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Lithium in Chile: present status and future outlook

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This paper provides a comprehensive overview of the current state of lithium in Chile, with a forward-looking assessment in the context of the ongoing national lithium strategy. The global and regional significance of lithium as a critical energy resource is examined. The evolution of Chile's lithium industry is analyzed, emphasizing two recent key policy initiatives: the 2015 National Lithium Commission report and the newly launched national lithium strategy. The salient features of these initiatives are outlined. Additionally, this paper reviews materials science research conducted in Chile since the 1960s, particularly focusing on the physical chemistry of lithium, batteries and brines. Finally, the paper argues that lithium, as a pivotal material in the shift from fossil fuels to renewable energy, holds strategic potential for advancing the country's sovereign technological development.

1 Introduction

Lithium is recognized as an increasingly important resource worldwide. For almost 10 years, the demand for lithium – along with its price – has been steadily increasing, with almost exponential growth observed since 2015.[1] This is because, in addition to its traditional uses in lubricants, glazes, glass and ceramics, among others, lithium is now considered a fundamental energy material. Thanks to its unique physicochemical properties, lithium-based batteries can store high energy densities while being very light. The development of these batteries, essential for the storage of electrical energy, is viewed as a key factor in the success of the energy transition required by the severe environmental crisis being experienced. It is imperative to move from an energy matrix based on fossil fuels to one based on renewable energies, such as photovoltaic solar energy and wind energy. As is known, these technologies are intermittent, so it is essential that an efficient, safe, and inexpensive method to store their energy is available. Lithium batteries have been proven to meet these requirements.[2] This has made lithium a key element, putting pressure on countries with abundant reserves of the element. In fact, the largest lithium reserves in the world are found in three neighboring countries in the Southern Cone – Argentina, Bolivia and Chile. This has sparked a scientific, technical, economic and political discussion ranging from what to do with lithium, its extraction and industrialization, to the discussion of the environmental damage and impact that its exploitation causes to local communities and indigenous peoples.[3]

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Several aspects of the ongoing debate concerning lithium in Chile are examined in the present paper. An overview is provided rather than an exhaustive analysis. In Section 2, the strategic significance of lithium as an energy source is delved into. Its classification as a strategic material, its various energy applications, and the reserves found in the salt flats of the southern cone are discussed. Section 3 provides an analysis of the current state of lithium in Chile, including its legal framework, a brief historical context, and the recent, under-development national lithium strategy. Section 4 presents an outline of research initiatives focused on lithium and salt flats, with an emphasis on ongoing scientific endeavors in the area of physical chemistry. Finally, it is emphasized in the Conclusion that lithium's importance extends beyond its economic value, with potential seen for it to drive strategic, sovereign scientific, and technological advancements within the region.

2 Lithium, a strategic element

The definition of the strategic or critical nature of a material is not a matter of universal or permanent concern but strongly depends on who, with respect to what, and when it is defined. For example, in the United States, the Department of Energy has a clear definition regarding the "criticality" of certain materials for its future, and based on that, has designed a strategy. In particular, lithium has been defined as a "near critical" element for the short term (2020–2025) about energy storage, and as a critical material for the medium term (2025–2030).[4] This is in line with the conclusions of the joint panel of the American Physical Society and the Materials Research Society of the U.S., that more than ten years ago concluded that there are 7 critical elements for the U.S. regarding energy: Te, Ge, Pt, Nd, Li, Re, and Tb. Regarding lithium, they emphasize that "lithium also has the potential for geopolitical risks because the world's known resources of easily extractable lithium are largely concentrated in three South American countries: Chile, Bolivia, and Argentina".[5] Similarly, the European Union and Japan have also progressed in defining the materials they consider strategic or critical for their development. For example, in march 2023, the European Union adopted the Regulation and Communication on critical raw materials, where lithium is considered a critical material.[6] It is also interesting to read the discussion in the UK Parliament in this regard, where a report from the Foreign Affairs Committee expressed that "the UK's critical minerals supply chains are vulnerable due to our continuing dependence on autocracies – in particular China – and the inaction of successive UK governments".[7] Reading these reports, it is clear that the strategic or critical nature of a material depends on many factors: availability, geopolitics, future importance, reserves, and several others.[8] Moreover, recent literature in social sciences and history argues that this is a historical and political concept. In this context, lithium price bubbles and volatility, such as the huge difference between prices in 2021 and 2022, would not reflect its "essentiality" for clean technology, but opacity and uncertainty.[9,10]

In the case of Chile, it is not difficult to argue that lithium indeed emerges as a strategic material. In fact, the "XIII Conference of Ministers of Mining of the Americas: Geopolitics of Strategic Minerals From National Priorities to Regional Opportunities", held in Santiago, Chile in October 2023, established the following definitions: countries that produce or extract these minerals refer to them as "strategic minerals" because they hold strategic importance for the domestic economy, such as generating foreign income through local production chains. Conversely, countries that consume these minerals (often the ones developing the technologies) term them "critical minerals" because they either do not have them domestically or their production does not meet internal demand, posing a risk of supply shortage. In addition, there are two fundamental reasons to consider lithium as a strategic material for Chile. The first is that lithium, in addition to its traditional uses from the last century, has become an essential energy material since the 21st century. The second relates to a fundamental geopolitical factor: the largest lithium reserves globally are located in three neighboring countries of the southern cone: Argentina, Bolivia, and Chile, the so-called "ABC triangle of lithium". These two aspects transform lithium into a material of strategic importance for the region. In the following sections, it will be explained where lithium is found and by whom it is exploited.

2.1 Lithium worldwide and in the southern cone

Although lithium is a ubiquitous resource in nature, as a mineral reserve it is limited to specific locations on Earth.† Naturally, it is mainly found in brines, followed by rock minerals such as pegmatites (mostly spodumene) and sedimentary minerals (such as hectorite), along with other sources such as geothermal brines or oil fields. Argentina, Bolivia, and Chile have the primary brine resources, while China and the United States have both brine and rock resources, and others such as Australia have primarily rock resources.

† While both resources and reserves refer to the existence of mineral deposits, resources are estimated based on geological knowledge and exploration data, and reserves specifically indicate those deposits that are economically viable to extract under current market conditions and technological capabilities.

Table 1 Lithium resources and reserves as of 2024

Country	Resources (million tons)	Reserves (million tons)
Bolivia	23	—
Argentina	22	3.2
USA	14	1.1
Chile	11	9.2
Australia	8.7	4.8–6.2
China	6.8	3.0
Germany	3.8	—
Canada	3	—
Congo	3	—
Mexico	1.7	—
Czechia	1.3	—
Serbia	1.2	—
Peru	1	—
Russia	1	—

Source: United States Geological Survey.[11]

Additionally, lithium can be produced from non-natural sources such as recycling, oil wells, and tailings. While extracting lithium from oil wells faces significant challenges that realistically hinder its medium-term exploitation, recovery from tailings is feasible. In fact, as early as 2019, the AMG-Mibra company achieved commercial-scale recovery from tailings in Brazil.

According to the United States Geological Survey (USGS), the lithium resource as of 2024, "owing to continuing exploration, measured and indicated lithium resources have increased substantially worldwide and total about 105 million tons".[11] These resources are distributed as shown in Table 1. As can be seen, there are 14 countries with resources or reserves over 1 million tons. Other countries have lithium resources, but in lesser amounts: Mali, 890 000 tons; Brazil, 800 000 tons; Zimbabwe, 690 000 tons; Spain, 320 000 tons; Portugal, 270 000 tons; Namibia; 230 000 tons; Ghana, 200 000 tons; Finland, 68 000 tons; Austria, 60 000 tons; and Kazakhstan, 50 000 tons. Importantly, the ABC triangle encompassed over 53% of the lithium resource, all of them in the brine of the high Andean salt flats.

