chain.

These differences are not arbitrary. Each strategy finds justification in different strands of economic thought. More orthodox theories, focused on specialization according to static comparative advantages, tend to promote liberal schemes where the focus is on the extraction of raw materials. In contrast, more developmentalist currents promote the construction of dynamic comparative advantages, especially in strategic sectors, either because of their knowledge intensity or their potential to generate productive and technological linkages.

In this context, a central question is: what criteria should be used to evaluate the performance of the strategies adopted in the region? One way to move forward in this direction is to identify three major economic objectives that are usually assumed, with varying degrees of weighting, by the strategies deployed: (i) increasing the volume of lithium production; (ii) improving the conditions for capturing the economic income generated by its exploitation; and (iii) promoting the development of different activities that use lithium as an input, mainly those linked to the battery value chain.

From this perspective, Chile has made progress on the first two objectives. It was a pioneer in the development of the sector and, especially since the renegotiation of CORFO contracts—prompted by the CNL's recommendations—it has significantly strengthened its capacity to capture income, particularly during the upward price cycle of 2022 and 2023.

Argentina, for its part, has managed to significantly expand its identified resources since 2010, generating a large number of mining concessions. However, projects only began to develop more steadily from 2022 onwards, which explains why Argentina's share of the global lithium market has fluctuated. After peaking at 15% in 2016, the average for the following decade fell to 6.5%. The projects currently under construction are expected to increase this share in the short and medium term. However, in terms of revenue collection, the state's capabilities remain limited due to the narrow margins established by investment promotion schemes for intervening in the appropriation of surpluses generated by this activity.

Bolivia is the country with the greatest difficulties in meeting the objectives set. The state plan to produce high volumes of lithium on an industrial scale has not been realized, which is a necessary condition for advancing with the other objectives. This situation has undermined the legitimacy of the national strategy and hinders the implementation of new projects, such as those based on EDL technologies, without a profound reformulation of the relationship between the state, political leadership, and society, especially in the Potosí region.

The performance of the three countries in relation to the downstream segments of the value chain deserves special mention. So far, all of them have failed to develop capacities in areas such as cathode material production or battery cell manufacturing. This result highlights the importance of thinking about the development of these links in conjunction with the creation of new markets. It is difficult to imagine the deployment of a national or regional value chain without significant demand for electric vehicles to drive that development.

Recent international experience offers telling examples in this regard. The most robust expansion of electromobility is led by China, while the United States and Europe face difficulties in consolidating competitive value chains in this sector. If this process is complex in countries with high income levels and consolidated industrial capacities, the challenges become even more severe in middle-income Latin American countries, where industrial capacities are limited and fiscal resources to boost the sector—whether through subsidies for electric vehicle demand or production supply—are scarce.

In short, recent experience shows that lithium wealth does not automatically translate into development. The exploitation of this resource depends on the design and implementation of consistent, sustained strategies that articulate a long-term vision, coordinate public and private actors, and rely on institutional and technological capacities. Without these elements, the risk of repeating the historical cycles of extractivism and dependence remains high, even in the context of a global energy transition that offers new opportunities.

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# 9. POTENTIAL SOCIO - ENVIRONMENTAL IMPACTS

This report seeks to comprehensively characterize the impacts associated with lithium extraction in Latin America, considering both social and environmental dimensions. Although much of the document focuses on technical, productive, and public policy aspects, it is essential to incorporate perspectives that account for territorial tensions, social demands, and legitimacy challenges that emerge in extraction territories.

In this regard, the ecopolitical conflicts surrounding lithium are analyzed from an ethnographic and socio-environmental perspective. Emphasis is placed on the importance of socio-environmental legitimacy as a premise for sustainable development and key elements for understanding disputes over water, territory, and participation in decision-making.

## 9.1. Socio-environmental impacts – Socio-environmental legitimacy and eco-political conflicts surrounding lithium: some ethnographic evidence

### 9.1.1. Socio-environmental legitimacy as a prerequisite for sustainable development

The climate imperative requires us to transition to a decarbonized economy, which implies a profound transformation of our socio-energy matrices. The expansion of storage technologies using battery systems plays a strategic role in this transition. These technologies make it possible to stabilize an electricity grid with a high penetration of renewable energies and to replace fossil fuel-dependent combustion engines in vehicles and mobile machinery with various forms of electromobility (Victoria et al. 2025).

With the technology currently available, lithium is an essential element for powering the electric batteries that must sustain the energy infrastructure of the 21st century. For this reason, various studies and research projects predict that lithium will play a central economic role in the coming decades, especially in plans to electrify the global automobile fleet. Some estimates suggest that by 2040, 30% of cars on the road will be electric, representing approximately 500 million vehicles. Assuming the International Energy Agency's 2DS scenario, the World Bank, in its report Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition, estimates that lithium production will need to increase by more than 500% in 2050 compared to 2018 production to meet expected demand (IBRD/World Bank, 2020). Similarly, according to Jones et al. (2021), the compound annual growth rate of global lithium demand will be an extraordinary 18.5% per year until 2030, increasing thereafter. These calculations explain why lithium was included in the list of critical raw materials published annually by the European Union in 2020.

The scenarios of strong growth in global demand for lithium have been fueling high expectations for the expansion of the lithium frontier around the world for more than a decade. This pressure is particularly noticeable in those geographical enclaves where deposits are concentrated, which, due to their geological qualities, in combination with commercially available extraction technologies, appear to be the most profitable. A good example is the territory formed by the high Andean salt flats spread across Argentina, Bolivia, and Chile, which account for almost 60% of the world's currently known lithium resources (Obaya, 2021) and have been dubbed the "Lithium Triangle": a powerful geographical image that has, in turn, sparked opposition from community and environmental movements due to its extractivist connotations (Morales Balcázar, 2021).

However, the alignment between the potential of the Lithium Triangle and its effective contribution to global decarbonization, and with it to the resolution of the climate crisis, is far from a guaranteed process. According to Jones et al. (2021), the current production capacity of the lithium triangle covers approximately one-third of the mineral that the region is expected to supply in 2030. The remaining two-thirds depend on projects that are not yet commercially operational. And they may never be. There are several reasons that could slow down the deployment of lithium mining in Argentina, Bolivia, and Chile. As previous comparative research has shown, the governance model prevailing in each country has proved to be a decisive variable in positioning each of these three nations in the global lithium market (Obaya and Pascuini, 2020; Arias et al., 2022). At the same time, it is important to note that the entire process is shrouded in a cloud of economic, technical, and geopolitical uncertainty that hinders decision-making at different levels: from the future price of the resource, which has experienced notable volatility, to the emergence of more competitive producers, to the possibility of technical disruption in the world of batteries, such as the large-scale commercialization of sodium-ion batteries, or changes in demand scenarios that could lead to policies that deny the climate emergency, such as those being implemented by the Trump administration.

In this chapter, we want to address the issue of the Lithium Triangle as a potential obstacle to global decarbonization from another perspective: one that addresses the eco-political conflicts generated by the present (and future) exploitation of lithium in the region. This perspective is different from the predominant technocratic approaches, as well as from purely utilitarian economic reasoning based on price information; moreover, it addresses a whole series of layers of sociological reality that are capable of clarifying the processes under study, but which are only accessible through the contribution of the social sciences.

Like any other dimension of the ecological transition, lithium mining might be thought of as a political dispute (Tejero and Santiago, 2019). At this point, the concept of politics must be understood in a broad sense, which includes but goes beyond public policies and partisan disputes: that is, we understand politics as the conflictive regulation of the processes of power that define, for a society, the problems of collective interest, manage their consequences, and organize plans aimed, or not, at solving them. These power processes never occur on a blank historical page but are inscribed in a complex and dense legacy of accumulated social tensions. The category of ecopolitics refers to those political realities in which the conflictive regulation of power processes takes place over an explicit dispute over socio-natural relations.

Thus, the expansion of the mining frontier in salt flats responds to an increase in demand for lithium defined by the international climate agenda, which is associated with different impacts that negatively affect neighboring communities in a continuum of social and environmental experiences (which is why we will use the category of socio-environmental impacts) and has opened an intense debate on the different options for minimizing or avoiding these negative impacts. These communities also tend to perceive themselves as substantially excluded from the benefits of extraction, in an asymmetrical relationship that perpetuates chronic socio-geographical inequality.

Consequently, new lithium mining projects in the triangle are generating a diverse phenomenology of eco-political resistance, which has also gained notable international visibility and must be taken into account based on two complementary approaches: a) on the one hand, as challenges with real potential for political veto over the plans that companies and governments may develop for the region; b) as an exercise of rights and an expression of fair material and cultural demands, which every democracy must weigh in its collective deliberation processes.

Therefore, our fundamental thesis is that implementing public policies aimed at building situations of intense socio-environmental legitimacy is more than an unavoidable moral commitment for any democratic regime: it is a guarantee of success for the establishment, at the speed demanded by the climate emergency, of new lithium mining projects that can respond to global decarbonization. We do so on the premise that the climate emergency and the depletion of the carbon budget to comply with the Paris Agreement impose a value symmetry between speed and justice: only if the transition is fair will it be rapid, as fairness will minimize eco-political conflict, and only if it is rapid will it be fair, as climate stability is a prerequisite for minimizing the unequal impacts that climate change is already producing and that will increase for future generations.

To deepen our theoretical framework, we defined socio-environmental legitimacy and compared it with the notion of social license, a term widely used to think about the acceptance of projects with socio-environmental impacts, although with some conceptual commitments that we find problematic.

We define socio-environmental legitimacy as the social and political recognition, with strong territorial roots, that a project with a significant environmental and social footprint acquires when, through structured processes of transparent information, intercultural dialogue, participatory cooperation, and fair compensation mechanisms (through the effective resolution of new or postponed demands), it manages to obtain the informed and active consent of the communities directly affected, integrating their values, needs, and visions of the territory into the decisions that shape the project.

Unlike the notion of social license, which has its origins in the corporate world and is utilitarian, pragmatic, and oriented toward managing reputational damage, the idea of socio-environmental legitimacy refers to a political-normative concept that alludes to the deep and sustained recognition of a project by the communities that host it, based on notions of epistemic, territorial, and environmental justice. Essentially, what the idea of socio-environmental legitimacy contributes is: i) the shift from passive acceptance to active consent; ii) from permission (with its connotations of administrative concession) to recognition (with its connotations of dialogical co-construction); iii) from risk management (reputational or political) to law; iv) from apparent pacification (with latent conflicts) to institutionalized dialogue as a transformative way of addressing conflict; v) from the procedural to the ethical-political. Consequently, the notion of socio-environmental legitimacy shifts the focus from technocratic management to the democratization of eco-political relations.

The usefulness of this distinction can be assessed by considering the shortcomings of social license approaches. Today, there is already a mandatory legal framework that serves to regulate relations between companies (and administrations) promoting large projects, such as mining or energy projects, and the local populations of the affected territories. The most paradigmatic example is the case of indigenous peoples and ILO Convention 169, although we could also cite here the various environmental impact assessment regulations contained in each national legislation.

However, as numerous studies have shown (Escosteguy et al., 2022; Argento and Puente, 2015, Clavijo et al. 2022), it must be acknowledged that in eco-political conflicts, what is legal and what

is legitimate do not always overlap: the law is far from being complied with in all cases, and when it is complied with at the procedural level, it does not always generate substantial consent among the affected populations. Furthermore, the way in which local communities have been integrated into projects with socio-environmental impact has been highly problematic in many cases, with forms of relationship that have been closer to subordination or co-optation than to equal participation. In other cases, these relationships have been based on mechanisms such as preferential employment for affected populations or on corporate social responsibility exercises that are very modest in terms of their actual financial commitment on the part of the promoting companies (Morales Balcazar, 2021). Finally, the fact that in some countries relations between companies and communities are conducted through a relinquishment of public functions by the state reinforces suspicions about a structural power asymmetry that conditions the legitimacy of the process.

Before continuing, a methodological clarification. The bulk of what we are going to present below are some qualitative reflections inspired by a small fieldwork project, lasting seven weeks, which took place in regions located between Chile (Atacama province) and Argentina (Jujuy province), as well as in their respective capitals, Santiago and Buenos Aires, between November 2024 and April 2025. Although the structure of the research project only allowed us to conduct ethnographic fieldwork in these two countries, in order to provide an overall analysis of the Lithium Triangle, we include references throughout the text based on existing literature on the specificity of the Bolivian context. We refer to these reflections as ethnographic evidence because they are provisional lines of research based on the qualitative knowledge provided by ethnography. Furthermore, given the brevity of this text, they cannot be adequately supported in the text with the empirical material on which they are based, in the form of interview excerpts or detailed descriptions. Nevertheless, despite their precarious epistemological status, we believe that their presentation may make a small contribution to the debate on lithium mining compatible with the United Nations' sustainable development goals.

### 9.1.2. The contribution of the socio-environmental perspective

The socio-anthropological perspective with which we approach the socio-environmental legitimacy of lithium mining in the Andean salt flats is based on a series of theoretical-epistemological premises that have shaped our approach to these realities, and which we consider it appropriate to explain before discussing the results of the research:

a) The procedural and historical perspective: the lithium scenario is defined by its openness, uncertainty, and continuous transformation. It is a market characterized by fluctuating demand and prices and influenced by an unstable macroeconomic and geopolitical context (Zicari et al., 2019). Added to this are the potential impacts that technological innovations in extraction methods or battery manufacturing components may have on the current market. This structural instability contrasts with the long-term vision required for the investments needed for extraction: it can take up to ten years from the initial approval of a project to the plant going into production.
This raises two fundamental questions. The first is that we do not intend to offer a definitive picture of the reality of lithium mining in these pages. We are aware that we are dealing with ongoing processes that are subject to changing political, economic, and technological circumstances. The second is that, without losing sight of the fact that we are dealing with a field of political disputes, this degree of openness can make this scenario fertile ground for the introduction of proposals for improvement in the

formulation of public policies that contribute to the construction of a solid socio-environmental legitimacy for these projects.

b) Conflict as a multi-causal reality inherent in social reality: from the perspective of the social sciences, conflict is understood as a reality inherent in the dynamics of societies. Clarifying this point is essential to understanding that, in the question of how to build socio-environmental legitimacy, the aim is not to reach a kind of zero point where eco-political conflicts disappear. Rather, the objective is to reflect on the tools that can contribute to generating optimal balances in the tensions that underlie the need to expand extractive activities to sustain the transformation of our energy matrices.
On the other hand, when addressing the complexity of these conflicts, we must avoid falling into monocausal explanations. As we will see, conflicts surrounding lithium articulate problems related to the transformation of the territory from social, environmental, and economic perspectives. At the same time, they channel historical demands that refer to social disputes over the recognition of rights and autonomy, which go beyond the mining or energy sectors.

c) The centrality of sociocultural and symbolic factors: approaches to processes linked to the energy transition can fall into two types of reductionism. The first consists of limiting the analysis to the technological capabilities that enable the transition, without considering the sociopolitical variables that traverse and define those capabilities. The second consists of limiting its social dimensions to economic or regulatory elements.
A socio-anthropological approach, on the other hand, understands that cultural and symbolic factors are not mere additions to these social processes, but central elements in defining their conditions of possibility, their meanings, and their disputes. The influence of social representations of mining in conflicts over lithium extraction, the existence of a mining cultural identity in the region as key to the acceptance of projects, the tensions between the indigenous conception of territory from a spiritual logic versus its perception in terms of natural resources, or the support of local festivals and rituals by mining companies as a tool for obtaining social license, are just a few examples that illustrate the importance of addressing these dimensions in the analysis of socio-environmental legitimacy and debates surrounding lithium mining in the high Andean salt flats.

d) The search for complexity and a relational perspective: the analysis of disputes surrounding lithium requires, of course, an approach to the social agents involved. The approval and development of these mining projects takes place within the relationships established between the competent public authorities, the companies involved, and the local communities settled in these territories (mostly indigenous peoples, although not exclusively). These actors are joined by other social agents concerned about the possible socio-environmental impacts of lithium extraction: mainly civil society organizations and collectives, research, academics, and economic agents whose productive interests compete with lithium projects. All of them play a key role in supporting, denouncing, and raising awareness of these conflicts.
When approaching these social agents, we have avoided conceiving them as homogeneous blocks driven by a single logic, interest, or position. Such a monolithic view obscures the internal conflicts, power struggles, and ambivalence of positions that, as we will outline throughout the text, characterize the social landscape of lithium conflicts. We also consider it essential to pay attention to the dynamics of opposition, rapprochement, and alliance between the different actors involved (dynamics that sometimes go beyond the expected logic), as well as the ways in which changes in these relational configurations affect the expression of the conflict.

e) The dialogue between the global scenario and specific contexts: understanding the socio-environmental legitimacy and eco-political conflicts surrounding lithium that we have approached in our ethnographic incursions requires a multi-level analysis that relates the specificities of the territory, the particularities of national governance models, and the international geopolitical and economic scenarios in which interest in this resource is situated. The exclusion of this situated analysis, attentive to contextual and conjunctural aspects, with a historical and institutional outline, could only lead us to a poor and biased interpretation of the processes studied. This is one of the central contributions that the ethnographic perspective, always attentive to this dialogue between the micro and the macro, can make to this field of study.
Given the synthetic nature of the text and its cross-cutting view of the Lithium Triangle, the presentation we are going to give is based on a systematization of aspects common to the different regional contexts. However, in order to maintain this dialogue, we will make continuous references to specific examples and to the need to situate the general reflections we present at the territorial level.

