Lithium factsheet

International Resource Panel

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NOTE: This factsheet was developed with public data up to April 2022.

Information and data related to lithium are available from a variety of sources, including scientific literature, reports from companies engaged in lithium exploration, mining, and the production of lithium chemicals, as well as reports from national and international institutions and consultancy firms. Due to cost constraints, the latter could not be utilized in the preparation of this factsheet.

Due to the highly dynamic nature of the lithium market and the timing of data compilation, certain sections of this report, including the scenarios, may no longer be fully up to date.

This Annex was not reviewed nor input and recommendation provided through a formal process by IRP membership.

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International Resource Panel

LIST OF ABBREVIATIONS

ANSES	French Agency for Food, Environmental and Occupational Health & Safety
BOF	Basic Oxygen Furnace
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CORFO	Chile's State Economic Development Agency
CRIRSCO	Committee for Minerals Reserves International Reporting Standards
EU	European Union
EVs	Electric vehicles
GHG	Greenhouse gas
FS	Feasibility study
IEA	International Energy Agency
LCA	Life-Cycle Analysis
LCE	Lithium carbonate equivalent
LCI	Life-Cycle Inventories
Li	Lithium
NMC	Lithium-nickel-manganese-cobalt cathode
PEA	Preliminary economic assessment
PFS	Pre-feasibility study
SDLO	Sustainable Development Licence to Operate
SQM	Sociedad Quimica y Minera de Chile
SS	Scoping study
TMX Group	The operator of the Toronto Stock Market
TSX	Toronto Stock Exchange
USGS	US Geology Survey

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INTRODUCTION

LIHTIUM IS AN ESSENTIAL RAW MATERIAL FOR THE GLOBAL ENERGY TRANSITION

INTRODUCTION

Lithium carbonate and lithium hydroxide are critical raw materials for the production of lithium (Li) batteries (Table 1), which are essential for electric vehicles (EVs) and the shift towards electromobility. These batteries are key components in electric cars, playing a central role in national strategies aimed at reducing greenhouse gas (GHG) emissions. By using electricity generated from renewable resources, these strategies seek to replace fossil fuels, thus contributing to a more sustainable energy system (Hund et al. 2020; IEA 2021).

Table 1: Lithium and other mineral raw material requirements for different types of Li-ion battery cathodes

Cathode raw materials (kg/ kWh)	Li	Co	Ni	Mn	Fe	P	Al	O
NMC-111	0.12	0.333	0.333	0.312	0	0	0	0.55
NMC-433	0.117	0.298	0.395	0.278	0	0	0	0.539
NMC-532	0.121	0.205	0.512	0.191	0	0	0	0.558
NMC-622	0.104	0.176	0.525	0.164	0	0	0	0.476
NMC-811	0.096	0.082	0.653	0.076	0	0	0	0.445
HE-NMC 2030	0.123	0	0.106	0.491	0	0	0	0.456
NCA15	0.098	0.125	0.661	0	0	0	0.019	0.451
NCA 5	0.095	0.065	0.725	0	0	0	0.011	0.439
LFP	0.084	0	0	0	0.674	0.374	0	0.772
LMO	0.08	0	0	1.266	0	0	0	0.738

Notes to Table 1:

1 – Abbreviations

- *NMC: lithium-nickel-manganese-cobalt cathode ($LiNi_xMn_yCo_{1-x-y}O_2$). The values of x vary from 1 (NMC 111) to 8 (NMC811). Nickel-rich cathodes offer higher energy density (= mileage per charge) while requiring less rare and costly cobalt.*
- *HE-NMC 2030: this high-energy NMC cathode chemistry is not yet industrially available but could become important later in this decade (see fig. 1). Such batteries would require no cobalt and much less nickel as compared to other NMC-type cathodes, a significant advantage in view of the criticality factors assigned to cobalt and nickel in several key markets (EU, Japan and US).*
- *NCA: lithium-nickel-cobalt-aluminium cathodes ($LiNiCoAlO_2$)*
- *LFP: lithium-iron-phosphate cathode ($LiFePO_4$)*
- *LMO: lithium-manganse oxide cathode ($LiMn2O_4$)*

2 – Lithium carbonate and lithium hydroxide requirements
Table 1 provides the equivalent in lithium carbonate and hydroxide of the Li demand for the production of different cathodes, the two key Li-chemicals used for Li-battery manufacturing.
The primary raw material required for cathode manufacturing is lithium carbonate, but lithium hydroxide is preferred for the production of high-nickel content NMC cathodes (NMC-622 and NMC-822), offering higher energy density (= extra mileage per charge) (Kelly et al. 2021; Marscheider-Weidemann 2021).

Source: Marscheider-Weidemann (2021), with permission.

The lithium market is highly complex and characterized by significant diversity across several dimensions:

- Geological resources: Lithium is sourced from a variety of geological formations, each with unique geochemical and mineralogical properties. These variations also affect local ecosystems, particularly with respect to water resources and biodiversity.
- Extraction and processing methods: There are multiple processes used to extract lithium from different geological sources and convert it into lithium chemicals that the market requires, such as lithium carbonate and lithium hydroxide.

In addition, the composition of lithium-ion batteries, especially at the cathode level, is continuously evolving. This leads to fluctuations in the demand for various other minerals, such as cobalt, graphite, and nickel, which are crucial for battery production.

Lithium batteries are also likely to become of rising importance for stationary utility-scale energy storage, to overcome the intermittent nature of electricity production from either sun or wind. Lithium batteries in home electric car loading systems, coupled with smart grid systems, could also provide power backup, contributing to overcome intermittence of electricity generated from sunshine or wind. Lithium batteries are also essential components for the production of portable electric and electronic equipment.

Lithium life-cycle inventories to date do not adequately capture the diversity of resources and processes used for the production of the two Li chemicals (Li carbonate and Li hydroxide) that are crucial for the global energy transition (Crenna et al., 2021). Consequently, lithium life-cycle analysis suffers from a paucity of public data documenting the "mining" and the actual processing of lithium brine or minerals into a Li chemical suitable for the manufacturing of the Li batteries, which are essential for Battery-operated Electric Vehicles (BEVs).

The scenarios and conclusions presented in this report regarding lithium are of temporary relevance. Future data and advancements in knowledge may alter the assumptions and conclusions presented here. To maintain accuracy, this report should be revised every 1 to 2 years.

All foresight elements provided are scenarios, stories about possible futures, based on variable assumptions that depend on the choices made by their authors, as well as on available data and knowledge.

Scenarios are prone to rapid and unpredictable evolutions of the many factors that underpin future demand and supply. Unknowns, or "black swans" (Taleb 2007), can deeply modify current scenarios. One black swan is the war in Ukraine, which will have profound, far-reaching impacts on the global economy, including impacts on its multiple geographically interconnected and interdependent supply chains. Another black swan is innovation, that can deeply modify the demand for any mineral or metal within few years.

Despite all the many data and information sources available, uncertainty remains about the future evolution of lithium markets. There is some persistent degree of opaqueness and uncertainty on Li production, resources and reserves, as well as on the environmental impacts related to Li production (Crenna et al. 2021). This is due to the fact that some important industry actors, or governments, do not disclose their information and data.

In literature, lithium-related data is reported using different units such as lithium metal, lithium oxide, lithium hydroxide or lithium carbonate. To facilitate the readability of this report, all the data, unless otherwise explicitly mentioned, is expressed in tonnes of Li metal equivalent, using the following conversion factors:

- Li carbonate (Li_2CO_3) to Li metal: 0.188
- Li hydroxide ($LiOH.H_20$) to Li metal: 0.165
- Li oxide (Li_2O) to Li metal: 0.464
- 1 ton spodumene concentrate ($LiAlSi_2O_6$) grading 6% Li_2O, to Li metal, contains 0.027 t Li, on the basis of the chemical formula of pure spodumene.

Note: all mass data in this report is expressed, unless otherwise indicated, in metric tonnes or in multiples of tonnes (kt = kiloton, or one thousand tonnes, Mt = megaton, or one million tonnes).

CHAPTER 1

DEMAND

1.1 END-USES, AND INFORMATION FOR THE 2006-2019 PERIOD

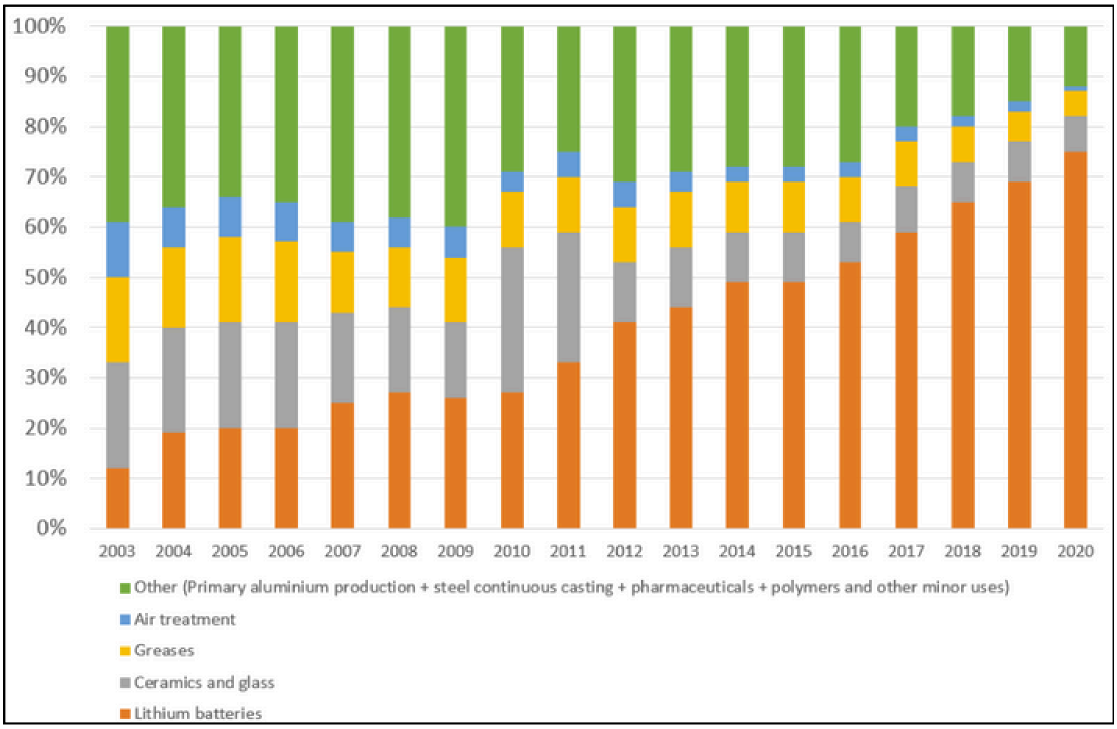
The end uses of lithium are very diverse.

The main uses of lithium, in alphabetic order, are in the production of:

- Air treatment agents (cooling, dehumidification, purification);
- Aluminium-lithium alloys, essentially for the aeronautics industry;
- Ceramics and glass-ceramics;
- Civilian and military nuclear technologies;
- Continuous steel casting, as an additive to mould fluxes;
- Lubricating greases;
- Pharmaceuticals (antidepressants) and fine chemicals;
- Primary (non rechargeable) lithium-metal batteries and secondary (rechargeable) lithium-ion batteries;
- Pyrotechnics (fireworks);
- Rubbers and thermoplastics;
- Glass that is resistant to thermal shocks.

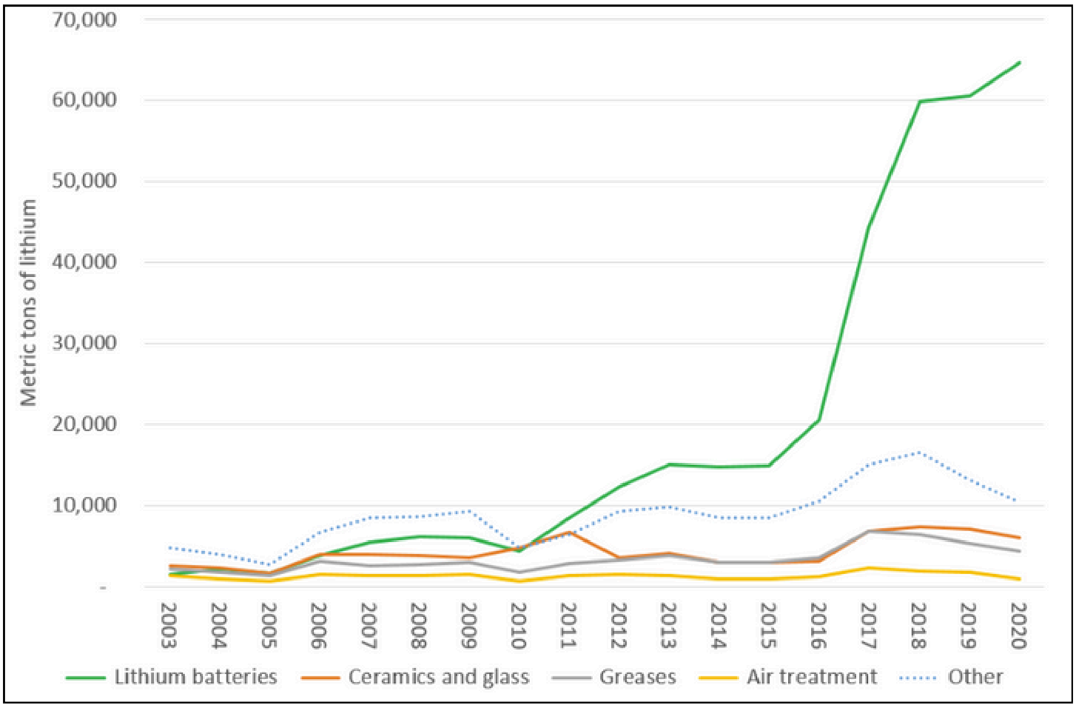
Based on data published in the annual reports of the Sociedad Quimica y Minera de Chile (SQM), one of the world largest producers of lithium chemicals, figs. 1 and 2 provide an overview of the evolution over the 2013-2020 period of the main uses of lithium chemicals. (SQM data refers to the global lithium demand for main uses expressed in per centage. Data on the global production was taken from Reichl and Schatz 2021).

Figure 1 - Evolution of lithium demand for its main uses over the 2003-2020 period, in % of the world production.



Data sources: SQM Annual reports from 2013 to 2020; Reich and Schatz (2021).

Figure 2: Evolution of lithium demand for its main uses over the 2003-2020 period, in tonnes of contained lithium metal equivalent.



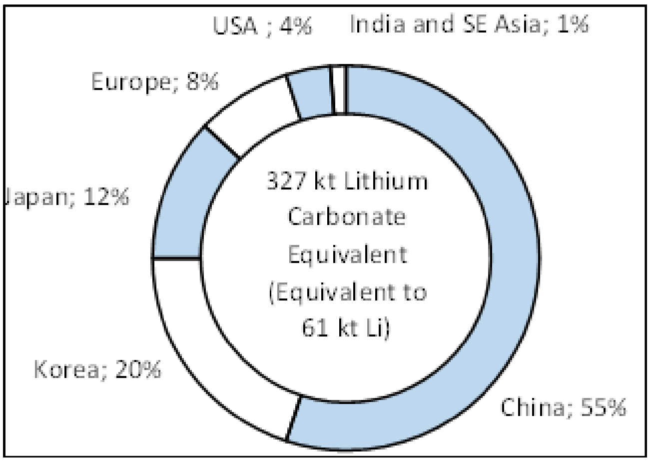
Data sources: SQM Annual reports from 2013 to 2020; Reich and Schatz (2021).

Figs. 1 and 2 show the very rapid growth of Li demand for the manufacturing of rechargeable batteries since 2010. SQM (2021) estimates that 72% of the 2020 battery-related demand was for battery-operated electric vehicles, the rest, being essentially related to Li-batteries, were used for a vast diversity of electric and electronic portable equipment. In the future there could be significant demand for stationary electricity storage. This demand could be partly met by the re-use of BEVs batteries no longer fit for that specific use, but suitable for stationary energy storage.

Over the period 2015-2020 the Li-battery-related demand grew by 34.2% CAGR (compound annual growth rate), the highest of any known mineral demand trend observed during that period.

Fig.3 represents the 2020 lithium demand estimate on a country basis (COCHILCO 2021).

Figure 3: Country-level 2020 lithium demand estimate.



Source: Translated from COCHILCO (2021, with permission).

China, Japan and South Korea together accounted for 87% of the global lithium demand, reflecting their dominance over global lithium battery manufacturing.

The lithium industry is very far from being a simple “one mineral resource for one end-use” industry. It is a very diverse and complex industry based on a diversity of geological resources (see Section 2.1).

Marketable lithium intermediate products (mineral concentrates, Li carbonate, Li hydroxide and Li chloride, see fig. 6) are produced from this diversity of resources and carrier minerals through the use of a wide range of physical and/or chemical processes, each being suited to produce a given lithium chemical from one of the resources listed in section 2.1.

Therefore, there is no single, homogeneous lithium market. On the contrary there is a diversity of Li markets driven by specific end-uses. The largest market nowadays is the Li chemicals (Li carbonate and hydroxide) market for Li-battery production. A wide range of physical and/or chemical processes connect the different categories of lithium resources to their respective different end-uses (fig. 6). The selection of the optimal process route linking a specific Li resource with a specific end-use is dictated by technological, economic and increasingly environmental considerations (energy and water efficiency, waste management).

Despite this diversity, for the sake of comparability, data presented is expressed (unless otherwise specified) in tonnes of lithium metal contained, the amount of Li metal actually present in the compound.