Regarding lithium reserves, as of 2023 are distributed with Chile at 36%, Australia at 24%, Argentina at 10%, China at 8%, the USA at 4%, and 18% allocated to other countries. Bolivia, despite having substantial lithium reserves in its salars, primarily Uyuni and Coipasa, is not included here due to its lack of official reserve declarations.[11]

The end-uses of lithium have undergone significant changes over the past decade. While lithium's primary applications in the 1990s included ceramics, glass, lubricants, refrigeration, nuclear, and photovoltaic industries, among others, with batteries accounting for less than 5% of its usage, today, over 80% of all lithium production is directed towards secondary batteries. Within this sector, 65% is allocated to the automobile industry, 11% to stationary storage and other battery systems (such as drones), and 7% to electronic devices like cell phones, digital cameras, notebook computers, small electronic equipment, aerospace, mechanical and electrical tools, as well as military communications and other fields.[1]

China stands out as the largest consumer of lithium, accounting for 55% of global lithium production. Additionally, the European Union comprises 21% of global lithium consumption, followed by the USA at 14%, and South Korea, Japan, and other Asian countries collectively at 7%. Notably, this significant demand of Chine is largely driven by its lithium-ion battery chain production, which, as of 2022, represents 76% of the world's manufacturing capacity. Following China, Europe accounts for 8%, the USA for 7%, and other countries for the remaining 8% of global battery production capacity.[12]

From a supply perspective, only a handful of countries engage in lithium mining, with production concentrated primarily in Chile, Australia, the United States, China, and Argentina. Among these, the Salar de Atacama in Chile stands out as the foremost source of lithium from brines globally, owing to its rich lithium and potassium content as well as its favorable evaporation rate.

As of 2022, Australia leads as the top mine producer globally, contributing approximately half of the world's production at 43%. (Notably, Australia's production account for 84% of the global lithium extracted from rock sources). Chile follows closely behind with a 34% share, while China and Argentina contribute 14% and 5%, respectively. Furthermore, several other countries hold relatively marginal shares of the global lithium supply, collectively amounting to 4%. These nations include Brazil, the United States, Portugal, Zimbabwe, Canada, and Bolivia. In the realm of lithium extracted from brines, the Atacama salt flat (Salar de Atacama) in Chile dominates production, representing 71% of the global output, with Argentina trailing behind at 12%.[1]

At present, the most competitive method for lithium extraction is solar evaporation, as it does not require extensive plant installations and relies on solar energy. Indeed, according to various estimations, the production cost using solar evaporation methods could range from two thirds to even less than one half of the cost associated with extraction from rock sources. Although conceptually simple, it is water-intensive because it involves evaporating water from the brine. Fig. 1 illustrates a schematic of this process as it operates in Chile.

It begins with the extraction of brine through pipelines approximately 10 cm in diameter, which is then deposited in settling ponds roughly the size of a soccer field. As the brine progresses through the ponds, various compounds precipitate and are removed (such as halites, silvinates, bischofite, *etc.*), until the lithium-rich brine is obtained, containing approximately 5% to 6% LiCl. This process can take between 12 to 18 months. Subsequently, this solution, similar in viscosity to olive oil, is extracted and transported to processing plants outside the salar, where solvents are used to extract the lithium. The final product is a whitish powder known as lithium carbonate, Li_2CO_3. However, certain conditions must be met for this method to be effective, including a high rate of solar radiation, absence of rain, and the brine must not contain ions that complicate lithium separation. Indeed, one of the challenges encountered in the evaporation method in the Salar de Uyuni in Bolivia is the relatively high concentration of magnesium in the Bolivian resources. This element complicates and increases processing costs, along with the occurrence of rainy seasons in Uyuni.

The lithium market is highly concentrated, particularly in the Southern Cone, where it is practically an oligopoly. It is a rather opaque market, not traded on the stock exchange but sold directly from company to company. Market participation of different companies can be described by two mechanisms: those responsible for operations and those controlling specific operations. The two largest companies are SQM (based in Chile, but with a complex shareholding structure, where the Chinese company Tianqi holds a 24% stake) and Albemarle (from U.S.A), both operating in the Salar de Atacama. Following them is the Chinese company Tianqi, Pilbara Minerals (based in Australia) and others. In 2019, only five companies accounted for two-thirds of the production, including Albemarle and SQM. As Cochilco points out, "this situation contrasts greatly, for example, with the copper market, where in the same year the world's largest player, Codelco, contributed no more than 10% of aggregate mine production, and more than 20 companies would need to be considered to reach a proportion equivalent to two-thirds of mine production".

The primary product supplied by the companies is lithium carbonate in various grades (such as technical grade, battery grades, *etc.*), estimated at 66%. The second product is lithium hydroxide, accounting for 34% of the supply. However, the production of hydroxide has exhibited a growing trend over

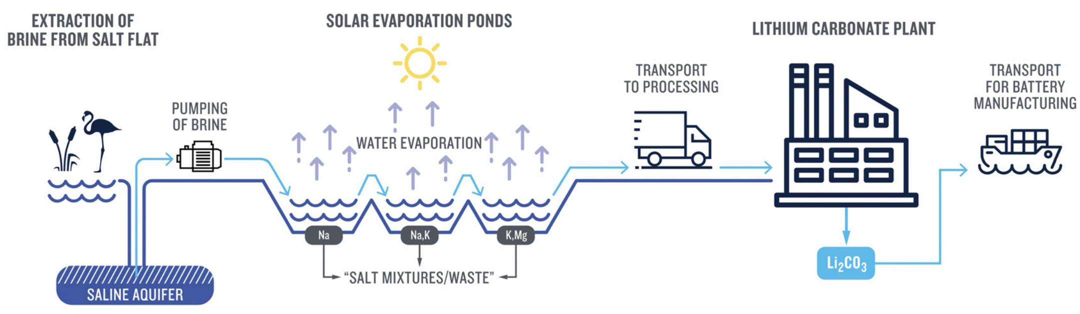

Fig. 1 Typical lithium production process in andean salt flats. (Taken from ref. 13).

time, which is anticipated to persist in the future. As a result, it is projected that the production of hydroxide and carbonate will gradually balance by 2035.[1]

2.2 Lithium as an energy material

The transition from fossil fuels to renewable energies is a central objective aimed at curbing greenhouse gas emissions into the atmosphere. This objective is enshrined in the 2015 Paris Agreement and has been emphasized in meetings of the Intergovernmental Panel on Climate Change (IPCC).[14] Lithium, as an energy material, could play a key role in three ways:

Firstly, the most significant current contribution is lithium for energy storage. The primary challenge encountered by emerging forms of energy, such as solar, wind, geothermal, or tidal power, lies in the transportation and storage of harvested energy. Currently, the most effective means of transporting and storing energy is through electricity. This necessitates the availability of efficient batteries. One such battery technology is lithium-based batteries, whose diversification and mass production are increasing. Another method of energy storage involves molten salts, utilizing brines found in salt flats as the primary component.

Secondly, lithium for energy efficiency involves the use of aluminum-lithium alloys. Energy saving represents a fundamental approach to addressing the current energy crisis. One strategy for achieving energy savings is through the construction of lighter transportation vehicles. Recently developed aluminum-lithium alloys, exemplified by the factory inaugurated by Alcoa in Indiana, USA, in 2014,[15] enable the creation of lightweight and durable structural materials. Their adoption in the aerospace and land transportation sectors promises significant energy savings.