## 9.2. Lithium extraction in the Triangle: general context and specific national contexts

Analyzing the socio-environmental legitimacy and eco-political conflicts in the Andean Lithium Triangle involves addressing some contextual particularities of the lithium industry (geographical, historical, sociocultural, and economic), both in its regional dimension, common to the three countries, and in its national specificities.

First, from a geographical and cultural perspective, beyond national political and administrative boundaries, the region that makes up the lithium triangle has several shared geographical and cultural features: the Atacama region. This region is characterized by being an arid area with low rainfall—an average of less than 200 mm per year—extreme temperatures, and fragile mountain ecosystems. The inhabitants of these high-altitude semi-deserts live in small communities (between 50 and 500 people), mostly belonging to the Kolla, Atacama, Quechua, and Aymara indigenous peoples (Argento and Puente, 2019). These communities have maintained certain historical structures of adaptation to the environment, such as networks of cooperation and integration with other ecological zones, which have favored the development of pastoral economies (llamas, sheep, goats), subsistence agriculture, and salt exploitation (Estruch, 2024; Göbel, 2013), which they currently combine with other strategies such as community tourism, social assistance, service provision, or employment in companies that occasionally establish themselves in the region (Pragier, 2024).

Secondly, we must note that the search for a balance between economic prosperity, environmental sustainability, and social equity, which is the conceptual matrix of sustainable development, is the predominant framework around which the eco-political conflict in the Lithium Triangle revolves. Although criticism of the very notion of development is not absent from the discourse of some actors, it is more common for some of the resistance to the expansion of the lithium frontier in the triangle to be articulated around criticism of extractivism. The term extractivism, popularized in Latin America by Eduardo Gudynas (2015), defines a production model based on the massive extraction of natural resources, mainly for export, with little industrial processing and high social and environmental impacts, which has historically been promoted by both conservative and progressive governments. The issue of extractivism is part of one of the most idiosyncratic economic and sociopolitical debates in Latin America: the problems of dependence caused by its peripheral position in the World System and the curse that affects raw material-exporting nations.

All of this is permeated by a tension between prioritizing approaches that strengthen national economic sovereignty, framed within a discourse of resource nationalism (Koch and Perrault, 2019), and approaches that are more open to facilitating foreign investment, inspired by liberal discourses.

Although the density of this debate is impossible to address within the scope of this article, we must define the basic features of the post-extractivist critique that underlie, like a diffuse horizon, many of the phenomena of eco-political conflict in the Lithium Triangle. Essentially, unlike the resource disputes of the 20th century, post-extractivist criticism introduces two emphases: an environmental emphasis that leads to questioning some of the axioms of prevailing economic rationality, and a renewed sensitivity to the cultural plurality of the affected communities and their rights.

### 9.2.1. The Chilean context

The eco-political conflicts related to the lithium frontier in Chile must be understood as an offshoot of a larger issue: the weight of mining in Chile's national identity, both in its socioeconomic structure and in its identity. Chile is recognized both nationally and internationally as a "mining country", where mining has been the main productive activity, contributing between 13% and 20.6% of GDP in the last decade. The other side of this process is that eco-political conflict is a line of tension that runs through the country's entire history. In general terms, lithium in the 21st century is not, in this sense, a phenomenon very different from copper in the 20th century or saltpeter in the 19th century.

Unlike copper, the lithium industry is still in its infancy, with significant weight but much smaller than copper in terms of exports. Until now, the main players have been private companies, whose governance framework is still under construction, and which serve a decentralized international market, leading to greater price volatility and significant challenges for the standardization and prediction of economic processes. However, these differences, which are inherent in comparing a consolidated global market with an emerging market fraught with uncertainty, do not prevent lithium from playing the role of "the copper of the 21st century" in imaginary terms. This explains, for example, the symbolic role that the National Lithium Strategy has been able to play for the Frente Amplio government as a sign of political identity for a new left, which must find differentiating content from the classic left to justify its commitment to generational renewal.

Some of the most notable milestones in the history of lithium in Chile[23] are as follows:

- In the context of the Cold War, under pressure from the US and given the nuclear potential of lithium, the military dictatorship established its strategic nature, which excluded it from the conventional mining concession system. Although this has not prevented private exploitation of the resource, which has been very notable since 1984, when Chile became the world's leading producer thanks to the competitive advantage offered by the Atacama Desert, the hierarchical control of the state has ultimately safeguarded a mechanism of public intervention that has been key in subsequent discussions on its governance. For this reason, the specialized literature classifies the Chilean governance model as mixed (public-private), which contrasts with Bolivia's 100% public approach and Argentina's much more private (and decentralized) model.

- Since 2005, lithium has gained notable international notoriety, and its market has become expansive and highly dynamic. Chile's lithium agenda has been reactivated, with new tenders resulting in failed processes, without abandoning the strategic conception of the resource. In 2015, Bachelet's second administration created the National Lithium Commission in an attempt to articulate a new governance model (which is the

[23] For more information on this historical reconstruction, see Poveda Bonilla, 2020

basis of the current National Lithium Strategy). During this period, contracts with the two major private operators in the Salar de Atacama (SQM and Albemarle) were also renegotiated with the aim of improving state royalties and promoting endogenous economic development initiatives.

- Piñera's second administration (2018-2021) marked the rise of eco-political conflict over lithium, driven by indigenous communities affected by its socio-environmental impacts in (complex) alliances with various actors far from the territories but committed to notions of environmental justice (activists, academics). The basis of these conflicts lay in the failure to comply with indigenous consultations.

- The Boric administration (2022-2025) has promoted the National Lithium Strategy, currently in force, as a framework for the overall governance of the resource and, in turn, although the political results have fallen short of expectations, as the flagship of the socioeconomic model embodied by the new policy of the Broad Front[24] . The central purpose of Chile's National Lithium Strategy is to establish a comprehensive and sustainable policy that takes advantage of the country's vast lithium reserves, maximizing economic benefits for Chile while ensuring high social and environmental standards in the context of the opportunities opened by the decarbonization of the global economy. At the programmatic level, the National Lithium Strategy was structured around a series of central axes, whose actual implementation has been asymmetrical depending on different political circumstances. These are as follows:

    - A mixed governance model through public-private collaboration.
    - Seeking to improve the rent taken by the state.
    - The pursuit of socio-environmental legitimacy, involving indigenous communities and protecting saline ecosystems. Projects must include indigenous consultation and commit to the use of advanced, more environmentally friendly technologies, such as direct lithium extraction.
    - Creation of a National Lithium Company to ensure state participation in new lithium operations.
    - Transparent tenders and selection of strategic partners based not only on economic and productive criteria, but also on social and environmental criteria.
    - Creation of a Public Technological and Research Institute for Lithium and Salt Flats, whose mission is to develop advanced scientific and technological knowledge, improving production efficiency and environmental conservation.
    - Creation of productive chains and value addition in the country through the production of battery components, such as cathode materials and electrolytes.
    - Establishment of a Network of Protected Salt Flats to conserve the most vulnerable ecosystems.

To design the processes for granting Special Lithium Operation Contracts (CEOL) for salt flats considered potentially exploitable, in April 2024, the Ministry of Mining launched a procedure for expressions of interest from national and international private operators. On July 9, the Ministry released the results: 88 expressions of interest were received. Based on this information, the Ministry of Mining established twelve priority areas for the allocation of the first Special Lithium Operation Contracts, which, together with state-led projects (such as Salares Alto Andinos -ENAMI- and Maricunga -CODELCO), make up a complex range of initiatives in different stages of development, on whose future production Chile's contribution to meeting global lithium demand depends.

The recent political situation in Chile has had an unfavorable impact on an ambitious agency implementing the National Lithium Strategy. On one hand, since the beginning of its term, the government led by Gabriel Boric has had to coexist with a Parliament in which the ruling party did

[24] The Chilean National Lithium Strategy program can be consulted at the following link: https://www.gob.cl/chileavanzaconlitio/

not have a sufficient majority to push through important legislative changes without negotiations with other parliamentary forces. For example, this parliamentary weakness explains the government's inability to create a National Lithium Company, having to channel its mixed public-private model through existing public companies such as CODELCO or ENAMI. On the other hand, and although the connections between the two phenomena are far from causal, the failure of the constitutional process in September 2022 was an indirect political blow to the National Lithium Strategy in several ways: the defeat of a constitution that defined itself as ecological helped to lower the high environmental demands that the Strategy aspired to respond to; on the other hand, the rejected Constitution involved redefining water property rights, which would have provided a window of opportunity to reform the mining model.

Currently, Chile has only one lithium deposit in commercial production (the Salar de Atacama), operated by two private companies, SQM (Chilean capital) and Albemarle (US capital). SQM's operation is the largest in the country (205,000 tons of lithium carbonate production in 2024) and one of the largest in the world, accounting for 20% of the global lithium market. SQM operates in the Salar de Atacama under a lease agreement with CORFO, signed in 1993, revised in 2018 to improve state royalties, and expiring in 2030. However, within the framework of the National Lithium Strategy, in 2023, the state-owned company CODELCO reached a controversial agreement with SQM to continue operations until 2060, with the state becoming a partner in 2025 and assuming a majority stake in 2031. Regarding Albemarle's operation, the oldest in Chile (1984), its volume is significantly lower, but still significant (47,000 tons in 2024). Albemarle operates under a contract with CORFO until 2043, which the Chilean government has announced it will honor, although it is foreseeable that in the future there may be a renewal agreement like the one promoted with SQM.

On the issue at hand, the socio-environmental legitimacy of lithium extraction in Chile, it should be noted that all new initiatives promoted within the framework of the National Lithium Strategy that may affect indigenous communities are holding their respective indigenous consultations organized by the Ministry of Mining. In turn, the Ministry of the Environment has also promoted a series of indigenous consultations in relation to the establishment of the future Network of Protected Salt Flats.

However, since 2015, Chile has experienced numerous socio-environmental conflicts and eco-political frictions related to both existing lithium exploitation in the country and the projected expansion of the lithium frontier in the future. Although each conflict is different, we can find a common pattern: some local communities belonging to indigenous peoples, or segments thereof, in alliance with other actors (environmental organizations, tourism interests, academia) have mobilized to prevent or reformulate lithium mining projects perceived as a socio-environmental threat. The main causes have been environmental (water, biodiversity protection), in many cases with a preventive motivation, but also respect for the rights of indigenous peoples (prior consultation, participation in benefits) and the demand for respect for traditional ways of life (such as grazing). Mobilization strategies have brought together complaints and demonstrations, media pressure, and significant legal action, which in many cases have resulted in substantial victories for local communities. Many of these conflicts are still ongoing, and their resolution is a sociological barometer for measuring the socio-environmental legitimacy of the lithium mining model in Chile.

### 9.2.2. The Argentine context

The beginning of lithium exploitation in Argentina dates to the 1990s, with Lithco obtaining the concession to operate in the Salar del Hombre Muerto, in the province of Catamarca. This operation gave rise to the Fénix project, which began production in 1998 with the company Minera del Altiplano SA (Argento and Puente, 2019). This move took place in a decisive context for the

structuring of the legal and institutional framework for mining in the country, characterized by strong incentives for foreign private investment and a multi-level regulatory framework that has led to great difficulties in formulating a common policy on lithium and recognizing it as a strategic resource at the national level (although it has been declared as such in provincial jurisdictions such as Jujuy and La Rioja).

The 1994 constitutional reform granted the provinces original ownership of the territory's natural resources and, therefore, the power to develop specific regulations for the granting of exploration and exploitation permits, the regulation of the administrative and environmental requirements for obtaining them, and the corresponding tax collection (Arias et al., 2024). On the other hand, in 1993, Mining Investment Law No. 24,196 was enacted, which, together with the Mining Code, forms the national legislative framework that regulates mining activity, including lithium. This law established a system of promotion and tax incentives to attract investment, as part of a broad process of regulatory flexibility and partial deregulation of the economy (Argento and Puente, 2019). This liberal orientation, together with the regulatory fragmentation resulting from the federalist system, constitutes the basic characteristics of its lithium governance model. Unlike its neighboring countries, the Argentine model is characterized by the prominence of private capital in lithium mining operations and by the limited capacity of public authorities to generate mechanisms to control companies' production and marketing strategies (Obaya, 2022). Under the current legal regime, concessionary companies acquire ownership of lithium resources once they have been extracted, and the state participates in a minority share of the profits from this exploitation, mainly through taxes and royalties. As a strategy to improve local revenue capture, the provinces have created public companies that participate to varying degrees in projects implemented in their territory, either as shareholders (JEMSE in Jujuy, with an 8.5% stake) or by signing agreements without equity participation (CAMYEN in Catamarca or REMSa in Salta, although with different institutional weight) (Amar et al., 2024).

This governance model has a direct impact on the forms taken by the eco-political conflicts surrounding lithium mining in Argentina. The decentralized, market-oriented model encourages interprovincial competition to attract investors, which can translate into the promotion of more lax environmental regulations or more favorable tax conditions for companies, without resulting in tangible benefits for the affected communities. It also poses major challenges for the management of lithium extraction in salt flats whose basins are interprovincial, such as Salar del Hombre Muerto or Salinas Grandes. To draw up a common roadmap for lithium exploitation and address these issues, a national lithium roundtable was established in 2021 at the initiative of the national government and the provinces of Catamarca, Salta, and Jujuy. However, despite this and other attempts at coordination, a harmonized regulatory framework for interprovincial lithium exploitation has not yet been established.

To this scenario must be added another basic element in the configuration of public debates on the socio-environmental legitimacy of lithium mining: the recognition of the ethnic and cultural pre-existence of Argentina's indigenous peoples, the legal status of their communities, and their communal possession and ownership of land, enshrined in the 1994 constitutional reform. This legal advance, coupled with the ratification of ILO Convention 169, became a lever for ethnic-political mobilization aimed at obtaining legal status as a basis for claiming territorial rights and autonomy.

However, despite formal progress in the recognition of indigenous rights, there is a broad consensus that the development of mechanisms for the effective implementation of these rights still has a long way to go. The gap between the formal recognition of indigenous rights and the absence of regulations to make them effective emerges as one of the main sources of eco-political conflict surrounding lithium in Argentina. It has even been pointed out that these conflicts were

also a driving force behind the processes of ethnic self-identification that took place in the 1990s (Göbel, 2013; Argento and Puente, 2019; Rubinstein et al., 2023). In fact, for many of the people interviewed, despite its importance, the core of the conflict in the country lies not so much in the environmental impact as in the enforcement of rights, institutional weakness, and the state's failure to ensure that the procedures required for lithium mining are carried out fairly, transparently, and in accordance with the law.

Since those early days, lithium mining has experienced steady growth in terms of production and investment attraction, consolidating its position as one of the world's leading lithium producers. Javier Milei's government has not introduced any significant changes to the lithium governance framework described above. Attracting foreign capital has remained a priority, reinforced by the approval of the controversial Incentive Regime for Large Investments (RIGI). However, his declared climate denialism, together with cuts to public research, is perceived as a threat to the development of just energy transition policies and to the exploitation of the national scientific and technological potential surrounding lithium.

The provinces of Salta, Jujuy, and Catamarca account for the bulk of lithium mining in Argentina. According to the latest data available from the Ministry of Mining[25], the three provinces together have 60 projects in different stages of development prior to exploitation, and the six projects currently active at the national level for the production of lithium carbonate and chloride. Catamarca is home to the Fénix project controlled by Rio Tinto (British capital), and shared with Salta, the Sal de Oro project, controlled by POSCO Holdings (South Korean capital). Jujuy is home to the Cauchari-Olaroz project (operated by Ganfeng Lithium, of Chinese origin, and Lithium Argentina, of Canadian origin), and the Olaroz project (Río Tinto and Toyota Tsusho, of Japanese origin). Finally, in Salta, the Centenario-Ratones project, controlled by the French company Eramet, and the Mariana project, by Ganfeng Lithium, have recently begun production.

However, the growth of lithium mining has resulted in strong territorial pressure on the Argentine Puna, an area that has historically been displaced in socioeconomic terms, fueling concerns about its potential environmental impacts and the transformation of community lifestyles. While in many regions opposition has not been significant enough to halt the development of these projects, and communities have negotiated certain benefits with the companies, in others, mainly Salinas Grandes and Laguna de Guayatayoc, resistance has been generated through lawsuits, roadblocks, cycles of mobilizations, artistic actions, and complaints to international organizations. One of the latest milestones in these mobilizations occurred in 2023 because of the express constitutional reform promoted in the province of Jujuy, perceived by numerous actors—indigenous communities, academics, NGOs—as a threat to the territorial rights of indigenous communities. Although these threats were not exclusively linked to lithium mining, they were fundamentally connected to it insofar as they could weaken the guarantee of community rights in the face of the advance of these mining projects. The protests led to the formation of the Third Malón de la Paz, which marched to the capital to present its demands. According to Amnesty International, this wave of protests led to a significant cycle of repression and human rights violations by state forces[26].

