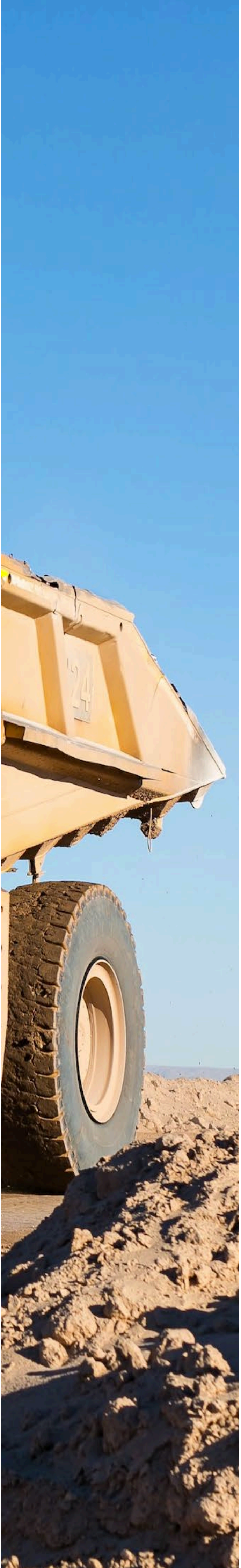
Lithium – Deficits Still on The Horizon But the Pace of New Supply is Picking Up

Lithium Commodity Market Report

August 2023



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Front picture: Olaroz, Jujuy Province, Argentina - Allkem

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Executive Summary

Following on from our recent in-depth sector reports on copper and nickel, this report is our first on the lithium sector.

Our intention with these reports is to present an informed understanding of the current and future dynamics of the industry in focus. Lithium, being one of the faster moving sectors at present with lots of investor interest, has been reasonably well-covered by the research industry but what we have found is a lack of research which gives the reader an in-depth primer on the industry as a whole.

This report aims to provide a detailed analysis of the global lithium commodity market and discuss the potential risks and opportunities associated with lithium supply chain developments. As with our two-part nickel report of late 2022 and early 2023, we will follow up with a second report focusing on lithium explorers, developers, and producers with a focus on recent, current, and expected M&A trends in the industry.

The Lithium Story

Lithium is the newest and certainly one of the faster growing mineral commodity markets seen for many years. Global mine production has increased by over 230% from 2016 to 2022, driven by the increase in demand for lithium-ion batteries used for electric vehicles (EVs). The demand growth is expected to continue with strong forecasts for the next two decades. These have seen constant upward revisions due to improved outlooks for global EV demand and announcements for new battery factories. This is stimulating a rapid rise in activity in the lithium mining industry with the aim of increasing supply to match demand.

Currently, market consensus is forecasting a supply deficit of 784 kt for 2030 (average demand 2.88Mt and supply 2.09 Mt) based on recent publicly available forecasts. This is a large deficit relative to the market size and suggests that higher lithium prices will be necessary to attract new supply or cause some demand destruction.

The story of a lithium supply deficit in the future is attractive to the mining industry. It gives room for new producers to enter the market, driven by the economic returns and potential supernormal profits. There is also interest from banks, investors, governments, and battery and auto manufacturers. Banks and investors are looking for good returns; governments are seeking taxes and royalties, increased employment, and the prospect of downstream industrial benefits; and battery and auto manufacturers are looking to encourage new capacity (through direct finance and forward sales) to satisfy their own lithium demand requirements, as well as hoping to help close the lithium supply gap so that prices remain within acceptable ranges.

This process is now well underway, and **the forecast deficit is stimulating strong growth in new lithium exploration, development, and mine supply.** The supply chain is starting to fill, but still has plenty of scope for longer-term capacity.

Eight new mines are expected to start production this year, with a further 11 under construction expected to start production in 2024 and 2025. Lithium exploration expenditure in 2022 increased by 134% from 2020, and the number of lithium exploration holes drilled has increased by 40 times over the past three years (from 2Q 2020 to 2Q 2023). Already in 2023, seven new Preliminary Economic Assessments (PEA) for lithium projects have been reported, compared with four in the whole of 2022. **A supply deficit is still forecast for 2030, but it continues to shrink,** as it has done over the past three years.

In this report, we have completed our own analysis of lithium supply which suggests that the market deficit in 2030 may now not be as large as currently indicated by consensus. It obviously depends on the ultimate level of demand, but the key difference, we believe, comes from an under estimation by the market of the new supply that could come on stream by 2030. Figure 2 on page 7 shows our risk adjusted lithium supply forecast and the market spread for lithium demand forecast in 2025 and 2030.

Additionally, **we believe that the assumptions on both the supply and demand for lithium continue to evolve rapidly and make forecasting an accurate market balance very difficult, even for 2030**. Both positive and negative factors continue to emerge that could change the market balance significantly and these are reflected in the wide spread of forecasts for 2030.

Risks Impacting Supply Assumptions

In addition to increased capacity from existing lithium operations, we have identified 56 lithium projects from PEA level through to construction. We forecast supply of 2.79 Mt in 2030, based on our risk-adjusted lithium supply forecast from these operations. This means a deficit of just 129 kt using consensus demand.

We have risk adjusted our supply forecasts as it is likely that not every project in the pipeline will make it to production or may not achieve full capacity. However, beyond the normal risks of developing new mines and achieving production targets, a number of additional positive and negative risks surround future lithium supply. **The most significant factors are the introduction of large-scale direct lithium extraction (DLE) technology, resource nationalism, and government and industry financial and structural support.**

Direct Lithium Extraction (DLE)

It is apparent that lithium extraction and recovery from continental, geothermal, and oilfield brines is becoming technically possible. Potential benefits of DLE for salar brine deposits compared with the evaporative processes include a significantly reduced physical footprint, up to 90% lithium recovery compared with 30-50% for conventional evaporation ponds, reduced water consumption, and a shorter expected lead time to production. The use of DLE for geothermal and oilfield brines makes these lithium deposits potentially economic.

Evidence of DLE application for salar brines includes SQM moving to DLE technology at Salar de Atacama in Chile with a US$1.5bn investment; Eramet is constructing an adsorption brine project in Argentina at Centenario; and Rio Tinto having acquired Rincon Mining for US$825m which owns the Rincon adsorption brine project, also in Argentina.

There are also a number of geothermal and oilfield brine projects being developed, including Vulcan Energy's geothermal brine project in the Upper Rhine Valley of Germany where construction is being planned.

The ongoing growth of the lithium supply chain relies on the successful implementation of DLE. Of the 56 lithium development projects in our analysis, 12 are planning to implement DLE. Nevertheless, despite significant progress at these projects, scepticism still remains around the use of DLE for high volume production.

Resource Nationalism

Another risk to lithium supply is resource nationalism. Recent moves include steps by Mexico and Chile to increase state controls on lithium mines and concessions, and Namibia and Zimbabwe which are introducing an unprocessed minerals ban. However, while the steps have been viewed as negative by the industry, they may prove to be positive steps for their domestic lithium industries and lithium supply in the longer term.

The government of Chile stated its intention to honour current lease arrangements and plans to submit a bill this year to establish a national lithium company. The bill will include a strategy to promote downstream investments. Separately, the government plans to present a bill early next year to streamline permitting in a bid to boost sustainable production. In Mexico, the general opinion is that the Decree passed by the government only impacts licenses, concessions, or contracts to be granted, not those already granted.

However, it appears that government intervention is creating problems for AVZ Minerals which is having difficulties progressing its exploration rights for the Manono project in DRC, while the Government of Serbia recently revoked Rio Tinto's licences related to the Jadar project. Unusually, the Canadian government has taken steps to restrict investments by Chinese companies in its lithium mining industry.

On a positive note (for supply), Bolivia, which has previously resisted the development of its lithium resources, has now taken steps to start production. Battery company CATL will invest US$1.4 bn for the development of Bolivia's lithium reserves, including the construction of two lithium plants that will extract lithium from the Uyuni and Oruro salt flats.

Government and Industry Financial Support

Meanwhile, companies along the lithium mine to EV supply chain are being lured by potential support from governments and industry participants. These steps are extremely positive for the lithium industry, although it could result in some trade distortion.

In March 2022, President Biden invoked the Defence Production Act to accelerate production of battery materials in the United States, and in August 2022 the Inflation Reduction Act (IRA) became law. The IRA includes a broad range of subsidies, incentives, and domestic manufacturing requirements meant to encourage renewable energy technological innovation.

In March 2023, the EU announced The Critical Raw Materials Act. The regulation sets clear benchmarks for domestic capacities along the strategic raw material supply chain and for diversifying EU supply by 2030.

This year, the United States, Canadian, and Australian governments have provided direct financial support to some lithium mining projects while battery manufacturers and auto companies are providing support to lithium mining projects through long-term offtake contracts and some direct equity investments. These financing measures are extremely important to the on-going development of new lithium capacity.

Risks Impacting Demand Assumptions

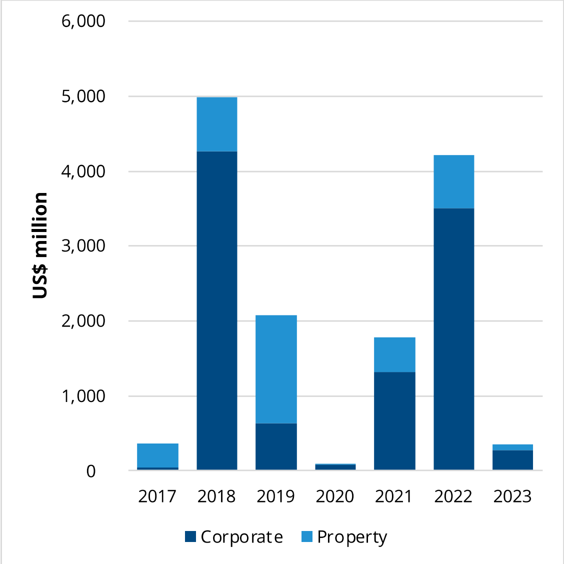
On the demand side there are a number of positive and negative risks that could impact the demand for EVs, lithium-ion batteries, and lithium. **The most significant demand factors are government policy to phase out internal combustion engine (ICE) vehicles, increased battery sizes, and new technology for batteries.**

Government support for EVs has moved from subsidising consumers to impacting structural demand for EVs, by implementing policy to accelerate electric car adoption, through the phase-out of the purchase of ICE vehicles, although some of the timescales are now being questioned.

At the same time, average battery pack sizes and new and next generation battery technology are expected to increase driving ranges. This is likely to include the solid-state lithium battery and the new condensed lithium battery announced by CATL (which has more than twice the energy density of a NCM battery). These batteries are expected to increase the demand for lithium.

Offsetting this trend of a larger average battery pack size is likely to be the introduction of smaller EVs for the mass markets which will have batteries with lower energy densities and lithium content. These vehicles will also likely include the use of sodium-ion batteries which are expected to substitute the demand for lithium-ion batteries at the lower end of the EV market.

Figure 1. Lithium M&A Activity



Source: S&P Global

Other Industry Dynamics

There are also several other interesting dynamics within the lithium industry which are also increasing the uncertainty of forecasts.

Industry M&A Continues

The positive dynamics of strong demand, recent higher prices, and government support for the lithium supply chain are driving increased activity and interest in M&A and consolidation of the lithium industry.

Figure 1 shows a sharp pickup in activity in 2022, which includes the continued acquisition of foreign lithium assets by Chinese companies. The number of deals in 2023 has slowed following the sharp fall in lithium prices, although in March this year Albermarle launched a US$3.4bn takeover bid for Liontown Resources and in May, Allkem and Livent announced a merger in an all-stock deal valued at US$10.6bn.

Processing Diversification

Increased global investment in lithium refining is expected, both at existing refining locations but also at new locations. In Australia significant new spodumene processing capacity is being installed to diversify processing away from China, while many other mining operations around the world are planning direct production of battery-grade lithium carbonate or lithium hydroxide.

Recent Price Explosion

Lithium prices were subdued in 2019 and 2020 due to a period of oversupply. Insufficient growth in global EV sales during this period contributed to lithium production outpacing demand, resulting in a build-up of lithium inventories.

Lithium prices started to rise in 2021 as demand continued to rise and the inventories were gradually reduced and in 2022 prices rose sharply from around US$10,000/t to peaks of US$65-80,000/t, depending on the product and market. This reflected strong lithium demand (driven by the strong rate of EV demand growth) and a reported rebuild of stocks throughout the supply chain. Prices came off their peaks in early 2023 as restocking eased and a number of new mining projects started production, although prices still remained at elevated levels of around US$40-50,000/t at the end of June 2023. Spodumene prices have largely moved in tandem with chemical prices.

Recent rapid price movements and the immaturity and uncertainty about the global lithium market balance mean that prices are likely to remain volatile and the price outlook uncertain, particularly in the longer term given the large number of upside and downside risks to both lithium supply and demand.

Conclusion

The lithium market is still evolving rapidly both from a supply and demand perspective. A deficit in 2030 is still on the horizon but the pace of supply is picking up. The mine supply pipeline beyond 2030 still has plenty of scope for longer-term capacity but will require further encouragement and financing of early-stage exploration projects.

1. The Lithium Market Outlook

This section covers the broad overall outlook for the lithium market to 2030, with more detailed analysis in later sections.

1.1 Shorter-term Outlook

The lithium market continues to be driven by strong demand primarily from demand for lithium-ion batteries in EVs, balanced against new supply being encouraged by investors, governments, battery producers, and OEMs.