Lastly, lithium for nuclear fusion energy, that is, the future use of lithium as nuclear fuel in fusion reactors. While controlled nuclear fusion is not yet achieved, there are two major projects, one in Europe and Japan, ITER (**https://www.iter.org**), and another in North America, NIF (**https://lasers.llnl.gov/**), advancing in this direction. In both projects, lithium will play a fundamental role, both as nuclear fuel and as a structural material. Indeed, in current designs, the fuel is a mixture of deuterium and tritium, both isotopes of hydrogen. While deuterium is naturally occurring, tritium must be produced artificially. The method of obtaining it involves Li-6, which when bombarded by neutrons, transmutes into helium and tritium. Thus, liquid lithium would have the dual mission of providing the necessary cooling for fusion reactors and producing tritium simultaneously.

Lithium-based batteries experienced rapid development following Sony's commercialization of them in 1991. Today, it is a mature technology with numerous suppliers, and its applications span from small electronic devices like watches, tablets, and computers to batteries for automobiles and even grid-scale storage systems capable of powering a city of around 30 000 inhabitants, as demonstrated in southern Australia in 2017.[16] The success of lithium-ion batteries stems from their high energy density, attributed to lithium's exceptional electrochemical potential (the highest among all elements in the periodic table) and its low weight. It is noteworthy that chemists who significantly contributed to this scientific and technical development were awarded the Nobel Prize in 2019.[17] Ongoing developments have led to cost reductions and the resolution of initial safety concerns, such as the risk of explosion at high temperatures.[18] As a result, lithium-ion batteries have established dominance in the market, and experts forecast that this trend will persist over the next 20 to 30 years. The emerging sodium battery and hydrogen fuel cell technologies under development are expected to complement lithium batteries rather than compete with them.

2.3 Lithium as a geopolitical factor

As previously discussed, the largest lithium reserves globally are situated in three neighboring countries: Argentina, Bolivia, and Chile, forming what is commonly referred to as the ABC triangle of lithium. In light of the anticipated significance of energy in the future (a topic that will not be addressed here due to the abundance of evidence on this matter) and the pivotal role lithium plays in its development, the possession of these reserves represents an immense asset, comparable perhaps to access to hydrocarbons at the dawn of the last century. In this regard, lithium belongs to the geopolitics of renewable energy.[19] A forward-thinking state policy, aimed at national benefit, should take this aspect into account. There ought to be consideration given to designing agreements among these neighboring nations to collaborate in the exploration, prospecting, and exploitation of lithium, while also maximizing value-added production, both upstream and downstream of the extraction process. Such action can be facilitated through collaboration agreements among Argentina, Chile, and Bolivia. Not only would this enhance efficiency within the lithium industry, but it would also foster closer collaboration in scientific and technological endeavors. More importantly than all of the above is the realization that these efforts would lead to improved relations among neighbors, yielding obvious mutual benefits.[20]

Conversely, the vast resources attract companies seeking access to lithium, as well as nations, particularly from the global North. This aligns with the "green industrial policy" adopted by several countries, exemplified by China's strategic plan "Made in China 2025" introduced in 2015, followed by the European Union's Green Deal in 2019, and the combined U.S. measures outlined in the infrastructure bill of 2021 and the anti-inflation bill of 2022. Additionally, various high-ranking officials from these countries have emphasized the necessity of sourcing critical raw materials from the global South. This naturally leads to geopolitical tensions in the region, reminiscent of historical dilemmas surrounding natural resources: either act as exporters of the raw material, thereby deepening existing center-periphery relationships, or promote local scientific and technological development to add value to the natural resource, leveraging lithium in this case to foster sovereign development. This tension has been a constant in Latin America.[21–23]

In this context, lithium, as a natural resource and part of an extractive activity, is not exempt from the paradox known as the resource curse.[24] In other words, countries with plentiful mineral and hydrocarbon resources should utilize these natural assets as a primary source of funding for economic growth and development. However, the exploitation of these resources is often associated with adverse outcomes, including poverty, inequality, poor public services, and slow economic growth. In the case of Chile, it is essential to consider the impact on the territory and local communities, including indigenous populations, as highlighted in the studies by Weinberg[25] and Cornejo.[26]

Thus, the geopolitical significance of lithium cannot be overlooked in any serious state policy pertaining to this mineral.

3 Lithium in Chile

Global interest in lithium expanded beyond its traditional uses starting in the mid-1950s, particularly within the context of its application in thermonuclear or "hydrogen" bombs, where tritium, a hydrogen isotope obtained from lithium, played a crucial role. In Chile, exploration efforts commenced in the 1960s, spearheaded by the state through the Geological Research Institute.‡ Subsequently, a committee known as the Mixed Salts Committee was established within Corfo,§ tasked with studying salt flats.

This committee explored nearly a third of the more than 60 salt flats in Chile and identified significant lithium deposits in more than 10 locations. However, it became clear that the Salar de Atacama had the highest concentration of lithium and was free of contaminants, making it highly commercially viable for exploitation. Thus, the initiative to explore, exploit and profit from lithium in Chile originated from the state in the 1960s and led to the creation of two companies in the 1980s: Sociedad Chilena del Litio and Sociedad Química y Minera de Chile, commonly known as SQM. In the following sections, we will provide a brief overview of this process and outline the various steps that led to the recently unveiled national strategic plan for lithium and salt flats.

3.1 Regulations on lithium: non-concessionable substance

The regulatory status of lithium, which is an exception to Chile's mining concession system, has a long history. In the 1970s, specific provisions regarding lithium were included in legislation that established a key role for the Chilean Nuclear Energy Commission (CCHEN): lithium was declared a "nuclear interest material", and it was established "that the extracted lithium and its derived or compound concentrates cannot be the subject of any legal act, except those carried out by the CCHEN, either directly or with its prior authorization".

Subsequently, the 1979 Decree-Law designated lithium as a resource reserved exclusively for the state, making lithium mineral non-concessionable. This designation was further solidified by the Organic Constitutional Law of 1982 and the Mining Code of 1983.

‡ This institution serves as the precursor to SERNAGEOMIN, the chilean geological survey, accessible at https://www.sernageomin.cl.

§ Corfo, the Corporation for the Promotion of Production, established in 1939, functions as a ministry for industrial development in Chile.

According to the Chilean Constitution, non-concessionable minerals can only be explored or extracted "directly by the state or by state-owned companies, or through administrative concessions or special operation contracts (CEOL), in accordance with the requirements and under the conditions established for each case by the President of Chile by Supreme Decree".

In essence, lithium has a unique status in Chile, similar to hydrocarbons. Under Chilean law, lithium is considered a strategic mineral belonging to the state of Chile, and exploration and operations can only be carried out under special operation contracts (CEOL).

3.2 Companies exploiting lithium in the Salar de Atacama

To date, the only lithium mining operations in Chile are located in the Atacama salt flat, the so-called Salar de Atacama, in the north of Chile, near the town of San Pedro de Atacama. The story of how Corfo leased its properties to two companies, SQM and Albemarle, is a long but interesting one.

In 1980, Corfo entered into an agreement with Foote Minerals to form the Chilean Lithium Company (SCL), with Foote Minerals holding 55% and Corfo holding 45%. With this partnership, SCL began lithium carbonate production in 1984. In 1984, Corfo conducted an international public potash and lithium tender to form another company. In 1986, an agreement was signed between Corfo, the American mining company Amax Exploration and the Chilean company Molymet to form MINSAL. Amax held 63.75%, Corfo held 25%, and Molymet held 11.25% of the shares.