The diversity of responses to the deployment of lithium mining projects in the region is not only a response to the socio-environmental concerns and asymmetries in the recognition of territorial rights mentioned above, but also to the absence of clear and consensual institutional mechanisms for community participation. Mining operations require companies to obtain a social license, but no province has developed protocols for prior, free, and informed consultation agreed upon with the communities (Arias et al., 2022). All of this, as we will discuss in the following sections, has a direct impact on the socio-environmental legitimacy of lithium mining in Argentina, creating a

[25] Data available at: https://public.tableau.com/app/profile/sec.mineria/viz/ProyectosMineros/Dashproyectos
[26] https://www.amnesty.org/es/documents/amr13/9390/2025/es/

climate of mistrust, negotiation through informal channels, and delegation of functions by public authorities, which calls into question the validity and legitimacy of some processes for obtaining this social license.

### 9.2.3. The Bolivian context

Bolivia has one of the world's largest lithium reserves concentrated in the salt flats in the south of the country. Despite this, it has not yet achieved its goal of producing compounds on an industrial scale (Obaya, 2022). According to official data, in 2024, approximately 2,000 tons were extracted from the only industrial plant in operation, a figure far below the 150,000 tons per year projected in the initial design of the national lithium industrialization strategy (Obaya and Pascuini, 2020).

The governance framework for Bolivian lithium differs significantly from the Chilean and Argentine cases, notably in its nationalist orientation and comprehensive public management (Obaya, 2022). With the arrival of Evo Morales to the presidency, Bolivian policy on lithium was defined by the establishment of a state monopoly on the exploitation of evaporative resources and the establishment of a national strategy for the industrialization of lithium from the salt flats to the battery (Slipak and Urrutia, 2019), initially proposed by the Regional Federation of Rural Workers of the Southern Altiplano (FRUTCAS), and whose design also incorporated business and scientific actors from the country (Argento and Puente, 2019).

According to Obaya (2022), the main milestones in the initial formation of the strategy were:

- The restoration in 2007 of the powers of exploration, exploitation, industrialization, commercialization, and administration of fiscal mining reserves to the Bolivian Mining Corporation (COMIBOL).
- The enactment in 2008 of Decree 29.496, which declared the industrialization of the Salar de Uyuni a national priority.
- The establishment of the strategic and public interest nature of the country's natural resources in the 2009 Constitution, which in Article 351 grants the State "control and direction over the exploration, exploitation, industrialization, transportation, and commercialization of strategic natural resources."
- The creation of the National Evaporative Resources Management Agency (GNRE) and the official presentation in 2010 of the National Strategy for the Industrialization of Bolivia's Evaporative Resources. This strategy, planned in three phases, included plans for the installation of research centers and production plants for lithium-ion components and batteries, with a model of state control of the entire lithium value chain that went beyond extractivist logic. This established the exclusive power of the state to exploit the salt flats, allowing private companies to participate to a minor extent in certain phases of the production process.

The initial strategy underwent modifications over the years as problems arose with financing, exploitation, and battery manufacturing, especially technical difficulties in combining economic profitability and environmental sustainability in the extraction process (Slipak and Urrutia, 2019). Thus, in 2017, along with the creation of the national company Yacimientos de Litio Boliviano (YLB), while maintaining the nationalist orientation of its policies, the possibility was opened up to make international companies strategic partners in the manufacture of lithium compounds (Obaya, 2022). According to the author, among the main reasons for this adjustment in strategy were the improvement of financing options and "the need to improve the technical efficiency of the process developed by YLB, which had low resource recovery rates" (2022:40). In this context, the joint venture YLB-ACI Systems (with German capital) was created to produce lithium salts, a partnership that broke down in 2019 due to opposition from the Potosí Civic Committee, which was opposed

to the Morales government, to the proposed distribution of profits. All this took place in the context of the widespread political crisis that the country went through after allegations of electoral fraud (Obaya, 2022; Molina, 2025).

If between 2008 and 2019 the Evaporative Resources Industrialization Strategy was characterized by the development of the lithium value chain under a comprehensive model of state control, from that moment on, some authors saw a turning point marked by the reconfiguration of the national industrialization program as it had been proposed up to that point. Under the government of Luis Arce, international calls for bids were launched for foreign companies to participate in the exploitation and industrialization of lithium, even though YLB retains majority control. Based on these calls for bids, the Russian company Uranium One Group and the Chinese consortium CBC Hong Kong Investment Corporation were selected to operate using direct Lithium extraction (DEL) methods rather than evaporative methods. At the time of writing, the signing of these contracts is currently being evaluated by the Plurinational Legislative Assembly (Molina, 2025).

Various civil society organizations have criticized the lack of transparency surrounding the signing of these contracts, in which the procedures for free, prior, and informed consultation and environmental impact assessment were not properly followed, claiming that they will be implemented once the projects are formally approved (Paredes, 2025).

In 2019, Argento and Puente described a scenario in which there were no territorial claims based on indigenous law (after the granting of titles to Community Lands of Origin) or environmental causes surrounding lithium mining in Bolivia (2019: 198). The design of the national industrialization strategy, with public support and the integration of peasant and indigenous territorial leaders, made it possible to reduce the level of eco-political conflict compared to neighboring countries (Obaya, 2022). However, following the changes made in recent years, socio-environmental concerns across the Lithium Triangle have taken on greater prominence in the country: the role of foreign capital, the impact of salt flat exploitation on water resources, biodiversity, and community life, the development of procedures to guarantee indigenous rights, and competition with key economic activities in the region, such as tourism. All this is taking place in a context of economic and political uncertainty regarding the viability of industrialization plans and the future of a production sector that has yet to take off.

## 9.3. Key points for fieldwork

### 9.3.1. Axis of eco-political conflicts

Before presenting what we consider, based on our research, to be essential factors for promoting the socio-environmental legitimacy of lithium mining projects, we will begin by drawing up a brief map to clarify the coordinates in which these eco-political conflicts are situated. This map is the result of a synthesis of the extensive academic literature that has been produced in the wake of the current interest in this strategic resource and of our own ethnographic work.

Resistance to the expansion of lithium mining is based on different axes of problematization linked to the modulations of the eco-social relations involved in these projects. As an analytical tool, we propose to differentiate conflicts according to whether the emphasis of the problematization falls on socio-environmental aspects or on socio-economic issues. In turn, these categories can be subdivided into two levels: local and national/global, which allows us to distinguish between conflicts on a territorial scale and those that operate on a broader geographical and political dimension.

The result of these cross-references gives rise to the following table:

**Table 19. Ecopolitical conflicts in lithium mining.**
Source: Own elaboration.

**Ecopolitical conflicts in lithium mining**

| | Socio-environmental | Socioeconomic |
|---|---|---|
| **Local** | Water consumption.<br>Pollution.<br>Impacts on biodiversity.<br>Impacts on soil. | Indigenous peoples' rights.<br>Impacts on traditional worldviews.<br>Fair redistribution of benefits.<br>Conflicting economic interests. |
| **National – Global** | Climate change.<br>Decarbonization. | Governance models.<br>Development models.<br>Just energy transition. |

- Local socio-environmental issues: High Andean salt flats are fragile ecosystems characterized by extreme environmental conditions in terms of temperature, altitude, solar radiation, and low rainfall. This is why there is shared concern about how the installation of mining infrastructure and the pumping of brine could alter the ecological balance of these regions. The salt flats are also critical habitats for various bird species and, in their microbial mats, are home to life forms of great interest due to their adaptation to extreme conditions, the systematic scientific research of which is still in its infancy.

- Although various reports have pointed to potential impacts on biodiversity, pollution associated with the chemicals required for lithium processing, and differential soil settlement, the greatest concern associated with this type of mining—commonly referred to as "water mining"—is the possible depletion of the region's water resources. Lithium extraction using the evaporative method, the most prevalent in production projects in the region, involves pumping brine into settling and evaporation ponds and includes the use of fresh water to purify the salts (Romeo, 2019). Certain lines of research warn that this pumping of brine could accentuate discharges from the salt flats and cause saline intrusion into freshwater reservoirs, thus reducing the water resources of a region that is already semi-desert and affected by drought problems associated with the climate crisis (Arias et al., 2022). However, there is currently no certainty about the impact of this extractive activity on the water balance of salt flats. This is due to the lack of scientific consensus on the applicable hydrogeological models, as well as the variability in the specific dynamics of each salt flat (Clavijo et al., 2022; Díaz et al., 2025). Despite this, the defense of water is one of the main drivers of eco-political conflicts surrounding this type of mining, which has prompted numerous efforts by researchers focused on proposing comprehensive monitoring tools for salt flats or more accurate indicators to measure water consumption (Real et al., 2024; Díaz et al., 2025).

- National/global socio-environmental: Lithium is a key element in the decarbonization of economies and the fulfillment of the international climate agenda. Therefore, without ignoring the need for extractive processes to be subject to strict local socio-environmental sustainability criteria related to water management and respect for biodiversity, the energy transition currently requires the development of this mining activity. However, from certain political positions, the environmental benefits of electrification facilitated by lithium extraction are overshadowed by the unequal distribution of environmental costs and benefits between the global North and South: while the South bears the environmental, social, and

landscape impacts of extractive processes, the North monopolizes consumption, especially in the form of electromobility. This type of criticism connects with debates around center-periphery inequality, extractivism, ecological debt, and socio-environmental justice. The debate becomes more complex from the perspective of socio-environmental justice, specifically related to climate: the countries on the periphery of the world system, which bear very little responsibility for the depletion of humanity's carbon budget, will be the ones to bear the most catastrophic impacts of the climate emergency in the coming decades (Tejero and Santiago, 2019). This should make these nations the first to be interested in implementing an ambitious climate agenda in all its manifestations. However, in a tension that has accompanied climate diplomacy since its inception, it is precisely the lesser historical responsibility of peripheral countries that discourages them from adopting public policies for decarbonization (such as the promotion of the "lithium frontier") as long as these entail an economic cost or political penalty for the governments that implement them. Ultimately, this axis of eco-political conflict brings together four specific features that make the climate crisis a very complex political problem to address: the difficulties in defining the contours of the climate threat in politically representable terms, the tension between the perspective of local damage and the perspective of global damage, the grievances arising from inherited power asymmetries around carbon production and consumption, and, finally, the obstacles inherent in managing a common good (the global atmosphere) from fragmented and competitive operational units, a scenario that, as game theory has studied, turns climate change into the perfect prisoner's dilemma (Rendueles, 2024).

- Local socioeconomic: at this level, resistance to lithium mining is concentrated in three main areas:

    a) Conflicts arising from the interests of other industries or productive activities in the region that may clash with mining. Mainly the tourism sector, due to the possible loss of aesthetic value that the installation of mining infrastructure would entail for the landscape, and, to a lesser extent, the exploitation of salt by community cooperatives.
    b) Relations with the indigenous communities that inhabit the territory. This area includes, first and foremost, the necessary fulfillment of indigenous rights in terms of autonomy, recognition, land ownership, and free, prior, and informed consultation, as established by ILO Convention 169. Secondly, the fair negotiation of the benefits and economic compensation to be received by the communities affected by the projects. And, finally, the existence of effective mechanisms for democratic participation in the socio-environmental assessment procedures for the projects.
    c) Debates focused on the possible impacts that both economic development and the ecological transformations associated with lithium mining may have on worldviews and traditional ways of inhabiting a territory conceived as a product of the symbolic-spiritual links between the human and the non-human (Göbel, 2013). These reflections take center stage in critiques of institutional environmental impact assessment tools, insofar as they tend to exclude the assessment of these eminently qualitative realities and privilege forms of knowledge and technical language that hinder intercultural dialogue.

- National/global socioeconomic: the fact that lithium is mainly used to manufacture batteries for electric vehicles in Northern countries, coupled with the shortcomings of energy transition policies in producing countries, opens the door to a debate on territorial justice at the global level and development models, which in the Latin American case tends to lean toward a historical controversy that revolves around the role of raw material exports as an engine of growth, and which is intensified by the difficulties faced by many Latin American countries in climbing the lithium value chain (Obaya, 2022). From certain critical perspectives, Latin American lithium economies, being fundamentally oriented towards the export of raw materials with a minimum degree of processing, are said to have a marked extractivist character (Svampa, 2019). The lithium governance model adopted by each country plays a key role in modulating this type of criticism. Controversies are accentuated in countries where private capital plays a predominant role, environmental regulations are lax, or there is weak public intervention to ensure the rights of indigenous communities are upheld. In contrast, they are mitigated in models with greater public control, robust environmental protection regulations, and effective rent-capture mechanisms at the national level.

Post-extractivist proposals, as an alternative to this development model, serve as the ideological center of gravity for a significant part of the eco-political conflict surrounding lithium mining. The content of these proposals falls into two dimensions, which are not always compatible: on the one hand, the search to overcome the status of extractors and exporters of raw materials, which aims to develop technological capabilities that allow for new productive links in the value chain; on the other hand, the consideration of the cultural particularities of the affected communities, especially in the case of indigenous peoples, as a fundamental criterion when building socio-environmental legitimacy. This is a strong feature of the era, which, with its national particularities, is present throughout the Lithium Triangle.

### 9.3.2. Ethnographic evidence

#### 9.3.2.1. Socio-environmental legitimacy as a matter of dispute, social license as a prerequisite

The first ethnographic evidence offered by our fieldwork that should be highlighted is the increase in recent years in the importance of social acceptance of mining activity in Latin America, essentially conceived under the category of "social license." This is particularly true in new developments linked to the expansion of the lithium frontier, where different forms of local resistance have been amplified and reinforced by significant national and international attention. This reality is an unmistakable sign of a historical juncture that is placing socio-environmental legitimacy at the center of public debate. And the management of eco-political conflicts as one of the key elements of tension for the success of any governance model. This phenomenon goes beyond mining to affect any economic project that may have an impact on that social space of belonging perceived and named with the diffuse category of territory, whether in its sociocultural or environmental dimensions.

As noted, the fieldwork for this research has shown that, far from being reducible to a technical administrative issue, in which social license and socio-environmental legitimacy coincide to the point of establishing a neutral and universally accepted procedure for obtaining and verifying them, socio-environmental legitimacy is a matter of dispute. It is an open field, without consensus, in which different actors fight to establish their definitions, indicators, and moral premises. Therefore, any analysis of the eco-political conflict surrounding lithium must begin by distinguishing between the regulatory requirements imposed in each country and socio-environmental legitimacy, since compliance with the former does not guarantee, by any means, the generation of the latter.

This is a process in which several trends of profound social change converge in a complex and contradictory manner: the rise of indigenous and native peoples' movements as political actors with an agenda of historical demands that revolves around the recognition of rights and control over land ownership, and which is part of a broader process of extending democratic logic within Latin American societies; the advance of environmental awareness on all fronts—civil society, academia, the judiciary, political institutions—modulated by the dual recognition of ecological impact and social justice; the emergence of new decentralized elites, far removed from the traditional centers of accumulation and decision-making, closely linked to new emerging economic sectors (such as ecotourism) or organized around the defense of their real estate assets. These motivations, which are very different from one another, converge on a premise that is already an essential part of the common sense of the era in which the eco-political conflicts of the 21st century are unfolding: at least in Latin America, we are in a historical context that is much less tolerant than in the past of any form of economic activity that is perceived as extractive abuse.

What our fieldwork has revealed is that this explicit awareness of the new importance of social license, that is, how obtaining a certain degree of territorial acceptance is a requirement of the times that no mining developer, whether public or private, can afford to ignore, is shared by all actors involved in lithium eco-political conflicts. In fact, this change of era can also be seen in the strategies that mining companies are currently deploying in their relationship with the territory, pursuing certain criteria of social and environmental sustainability through practices such as negotiation with communities, the development of social responsibility programs, and periodic and participatory environmental monitoring mechanisms. These types of practices not only comply with current national regulations but have also gone hand in hand with the proliferation of private transnational standards for sustainable mining (among others, IRMA -Initiative for Responsible Mining Assurance- or TSM -Towards Sustainable Mining-). Although adherence to these standards is voluntary, obtaining this type of certification has become, if not a formal requirement, at least a competitive advantage in the global market.

In the case of Chile, the design of the National Lithium Strategy as public policy has been extremely conscious of this problem. In fact, one of its basic pillars is the need to generate socio-environmental legitimacy around the process. This task has gone beyond strict compliance with international legislation, such as ILO Convention 169, to become an active political vector that has been worked on extensively by the government of Gabriel Boric.