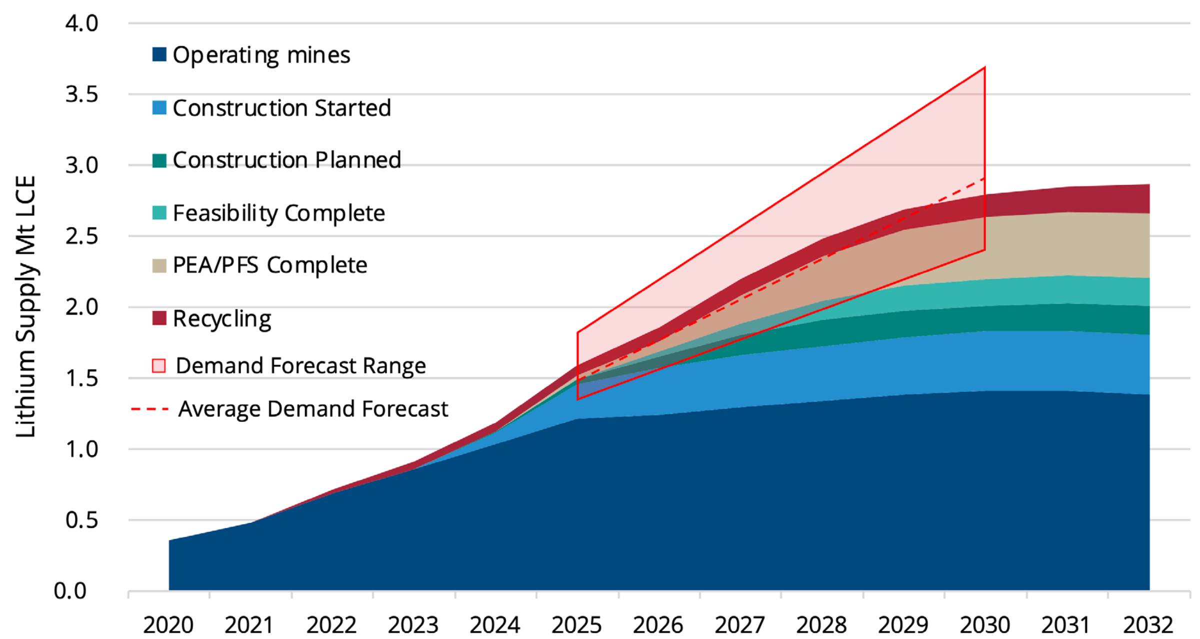
The biggest downside risk to EVs and lithium demand in the short term is the reduction and cessation of government subsidies for EVs and a potential slowdown in global economic growth, including Chinese demand. China ended subsidies for EV sales in December 2022, and many other countries are now also reducing or changing the nature of purchase incentives. In response, EV automakers have increased discounts to customers to maintain sales. Global EV sales strength has continued in 2023. At the same time, supply in expected to be strong with eight new mines expected to start production in 2023.

1.2 Longer-term Outlook

Consensus lithium demand in 2030 is forecast at 2.92 Mt. This compares with demand of about 720 kt in 2022 and represents a CAGR of 19%. Lithium supply is forecast by consensus at 2.16 Mt for 2030. This compares with supply of about 748 kt in 2022, which represents a CAGR of 16%. However, the spread of forecasts for both supply and demand is wide.

The consensus forecast numbers suggest a supply deficit of 761 kt for 2030. This is a large deficit relative to the market size and suggests that higher lithium prices will still be necessary to attract new supply or cause some demand destruction. Based on our own analysis of lithium supply in this report, we also expect that the market will be deficit in 2030, but that the deficit may not be as large as currently indicated by consensus because the pace of new supply is picking up.

Figure 2. RFC Ambrian Risk Adjusted Lithium Supply Forecast and Market Demand Forecasts



Source: RFC Ambrian.

We forecast supply of 2.79 Mt in 2030, based on our risk-adjusted lithium supply forecast, as shown in Figure 2. This means a deficit of just 129 kt using consensus demand. The key difference, we believe, comes from an under estimation by the market of new supply that could potentially come on stream by 2030. However, the spread on the demand forecasts is wide and depending on which forecast is selected the market could be in a surplus or deficit in 2030.

1.3 Factors Affecting the Outlook

A key issue affecting the outlook for any commodity is that there are a series of upside and downside risks to the forecasts of both supply and demand. For the relatively immature lithium market, these risks are magnified somewhat and each of them could materially impact the market balance outcome for 2030.

On the supply side, not all the projects are guaranteed to come on stream or achieve stated capacity due to normal mining and financial hurdles and constraints. However, these are not straightforward to assess in the case of lithium as other dynamics are at play.

The strong demand outlook for lithium is attracting capital to build global supply, incentivised through financial support by governments and industry participants. Nevertheless, companies are also witnessing an increased level of resource nationalism in a number of countries. Some of these are clearly negative, while measures by Chile and Mexico to increase control of their domestic lithium industries initially appeared negative, they may ultimately increase lithium capacity in the longer term.

Also, the ongoing growth of the lithium supply chain relies on the successful implementation of DLE. Of the 56 lithium development projects identified in this report, 12 are planning to implement DLE. It is apparent that lithium extraction and recovery from continental, geothermal, and oilfield brines is becoming technically possible. Nevertheless, despite significant progress at a number of projects, scepticism still remains around the use of DLE for high volume production.

On the demand side, forecasts for EV demand have been rising, driven by an increasing number of countries implementing policy to accelerate electric car adoption, through the phase-out of ICE vehicles.

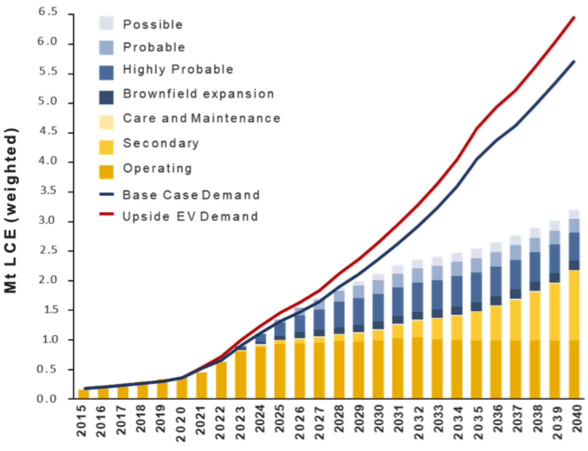
In addition, average battery pack sizes are expected to increase in a continued trend to increase driving ranges. This is likely to include the introduction of the solid-state lithium battery and the new condensed lithium battery announced by CATL (which has more than twice the energy density of a NCM battery). These batteries will increase the demand for lithium.

However, offsetting this trend of a larger average battery pack size is likely to be the introduction of smaller EVs for the mass markets with lower energy densities and lithium content. These vehicles will also likely include the use of sodium-ion batteries which will substitute the demand for lithium at the lower end of the EV market.

Consequently, due to the large structural adjustments and the major logistical, regulatory, financial, and technological challenges facing companies and governments, we expect periods of over- and under-supply of lithium during its longer-term evolution.

The key factors affecting the supply and demand outlook are discussed in more detail in the following two sections.

Figure 3. Example of a Lithium Market Balance



Source: Benchmark Minerals Intelligence.

1.4 Beyond 2030

Parts of the market are now also starting to highlight the large market deficit forecast in 2040. Figure 3 shows a chart that is frequently presented by lithium exploration companies. It is the chart of lithium supply and demand out to 2040 produced by Benchmark Minerals Intelligence (BMI). Comments such as "significant supply shortage looming" are being attached to the chart by third parties pointing to the large deficit in 2040. While the statement is likely true at this point in time, these comments are somewhat misleading because it is very difficult to reliably identify supply growth beyond the early 2030s because the projects that will fill this gap are unidentifiable, particularly because most of them are still only at an early stage of exploration.

2. The Industry Basics

This section provides a general background to global lithium resources, mining, and processing. More detail can be found in Appendices 1 and 2.

Lithium is a very light metal and has excellent electrical conductivity. Its physical and chemical properties make it useful in chemical and metallurgical applications, including ceramics and glass, lubrication greases, aluminium production, and most importantly, lithium-ion batteries.

2.1 Lithium Geology

Lithium is a relatively abundant and widely distributed metallic element, usually found as a trace element in various mineral compounds and salts in the earth's crust and in seawater. The average crustal abundance of lithium is approximately 17-20 parts per million (ppm) with higher abundances in igneous (28-30 ppm) and sedimentary rocks (53-60 ppm). Lithium does not naturally occur in its elemental form due to its reactivity but occurs in 145 different mineral compounds.

Economically viable deposits of lithium are relatively rare and until recently have fallen into two broad categories:

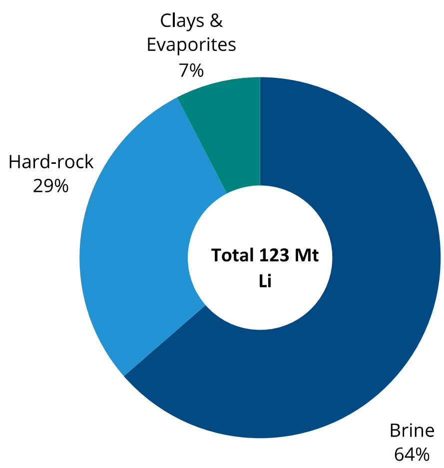
- Hard-rock deposits comprised of silicates found mostly in granite pegmatites.
- Brines comprised of aquifers containing mineral-rich dissolved solids.

Other sources of lithium are now under development which have not previously been exploited on a commercial scale. These include volcano-sedimentary deposits (including clays) and geothermal and oilfield brines.

In the case of hard-rock silicate minerals, there are only a few that are economically worthwhile to process for lithium: spodumene, petalite, and lepidolite, all found in granitic pegmatites. Pegmatites are common throughout the earth's crust; however, lithium-bearing pegmatites make up only one percent of the world's pegmatite resources. Spodumene (aluminium silicate) is the most commonly available economic lithium-bearing mineral, followed by petalite.

Spodumene has a maximum theoretical grade of lithium oxide (Li_2O) of 8.03% (3.7% lithium), petalite has a maximum grade of 4.88% Li_2O (2.2% lithium), and lepidolite has a maximum grade of 7.70% Li_2O (3.6% lithium). Typically, a mineralised rock contains approximately 12% to 20% spodumene, or about 1.5 to 4.0 % Li_2O (0.7 to 1.9% lithium)[1].

Figure 4. Global Lithium Resources by Ore Type



Source: RFC Ambrian

Commercial quantities of lithium also exist in brines. The main type of brine deposit mined for lithium exists in interior saline desert basins (continental brines). The surface water of these basins has evaporated leaving behind a dry lakebed crust above the concentrated brine reservoir. The chemistry of saline brines is unique to each site and can change dramatically even within the same salar.

The typical grade of an economic brine deposit is around 0.04-0.15% lithium (about 400-1,500 ppm). The salars of Chile and Argentina have the highest lithium concentration of brines. Table 10 in

[1] British Geological Survey

Appendix 1 gives the lithium composition of a range of brine deposits. Companies usually report lithium content in brines in milligrams per litre (mg/l) which range from about 200 to 1,800 mg/l for mines and projects in Appendix 4.

There are currently seven volcano-sedimentary lithium projects, including lithium clays (mainly containing hectorite) in our group of 56 exploration and development projects, and a further four in our list of 34 projects with resources. These are nearly all in North America and principally in the United States. Lithium clays typically grade 0.24-0.53% lithium[2]. The most advanced is Thacker Pass in Nevada where construction is underway.

We have identified nine geothermal and oilfield brines in the list of 56 exploration and development projects and 34 projects with just resources. The most advanced is the Vulcan geothermal brine project in the Upper Rhine Valley of Germany operated by Vulcan Energy Resources, where a pilot plant is being installed and plans for construction of a 24 kt/y lithium hydroxide plant are underway.

2.2 Lithium Resources

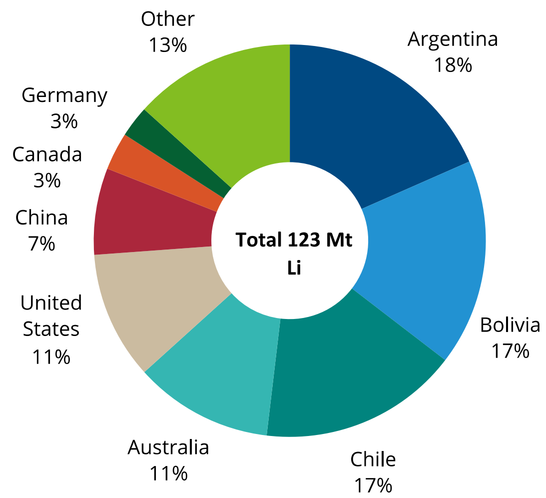
Brine resources account for approximately 64% of available reserves and resources, hard-rock deposits account for approximately 29%, and clay and evaporite deposits for approximately 7%, as shown in Figure 4.

The USGS reports that Argentina (18%), Bolivia (17%), and Chile (17%) hold the largest reserves and resources of lithium, the overwhelming majority of which are brine deposits. The Salar de Uyuni in southwest Bolivia has one of the largest reserves in the world, with up to 9.0 Mt of lithium. Bolivia has yet to economically exploit its lithium resources. Extraction of lithium at Uyuni is complicated by high concentrations of magnesium and potassium.

Australia also has large amounts of lithium, holding approximately 11% of global reserves and resources (primarily hard-rock pegmatite deposits). The United States holds 11% (hard-rock, brine, and sedimentary) and China holds 7% (brine and hard-rock). Canada, Zimbabwe, and Brazil are among other countries with hard-rock reserves.

Figure 5 shows a breakdown of global lithium reserves and resources by country.

Figure 5. Global Lithium Reserves & Resources



Source: USGS 2023

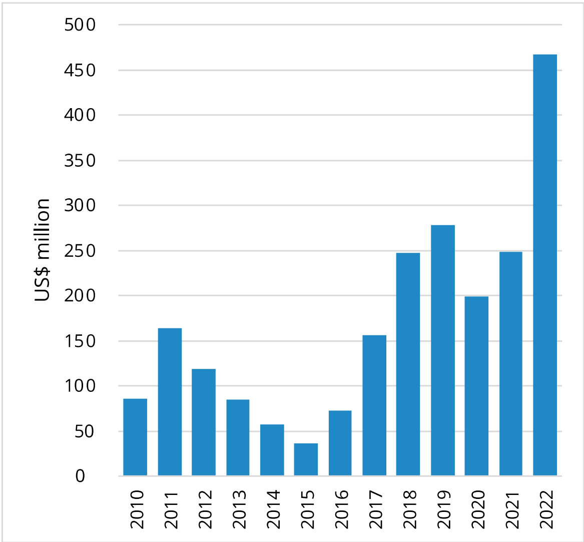
2.3 Lithium Exploration

The process to achieve lithium production starts with exploration and successfully identifying new deposits that are economic. The lead time (from the start of successful exploration to commencement of commercial production) can take from 5 to 10 years, depending on the type of orebody. Understanding the geology and metallurgy are normal steps in the process of development, as are obtaining social and environmental 'licences', however the ESG process has become more onerous, with typical timescales to development extended and likely to become more complex in the future.

Figure 6 shows lithium exploration expenditure from 2010 to 2022. As with many commodity markets, following a peak in 2011, lithium exploration expenditure declined until 2015.

[2] Deutsche Rohstoffagentur (DERA).