In 1989, Corfo sold its 45% stake in SCL to Foote Minerals for US$15.2 million. Subsequently, SCL was acquired by Rockwood of Germany, which was later acquired by Albemarle in 2016. Meanwhile, in 1992, Amax and Molymet sold their shares in MINSAL to the Chilean company SQM, which had been privatized by the Pinochet dictatorship, becoming the major stakeholder with a 75% ownership. SQM began potash production in 1995. In the same year, Corfo sold its shares to SQM, retaining only the lease agreement. MINSAL was rebranded as SQM Salar, which is the current company, and commenced lithium carbonate production in 1996. Thus, the state, through Corfo, withdrew its participation in these companies, retaining only the lease agreement for its mining properties.

Currently, the primary players in Chile's lithium industry are SQM, accounting for approximately 65% of production, and Albemarle, holding 35%. Both companies operate in the Salar de Atacama, where they control 34% of the world's lithium supply, equivalent to approximately 44 000 tons. In this landscape of significant economic concentration, it's crucial to note that lithium differs from other minerals in that it isn't traded on the metal exchange; instead, its price is determined through negotiation between producers and consumers. Therefore, the terms governing the use and exchange of this strategic substance are at the discretion of the companies that dominate the market.

The lithium reserves in the Salar de Atacama, owned by Corfo, are globally significant. Of the estimated 28.3 million tons of lithium reserves, 7.5 million are located in this salt flat. Furthermore, in terms of cost advantages, the production expenses for lithium in Atacama are the lowest worldwide due to favorable evaporation conditions resulting from the region's climate and the existing infrastructure facilitated by the presence of major copper mining operations nearby.

3.3 National Lithium Commission

In 2014, the growing significance of lithium became increasingly evident, highlighting its potential strategic importance for the country's development. In response to this, President Bachelet proposed the formation of a diverse panel of experts, encompassing various political perspectives and professional backgrounds, tasked with designing a comprehensive lithium policy. The objective was to harness this natural resource in a manner that serves the country's broader interests while ensuring environmental protection and community well-being, including indigenous people. This initiative led to the establishment of the National Lithium Commission in June 2014, which unanimously approved its final report in January 2015. The report, consisting of 40 main pages and 60 annex pages, provides a detailed examination of the lithium landscape in Chile and outlines proposed policies across different domains, serving as essential reading for anyone seeking to grasp the lithium situation in the country.[27]

One of the first tasks undertaken by the Commission was to conduct a diagnostic assessment. It revealed that lithium had been neglected by the state, with a lack of understanding regarding salt flat dynamics, community situations, and sustainability concerns. Particularly concerning was the absence of a hydrogeological model to inform extraction quotas, which had been assigned to companies without proper scientific-technical insights. Moreover, there was a glaring absence of regulation, oversight, and public policy, resulting in a failure to capture revenue and generate value by the companies – indicating a dire situation.

The Commission underscored the fragility and complexity of salt flat ecosystems, which serve as habitats for ancestral indigenous peoples and surrounding communities. It concluded that any analysis regarding lithium must consider the entire salt flat ecosystem holistically. Consequently, rather than just a lithium policy, there was a pressing need for an overarching policy addressing the preservation and sustainable management of salt flats.

This led to confirming the non-concessionality of lithium, as mining legislation is for rock mining and not for salt flats. The latter is more like fishing than mining. Thus, it was established that

> *it is noted that the salt flats where lithium is found constitute dynamic ecosystems, of great complexity and fragility. It is necessary to consider not only the lithium content but also each salt flat as a whole.*

and also

> *the strategic nature of lithium is reaffirmed, given its high potential for use in energy applications, and it is recommended to maintain the non-concessionable nature of the mineral, due to the fact that the current mining concession system does not adapt to the peculiarity and complexity of salt flat exploitation. Likewise, it is recommended to elevate the non-concessionality of lithium to a constitutional level.*

Regarding the governance of salt flats and lithium, it was recommended

> *to reinforce the role of the state as the true owner of these resources, which defines the conditions and participates primarily in their exploitation; maximizes and captures their economic rent with a long-term view, allocating part of it to the development of scientific and productive linkages; and is a promoter and guarantor of public–private partnerships that generate greater added value to the country and greater social profitability in the exploitation of the salt flats – especially lithium –, always safeguarding environmental sustainability and project sustainability.*

In summary, the proposal outlined the establishment of a regulatory and oversight body to monitor salt flat conditions, followed by a state-owned company tasked with responsibly exploiting salt flats while prioritizing environmental and community considerations. Additionally, a salt flat institute, affiliated with state universities and research centers, would focus on scientific and technological advancements and provide evidence-based guidance to both the regulatory body and the state-owned company.

Special importance was given to the need for the state to be an entrepreneur in lithium, with the creation of a state-owned company to promote value addition:

> *At the same time, the commissioners almost unanimously consider it necessary to create a company controlled by the state dedicated to the exploitation of salt flats, especially lithium.*

Regarding research and development, certain ideas were advanced:

> *Given the diversity and complexity of the possible present and future applications of lithium, it is necessary to generate policies to encourage technological research and development of its extraction form and its multiple uses. Within the possible areas of work, we can mention: the development of productive processes of lithium carbonate for the production of batteries and energy accumulator salts, both for vehicle propulsion and for energy storage in renewable energy plants, such as solar, photovoltaic, and wind energy; tritium generation for nuclear energy applications; lithium–aluminum and lithium–magnesium alloys for the production of lightweight, high-strength materials; uses in the pharmaceutical industry and possible synergies with nanotechnology, among others.*

These actions were proposed in synergy with the productive and innovative activities of other sectors of the economy and science and technology, which effectively allow the use of a natural resource to strengthen long-term development, so that when the resource is no longer available, it has been used in the development of people's intelligence, and thus create a true sovereign industrial development:

- *It is proposed to generate and strengthen a sectorial cluster linked to lithium, which allows the strengthening of research and innovation centers associated with universities and/or industry, as well as public–private partnerships for the*

Table 2 Lease agreement conditions for operations in Salar de Atacama

Item	Albemarle conditions	SQM conditions
Lithium extraction quota	New quota of 262 131 tons + remnant of 110 000 from the previous quota of 200 000	349 553 tons + remnant of 64 816 from the previous quota of 180 001
Brine and water usage	442 L s^{-1} and 23.4 L s^{-1}, respectively	1500 L s^{-1} and 240 L s^{-1}, respectively
Expiration	12/31/2043 (not set previously)	12/31/2030 (maintained)
Royalty (fee payment)	6.8% to 40% of Li price (not set previously)	6.8% to 40% of Li price (previously 6.8% fixed)
R&D contributions	Between U$6 million and U$12.4 million (not set previously)	Between U$10.7 million and U$18.9 million (previously 0.8% of 6.8%)
Added-value incentives	Up to 25% of production at preferential prices	Up to 25% of production at preferential prices
Local communities	3.5% of revenue	Between U$10 million and U$15 million
Oversight and inspection	Access to operational, financial, and environmental information	Access to operational, financial, and environmental information

Source: adapted from ref. 27 and 28.

exploitation of lithium, which will generate knowledge, technologies, research and development.

– *It is proposed to design, together with Conicyt and Corfo, research and development programs necessary for the development of capacities and knowledge to face this country's challenge, with long-term criteria*.