It is significant, for example, that all the indigenous consultation processes carried out within the framework of the National Lithium Strategy, both those related to the Special Lithium Operation Contracts (CEOL) and those related to the definition of the Protected Salt Flats Network, are posted on a ministerial website that allows access to the files. According to official information collected from the websites of the Ministries of Mining and Environment, in the last two years the Chilean government has proceeded to promote nine indigenous consultations related to the Special Lithium Operation Contracts (at the time of writing this article, two of them—Salares Altoandinos and Maricunga—have already been closed, with 13 and 11 agreements respectively, and seven are in progress)[27], and seven indigenous consultations related to the creation of the Protected Salt Flats Network (at the time of writing, all are in progress)[28].

Furthermore, as we learned during our fieldwork, in order to create a climate conducive to the establishment of the planned CEOLs, the Chilean state, through various mechanisms and agencies, has created direct and rapid intervention teams in the lithiferous territories. That is, people with mandates to execute agile public policies, less affected by the dynamics of bureaucratic delay that are so common in modern states. Their objective has been to respond to basic and unmet demands of communities likely to be affected by indigenous consultations within the framework of the CEOLs. The explicit objective of these teams covering basic local demands, anchored in everyday life (problems related to water, energy, transportation, or local education), is to "repair the trust" of communities after decades of state neglect, intensified by the cycle of neoliberal governance. This is an urgent attempt to repair historical marginalization, whose accumulated grievances could amplify rejection of the projects.

This change in sensitivity on the part of the Chilean state should be interpreted in two ways: on the one hand, there is an ideological commitment by the Frente Amplio government to environmental justice, although its practical results do not always match the demands of environmental movements, indigenous communities, or its own electoral support base; but, in addition, recent historical experience has shown that the alternative is doomed to failure.

[27] The files on indigenous consultations related to Special Lithium Operations Contracts can be consulted at the following link: https://participa.minmineria.gob.cl/es-CL/folders/consultas-indigenas

[28] The files on indigenous consultations related to the Protected Salt Flats Network can be consulted at the following link: https://consultaindigena.mma.gob.cl/

Sebastián Piñera's government was unable to expand Chile's lithium frontier in the midst of the international lithium boom. One of the fundamental reasons for this was the lack of attention to issues not only of social legitimacy in an ambitious sense, but also of the more restrictive regulations established nationally and internationally to certify some degree of social license, such as the holding of indigenous consultations (one of the arguments that led the courts to reverse Piñera's final attempts to grant concessions to private actors in the final stretch of his administration).

However, despite this notable progress in terms of social license, eco-political tensions around lithium continue to exist. The conflict surrounding the country's largest deposit, the Salar de Atacama, remains unresolved. This conflict has been reactivated at different stages: with the renegotiation of the contract with SQM in 2018, with the memorandum for collaboration between CODELCO and SQM in 2023, already within the framework of the implementation of the National Lithium Strategy, and with a complaint filed by the Council of Atacameño Peoples at the end of 2024, related to a study that demonstrated the progressive sinking of the salt flat due to overexploitation of its aquifers. However, on January 2, 2025, President Gabriel Boric held a previously unprecedented meeting with the Council of Atacameño Peoples Lickananatay, which focused on the eco-political conflict over lithium in the Salar de Atacama. Both parties considered the meeting historic, and during it, the highest authority of the Chilean state referred to the relationship with the salt flat communities in terms of a debt that the state owed and must repay. Regardless of whether the Boric administration manages to redirect the conflict in the salt flat caused by the memorandum between SQM and Codelco, this event demonstrates a concern for socio-environmental legitimacy that is substantially different from the past.

The fact that the Chilean government's efforts are far from being recognized by all the actors involved was also evident in the opposition that Chile's National Lithium Strategy has aroused in the country's environmental movement. Following the presentation of the ENL, nearly a hundred socio-environmental organizations from across Chile signed a public statement warning of the risks of such expansion (March 28, 2024), expressing their rejection of the possibility that half of the country's salt flats could be declared suitable for exploitation without completed hydrogeological studies or adequate assessment of their ecosystem and cultural services.

In summary, what the fieldwork has revealed is that the Chilean government's desire to build socio-environmental legitimacy can be interpreted by some of the territorial actors most reluctant to expand the lithium frontier as "greenwashing" or as sophisticated forms of political bribery: a clear symptom that socio-environmental legitimacy remains a matter of dispute in Chile.

The eco-political conflict in Argentina is a paradigmatic case of the distance between social license understood as a technical-administrative requirement and socio-environmental legitimacy conceived in a political-normative sense. Although companies comply with a series of minimum requirements in environmental matters and in their relationship with indigenous communities, these requirements have proven insufficient to guarantee the socio-environmental legitimacy of these projects.

One of the most recurrent criticisms of the lithium governance model in Argentina is the lack of specific protocols to ensure compliance with the socio-environmental rights enshrined in state regulations and international agreements signed by the country. Added to this is the weak public intervention in relation to these procedures. In comparison with the Chilean case, for example, there is a lack of clear and accessible information through official platforms on consultations with indigenous communities or environmental assessment reports, with even the authorities themselves recognizing that this is an area that needs to be improved in order to gain transparency and public trust. Secondly, despite having signed the Escazú Agreement and developed

environmental protection regulations that establish minimum standards at the national level, the country has not developed a specific strategy for the protection of the high Andean salt flats, as Chile has done.

Free, prior, and informed consultation is recognized as a right, but in the absence of agreed-upon protocols for its implementation, the means by which companies obtain social license have become a source of conflict that has generated significant resistance movements (Pragier, 2019). The most paradigmatic case is the opposition to lithium extraction by the Mesa de las 33 communities of Salinas Grandes and Laguna de Guayatayoc, following the refusal of the authorities and companies involved to apply the prior consultation protocol that had been drawn up by the communities themselves in collaboration with organizations such as the Fundación Ambiente y Recursos Naturales (FARN): the "kachi yupi" or "footprints of salt.". According to some informants, the initial position of these communities was favorable to negotiation, but the refusal of the companies to comply with the established procedures ultimately led to collective rejection of mining operations[29].

On the other hand, the negotiation of benefits to be received by local communities is not subject to specific legal development, so it becomes a kind of agreement between private parties, without public mediation or minimum legal criteria. Compared to other countries in the region, there is a perception that the amounts of financial compensation received by communities are considerably lower. Even people linked to mining companies have expressed in interviews a certain unease about this delegation of state functions. According to them, this could be a way for the state to avoid becoming involved in potential conflicts with communities that would negatively affect its image. This lack of regulation also leaves room for the deployment of business negotiation strategies that are considered illegitimate and contrary to the law. These often include seeking to divide communities internally through practices such as negotiating benefits with individual community members, approving licenses in assemblies where the entire community is not represented, or starting operations without the acceptance of all the communities linked to the salt flat.

In general terms, the delegation of state functions has been identified as part of a broader process affecting the relationship between the state, companies, and communities in Argentina: substitute governance (Pelfini et al., 2020). The difficulty of access to basic services by the local population, coupled with the state's failure to guarantee certain rights, opens a space that mining companies take advantage of by including the provision of basic goods and services (municipal equipment, school improvements, or health campaigns) in their negotiations. While these actions are viewed positively by some communities and make it easier for companies to obtain social licenses, others have rejected these health campaigns, demanding that the state assume its institutional responsibilities and comply with the right to prior consultation[30]. In any case, the consent of communities obtained on the basis of this type of agreement calls into question the socio-environmental legitimacy of the projects for many.

In the case of Bolivia, the National Strategy for the Industrialization of Evaporative Resources included indigenous and peasant communities in the project's area of influence in its initial design. The Bolivian Mining Corporation, in collaboration with trade unions, promoted assemblies, open meetings, and awareness-raising activities. Policies were also developed to boost local employment through technical training for secondary school students and the incorporation of community cooperatives into the production chain, as was the case with Delta in Río Grande (Obaya, 2019; Obaya and Pascuini, Argento, 2018). With these types of measures, despite the fact that the

[29] The protocol is available at: https://naturaljustice.org/wp-content/uploads/2015/12/Kachi-Yupi-Huellas.pdf

[30] As an example, you can consult the statement published by the Community of Pozo Colorado (Jujuy). The statement is available at: https://www.instagram.com/p/DCp2mOJxgpj/

communities furthest from the salt flats claimed comparative redress in the perception of direct benefits (Fornillo, 2018), a high degree of socio-environmental legitimacy was achieved in the national lithium industrialization policy.

However, over the years, difficulties in getting production off the ground and changes made to the strategy have led to more conflictive relations with trade unions and some indigenous communities, and increased criticism of the socio-environmental legitimacy of the new lithium exploitation contracts with Russian and Chinese companies. Communities in the Uyuni and Pastos Grandes salt flats, such as the Central Única Provincial de Comunidades Originarias de Nor Lípez (Provincial Union of Indigenous Communities of Nor Lípez), together with environmental and indigenous rights organizations, have denounced the lack of transparency with which these agreements have been made and the failure to comply with the right to free, prior, and informed consultation, a mechanism that, according to Obaya and Pascuini (2020), has never been prioritized in the Bolivian state's relationship with local communities.

Environmental concerns surrounding these salt flats have also skyrocketed following the signing of these agreements. This is mainly due to uncertainty about how this activity will affect the region's water resources, agricultural activity, and the ecosystems of the salt flats, lagoons, and wetlands[31]. Similar to the case in Argentina, there is no specific network of protected salt flats as in Chile, but rather a series of broad environmental protection regulations and mechanisms which, according to various authors, are difficult to implement effectively due to a lack of institutional capacity and a shortage of technical and financial resources to carry out independent assessments (Romeo, 2019; Ströbele-Gregor, 2013).

In short, the first ethnographic indication provided by our fieldwork points to the strong influence, compared to the past, of project promoters, whether companies or governments, obtaining some form of territorial consent to ensure the success of productive projects linked to significant socio-environmental impacts. The expansion of the lithium frontier will not be achieved unilaterally. In this vein, our fieldwork also suggests a certain exhaustion of the "social license" paradigm: in Latin America, the various agents of territorial opposition are calling for a shift from the rhetoric of shared value to concrete benefits based on verifiable facts. All this is taking place within a context of substantially increased demands for respect for the parameters of cultural diversity and recognition of the ontological, epistemological, and ethical approaches of local communities.

#### 9.3.2.2. The lack of uniformity in the positions of the local population

Given the breadth and complexity of the ecological, political, cultural, and economic elements at play in these debates, there is no single position among the local population regarding the advancement of lithium projects in the region, as has been pointed out in the literature on the subject and as we have been able to verify during our fieldwork (Göbel, 2013; Clavijo, 2022; Lorca et al., 2022).

[31] The following link provides access to the statement issued by the communities of Pastos Grandes in 2023: https://salares.org/3117-2/

**Table 20. Ethnographic evidence in lithium mining.**
Source: Own elaboration.

| Favorable arguments | Arguments against |
|---|---|
| Economic compensation | Violation of indigenous rights: prior, free, and informed consultation, autonomy, participation, and land ownership |
| Employment | Ecological damage (water, biodiversity, etc.) |
| Other material benefits and improvements to deficient infrastructure and services provided by companies through their social programs and community relations | The leading role of companies in providing services that should be guaranteed by the state (health campaigns, construction, or provision of materials for schools, etc.) |
| Settling the population in the territory | Transformation of the landscape, ways of life, and ties to the territory |

This ethnographic evidence indicates that the final responses of acceptance or rejection are more ambivalent than might be inferred from some activist campaigns or mining companies' impact reports, and do not exclude the existence of internal tensions and debates within communities that call into question the socio-environmental legitimacy of projects, beyond compliance with technical approval requirements. Community's favorable positions on lithium exploration and extraction are often associated with expectations of economic development, services, infrastructure, and employment niches that will improve their living conditions. However, the acceptance derived from these expectations is also often accompanied by uncertainty and concern about the impacts that the transformation of their territories may bring. Similarly, rejection of the introduction of companies does not necessarily imply opposition to mining activity itself but may be based on criticism of the lack of guarantees in the consultation process, demands for greater benefits, or conflicts with other economic interests.

A further level of complexity arises from the fact that the economic and environmental impacts of lithium mining are not the only factors that influence the responses of the local population. During fieldwork, it became clear that special attention must be paid to the fact that these eco-political conflicts also involve historical demands by indigenous communities related to autonomy and land recognition, which directly influence their position on these projects. An illustrative example is the contrast that occurred in the Argentine province of Jujuy between the acceptance and negotiation with mining companies by the communities around the Salar de Olaroz-Cauchari, compared to the sustained resistance over many years by those located in Salinas Grandes and Laguna de Guayatayoc. Ethnographic research indicates that a key factor in explaining this divergence is the uneven progress in the processes of identity recognition and the acquisition of community land titles. Those communities that already had land titles when the companies arrived were more inclined to negotiate. Meanwhile, those that were at an early stage in the recognition of collective rights took advantage of their insertion into the global lithium scene to reposition their demands for territorial autonomy (Argento and Puente, 2019; Pragier, 2019; 2024).

Another key element points to the importance of addressing the possible variations and nuances that these responses may acquire over time, since the dialogue between communities and companies is ongoing as long as they are operating in the territory. Just as communities, once that social license has been granted, continue to negotiate with companies to improve their benefits or achieve specific demands, companies, for their part, implement different strategies to reverse the initially unfavorable positions of some communities and achieve their acceptance. This has been

precisely the case with some oil companies that have recently managed, through the negotiation of benefits with communities far removed from other economic centers in the region, such as tourism, to break the consensus that the communities of Salinas Grandes had maintained for years to prevent mining development in the salt flats.

Finally, although there are elements that cut across different countries and regions, it is essential to pay attention to the contexts, nuances, and specific factors that, in each particular case, can tip the local population's responses toward acceptance or rejection of these projects and influence the construction of socio-environmental legitimacy. Among these factors, the following stand out: the specific procedures followed in the consultation and social license processes, the quality of previous experiences with mining in the region, and the presence of mining activity as a key element in the construction of the cultural and economic identity of the population.

These latter aspects are well reflected in the Chilean case. Chile is a country with a mining tradition, where mining has a very significant identity footprint and is capable of activating various layers of memory laden with very different resonances. For example, fieldwork indicated that for some environmentalists, lithium activates memories of 19th-century saltpeter, an industry whose geography overlapped with that of the expansion of the lithium frontier and which is remembered as an example of extractive activity with high social and environmental impacts in pursuit of ephemeral wealth, turning the far north of the country into a sacrifice zone (with additional imperialist connotations, as territories annexed from Bolivia during the War of the Pacific 1879-1884). However, the memory of copper triggers other processes of identification and analogy: for mining regions, it activates an identity linked to mining as a source of economic prosperity; for the left, copper has mythological resonances because its nationalization was the backbone of the Popular Unity project between 1970 and 1973, which in turn generated certain expectations when assessing the implementation of lithium policies in the 20th century.

#### 9.3.2.3. Environmental impacts as certain as they are uncertain: understudied ecosystems, public information deficits, and lack of consensus on the notion of damage

The third strong ethnographic indication revealed by our fieldwork has to do with an element of epistemic uncertainty surrounding the environmental dimension of the eco-political tensions surrounding lithium. Although, as in any other socio-environmental conflict, the expansion of the lithium frontier and the resistance to it involve a clash of values and interests, a particular feature of the lithium phenomenon in Argentina, Chile, and Bolivia is that this friction is amplified by a notable lack of information and scientific certainty on key issues that could contribute to political negotiations based on the confidence provided by shared data and well-established evidence for democratic risk management.

Although the potential or generic impacts of lithium extraction in the triangle are known, the specific environmental impacts linked to the development of concrete projects are much more uncertain and subject to review and debate. Several factors contribute to this uncertainty: on the one hand, the Andean salt flats are, in many cases, very inaccessible territories, historically abandoned and ignored even by many people in the nearest population centers. This marginalization has contributed to their status as understudied ecosystems: scientific knowledge about the natural and hydrogeological dynamics of salt flats is still in its early stages of development. This necessarily takes its toll when it comes to establishing environmental monitoring parameters in specific projects: for many salt flats, there is no baseline data that would

provide a historical reference point for distinguishing, for example, between overexploitation of water and seasonal or cyclical variations in hydrogeological systems.

These gaps in accurate and localized knowledge of salt flats are exacerbated because, in countries such as Chile and Argentina, fieldwork reveals a problem that is no longer just a lack of data, but barriers to accessing existing data: each company promoting lithium mining projects manages its own privately developed hydrogeological model, without a public hydrogeological reference model with which to compare it. Nor does the state have the capacity to monitor the situation in real time. Consequently, the eco-political conflicts in the lithium triangle are reinforced by the remarkable opacity that exists regarding the actual extraction of water in the production processes that take place there. This dynamic generates suspicion and leads local resistance movements to argue that the promoting companies are either lying in order to further their interests or are basing their arguments on partial and incomplete studies, the misguided nature of which could give rise to unforeseen future environmental impacts.