1.2 2019-2040 DEMAND SCENARIOS

There is much uncertainty regarding the future demand for lithium as numerous factors determine the future demand for Li-batteries, and thus for battery materials such as lithium including:

- The sales of battery electric vehicles (BEVs) - In the IEA (2021) Sustainable Development Scenario, about 72 million BEVs would be sold worldwide, as compared to 3 million BEVs sold in 2020;
- The average storage capacity, expressed in kWh, of the Li-batteries mounted in individual cars - It currently varies from 6.1 kWh for a small Renault Twizy up to around 100 kWh for top-of-the range BEVs. According to Statista (2022), the estimated average battery capacity in electric vehicles worldwide was 41 kWh in 2017 and may rise to 45 kWh by 2025;

- The pricing of BEVs – This price depends on the cost of the batteries, which depend on the cost of battery raw materials, such as lithium, cobalt, nickel or graphite. The cost of the raw materials is one of the key cost factors for battery production (see section 3.3 on Li price trends);

- Public policies that, through subsidies and regulations, encourage the purchase of BEVs and the phasing out of vehicles using internal combustion engines requiring carbon-based fossil fuels;

- Technology shifts that may decrease the demand for Li-batteries - In the longer-term (beyond 2035) Li-demanding battery technologies may be replaced, at least partly, by other energy storage technologies such as supercapacitors and/or zinc-air batteries. Such shifts are impossible to predict but the internationally very active energy storage research and innovation scene may well deliver economically feasible technological breakthroughs that can radically modify the future of Li demand. However, innovations may not be industrialized rapidly. Investors, who will have invested billions of $US in a gigafactory based on a given battery technology, are unlikely to write off their investment and re-invest in a new technology without having first recovered their initial investment and made their profit, which may take years;

- The evolution of charging times and the number of possible charge/ discharge cycles of Li-batteries;

- The evolution of the energy density of Li-batteries, which translates into km of BEV travel between two charging sessions. This is an important factor for the development of BEV use in long-distance travel;

- The availability of a network of fast-charging stations and of the electrical grid needed to supply them, for the recharge of BEVs used in long-distance travel;

- The safety of Li batteries;

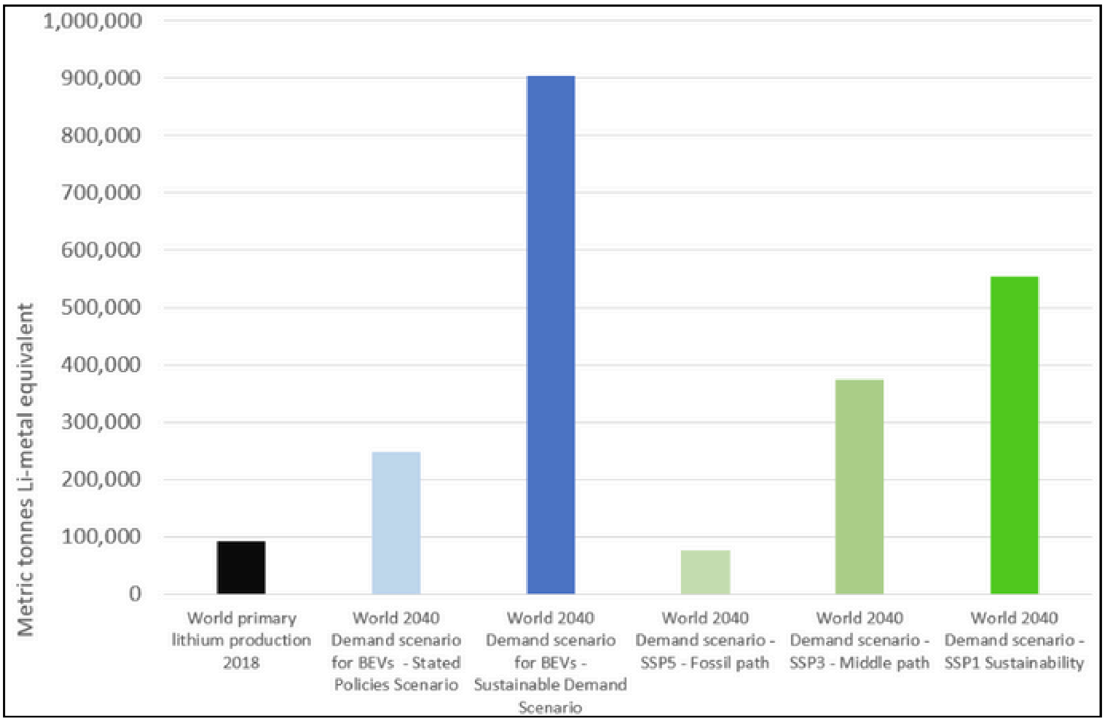
- The vulnerability of the BEV industry to external shocks, such as geopolitical tensions or public acceptance of lithium production operations, both having the potential to disrupt global supply chains, which so far appear to lack the resilience to survive major external shocks. The production of BEVs implies geographically disconnected supply-chains and geographically disconnected capitalistic controls over various stages of the supply chain, that can significantly postpone/ block future lithium production projects. For instance, the lithium supply of a European battery gigafactory can depend on lithium carbonate or hydroxide production from an Argentinian lithium production site controlled by Chinese capital;

- Global economic trends - The war in Ukraine, the looming crisis in the seas around China, the rise of nationalisms rather than the international cooperation needed to address the pressing sustainability challenges humanity is confronted with, and the return of inflation, all foster much uncertainty on the future trends of the global economy. This does not stimulate the multi-billion $US investments needed to fully engage in the global energy transition, including in lithium chemicals production and in the development of electromobility.

There is a relative abundance of literature providing scenarios of possible future electromobility-related lithium demand (e.g.: COCHILCO 2021; Grandell et al. 2016; Hund et al. 2020; IEA 2021; Marscheider-Weidemann et al. 2021; Watari et al. 2021). The development of electromobility is one of the key components of national strategies for a transition to low-carbon energy production and use, in support of the Paris Accord signed in 2015 at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change.

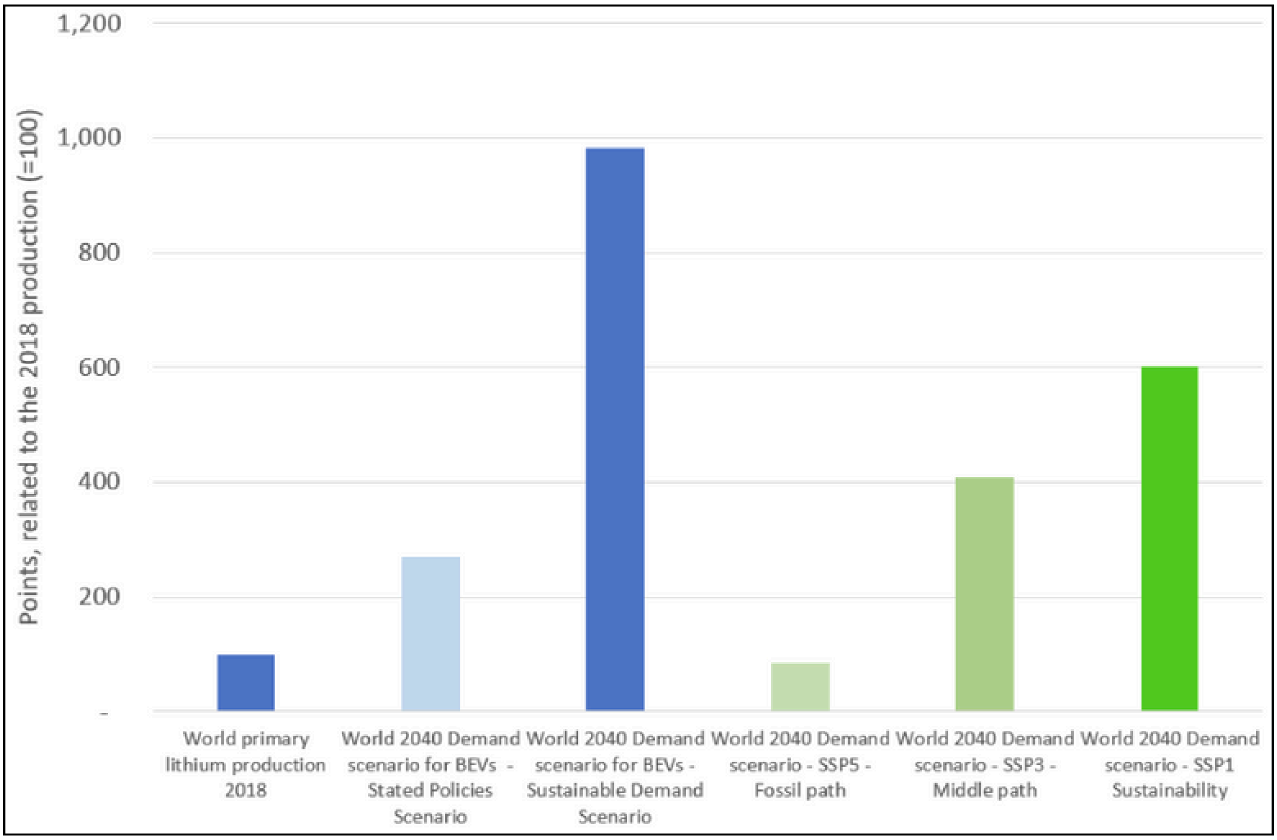
Fig. 4 and 5 provide an overview of the 2018 world lithium primary production (from natural resources), and lithium demand scenarios by 2040 (2 from IEA 2021; and 3 from Marscheider-Weidemann). In fig. 4 it is expressed in tonnes, and in fig. 5 in percentage points compared to the 2018 world primary Li production (basis 100 in 2018). Due to the above listed uncertainty factors, 2040 is arbitrarily chosen as a limit to what scenarios may say about the future. Considerations beyond that date appear to be too speculative to have a reasonable chance of relevance. This is well-illustrated in the review of critical metal dynamics to 2050 for 48 elements, including Li, published by Watari et al. (2020). The Supplementary Information provides the detailed data resulting from the review. Compiling scenarios on 2050 lithium demand from 12 different publications, it concludes that by 2050 Li demand for low-carbon technologies, which is equivalent to Li demand for electromobility, could be between 0 and 2 000 kt Li metal equivalent.

Figure 4: World primary lithium production 2018 and 2040 demand scenarios, expressed in tonnes of contained Li.



Data sources: Reichl C. and Schatz M. (2021, production data); IEA (2021) 2040 demand scenarios; Marscheider-Weidemann et al. (2021) demand scenarios. Data is expressed in tonnes contained lithium.

Figure 5: World primary lithium production 2018 and 2040 demand scenarios.



Note: The 2040 demand is expressed in points compared to the 2018 production (100 points). Data sources: Reichl C. and Schatz M. (2021, production data); IEA (2021) 2040 demand scenarios; Marscheider-Weidemann et al. (2021) demand scenarios. Data is expressed in tonnes contained lithium.

Although figs. 4 and 5 show variable outcomes, they indicate that under the pro-sustainability development scenarios, the demand for lithium is going to be very strong in the period up to 2040, and probably beyond, if by then no alternative lithium-free chemistries demonstrate their superiority in terms of energy density, possible charge/ discharge cycles, cost and safety.

This would mean, that taking a 9.7% CAGR as an average figure, about 6.9 Mt Li would need to be produced from 2019 to 2040, just to meet the needs arising from the development of the global BEVs market, the derived 2040 annual production needed for Li batteries being 706 kt Li.

On the basis of the demand data in SQM annual reports, lithium uses, other than for Li-battery production, grew at a 4% CAGR over the 2003-2020 period. In 2018 those other uses were estimated to have represented 32.2 kt Li. Assuming that the other uses of Li will continue to develop at the same rate up to 2040, 1 148 kt Li would need to be produced over the 2019-2040 in addition to the needs for Li-battery production. Under this scenario, in 2040 the resulting total annual world Li demand would be 782 kt Li, 90% of which is needed for the production of Li batteries (fig. 6), and the cumulated Li production needed for all its uses from 2019 to 2040 would amount to about 8.1 Mt Li metal equivalent.

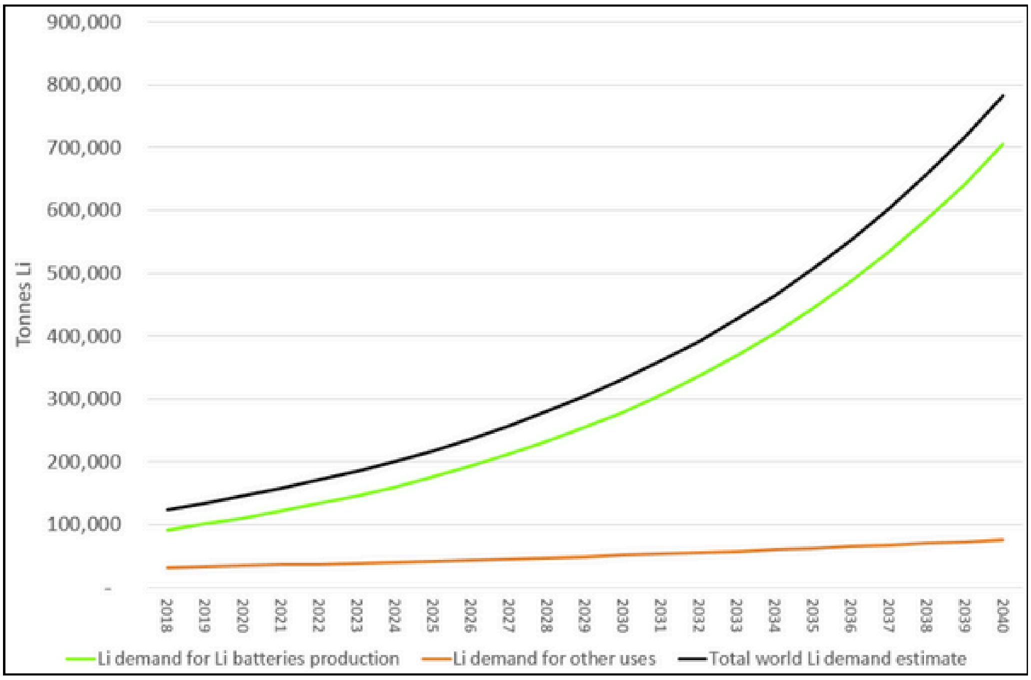
In response to the rapid demand growth for BEVs, the global industry is planning very large investments in the construction of Li-battery manufacturing gigafactories. A compilation of data published in 2022 by CICENERGYGUNE on global gigafactory construction projects expected to become producing gigafactories between 2022 and the end of 2024, shows that 272 GWh additional Li-battery production capacities are planned worldwide. Assuming that, on average, 110 grams Li are required per kWh Li-battery storage capacity (Marscheider-Weidemann 2011) this would represent an additional demand of nearly 30 kt Li equivalent by the end of 2030. The capital expenditure needed per GWh battery production capacity is variable, larger facilities allowing economies of scales. One capital expenditure example is the 54 GWh Statevolt Gigafactory project in California with a planned 4 billion $US investment (PV Magazine 2022).

Any such large capital investment is made on the basis of technological choices that can hardly be deeply modified before the investment has been recovered, and profits have been made. Therefore, even if alternative, non-lithium energy storage technologies suitable for the manufacturing of BEVs become available it may take many years to see them gain a significant market share, except if they provide breakthroughs in some commercially important factors such as production and ownership costs or the mileage that can be driven between two recharges.

While the 2040 scenarios in figs. 4 and 5 show large differences in future Li demand estimates, caused by differing assumptions used in the demand modelling, two important conclusions can be derived from the data:

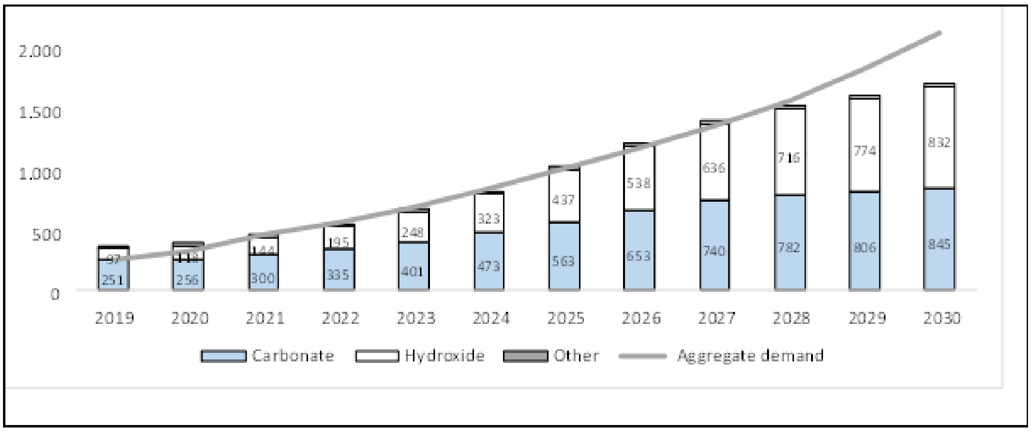
- Scenarios that are underpinned by high sustainable development ambitions [IEA (2021) Sustainable Development Scenario and Marscheider-Weidemann et al. (2021) SSP1 Sustainability Scenario], including through a rapid transition to electromobility, are those resulting in the highest lithium requirement. By 2040 the Li demand for BEV batteries alone may represent about 6 to 10 times the total world 2018 Li production, an enormous challenge as it would require an annual increase in Li production between 8.5% and 10.9%.
- The demand for lithium is going to rapidly rise in the considered period, with a probability of temporarily outstripping the capacity of the minerals and metals industry to provide sufficient supply (see Section 2.2 on demand scenarios).

Figure 6: 2018-2040 Li demand scenario: Li batteries production, other uses and total demand estimates, in tonnes contained Li.



Data sources: Derived from data in IEA (2021), Marscheider-Weidemann and SQM annual reports.

Figure 7: Lithium composite supply projection and aggregate demand (in kt lithium carbonate equivalent, LCE), 2019-30.



Note: 1 t Li carbonate contains 0.188 t Li metal.
Source: Translated with permission from COCHILCO, 2021.

Various supply-demand scenarios are available from public company reports (feasibility studies, presentations). An example of such a scenario, published by COCHILCO (2021) is presented in fig. 7. This scenario highlights the rising importance of lithium hydroxide over lithium carbonate, due to the development of Ni-rich cathodes (such as NMC 622 and NMC 811), fostered by the relative scarcity and higher price of cobalt. Li hydroxide is favored over Li carbonate for the manufacturing of Ni-rich Li-batteries (COCHILCO 2021), offering advantages in terms of energy density (= longer mileage per charge).