In essence, the National Lithium Commission put forth a blueprint for harnessing a natural resource as a catalyst for development. However, a political scandal ensued, revealing corruption involving SQM and its controller, Julio Ponce Lerou. This corruption extended to parliamentarians and government officials, stalling progress on lithium-related initiatives.¶

Subsequently, efforts were made to renegotiate Corfo's contracts with SQM and Albemarle, resulting in a mutual beneficial agreement for both parties. The renegotiated agreements extend until 2043 for Albemarle and 2030 for SQM. These revised contracts include provisions such as a royalty on sales ranging from 6.8% to 40%, depending on lithium prices, and reserving 15% to 25% of extracted lithium for sale at preferential rates to manufacturing companies establishing operations in Chile. Both companies are also required to allocate US$12 to US$15 million annually towards research and development in lithium, salt flats, and clean energy technologies. Additionally, contributions to indigenous communities near the Salar are stipulated. Further details are shown in Table 2, which provides a comparison of the terms of Corfo's lease agreements with Albemarle and SQM.

3.4 National lithium strategy: for Chile and its people

The national lithium strategy was presented to the country by President Gabriel Boric on April 20, 2023, described in a comprehensive 32-page document titled "national lithium strategy: for Chile and its people".[29] This strategy builds upon prior work and proposals, particularly stemming from the discussions outlined in the National Lithium Commission report convened by President Bachelet in 2014.

The strategy begins by acknowledging lithium as a strategic resource for the country, aligning with its exceptional legal status. Under the title "development opportunities arising from progress toward a green economy and new extraction technologies," it underscores that the development of the lithium industry in Chile offers unique opportunities driven by the increasing global demand for lithium. Specifically, the country's prospects are intertwined with its abundant lithium reserves in its salt flats, the imperative to develop more sustainable extraction technologies, the potential to establish a scientific-technological-industrial ecosystem domestically, the creation of productive linkages, and the cultivation of an industry with higher added value. Chile is positioned to lead global technological advancements in lithium production and capitalize on the associated economic benefits for national and regional development. Therefore, a national strategy is essential to effectively seize these opportunities.

3.4.1 Objectives and strategic pillars of Chile's national lithium strategy. The national lithium strategy sets out seven main objectives. The first objective is to ensure the "sustainable development of lithium production potential" in Chile. This involves increasing lithium production sustainably, both in existing operations in the Atacama salt flat and in other salt flats, by establishing conditions for exploration and extraction projects. The second objective is "social and environmental sustainability," which aims to minimize social and environmental impacts and ensure community participation, especially in the case of salt flats in Chile, which host valuable biodiversity and delicate hydrogeological balance. The third objective relates to "technological developments and productive linkages" that Chile seeks to promote with local companies. This entails upstream development of knowledge and technologies associated with lithium exploration and extraction in Chile, and downstream promotion of industrialization in other segments of the value chain.

The fourth objective concerns "participation in lithium revenues," aiming to maximize state revenues sustainably by leveraging the current lithium price cycle. The fifth objective is "fiscal sustainability," associated with implementing adjustments in lithium fiscal revenues to maintain long-term fiscal sustainability and enable savings of the transitional portion of lithium revenues to finance investments in social, scientific-technological, and productive areas. The sixth objective involves the "diversification of actors" in the lithium industry in Chile, which is expected to be promoted through private or state partnerships to create a more competitive and transparent

¶ The accusation involves illegal financing of Chilean politics through the offering of favors and financial support to various political parties, with the exception of the Communist Party and Frente Amplio.

market. Finally, the seventh objective focuses on "contributing to productive diversification and growth potential," aiming to position Chile as a significant player in advanced stages of the global lithium value chain. This involves establishing partnerships with major global technology companies to promote local industrial development in the country.

To achieve these objectives, fundamental strategic pillars are established:

Firstly, there is the conviction of the "involvement of the state throughout the industrial cycle." The national lithium strategy seeks to energize the industry by involving the state in the entire production cycle, from exploration to manufacturing, through public–private partnerships and value chain development.

Another strategic definition corresponds to the need for "building scientific and technological capacities" within the country. This entails the fundamental need for a public technological and research institute to drive the generation and knowledge related to lithium and salt flats.

A third strategic definition is the promotion of "public–private partnership," as there is a strong belief in the mutual benefit of developing projects between the private and public sectors, promoting lithium exploration and technological development, productive linkages, and value addition, with respect for the environment and communities.

A fourth strategic definition relates to the need to update the "institutional framework" around lithium and salt flats, which should reflect the complexity and importance of salt flats and activities related to the exploitation of brines and lithium.

Finally, we have the fifth strategic definition of "social and territorial sustainability, related to community involvement," which emphasizes the importance of establishing high socio-environmental standards and fostering dialogue and participation among various stakeholders interested in the development of the lithium industry, including indigenous communities.

3.4.2 Implementation: strategic milestones 2023–2024. To implement the strategic definitions outlined above, in line with the objectives of the strategy, specific actions are required. These correspond to eight milestones to be developed in the short and medium term that operationalize the strategy:

(1) The creation of a strategic committee for lithium and salt flats, led by the Ministry of Mining, with participation from the Ministries of Finance, Economy, Foreign Affairs, Environment, and Science, as well as Corfo. The aim is to oversee the implementation of various actions outlined in the strategy. This committee will establish coordination with other ministries, public institutions, regional governments, and the private sector. This committee has been in place since May 2023 under the figure of a Corfo committee. A work schedule has been defined, including monthly sessions. Additionally, a technical group operates in support of the lithium and salt flats strategic committee, comprising specialists appointed by each of the counselors, who elaborate and delve into technical matters as determined by ministers.

(2) Initiation of a process of dialogue and participation with various stakeholders, including indigenous communities, regional governments, academia, companies, civil society, and public agencies. The purpose is to gather their expectations and proposals related to the development of the lithium industry. The results of this process will influence decisions of the national strategy. It's important to note that all dialogue and participation efforts do not replace the need for necessary indigenous consultations in acts or projects where there is a perceived susceptibility to affect indigenous communities, in accordance with ILO Convention 176. These dialogue's processes began on October 2023, in the Atacama region, and a total of 17 dialogue activities were conducted in the regions of Arica and Parinacota, Tarapacá, Antofagasta, Atacama, and the Metropolitan Region. In January 2024, the results of this process were delivered, and it has been proposed to continue with a permanent dialogue process. The highest authorities of the Ministry of Mining, as well as Environment, Science, and Economy, have been involved in these dialogues.

(3) Creation the National Lithium Company that can participate in the entire industrial cycle, from resource assessment and mineral exploitation to treatment and subsequent industrial stages, such as battery assembly and recycling. This milestone is currently being developed through state-owned companies with mining operations, such as Codelco and Enami, which have created subsidiaries dedicated to lithium and salt flats and are seeking private partners to develop their projects. Similarly, value addition and manufacturing are being carried out through tenders developed by Corfo for obtaining lithium at a preferential price for companies that establish themselves in Chile. Currently, two tenders have been conducted, and the awardees have been the company BYD and the company Tsingshan.

(4) Creation of a network of protected salt flats and the promotion of low-impact environmental technologies in the salt flats, with the aim of ensuring their long-term sustainability. The goal is to protect at least 30% of ecosystems by 2030, in line with international obligations established in the Convention on Biological Diversity.[30] This is an unprecedented measure in mining and follows a precautionary principle, considering that decisions should be left to future generations and recognizing that salt flats, besides lithium, have other valuable assets, such as biodiversity or cultural value. This Network was sanctioned by the Ministerial Committee for Sustainability and Climate Change in March 2024, and must comply with several technical and administrative requirements that are currently being worked on. The ministries involved in this task, especially Mining (through the Geological Service), Environment, Public Works (through the General Water Directorate), and Corfo, have been gathering information for its development, as well as considering suggestions and concerns raised in the dialogue process.