In the Chilean case, the socio-environmental conflict surrounding the Maricunga Salt Flat is very significant in this regard: the same salt flat is divided into two areas, one granted for lithium mining and the other established as a protected area and national park. In this context, the compatibility of both uses on the same salt flat rests on the hypothesis that the aquifers that feed both areas are disconnected. Nevertheless, local resistance movements denounce that this hypothesis lacks sufficient empirical validity. Therefore, the precautionary principle that such a socially and environmentally valuable territory would require is not being applied. Far from being an isolated case, public ignorance of both the hydrogeological systems of the salt flats and their value in terms of biodiversity (both in terms of endemic microbiota—flamingos, reptiles, and crustaceans—and unique bacteria) negatively affects the conditions for an informed democratic debate in the Lithium Triangle.

One of the recurring complaints of Chilean environmental activists against the Boric administration's National Lithium Strategy is that the Protected Salt Flats Network was established with insufficient information. In fact, one of the most interesting aspects revealed by our fieldwork is that these information gaps on relevant environmental issues have an impact on the very process of designing and implementing public policies: to the extent that the National Lithium Strategy was the result of a complex process of mediation between three different ministries (Finance, Mining, and Environment), each with its own emphasis on the objectives of the strategy, some informants testified that the lack of solid scientific information weakened the Environment Ministry's negotiating position in the process.

To this basic epistemic uncertainty, we must add two important considerations that complicate the issue. Both have been put on the agenda by some indigenous communities and environmental movements, both those promoted by civil society and those acting from academic circles. On the one hand, there is the validity or invalidity of established environmental assessment models. On the other hand, there is a systematically underestimated conception of ecological damage, which introduces a flawed premise into the public discussion on the subject.

Mistrust of the environmental assessment models that lithium companies must comply with in order to obtain legal approval for their operations is fueled by the following shortcomings:

- The legal definition of area of influence. The Environmental Impact Assessment System requires the area of influence of each project submitted for evaluation to be defined. This concept refers, in general terms, to the geographical space covered by the environmental effects of the initiative. However, in the case of Chile, the regulations do not specify precise methodologies for drawing these boundaries, leaving room for technical interpretation in each case, which generates a certain legal uncertainty, the application of which

will depend on the context and the arbitrary criteria of the authority in charge. In Argentina, one of the reasons for the controversy generated by the decree published in 2023 to reform the regulation of environmental impact procedures in the province of Jujuy has been precisely the limitation of the definition of the area of influence to the communities closest to the mine and not to all those that may be affected by the environmental alterations resulting from that activity. Furthermore, these limitations not only have an impact on the environment but can also erode the rights of local communities to consultation and participation.

- The lack of a comprehensive assessment of watersheds and their overall behavior, which would provide a complete picture of the water system and its functioning.

- The lack of an "industrial synergy" approach that would make it possible to go beyond the evaluation of individual projects in order to carry out joint assessments of the cumulative impacts involved, for example, the saturation of projects in the same watershed or the same salt flat. In this regard, in 2024, the Catamarca Court of Justice issued a ruling ordering the suspension of new permits for lithium mining in the Salar del Hombre Muerto until comprehensive cumulative impact reports were submitted, after a major river in the area had dried up. This ruling could be a milestone in the environmental protection of Argentina's salt flats, although, according to several people interviewed, there is still much uncertainty about its scope and potential to bring about structural changes in environmental assessment procedures.

- The lack of recognition of early warning systems that would allow for the activation of preventive mechanisms to halt operations in the event of unforeseen impacts that could lead to irreversible tipping points for the system (as could occur with the collapse of a salt flat's water system).

- The difficulty of including in these models qualitative impacts derived from mining development in the region, mainly alterations in the ways in which indigenous communities perceive, know, and relate to the territory.

As for the consideration that the very concept of environmental damage on which the public debate revolves is based on an idea of underestimated ecological impact, this is undoubtedly one of the historical motivations of ecological activism: to shift the boundary of what is considered normal activity, to confront a whole series of negative consequences that conventional productivist thinking tends to externalize, and mere habit tends to render invisible. In the case of lithium mining in the triangle, there are numerous contributions being made by various environmental voices, both academic and from social movements and NGOs, to build a more demanding standard of sustainability around lithium. Some examples are:

- The attempt to redefine salt flats as wetlands, a category eligible for a higher degree of legal protection. In fact, one of the reasons for the stagnation in the approval of Argentina's Wetlands Law may be related to the impact it would have on the environmental protection of the high Andean salt flats and, therefore, on the restriction of lithium mining.

- The introduction by Bonelli and Dorador (2021) of the notion of micro-disasters to conceptualize the slow and often invisible impacts of extractivism, which affect the ancestral microbial ecologies of salt flats. These ecologies, which have developed over billions of years and were key to the oxygenation of the Earth, are essential for understanding both the origins of life and the interdependencies between current organisms.

- The extension of ecological damage to its landscape expression, with an emphasis on the aesthetic and sensory uniqueness of the Andean salt flats and the danger that mining activity poses to their preservation ("revealed landscapes" in the proposal by Arizaga et al., 2020).

In short, the fieldwork has suggested to us that one of the greatest obstacles to reconciling lithium extraction with strong socio-environmental legitimacy has to do with the fact that the lithium frontier is advancing into understudied ecosystems, generating data that is not public, through dynamics that the government has difficulty monitoring in the name of the general interest, on uncertain issues where scientific consensus is controversial, and in which the very scope of the debate (what constitutes environmental damage linked to lithium mining?) is still under discussion.

## 9.4. Conclusions

The expansion of the lithium frontier in the Lithium Triangle cannot be analyzed exclusively from technical or economic parameters. Both in its history of accumulated tensions and in its future trajectory, in which significant growth in mining projects is expected, driven by the increase in global demand for lithium, the reality of the region is fraught with eco-political disputes. These disputes bring into play, in a complex and changing map of actors, major economic interests, long-delayed historical demands from local communities, different claims on the territory, socio-environmental fears and uncertainties of various kinds, and conflicting views on the meaning of development.

Addressing this socio-anthropological complexity is essential if we want to ensure that the friction and resistance aroused by the lithium boom in the region does not slow down the process of global decarbonization or lead to a regression in the democratic standards of the countries in the area, where, with great effort, the right of local communities and indigenous peoples to be protagonists (and not victims) of an economic model that is inclusive of their values, interests, and sociocultural identities has been consolidated. This socio-anthropological perspective is an essential approach to enriching reflections on decarbonization at all levels.

From this starting point, this brief summary of the ethnographic evidence from the fieldwork that supports this study has shown us that:

- Socio-environmental legitimacy is a key qualitative category for considering the acceptance or rejection of mining projects, going beyond the limited notion of "social license." This legitimacy goes beyond the legally established parameters for obtaining consent as an administrative procedure and implies recognizing the contested, negotiated, and therefore political nature of the acceptance, or rejection, of a mining project in a territory. And while comparatively, at least since the implementation of the National Lithium Strategy, the Chilean model of social license has shown greater institutional strength than that of its neighboring countries in guaranteeing prior, free, and informed consultation processes, with formalized indigenous consultations, whose files are accessible on the web and whose initial processes are capable of reaching agreements with indigenous communities, this does not mean that the socio-environmental legitimacy of lithium mining in Chile is not still a matter of dispute.

- There is great heterogeneity in community responses to lithium projects, ranging from acceptance, negotiation with developers and the government with varying degrees of success in achieving objectives, to confrontation and rejection through various means. It is important to note that in no case can simplistic schemes be established that fix actors in static and homogeneous positions: not all indigenous communities act unanimously, not all indigenous peoples reject mining, and positions of acceptance or rejection are not permanent but can change depending on circumstances. Similarly, although indigenous peoples play a central role in the eco-political tensions surrounding lithium, the actors involved in these conflicts are more diverse, and the potential alliances complex: the patronage network of large mining companies established in the territory, local or regional communities not linked to indigenous peoples, activist or academic groups normally external to the territory, and other economic interests in the area.

- The generic environmental impacts associated with lithium mining (excessive water consumption, loss of biodiversity) are a difficult issue to discuss and negotiate politically. This is due to significant gaps in the production of scientific information on specific salt flats at different levels (from microbial mats to knowledge of hydrogeological basins), as well as significant barriers to accessing existing information held by private companies. This uncertainty, coupled with the technical and bureaucratic inability of the state to monitor in real time, plus the fact that environmental assessment systems have weaknesses that could be improved, undermines the socio-environmental legitimacy of lithium projects in the region. However, our fieldwork suggests that this is an area where the implementation of a series of transformative yet realistic public policies could significantly ease existing eco-political tensions and contribute to gains in terms of the socio-environmental legitimacy of lithium governance models. These public policies could be aimed at financing scientific research to establish baselines for various data related to salt flat ecosystems, creating public open science models on their hydrogeological dynamics and comprehensive monitoring, or reforming environmental assessment procedures.

- None of the eco-political conflicts in the Lithium Triangle can be understood without paying special attention to their contextual outline, both at a deeper and more structural level (e.g., the role of mining in regional identities, inherited tensions between the center and the periphery linked to long-standing socio-spatial inequalities, the level of recognition of rights achieved by indigenous peoples) and at the immediate juncture (e.g., how the correlation of parliamentary political forces at a given moment translates into the issue of lithium). Due to its idiosyncrasies and publication rhythms, academic literature, while not averse to paying attention to contextual elements, tends to be insensitive to incorporating aspects of the current situation into its reflections. However, our research shows us that, in a phenomenon as emerging and dynamic as the recent boom in lithium mining, this premise implies biases and blind spots that lead to a decline in analytical capacity. The eco-political conflicts surrounding lithium require us to take a highly fact-based investigative approach.

In short, the ethnographic evidence compiled here paints a picture of the Lithium Triangle as a socio-geographical space traversed by a complex network of eco-political conflicts, in which social license and legitimacy are far from synonymous categories, in which the actors in dispute are much more heterogeneous and dynamic than a certain essentialist view presupposes, and in which projects with a notable degree of consent coexist with others that manifest strong hostility or rejection. These projects are marked by highly specific empirical circumstances, which my research has a duty to address without resorting to pre-established schematic formulas. And due to the lack of basic scientific information and public access to company data, it negatively conditions the political conversation on the subject.

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# 10. ECONOMIC IMPACTS

## 10.1. Economic impacts in Chile

In recent years, Chile has consolidated its position as one of the main global players in the lithium industry. With around 30% of global production and 40% of known reserves of this mineral by 2022 (NRGI, 2024), the country has experienced a significant role in the lithium production industry, especially after the renegotiation of contracts with Albemarle (2016) and SQM (2018), which operate in the Atacama salt flat.

The immediate and visible economic effects have had a positive impact on the country's fiscal coffers. In 2022, lithium-related tax revenues reached USD 5.4 billion, equivalent to 1.8% of the national GDP and 6.9% of the country's total tax revenues in that same year, according to estimates by the Autonomous Fiscal Council (CFA). This figure considerably exceeds in the same year the contributions made by Codelco, Chile's main state-owned copper company, whose gross contribution was 0.7% of GDP.

Lithium-related tax revenues come mainly from four sources:

1. Rental income paid to the Production Development Corporation (CORFO).
2. Income tax.
3. Specific tax on mining activity.
4. Mining patents.

### 10.1.1. Lease payments paid to the Chilean Economic Development Agency (CORFO)

In Chile, mineral resources are owned by the State, as established in Article 19, No. 24 of the Constitution. However, the way lithium is managed differs substantially from other minerals such as copper or gold, as it has been declared non-concessible by Law No. 2,886 of 1979. This means that lithium cannot be mined under ordinary mining concessions, but only through special operating contracts signed between the State and private companies, authorized by the Ministry of Mining (BCN, 2023).

CORFO, a state-owned institution and owner of the mining rights to the Salar de Atacama, has signed contracts with two lithium-producing private companies: American-based company Albemarle (2016) and Chilean-based company SQM (2018). These contracts establish a system of lease payments, commonly known as variable royalties, which allow the State to capture part of the gross income generated by the exploitation of the resource. These are progressive payments calculated as a percentage of the sale price of lithium, with rates increasing when the value reached per ton of lithium carbonate equivalent (LCE) increases. This design allows the State to take a higher portion of the return value in periods of high prices without having to modify the tax framework or affect the viability of the business in periods of low prices (CORFO, 2016).

The *royalty* scale ranges from 6.8% to 40% of the sale price, depending on the market price. This mechanism, established contractually and not by law, has been considered by the Economic Commission for Latin America and the Caribbean (ECLAC) and the Autonomous Fiscal Council (CFA) as an efficient way to capture economic rent without discouraging investment (ECLAC, 2022; CFA, 2023).

Between 2012 and 2023, rental income generated by lithium exploitation exceeded USD 7.309 billion, with an annual average of USD 609.2 million. However, there is considerable variability in the amounts collected from year to year, with 2022 setting a historical record of USD 3.8 billion, influenced by the sharp increment observed in the international price of lithium (Table 21).

**Table 21. Lease revenues paid to Corfo between 2012 and 2023 (millions of USD).**
Source: Corfo, in NRGI, 2024

**Lease payments paid to Corfo by company (millions of USD)**

| Year | Albemarle | SQM | Total |
|---|---|---|---|
| **2012** | 2.1 | 27.6 | 29.7 |
| **2018** | 83.6 | 151 | 234.6 |
| **2022** | 776.9 | 3,069 | 3,846.8 |
| **2023** | 833.8 | 1,619.4 | 2,453.2 |

One of the most significant components of leasing income is the progressive *ad valorem royalty* contractually agreed with SQM. Unlike the "mining royalty" established by law (which is levied on operating income), this *royalty* is applied directly to the sale price and is clearly defined in the contracts with Corfo. According to data provided by SQM, payments under this concept remained below USD 100 million per year until 2020, when they rose sharply.

This increment is a direct response to the behavior of the international price of lithium, which exceeded USD 60,000 per ton on the 2022 spot market. The structure of the contract allows application up to 40% of the sale value, income that can be transferred to the State in the form of *royalties*. Figure 64 shows how payments rise sharply from 2021 onwards.

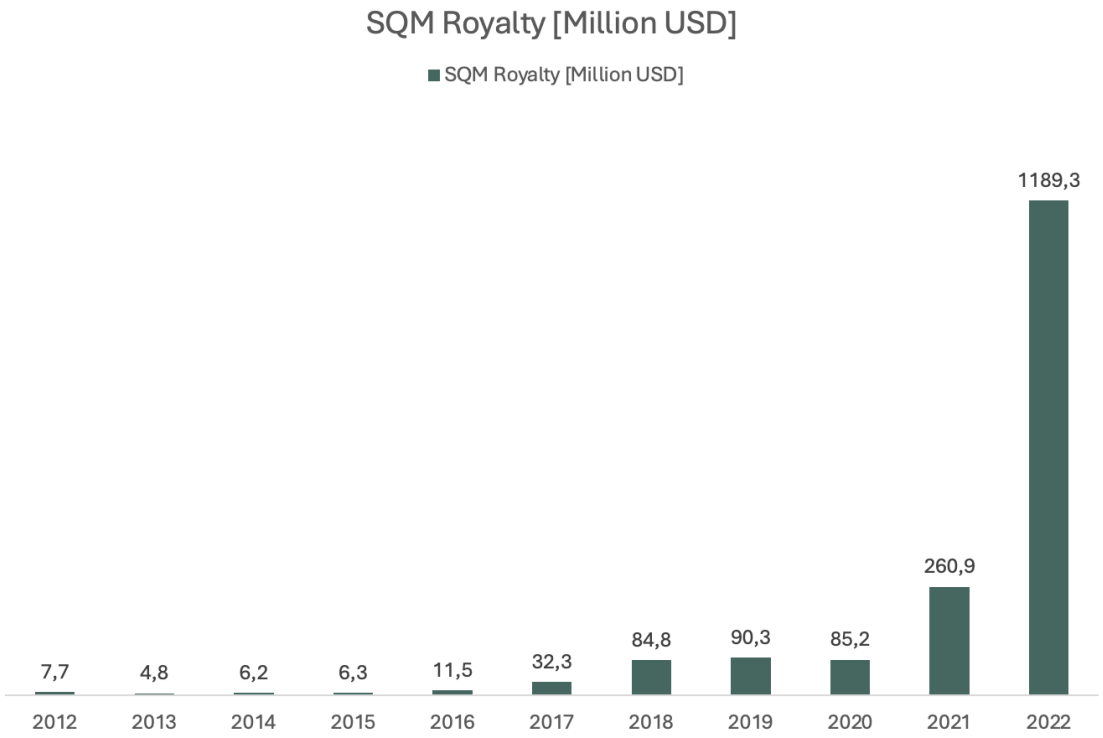



**Figure 64. Royalties paid by SQM from 2012 to 2022 (millions of USD).**
Source: NRGI, with data from SQM, 2023

### 10.1.2. Income tax

In addition to the lease income agreed with Corfo, the second significant source of tax revenue from lithium in Chile is income tax, applied to the net profits obtained by the private companies.