CHAPTER 2

SUPPLY-SIDE

2.1 LITHIUM DEPOSITS

Lithium is a relatively scarce element in the Earth's crust, with an average abundance of 20 parts per million (ppm), less than copper (60 ppm) but more than lead (14 ppm). It easily forms concentrations of economic importance due to its immiscibility in common rock-forming silicate minerals.

There is a great mineralogical and geochemical diversity of lithium deposits (Table 2):

Table 2: Indicated and measured resources, published in compliance with one of the national reporting codes recognized by the Committee for Minerals Reserves International Reporting Standards (CRIRSCO), broken down by ore deposit category.

Ore deposit category	Typical minerals	Locations	Tonnage (in metric kilotonnes contained Li metal equivalent) in CRIRSCO compliant indicated and/or measured resources	Share of the CRIRSCO compliant indicated and/or measured resources
Salt lake brines (salars)	Lithium and other alcaline metal (Na, K, Mg) chlorides in solution	Argentina, Chile, China	14 589	54%
Pegmatites	Spodumene, petalite, amblygonite, lepidolite	Austria, Australia, Brasil, Canada, Democratic Republic of Congo, Finland, Ghana, Mali, Namibia, Portugal, USA, Zimbabwe	5 367	20%
Clays and Li-bearing sediments	Clays, volcanic tuff, lake evaporite rocks	Mexico, USA	4 098	15%
Groundwater related brines, including geothermal reservoirs	Lithium and other alcaline metal (Na, K, Mg) chlorides in solution	Canada, Germany, USA	1 144	4%
Aplite and greisen	Li-micas: Lepidolite, zinnwaldite	Czech Republic, Germany, Spain	1 122	4%
Lithium-boron deposits	Jadarite or searlesite-rich (volcano) sediments	Canada, Serbia	633	2%
Total			26 953	

Data sources: company reports and presentations.

Salt lake brines (or 'Salars', in Spanish): Together with other alkaline elements (potassium, magnesium and sodium), lithium can be concentrated over thousands, if not millions of years, in the interstitial brines of salt lakes with no exits to the sea, where evaporation rates are higher than water inputs, providing ideal conditions for the crystallization of salt, essentially sodium chloride (table salt) with the residual interstitial brine being enriched in lithium.

Lithium-rich salt lakes form in regions underlain by acid magmatic rocks from where lithium can be leached and transported by groundwater circulations. The presence of acidic magmatism, especially of explosive ignimbritic/ rhyolitic volcanism, as a source of lithium is an important factor for the development of lithium-rich salt lakes (Munk et al. 2016; Li et al. 2018, Godfrey et al. 2020; Alvarez-Amado et al. 2022). Li can be slowly leached from such volcanic materials further to warm groundwater circulations controlled by geological features such as fault systems and differences in the porosity of different geological formations. Salt lakes, whether Li-rich or not, are named "salars" in Spanish, a term frequently found in English literature as well, as the world's largest spatial concentration of Li-rich salt lakes occurs in the Spanish-speaking Lithium Triangle of South America (comprising parts of Argentina, Bolivia and Chile), a region also known as the Central Andean Dry Puna.

Tibet (China) is the world's second largest region with Li-rich, producing salars with the Qarhan, Taijinar and Zhabuye salt lakes (Li et al. 2018).

The largest known lithium deposit of this type is the yet largely underexplored and unexploited Salar de Uyuni, in Bolivia (fig. 8).

Figure 8: Artisanal table salt production at the Salar de Uyuni in Bolivia, the word largest salt lake (10 582 km^2, located at 3 663 m above sea-level). Probably the world's largest lithium resource.

Source: Tetraigofotos, Wikimedia (2022).

These lithium deposits are not exploited by conventional mining methods, but by pumping the interstitial brine from drill-holes made in the salt core (“nucleus”) of the salt lake. Lithium chloride can then be recovered by progressive evaporation of the pumped brine, leading to the crystallization of the contained chorides (successively Na, K and Mg chlorides). The enriched Li chloride brine is then transformed into lithium chemicals (Li carbonate and Li hydroxide) needed for Li battery-making (see Section 4.2.1.1, outlining the Li-recovery process from salt lake brines).

Typical Li concentrations in brines vary from 0.200 to, very exceptionally, 4 g Li per litre brine (Gruber et al. 2011; Kesler et al. 2012). Based on data available for 24 deposits with published indicated and/or measured resources, the average Li content in brines is 538 mg Li per litre. The highest grade industrially exploited is the Li-brine from Chile’s Salar de Atacama exploited by SQM, grading about 0.15% Li (CORFO 2016).

Potassium is a frequent economically valuable by-product in these deposits, which can also be possible sources for magnesium production. Very occasionally, bromine can be an additional by-product.

According to COCHILCO (2021), 60% of the world lithium production comes from salt lakes. They contain 60% of the world’s known reserves. Nowadays salars are important lithium production sources in Argentina, Chile and China.

On the basis of published indicated and/or measured resources compliant with one of the national reporting codes recognized by CRIRSCO, the resources documented by end of April 2022 are 14.6 Mt Li metal equivalent, that is 54% of all published indicated and measured resources (Table 2).

There is much potential for further growth of lithium production from brines. In the future, Bolivia's huge potential resources of the Salar de Uyuni, which remain so far essentially unexplored and untapped, could play a major role in meeting the future lithium demand.

Groundwater related brines, including geothermal reservoirs: These are saline groundwater systems related to acidic magmatic intrusions, the primary source of lithium, some being hot brines that can be used for the recovery of geothermal heat for district heating purposes, as exemplified by the Vulcan Energy Resources project striving at both providing district heating and Li recovery from deep geothermal brines in the Rhine valley graben. A feasibility study was in progress in June 2022 for this very innovative project that could allow the first ever carbon-neutral production of Li hydroxide. While the targeted production of 40 000 t Li hydroxide / year would require pumping about 70 m^3 brine per year, water use would be minimal as the depleted brine would be re-injected in the aquifer system from where it was pumped.

The only current production from geothermal brine is by Albemarle at Silver Peak, Nevada, US Li-bearing groundwater systems are also the feeders of Li-bearing salt lakes.

Data from 2 deposits with published indicated and measured resources indicate an average of 175 mg/ l brine.

Li-enriched groundwater systems are also the main feeders of the above-described salt lakes. Lithium is also recovered from groundwater pumped from wellfields.

This category represents 4% of the resources documented in Table 2.

Pegmatites are the second most important category of deposits. They are vein-shaped, very coarse-grained mineral assemblages, that are formed at the periphery outside of some large intrusions, mostly of granitic nature, or in crystalline basement areas that underwent partial melting (migmatisation). Pegmatites, being the result of geochemical and mineralogical differentiation processes during their very slow cooling, concentrate elements such as beryllium, boron or lithium that are not miscible in ordinary silicate minerals.

The average Li content in 24 pegmatite deposits with published indicated or measured resources is 0.6% Li.

The main Li-carrying minerals in pegmatites are:

- Spodumene, $LiAl(SiO_3)_2$, by far the most abundant Li containing silicate mineral with an average grade of 3.72% Li. This is the most commonly occurring, and used, of these minerals;
- Lepidolite, a mica containing lithium, $K(Li,Al)_3(Si,Al)4O_{10}(F,OH)_2$, containing between 1.9 and 3.6% Li;
- Zinnwaldite $(KLiFeAl(AlSi_3)O_{10}(F,OH)_2$, a rarer Li-mica, containing 0.9 to 1.8% Li;
- Petalite, $LiAl(Si_2O5)_2]$, much less abundant, containing 2.1% of Li.

Some pegmatites (the Lithium, Caesium, Tantalum or "LCT" pegmatites) are the source of the global caesium and tantalum supply, two very rare elements with important industrial applications.

According to COCHILCO (2021), pegmatite deposits are the main current source of Li production, representing 52% of the world production, and holding 27% of the world resources.

Pegmatites represent 20% of the indicated and measured resources documented in table 2; and are the basis of Australia's thriving lithium production. There is an important potential for future lithium production from pegmatites in a diversity of jurisdictions, especially in Africa (Democratic Republic of Congo, Ghana, Mali and Zimbabwe), Europe (Austria, Czech Republic, Finland, Portugal and Spain) and Canada with good potential in other countries that are so far underexplored: Afghanistan, China, Russia, Ukraine and more.

Aplites and Greisens are genetically and mineralogically close to pegmatites. Like the latter, they also form vein-shaped deposits, but are made of very fine-grained minerals, reflecting much faster cooling than pegmatites. Greisens are highly altered zones capping some granites, resulting from the release of volatile (e.g.: fluor) and immiscible elements (e.g.: lithium, boron) from the cooling and progressive crystallisation of granitic magmas.

This category of deposits is much less common than pegmatites. On the basis of 3 deposits with published resources, the average Li grade is 0.3%.

This category represents 4% of the total resources recorded in Table 2.

Clays and Li-bearing sediments: Lithium may occur in the porous volcanic materials (ashes, pumices) accumulated in volcanic calderas further to explosive acidic volcanic activities, some calderas being very large structures. For instance, in Nevada (US) the McDermitt caldera, home to several lithium-mining projects (including the Thacker Pass and Jindalee projects), is about 30 x 40 km in size, with an enormous erupted volume of about 1,000 km^3. With time, some of these volcanic sediments are turned into lithium-containing clay, from where lithium can be economically recovered. While no deposit of this category is actually mined, several projects are at the development phase, with two major projects nearing production:

- Thacker Pass (Nevada, US, owned by the Lithium Americas/ Ganfeng Joint-Venture, about 590 000 tonnes Li equivalent contained in 179 Mt reserves, grading 0.33% Li, on the basis of the 2018 NI 43-101 compliant Prefeasibility Study);
- Bacanora (Sonora, Mexico, owned by the Ganfeng – Bacanora J.V, about 850 000 tonnes Li-equivalent contained in 244 Mt reserves, grading 0.35% Li, on the basis of the 2018 NI 43-101 compliant Feasibility Study).

Such deposits will play an important role in meeting the future Li demand. The geological conditions favourable to the formation of such deposits exist in a number of countries, forming an interesting target for future deposits.

Clay deposits are low-grade high tonnage deposits: On average, the 6 deposits with published indicated and/or measured resources contain 0.2% Li.

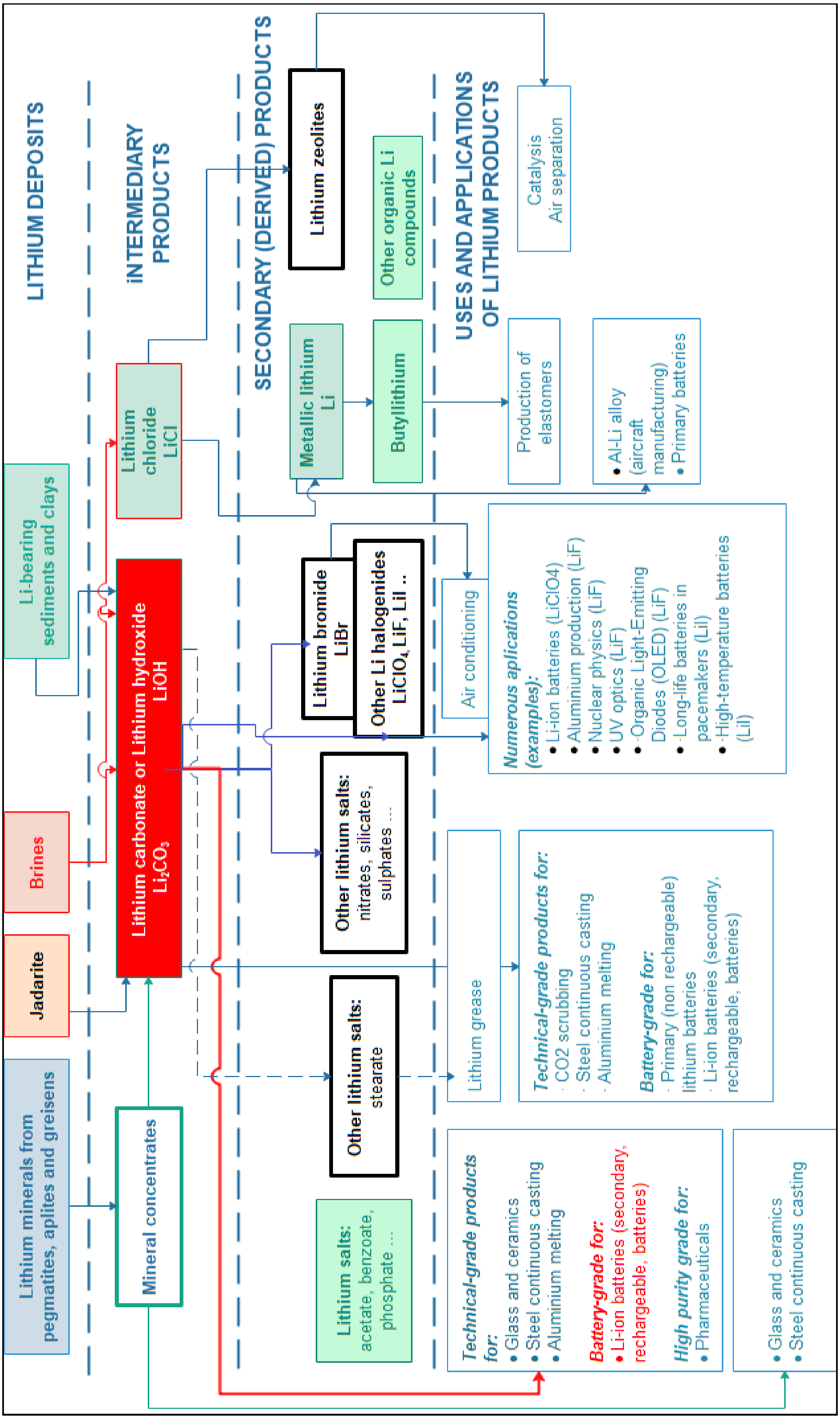
COCHILCO (2021) estimates that this type of deposits hosts about 7% of the known world Li resources, while the resources documented in table 2 are 15% of the total resources. As this kind of geological setting may exist in various regions of the world where it has not been explored so far, this category of resources could become economically more important in the future.

Lithium-boron deposits: This last category are particular sediment-hosted deposits where boron and lithium are economically important. For the time being, there are only 2 deposits with documented resources pertaining to this category:

- Jadar, in Serbia where jadarite, [$LiNaSiB_3O_7(OH)$ or $Na_2OLi_2O(SiO_2)_2(B_2O_3)_3H_2O$], (7.3% of LiO_2), a lithium and boron-rich mineral so far only known from this deposit, accumulated in lacustrine sediments from a past lake. The deposit is owned and developed by Rio Tinto, who in 2022 declared indicated and measured resource, of 85.4 Mt ore grading 0.82% Li, equivalent to about 700 000 t Li (Rio Tinto, 2022), making it a world-class deposit. In addition, the resource also grades 5% boron, that is 4.27 Mt boron. This resource and reserve statement is compliant with the compliant with the Australasian Joint Ore Reserves Committee (JORC) resources and reservces reporting standard applicable to companies publicly listed on an Australian stock market.
- Rhyolite Ridge, Nevada, US where searlesite, a boron mineral [$NaBSi_2O_5(OH)_2$] is abundant in some layers of lithium-bearing sediments. The 127 Mt indicated and measured resources grade 0.16% Li and 1.42% B, translating into 203 kt Li and 472 kt B.

These deposits represent 2% of the indicated and measured resources stated in Table 2. Lithium present in these deposits is in silicate mineral.
The association of lithium with a wide range of minerals and brine chemistries, and the diversity of lithium end-uses, translates into the complex industrial realm of multiple Li-dependent supply-chains, involving different resource extraction and processing pathways, summarized in fig. 9.

Figure 9: Lithium dependent supply-chains, a complex industrial realm.



Source: Derived, from Christmann et al. (2015), with permission.

2.2 TOP 5 PRODUCING COUNTRIES IN 2009 AND 2019, AND THEIR PRODUCTION

2.2.1 At the mining level

Table 3 and 4 show the top lithium producing countries in 2009 (for reference) and 2019 respectively, together with the world production.

Table 3: Top 5 lithium producing countries in 2009, and world production (in t Li contained in the ore).

	MINE PRODUCTION 2009, in metric tonnes contained Li				
	Top 5 producing countries	Annual mine production, in metric t contained Li (1)	Mineralisation type	Production share, in % of world total	HHI geographic concentration index
	Chile	5,610	Brine	31%	0.10
	Australia	4,582	Pegmatite	25%	0.06
	Argentina	2,622	Brine	14%	0.02
	U.S.A.	1,392	Brine	8%	0.01
	China	2,436	Brine	13%	0.02
Total of top 5 producing countries, and share of the world total >>>				92%	0.20
World Total >>>		***18,158***			

Data source : Reichl et al. (2015).

Table 4: Top 5 lithium producing countries in 2019, and world production (in t Li contained in the ore).

	MINE PRODUCTION 2019, in metric tons contained Li							
	Top 5 producing countries	Annual mine production, in metric t contained Li (1)	Mineralisation type	World Bank Income Level, 2019	Governance Indicators, 2019 average of the 6	Production share, in % of world total	HHI geographic concentration index	CAGR 2009-2019
	Australia	47,792	Pegmatite	High income	1.53	54%	0.30	26.4%
	Chile	20,852	Brine	High income	0.90	24%	0.06	14.1%
	China	8,816	Brine	Upper-middle income	- 0.36	10%	0.01	13.6%
	Argentina	6,343	Brine	Upper-middle income	- 0.10	7%	0.01	9.2%
	Zimbabwe	1,230	Pegmatite	Lower-middle income	-1.21	1%	0.00	Not significant
Total of top 5 producing countries, and share of the world total >>>		85,033				97%	0.37	
World Total >>>		*87,780*						*17.10%*

Data sources: production (Reichl and Schatz 2022); World Bank Income Levels (World Bank 2022); Word Governance Indicators (Kaufmann and Kraay 2022).