Figure 6. Lithium Exploration Expenditure



Source: S&P Global Market Intelligence

Since then, exploration expenditure has been rising strongly, apart from a pullback in 2020, and the amount of exploration drilling undertaken (data not shown) has also increased, according to data from S&P Global Market Intelligence.

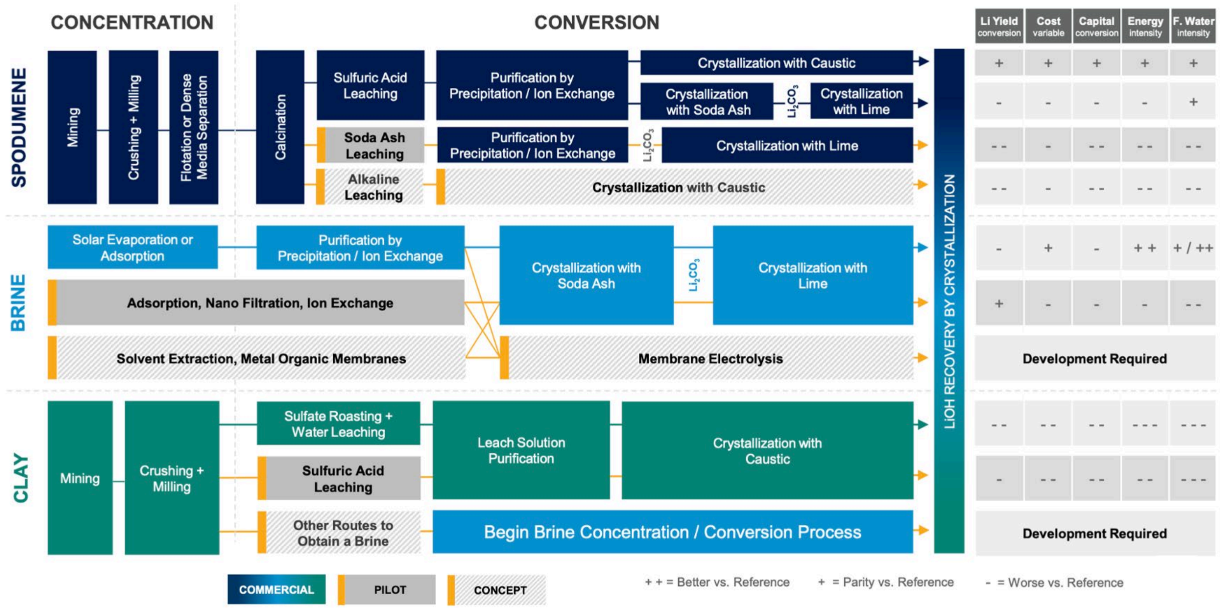
2.4 Lithium Mining and Concentrating

Around 94% of total lithium production is currently produced in just four countries: Australia, Chile, China, and Argentina. Lithium from hard-rock mines, both open pit and underground, is currently beneficiated to a spodumene concentrate which is then transported to a refinery for processing into a lithium chemical salt.

Australia is the predominant supplier of this lithium hard-rock concentrate, which historically has principally been processed in China. Australia's competitiveness is derived from the quality of the deposits, the proximity to Asia, and expertise in large-scale mining. The spodumene concentrate typically grades 5.5-6.0% Li_2O. Higher grade concentrates with a low iron content are used in ceramics and some other industries.

Lithium from brine operations conventionally undergoes a process of concentration via evaporation ponds. The brine remains in the evaporation pond for a period of months or years until most of the liquid water content has been removed through solar evaporation. A lithium carbonate salt is produced, although it can be further converted to lithium hydroxide if required. Consequently, brine operations are simultaneously mines and lithium chemical producers. Large brine producers, such as Albemarle (United States), SQM (Chile), and Livent (United States) traditionally regard themselves as chemical companies. Appendix 2 gives more detail on mining and processing of lithium.

Figure 7. Key Process Routes to Lithium Hydroxide



Source: Albemarle

2.5 Lithium Processing

Lithium chemical salts are produced, either directly or indirectly, from processing lithium ore deposits, and are used as building blocks for other lithium derivatives.

A large number of lithium salts exist in market applications, but the three main chemicals in the production chain are lithium carbonate (Li_2CO_3), lithium hydroxide (LiOH), and lithium chloride (LiCl).

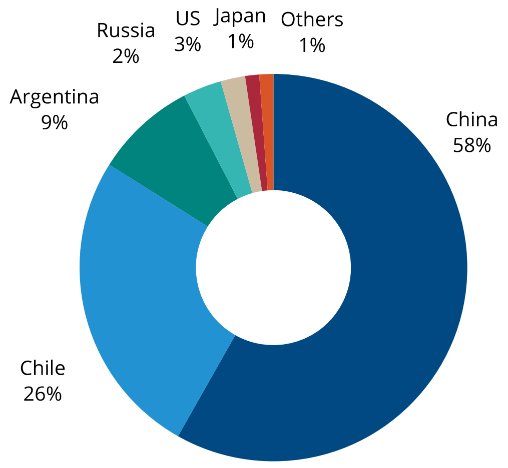
- **Lithium carbonate**: It is the main building block for other lithium derivatives and used in a large variety of applications, including the ceramic and enamel industries, heat resistant glass, aluminium production, pharmaceuticals, and lithium-ion batteries.
- **Lithium hydroxide**: Its main use is as a reagent in high-performance lithium greases, dyes, and in lithium-ion batteries.
- **Lithium chloride**: As a very hygroscopic salt (absorbs moisture from the air), it is used in fluxes, humidity control, and zeolites. It is also a raw material required for the electrolysis of lithium metal.

Both lithium hydroxide and lithium carbonate can be produced from both hard-rock and brine operations, and both are consumed by lithium-ion battery manufacturers. Each industry has unique requirements for lithium chemicals with regard to chemical composition, particle size, and tolerable levels of impurities.

Lithium is a key component across the structure of the battery – it is present both in the cathode and the electrolyte, allowing charge to flow between the anode and cathode. Companies can use both lithium hydroxide and lithium carbonate to produce lithium-ion batteries, but companies usually report production in terms of lithium carbonate equivalent (LCE). Figure 7 provides an overview of how lithium chemicals are in produced from hard-rock, brine, and clay deposits.

China currently dominates non-integrated lithium processing with refineries producing lithium carbonate, lithium hydroxide, and lithium chloride, predominantly from hard-rock concentrate.

Figure 8. Lithium Processing by Country



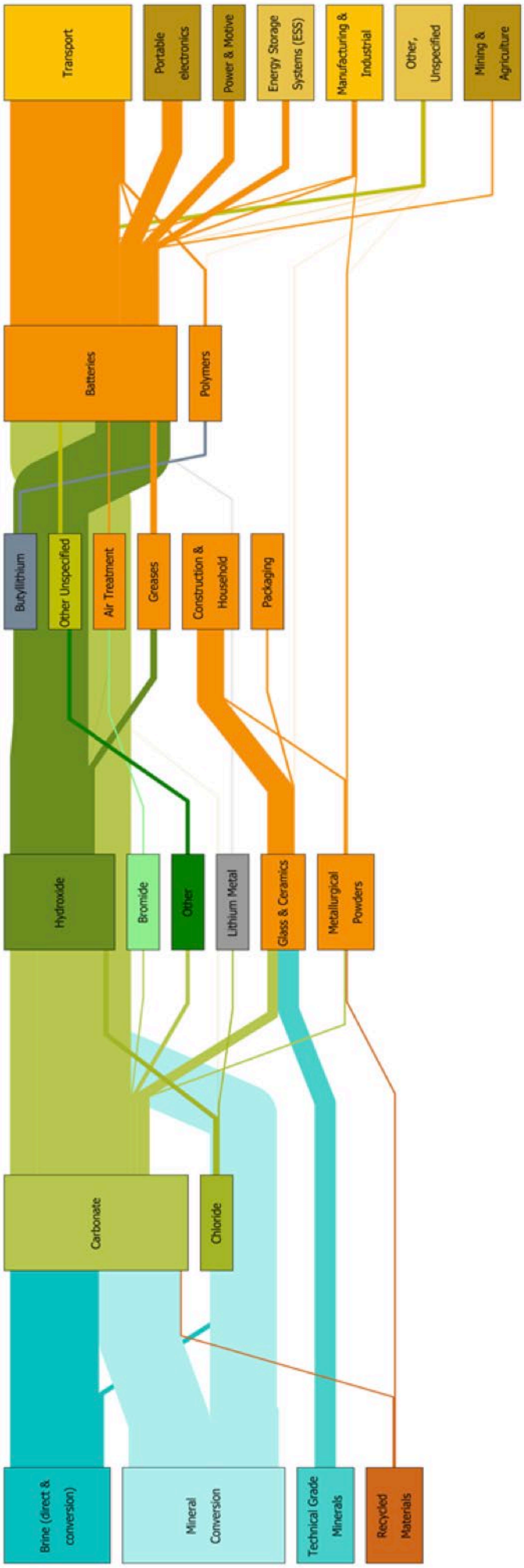
Source: BMI, RFC Ambrian.

China dominates the market primarily due to its competitive advantage and accumulated capacity in lithium processing. Chinese companies Ganfeng Lithium and Tianqi Lithium are the two main purchasers of spodumene concentrate in the global market, which is then shipped and processed into chemical lithium in China.

China has cheaper capital required to build conversion plants, access to low-cost reagents, and power costs that are competitive relative to the global average. Moreover, Chinese chemical processors are part of, or close to, the major companies involved in the current global lithium-ion battery supply chain. As a result, Figure 8 shows how China accounted for an estimated 58% of global lithium chemical output in 2020, despite producing only around 10% of the global mined lithium. However, China's share of processing is likely to decline as more spodumene processing takes place closer to the site of production.

However, in order to secure supply and market share, some Chinese lithium chemical processors (Tianqi and Ganfeng) have purchased interests in Australian mines. Other South American brine producers (Albemarle and SQM) have also purchased interests in Australian mines and projects to diversify and grow their production. Albemarle is also investing in lithium chemical processing in China.

Figure 9. Lithium Industry Flowchart 2021



Source: Wood Mackenzie

To date, only three countries, China, Japan, and South Korea, have built battery cathode plants that convert lithium chemicals into cathode-active material. According to BMI, Chinese cathode plants consumed about two-thirds of the lithium chemicals used in global battery production during 2020. Japan and South Korea split most of the remainder, with smaller amounts going to Taiwan, North America, and Europe.

2.6 ESG

There are relatively few known ESG risks of significance relating to the lithium industry, beyond the normal risks associated with the mining industry. The most discussed ESG issue for lithium operations is the high-water usage of lithium production from brine deposits. Brine deposits usually occur in regions that are often particularly arid, and according to Roskill's analysis, 70% of lithium extracted from brine-based resources originates from areas that are categorised as being at 'high water risk' by the World Resources Institute's (WRI) Water Risk Atlas. This could affect local communities and the ecosphere. Water consumption could be significantly reduced with the introduction of DLE technology for salar brines.

2.7 Conversion Factors

Care should be taken in studying lithium data from varying sources as it can be presented in different terms and sometimes presented in 'equivalents' for comparison. These include contained lithium metal, lithium oxide, lithium carbonate, lithium hydroxide, or lithium carbonate equivalent (LCE). As the lithium content of each lithium chemical differs, supply and demand are often denominated in terms of LCE. For example, lithium hydroxide contains less lithium than lithium carbonate and so one tonne of lithium hydroxide is converted by a factor of 0.878 when expressed in LCE terms. Table 1 shows the standard lithium conversion factors.

Table 1. Lithium Conversion Factors.

Convert From	Chemical Formula	Convert to Lithium	Convert to Lithium Oxide	Convert to Lithium Carbonate
Lithium	Li	1.000	2.152	5.322
Lithium Oxide	Li_2O	0.465	1.000	2.473
Lithium Carbonate	Li_2CO_3	0.188	0.404	1.000
Lithium Hydroxide	LiOH H_2O	0.169	0.356	0.878

Source: British Geological Society. The conversion factors are calculated on the atomic weights and number of atoms of each element in the various compounds.

3. Demand Fundamentals

Global lithium demand increased to about 720 kt of LCE in 2022, from about 196 kt in 2016, a CAGR of 24%, based on the average of reported numbers. This growth has been mostly driven by the high demand of lithium-ion batteries used in EVs.

In 2022, lithium-ion batteries for mobility consumed about 65% of this demand, a further 12% was used in other battery applications, and the balance was used in other industrial sectors. Glass and ceramics were the second largest applications of lithium and consumed 8% of demand, followed by lubricating grease at 4% (see Figure 10).

3.1 Lithium-ion Batteries

This section contains a brief overview of lithium-ion batteries. Appendix 3 has a more detailed analysis.

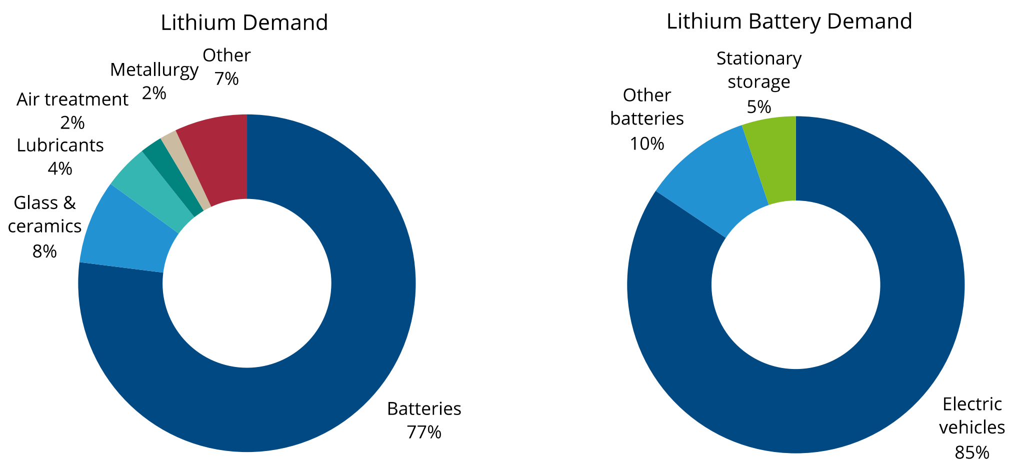
The overwhelming majority of light duty EV sales to date are concentrated in three markets: China, Europe and the United States. China is the largest market, accounting for 60% of global EV sales in 2022, and more than half of all EVs on the road worldwide are in China. This strong growth in EVs is the key driver for ongoing strength in lithium demand and is discussed in more detail in the following section '4. Lithium Demand Outlook'.