(5) Modernizing the institutional framework, to allow the development and growth of the industry while safeguarding impacts on salt flats and communities, ensuring coherence among existing and new organizations, and regulating the relationship between central decisions and regional and local governments, all by the objectives of the strategy. In this regard, the basic analyses of potential institutional modifications necessary to develop the lithium industry and ensure

environmental, social, and territorial responsibility in its development are being reviewed and prepared.

(6) Creation of a Public Lithium and Salt Flats Technological and Research Institute, whose central purpose is to advance knowledge and technologies related to lithium extraction, production, value addition, applications, and recycling, as well as understanding and protecting salt flats and the situation of communities. The institute in under the direction of the Ministry of Mining and also the Ministries of Science, Knowledge, Technology, and Innovation, Environment, Economy, and Corfo, as well as representatives from the regional governments of Tarapacá, Antofagasta, and Atacama. Similarly, representatives of indigenous peoples will be integrated. The Institute has already been created and is expected to start its activities by the end of 2024. It will be located in the Antofagasta region and is expected to have branches in other regions, such as the Atacama region. The Institute will be a focus for scientific and technological development around lithium and salt flats for these particular regions and for lithium development throughout the country in general.

(7) Involvement of the state in productive activities in the Atacama salt flat. Codelco has been asked to find the best way for the state to participate in the exploitation of the Atacama salt flat, taking into account two considerations: first, if a new public–private company is created to exploit lithium there, the state will have a majority participation. Second, everything established in the currently valid contracts will be fully respected, including revenues for the state, benefits for the regions and local communities, investments in research and development, and improved socio-environmental standards. Codelco has already signed an agreement with SQM, and according to what has been said, the new company resulting from this merger is expected to be operational in the first half of 2025.

(8) Prospection of other salt flats, with the aim of evaluating the extraction of lithium in other salt flats in a responsible and sustainable manner, provided that they are not included in the network of protected salt flats. In strategic exploitation projects for the country, public–private partnerships will be established with the state. Subsidiaries of state-owned companies, such as Codelco and Enami, will be granted special lithium operation contracts (CEOL) for exploration and exploitation in salt flats where they already have projects in development, and a public and transparent exploration bidding process will be held for other salt flats that may be exploited. The Ministry of Mining has already launched a request for information process and news on this matter is expected in the second half of 2024.

All in all, the national lithium strategy is an urgent task, but also a long-term one. In these sense, Chilean government is moving forward with steady steps in a field where improvisation is not an option.

4 Materials science and related research on lithium

In this section, some examples of lithium research conducted in Chile since the 1970s will be presented. The focus is placed on the physical chemistry aspects, including studies on brines, new extraction methods, and contributions to lithium battery research. Hydrogeological aspects of salt flats[31] or environmental studies on saline basins or the impact of extraction on salt flats[13] are not delved into. Additionally, studies on communities and indigenous peoples near the salt flats[32] are not reviewed here. The research specifically conducted in Chile is highlighted. For science and technology research in South America, ref. 33 and references therein should be consulted.

After lithium was discovered in the Salar de Atacama by Anaconda Company in 1962, the Salar was surveyed by the Geological Research Institute beginning in 1969. The pioneering fieldwork study was conducted by Chilean geologists Aldo Moraga, Guillermo Chong, María Angélica Fortt, and Hugo Henríquez, and was published in 1974 in the Bulletin of the Geological Research Institute.[34] The potential of the Salar for lithium was established by this study. Many additional studies were initiated by Corfo beginning in the 1970s,[35] including studies of the geology, hydrology, climatology, and mineralogy of the salt flat, confirming the excellent conditions that the brines of the Salar de Atacama had to produce lithium at a lower cost than brine deposits in the United States.[36]

During that period, the potential uses of lithium in different technologies began to be discussed in many scientific magazines in Chile. In 1972, the use of lithium in Aerospatiale and nuclear technologies and the efforts of developed countries to design an electric vehicle based on higher energy density lithium-based batteries were discussed and explained by Orbita magazine.[37] By the 1980s, Creces magazine posed the challenges associated with the problem of only exporting raw materials, highlighting the need to develop the technologies that would allow for the establishment of a transformation industry in which value could be added to the market price of this product,[38] a problem that Chile is still facing. Since then, and for the last 60 years, research associated with the lithium ecosystem has been carried out by many groups of researchers in Chile.

During the 1990s, studies on lithium intercalation processes in transition metal chalcogenides were initiated by some research groups.[39] Among the investigations conducted, studies on cluster architecture and lithium motion dynamics were carried out in nanocomposites formed by the intercalation of lithium and a dialkylamine in molybdenum disulfide using the ^{7}Li nuclear magnetic resonance (NMR) technique. It was found that lithium spin–lattice relaxation was mainly due to the interaction between the quadrupolar moment of the ^{7}Li nuclei and the fluctuating electric field gradient at the site of the nucleus, produced by the surrounding charge distribution. The studied relaxation mechanism was found to be consistent with a fast exchange motion of lithium ions between the coordination sites within the aggregates.[40]

In the same context, the electrochemical formation of intercalates Li_xMoS_2 was analyzed at the molecular level by developing a quantum chemical model focused on the variation of the electron chemical potential. The model allowed for the identification of a sequence of octahedral and tetrahedral sites as the more favorable migration pathway for the diffusion of lithium through the interlaminar space.[41] A new nanocomposite was developed by the same group, obtained from the intercalation of the cyclic ether 12-crown-4 into MoS_2, $Li_{0.32}MoS_2$ (12-crown-4) 0.19. The laminar product showed an interlaminar distance of 14.4 Å. The electrical conductivity of the nanocomposite was enhanced from 2.5×10^{-2} to 4.3×10^{-2} S cm^{-1} in the range of 25–77 °C, being about four times higher than the analogous poly(ethylene oxide) (PEO) derivative at room temperature.[42]

Nonetheless, efforts were focused by other groups of researchers on new materials for developing new cathodes, anodes, and electrolytes for lithium batteries. Studies of lithium insertion into different oxide materials like LiM_2O_4 (M = Mn, Fe, Co)[43] and lithium transition double metal oxides $LiMO_2$ (M = Co, Mn, Ni) were performed, showing that the discharge curves follow the reactivity order: Li–Co > Li–Mn > Li–Fe oxides.[44] The reactivity was found to depend on the nature and oxidation state of the cations placed in the B sites of the spinel structure. Other studies were focused on nanoparticle oxides based on Fe_3O_4@rGO nanocomposite for supercapacitors and lithium-ion battery anode performance,[45] showing that the key findings of high efficiency and low cost, as well as superior capacitance and LIB anode performances, can potentially serve as electrodes in supercapacitor-battery hybrid storage devices for both high energy density and high-power density. The development of new anodic and electrolytic materials was also studied. Pyrrolidinium-based room temperature ionic liquids (RTIL) were used as electrolytes in Li-ion batteries, with zinc stannate being used as the anodic material. It was shown that the use of non-flammable and safer electrolytes is possible in lithium batteries based on Zn_2SnO_4 (ZTO), which, considering the discharge capacity values obtained, can be considered a potential candidate to replace graphite as the anode in more complex devices. The structure of the cation in the ionic liquid was found to have a direct impact on the electrochemical performance of the device, altering the pathway by which the device stores lithium ions.[46]