Two columns with color-coded data indicate each producing country's income level according to the World Bank classification, as well as the 2019 governance estimate according to the World Bank's World Governance Indicators. A four-tiered color coding is used, from the highest values (dark green) to the lowest value (right).

In 2019, the world lithium mine level production recorded by Reichl and Schatz (2022) was concentrated in just five countries, with Australia and Chile being the dominating producers (together they represent 78% of the 2019 world production). The respective importance of Australia and Chile varied over the years; much depending on the market price of Australian spodumene concentrates, past low Li prices having led to some of Australia's productive capacities put to care and maintenance. In 2019, Australia alone has provided 54% of the world production from its Western Australia pegmatite fields, the largest worldwide known so far.

The list and relative weight of key lithium-producing countries is likely to change in the coming years, as several important projects in other countries are likely to start producing (See Section 4.3).

Over the 2009-2019 period, the world production rose by about 380%, or by a Compound Annual Growth Rate of 17.1%, reflecting the rapidly growing demand for lithium-ion batteries, especially for plug-in battery-operated vehicles (BEVs, mostly cars), whose sales were much less than 100 000 vehicles sold in 2010, against about 4.3 million BEVs sold in the first half of 2022, according to EV-volumes, a specialized Swedish consultancy.

The capacity of the lithium-producing industry to develop at such a pace over the 2009-2019 period is no guarantee that it will be able to grow its future production (see Section 4.3) sufficiently to meet the demand scenarios presented in Section 2.2.

2.2.2 At the metallurgical / refining level

There is very little lithium metallurgy as the demand for lithium metal is extremely marginal (+/- 1% of the total lithium market).

According to COCHILCO (2021) the main lithium products produced in 2020 were:

- Lithium carbonate: about 219,000 tonnes, or 67% of the total lithium products production. 79% of that production was battery-grade lithium carbonate;
- Lithium hydroxide: about 92,000 tonnes, or 28% of the total production, of which 72% was battery-grade;
- Other lithium containing semi-products: 5% of the total production, including the production of lithium metal.

2.3 Li CHEMICALS MARKETS, LONG-TERM AND RECENT Li PRICE TRENDS

Most of the lithium products traded worldwide are traded via direct agreements between lithium producers and either battery manufacturers or even car manufacturers, frequently via offtake agreements concluded before the actual start of production. The terms of such agreements are mostly kept confidential. Buyers entering in offtake agreements may provide loans and/or take an equity participation in the developing project, in order to facilitate and accelerate its development. Immediate spot delivery of Li products via traders is likely to represent only a few percent of the global Li business, no data being available to quantify the relative importance of the Spot market, as compared to direct agreements. Some traders disclose the price agreed for their spot transactions, which are then published, mostly by commercial information services.

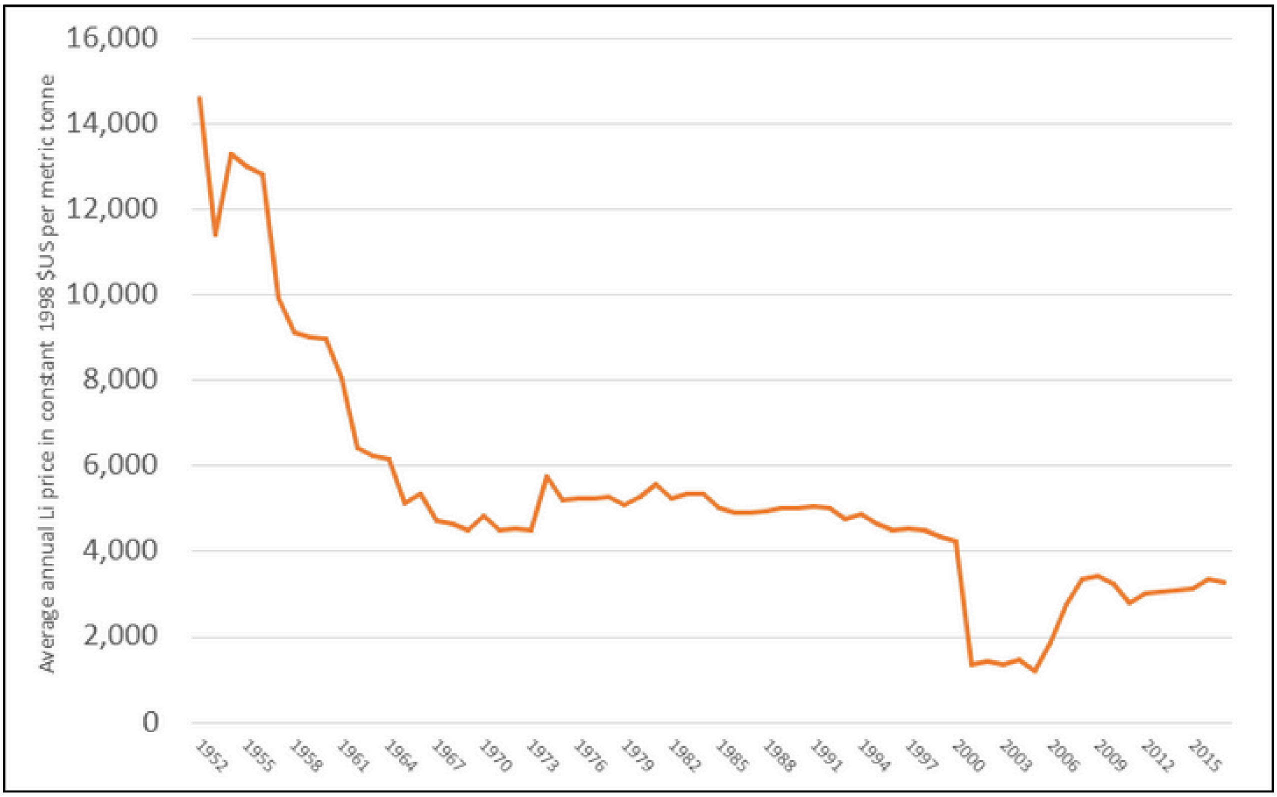
Some Spot market prices for Li products are available from free-of-charge sources such as Trading Economics or the Shanghai Metals Market, commercial sources providing further references.
Spot prices, despite not reflecting a commodity's full market, reflect the market sentiment and are widely used by traders, investors and the industry as references they use for their own business.

Some recent examples of offtake agreements are:

- In November 2021, Renault, a French car-maker and BEV producer, signed a binding offtake agreement with Vulcan Technologies, developing a Li-production project from the geothermal brines of the Rhine Graben (Batteries News 2021). Renault will buy 26 000 to 32 000 t/year Li chemicals from Vulcan Technologies during the agreement's five-year initial term. The Li price is announced to be market-based, or on a take-or-pay basis.

- In March 2022, Tesla, a leading BEV and Li-battery manufacturer, entered into a binding agreement with CORE Lithium to buy up to 110 000 tonnes of spodumene concentrate over 4 years from CORE's Finniss project in Australia (CORE Lithium 2022). The pricing will reference spodumene market prices.
- BNAmericas (2021) reported an off take between Japan's Mitsui company and the Maricunga lithium brine project in Chile, whose main shareholder is the Australian Lithium Power International company.
- The US Geological Survey (USGS) (Kelly and Matos 2022) provides its assessment of annual average lithium prices from 1952 to 2017, based on the Li carbonate process, in constant 1998 $US (fig. 9), allowing assessment of Li price trends over 65 years.
- Over that period, average annual Li prices published by the USGS were on an almost continuous downward trend (fig. 10). The strong price depression having occurred from 2001 to 2006 is probably related to an oversupply situation as no changes in the demand structure or intensity explain it.

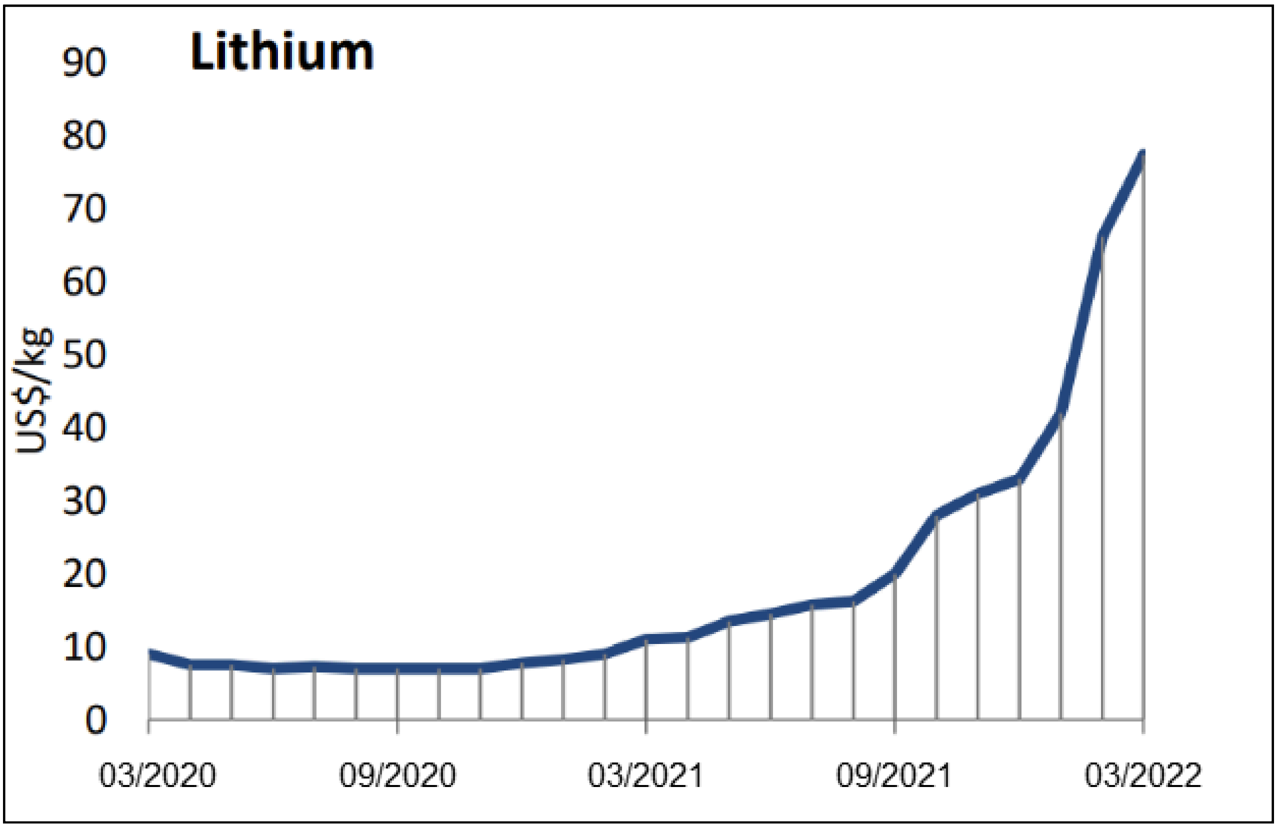
Figure 10: Average annual lithium price from 1952 to 2017, in constant 1998 $ US per ton. Deflator: US Consumer Price Index.



Data source: USGS (Kelly and Matos, 2022).

The very rapid rise in lithium demand driven by the Li-battery demand (see fig. 2) observed since 2016, has reversed the decline of lithium prices (see fig. 11). According to Trading Economics (2022), spot Li carbonate prices for Li traded within China, expressed in Chinese RMB/t, have increased by 871% between January 1st 2021 and May 1st 2022. This reflects the very rapid demand growth as well as possible anticipation of a possible forthcoming supply shortfall, which could have partly been caused by the COVID-19 crisis in China, a major supplier of Li chemicals. As for any other commodity, speculative positions are likely to further amplify market anticipations.

Figure 11: Changes in Spot Li carbonate price, in $US/kg, from March 2020 to March 2022.



(Lithium carbonate 99% technical and industrial grade, delivery and duty paid to Europe or US)

Data source: Graphic form DERA Rohstoff Preismonitor, March 2022 edition, https://www.deutsche-rohstoffagentur.de/DERA/DE/Aktuelles/Monitore/2022/03-22/2022-03-preismonitor.pdf;jsessionid=B213CC7B7E5B8E4CA28696A46327E0D5.2_cid292?__blob=publicationFile&v=2 , with permission.

The current high prices of lithium, together with the increase of cobalt and nickel prices, the other raw materials needed for the manufacturing of most Li-battery cathodes [Co (+154%) and Ni (+115%) price increase between 01/01/2021 and 01/05/2022] reverse the steady decline in Li-battery pack prices observed over many years. Cathodes are, by far, the most costly components of Li-battery cells. Bhutada (2022) estimates that in 2021 they represented 51% of the average 101 $/kWh battery cell cost. Due to the strong demand dynamics and the difficulties (see Chapter 6) the mining industry is confronted with increasing its production capacities in parallel with the booming demand, further increases in raw material prices are possible. This will lead to increases of battery and BEV prices, which in turn could cool down the demand for these vehicles, potentially threatening the whole dynamics of the global transition towards electromobility.

Bloomberg NEF (2021) stated, on Nov. 30, 2021: "*Lithium-ion battery pack prices, which were above $1,200 per kilowatt-hour in 2010, have fallen 89% in real terms to $132/kWh in 2021. (...) Higher raw material prices mean that in the near-term, average pack prices could rise to $135/kWh in 2022 in nominal terms. In the absence of other improvements that can mitigate this impact, this could mean that the point at which prices fall below $100/kWh could be pushed back by two years. This would impact EV affordability or manufacturers' margins and could hurt the economics of energy storage projects.*".

The IEA (2022b) issued a comparable warning "If metal prices in 2022 remain as high as in the first quarter, battery packs would become 15% more expensive than they were in 2021, all else being equal.". This would reverse the steady decline, expressed in $US per kWh storage capacity, of Li-battery prices observed over many years. According to the IEA, from 2015 to 2021 included, Li-battery prices declined by 65%. While further declines are essential to foster the development of electromobility, this cannot be taken for granted.

New Li production capacities are expected to start producing in the coming years (see section 4.3). This could put a downward pressure on Li product prices. The current rise of raw material-related costs of electric cars may also negatively impact on demand and thus put a downward pressure on Li-chemicals prices. A downward price trend can be further compounded by a slowdown of the global economy due to a continuation of the COVID-19 crisis and/or the economic consequences of the war in Ukraine or other looming geopolitical crises that may engulf several of the world largest economies. All these factors illustrate the complex dynamics of mineral and metal prices, reflecting the feedback control cycle of mineral supply, documented by Wellmer and Hagelüken (2015).

CHAPTER 3

LITHIUM RESOURCE AND RESERVE ESTIMATES, RESERVE DYNAMICS

3.1 RESOURCES

USGS (2022) provides a country-level estimate of lithium resources and reserves (columns a and c in Table 5), based on a wide range of sources (see Annex C, Part B of this reference, describing the data sources compiled by USGS). In parallel data is provided on indicated and measured resources (Column b) and reserves data (Column d) of projects still at various levels of development (no actual production), publicly available from companies disclosing their resources and reserves according to one of the national reporting codes recognized by the Committee for Minerals Reserves International Reporting Standards (CRIRSCO) and conformably to its standard definitions (CRIRSCO 2012).

As reflected in Table 5, the world resources compiled by USGS at the end of 2021 amount to nearly 89 Mt Li, those present in new projects publishing their data in compliance with a national reporting code amount to over 31 Mt Li metal equivalent in 54 deposits.

Data in column b, being available from public company reports, limited to well-documented indicated and measured resources, can be considered with a higher level of confidence than data in column a, which can include undocumented or inferred resource data.

However, indicated and measured resource data is no indication about the future economic, environmental and social viability of a given project, and no indication about when new production will become available. It is only an indication of potential.

Even when considering the lowest of the two stated global resource figures (31.3 Mt Li), the comparison with the cumulative 2019-2040 demand scenario stated in section 2.2 (8.1 Mt Li) shows that the already documented indicated and measured resources are well above the anticipated demand. Consequently, there is no foreseeable geological shortage of lithium for the next few decades. Moreover, beyond 2040, technological shifts to other electricity storage systems, for instance using carbon nanotubes, sodium-sulphur or zinc-air technologies, may reduce the further demand for lithium.

Li resources are geographically widely distributed, and there is considerable geological potential for the discovery of new deposits as the current high lithium prices and the strong demand projections attract investment in Li exploration. Up to few years ago, when Li demand started to boom, there was little economic incentive to engage in Li exploration, and the world's geological Li potential remains widely underexplored, especially considering Li concentrations that are difficult to detect without significant efforts in geological knowledge development, such as Li concentrations related to acidic volcanic systems and or geothermal brines related to acidic intrusive materials.

Table 5: World resources and reserves estimates.

	RESOURCES		RESERVES	
	Metric tonnes contained Li			
Column reference >	a	b	c	d
Country	USGS (2022)	Indicated and measured resources computed on the basis of company reports on projects in development as of April 2022, produced using a CRIRSCO recognized national reporting code	USGS (2022)	Reserves computed on the basis of company reports on projects in development as of April 2022, produced using a CRIRSCO recognized national reporting code
Argentina	19.00	14.52	2.20	1.31
Australia	7.30	2.13	5.70	1.13
Austria	0.06	0.05		
Bolivia	21.00	0.00		
Brazil	0.47	0.30	0.10	0.01
Canada	2.90	1.09		0.46
Chile	9.80	0.48	9.20	0.08
China	5.10	0.00	1.50	0.00
Czech Republic	1.30	0.87		
Democratic Republic of Congo	3.00	2.06		1.00
Finland	0.05	0.07		0.05
Germany	2.70	3.11		0.09
Ghana	0.13	0.03		
Kazakhstan	0.05	0.00		
Mali	0.70	0.51		0.36
Mexico	1.70	0.95		0.85
Namibia	0.05	0.02		0.01
Peru	0.88	0.18		
Portugal	0.27	0.14	0.06	0.00
Russia	1.00	0.00		
Serbia	1.20	0.43		
Spain	0.30	0.13		
United States	9.10	3.92	0.75	1.03
Zimbabwe	0.50	0.31	0.22	0.23
Other countries	0.00	0.00	2.70	0
TOTAL >>>	88.56	31.30	22.43	6.61

Note: Columns a and c show data from USGS (2022) while columns b and d represent data on new projects (not in production in April 2022).