Lithium-ion batteries use lithium hydroxide and lithium carbonate. The most important application of these lithium salts in battery technology is their use in cathode material production. Manufacturers favour lithium hydroxide for cathode technologies with high nickel chemistry batteries such as NCM811 (nickel-cobalt-manganese or NCM), which have a higher energy density. The numbers represent the ratio of each of the three products in the battery respectively. NCM622 cathodes can use either lithium hydroxide or carbonate, while lower nickel-bearing NCM cathodes such as NCM111 require lithium carbonate.

Other lithium batteries such as lithium-iron-phosphate (LFP), which have a lower energy density but are lower cost, also use lithium carbonate. Lithium salts produced for batteries require a higher purity of product and usually designated as 'battery-grade'.

In 2022, nickel-manganese-cobalt (NMC) lithium battery technology remained the dominant battery chemistry with a market share of 60%, followed by lithium-iron-phosphate (LFP) with a share of just under 30%, and nickel-cobalt-aluminium oxide (NCA) with a share of about 8%.

Figure 10. Global Lithium Chemical Demand by End Use



Source: Fastmarkets, RFC Ambrian estimates.

Demand going forward is expected to be stronger for high energy density lithium-ion batteries and the consumption of lithium hydroxide. However, battery chemistry continues to evolve and the impacts of changes in battery technology on future lithium demand are discussed in Appendix 3.

Lithium is an important contributor to the overall cost of battery cell production, but not so much to be a primary focus. At 2020 price levels, lithium accounted for roughly 8-10% of the cost of an NCM811 battery cell but has risen with the increase in lithium prices. According to BNEF, after more than a decade of declines, volume-weighted average prices for lithium-ion battery packs across all sectors increased to US$151/kWh in 2022, a 7% rise from 2021 in real terms. Lithium prices rose significantly in 2022 (along with some other battery commodity prices). As a result, the upward material cost pressure outpaced the higher adoption of lower cost chemistries like LFP.

Table 2 shows the metal content for a selection of different cathode types and shows that a typical lithium-ion battery has between 80 and 120 g/kWh of lithium. An average EV battery has a 60 kWh battery, meaning it has some 7.2 kg (NMC111) to 5.0 kg (LFP) of lithium content (38.3 to 26.8 kg of LCE), depending on the type of battery technology. The average EV battery size, and the market share of different battery types are important assumption in forecasting battery and lithium demand.

3.2 Other lithium-ion Batteries

Non-rechargeable (primary) batteries use metallic lithium for the anode. These batteries are more expensive than most of other types of disposable batteries like alkaline batteries but are superior concerning operational lifetime, size, stability, and durability. These batteries are primarily employed in various household applications.

Smaller re-chargeable lithium-ion batteries are used in a wide variety of products, including hand-held power tools, portable electronics, e-bikes and e-scooters, and energy storage systems (ESSs), and form important end-use markets for rechargeable batteries.

3.3 Other Lithium Uses

Non-battery uses for lithium are largely comprised of end uses that consume lithium chemicals, predominantly (but not exclusively) lithium hydroxide and carbonate. However, some of the lithium consumed by the glass and ceramics sector is in the form of hard-rock concentrate (spodumene or lepidolite). Material specification will tend to differ between application.

The second most important application of lithium is in the field of glass and ceramics which accounted for 8% of demand in 2022. Lithium reduces the viscosity and lowers the production temperatures of glass and ceramic manufacturing processes, thereby reducing costs. It results in additional durability, particularly in heatproof ceramic and glass cookware. Lithium also improves the colour fastness of glazes and decreases shrinkage during production.

Lithium is also an additive to multi-purpose, high-performance lubricants. Lithium hydroxide or lithium carbonate is mixed and heated with fatty acids to produce lithium grease, a thickening agent which combines within the lubricant's final formulation to ensure that lubrication properties are maintained over a wide range of temperatures and extreme load conditions. Lithium grease is one of the most used types of lubricating grease due to its cost-efficiency, excellent water resistance, and effectiveness over a wide temperature range. An estimated 70% of all industrial lubricants produced globally contain lithium.

A range of air treatment applications also use lithium. Lithium bromide solutions are used in combination with water in water-lithium-bromide absorption chillers. Absorption based air de-humidifiers use lithium chloride.

Lithium is also used in metallurgy. The steel casting industry uses lithium fluxes to optimise the casting process or to minimise the risk of faulty goods. The industry uses lithium in the form of spodumene or petalite, which reduces the viscosity of the melt. The production of natural rubber compounds uses butyllithium as reagent or catalyst.

Table 2. Metal Content of Different Battery Cathodes kg/kWh

Metal	NMC111	NMC622	NMC811	NCA5	LFP
Nickel	0.333	0.525	0.653	0.725	0.000
Cobalt	0.333	0.176	0.082	0.065	0.000
Lithium	0.120	0.104	0.096	0.095	0.084
Manganese	0.312	0.164	0.076	0.000	0.000
Aluminium	0.000	0.000	0.000	0.011	0.000
Iron	0.000	0.000	0.000	0.000	0.674
Phosphate	0.000	0.000	0.000	0.000	0.374

Source: Fraunhofer ISI & Fraunhofer IZM 2021 for DERA 2021.

3.4 Lithium Substitution

Substitution for lithium compounds is possible in many applications such as batteries, glass and ceramics, and greases. There is often little incentive however, to use the available substitutes because of lithium's relatively low historical price and the stability of its supply. Lithium-ion batteries may become replaced by sodium-ion batteries in the lower-end of the auto market, and in other cheaper forms of e-mobility in the future, however, lithium consumption could also increase with the introduction of solid-state lithium-ion batteries.

4. Demand Outlook

Market consensus is currently forecasting lithium demand of 2.92 Mt for 2030, although the spread of forecasts is wide. This compares with demand of about 720 kt in 2022 and represents a CAGR of 19%. The low end of the range represents a CAGR of 16% and the high end represents a CAGR of 23%. The market available forecasts are shown in Table 3.

A sharp rise in demand for lithium is expected as a result of the increase in demand for lithium-ion batteries used for EVs. Demand forecasts have been rising over the past three years from improved outlooks for global EV demand and the large number of capacity announcements for new battery gigafactories.

Table 3. Lithium Demand Forecasts 2030

Organisation	Kt LCE	Date
Benchmark MI	2,400	Jan-23
Bloomberg NEF	2,400	2022
PWC	2,708	Jul-22
IEA	2,746	Jun-22
DERA	2,974	2023
Fastmarkets	3,035	Nov-22
Roland Berger	3,127	Apr-22
McKinsey	3,200	Jan-23
Albemarle	3,700	Mar-23
Average	**2,921**	

Source: Publicly available data. References are linked to the dates.

A rigorous calculation of lithium demand in 2030 requires a large number of assumptions and forecasts. Some of the most important include:

- The number of electric vehicles (light and heavy duty) being produced in 2030.
- The average battery size for different vehicle types.
- The profile of the different types of battery that are in use.
- The average lithium content of each type and size of battery.

A key difficulty for market participants lies in getting a thorough understanding of demand forecasts from market participants. Our research shows that some of these assumptions are presented or discussed by some of the organisations, but never presented in the whole (in publicly available documents). To add to the confusion, data is often presented in different units by different organisations at different times. This may include the number of EVs in units or GWh (either as LDV, BEV, PHEV or a combination of these), e-mobility units (which may also include heavy duty and e-bikes), e-mobility and battery demand in GWh or tonnes LCE, battery gigafactory capacity in GWh or US$ of investment, and lithium supply and demand usually in tonnes LCE but sometimes in tonnes of a different lithium product. **These are usually large numbers, often thrown out to impress, but without relevance and context and difficult to put into perspective.**

Table 4. EV Sales Forecasts 2030

Organisation	EV sales m	Date
Wood MacKenzie	30.0	Apr-23
IEA (STEPS)	40.0	Apr-23
McKinsey	40.0	Feb-23
PWC	41.9	Aug-22
Bloomberg NEF	43.0	Nov-22
EV Volumes	44.5	Aug-22
S&P Global	46.9	Nov-22
Albemarle	46.9	Mar-23
Fastmarkets	50.0	Apr-23
Benchmark MI	50.0	Feb-23
Average	**43.3**	

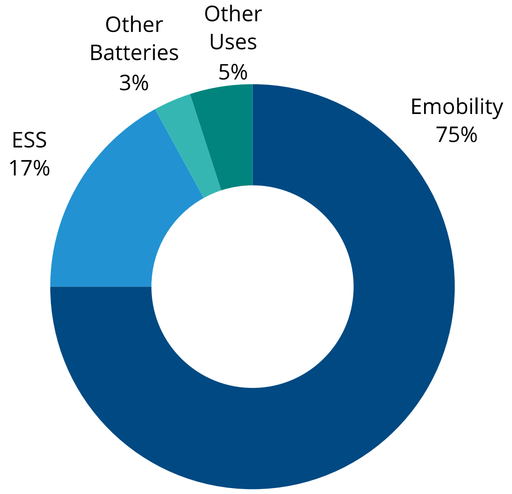
Source: Publicly available data. References are linked to the dates.

4.1 Long-term EV Sales Outlook

The IEA forecasts that by 2030, the average share of electric cars in total sales across China, the EU and the United States is set to rise to around 60%. Consensus EV sales are forecast to increase at a CAGR of 19%, to 43.3m units in 2030 up from about 10.8m units in 2022. Table 4 shows a collection of market available forecasts for light duty EVs in 2030. Even at this starting point, the spread of forecasts is large.

The increase in EV demand has until recently been supported by a range of government subsidies, primarily to EV consumers. These subsidies are now being reduced or removed and EV forecasts are now being supported by a different type of policy intervention from governments, directed at essentially mandating the introduction of EVs.

Figure 11. Forecast Lithium Demand 2032



Source: Fastmarkets.

In November 2022, the California Air Resources Board approved the Advanced Clean Cars II (ACC II) rule, which sets a minimum zero-emission vehicle (ZEV) sales shares for passenger LDVs ranging from 35% in 2026 to 100% in 2035. Any vehicle sold from 2035 onwards must be a zero-emission vehicle or PHEV. Other states have already followed California's lead.

In March 2023, the European Union adopted new CO_2 standards for cars and vans requiring a 55% and 50% reduction in emissions of new cars and vans by 2030 (compared with 2021), and 100% for both by 2035.

In 2022-2023, an increasing number of countries proposed policy to accelerate electric car adoption, either by strengthening existing plans or introducing a support mechanism for the first time principally around the phase out of ICE vehicles.

Also, there is a greater choice for consumers as auto OEMs bring more EV models to the market. At the end of 2020 there were 244 battery EVs and 126 plug-in hybrid vehicles models available globally, and by the end of 1H22 this had risen to 318 and 145 models, respectively.

New government policy, increased long-term investment from auto manufacturers, and shifting consumer sentiment, all suggest rapidly rising EV adoption. These factors are leading to rising forecasts for EVs. For example, in its 'Long Term Electric Vehicle Outlook', BNEF projects the global passenger and commercial ZEV fleet to hit 781m vehicles by 2040. In 2020, this forecast had just 491m ZEVs on the road in 2040. The 2022 outlook sees passenger ZEVs making up 45% of the 2040 passenger vehicle fleet, up from 39% in the 2021 report.

4.2 Short-term Demand Dynamics

The biggest downside risk to EVs and lithium demand in the short term is the end of government subsidies for EVs and a potential slowdown in global economic growth, including Chinese economic demand. China's market experienced a slowdown in the growth rate of EV sales at the end of 2022 and early 2023, largely attributed to increased uncertainty following the end of the zero-COVID policy. Additionally, China ended subsidies for electric vehicle sales in December 2022, and many other countries are now also reducing or changing the nature of purchase incentives. In response, EV automakers have increased discounts to customers to maintain sales. Global EV sales strength has picked up again in 2023. The IEA forecasts global EV sales of 14m vehicles in 2023, representing a 35% year-on-year increase.

4.3 Battery Pack Sizes

Globally, BEV models launched in 2022 had an average range of 337km, up from 230km in 2018. At the same time, average battery pack sizes have increased at 10% annually over this period, going from 40kWh to about 60kWh. Bloomberg NEF points out that ranges remain below consumer expectations in most markets and segments, prompting automakers to launch longer-range models to ease range anxiety. Continued improvements in battery and powertrain technologies could quickly push range up to consumer expectations, while improved charger density and charging speed could reduce range requirements in the long term. Increasing BEV ranges will further boost demand for lithium-ion batteries as EV adoption accelerates, putting more pressure on the battery materials supply.

However, offsetting this trend is likely to be the introduction of small EVs for the mass markets, as government mandates to ban new petrol and diesel autos start to take effect. The smaller and mid-size auto consumers are likely to be less concerned with long ranges and more influenced by cheaper batteries, such as LFP, with lower lithium contents. CRU forecasts that average battery sizes for light duty EVs will plateau around 70kWh by 2030 and then gradually decline as pack sizes reach a point where ranges are sufficient for most drivers, public charging networks improve, and various cost and legislative pressures necessitate rightsizing.

4.4 New and Next Generation Technology

Several important new battery technologies are entering the commercialisation phase. These are expected to drive further performance and cost improvements. Improvements in battery energy density to date have been driven by advances in cathode materials, such as the move towards chemistries with higher nickel content. New technology includes solid-state batteries and silicon anodes, while next-generation technologies include sodium-ion batteries and condensed batteries. These batteries will shift raw material supply chains.

To the downside for lithium, sodium-ion cells are likely to start to displace lithium-ion batteries at the lower price range of EVs and be used for 2- and 3-wheel e-mobility. Thrifting of raw materials is also likely to occur. Both of these could reduce the demand for lithium.

To the upside for lithium, BNEF estimates that 45% to 130% more lithium would be needed on a battery cell level if the solid-state electrolyte were to substitute both the liquid electrolyte and separator. Solid electrolytes contain more lithium due to slower diffusion of lithium ions through the solid electrolyte than a liquid one.

The condensed lithium battery, announced by CATL in March 2023 could be an industry game-changer. It has an energy density of more than twice that of existing NCM batteries. It has an energy density of up to 500 Wh/kg and is currently being aimed at opening up the electrification market for passenger aircraft. However, CATL will also launch an automotive-grade version of the condensed battery, which is expected to be put into mass production within this year. This battery is expected to be utilised at the top end of the auto market, but its impact on the lithium market is not yet known.