The theoretical aspects concerning lithium batteries have also been studied. In this context, a novel approach to the estimation of the state of maximum power available (SoMPA) in lithium-ion batteries was studied. This method formulated an optimization problem for the battery power based on a non-linear dynamic model, where the resulting solutions are functions of the state of charge.[47] Another study analyzed and compared the performance of several approaches implemented for the detection of capacity regeneration phenomena in the degradation, particularly in lithium-ion battery cells. It was found that the implementation of hypothesis testing procedures outperforms information measurement-based approaches for the detection of capacity regeneration, although the choice between classic PF algorithms and risk-sensitive variants depends on the desired probability of detection. The latter is due to the fact that a detector that computes a fault indicator from the posterior state PDF estimate is more capable of isolating regeneration phenomena in the degradation curve if the *a priori* PDF incorporates those phenomena in the importance sampling distribution.[48]

Lithium isotope separation with tunable diode lasers has also been studied. This was the first report of lithium's laser-isotope-separation (LIS) utilizing a tunable diode laser. The application of this tunable-diode laser, in conjunction with a simple and compact mass selector, contributed significantly towards the ease of use and the overall compactness of the experimental apparatus for LIS experiments in light atoms.[49]

The center for advanced research in lithium and industrial minerals (CELIMIN), located at the University of Antofagasta, has made significant efforts over the last few years to study chemical processes for the purification of brines, combining public and private funding. In this case, the removal efficiencies obtained for Ca^{+2}, Mg^{+2}, and SO_4^{-2} were 98.93%, 99.93%, and 97.14%, respectively. Thereafter, the concentration of Ca^{+2} and Mg^{+2} was reduced to values below 1 ppm through the use of ion-exchange resins. The combined use of both processes provided promising results that could be applied in the industry.[50,51] In the case of processes for producing battery-grade lithium hydroxide by membrane electrodialysis, the effects of current density, electrode material, electrolyte concentration, temperature, and cationic membrane (Nafion 115 and Nafion 117) on cell performance were determined. Tests showed that a high-purity product was obtained at temperatures below 75 °C, with a Nafion 117 membrane and low electrolyte concentration.[52] The green solvothermal synthesis particle size distribution of LFP demonstrated that the alternative green synthesis process represents 60% and 45% of the resource depletion impact category (water and fossil fuels, respectively) of the conventional method.[53,54] Concerning the development of inorganic composite phase change materials for passive thermal management of Li-ion batteries, two inorganic phase change materials (PCM) were tested for thermal control of lithium-ion batteries, demonstrating that low cost and incombustibility make inorganic PCMs a viable alternative to organic PCMs, with a positive impact on environmental and economic issues.[55]

In the same context, the lithium center was formed in 2022 by the Universidad Católica del Norte, in association with the mining company SQM. This center is a research initiative focused on technological innovation for the entire value chain of lithium batteries.[56]

Another Chilean center focused on developing lithium technologies is the Advanced Mining Technology Center (AMTC), located at the University of Chile. Research has been focused on new sustainable technologies for lithium brine processing and direct LiOH production. In particular, the LISa process, which allows for the purification and concentration of lithium brine from salars without evaporating water, using reagents, or external chemical agents, was developed. This process generates a dilute brine or ultra-pure water and a brine concentrated in lithium and free of impurities.[57]

However, lithium research in Chile is not only focused on technological developments, but examples of basic science are also being conducted, as seen in ref. 58 and 59. It is also worth noting that some investigations have been pointed out by researchers with the idea of evaluating the impact of lithium extraction, mining, and climate change on the Salar biodiversity.[60] In particular, it was found in these studies that, regionally, flamingo abundance fluctuated dramatically from year to year in response to variations in surface water levels and primary productivity, but no temporal trends were exhibited.[61] The same group has studied prokaryotic and eukaryotic communities from microbial mats and underlying sediments across contrasting areas of this athalassohaline ecosystem in Salar de Huasco, situated in the high-altitude Andean Altiplano, finding that photosynthetic eukaryotes exhibit a strong correlation with prokaryotic communities, specifically diatoms with certain bacteria and other protists.[62]

Conclusions

The extraction and production of lithium present a series of challenges that extend beyond the purely industrial sphere. In this paper, the lithium situation in Chile is examined through this lens, with an exploration of two recent public policies aimed at positively addressing these challenges and an emphasis on the need for active state involvement in these efforts. Additionally, the contributions made by Chile to research and developments in the field of lithium, including its physical chemistry, brines, and batteries, are reviewed. It is noteworthy that, in contrast to other regions, a thriving lithium industry has been driven in Chile by an entrepreneurial state that identified the potential of this mineral as early as the 1960s.

In recent years, lithium has emerged as a critical component in enabling the necessary energy transition from fossil fuels to renewable energy sources. It is crucial to initiate this transition in order to mitigate the effects of greenhouse gases and combat climate change. Lithium is a strategic energy material with significant potential for countries with abundant reserves, such as Argentina, Bolivia, and Chile, given its use in rechargeable batteries. However, this positive aspect also presents a complex challenge: the exploitation of lithium can have significant negative impacts on communities and indigenous peoples living near the operations. Furthermore, it places additional strain on the center-periphery relationship, reminiscent of the historical role assigned to the Global South as a supplier of raw materials. It is hoped that recent strategy put forward by Chile will effectively overcome ''the curse of natural resources'' and support the country's sovereign development.

Author contributions

G. Gutiérrez: conceptualization, investigation, writing – original draft, review & editing; D. Ruiz-León: investigation, writing – original draft, review & editing.

Data availability

This item does not apply here. We do not present any original data.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

1 Cochilco, *El mercado de litio: Desarrollo reciente y proyecciones al 2035*, 2023, See https://www.cochilco.cl; Cochilco is the is the acronym for ''Comisión Chilena del Cobre'', which is the specialized body of the Chilean government in matters related to the production, information, and diagnostics of all metallic and non-metallic mineral substances.
2 *Lithium-ion Batteries: development and Perspectives*, ed. D. Bloch, S. Martinet, T. Priem and C. Ngo, EDP Sciences, Paris, France, 2021.
3 *Lithium, states of exhaustion*, ed. F. Díaz, A. Kubrak and M. Otero, ARQ Ediciones-Het Nieuwe Instituut, Santiago, Chile, 2021.
4 See for example https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals.
5 *Securing Materials for Emerging Technologies*, 2011, A Report by the American Physical Society Panel on Public Affairs & the Materials Research Society.
6 See for example https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661.
7 See https://publications.parliament.uk/pa/cm5804/cmselect/cmfaff/371/report.html.
8 R. G. Eggert, *Nat. Chem.*, 2011, **3**, 688.
9 N. Restrepo, J. C. Ceballos and J. M. Uribe, *Resour. Policy*, 2023, **86**, 104135.
10 A. N. Wojewska, C. Staritz, B. Tröster and L. Leisenheimer, *Extr. Ind. Soc.*, 2024, **17**, 101393.
11 See for example https://www.usgs.gov/centers/national-minerals-information-center/lithium-statistics-and-information; in particular https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-lithium.pdf.
12 IEA (2023), Lithium-ion battery manufacturing capacity, 2022–2030, IEA, Paris, https://www.iea.org/data-and-statistics/charts/lithium-ion-battery-manufacturing-capacity-2022-2030, Licence: CC BY 4.0.
13 J. J. A. Blair, R. M. Balcázar, J. Barandián and A. Maxwell, Exhausted: how we can stop lithium mining from depleting water resources, draining wetlands, and harming communities in south america, Nrdc, uc santa barbara, observatorio plurinacional de salares andinos technical report, 2022.
14 See https://www.ipcc.ch/sr15/.
15 Alcoa Opens Worlds Largest Aluminum-Lithium Aerospace Plant in Indiana, en news 2 octubre 2014, https://www.alcoa.com/.
16 See https://en.wikipedia.org/wiki/Hornsdale_Power_Reserve.
17 See https://www.nobelprize.org/prizes/chemistry/2019/popular-information/.
18 See https://en.wikipedia.org/wiki/Lithium-ion_battery.
19 M. O'Sullivan, I. Overland and D. Sandalow, *HKS Working Paper No. RWP17-027*, 2017, DOI: 10.2139/ssrn.2998305.
20 M. Bruckmann, *ABC del Litio Sudamaricano: soberanía, ambiente, tecnología e industria*, Universidad Nacional de Quilmes, 2015, pp. 17–45.