The First Category Tax, regulated by Decree Law No. 824 of 1974, is levied on income from capital and productive activities in general, including mining. Since the 2014 tax reform came into effect, the tax rate has been gradually increasing, reaching 27% in 2018, a rate that remains in effect to date (SII, 2023). This tax is determined on the basis of taxable net profits, after deducting tax-deductible costs and expenses, and applies to both domestic and foreign companies in Chile.

The share of income tax in the lithium tax structure has become particularly relevant in recent years due to the significant rise in international prices for the mineral and, with it, the profits of mining companies. This is reflected in the case of SQM, whose tax burden increased significantly between 2021 and 2022. In 2021, SQM reported income tax payments of USD 179.1 million. In 2022, this figure rose to USD 1,525.8 million, an increase of more than 750% in a single year. Albemarle, although on a smaller scale, also recorded significant increases. Its payments for this item rose from USD 15.2 million in 2021 to USD 32.1 million in 2022 (NRGI, 2024). Figure 65 shows the evolution of income tax payments by these companies.

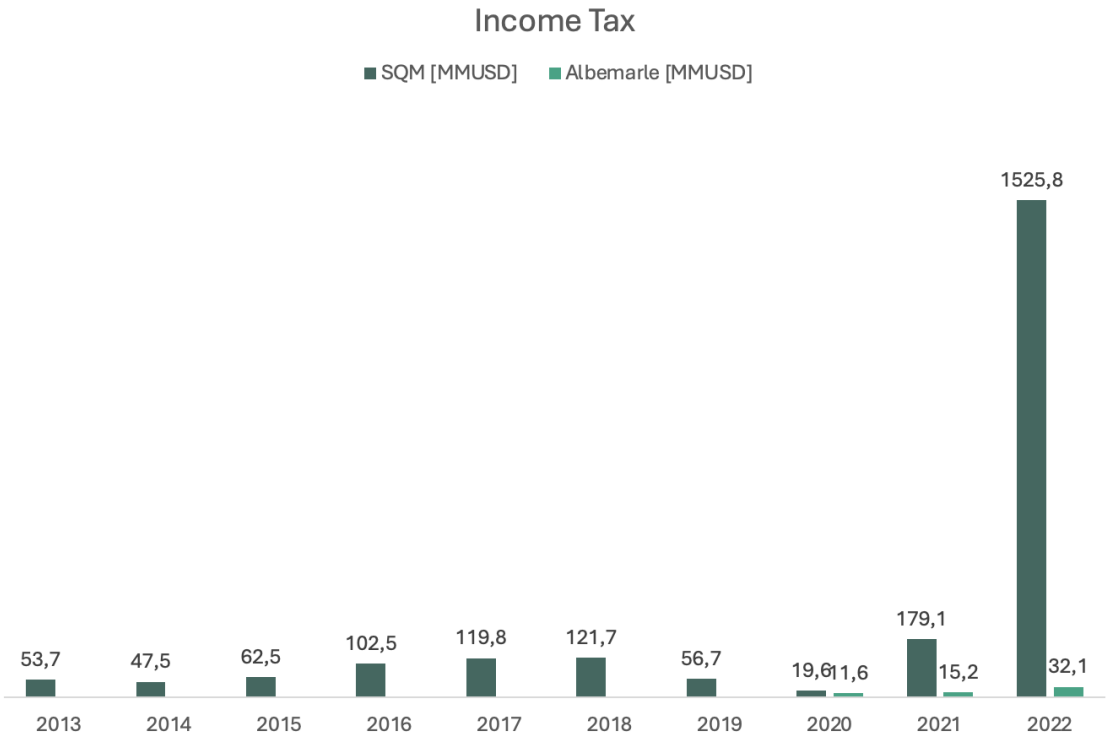



**Figure 65. Income tax declared by SQM and Albemarle from 2013 to 2022 (millions of USD).**
Source: NRGI, with data from SQM and Albemarle, 2023

### 10.1.3. Specific tax on mining activity

On the other hand, the Specific Tax on Mining Activity (IEAM), commonly known as the "mining royalty," is a tax created in 2005 by Law No. 20,026 and subsequently modified by Law No. 20,469. Unlike the *ad valorem* royalties agreed upon in contracts such as those of SQM and Albemarle, the IEAM is generally applied to all concessionable mining activities and is calculated on the basis of mining operating income. Its objective is to capture a portion of the economic income generated by the exploitation of mineral resources, especially in the context of high operating margins (Ministry of Finance, 2023).

This tax is levied on the mining operating margin (MOM), defined as the ratio of operating profit to the company's gross income. The rates are progressive and range from 5% to 14% under the original law and from 5% to 34.5% after the reform. The tax base is determined from net operating income, minus directly related costs, as established in the Income Tax Law (SII, 2023b).

The application of the IEAM to lithium mining has been particularly problematic because lithium, as a non-concessionable mineral, is not governed by the general concession regime. However, companies that mine it, such as SQM, still generate income from the exploitation of a non-renewable natural resource, which would justify the application of the IEAM based on the principle of tax fairness. The Internal Revenue Service (SII) has interpreted that these activities should be subject to the IEAM, while SQM has challenged this interpretation in tax courts and the Supreme Court, arguing for the exclusion of lithium from the general concession regime (NRGI, 2024).

Despite this, SQM has made IEAM payments on an ongoing basis. According to data from the NRGI report (2024), between 2016 and 2021, the company paid a total of USD 306.1 million in this regard. These payments made by the company are detailed below.

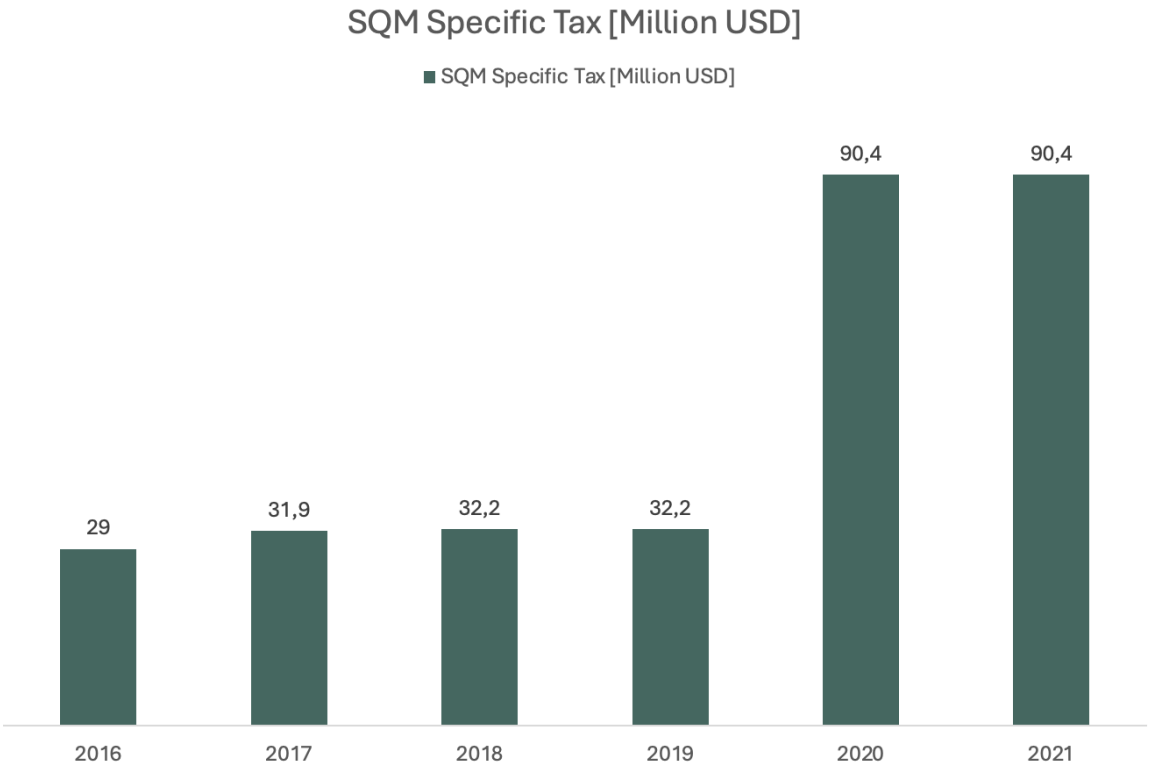



**Figure 66. Specific mining tax paid by SQM from 2016 to 2021 (millions of USD).**
Source: NRGI, with data from SQM, 2024

However, these payments do not represent the total amount that the SII considers SQM owes. In 2022, the company was billed an additional USD 164 million for the fiscal years 2012 to 2019. In addition, the SII anticipates that for fiscal years from 2020 onwards, the company could owe another USD 745 million in IEAM, not including interest and penalties. Although SQM has made some payments, it has also filed legal claims seeking to annul or reduce these settlements.

This conflict reveals a gray area in the regulations, given that, although lithium is outside the concession regime, its commercial exploitation generates revenues similar to those of the rest of the mining sector, so its exclusion could create tax loopholes. In 2023, the Budget Office and the Congressional Finance Committee discussed the need to reform the IEAM to formally include lithium mining and avoid ambiguous interpretations (Dipres, 2023).

### 10.1.4. Mining patents

Finally, mining patents are periodic payments that must be made by holders of mining exploration or exploitation concessions to maintain their rights over certain mining properties. These patents are not a tax in the strict sense, but rather a right to use mining property, regulated by the Chilean Mining Code (1983), specifically in Articles 139 to 151 (BCN, 2023).

The main function of these patents is to prevent speculative hoarding of mining areas, discouraging inactivity in areas with economic potential. In this sense, they are configured as a mechanism for land use planning in the extractive sector rather than as a significant source of tax revenue.

According to Article 142 of the Mining Code, the amount of mining patents is determined based on the type of concession and the area involved. Exploration concessions pay 1/50 of the Monthly Tax

Unit (UTM) per hectare annually, while exploitation concessions pay 1/10 of the UTM per hectare annually. This payment must be made before March 31 of each year, and failure to do so for two consecutive years results in the automatic expiration of the concession, without the need for a prior trial (SERNAGEOMIN, 2022).

In the case of lithium, the situation is unique. As it is a non-concessible mineral, the properties exploited by companies such as SQM and Albemarle in the Salar de Atacama are not subject to the general mineral concession regime. Consequently, the mining patents applied in this context do not comply with concessions granted by the judiciary, but rather with contractual agreements with Corfo, which is the holder of mining rights in that area (NRGI, 2024).

However, the contracts between Corfo and private companies stipulate that the latter must pay the mining patents associated with the properties they exploit. Therefore, although the companies are not direct holders of the concessions, they do comply with the corresponding payment as part of their contractual obligations.

In quantitative terms, mining patents represent a very minor source of tax revenue compared to income tax, IEAM, or royalties. According to data compiled by NRGI (2024), between 2013 and 2022, SQM paid a total of USD 2.2 billion for this concept. The annual average of these payments has been less than USD 330 million, a figure much lower than the more than USD 3 billion per year that the State received from lease income at the peak of those years. The SQM data is presented below.

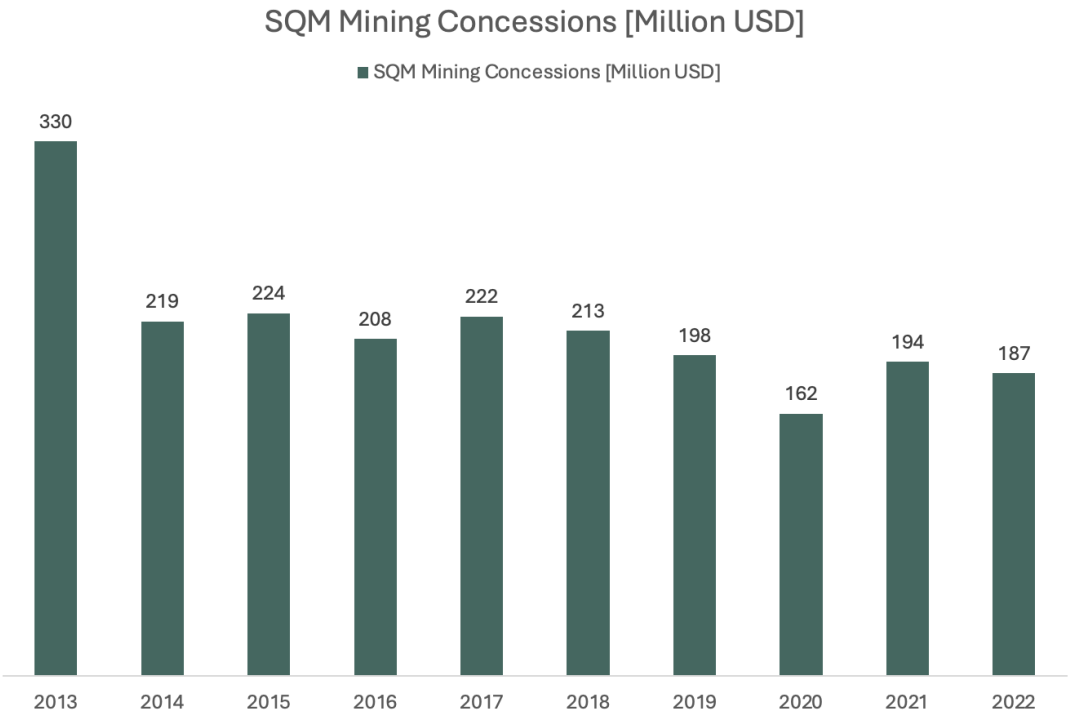



**Figure 67. SQM mining patents from 2013 to 2022 (millions of USD).**
Source: NRGI, with data from SQM, 2024

In addition to direct tax contributions to the State, the lithium exploitation contracts signed by SQM (2018) and Albemarle (2016) with Corfo include clauses that force these companies to make direct payments to third parties. These actors include regional governments, indigenous communities, and research and development (R&D) centers. Although not taxes in the strict sense, these contractual contributions represent a significant form of lithium revenue redistribution, with effects on local governance.

Between 2018 and 2022, SQM transferred approximately USD 230 million to subnational governments in the Antofagasta Region, of which 77% went to the Regional Government and the remaining 23% to the municipalities of San Pedro de Atacama, Antofagasta, and María Elena. These transfers correspond to 1.7% of the net sales value of lithium, as stipulated in its contract with Corfo.

In 2022, these payments exceeded USD 100 million, consolidating a decentralized and automatic financing model directly linked to the commercial performance of the mineral (NRGI, 2024). Albemarle has reported similar contributions, but public information is limited due to confidentiality clauses.

Since 2018, SQM has had an agreement with the Council of Atacameño Peoples (CPA), which brings together 18 communities from the Atacama salt flat. Under this agreement, it has already transferred USD 63.5 million between 2018 and 2022 for basic infrastructure, education, productive development, and drinking water projects (La Tercera, 2023).

Albemarle, for its part, signed an agreement in 2016 committing to deliver 3.5% of its net sales of lithium and potassium chloride to surrounding indigenous communities (MCH, 2022). The company has not published a breakdown of these contributions by beneficiary, which makes external monitoring difficult.
Both contracts also establish the obligation to finance research, development, and technological innovation initiatives. As of November 2023, Corfo had channeled nearly USD 198 million toward such initiatives, coming from SQM and Albemarle (NRGI, 2024).

Among the main beneficiaries are the Institute of Clean Technologies (ITL) with USD 125 million, the Circular Economy Center, the Electromobility Center, and various green hydrogen pilot projects. However, implementation has been uneven. For example, SQM has delivered more than USD 62 million to Corfo that has not yet been used, remaining in Banco Estado accounts without effective allocation to projects due to administrative delays and lack of operational definition (Ex-Ante, 2023).

In summary, between 2012 and 2023, Chile has received more than USD 9 billion from lithium exploitation, including revenue from royalties (USD 7.309 billion), income tax (more than USD 1.6 billion in 2022 alone), specific mining tax, patents, and direct contributions to communities and regional governments. These figures have positioned lithium as one of the most important resources in Chile's fiscal structure during its years of prosperity, given its high market price. In particular, 2022 marked a milestone, with total lithium revenues exceeding $5.4 billion, representing 1.8% of GDP and 6.9% of the country's tax revenues, a figure even higher than that of public companies such as Codelco. The following figure shows the evolution over time of the taxes paid by SQM, broken down by type of taxation.