4.5 New Battery Gigafactories

The demand for lithium-ion batteries for EVs is causing a proliferation of announcements about new battery factories being planned to satisfy demand, particularly in the United States and Europe. Capacity is currently far exceeding projected demand, suggesting that some of these projects will not be constructed and/or there will be strong competition for battery sales and battery margins may be compressed. As an example, McKinsey forecasts battery demand of 4,700 GWh in 2030, versus its forecast for battery factory capacity of 6,500 GWh, suggesting a capacity utilisation of just 72%. Table 5 shows the battery factory forecasts in GWh for 2030 reported publicly in the market.

Table 5. Battery Factory Capacity Forecasts 2030

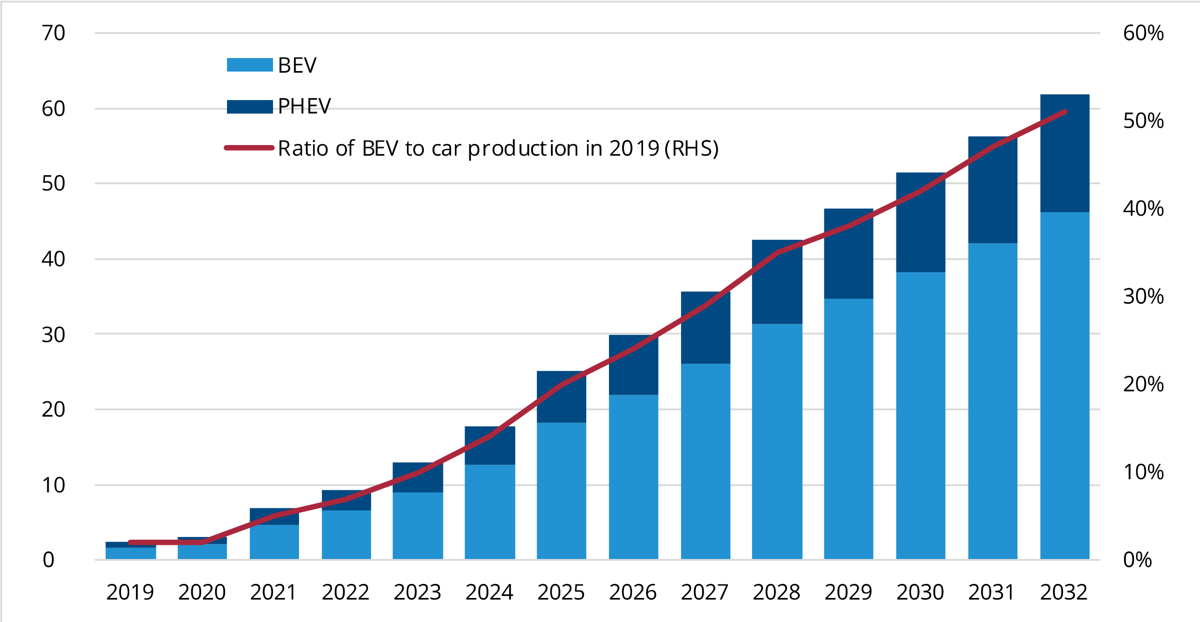
Organisation	GWh	Date
Roland Berger	4,200	Apr-22
Wood MacKenzie	5,500	Mar-22
McKinsey	6,500	Jan-23
Benchmark MI	6,800	Mar-23
S&P Global	7,021	Nov-22
Bloomberg NEF	7,396	Oct-22
Goldman Sachs	7,800	Mar-22
SNE Research	8,247	May-22
Average	**6,683**	

Source: Publicly available data. References are linked to the dates.

4.6 Other Lithium Demand

Demand for energy storage systems (ESS) is expected to grow strongly along with the rollout of various renewable energy applications. Demand in other sub-sectors of the lithium market is expected to be more modest and in line with forecast industrial growth. Albemarle forecasts industrial uses (specialty glass, lubricants, automotive) to grow at 2 to 4% annually, and Specialties (healthcare, pharmaceuticals, agriculture) to grow at 3 to 5% annually out to 2025.

Figure 12. Global BEV and PHEV Sales Forecast

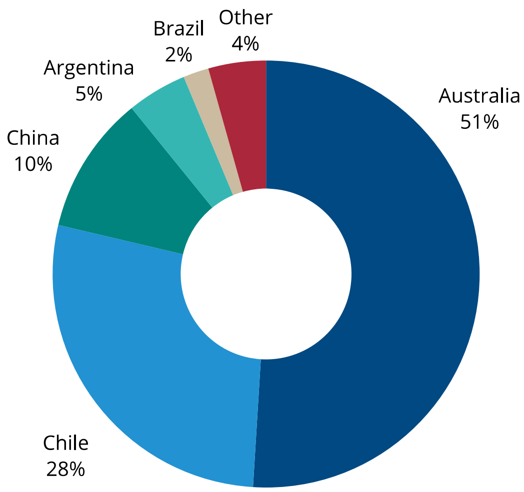


Source: Fastmarkets

5. Supply Fundamentals

The USGS estimated that lithium produced from hard-rock and brine operations totalled about 130 kt of lithium (692 kt LCE) in 2022. S&P Global estimated output of 767 kt LCE of lithium raw material and 703 kt of chemical lithium supply. The chemical supply is lower than the raw material supply due to hard rock conversion losses. Data varies between sources, partly because some producers do not report output and it must be estimated. Figure 13 shows a breakdown of lithium production in 2022 by country with just four counties accounting for 94% of output; Australia 51%, Chile 28%, China 10%, and Argentina 5%.

Figure 13. Lithium Production by Country 2022



Source: USGS 2023, RFC Ambrian estimates.

Chile and Argentina produce lithium from continental brines and produce a lithium chemical product. Australia is predominantly a supplier of spodumene concentrate and third parties in China currently undertake a significant proportion of the chemical processing. To secure supply and market share, some Chinese lithium chemical processors (Tianqi and Ganfeng) have purchased interests in lithium mines producing spodumene, around the world. Meanwhile, spodumene processing facilities are being constructed in other parts of the world.

New spodumene processing facilities are being built at Kemerton and Kwinana in Australia to produce lithium chemicals which will help to diversify spodumene processing away from China (although Chinese companies are still involved) and some projects are being planned to process hard-rock lithium concentrates directly to lithium chemicals at, or near, the planned mine site.

5.1 Lithium Mine Supply

Mine production in 2002 was dominated by just ten companies as shown in Figure 14 and just 16 mining operations accounted for 95% of mine output, as shown in Table 6. These mines comprised five active hard-rock operations in Australia, two brine operations each in Argentina and Chile, a hard-rock operation each in Brazil and Canada, a brine operation in the United States, and three brine and one hard-rock operation in China. In 2022, lithium hard-rock sources accounted for about 58% of global lithium feedstock with 42% coming from brine operations. A map of the currently active mines is shown in Figure 15. The number of mines is expected to continue rising steadily as new projects come on stream.

The largest pegmatite operation is Greenbushes mine in Australia, owned by Albemarle (49%) Tianqi (26%) and IGO (25%), followed by Mount Marion, also in Australia, owned by Mineral Resources (50%) and Ganfeng (50%). China also produces ore from domestic hard-rock lithium deposits. Yichun, in the Jiangxi province is the largest, which produces lithium from lepidolite ore.

The largest brine operations are at the Salar de Atacama in Chile where SQM and Albemarle both have mining operations. The third largest brine operation is the Salar del Hombre Muerto in Argentina operated by Livent. China produces lithium from domestic brine deposits. Chaerhan Lake in Qinghai is the largest.

Table 6. Top 16 Lithium Mine Operations (Approximately 95% of 2022 Production)

Mine	Mine location	Owner	Ore Type	2022 Production kt LCE
Greenbushes	Australia	Albemarle/Tianqi/IGO	Pegmatite	200,000
Salar de Atacama	Chile	SQM	Brine	156,800
Mount Marion	Australia	Mineral Res./Ganfeng	Pegmatite	68,300
Pilgangoora ops	Australia	Pilbara Minerals	Pegmatite	56,100
Salar de Atacama	Chile	Albemarle	Brine	50,600
Wodgina	Australia	Albemarle/Mineral Res.	Pegmatite	30,000
Mt Cattlin	Australia	Allkem	Pegmatite	27,000
Chaerhan Lake	China	Qinghai Salt Lake Industry	Brine	24,900
Salar del Hombre Muerto	Argentina	Livent	Brine	21,100
Olaroz	Argentina	Allkem/Toyota Tsusho/Jujuy	Brine	12,900
Mibra	Brazil	AMG Critical Minerals	Pegmatite	12,000
Tanco	Canada	Sinomine	Pegmatite	11,900
Silver Peak	USA	Albemarle	Brine	10,600
East Taijinair	China	Western Mining Group	Brine	10,300
Yichun	China	Yichun Tantalum	Granite	9,800
Qarhan Lake	China	Zangge Mining	Brine	9,400
Total*				**711,500**

Source: Company data, RFC Ambrian estimates. * Numbers may not sum due to rounding.

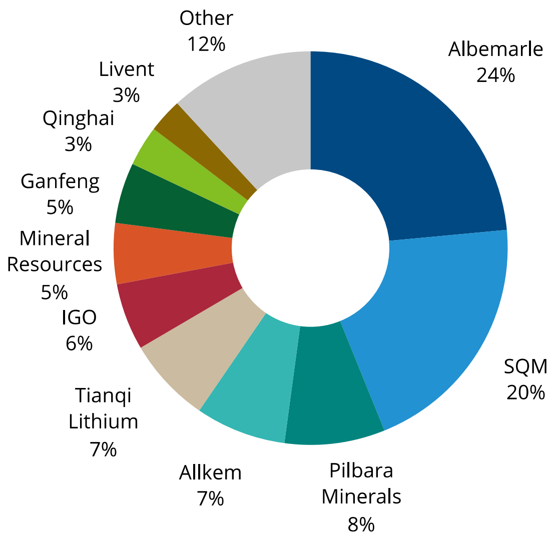
Other hard-rock sources from China are reported to be comparatively low-quality and potentially uncompetitive as sources for conversion to lithium chemicals. As a result, China has been, and is forecasted to remain, mainly dependent on imported feedstock for conversion into lithium chemicals.

5.2 Lithium Producing Companies

Figure 14 shows the main companies involved in the production of lithium raw materials in 2022. The main operators of lithium brine mines are based in South America. The largest brine producers are Albemarle, SQM and Livent. Outside of South America, China is the next largest brine producer. The largest hard-rock producers are Albemarle, Pilbara Minerals, IGO, and Allkem, with the largest assets located in Australia.

Over the past few years, the lithium industry has been undergoing a process of rationalisation through takeovers and the number of corporate deals has been increasing since 2020. In 2021, the largest takeovers include Orocobre acquiring Galaxy Resources for US$1.21bn and North American Lithium acquiring Sayona Quebec for US$78m.

Figure 14. Lithium Production by Company 2022



Source: Company reports, RFC Ambrian estimates, S&P Global.

Figure 15. Location of Significant Producing Lithium Mining Operations 2023

Source: RFC Ambrian. Positions are indicative only.

In 2022, the largest takeovers included Ganfeng Lithium acquiring Lithea for US$962m and Bacanora Lithium for US$262m, Rio Tinto acquiring Rincon Mining for US$825m, Zijin Mining acquiring Neo Lithium for US$721m, Lithium Americas acquiring Millenial Lithium for US$363m, and Sinomine Resources acquiring Bikita Minerals for US$212m.

So far in 2023, completed deals include Lithium Americas acquiring Arena Minerals for US$138m. In March Albermarle launched a US$3.4bn takeover bid for Liontown Resources and in May, Allkem and Livent announced a merger in an all-stock deal valued at US$10.6bn.

In terms of property acquisitions, the largest in 2021 included Pilbara Minerals acquiring the Altura project for US$174m and Sayona Mining acquiring the Moblan project for US$88m. In 2022, the largest included Zhejiang Huayou Cobalt acquiring 87% of the Arcadia project for US$343m, and Ganfeng Lithium acquiring 50% of the Goulamina project for US$194 m.

China has been actively investing in mining assets in Africa and Latin America, and started investing in overseas refining and downstream facilities, with an aim to secure strategic access to raw materials.

The IEA reports that between 2018 and the first half of 2021, Chinese companies invested US$4.3bn to acquire lithium assets, twice the amount invested by companies from the United States, Australia, and Canada combined during the same period. We expect the M&A activity to continue as the larger producers look to acquire the better-quality lithium projects.

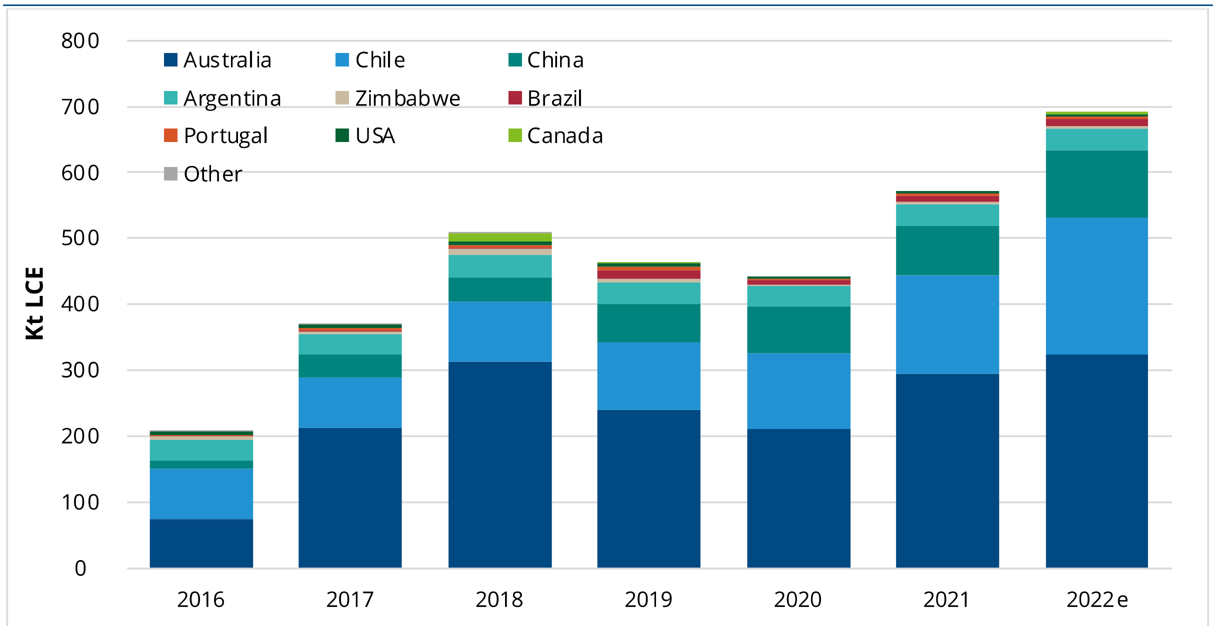
RFC Ambrian intends to follow up this commodity report later in the year with a second lithium report looking more closely at the lithium projects that could come on-stream in the foreseeable future, the companies involved, and the potential for further M&A.