21 H. Altamonte and R. J. Sánchez, *Hacia una nueva gobernanza de los recursos naturales en América Latina y el Caribe*, CEPAL, 2016.
22 M. Torres and J. M. Ahumada, *Trimestre Económico*, 2022, **83**, 151–195.
23 S. E. Uribe-Sierra, A. Toscana Aparicio and A. I. Mora-Rojas, *Investigaciones Geográficas*, 2023, 1–20.
24 D. Itriago, *Lifting the Resource Curse*, Oxfam International Technical Report 134, 2009.
25 M. Weinberg, *Extr. Ind. Soc.*, 2023, **15**, 101309.
26 S. M. Cornejo Puschner, *Extr. Ind. Soc.*, 2024, **18**, 101448.
27 See **https://ciperchile.cl/pdfs/2015/06/sqm/INFORME_COMISION_LITIO_FINAL.pdf**.
28 R. Poveda Bonilla, *Estudio de caso sobre la gobernanza del litio en Chile*, CEPAL, 2020.
29 See **https://www.gob.cl/chileavanzaconlitio/**.
30 Explore the salt flats and lagoons here: **https://hablemosdelitio.minmineria.gob.cl/descubre/donde-estan-los-salares/**.
31 V. Flexer, C. F. Baspineiro and C. I. Galli, *Sci. Total Environ.*, 2018, **639**, 1188–1204.
32 B. Jerez, I. Garcés and R. Torres, *Political Geography*, 2021, **87**, 102382.
33 B. Fornillo and M. Gamba, in *Litio en sudámerica: geopolítica, energía y territorios*, Editorial El Colectivo, 2019, pp. 133–172.
34 A. Moraga, G. Chong, M. A. Fortt and H. Henríquez, *IIG*, 1974, **29**.
35 P. Pavlovic, Química e Industria, Revista de la Sociedad Chilena de Química, 1990, pp. 4–19.
36 G. Lagos, El Desarrollo del Litio en Chile: 1984–2012, Santiago, 2012, See **https://www.gustavolagos.cl**.
37 T. Vila, *Órbita, Revista de Ciencia y tecnología*, 1972, **9**, 1.
38 M. Córdova, *Revista Creces*, 1982, **22**.
39 M. A. Santa-Ana, V. Sanchez and G. Gonzalez, *Electrochim. Acta*, 1995, **40**, 1773–1775.
40 J. P. Donoso, C. J. Magon, J. Schneider, A. C. Bloise, E. Benavente, V. Sanchez, M. A. Santa Ana and G. González, *Braz. J. Phys.*, 2006, **36**, 55–60.
41 F. Mendizábal, M. A. Santa Ana, E. Benavente and G. González, *J. Chil. Chem. Soc.*, 2003, **48**, 69–75.
42 M. Santa Ana, N. Mirabal, E. Benavente, P. Gómez-Romero and G. González, *Electrochim. Acta*, 2007, **53**, 1432–1438.
43 J. L. Gautier, R. Ahumada, E. Meza and G. Poillerat, Boletín de la Sociedad Chilena de Química, 2001, vol. 46, pp. 373–381.
44 E. Meza, D. Alburquenque, J. Ortiz and J. L. Gautier, *J. Chil. Chem. Soc.*, 2008, **53**, 1494–1497.
45 B. Bhaskara Rao, D. Pabba, R. Aepuru, A. Akbari-Fakhrabadi, P. Lokhande, R. Udayabhaskar, M. Rosales and R. Espinoza, *J. Mater. Sci.: Mater. Electron.*, 2023, **34**, 1910.
46 D. Quezada, J. Honores and D. Ruiz-León, *Int. J. Electrochem. Sci.*, 2021, **16**, 210212.
47 C. D. Burgos Mellado, M. Orchard, M. Kazerani, R. Cardenas and D. Saez, *Appl. Energy*, 2016, **161**, 349–363.
48 M. E. Orchard, M. S. Lacalle, B. E. Olivares, J. F. Silva, R. Palma-Behnke, P. A. Estévez, B. Severino, W. Calderon-Muóoz and M. Cortés-Carmona, *IEEE Trans. Reliab.*, 2015, **64**, 701–709.
49 I. E. Olivares, A. E. Duarte, E. A. Saravia and F. J. Duarte, *Appl. Opt.*, 2002, **41**, 2973–2977.
50 M. Grágeda, A. González, W. Alavia and S. Ushak, *Energy*, 2015, **89**, 667–677.
51 M. Grágeda, A. González, M. Grágeda and S. Ushak, *Int. J. Energy Res.*, 2018, **42**, 2386–2399.
52 M. Grágeda, A. Gonzalez, A. Quispe and S. Ushak, *Membranes*, 2020, **10**, 9.
53 P. Cofré, A. Quispe and M. Grágeda, Revista Mexicana de Ingeniería Química, 2022, vol. 21, pp. 1–12.
54 P. Cofré, M. D. L. Viton, S. Ushak and M. Grágeda, *Nanomaterials*, 2023, **13**, 1486.
55 Y. Galazutdinova, S. Ushak, M. Farid, S. Al-Hallaj and M. Grágeda, *J. Power Sources*, 2021, **491**, 229624.
56 See **https://www.lithium.ucn.cl/**.
57 See **https://www.amtc.cl/proyectos-destacados/proceso-lisa/**.
58 R. Donoso, J. R. össler, S. Llano-Gil, P. Fuentealba and C. Cárdenas, *J. Chem. Phys.*, 2016, **145**, 094301.
59 M. A. Flores and G. Gutiérrez, *arXiv*, 2018, preprint, arXiv: 1802.08985, DOI: **10.48550/arXiv.1802.08985**.
60 R. O. Chávez, O. Meseguer-Ruiz, M. Olea, M. Calderón-Seguel, K. Yager, R. Isela Meneses, J. A. Lastra, I. Núñez-Hidalgo, P. Sarricolea, R. Serrano-Notivoli and M. Prieto, *Int. J. Appl. Earth Obs. Geoinf.*, 2023, **116**, 103138.
61 J. S. Gutiérrez, J. N. Moore, J. P. Donnelly, C. Dorador, J. G. Navedo and N. R. Senner, *Proc. R. Soc. B*, 2022, **289**, 20212388.
62 C. F. Cubillos, P. Aguilar, D. Moreira, P. Bertolino, M. Iniesto, C. Dorador and P. López-García, *Microbiol. Spectrum*, 2024, **12**, e00072-24.