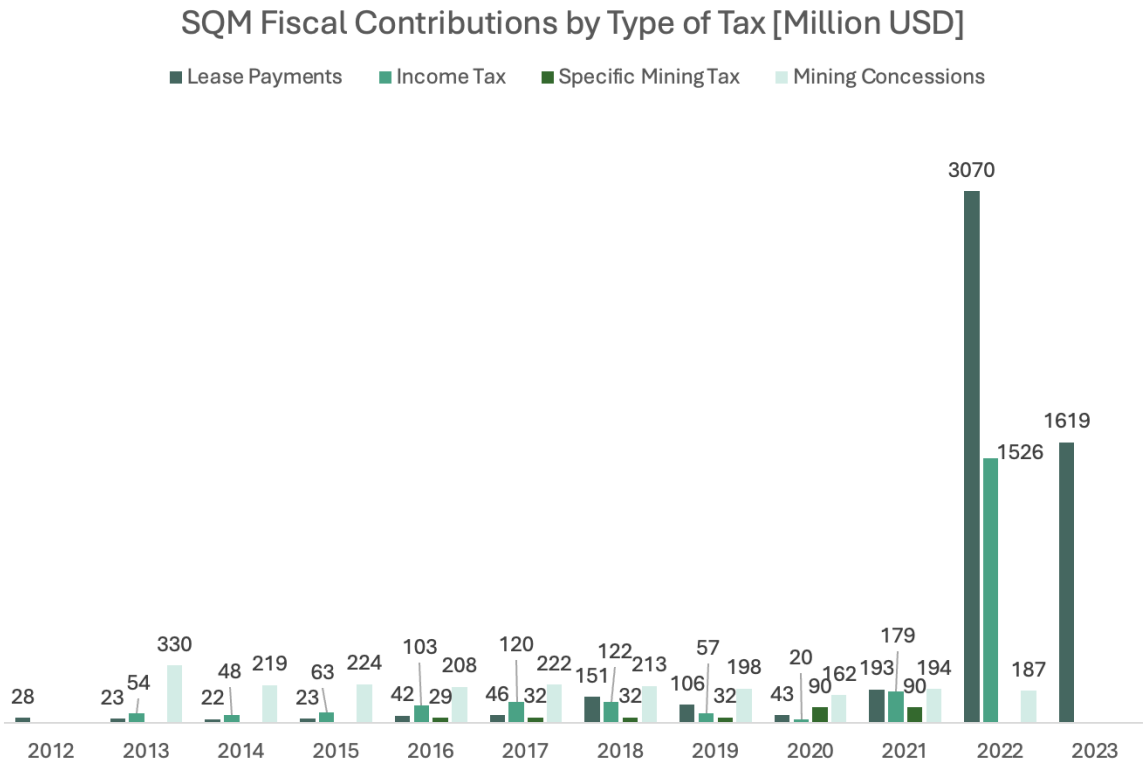



**Figure 68. SQM tax contributions by type of tax 2012–2023 (millions of USD).**
Source: NRGI, with data from SQM, 2024

The economic impact of lithium in Chile goes beyond the fiscal sphere. Contracts with SQM and Albemarle have allowed resources to be channeled directly to indigenous communities, municipalities, and research centers, strengthening territorial governance and technological development. However, they have also revealed significant challenges in terms of transparency, local institutional capacity, and public policy sustainability.

## 10.2. Economic impacts in Argentina

Argentina has positioned itself as one of the world's leading lithium producers, accounting for 5.3% of global production in 2023, which ranks it as the fourth largest producer worldwide after Australia, Chile, and China (Ministry of Mining, 2024). With more than 117 million tons of estimated resources and 19.2 million tons of lithium reserves in brines, the country is part of the "lithium triangle" along with Bolivia and Chile, accounting for more than 53% of known global resources, of which this country accounts for 21% (USCS, 2023).

The economic impact of this industry is evident, first and foremost, in the sustained growth of exports. In 2022, exports of lithium compounds reached USD 696 million, with a year-on-year increase of 234%, and are estimated to have reached USD 819 million in 2023, according to data from the Mining Secretariat (2024). By 2030, these figures are projected to rise to USD 8.73 billion annually, with Catamarca, Salta, and Jujuy as the provinces benefiting the most.

In terms of tax revenue, Argentina has a mixed system involving the national government and provincial governments. Tax revenue comes mainly from five sources:

1. Provincial mining *royalties*.
2. Corporate income tax.
3. Export duties.
4. Tax on bank credits and debits.
5. Annual environmental tax.

### 10.2.1. Provincial mining royalties

The provincial mining royalties correspond to payments that mining companies must make to provincial governments as compensation for the exploitation of natural resources, which are owned by the provinces according to the National Constitution, reformed in 1994. The general royalty rate is 3% of the "mine mouth" value (value of the mineral at the point of extraction, before processing), although the provinces have the autonomy to define different bases and rates, which allows them to establish different calculation bases (not only "mine mouth") and apply higher or lower effective rates according to their provincial regulations. In Catamarca, for example, royalties are calculated on the gross sales revenue, which increases their effective collection and could exceed 3%.

The amount collected in royalties has shown an upward trend over the last decade due to rising international prices and production. According to the Mining Secretariat (2024), in 2022, Jujuy received more than USD 19 million in lithium royalties, and Catamarca approximately USD 6 million.

With regard to specific data by company, although access to detailed public figures is limited, transparency reports from the EITI Argentina Initiative (2024) have revealed that companies such as Sales de Jujuy S.A. (operated by Allkem Limited), Minera del Altiplano S.A. (operated by Livent Corporation), and Minera Exar S.A. (a joint venture between Ganfeng Lithium and Lithium Americans) are some of the largest contributors to lithium mining royalties. According to the latest reports, Sales de Jujuy contributed nearly USD 15 million in 2022, Minera del Altiplano contributed approximately USD 4 million, and Minera Exar, which began production in 2023, is expected to increase its contribution in the coming years.

### 10.2.2. Corporate income tax

Argentina applies a corporate income tax at a 35% annual rate. This tax is levied on the net profits obtained by commercial companies, including lithium companies. It is calculated on the taxable income determined in accordance with the Income Tax Law. According to the EITI Argentina report (2024), Sales de Jujuy made payments of approximately USD 6.5 million in corporate income tax in 2022, while Minera del Altiplano contributed around USD 2 million. Minera Exar, which was in the development phase during that period, did not record any significant payments under this heading.

### 10.2.3. Export duties

Another source of income for Argentina is the export of duties tax. These are taxes levied on sales of products abroad, in this case, lithium and its derivatives. For lithium, the rate applied is 4.5% of the FOB (*Free On Board*) value of exports. The aim is to capture part of the income from natural resources that are traded internationally and to strengthen national tax collection. This tax is national in nature and is not shared with the provinces. In 2022, Sales de Jujuy paid approximately USD 3 million in export duties, while Minera del Altiplano contributed nearly USD 1.2 million. The

amount collected tends to fluctuate directly with international lithium prices and the volume of foreign sales.

### 10.2.4. Tax on bank credits and debits

Another source of revenue for the Argentine treasury is the tax on bank credits and debits, known as the "check tax," which levies a general rate of 1.2% on fund movements in bank accounts. Although it represents a smaller fraction than other taxes, it is a stable source of national revenue. Sales de Jujuy and Minera del Altiplano made joint payments estimated at USD 700,000 under this concept in 2022.

### 10.2.5. Annual environmental tax

Finally, another source of revenue is the annual environmental tax. Some provinces establish a specific tax linked to the environmental monitoring and control of mining projects. Sales de Jujuy, for example, allocated nearly USD 200,000 in 2022 to comply with environmental obligations, including inspection and monitoring fees.

The following graph shows the main sources of lithium tax revenue for Argentina in 2022. As can be seen, provincial royalties account for the largest share, followed by income tax and export duties.

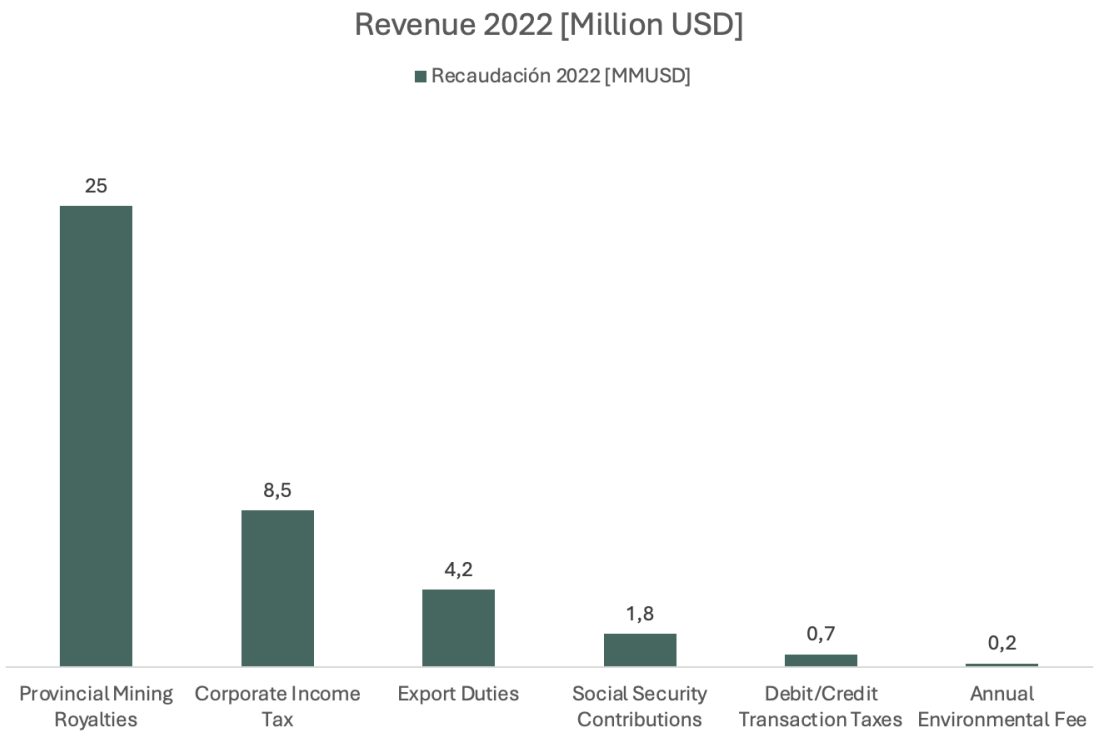



**Figure 69. Main sources of tax revenue from lithium in Argentina for 2022 (millions of USD).**
Source: Prepared by the authors, with data from EITI Argentina, 2024, and the National Mining Secretariat, 2024

In addition to the above, lithium companies must contribute to the social security system by paying contributions on their workers' salaries. This includes pensions, health insurance, and family allowances, among other components, generating revenue to finance the social protection system. By 2022, Sales de Jujuy allocated approximately USD 1.8 million in social contributions.

The total effective tax burden is estimated at between 28% and 44% of the economic income, depending on the type of project, its profitability, and its location (ECLAC, 2022). Although there are no official figures broken down by company and type of tax, some reports indicate that between 2007 and 2018, in Jujuy alone, lithium mining projects generated more than USD 500 million in tax revenues, combining national and provincial contributions (Jujuy Report, 2019). Argentina's federal system means that a large part of the revenue is distributed in a decentralized manner, which has had a significant economic impact on the leading provinces in the sector.

There is also a significant investment-inducing effect: in the first four months of 2023 alone, investments for USD 7.711 billion were announced, mainly in Salta, Catamarca, and Jujuy, with foreign capital coming from China, Australia, and France (Secretariat of Mining, 2023). These investments not only boost production and exports but have also stimulated employment and local infrastructure.

However, significant challenges remain in terms of fiscal transparency, regulatory harmonization between provinces, institutional capacity, and control of the revenues generated. Currently, Argentina does not have a unified public information system that provides detailed information on lithium tax flows, which limits social control and the planning of regional development policies.

## 10.3. Economic impacts in Bolivia

Bolivia has one of the largest lithium reserves in the world, estimated at more than 21 million tons, mainly concentrated in the Salar de Uyuni (USGS, 2023). However, its production level is significantly lower than Chile and Argentina. In 2022, Bolivia exported lithium products worth approximately USD 700 million, with a production volume not exceeding 1,200 tons of lithium carbonate equivalent per year (Ministry of Hydrocarbons and Energy, 2023).

In Bolivia, lithium exploitation is done by the state-owned company, Yacimientos de Litio Bolivianos (YLB), which is responsible for the extraction, industrialization, and commercialization of lithium. There are no private mining concessions for this resource. As a result, tax revenues from lithium come mainly from three sources:

1. Profits from the state-owned company.
2. Corporate Income Tax (IUE).
3. Value Added Tax (VAT) and Transaction Tax (IT).

First, the profits of the state-owned company are the earnings generated by YLB, once its operating costs have been covered, which form part of the surplus that is transferred directly to the National Treasury. According to YLB's Management Report (2022), the contribution of profits for 2021 was approximately USD 5 million.

Second, the Corporate Income Tax. YLB pays CIT at a rate of 25% on its net profits. In 2022, YLB contributed approximately USD 6 million under this concept (Ministry of Hydrocarbons and Energy, 2023).

Finally, Value Added Tax and Transaction Tax. YLB also pays VAT on its domestic sales and IT (at a rate of 3% on gross income). Although exact disaggregated figures are not available, it is estimated that revenue from these items in 2022 was close to USD 3 million (Ministry of Hydrocarbons and Energy, 2023). Below is a comparison of the three forms of Bolivian tax revenue.

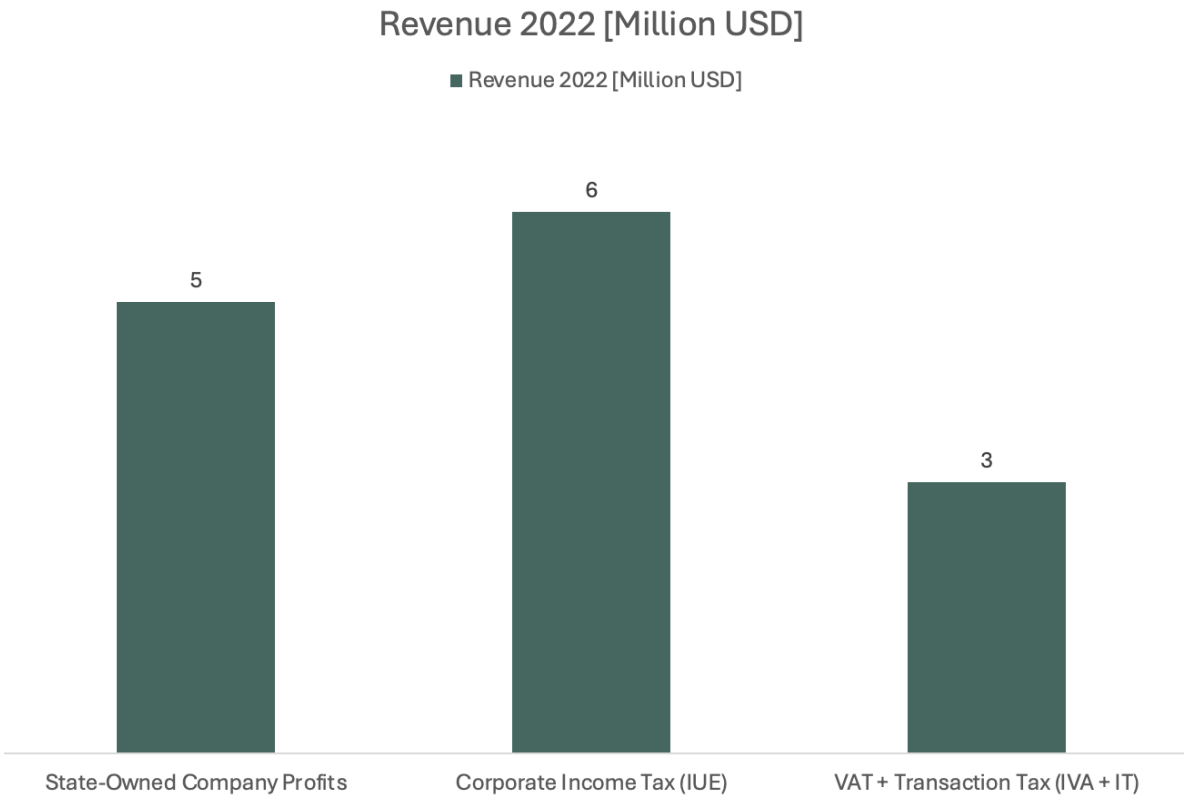



**Figure 70. Main sources of lithium tax revenue in Bolivia (millions of USD). State profit data corresponds to 2021, while IUE and VAT+IT correspond to 2022.**
Source: Own elaboration, with data from YLB, 2022, and Ministry of Hydrocarbons and Energy, 2023

Unlike Argentina or Chile, Bolivia does not apply mining royalties to lithium because exploitation is 100% public. In 2023, Bolivia signed partnership agreements with foreign companies, such as CATL and CBC, both Chinese companies, for the development of operations running on direct lithium extraction (DLE) technologies. However, these projects are in the early stages of investment and have not generated tax revenues yet.

According to ECLAC estimates (2022), considering YLB's contributions and indirect taxes, effective tax collection in Bolivia is between 35% and 45% of the income generated by lithium. This percentage is like that of countries that apply royalties and mixed regimes, although the absolute amount of revenue remains low due to the limited volume of production.

So far, the main economic impacts of lithium in Bolivia are concentrated in the department of Potosí, where the Salar de Uyuni is located. However, due to the low level of exploitation and commercialization, some of YLB's contributions have been channeled into infrastructure, education, and social programs in surrounding municipalities, although the amounts are not significant.