Data sources: compiled from company reports publishing their resources and reserves using one of the national reporting standards recognized by Committee for Minerals Reserves International Reporting Standards (CRIRSCO).

3.2 RESERVES AND RESERVES DYNAMICS

Reserves are derived from resources by applying modifying factors (CRIRSCO 2012), such as the mining method, ore processing and (where applicable) metallurgical processing, economic, legal, environmental and social factors that define the feasibility of a project. Reserves data for any given deposit are dynamic as several of the modifying factors vary over time.

Reverses data indicate which part of a resource offers a documented perspective of economically profitable exploitation given the framework set by the modifying factors determined at a specific moment in time.

The USGS estimate of world Li reserves at the end of 2021 is 22.4 Mt (column c, Table 5), encompassing reserves of already producing operations as well as information from public authorities. Reserves from projects at the development stage are estimated to be 6.3 Mt (column d), produced and published by mining companies according to one of the CRIRSCO-compliant national reporting codes.

The reserves stated by the USGS are also higher than the cumulated 2019-2040 Li demand estimates shown in section 2.2. (8.1 Mt Li), and reserves in developing projects with CRIRSCO compliant reserves statements are close to the demand estimate level. In view of the resource level, providing Li-chemicals price levels justify further investment in exploration and project development, reserves could be expanded to match the demand level.

However, future supply will very much depend on any project overcoming two important hurdles:

- The timely completion of all the permitting procedures needed prior to the final investment decision;
- The timely commitment of the investments needed to expand, where feasible, production of existing mines and the commissioning of new ones. This, in turn, depends on numerous factors such as environmental issues and the social acceptance of the expansion of existing projects or the development of new operations.

Supply bottlenecks may happen if new production capacities that will be needed, in addition to the expansion of some existing capacity to match the rapidly rising demand, fail to become available in time.

Out of the resources and reserves stated in columns b and d of Table 5, 9.09 Mt of Li indicated and measured resources, and 2.52 Mt Li reserves, are in new projects currently at the construction stage, expected to start production between 2022 and 2025, with an important addition to existing Li production (see Table 7). While these projects have overcome the two above hurdles, social conflicts can nevertheless develop at any stage of the construction or the operation of a new facility, delaying production. Delays caused by unanticipated technical problems may also happen during the production ramp-up time occurring between the start of a new operation and the attainment of its full production capacity. While ramp-up time is duly planned for in feasibility studies, the transition from pilot-scale ore-processing tests performed as part of the feasibility studies to full-sized industrial operations can require the need for sometimes complex, and time-consuming, technical fine-tuning of the operations.

Fig. 12 provides a view of the evolution of production and reserves over the 1996 – 2019 period. The reserves stated for each year are indicated in terms of years of Li production that would be possible from the reserves, at the stated year's production level. While there is a sharp decline of the production capacity from known reserves observed since 2010, this is no cause for alarm, nor even a sign of resource depletion. At the end of 2019, the reserves would entail over 200 years of production at the 2019 production rate, with a huge potential for further lithium deposit discoveries in areas so far underexplored as lithium exploration is a quite recent activity compared to more traditional exploration interest in gold, base or ferrous metals.

Figure 12: Annual lithium production (in tonnes Li metal equivalent) and reserves (expressed in years of potential production from the stated annual reserves estimate.

Data sources: Reichl and Schatz (2021); for reserves data: USGS Mineral Commodity Summaries, annual editions from 1997 to 2020.

3.3 IS THERE ENOUGH LITHIUM TO MEET THE DEMAND SCENARIOS?

Future Li supply depends on a range of factors:

- The capacity of already producing operations to expand their production;
- The timely launch of production from new projects still at the development stage, which in turn will be conditioned by:
  - Investment decisions needed to meet the initial capital expenditure (CAPEX), needed to develop, build and commission any new production site, including all its related facilities and infrastructure;
  - Securing the necessary legal permits needed to develop and operate new operations. In most world jurisdictions a separate mining permit and environmental licence are needed;
  - Recruiting and training the necessary workforce, which can be problematic during boom periods;
  - Securing the informal, but highly important, Sustainable Development Licence to Operate (SDLO; IRP 2020), which comprises the Social Licence to Operate as well as all other sustainability considerations;
- The development of exploration activities, much needed to meet the long-term demand;
- The development of secondary Li supply from battery recycling.

The assessment of future supply is constrained by data availability and reliability.

So far, only companies publicly listed on some stock markets are bound to report and publish data and information about their activities, including exploration and mine development activities, according to one of the national reporting codes recognized by CRIRSCO. The data and information provided by these companies have the best current level of confidence as they are produced according to written published rules, under the responsibility of identified competent persons, whose roles and responsibilities are clearly defined (CRIRSCO 2019). Private-equity funded or state-owned companies have no disclosure obligations. Whatever they disclose, and the contents/ reliability of such disclosure is left to their discretion.

Public authorities are also important data and information sources, but the amount and reliability of the data / information is very variable. Language barriers also make it difficult to identify and use data and information published in languages other than English.

The data compiled in this section reflects public data and knowledge available in April 2022.

The projects that are of major importance to the Li supply of this decade are:

- Production expansions of already producing operations;
- Production from new projects now at the construction stage.

As several major Li producers do not make public their data and information it is not possible to fully evaluate the potential of continued production expansion from existing producers.

Nevertheless, the following expansion plans have been publicly announced by existing Li producers:

- SQM (2022) announced its intent to expand its Li carbonate production capacity from the Salar de Atacama (Chile) brine from 120 000 t (2021) to 180 000 Li carbonate in 2022 (+ 60 000 t Li carbonate, equivalent to + 11 280 t Li). A further expansion to 210 000 t Li carbonate production is planned in 2023. At the end of 2023, this would translate into a production rise of nearly 17 000 t Li-equivalent by the end of 2023. Part of SQM's Li carbonate production will be converted into Li hydroxide.

- Pilbara Minerals (2021) announced its plan to increase in 2022 its production from its Western Australian Pilbara pegmatite from 324 000 t spodumene concentrate t 6% Li_2O (equivalent to about 9 000 t Li) to 580 000 t spodumene concentrate (+ 256 000 t concentrate, equivalent to approximately +7 100 t Li). In some unspecified number of years, the production could reach 1 000 000 t concentrate (approximately+ 18 800 t Li equivalent as compared with 2021).

- In 2022, Mineral Resources (2021) announced its plan to increase its production from its Western Australian Mount Marion pegmatite from 485 000 t spodumene concentrate at 6% Li_2O (equivalent to about 13 500 t Li) to 580 000 t spodumene concentrate (+ 256 000 t concentrate, equivalent to approximately + 7 100 t Li). Furthermore, in 2022 it will restart production from its Wodgina pegmatite, which was on care and maintenance since 2019, due to low spodumene concentrate prices. Wodgina production capacity is rated at 750 000 t/yr spodumene concentrate at 6% Li_2O, equivalent to about 20 900 t Li.
  The Kemerton Li hydroxide plant, fed by spodumene concentrates from the Mount Marion and Wodgina mines, is due for commissioning in 2022. It is planned to reach a production capacity of 50 000 t/yr Li hydroxide (approximately 8 200 t Li equivalent) in 2 to 5 years.
  Mineral Resources' plans are, within an unspecified number of years, to raise its attributable lithium hydroxide production from 35 000 t/yr in 2020 up to 74 000 t/yr (+ 39 000 t Li hydroxide/yr). As it is in 50/50 joint-ventures for all its activities, this means that the full production increase could reach 78 000 t/ Li hydroxide (about + 12 900 t Li equivalent).

- Livent (2022), plans to expand Li production from its Salar de Hombre Muerto brine operation (Argentina) production site, equivalent to 20 000 t Li carbonate in 2021 (approximately 3 800 t Li equivalent), to 70 000 t Li carbonate in 2025 (+ 9 400 t Li equivalent), and 100 000 t Li carbonate by 2030 (approximately + 15 000 t Li from the 2021 production level).

Table 6 summarizes those potential expansions, which will much depend on future Li prices.

Table 6: Planned Li production expansions reported by producing companies.

		SHORT-TERM OBJECTIVES (2022 and 2023)		LONGER-TERM OBJECTIVES (Beyond 2023)		Notes
COMPANY	2021 Production (in contained metric tonnes Li)	Additional planned Li production capacity, in metric tonnes Li equivalent	Targeted year	Additional planned Li production capacity, in metric tonnes Li equivalent	Targeted year	
SQM	22,560	17,000	2023			
PILBARA MINERALS	9,000	7,100	2022	18,800	Unspecified	
MINERAL RESOURCES Ltd.	13,500			12,900	Unspecified	On the basis of the stated Li hydroxide production plans
LIVENT	3,800			9,400	2025	
Totals	48,860	24,100		41,100		

Data sources: company documents (see references in the text).

Those reported expansions would, by the end of 2023, add 24 100 t/yr to the Li production, estimated by USGS (2022) to be 100 000 t Li in 2021. By the end of 2025, the stated production expansions may add 41 100 t to the stated 2021 Li production.

More additional production expansions could come from companies that do not report about their development plans.

In addition to production expansions, the commissioning of new production facilities will play a major role in meeting the booming lithium demand of the coming years.

Table 7 provides a summary overview of new lithium production projects expected to start production between 2022 and 2024, according to the data and information made public by the companies operating these projects. These projects may attain their nameplate production capacity 1 to 2 years after the beginning of their production, depending on the ramp-up time needed by mining projects to fine tune their production process after the beginning of production.

Together, these projects have the potential to add 66 000 t Li-equivalent production to the production reported for 2021. This requires an initial capital investment of nearly 3.8 bn $US, no initial capital requirement being indicated for the Wodgina project (20 900 t Li equivalent production capacities).

These projects have about 9.5 Mt Li in indicated and measured reserves, of which about 3.6 Mt Li are probable and proven reserves. These resources and reserves data are likely to be already included in the world resources and reserves estimates published by USGS (2022) (see sections 4.1.1 and 4.1.2).

More projects may be at the construction stage by companies that do not communicate publicly on their activities.

Table 7: New Li production sites, in construction on April 30, 2022 (or planned to start being constructed before the end of 2022), planned to be in full production between 2023 and 2025.

										Initial capital required		Hard-rock deposits – Indicated and measured resources			Brine deposits – Indicated and measured resources			Hard-rock deposits – Probable and proven reserves			Brine deposits – Probable and proven reserves		
Country	Macro-region	Deposit name	Operator	Deposit type	Reporting standard applied	Current status of the project	Stated production start	Foreseen production at full capacity	Li equivalent production in kt/yr	Initial CAPEX in M$ US	CAPEX estimate year	Ore tonnage, kt	Ore grade, % Li	kt Li contained	Brine volume (km3)	Brine grade (mg/L)	kt Li contained	Ore tonnage, kt	Ore grade (reserves), % Li	Reserves, in kt Li	Brine volume (km3)	Brine grade (mg Li/L)	Reserves, in kt Li
ARGENTINA	Latin America	Cauchari Olaroz	Lithium Americas	Brine (salt lake)	NI 43 101	In construction	Q3 2022	20 000 t/yr Li carbonate (Phase 1) 40 000 t/yr Li carbonate (Phase 2)	3.8	525	2019				6.3	592	3,730				1.12	607	367
ARGENTINA	Latin America	Rincon	Argosy Minerals Ltd.	Brine (salt lake)	JORC	Production launch mid 2022 Full FS in progress	Mid 2922	2000 t/yr Li carbonate. Expansion planned to 10 000 t Li carbonate pending	0.4	141	2018				0.144	325	46						
ARGENTINA	Latin America	Sal de Vida (Hombre Muerto South	Allkem	Brine (salt lake)	NI 43 101 JORC NI 43 101	In constructio n	H2 2023	32 000 t/yr Li carbonate	6.0	506	2021				1.2	741	898						242
ARGENTINA	Latin America	Cuenca Centenario R	ERAMET TSINGSHAN	Brine (salt lake)	JORC	In construction	2024	24 000 t/yr Li carbonate	4.5	400	?				2.523	391	987				0.548	438	209
AUSTRALIA	Oceania	Wodgina	Mineral Resources Ltd.	LCT Pegmatite	JORC	Production restart planned in	2022	750 000 T spodumene concetrate @6%	20.9			196,900	0.5%	1,069				151,940	0.54%	825			
AUSTRALIA	Oceania	Finniss	Core Lithium	Pegmatite	JORC	In construction	Q4 2022	175 000 t/yr spodumene concentrate (Phase	4.9	65	2021	2,560	0.7%	18				7,400	0.60%	45			
AUSTRALIA	Oceania	Mount Holland/ Earl	Covalent Lithium	Pegmatite LCT	JORC	In construction	H2 2024	50 000 t/yr of Li hydroxide	8.3	1,400	2018	172,000	0.7%	1,231				94,200	0.70%	656			
BRASIL	Latin America	Grota de Cirilo	Sigma Lithium Resources Corp.	Pegmatite	NI 43 101	Phase 1 in construction	2022 Q4	230 000 t/yr spodumene concentrate (Phase 1) 460 000 t/yr spodumene concentrate (Phase	7.0	Phase 1 – 98.3 M$ US Phase 2 – 38 M$ US	0.08	45,764	0.7%	303				13,790	0.68%	93			
CANADA	North America	Authier	Sayona Mining	Pegmatite	JORC	In construction	2023	114 100 t/yr spodumene	3.2	94	2019	14,140	0.5%	66				12,100	0.46%	56			
MEXICO	North America	Bacanora (Total of El Sauz, Fleur, La Ventana)	Bacanora Minerals Ltd.	Clay	NI 43 101	In construction	2023	17 500 t/yr Li carbonate (Phase 1) 35 000 t/yr Li carbonate (Phase 2)	6.6	420	2018	291,000	0.3%	946				243,808	0.35%	848			
NAMIBIA	Africa	Karibib project (Rubicon and Helikon 1)	Lepidico Ltd.	LCT pegmatite (lepidolite + petalite + amblygonite) with Cs	JORC	Construction to start Q3 2022	2024	4 879 t/yr Li hydroxyde + 240 t /yr Cs sulphate + 12 000 t/yr K sulphate	0.8	139	2020	8,860	0.2%	18				6,790	0.21%	14			
								Totals >>>	66.2	3,788.9				3,748.8			5,759.1			2,635.9			916.2

Data sources: company reports and presentations. Tonnage data is in tonnes.

Brine deposits, dominated by the giant Cauchari-Olaroz resource in Argentina, represent 61% of the stated total resources, while hard-rock deposits represent 39% of that total. Within the latter category, the Bacanora project in Mexico deserves particular attention as it is the first ever Li-clay resource to be put in production.

Table 8 provides a longer-term (beyond 2025) summary overview of lithium production projects for which data/ information is available from completed feasibility studies. Most of these were prepared conformably to one of the CRIRSCO recognized national mining projects reporting standards and are public in full (under the Canadian NI 43-101 reporting code's obligations) or in a summarized form (under the Australian JORC Code).

Pending the prior receipt of all necessary permits required by national/ regional jurisdictions, and the final investment decision due before commencing the construction, these projects may start production from 2025 onwards and reach their nameplate production capacities 1 to 2 years after the beginning of their production. Lithium chemical price levels will play an important role in the investment decisions, but social acceptance of new production projects is likely to be of even greater importance.

Altogether, these projects could add about 66 000 t/yr Li-equivalent production, not counting projects that are at the same development level but are not publicly reported on.

Summing up, a rough estimate of the 2030 Li equivalent production level could be:

- 100 000 t Li metal equivalent from existing producing sites (2021 production estimate, USGS (2022));
- 65 000 t Li metal from announced expansion of the production of already active sites;
- 66 000 t Li metal from new production sites, currently at the construction stage;
- 107 000 t Li metal from projects supported by completed feasibility studies, but not yet at the construction stage.

This points to an annual world potential production level of around 400 000 t Li metal equivalent by 2030, significantly higher (+ 69 000 t, + 21%) than the demand estimates scenario (331 000 t Li equivalent in 2030) presented in section 2.2. Under this scenario there is no trend towards a lasting Li supply deficit. This does not exclude temporary supply deficits in case of a demand growth exceeding the projections made in section 2.2 and/or delays/ cancellation of expansion or new production stated in tables 6, 7 and 8. However, any excess of supply is likely to depress the Li prices and make it economically unattractive to develop new projects.

This estimate does not include:

- The potential contribution to Li production from projects that are not yet as advanced as those listed in tables 7 and 8. Table 9 provides a list of projects that are at the advanced exploration stage and are publicly documented by either a scoping study (SS), a preliminary economic assessment (PEA) or a pre-feasibility study (PFS), including indicated and/or measured resources. Such studies have a lesser accuracy than a feasibility study, which generally is to be undertaken afterwards, if the extra effort and cost are justified. Projects with a completed SS, PEA or PFS are further away from actual projects and may never make it to a full feasibility study (FS) and, from there, to production. However, some of the projects of table 9 with attractive preliminary economic estimates could well start producing by the end of the current decade, adding to the above potential 2030 Li production estimate.

- Possible additional or new production from companies that do not report on their activities, such as many non-listed companies or companies from China, the world's third largest Li- producing country, and an important investor in Li projects in Africa and Latin America.

Numerous junior companies are currently engaged in lithium-related mineral exploration. TMX Group, the operator of the Toronto Stock Market publishes a regularly updated list of companies listed on the Toronto Stock Exchange (TSX sector for senior issuing companies and TSX-V sector for junior companies looking for growth capital), indicating which minerals and metals are the business object of listed companies belonging to the mining sector (Toronto Stock Exchange and TSX Venture Exchange 2022). TMX Group states that 43% of the world's listed companies are listed on the Toronto Stock Exchange.