5.3 Recycling

Recycling currently only accounts for around 2% of total supply but is a growing contributor of lithium compounds. However, the supply of lithium from secondary sources and recycling does not yet play a major role, partly because of the low volume of lithium-ion batteries yet to reach their end-of-life. According to London-based Circular Energy Storage, a consultancy that tracks the lithium-ion battery-recycling market, about 100 companies worldwide are planning to recycle lithium-ion batteries.

The industry is concentrated in China and South Korea, where most lithium-ion batteries are currently made, but there are also around 30 to 40 recycling start-ups in North America and Europe. Some country governments are encouraging recycling within the sector with targets to recycle lithium-ion batteries from 2030 onwards. EV batteries can also be repurposed for other uses such as stationary storage.

Figure 16. Production of Lithium (LCE kt) 2016-2022



Source: USGS 2023

6. Supply Outlook

Consensus is currently forecasting lithium supply of 2.16 Mt for 2030 although the spread of forecasts is wide. This compares with about 748 kt in 2022 and represents a CAGR of 14%. However, based on detailed analysis of exploration and development projects, we believe that consensus supply forecasts have been slow to reflect the lithium industry's rapidly rising production potential. We forecast supply in 2030 of 2,792 kt LCE, towards the top-end of the spread. This is despite applying conservative risk adjustments to our forecast. The market available forecasts are shown in Table 7.

Table 7. Lithium Supply Forecasts 2030

Organisation	Kt LCE	Date
McKinsey	1,450	Jan-23
Roland Berger	1,585	Apr-22
DERA (high)	1,904	2023
Benchmark MI	2,100	Jan-23
IEA (STEPS)	2,500	Apr-23
Deloitte	2,500	Nov-22
Fastmarkets	3,084	Nov 22
Average	**2,160**	

Source: Publicly available data. References are linked to the dates.

Increases in supply are being driven by the strong demand outlook. Recent higher prices and support from investors, governments, and the upstream industry, are stimulating a rapid rise in activity in the lithium mining industry with the aim of increasing supply to match demand. This process is now well under way and there is strong growth in new lithium exploration, development, and mine supply. The lithium mine supply chain is starting to fill, but supply deficits are still forecast and so there is still plenty of scope for longer-term capacity additions.

6.1 Supply Chain Support

We previously noted that the increase in EV demand is now being supported by new policy intervention and regulations from governments, which from a demand perspective is directed at essentially mandating the introduction of EVs. From a supply perspective this support is being given to OEMs and the lithium mining and processing industries to increase lithium-ion battery production, reduce production costs, and increase the supply of raw materials. It also aims to diversify lithium processing and battery production away from China.

Companies along the lithium mine to EV supply chain are being lured by potential support by governments as well as financial backing from industry participants. These steps are extremely positive for the lithium industry. Major economies, including the United States and the EU, have announced policies aimed to support the development of the lithium supply chain both domestically and with select trading partners. Battery and auto companies are taking stakes in the supply chain to encourage increased production of critical minerals. This is expected to spur increased investment in the development of the lithium supply chain for countries with resources who satisfy the criteria.

Government Support for the Industry

In March 2022, the US enacted the Defence Production Act, providing access to US$750 million to encourage domestic investment in the extraction and processing of critical minerals.

In August 2022, the US Inflation Reduction Act (IRA) became law which also provides benefits to the domestic critical minerals sector and select trade partners, providing incentives for the supply of critical minerals and battery manufacturing. Under the IRA, a US$7,500 tax credit is available for 'clean vehicles' including EVs. Half of the tax credit depends on criteria relating to critical minerals. Notably, a minimum threshold of the value of the battery's critical minerals must be extracted or processed in the US or by a US FTA partner (see Table 8) or recycled in North America. This threshold increases by 10% each year from 40% in 2023 to 80% in 2027. Furthermore, an eligible clean vehicle must not contain critical minerals that are extracted, processed, or recycled by a 'foreign entity of concern' (FEOC) from 2025. However, the US government has not yet classified the FEOC list.

Table 8. US FTA partners

US FTA Partner
Australia
Bahrain
Canada
Chile
Colombia
Costa Rica
Dominican Republic
El Salvador
Guatemala
Honduras
Israel
Japan*
Jordon
Korea
Mexico
Morocco
Nicaragua
Oman
Panama
Peru
Singapore

Source: US Government. * For free trade in critical minerals.

In March 2023, the EU proposed the Critical Raw Materials (CRM) Act, with targets aimed at increasing domestic production and limiting supply from third-party countries. The CRM sets targets for domestic extraction and processing of 10% and 40%, respectively, by 2030. Furthermore, no more than 65% of consumption at any stage of processing must come from any single third-party country. The benefits of the CRM include reduced procedural burdens for projects in the EU, and the provision of financial support and shortened timeframes for selected strategic projects. As part of this, the EU has promised US$11bn of investments to South America as part of measures to source critical minerals from the region.

The Australian government provides a number of incentives, grants, and support to the critical minerals industry. This includes, the Critical Minerals Facility established in 2021. The Facility is managed by Export Finance Australia and provides financing to projects that are aligned with the Australian Government's Critical Minerals Strategy. The Facility has been funded with A$2.0bn to help projects suffering from gaps in private finance to overcome these gaps and get off the ground. The funding can come in the form of loans, loan guarantees, bonds, and working capital support and is intended as a complement to commercial financing. In July 2023, the Queensland State announced that it would invest A$245m into helping expand its critical minerals sector. The amount includes a fund of A$100m that will support new investment into mining projects in the region.

In Canada, the government recently committed to invest C$344m towards its federal critical minerals strategy to prioritise the development of domestic supply chains for critical minerals. It also has a 30% Critical Mineral Exploration Tax Credit for targeted critical minerals. In November 2022, the Canadian government ordered three Chinese companies to divest their investments in Canadian lithium companies, citing national security.

In July 2023, the IFC announced a loan of up to US$180m to Allkem for the development of the Sal de Vida lithium project in Argentina.

Finally, it is interesting to note that in the recent IEA publication 'Energy Technology Perspective 2023' on measures to reduce clean energy supply chain risks, it includes "strategic oversizing of supply capacity" which we interpret as encouraging over supply. This is certainly not a positive strategy for commodity pricing or the mining industry and encourages increased cyclicality.

Corporate Interest in the Lithium Industry

At the corporate level auto and battery companies are providing investment and off-take agreements for miners and projects. General Motors is investing US$650m in two tranches, directing into Lithium Americas for an approximate ultimate 17% interest in the company. The proceeds will be used to develop the Thacker Pass project in Nevada. Auto company Stellantis has invested US$52m for an 8% stake in Vulcan Energy which operates the Vulcan geothermal brine project in Germany. In June 2022 Ford provided Liontown Resources a A$300m debt facility in conjunction with a binding offtake agreement for construction of the Kathleen Valley project in Western Australia.

Chinese auto and battery maker BYD is reported to be investing Y28.5bn (US$4.0 bn) in a battery factory and lithium project in Yichun in China's Jiangxi province, as well as negotiating for a mining project in Chile. A partnership deal has been signed this year between Bolivia's state-run lithium company, Yacimientos del Litio Bolivianos (YLB), and a Chinese consortium, in which Chinese battery maker CATL plans to invest over US$1.4bn in two lithium operations at Bolivia's Uyuni salt flat. In 2019, CATL purchased a 4.9% interest in Pilbara Minerals (and sold it in 2023) and subsequently purchased an interest in AVZ Minerals and in Global Lithium.

Korean battery maker LG Energy Solution has this year taken a 7.9% stake in Green Technology Metals which operates the early-stage Seymour Lake project, and a 5.7% stake in Piedmont Lithium which operates the Carolina Lithium project.

It is relatively unusual to see these types of investors in mining assets, but these purchases highlight the tightness in the supply chain and desire by OEMs to secure raw materials for their products. These steps carry the expectation that acquiring a stake will enable a stronger control over the critical minerals supply, help safeguard their production pipeline, and mitigate exposure to market risks in the longer term. Other sourcing strategies by OEMs to secure lithium supplies include procurement strategies involving long-term offtake agreements.

6.2 Resource Nationalism

A potential negative risk to lithium supply is resource nationalism. This includes recent steps by Mexico and Chile to increase state controls on lithium mines and concessions, and Namibia and Zimbabwe which are introducing an unprocessed minerals ban. However, while the steps have been viewed as negative by the industry, they may prove to be positive steps for their domestic lithium industries and lithium supply in the longer term.

The government of Chile stated its intention to honour current lease arrangements and plans to submit a bill this year to establish a national lithium company. The bill will include a strategy to promote downstream investments. Separately, the government plans to present a bill early next year to streamline permitting in a bid to boost sustainable production. Chile also plans to auction permits to explore for lithium from early 2024. The permits will apply to salt flats registered by Chilean geological and mining service Sernageomin and considered suitable for development.

In 2021, a decree was passed by the Mexican government to reform the domestic energy sector. The Decree stated that lithium would be included among the minerals considered strategic for an energy transition. As a result, no new concessions for lithium exploitation by private companies would be granted. However, in March 2023, the Mexican government passed a presidential decree confirming that within a 900 square-mile lithium mining zone in northern Sonora state, existing concessions would "remain safe". This aligns with the general opinion that the Decree passed by the Senate only impacts mining licenses, concessions, or contracts to be granted, not already those granted.

In Bolivia, which has previously resisted the development of its lithium resources, the government has recently taken steps to start large-scale production. Meanwhile, it appears that there are issues between the DRC government and AVZ Minerals which is holding up the progression of its exploration rights for the Manono project, while the Government of Serbia last year revoked Rio Tinto's licences related to the Jadar project.

6.3 New Mine Supply

RFC Ambrian has assembled a database of lithium projects that have the potential to come onstream by 2030. The data has been collected directly from company reports, technical papers, and news sources. We believe that the list of projects is fairly comprehensive but may exclude some private projects where data is unavailable.

Figure 17. Location of Significant Lithium Projects That Could Come Onstream by 2030.

Source: RFC Ambriian. Positions are indicative only.

We have identified 31 existing mines of significance that are expected to produce lithium in 2023, including nine in China (see Figure 16, and Appendix 4 - Table 11). Nearly all the non-Chinese mines are planning to increase capacity out to 2030 (we have not accounted for any production increases from the existing Chinese operations due to the lack of data but have included one new project).

We forecast production of 857 kt LCE from these operating mines in 2023, increasing to 1,213 kt in 2025, and 1,412 kt in 2030, equivalent to a 7% CAGR. Particularly strong growth in production is anticipated over this period from the Greenbushes mine in Australia, the Groto do Cirilo operation in Brazil, Pilgangoora in Australia, and Salar del Hombre Muerto in Argentina.

In addition to the operating mines, we have identified 56 projects where the minimum of a PEA has been completed and they appear to have the potential to come onstream by 2030 (see Appendix 4). Albemarle points out that it typically takes 4.5 to 7 years from PEA to initial production.

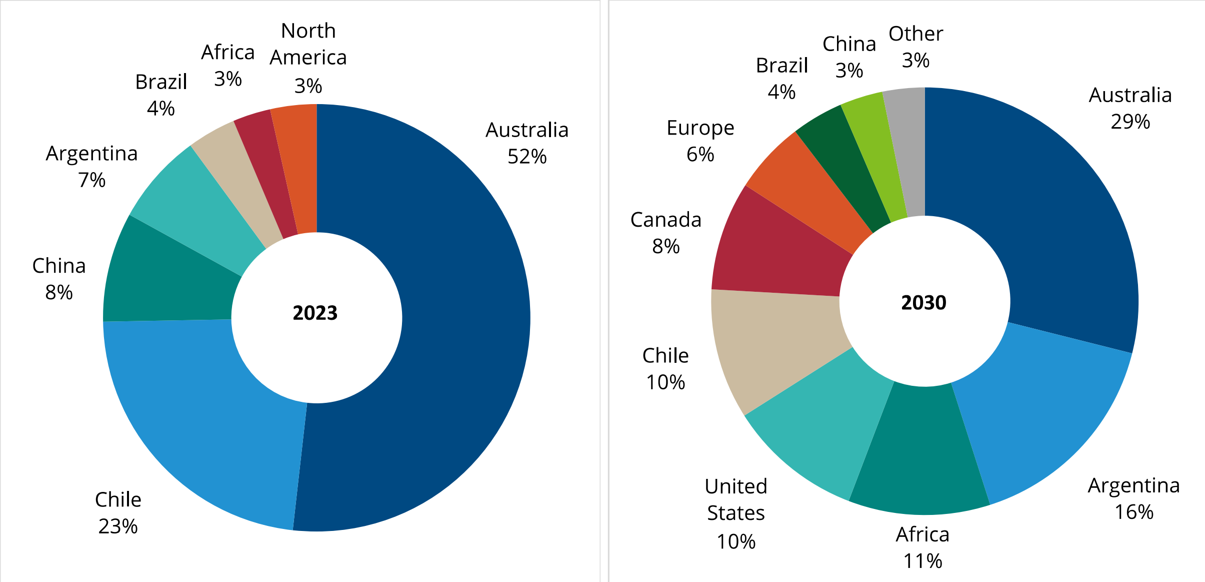
Table 9. Risk Adj. Lithium Chemical Potential

Mine/Project kt LCE	2025 Prodn	2030 Prodn	Risk Adjustment
Operating mines	1,213	1,412	0.95
Construction Started	239	416	0.90
Construction Planned	35	181	0.85
Feasibility Complete	6	192	0.75
PEA/PFS Complete	21	431	0.65
Recycling	80	160	
Total	**1,594**	**2,792**	

Source: Company data, RFC Ambrian forecasts.

The number of mines is expected to continue rising steadily as new projects come on stream. Eight new significant mines are expected to start production in 2023. These are Grota do Cirilo, Finniss, North American Lithium, Cauchari-Olaroz, Zulu, Rincon, and Arcadia. Combined these have a capacity of about 240 kt/y LCE, equivalent to about 32% of 2022 output.