Bolivia faces several challenges in converting its lithium potential into a source of sustainable development. Firstly, there is the low scale of production, due to technical and logistical difficulties that YLB's industrial plants have had in reaching their planned capacity. Secondly, the exclusive state model leads to a lack of private investment, which limits the rapid expansion of the industry. Thirdly, there are transparency issues, as YLB's public reports on production, costs, and tax revenues are limited and restricted in access. Finally, there are delays in the adoption of modern technologies, as Bolivia only began interacting with foreign countries, signing agreements in 2023 to implement direct extraction technologies (EDL), which are essential for competing in terms of efficiency.

## 10.4. Conclusions

A comparative analysis of the three lithium-producing countries in South America reveals significantly different governance models and fiscal outcomes. Chile, with a mixed model and special contracts with private companies, has managed to capture a substantial share of mining revenue through CORFO contracts that include progressive mechanisms linked to international prices. Argentina maintains a decentralized model in which provinces have control over the resource, applying royalties of up to 3% of the "mine mouth" value and other national taxes. Meanwhile, Bolivia operates under a completely state-owned scheme, with no private presence, which allows it to capture a high proportion of the revenue, albeit with low amounts due to its low production.

The figures for 2022, based on official documents and estimates contained in reports by ECLAC, NRGI, and YLB, show significant differences in tax revenue from lithium (Table 22). This comparison shows that tax collection does not depend exclusively on the model of ownership of the resource, but also on contractual mechanisms, the level of transparency, the scale of production, and the institutional capacity to administer revenues. In light of the results, Chile has been able to capture the highest benefit of the Lithium production in the region. Argentina is growing and could become a significant player in the region. Bolivia is lagging and may benefit from the Lithium era by following some of the Chile and Argentina policies, also by taking advantage of the technologies, infrastructure, and human capabilities already built in the region.

**Table 22. Lithium Tax Comparison.**
Source: Prepared by the authors based on ECLAC, NRGI, and YLB data.

| Category | Chile | Argentina | Bolivia |
|---|---|---|---|
| **Type of exploitation model** | Private concessions with special contracts (Corfo) | Private concessions with provincial regulation | Direct state operation (YLB) |
| **Type of tax revenue** | Lease income, *royalties*, specific income tax, and payments to third parties | Provincial royalties, income taxes, export duties, VAT, and social security | State-owned enterprise profits, corporate income tax, VAT, transaction tax |
| **State participation** | High, via Corfo as state owner and contract negotiator | Medium, via provincial control of resources | Very high: YLB controls the entire value chain |
| **Main players** | SQM, Albemarle | Sales de Jujuy, Minera Exar, and Livent | Bolivian Lithium Deposits (YLB) |
| **Use of royalties or special contracts** | Yes, contractual income with progressive *royalties* | Yes, provincial royalties (up to 3%) | No royalties: everything is state-owned |
| **Estimated tax revenue 2022** | USD 2.755 billion | USD 23 million (only for provincial royalties, Jujuy and Catamarca) | USD 14 million |
| **Estimated tax burden (as % of economic income)** | Up to 60% of income, variable depending on contract | 28% - 44% of income | 35% - 45% of income |

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# 11. RECOMMENDATIONS FOR SUSTAINABLE DEVELOPMENT

To offer some final recommendations, we have done a series of interviews to compile a broad source of opinions that lead to the following chapter. This chapter reflects a source of consensus between the authors and people interviewed, and therefore, it does not represent an extensive list of things that should be done.

There is, in general, a consensus that the development of lithium projects in Chile, Argentina, and Bolivia requires coordinated decisions on three levels:

- Technological and environmental performance: selection of processes, reinjection, and impact control.
- Political, contractual, and economic framework: regulatory stability and revenue capture.
- Social license: participation with impact and traceability.

Chile is an example of public-private development with a state-led role. The evaporite technology is mature and has sustained growth in the last decades. Some successful strategies are recognized in how to deal with the value distribution and salt flats exploitation, for example, it is mentioned the recent partnership between Codelco and SQM with a production plan for 2031–2060, but still subject to pending milestones, which condition deadlines, CAPEX/OPEX, and bankability (FNE, 2025; Reuters, 2025).

Argentina has shown a private company driving growth with provincial control of resources. Argentina's technology has involved evaporative and recently DEL-based projects. The 1994 constitutional reform explains the regulatory heterogeneity and the coexistence of evaporation and DEL pilots/plants depending on the salt flat and logistics (Argentine National Congress, 1994).

Bolivia is a state driving the lithium industry with no sign of growing yet. It has shown a preference for DLE technologies, although the uncertainties associated with it. The judicial suspension of contracts with Chinese and Russian consortia in 2025 reinforces the need for gradual validation with technical and contractual milestones before scaling up (Mining, 2025; Business & Human Rights Resource Centre, 2025).

To contextualize the state of the art in technology, interviewees note that DLE is advancing but still requires large-scale demonstrations: "*None have made it to the other* side" (Bunel, 2025). The same pattern can be observed in Argentina: "*there is no 100% DLE industrial plant that works properly... [the company] has serious difficulties in getting the plant up and running*" (Gigante, 2025). At the same time, reinjection is a necessary but not sufficient condition due to its possible geochemical and mechanical effects: "*one may not affect the volume... but it does affect the geochemical conditions... there may be* subsidence" (Jara, 2025).

In cross-cutting terms, the interviewees agree on: (i) the need for phased scaling with go/no-go criteria. (ii) Reinjection as a condition for closing the water balance, but with operational risks if geochemical compatibility is not validated. (iii) The advisability of public clauses in tenders to reduce litigation. (iv) Social participation with verifiable impact. The most notable differences are observed in the pace of DLE adoption (more demanding in Chile, more heterogeneous in Argentina, and more declarative in Bolivia), in tolerance for technological risk (companies moving forward with more technical uncertainty than regulators), and in expectations for industrialization (more pronounced in Bolivia).

## 11.1. Technological dimension

Technology selection should be based on site characterization: brine composition (Mg, Ca, B), hydrogeology (connectivity and gradients), and ecosystem sensitivity. The comparison between evaporation and DLE (adsorption/ion exchange, solvents, membranes) should be made using verifiable indicators: selectivity and recovery versus local brine, reagent consumption and recovery, fouling risk, kWh/t LCE, and tCO2e/t LCE, among others. Evidence suggests that DLE offers potential advantages in land/time use, but its scaling remains the main challenge, so the decision must be based on pilot and demonstration data, not assumptions (Warren, 2021; Vera et al., 2023).

The TRL roadmap highlighted by specialists emphasizes pilots of 1 to 3 kt/year before jumping to 10–20 kt/year: "*You invent... you demonstrate... until you reach a demonstrable scale... and from there you jump to 10,000 or 20,000*" (Bunel, 2025). This caution is explained by performance that has not yet been consolidated on an industrial scale (Gigante, 2025) and by an intermediate TRL (3–5) on several routes (Jara, 2025).

Reinjection requires prior demonstration: geochemical compatibility tests (to avoid precipitation and permeability reduction), well design to control gradients, use of tracers to verify connectivity, and observation networks with thresholds and response plans. Scaling up from laboratory to pilot to industrial suitability must be conditioned on decision gates (*go/no-go)* associated with metrics of net water balance, effective return percentage, piezometric stability, and energy/chemical performance (Halkes et al., 2024; Zelandez, 2024).

In general, there is consensus that reinjection must be tested for both compatibility and hydrodynamics: *"it can dissolve salts... there may be* subsidence" (Jara, 2025). In addition, the main challenge is regulatory and environmental, in order to demonstrate its safety to the authorities (Bunel, 2025). It is therefore suggested that similar hydrocarbon standards be used for reinjection criteria (Quiñones, 2025).

In Chile, sectoral policy promotes projects with higher performance requirements and state participation. The Codelco-SQM framework projects production for 2031-2060 with quotas approved by the Chilean Nuclear Energy Commission (CChEN), which requires improving efficiency and impact control to meet production and environmental goals, with pending approvals/consultations that determine the sequence of permits (FNE, 2025; Reuters, 2025). The availability of renewable energies and, in certain districts, desalination can support energy and water balances, without replacing the obligation to demonstrate hydrogeological stability and brine traceability at the salt flat level (Cemtrp Competencia – UAI, 2025).

The environmental permitting process appears to be the dominant bottleneck, and the time frame for a DLE plant is close to 10 years. In addition, standards for access to demanding markets such as the EU and the US are valued: "*all this has to be accompanied by certification... one has to generate a lithium standard*" (Quiñones, 2025).

In Argentina, provincial heterogeneity, complex brine chemistry, and high-altitude logistics increase the OPEX. Operations with evaporation ponds are running in the Salar del Hombre Muerto system (Fenix/Arcadium Project), in parallel with DLE evaluations/trials where selectivity and the supply of inputs/energy allow it (Arcadium Lithium, 2025; Responsible Mining Foundation, 2025). In the Los Patos – Hombre Muerto basin, new environmental studies have been required before new permits are granted, reinforcing the importance of reinjection and monitoring protocols for social acceptability and bankability (El País, 2025).

The fine-tuning of DEL remains challenging: "*there is no 100% DLE industrial plant... [with] serious difficulties in fine-tuning the* plant" (Gigante, 2025). This is combined with higher CAPEX/energy and the need to assess the actual carbon footprint (Gigante, 2025).

In Bolivia, however, the preference for DLE must be implemented with a modular approach (from pilot to demo and finally industrial) and performance thresholds that unlock investment phases, incorporating logistical variables and export points from the design stage, as it is a landlocked country (impact on CAPEX/OPEX). The judicial pause on contracts with CBC (CATL) and Uranium One reinforces the need for technical robustness and performance and capacity transfer clauses (IntelliNews, 2025; Fundación Andrés Bello, 2025).

As additional context for Atacama, studies show hydrodynamic impacts associated with brine extraction pumping (e.g., subsidence or flow changes), underscoring the need for monitoring and hydrogeological reconciliation between operators (Marazuela et al., 2019; Reuters, 2024).

Among the consensus points, technicians and managers agree on requiring real brine selectivity tests against Mg/Ca/B before scaling up DLE; on treating reinjection as a system with design, monitoring, and thresholds; and on anticipating a hybrid transition (temporary CLE-evaporation coexistence) where chemistry or logistics requires it.

Among the differences, in Chile, interviewees tend to require more dense monitoring and traceability standards. In Argentina, operational teams emphasize logistical feasibility and the provision of inputs/energy. In Bolivia, authorities and potential partners show greater optimism about DLE adoption times, conditioned by the definition of the export point and technological maturity.

The need in the region for pilot testing facilities that can evaluate several technologies, different brines, and therefore accelerate the project's development time is clear. These facilities and infrastructure are expensive, going well beyond the hundreds of millions of dollars, and in such regard, it seems difficult for these nations by themselves would be able to invest by their own in these capabilities.

## 11.2. Political dimension

To attract foreign investment to the region, a clear and stable property and tax structure is needed so companies are able to design and execute long-term plans. Contracts should have sufficient duration for CAPEX distribution, take into account countercyclical fiscal mechanisms (price escalators and rent floors), and verifiable operational obligations (pilot/demonstration milestones, reinjection targets, waste traceability, and water-energy efficiency), as well as public evaluation criteria that reduce litigation and lower the cost of capital (Competence Center – UAI, 2025).

Experts propose verifiable standards (water, energy, waste) and traceability linked to certification: "*create a lithium standard... seal with low water/energy consumption and traceability*

*requirements*" (Quiñones, 2025). Community acceptance is considered a condition of bankability: "*the main barrier... is interaction with communities, ensuring that there is no destruction of the environment or astronomical water extraction*" (Bunel, 2025).

For Chile, the National Lithium Strategy defines a greater role for the state (Codelco/ENAMI) and partnerships in strategic salt flats, along with a permitting architecture that includes competition control and CChEN quotas. The FNE approved the Codelco – SQM joint venture with mitigation measures, CChEN granted a 2031–2060 quota (with the option to partially bring it forward to 2029), and approvals/consultations remain pending before final signing (FNE, 2025; Reuters, 2025).

In Argentina, provincial control of resources (Article 124 of the Constitution) means that permits, taxation, and timelines vary by jurisdiction. Therefore, common technical minimums (reinjection, monitoring, traceability) and fiscal certainty (royalty parameters and tax treatment) are different in different provinces, along with bidding criteria that define water-energy performance, scaling plans, and local linkages (Argentine National Congress, 1994). Even with a multiplicity of projects, effective production faces technical bottlenecks, reinforcing the need for comparable technical criteria and on-site pilots prior to scaling up (Quiñones, 2025).

In Bolivia, the DEL-focused approach should be implemented in phases based on milestones (technical goals verified by third parties) and early definition of logistics/export points and common infrastructure. The judicial suspension of agreements with CBC and Uranium One suggests the need to strengthen performance clauses, guarantees, and technology transfer to reduce the risk exposure of the state partner (Business & Human Rights Resource Centre, 2025; Mining.com, 2025).

## 11.3. Socio-environmental dimension

Social license requires processes with impact and traceability, understandable technical information, windows in which observations could modify the design, public records of how comments are received (or not), and independent expert opinions when technical controversy exists.

Traceability is seen as an enabling condition: "*the main barrier... is interaction with communities, ensuring that there is no destruction of the environment or astronomical extraction of* water" (Bunel, 2025). Recent experiences recommend technical dialogue with communities and training to understand decisions. From the perspective of salt flat hydrogeology, increasing extraction rates without support can affect ecosystems (Jara, 2025).

In the case of Chile, progress is being made toward governance schemes with greater participation by indigenous peoples in strategic environmental decisions (water and biodiversity) in Atacama, in parallel with the implementation of the Codelco-SQM joint venture. This is expected to result in high standards of monitoring, transparency, and binding complaint mechanisms (El País, 2025; Reuters, 2025).

The demand for public data and certification is growing in parallel with permitting: *"if I have a highly polluting technology, we will be rejected... everything must come with* certification" (Quiñones, 2025).

In Argentinian provinces with a history of evaporation, acceptance improves when measurable improvements over the baseline are demonstrated (lower water consumption per t LCE, compatible reinjection, management of reject brines, and GHG reduction) and when there are previously agreed-upon audits and contingency plans. In the Los Patos-Hombre Muerto basin, new studies

were required for new permits to maintain the current production, which reinforces traceability and public access to data (EL País, 2025).

In Bolivia, on the other hand, industrialization (from carbonate to materials) requires building more capabilities (laboratories, certifications, pilot lines) and local workforce training relative to DLE operations. Early transparency and public access to technical information help reduce uncertainty in judicial or administrative phases (Fundación Andrés Bello, 2025).

## 11.4. Conclusions

Although there is broad consensus among experts on the minimum conditions for advancing lithium projects, such as phased validation, traceability of reinjections, and the need for stable contractual instruments, there are also significant differences in intensity, depending on industry maturity and level of development. For example, while Bunel (2025) considers that DLE technology is mature enough to scale up in Bolivia with the right approach, Gigante (2025) argues that there is still a considerable gap between technological promises and actual performance, especially in terms of ionic selectivity and geochemical compatibility. Quiñones (2025), for his part, agrees on the importance of technically validating reinjection, although they differ in scope: national standards with public traceability versus logistics and energy resources, which may be more relevant constraints in Argentina.

Differing approaches can also be seen at the political and socio-environmental levels. While some propose robust co-governance in sensitive areas such as the Salar de Atacama, with total transparency in environmental management, Jara (2025) emphasizes that structural benefits, such as technical training and supplier development, are more valued by communities than environmental consultation alone. Bunel suggests that the inclusion of quantifiable social indicators in contracts (e.g., percentage of local employment) could facilitate community acceptance, while Gigante points out that without reliable institutions to validate this information, commitments lose legitimacy.

Thus, in general, increasing investment without lowering socio-environmental standards in the Lithium Triangle requires:

I. Technological decisions based on site characterization and phased verification (with an emphasis on selectivity, reagent consumption, energy, and compatible reinjection).
II. Predictable contracts that reward performance and capture income with countercyclical instruments, public signatures, and terms modulated by compliance.
III. Socio-environmental processes with impact, traceability, and open monitoring.

In Chile, this might translate into long-term partnerships with defined technical and regulatory goals. In Argentina, it might translate into common technical and fiscal minimums that facilitate interprovincial comparability and improve bankability. In Bolivia, it means implementing DEL by milestones with guarantees and integrated logistics from the design stage. This approach reduces technical, regulatory, and social risk, improves time to first production, and stabilizes revenue collection throughout the cycle (FNE, 2025; Argentine National Congress, 1994; Andrés Bello Foundation, 2025).

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Interview on DLE, technological maturity, and community relations (semi-structured interview)
Internal transcript (no public link)

**Gigante, E. (2025)**
Interview on DLE, reinjection, and the technological ecosystem (semi-structured interview)
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**Jara, J. (2025)**
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**Quiñones, S. (2025)**
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