In March 2020, 5 mining companies active in lithium exploration and project development were listed on the TSX sector, and 61 companies on the TSX-V sector. Out of these 66 listed companies, 33 were pure lithium players, with a market capitalization varying from about 6 bn $US to about 2 M $US, reflecting very diverse activities, from production to early-stage exploration and a great diversity of development projects from an economic attractiveness perspective. SP Global, one of the leading global commercial minerals and metals industry related data and information providers, estimates that in 2021 (S&P Global 2021a) 111 companies had lithium exploration activities, with a total budget of 249 M$, a 2% share of 11.2 bn $US estimated 2021 global exploration budget (S&P Global 2021b). Even if lithium exploration appears as a small component of the global exploration activities, it is developing fast, from nearly zero a decade ago. Tables 7, 8 and 9 provide an overview of the successes of the very dynamic lithium exploration activities of the last decade. However, past developments are no indication of future trends, and many companies could go from boom to bust if the global economic outlook seriously deteriorates.

Geographically, Argentina, Australia and Chile are attracting most of the current documented exploration activities.

The above supply scenario rests on the very optimistic assumption that all projects that have demonstrated their economic feasibility will effectively be turned into producing operations by 2030.

Table 8: Li projects documented by a feasibility study, but not yet at the construction stage on April 30, 2020.

										Initial capital required		Hard-rock deposits – Indicated and measured resources			Brine deposits – Indicated and measured resources			Hard-rock deposits – Probable and proven reserves			Brine deposits – Probable and proven reserves		
Country	Macro-region	Deposit name	Operator	Deposit type	Reporting standard applied	Feasability study available?	Anticipated production start	Foreseen production at full capacity	Li equivalent production	Initial CAPEX in M$ US	CAPEX estimate year	Ore tonnage, kt	Ore grade, % Li	kt Li contained	Brine volume (km3)	Brine grade (mg/L)	kt Li contained	Ore tonnage, kt	Ore grade (reserves), % Li	Reserves, in kt Li	Brine volume (km3)	Brine grade (mg Li/L)	Reserves, in kt Li
ARGENTINA	Latin America	Pastos Grandes	Lithium Americas	Brine (salt lake)	NI 43-101	Yes		24 000 t/yr Li carbonate	4.5	448	2019				1.8	427	774				0.73	439	177
ARGENTINA	Latin America	Tres Quebradas (3Q) Lithium Project	Neo Lithium Corp	Brine (salt lake)	NI 43-101	Yes		20 000 t/yr Li carbonate	3.8	371	2021				1.58	637	1,009				0.41	786	314
AUSTRALIA	Oceania	Kathleen Valley	Liontown Resources	Pegmatite LCT	JORC	Yes	2024 Q2	658 kt/yr spodumene concentrate	18.3	356	2021	131,000	0.6%	839				68,500	0.62%	426			
CANADA	North America	James Bay	Allkem	Pegmatite	NI 43-101	Yes	2023	321 000 t/yr Spodumene concentrate	8.9	299	2021	40,330	0.6%	262				37,207	0.60%	224	Not relevant		224
CHILE	Latin America	Maricunga	Minera Salar Blanco (Lithium Power International + Bearing Lithium)	Brine (salt lake)	NI 43-101	Yes		15 200 t/yr Li carbonate	2.9	626	2021				0.378	953	358				0.125	1117	81
D. R. CONGO	Africa	Manono/Kitotolo	AVZ Minerals	Pegmatite	JORC	Yes	2023	700 000 t/yr spodumene concentrate + 46 000 t/ yr Li	25.3	546	2019	269,000	0.8%	2,059				131,700	0.76%	996			
FINLAND	Europe	Syväjärvi, Rapasaari, Länttä, Emmes, Outovesi	Keliber	Pegmatita	JORC	Yes		15 000/yr Li hydroxyde	2.5	475	2021	13,690	0.5%	67				12,302	0.44%	54			
GERMANY	Europe	Zinnwald	Zinnwald Lithium PLC (	Greisen/ Aplite, Zinnwaldite (Li mica) deposit	NI 43-101	Yes		5112 t/yr Li fluoride	1.4	159	2020	35,510	0.4%	125				31,203	0.30%	94			
MALI	Africa	Bougouni	Kodal Minerals	Pegmatite	JORC	Yes		220,000 t/yr spodumene concentrate	6.1	117	2020	11,500	0.5%	61				N/A	N/A				
MALI	Africa	Goulamina	Firefinch	Pegmatite	JORC	Yes		726.000 t/yr spodumene concentrate	20.2	275	2021	64,600	0.7%	447				52,000	0.70%	364			
USA	North America	Carolina/ Piedmont	Piedmont Lithium Ltd.	Pegmatite	JORC	Yes		30 000 t/yr Li hydroxyde	5.0	988	2021	28,220	0.5%	145				18,260	0.51%	93			
USA	North America	Rhyolite Ridge	IONEER	Volcanosediment Searlesite (boron silicate)	JORC	Yes	2H 2024	22 340 t/yr Li carbonate (years 1 to 3), then 21 951 t/yr Li hydroxide (year 4 onwards)	3.6	785	2020	127,000	0.2%	203				60,000	0.18%	108			
ZIMBABWE	Africa	Arcadia	Huayou/ Prospect Resources Ltd. JV.	Pegmatite LCT	JORC	Yes		147 000 t/y spodumene concentrate + petalite + tantalite	4.1	192	2021	61,400	0.5%	306				42,300	0.55%	234			
				Totals >>>					106.6	5,636.4				4,515.0			2,141.0			2,592.9			796.4

Data sources: company reports and presentations. Tonnage data is in tonnes.

Table 9: Li projects documented by a scoping study, or a preliminary economic assessment, or a pre-feasibility study.

							Hard-rock deposits			Brine deposits			Hard-rock deposits			Brine deposits		
							Indicated and measured resources			Indicated and measured resources			Probable and proven reserves			Probable and proven reserves		
Country	Macro-region	Deposit name	Operator	Deposit type	Available NI 43-101 or JORC report(s)	Reporting standard applied	Ore tonnage, kt	Ore grade, % Li	kt Li contained	Brine volume (km3)	Brine grade (mg/L)	kt Li contained	Ore tonnage, kt	Ore grade, % Li	Reserves, in kt Li	Brine volume (km3)	Brine grade (mg Li/L)	Reserves, in kt Li
CANADA	North America	Separation Rapids	Avalon Advanced Materials	Pegmatite LCT (petalite, lepidolite)	PEA Updated PEA	NI43-101	8,410	0.65%	55						37			
CANADA	North America	PAK + SPARK	Frontier Lithium Inc.	Pegmatite	PEA	NI43-101	10,491	0.62%	65									
CANADA	North America	Georgia Lake	Rock Tech Lithium Inc.	Pegmatite	PEA	NI43-101	6,620	0.47%	31									
GERMANY	Europe EU-27	Insheim, Upper Rhine Graben	Vulcan Energy Resources	Geothermal brine	PFS	JORC					181	544					181	211
GHANA	Africa	Ewoyaa	Atlantic Lithium (previously: IronRidge Resources Ltd.)	Pegmatite	Scoping Study	JORC	5,200	0.64%	34									
PERU	Latin America	Falchani + Ocacasa	American Lithium (previously: Plateau Uranium)	Acidic volcanic pyroclastic rocks	PEA	NI 43-101	60,920	0.29%	180									
PORTUGAL	Europe EU-27	Mina do Barroso	Savannah Resources Plc	Pegmatite	Scoping Study	JORC	15,200	0.46%	73									
SPAIN	Europe EU-27	San Jose	Infinity Lithium Corporation Ltd.	Zinnwaldite mica replacement deposit	Scoping Study	JORC	36,800	0.35%	129									
USA	North America	McDermitt	Jindalee Resources Limited	Li-bearing sediments	Scoping Study	JORC	233,000	0.14%	333									
USA	North America	Zeus	Noram Lithium Corp.	Li-bearing sediments	PEA	NI43-101	363,150	0.09%	335									
USA	North America	Thacker Pass/ Lithium Nevada King's Valley	Lithium Americas (previously Western Lithium)	Clay (Hectorite)	Pre-Feasibility	NI43-101	385,260	0.29%	1,124				179,422	0.33%	589			
USA	North America	Clayton Valley	Cypress Development Corp	Li-bearing sediments	PFS	NI 43-101	1,304,200	0.09%	1,180				213,000	0.11%	240			
USA	North America	Smackover	Standard Lithium Ltd. + LANXESS JV	Brine	PEA	NI43-101			591			591						
								Totals >>>	4,130			1,135			866	-		211

These projects are less advanced than the projects listed in Tables 7 and 8.

Data sources: company reports and presentations assessed up to April 30, 2022. Tonnage data is in tonnes.

CHAPTER 4

SUSTAINABILITY CONSIDERATIONS

4.1 INTRODUCTION

This section discusses the sustainability of the extraction of the two economically most important lithium resources, as of 2022, representing 74% of the world resources stated in Table 2:

- Li bearing salt lake brines;
- Spodumene from spodumene-rich pegmatites;

and of their processing into either Li-carbonate or Li-hydroxide, the two key chemicals used for Li battery manufacturing, as well as some other uses (fig. 9). According to COCHILCO (2021) these two Li-chemicals represent 95% of the total 2020 world Li demand.

The expression "resource" is used rather than "mineral", as a large share of the resource is not a mineral, but lithium chloride dissolved in a brine.

As all minerals and metals production processes, lithium related production activities require chemicals, energy and water inputs, and generate solid waste, liquid emissions as well as greenhouse gas (GHG) emissions. Lithium production also demands land and may impact on biodiversity.

The inputs required for lithium chemicals production are very variable as they depend on:

- the physical and chemical nature of the lithium resources exploited. Brines, in particular have very variable contents of B, K, Mg, Na and sometimes Br, which require to adapt the processing route used for brine processing;
- the process used to produce a given Li chemical from a given resource;
- local environmental conditions such as, for instance desert environments with no or very limited surface water flows, a common condition in regions with salt lakes, which can only form when water evaporation rates exceed water inflows. The lithium production in Argentina, Australia and Chile, which represents 85% of world production (Table 3), is taking place in regions with no, or extremely limited, surface water run-off in permanent streams and rivers. Several major developing projects are also located in these regions.

Impacts as well are highly variable and site-specific. For instance, locally, the impacts of water use will depend on factors such as:

- water resource replenishment from rainfall (surface water) or recharge (groundwater systems);
- impacts on surface water sources fed by groundwater systems further to intense groundwater (be it freshwater and/or brine pumping);
- impacts on the groundwater system, for instance on porosity and transmissivity, of the pumping of large amounts of water;
- competing water uses.

So far, the public data available from scientific literature and company reports, such as feasibility studies or sustainability reports, is too limited, from both quantitative and qualitative perspectives.

In addition, the above noted inherent variability related to individual projects is too high to provide a robust basis for the assessment of the sustainability of some individual projects and of the various Li-chemicals production processes.

Therefore, the data shown in this chapter must be considered as indicative. Much further effort from companies and from regulatory authorities is needed to provide a reliable analytical framework to better document potential sustainability issues related to the production of lithium chemicals. The downstream industry, such as the automotive industry, consumers and NGOs have an important role to play to see improvements in the public data and information needed to fully document the environmental dimensions of Li production and use.

The purpose of this chapter is not to evaluate the sustainability pros and cons of individual lithium projects, and/or production processes. It rather aims to provide an overview of potential issues that require the attention of all lithium industry stakeholders, especially industrial end-users such as battery and car manufacturers, public authorities at different geographic levels (local, regional, national and international), and end-users of lithium-derived products.

Documenting these aspects requires due diligence from both companies and regulatory authorities, not later than at the stage of a project's feasibility report preparation, and as part of the environmental permitting procedure. These sustainability aspects should be fully assessed and documented in compulsory public reports, as a major step towards a much-needed development of trust among all the stakeholders of Li-dependent supply chains. Trust is critical for any minerals and metals production project to obtain its Sustainable Development Licence to Operate (SDLO), as defined by IRP (2021). In its latest annual assessment of risk perception by the global minerals and metals industry, EY (2021) rates social and environmental issues as the main risk factor.

While there is abundant literature on lithium-related Life-Cycle Analysis (LCA), there is much inconsistency in the boundaries and in the quality/ level of detail of the Life-Cycle Inventories (LCI) that serve as their basis. In their review of 79 LCAs on Li-batteries and of 34 LCAs on electric mobility, Peters et al. (2017) noted the heterogeneity of the LCAs they reviewed, and the difficulty of comparing their results. While it is of utmost importance, from a sustainability perspective, to document the inputs, outputs and impacts related to primary production (including the extraction process from a given geological resource) of lithium chemicals, many Li-LCAs only rely on secondary data and information sources such as pre-existing LCA studies, models and publications (Jiang et al., 2020).

It also appears that these LCAs are much focused on determining the energy used for the production of Li-batteries, while water use and potential biodiversity- or waste-related issues are not, or are insufficiently, covered, although they are of high importance to local populations living nearby Li-production sites. Water and/or waste-related issues in particular can evolve towards conflicts between the impacted populations and producers.

Crenna et al. (2021) stress the difficulties and uncertainties in the evaluation of the environmental impacts of Li-batteries production. The authors note that available studies "differ up to three orders of magnitude in the assessment of the energy demand in the various production steps".

Recent research by the US Argonne National Laboratory (Kelly et al. 2021), working with SQM and with access to industry data related to Li-carbonate and Li-hydroxide production from the Atacama salt lake brine in Chile and from spodumene-bearing pegmatites in Australia, provides a detailed analysis of related energy and water requirements, used in the preparation of this report, including Tables 10 and 11 in this chapter.

4.2 POTENTIAL LITHIUM SCARCITY / DEPLETION

As discussed in section 4.1.2 there are no tangible signs of depletion or scarcity of geological resources of lithium. Supply/demand imbalances may however result from delays in expanding the production of existing production sites and/or launching the production of new sites.

There are many uncertainties regarding future lithium production, and its capacity to meet the booming global energy transition demand. Several interrelated factors will play an essential role in determining the future demand/supply balance:

- Investment into the capital expenditure needed to expand lithium chemicals production;
- The capacity of the industry and of the regulatory authorities to transparently and efficiently manage the lithium industry sustainability issues;
- Social acceptance of individual lithium production projects.

4.3 LITHIUM CARBONATE AND HYDROXIDE PRODUCTION PROCESSES

Lithium production processes are described in detail by Tran and Luong (2015) and Kelly et al. (2021). Anush Dietz (2021) provides additional information on the production of lithium chemicals from the Atacama salt lake brine (fig.13), the world largest salt lake brine deposit in production. Feasibility studies made public by companies developing lithium extraction projects are also very valuable data and information sources.

Figure 13: Lithium-bearing brine pumping wellfields (indicated as number 1 in fig. 14) and brine evaporation ponds at the Salar de Atacama, Chile. This group of ponds covers an area of over 30 km.

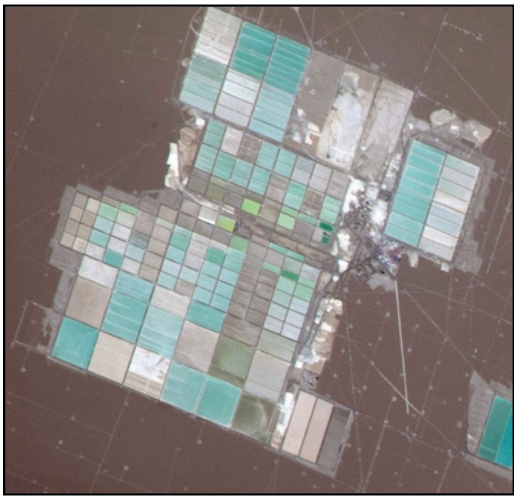


Image source : NASA via Wikimedia Commons (Public domain image).

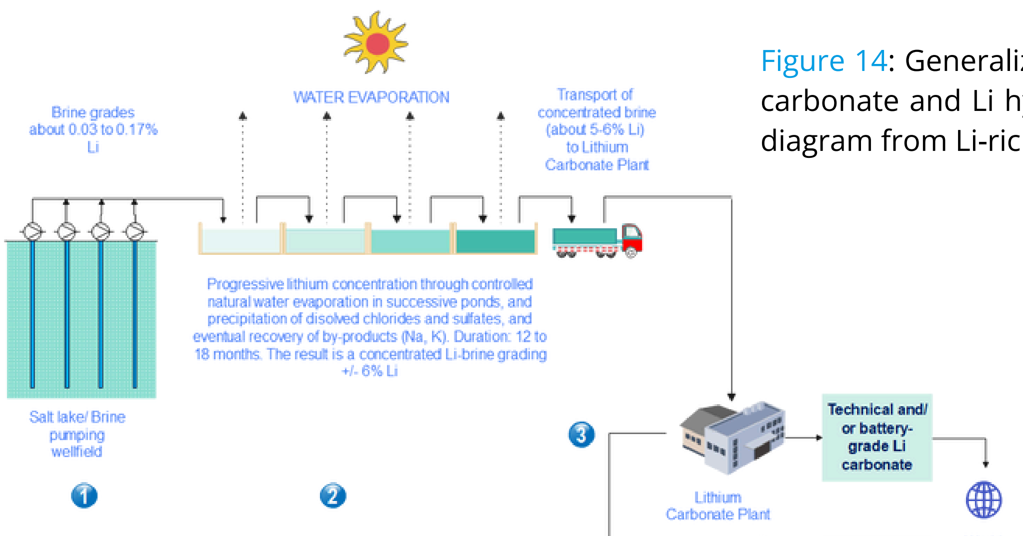
4.3.1 Production from salt lake brines

The production process comprises three main stages (shown by the numbers 1 to 3 in fig. 14):

- The pumping of interstitial brine. This is done by means of a wellfield drilled in the salt (Na Cl, halite) core of the salt lake, where natural evaporation over thousands, in some cases even over a million years, of brines rich in alkaline metals, especially K, Li, Mg and Na will have led to the saturation in sodium chloride (table salt) and its crystallization as a core, or nucleus, with residual brine enriched in Li, Mg and Na. The wellfield is schematically represented in position 1, fig. 14. From there the pumped brine goes, via pipes, to the first stage evaporation ponds;

- The staged evaporation of the pumped brine in successive shallow evaporation ponds (fig. 13 and position 2 in fig. 14). The controlled and staged evaporation of the brine, thanks to the intense sunshine, and windy, arid conditions, leads to the saturation and successive crystallization of its dissolved chlorides (and in, some locations, sulphates). In the first pond, halite (NaCl) and, if present, gypsum are precipitated. The residual brine is then transferred to the second pond where sylvinite, a mixture of sodium and potassium chloride, precipitates. The third pond is for the precipitation of bischofite [$MgCl_2.6(H_2O)$], a magnesium chloride. Finally, the last pond concentrates Li-carnallite [$LiCl.MgCl_2.7H_2O$] in solution, which is recovered once the grade is about 5 to 6% Li;

- The concentrate is then transferred to a Li-carbonate plant where boron as well as residual magnesium and calcium are precipitated and removed. Sodium carbonate is added to the filtered residual brine to generate a lithium carbonate precipitate, which is filtered and washed with warm de-mineralized water. After drying, the lithium carbonate, of over 99% purity, is packed and marketed. The lithium carbonate obtained can also be further processed to produce lithium hydroxide by reacting it with lime [$Ca(OH)_2$].