Figure 18. Potential Lithium Production Un-risked 2023 and 2030 by Country



Source: RFC Ambrian, company reports

Exploration and Development Increasing

Lithium exploration expenditure in 2022 increased by 134% from 2020, and the number of lithium exploration holes drilled has increased by 40 times over the past three years (from 2Q 2020 to 2Q 2023). Already in 2023, seven new Preliminary Economic Assessments (PEA) for lithium projects have been reported, compared with four in the whole of 2022.

Of these 56 projects, construction has started at 11 projects, and they are expected to start production in 2024 and 2025. Construction is planned at a further 10 projects, a feasibility has been completed at eight projects, and a PEA or PFS has been completed at 28 projects. We have not considered any other projects in our calculations, although we have identified 32 further projects that have a resource of at least 100 kt LCE, some of which could come onstream by 2030, but for which there is currently insufficient data. The lithium projects that could come onstream by 2030 include Kings Mountain, Bald Hill (mine in administration), St Austell, and Beauvoir. These projects are listed in Appendix 4.

For each individual project we have forecast a production profile. We have assumed that only 40% of planned capacity is achieved in year one, 90% in year two, and 100% in year three. We have also adjusted down the spodumene raw material production (LCE) to account for chemical recovery factors (approximately 85%).

Finally, we have risk adjusted our overall supply forecasts to take into account that not every project in the pipeline will make it to production or may not achieve full capacity. Our supply forecast and risk adjustment assumptions are detailed in Table 9. We believe our risk adjustments are conservative given the global drive to produce more lithium.

Overall, we forecast global lithium chemical production of 1,594 kt LCE from these operations in 2025, increasing to 2,792 kt LCE in 2030, equivalent to a 17% CAGR. Un-risked, the total capacity of all the mines and projects is 3,297 kt LCE in 2030.

Figure 18 shows the geographic breakdown of potential production by country in 2023 and 2030. It demonstrates a more balanced global production profile for 2030.

6.4 Direct Lithium Extraction

It is apparent that lithium extraction and recovery from continental, geothermal, and oilfield brines is becoming technically possible. Potential benefits of DLE for brine deposits compared with the evaporative processes include a significantly reduced physical footprint, up to 90% lithium recovery compared with 30-50% for conventional evaporation ponds, reduced water consumption, and a shorter expected production lead time.

Recent evidence of DLE application for salar brines includes SQM moving to DLE technology at Salar de Atacama in Chile with a US$1.5bn investment. Eramet is constructing an adsorption brine project in Argentina at Centenario, and Rio Tinto acquired Rincon Mining for US$825m which owns the Rincon adsorption brine project, also in Argentina. Chile's recent National Lithium Policy calls for new lithium projects to implement DLE due to environmental concerns.

With regards to geothermal and oilfield brine projects, in December 2021, Standard Lithium raised US$100m directly from Koch Strategic Platforms for the Lanxess and the SW Arkansas projects in Arkansas, United States. Australian-based, Vulcan Energy Resources has raised almost A$300m for its geothermal brine project in the Upper Rhine Valley of Germany where it is planning to use sorption technology.

The ongoing growth of the lithium supply chain relies on the successful implementation of DLE. Of the 56 lithium development projects identified in this report, 12 are planning to implement DLE. Nevertheless, despite significant progress at a number of projects, scepticism still remains around the use of DLE for high volume production and there are still concerns around water consumption and brine reinjection.

6.5 New Lithium Processing Capacity

In 2021, there were 46 companies producing lithium chemicals. The largest five producers accounted for 52% of the total output. The number of processors is expected to rise and Wood MacKenzie forecasts the number to rise to 70 in 2030 with the five largest accounting for 43% of the total. Figure 19 shows the Chinese chemical producers.

Increased global investment in lithium refining is expected, both at existing refining locations and at new locations. Importantly significant new spodumene processing capacity is being installed at or close to new mine sites to produce battery-grade lithium carbonate or lithium hydroxide and to diversify processing capacity away from China (although Chinese companies are still involved in some of them). This is viewed as a positive trend for the security of supply, although the challenges associated with producing and qualifying a battery-grade product should not be underestimated.

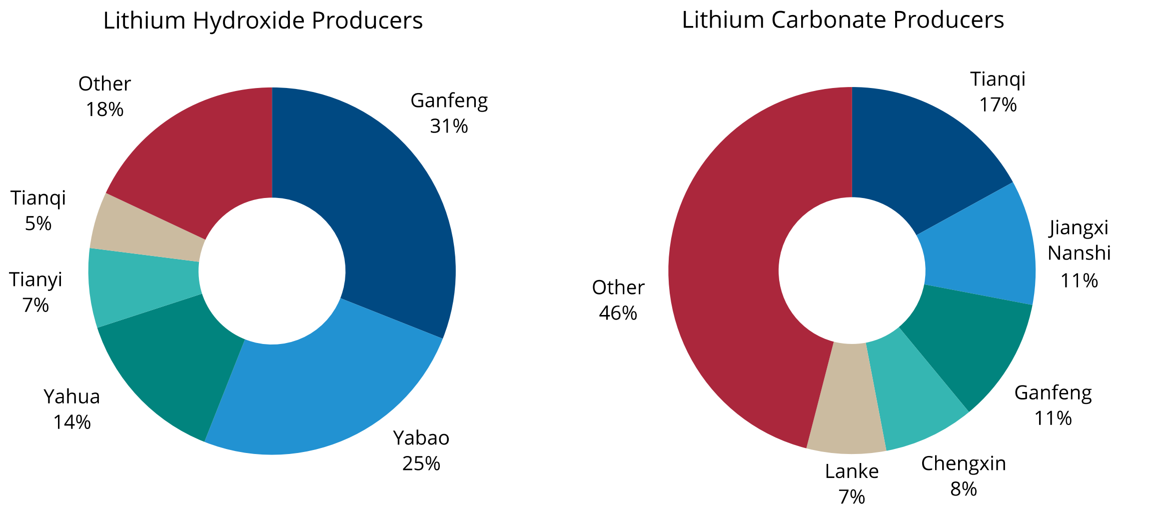
At Kemerton in Australia, Albemarle has constructed a high-quality spodumene conversion plant which came on stream in 2022. The plant will process concentrate from Greenbushes and the Wodgina mines to produce 50 kt/y LCE of lithium hydroxide and will be expanded to 100 kt/y LCE.

China-based Tianqi Lithium is constructing a two-stage lithium processing plant in Kwinana, Western Australia to process its share of concentrate from Greenbushes mine. The first stage of the plant was commissioned at the end of 2022, with a capacity of 24 kt/y of battery-grade lithium hydroxide.

New lithium projects such as Wesfarmers' Mt Holland in Australia will produce a spodumene concentrate at the mine site which will be treated at a new refinery in Kwinana to produce an average of 50 kt/y of lithium hydroxide. At Sibanye-Stillwater's Keliber project in Finland, spodumene will be mined from five mining areas and then transferred to a new refinery at Kokkola to produce 15 kt/y of lithium hydroxide. At the Nemaska Lithium's Nemaska project in Canada, spodumene concentrate will be transferred to a 34 kt/y electrochemical lithium hydroxide plant at Bécancour. At Lepidoco's Karibib project in Namibia, the mine will produce a lithium mica concentrate that will be transported to Abu Dhabi to a chemical plant to produce 4.4 kt/y lithium hydroxide and other by-products using proprietary process technology.

In the United States, Tesla is constructing its own lithium refinery at Corpus Christi, Texas. In the future, it expects this facility to also process other intermediate lithium feedstocks, including recycled batteries and manufacturing scrap.

Figure 19. Chinese Lithium Chemical Producers 2020



Source: SMM

7. Markets & Prices

The main trade in lithium is in exports of concentrates or chemicals to Asia. South American brine producers mainly export lithium carbonate to Asia (China, Japan, and South Korea) for direct use or processing to lithium hydroxide or other salts. Spodumene concentrates produced in Australia mainly flow to China for processing to lithium carbonate, lithium hydroxide, or other salts. However, lithium ore concentrates are now starting to be processed in other parts of the world in an effort to diversify the concentration of processing away from Asia, and China in particular.

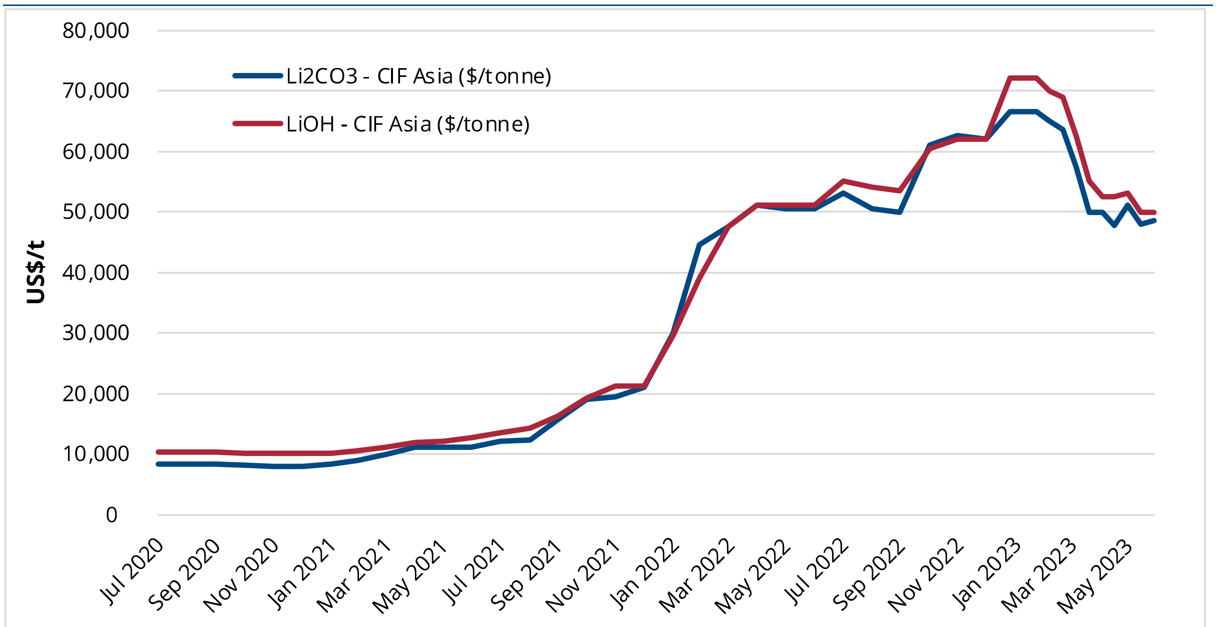
7.1 Lithium Trade

Trade in lithium centres around key raw materials and chemicals – spodumene concentrate, lithium carbonate, and lithium hydroxide, which vary significantly in their lithium content. The production of lithium-ion-batteries requires both lithium carbonate and lithium hydroxide, depending on the type and quality of the battery.

Despite its rapid growth profile in recent years, the lithium market remains a modestly sized specialty market and lithium pricing remains relatively opaque in comparison to the much larger (and more liquid) markets for precious and base metals and bulk commodities. The majority of lithium material is bought and sold under long-term contractual agreements with pricing formulas based on published prices. These are then adjusted for various factors including product quality and delivery/dispatch location. Each industry has unique requirements in terms of desired chemical composition, particle size, and impurities.

Spodumene concentrates are usually graded and priced according to their lithium-oxide content and impurity levels. Concentrates for the battery industry are rated 'chemical grade' or 'battery grade' and concentrates for the glass industry are rated 'technical grade'. The current industry standard for lithium concentrates in the battery industry is SC6, a chemical grade spodumene-concentrate that contains approximately 6% lithium oxide. In general, the glass industry has tighter limits on certain impurities in the concentrate than the battery industry due to the direct use of the concentrates in the process.

Figure 20. Recent Price History for Lithium Carbonate & Lithium Hydroxide to end June 2023



Source: Thompson Reuters

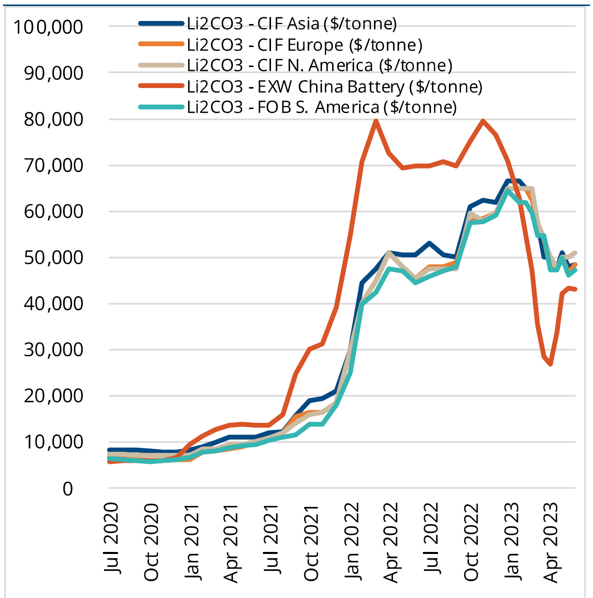
Lithium carbonate is the most commonly traded lithium compound on the international market. The vast majority of this trade is material flow from Chile and Argentina. In terms of lithium carbonate trade values, based on data from OEC, Chile was the largest exporter in 2021 with goods valued at US$896m, followed by Argentina (US$247m), China (US$95m), and Netherlands (US$50m). The largest importers were China (US$583m), South Korea (US$326m), and Japan (US$164m).

In terms of lithium oxide and hydroxide trade values, based on data from OEC, China was the largest exporter in 2021 with goods valued at US$826m, followed by Chile (US$105m), the United States (US$94m), and Russia (US$82m). The largest importers were South Korea (US$625m), Japan (US$347m), India (US$24m), and Germany (US$23m).

7.2 Lithium Pricing

Several providers publish prices for spodumene and a number of other lithium chemicals including lithium carbonate, lithium hydroxide and lithium chloride. These prices are available in various currencies and based on dispatch or delivery at a number of relevant locations. The premium of battery grade over technical grade has historically been about 10%.