A parallel evaporation process, not represented in the diagram, exists in several operations to recover potash (KCl) as a co-product.

Figure 14: Generalized and simplified Li carbonate and Li hydroxide production diagram from Li-rich salt lake brines.

The concentration by natural evaporation from salt lake brines requires 12-18 months, making it impossible for producers to swiftly adjust their production according to rapid changes in demand.

4.3.2 Production from spodumene-bearing pegmatites

In this case too, the production process comprises several phases (Tran and Luong 2015; Abdullah 2019; Kelly et al. 2021), represented by the numbers 1 to 4 in fig. 15:

- Spodumene-bearing pegmatites are vein- or lens-shaped bodies, that are mined most frequently using conventional open-pit methods, involving drilling, blasting, loading and hauling of the ore to a nearby spodumene concentration plant (Phase 1 in fig. 15). Based on the data of tables 5 to 7, the average Li grade in spodumene pegmatites is about 0.6% Li, equivalent to 1.3% Li_2O. As no data on the energy requirements of this stage could be found in the literature examined, including in the feasibility studies of the projects reported in Tables 7 to 9, a proxy value is used in Table 12, based on the assessment by the US Department of Energy (2007) of the average energy used for mining 1 ton of metallic ore in the US;

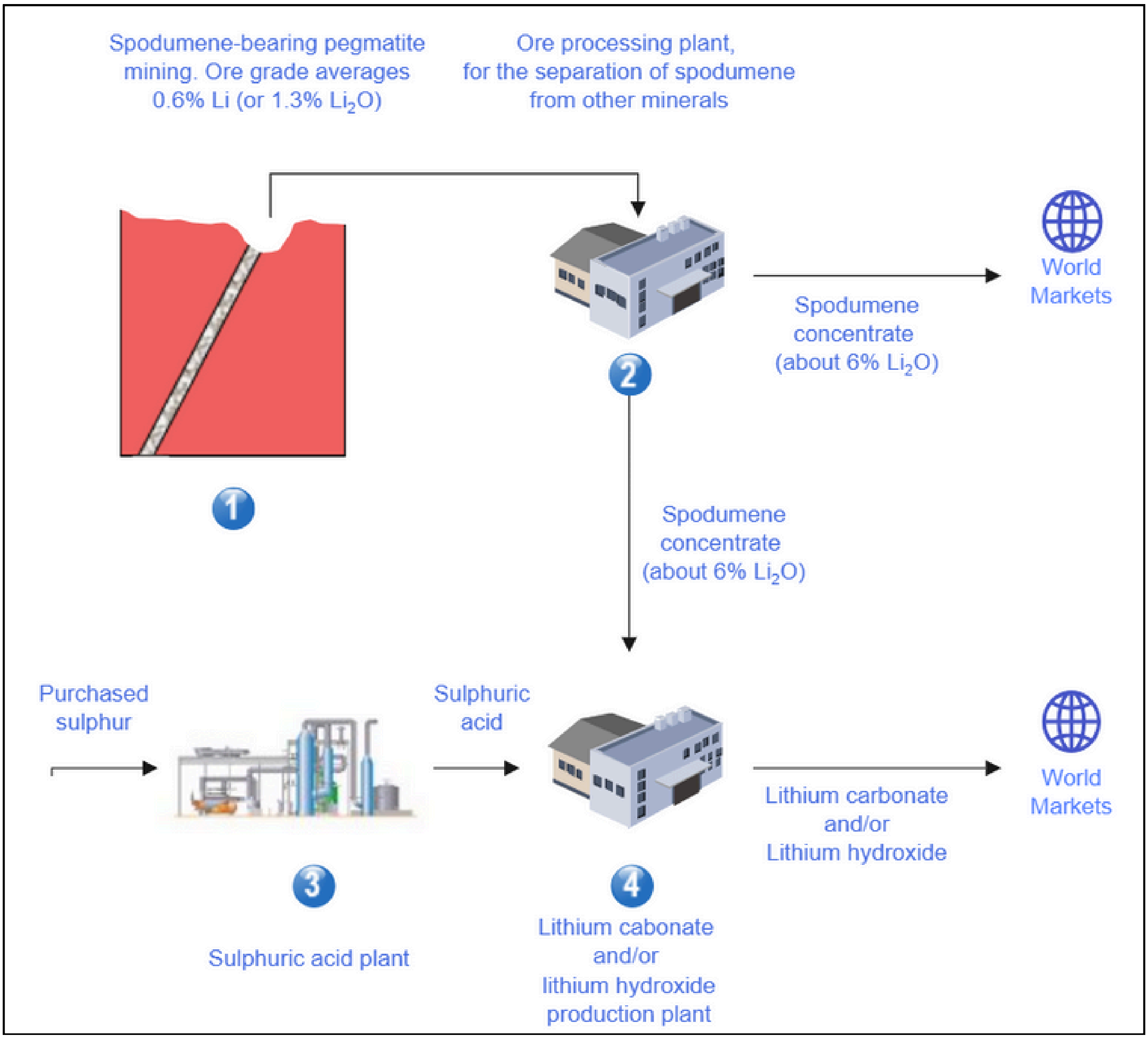
- The bulk spodumene ore is then transported to a spodumene concentration facility (Phase 2 in fig. 15), located near the mine, where the ore is crushed and ground to a grain size liberating the spodumene grains. Combinations of gravity, magnetic and dense-media separation techniques are used, depending on the exact nature of the ore to be processed, to produce a spodumene concentrate containing about 6% Li_2O. This concentrate is then either sold to companies that have their own Li-carbonate and/or hydroxide facilities or sent to the spodumene producer's own facility. In the case of sale to an external company, spodumene concentrates can be economically transported by bulk-freighting ships over thousands of kilometres, mostly from Australia to China (as is case for the energy and water demand estimates by Kelly and al. (2021), tables 12 and 13);

- The current conventional production process of Li-carbonate and/or hydroxide (Phase 4 in fig. 15) involves roasting of the spodumene concentrate at about 1 000-1 090° C, to convert the naturally occurring α-spodumene into β-spodumene, through crystalline phase transformation, and to make it amenable to sulphuric acid leaching. Fosu et al. (2021) suggest a 1 000° C thermal treatment for 60 minutes to optimally achieve the necessary phase conversion;

- Lithium sulphate can then be produced from β-spodumene by sulphuric acid leaching at 250° C (Phases 3 and 4 in fig. 15), sulphuric acid being either purchased from an external provider or produced onsite, from purchased sulphur, via a sulphuric acid production plant. The sulphuric production process, being exothermic, also generates part of the heat needed in the overall Li-carbonate and/or hydroxide production process. Either lithium carbonate or hydroxide can then be produced from the Li sulphate solution.

A detailed review of spodumene conversion technologies and possible ways forward to achieve the necessary spodumene phase conversion is provided by Abdullah (2019).

Figure 15: Generalized and simplified Li carbonate and Li hydroxide production diagram from spodumene-bearing pegmatites.



Source for the sulphuric acid plant representation: Valmet (Finland), with permission.

Research is ongoing to reduce the complexity and energy-intensity of Li carbonate and/or hydroxide production from spodumene, with several important goals:

- To reduce the current high temperature needed for spodumene conversion;
- To eliminate the need for suphfuric acid leaching;
- To reduce production costs, the energy use and the GHG emissions related to the conventional production process depicted above.

4.4 Energy use, GHG emissions and water use related to Li-chemicals production needed for the energy transition

4.4.1 Energy use

Energy requirements for the extraction of Li-resources and their transformation in either Li-carbonate or Li-hydroxyde are very variable, as they depend on multiple factors:

- The diverse nature of the Li resources used for the production of these Li-chemicals (see Section 3.1);
- The various processes used for the production of Li-carbonate or Li-hydroxide (see Section 5.2). In addition, local conditions also have an impact on energy demand, for instance, to pump and transport the groundwater needed for the production operations.

Energy use comparison between individual projects, especially when by-products are present and recovered, is difficult due to different boundaries and input allocations chosen by different authors for their life-cycle analysis, and/or different ways to allocate energy inputs, for instance on a mass or a value basis.

Kelly et al. (2021) provide a detailed comparison of energy use for the production of Li-carbonate and Li-hydroxide from the Atacama (Chile) salt lake brine and from Australian spodumene-bearing pegmatites. The data used for the energy and water/brine use is product-level mass-related data, as it relates to the production of 1 ton Li-carbonate and, separately, 1 ton Li-hydroxide. As lithium chemicals and potash are both produced from the Salar de Atacama brine as co-products, Kelly et al. treated their respective process routes as separate entities with energy, water an other inputs being attributed to each of the stated end-products.

As compared to the generic process description provided in section 5.2.1. and fig. 14, the following data is specific to the Li-carbonate and to the Li-hydroxide production from the Salar de Atacama brine, with the following key parameters:

- Average Li-grade of the brine (Kelly et al. 2021): 0.17% Li;
- Average brine density (derived from CORFO 2016): 1.225;
- Geochemical characteristics of the brine of importance at the concentrated brine purification stage, necessary to remove boron, magnesium and potassium impurities (part of stage 3, fig. 14): 0.04-0.07% B, 0.93-1.30% Mg and 1.8-3.1% K (Garrett 2004);
- Li grade of the concentrated brine sent to the Li-carbonate plant: 6% Li (Garrett 2004; Kelly et al. 2021);
- 4 t concentrated brine at 6% Li (about 3.3 m3) are needed to produce 1 ton Li carbonate (Kelly et al. 2021);
- 1.05 ton of Li carbonate is needed to produce 1 ton of Li hydroxide (Kelly et al. 2021).

The Atacama salt lake brine has the best, so far known, Li content of salt lake brines and a relatively low content in B and Mg impurities. This reduces the energy and water requirements for the concentrated Li brine processing, making it a very favorable case for Li chemicals production from salt lake brines.

Table 10 provides data, taken from Kelly et al. (2021), detailing the average energy requirement for:

- the production of one ton Li-carbonate and one ton Li-hydroxide from the Salar de Atacama (Chile) salt lake brine ll (Stages 1 through 3 (Li-carbonate), or 4 (Li-hydroxide), and
- the production of the Li-carbonate or the Li-hydroxide from the concentrated salt lake brine.

Table 10: Energy requirements for the production of 1 ton Li-carbonate or of 1 ton of Li hydroxide from the SQM Atacama salt lake brine (Chile).

Energy requirements for the production of Li-carbonate or of Li hydroxide from the SQM Atacama salt lake brine (Chile).				
	Amount	Unit	Data source	Notes
Brine pumping and production of concentrated brine (Stages 1 and 2 of the simplified process diagram of fig. 14)				
Concentrated Li brine production from pumped raw brine (6% Li) (Stages 1 + 2 in fig. 14)	970	MJ per tonne	Kelly et al. (2021)	624 MJ electricity (64%)+ 346 MJ diesel (36%)
Production of Li-carbonate from concentrated brine (Stage 3 of the simplified process diagram of fig. 14)				
Production of 1 tonne Li carbonate from concentrated Li brine (6% Li) (Stage 3 in fig. 14)	4700	MJ per tonne	Kelly et al. (2021)	1500 MJ electricity (32%)+ 400 MJ diesel (9%) + 2800 MJ Natural gas (59%)
Production of 1 tonne Li carbonate: total energy requirement , considering the use of 4 t concentrated Li brine for the production of 1 t Li carbonate (Stages 1 through 3 in fig. 14).	8580	MJ per tonne	Kelly et al. (2021)	
-of which from electricity	3996	MJ per tonne	Kelly et al. (2021)	
-of which from diesel	1784	MJ per tonne	Kelly et al. (2021)	
-of which from natural gas	2800	MJ per tonne	Kelly et al. (2021)	
Production of Li-hydroxide from Li-carbonate (Stage 4 of the simplified process diagram of fig. 14)				
Production of 1 tonne Li hydroxide: energy embedded in 1.05 tonne Li carbonate used	9009	MJ per tonne		
Production of 1 tonne Li hydroxide: total energy used	29000	MJ per tonne		
-of which from electricity	5000	MJ per tonne	Kelly et al. (2021)	
-of which from diesel	3000	MJ per tonne	Kelly et al. (2021)	
-of which from natural gas	21000	MJ per tonne	Kelly et al. (2021)	
Production of 1 tonne Li hydroxide: total energy requirement	**38009**	**MJ per tonne**		

Table 11 provides an estimate of the average energy requirement for the production of one ton Li-carbonate and one ton Li-hydroxide from an Australian spodumene-bearing pegmatite, further to the process stages outlined in fig. 15:

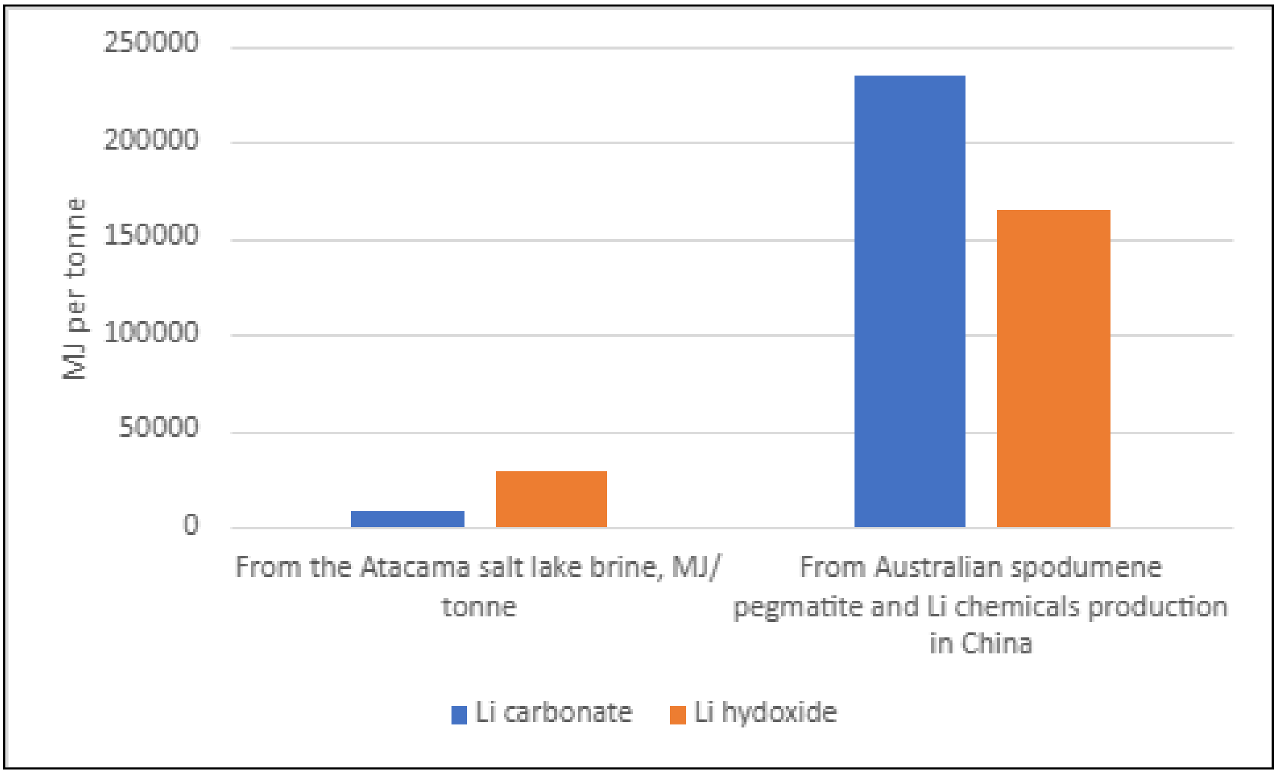
- Mining of an Australia spodumene-bearing pegmatite (Stage 1);
- Production of a spodumene concentrate grading about 6% Li_2O (equivalent to about 2.8% Li), at a concentration plant located near the mining site (Stage 2);
- Seaborne transport to China;
- Processing in an unspecified Chinese plant of the imported spodumene concentrate for the production of Li-carbonate or the Li-hydroxide (Stages 3 and 4).

Table 11: Energy requirements for the production of Li-carbonate or of Li hydroxide from an Australian spodumene pegmatite, with Li-carbonate and hydroxyde production taking place in China.

Energy requirements for the production of Li-carbonate or of Li hydroxide from an Australian spodumene pegmatite, with Li-carbonate and hydroxyde production taking place in China.				
	Energy required	Unit	Data source	Notes
Production of a spodumene concentrate @ 6% Li2O				
Spodumene ore extraction (mining) Stage 1 in fig. 15) for the production of 1 tonne Li concentrate @ 6% Li2O.	1,791	MJ per tonne	US Dept. Of Energy	Proxy value (average MJ per tonne metal ore extracted in the U.S.), used in absence of reference data for spodumene-pegmatite mining. Kelly et al. (2021) state that 4.5 tonnes spodumene ore are needed to produce 1 tonne Li concentrate.
Production of 1 tonne spodumene concentrate @ 6% Li2O from 4.5 tonnes spodumene ore (Stage 2 in fig. 15)	4,500	MJ per tonne	Kelly et al. (2021)	100% from Diesel
Production of Li-carbonate in China, from spodumene concentrate imported from Australia (Stage 3 of the simplified process diagram of fig. 15)				
Production of 1 tonne Li carbonate (Stages 3 and 4 in fig. 15)	142,370	MJ per tonne	Kelly et al. (2021)	6 480 MJ electricity (5%)+ 135 890MJ coal (95%)
Production of 1 tonne Li carbonate: total energy requirement, including the energy needed to produce 7.3 tonnes spodumene concentrate (6% Li2O) for this production stage. (Stages 1 through 4 in fig. 15)	234,054	MJ per tonne		
Production of Li-hydroxide in China, from spodumene concentrate imported from Australia (Stage 3 of the simplified process diagram of				
Production of 1 tonne Li hydroxide from imported spodumene concentrate (Stages 3 and 4 in fig. 15)	83,943	MJ per tonne	Kelly et al. (2021)	12 600 MJ electricity (5%)+ 71 343 MJ coal (95%)
Production of 1 tonne Li hydroxide: total energy requirement, including the energy needed to produce 6.42 tonnes spodumene concentrate (Stages 1 through 4 in fig. 15)	164,575	MJ per tonne		

Fig. 16, summarizing the data in Tables 10 and 11, shows the total energy (in MJ) required to produce 1 ton Li carbonate or hydroxide from either the Atacama salt lake brine or an Australian spodumene-bearing pegmatite.

Figure 16: Energy required (in MJ) for the production of one ton of Li carbonate or hydroxide.



It shows that the production of the two main lithium chemicals from a spodumene-bearing pegmatite in Australia, demands up to 25 times more energy than from the Chilean Atacama salt sake brine. This is essentially related to the comminution of the ore (crushing and grinding prior to the physical separation of spodumene from its silica (quartz) matrix), and to the high-temperature conversion process of the naturally occurring α-spodumene into β-spodumene, only the latter being suitable to the sulphuric acid leaching needed to extract lithium from spodumene, for further processing in either Li carbonate or hydroxide.

Lithium carbonate production from spodumene-bearing pegmatites requires nearly as much energy as the production of raw steel from iron ore, via the conventional Basic Oxygen Furnace (BOF) route, stated as averaging 24 500 MJ / ton steel (Martelaro N. 2016). Nevertheless, due to the very small tonnages produced when compared to the world raw steel production, the lithium industry only has a limited energy footprint.

According to Kelly et al. (2021, Supplementary Information), the energy needed for the production of Li carbonate or hydroxide represents only a few percent of the total energy needed to produce a Li-battery with an NMC 622 or 811 cathode. Even in the most energy-intensive case (Li carbonate production from a spodumene-bearing pegmatite), the production of Li chemicals represents only about 10% of the total energy used for the production of Li batteries with NMC 622 or NMC 811 cathodes (Kelly et al. 2021, Supplementary Information, fig. S20).

4.4.2 Water-related issues

Water is an essential input for the production of Li carbonate and Li hydroxide, the two key Li chemicals used for Li-battery manufacturing. However, few scientific papers quantify the water requirements of specific production processes of Li-chemicals, comparing key production processes and discussing potential impacts on other local and regional water uses. In their review of the environmental impacts of Li-ion battery manufacturing, Peter et al. (2017) reviewed 79 studies assessing the environmental impacts of Li-battery manufacturing. While much attention is given to energy use, water use is not mentioned in this review, which further underlines the scarcity of detailed Li-carbonate and hydroxide production-related data.

The main data source available on water use for lithium chemicals production is Kelly et al. (2021), who as for energy, provide data on water use for the production of Li-carbonate and Li-hydroxyde from the Atacama (Chile) salt lake brine and from Australian spodumene-bearing pegmatites.

The distinction made between brine and freshwater requirements is because Li-rich salt-lake brines have a very high salinity, with total contents of sodium + potassium + magnesium that can be in excess of 10% of the water mass (Garrett 2004), whereas the total salinity of seawater is about 3.5% (Anderson and Martin 2022). This makes them unsuitable for human consumption or agriculture. In addition, the high potassium content of the brines would make them toxic to humans. From a sustainability perspective it is of importance to understand if brine extraction has, or not, an impact on freshwater resources, or if brine and freshwater are two independent systems.

Table 12, provides data on the average freshwater and brine requirements for the production of Li-carbonate and of Li-hydroxide.

Table 12: Water requirements for the production of 1 ton of Li-carbonate or of 1 ton Li hydroxide from the SQM Atacama salt lake brine (Chile).

Water requirements for the production of 1 tonne of Li-carbonate or of 1 tonne Li hydroxide from the SQM Salar d Atacama deposit				
	Amount	Unit	Data source	Notes
Brine pumping and production of concentrated brine (Stages 1 and 2 of the simplified process diagram of fig. 14)				
Brine density	1.23	tonne/m3	Garrett (2004)	
Raw brine used for the production of 1m3 of concentrated Li brine ((6% Li) from pumped raw brine (Stages 1 + 2 in fig. 14)	19.64	m3	Kelly et al. (2021)	
Fresh water used for the production of 1m3 of concentrated Li brine (6% Li) from pumped raw brine (Stages 1 + 2 in fig. 14)	3.7	m3	Kelly et al. (2021)	
Production of Li-carbonate from concentrated brine (Stage 3 of the simplified process diagram of fig. 14)				
Raw brine used for the production of 1 tonne Li carbonate, considering the use of 4 t concentrated Li brine for the production of 1 t Li carbonate (Stages 1 through 3 in fig. 14).	78.57	m3	Kelly et al. (2021)	
Fresh water used for the production of 1 tonne Li carbonate, considering the use of 4 t concentrated Li brine for the production of 1 t Li carbonate (Stages 1 through 3 in fig. 14).	14.8	m3	Kelly et al. (2021)	No fresh water use specific to this process stage is reported.
Production of Li-hydroxide from Li-carbonate (Stage 4 of the simplified process diagram of fig. 14)				
Raw brine used for the production of 1 tonne Li carbonate, considering the use of 1.05 t Li carbonate for the production of 1 t Li hydroxyde (Stages 1 through 3 in fig. 14).	82.49	m3	Kelly et al. (2021)	
Fresh water used for the production of 1 tonne Li hydroxide, considering the use of 1.05 t Li (Stages 1 through 3 in fig. 14).	16.04	m3	Kelly et al. (2021)	

Depending on local geological and hydrogeological features, brine use may impact on freshwater resources (groundwater) as brine systems can be interconnected to broader groundwater circulation patterns. These can be complex to document and understand due to the local geological features guiding groundwater circulations and to local meteorological conditions over decades.

Groundwater modelling of the Salar de Atacama in relation to broader regional groundwater flows has attracted important research efforts in recent years, probably making it the most studied lithium-bearing salt lake water system worldwide (Corenthal 2016 a; Corenthal et al. 2016 b; Godfrey et al. 2020; Marazuela 2020a; Marazuela et al. 2020b; Munk et al. 2021; Boutt et al. 2021; Álvarez-Amado et al. 2022; Valdivielso et al. 2022). This much needed knowledge development happened amidst rising concerns, and potential conflict (Gutiérrez et al. 2021; Jerez et al. 2021) between various local stakeholders, about the potential impacts of Li-production from salt lake brines:

- on overall water availability for the populations in the Atacama region, one of the driest places on Earth;
- on biodiversity, in particular on populations of endemic pink flamingo species that depend on open water ponds existing around the Salar de Atacama's salt nucleus.

Thorough 3D, dynamic groundwater modelling should be a regulatory constraint in such regions. It should be performed not later than during the feasibility study stage, to serve as a basis for permitting the use of precisely defined amounts of water. The continuously monitored volume and chemical characteristics of the used water should be publicly reported. Groundwater modelling and monitoring are equally valuable as a basis of dialogue between impacted populations, producers and regulatory authorities.

Dynamic 3-D groundwater modelling or isotopic water geochemistry can be scientifically complex, and their outcomes may be difficult to understand and be accepted by populations with cultural values differing from those of producers or governments. This underlines the need for more joint work between the different strands of science, in order to provide factual, policy-relevant data and knowledge, and to create bridges and linkages among the different stakeholders concerned with lithium production and use. This is of major importance to the future of the lithium industry and the role it has in support of the global energy transition.

4.4.3 Biodiversity issues

Like other minerals and metals production activities, the production of lithium chemicals can exert pressures and negatively impact on biodiversity, either directly through open-pit mining activities, or indirectly via the connections between groundwater and surface water systems on one hand and biodiversity, on the other.

Two different issues require particular attention and collaborative action from stakeholders, as they may be a source of conflicts that could hamper future lithium production:

- The pressure that the exploitation of salt-lake brines may exert on local biodiversity, dependent on freshwater ponds located at the periphery of their salt cores. The most emblematic case concerns the endemic pink flamingo populations that thrive on the freshwater ponds around the Salar de Atacama (Chile) salt core, fueling local tensions between the operators of lithium brine extraction and the local populations (Jerez et al. 2021; Liu and Agusdinata 2019 and 2021; Gutierrez et al. 2022);
- The potential impacts on the local flora and fauna of future large-scale open-pit stripping of lithium-bearing clays. For instance, the anticipated land disturbance of the Thacker Pass lithium clay project, one of the lithium clay and sediments projects listed in tables 7 to 9, would be about 40 km^2 (US Bureau of Land Management 2020), with impacts on flora and fauna. Such large-scale open-cast operations cause concerns among local populations, while lithium-clay mining projects are of major importance to the future availability of lithium for electromobility.

4.5 LITHIUM CHEMICALS TOXICITY

In December 2019, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) stated that three Li chemicals essential for the production of Li batteries, namely Li chloride, carbonate and hydroxide, are hazardous to fertility and foetal development (ANSES 2020), and submitted a proposal to the European Chemicals Agency (ECHA) for their harmonized classification under the EU CLP Regulation (Classification, Labelling and Packaging of products). According to ANSES “lithium salts are to be regarded as having proven toxic effects on human foetal development, which corresponds to Category 1A of the Regulation”.

In June 2022 no European Commission decision had been taken on the inclusion of Li salts in the list of Category 1A of reproductive toxicants, the category of highest concern, but this decision is pending. This classification could have far reaching consequences for the lithium industry and the feasibility of the rapid transition towards electromobility foreseen in energy transition scenarios necessary to meet the Paris Accord objectives.

4.6 SOCIAL ISSUES THAT MAY IMPACT THE FUTURE SUPPLY

Like the production of many other minerals, lithium brine or minerals extraction activities and projects can be impacted by local opposition and become locally politically sensitive, creating uncertainty about future lithium supply.

Social tensions may limit the further expansion of the Salar de Atacama and/or postpone projects as important as Thacker Pass in the US or Jadar, in Serbia (Biesheuvel and Savic 2021), to name some examples.

While there is no panacea to avoid such issues, early dialogue between companies engaged in exploration and the development of new projects, local populations that may be impacted and authorities is the best way to minimize risks. This dialogue should be based on environmental and social baseline and impact studies, of the highest scientific standard, involving the local population, to identify in a transparent manner what the initial conditions are, how a given project may impact on these initial conditions, and how the potential impacts will be monitored, managed and publicly reported.

Investment in trust building among stakeholders may appear costly to some investors, but it can generate significant rewards by avoiding later delays in project development. This dialogue can be particularly challenging where stakeholders belong to different cultural realms with differing world views, calling for specific cross-cultural communication actions and expert support.

4.7 RECYCLING FROM END-OF-LIFE PRODUCTS

In view of the expected Li demand growth (see section 2.2), and of the potential impacts of some of the Li chemicals production, recycling Li from end-of-life batteries appears as a potentially attractive alternative as compared to primary Li production. A detailed, illustrated, introduction to Li-battery recycling is presented by RWTH Aachen University, the German Engineering Federation (VDMA), and the Technical University of Braunschweig (2021). However, compared with the very widespread and successful recycling of lead used as starter batteries for cars with internal combustion engines, Li-battery recycling is way more complex. This is because there is no standard battery format, as the chemistry of a Li-battery is complex and evolving over time, so that the technology inside end-of-life batteries is generally undocumented, and as recycling processes are complex and costly. The complexity and costs partly relate to the hazardous nature of Li-batteries, containing highly reactive, flammable, electrolytes.

Public data on Li production from recycling is very limited. This is due to intellectual property and commercial information protection.

So far operational industrial-scale recycling of Li from end-of-life batteries appears very limited. Most of the existing recycling activities are located in Europe, Japan and the US while Li-battery recycling in China, the world's largest producer and consumer of such batteries, is less developed (Chen et al. 2021). However, this business is expected to develop as more and more Li-batteries will reach their end-of-life, probably only in the 2030-2040 decade.

In the EU, the European Commission (Vidal-Legaz et al. 2021) estimates that the current Li end-of-life recycling rate is 0.4% and the Li end-of-life recycling input rate in new products is 0.1%.

COCHILCO (2021), quoting Roskill (now WoodMckenzie), a leading analyst of global minerals and metals markets, states that in 2020, there were 53 Li-battery recycling facilities worldwide. COCHILCO estimates that, in 2020, 5000 tonnes of lithium carbonate equivalent were produced from recycled lithium batteries. This amounts to only 1.3% of the 2020 amount of lithium chemicals used for battery manufacturing, based on COCHILCO's data. By 2030, the production of secondary Li from batteries recycling could reach 64 kt Lithium carbonate equivalent (LCE), equivalent to 12 kt Li. This would represent 3.6% of the Li demand estimated on the basis of the scenario presented in section 2.2 (fig. 5).

This estimate is very speculative, as the flow of recyclable end-of-life Li batteries over the coming years is almost impossible to estimate as their average useful lifetime in BEVs is still a question mark, with limited real-life statistically significant and documented experience available so far. Moreover, Li-batteries used in BEVs are likely to see their use-phase extended by an unknown number of years, for instance as stationary batteries in support of solar and/or wind-based electricity production systems (Gaines 2010).

Li-battery recycling attracts many research and industrial development efforts (e.g. Jin et al. 2022, Makwarimba et al. 2022; Sommerville et al. 2021) with many important open questions, for instance regarding the energy and water demand per ton of marketable secondary lithium chemical produced, the environmental advantages of specific processes, their operating costs and likely profitability.

Most of the current industrial Li-battery recycling activities are focused on cobalt recovery which has a much higher recycling rate than lithium. In the EU, Vidal-Legaz et al. (2021) estimate that the recycling rate of cobalt from end-of-life products is 32%, while the recycled cobalt input rate in new products is 22%. USGS (2022) estimates that in 2021, in the US, 24% of the cobalt consumption came from scrap recycling.

4.8 SUBSTITUTION

While Li-battery chemistries are continuously evolving, there is a high likelihood that lithium will continue to play a key role in energy storage, at least up to 2040. One of the reasons underpinning this statement is that once investors will have invested the billions of $US to build the gigafactories that will produce the Li-batteries needed by the BEV industry, and other industrial uses of Li batteries, they will not be easily convinced to do another investment in a new technology before having recovered their initial investment and made a profit.

The main technological substitution likely to happen in the current decade is the development of solid-state, or near solid-state lithium metal batteries. These batteries, which are at the near-market development stage by companies such as Quantumscape and SES have in common a Li-metal anode not requiring any graphite and offer several advantages including much faster charging times and higher energy densities than current Li-ion batteries. These new technologies, which attract much interest and support from BEV-makers, could significantly reduce the demand for natural graphite by the end of this decade but they would have little effect on Li demand.

Beyond 2040, non-lithium battery chemistries such as sodium-sulphur, zinc-air batteries, carbon-based supercondensators may earn market shares, but they are too distant potential developments to be considered in this report.

CONCLUSIONS

Governments, international institutions, the manufacturing industry, and investors have a high moral responsibility to ensure that their activities and their choices are aligned with the UN Sustainable Development Goals (SDGs). This implies that lithium production-related activities, from mining to the production of the different Li chemicals needed for downstream industrial products, should be fully, transparently and publicly documented. It should recognize the fundamental role of all minerals and metals stakeholder in the development of transparency and the fundamental right for customers and citizens in general to know the economic, environmental, governance and social conditions under which products and services they use were produced, with what potential impacts, and to choose accordingly.

While progress has been achieved over the last two decades thanks to the reporting obligations set by some national stock market authorities and to the disclosure efforts by some producers, there are still important data and knowledge gaps to be filled in. A presentation by CORFO (2016), to the Chilean Parliament provides a rare insight of transparency issues that were, at that time, related to the Li production from the Salar de Atacama (Chile), the world largest exploited Li-brine resource. CORFO, Chile's State Economic Development Agency, is the owner, on behalf of the State, of the Atacama salt lake brine resource.

Transparently, publicly, sharing data and knowledge among all stakeholders, defined in this IRP report 'Financing the responsible supply of energy transition minerals or Sustainable Development', in an understandable and usable manner, appears essential to build trust among stakeholders to secure the SDLO by addressing looming environmental and social issues.

From a sustainability perspective there is much scope for further improvement of the reporting practices on lithium production projects and actual production activities. There is a need for public data on:

- The nature and the quantity of energy used for the production of one unit of a defined marketed lithium chemical;
- The nature (surface water, groundwater, brine) and quantity of water used for this production, as well as a documented discussion of the long-term impacts this water consumption can have on other human activities, on aquifer functionalities and on overall ecosystem services;
- The nature and quantity of emissions (gas, liquids and solids) generated for this production.

So far, only some development projects and even less production activities are documented with public detailed reports, providing factual information and data on the topics discussed in this section.

Regarding producers, some key producers are nowadays publishing annual sustainability reports, but the data tends to remain aggregated at company level, making it difficult to appreciate the sustainability performance of their individual operations. Moreover, reporting may not equally well cover the different sustainability matters (biodiversity, energy, emissions and wastewater). This situation is not specific to the lithium producing industry.

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