Figure 21. Lithium Carbonate Price US$/t



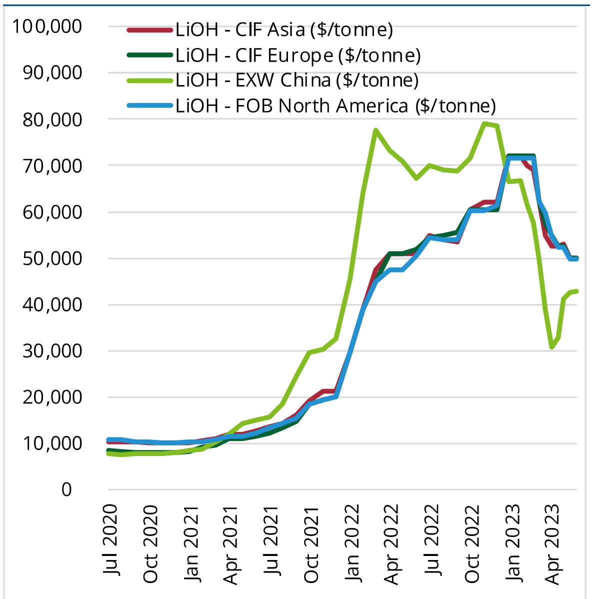
Source: Thompson Reuters.

The number of lithium futures markets are increasing. In June 2021, the London Metal Exchange (LME) launched a cash-settled futures contract for lithium hydroxide. Lithium futures trading is now also available for lithium hydroxide from the CME Group in the United States, and SGX in Singapore. SGX also has a futures market for lithium carbonate, as does Guangzhou futures exchange and the EXBXG exchange, both in China. These contracts offer the industry a price risk management tool.

7.3 Recent Sharp Volatilty in Pricing

Lithium prices were subdued in 2019 and 2020 due to a period of oversupply. Insufficient growth in global EV sales during 2019 and 2020 contributed to lithium production outpacing demand, resulting in a build-up of lithium inventories.

Figure 22. Lithium Hydroxide Price US$/t

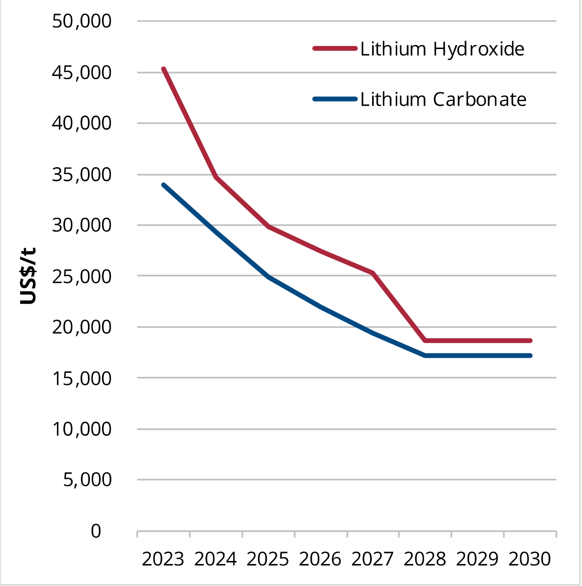


Source: Thompson Reuters.

Lithium prices started to rise in 2021 as demand continued to rise and the inventories were gradually reduced and in 2022 prices rose sharply from around US$10,000/t to peaks of US$65-80,000/t, depending on the product and market. This reflected strong lithium demand (driven by the strong rate of EV demand growth) and a reported rebuild of stocks throughout the supply chain. Prices came off their peaks in early 2023 as restocking eased and a number of new mining projects started production.

A notable trend was the higher volatility of the price index in China compared with other regions. In 2022, Chinese prices rose to higher levels than those in Europe and between January and April 2023, lithium carbonate prices in China fell by over 60% whereas those in Europe dropped by only 20%. Nevertheless, prices have generally stabilised and remained at elevated levels of around US$40-50,000/t at the end of June 2023. Spodumene prices have largely moved in tandem with chemical prices.

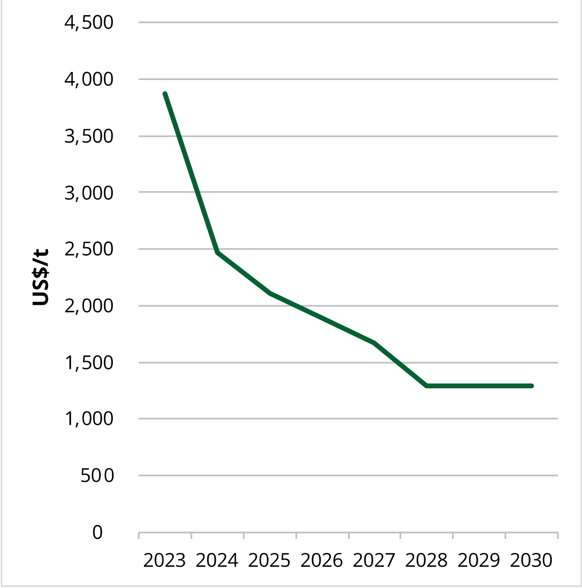
Figure 23. Consensus Chemical Price Forecast



Source: Consensus Economics. Nominal prices.

The Australian resources and energy quarterly review reports that in 2022, spot prices for spodumene averaged US$4,368/t, well above the average level of US$671/t over the 3 years to 2021. The spot price of lithium hydroxide averaged US$69,370/t in 2022, dramatically higher than the average price of US$12,163/t over the 3 years to 2021. Trade in the spot market is currently relatively minor, but this may change if the market expands significantly over the next decade as expected. Most producers have historically utilised long-term contracts, and prices received take time to adjust to shifts in spot prices. However, prices reported by producers confirm that recent higher prices are now flowing into contract prices.

Figure 24. Consensus Spodumene Price Forecast



Source: Consensus Economics. Nominal prices.

Recent rapid price movements and the immaturity of the global lithium market mean that prices are likely to remain volatile and the price outlook remains uncertain, particularly in the longer term given the large number of upside and downside risks to both lithium supply and demand.

Figure 23 and Figure 24 show the consensus forecasts for lithium carbonate, lithium hydroxide, and spodumene. The lithium hydroxide price is estimated to average about US$45,400/t in 2023, before moderating to a long-term nominal price of US$18,680/t in 2028 onwards. The lithium carbonate price is estimated to average about US$33,900/t in 2023, before moderating to a long-term nominal price of US$17,165/t in 2028 onwards. The spodumene price is estimated to average about US$3,900/t in 2023, before moderating to a long-term nominal price of US$1,292/t in 2028 onwards. These consensus price forecasts will be used for modelling but are contradictory to an expectation of deficits at the end of this decade.

Appendix 1 – Lithium Resources

This appendix provides a more detailed overview of lithium geology and resources.

There are five naturally occurring sources of lithium, of which the most developed are hard-rock lithium pegmatites and continental lithium brines. Other sources of lithium include oilfield brines, geothermal brines, and sedimentary rocks (including clays).

Hard-Rock Lithium Minerals

Spodumene [$LiAlSi_2O_6$] is the most commonly mined mineral for lithium, with historical and active deposits exploited in China, Australia, Brazil, the US, and Russia. The high lithium content of spodumene (8% Li_2O) and well-defined extraction process, along with the fact that spodumene typically occurs in larger pegmatite deposits, makes it an important mineral in the lithium industry.

Lepidolite [$K(Li,Al)_3(Si,Al)_4O_{10}(OH,F)_2)$] is a monoclinic mica group mineral typically associated with granite pegmatites, containing approximately 7% Li_2O. Historically, lepidolite was the most widely extracted mineral for lithium; however, its significant fluorine content made the mineral unattractive in comparison to other lithium bearing silicates. Lepidolite mineral concentrates are produced largely in China and Portugal, either for direct use in the ceramics industry or conversion to lithium compounds.

Petalite [$LiAl(Si_4O_{10})$] contains comparatively less lithium than both lepidolite and spodumene, with approximately 4.5% Li_2O. Like spodumene and lepidolite, petalite occurs associated with granite pegmatites and is extracted for processing into downstream lithium products or for direct use in the glass and ceramics industry.

Sedimentary Lithium Deposits

Sedimentary lithium deposits are created when lithium is washed out of volcanic minerals into basins where it reacts with other minerals, creating chemical structures in which the lithium is bound up in a mineral, but is much less strongly bound than spodumene. Much of the lithium exploration and development in the United States is focused on sedimentary lithium deposits, including Thacker Pass (hectorite), Rhyolite Ridge (sepiolite), Bonnie Claire (lithium carbonate and lithium salts), McDermitt (clay) and Clayton Valley (clay). Sedimentary projects in other parts of the world include Jadar (Jadarite) in Serbia, and Sonora (clay) in Mexico.

Lithium Clays

Lithium clays are formed by the breakdown of lithium-enriched igneous rock which may also be enriched further by hydrothermal/metasomatic alteration. The most significant lithium clays are members of the smectite group, in particular the lithium-magnesium-sodium end member hectorite [$Na_{0.3}(Mg,Li)_3Si_4O_{10}(OH)_2$]. Hectorite ores typically contain concentrations of 0.24%-0.53% lithium and form numerous deposits in the United States and northern Mexico.

As well as having the potential to be processed into downstream lithium compounds, hectorite is also used directly for its physical properties in aggregate coatings, vitreous enamels, aerosols, adhesives, emulsion paints and grouts. Other lithium bearing members of the smectite group are salitolite and swinefordite.

Continental Lithium Brines

Evaporative saline lakes and salars are formed as lithium-bearing lithologies which are weathered by meteoric waters forming a dilute lithium solution. Dilute lithium solutions percolate or flow into lakes and basin environments which can be enclosed or have an outflow. If lakes and basins form in locations where the evaporation rate is greater than the input of water, lithium and other solutes are concentrated in the solution, as water is removed via evaporation. Concentrated solutions (saline brines) can be retained subterraneously within porous sediments and evaporites or in surface lakes, accumulating over time to form large deposits of saline brines.

The chemistry of saline brines is unique to each deposit, with brines even changing dramatically in composition within the same salar. The overall brine composition is crucial in determining a processing method to extract lithium, as other soluble ions such as magnesium (Mg), sodium (Na), and potassium (K) must be removed during processing. Brines with a high lithium concentration and low lithium to magnesium and lithium to potassium ratios are considered most economical to process. Brines with lower lithium contents can be exploited economically if evaporation costs or impurities are low. Lithium concentrations at the Salar de Atacama in Chile and Salar de Hombre Muerto in Argentina are higher than most other locations, although the Zabuye Salt Lake in China has a more favourable lithium to manganese ratio.

Oilfield Brines

Deep oilfield brines may contain up to several hundreds of parts per million lithium. Examples include oilfield brines in Arkansas, North Dakota, Oklahoma, Texas, and Wyoming, with lithium concentrations of up to 700 ppm. One of the best-known of the oilfield brines is contained in the Smackover Formation in the Gulf Coast area of the south-central United States. The brine occupies pore space in an approximately 200-m-thick limestone at depths of 1,800 to 4,800 m. The brine has been interpreted to be trapped seawater that was subsequently hydrothermally enriched in lithium and other trace elements.

Geothermal Brines

Geothermal brine is a hot and concentrated saline solution, having circulated through the very hot rocks of geothermal areas and enriched with minerals, such as lithium, boron, and potassium. Geothermal brines traditionally derive their value from their contained heat, which can be converted to mechanical energy. Geothermal brines contain lithium in the range of 12 to 350 ppm.

Areas of interest for the recovery of lithium from geothermal brines include the Upper Rhine Valley alongside the German French border, the Salton Sea in California in the US, Wairakei in New Zealand, and Cornwall in the UK.

Table 10. Lithium Brine Compositions.

	Source	Country	Lithium % wt	Sodium % wt	Magnesium % wt	Potassium % wt	Calcium % wt
1	Clayton Valley	USA	0.0163	4.69	0.019	0.40	0.045
2	Salton Sea	USA	0.010-0.040	5.00-7.00	0.070-0.570	1.30-2.40	2.260-3.900
3	Salar de Atacama	Chile	0.1570	9.10	0.965	2.36	0.045
4	Hombre Muerto	Argentina	0.068-0.121	9.90-10.30	0.018-0.014	0.24-0.97	0.019-0.090
5	Salar de Uyuni	Bolivia	0.0321	7.06	0.650	1.17	0.0306
6	Searless Lake	USA	0.0054	11.80	0	2.53	0.0016
7	Great Salt Lake	USA	0.0018	3.70-8.70	0.500-0.970	0.26-0.72	0.026-0.036
8	Dead Sea	Israel	0.0012	3.01	3.090	0.56	1.29
9	Sua Pan	India	0.0020	6.00	0	0.20	0
10	Bonneville	USA	0.0047	8.30	0.400	0.50	0.0057
11	Zabuye	China	0.0489	7.29	0.0026	1.66	0.0106
12	Taijinaier	China	0.0310	5.63	2.020	0.44	0.020

Source: Johnson Matthey 2018.

Appendix 2 – Lithium Mining & Processing

This appendix provides an overview of lithium mining and processing methods.

Lithium Mining

The main sources of lithium for commercial extraction are hard-rock (mostly pegmatite granites) and brines (aquifers containing mineral-rich dissolved solids). However, other sources of lithium, including geothermal brines, oilfield brines, and sedimentary deposits are also being developed.

Hard-Rock Lithium Production

Within the hard-rock category, there are three lithium minerals commercially mined today: spodumene, petalite and lepidolite. Spodumene is by far the most important lithium mineral given its naturally higher lithium content. Extraction of lithium minerals uses both open-pit and underground mining methods. Typically, the mineralised rock contains 12 to 20% spodumene, or approximately 1.0 to 1.5% lithium oxide (Li_2O). Spodumene typically occurs in pegmatites which are igneous rocks similar in mineral composition to granites but with very coarse grain sizes. With the expansion of the lithium mining industry in recent years, hard-rock production has been re-established as the single largest source of lithium raw material globally.

To produce lithium from hard-rock sources, the material typically undergoes an initial process of concentration at a mine site. Crushed ore is milled to produce a fine product, which is suitable for separation in flotation cells. In these cells, the removal of various other minerals, including quartz, feldspar, and micas, takes place. Different separation processes will produce concentrate with differing levels of lithium content, which can take place in either the technical or chemical-grade markets. Figure 25 shows hard-rock mining at the Grota do Cirilo open pit lithium mine in Brazil.

In the case of spodumene, producers typically concentrate the material to 6% lithium-oxide content. This material can then be processed into a chemical product (either lithium carbonate or lithium hydroxide) or sold as spodumene concentrate. Australia is the predominant supplier of spodumene concentrate and third parties in China undertake most of the chemical processing.

Figure 25. Grota do Cirilo Hard-Rock Mining Operations, Brazil.

Source: Sigma Lithium

China also produces ore from domestic hard-rock lithium deposits, the largest being lepidolite from Yichun, in the Jiangxi province. Other sources are reported to be comparatively low-quality and potentially uncompetitive as sources for conversion to lithium chemicals. As a result, China has been, and is forecasted to remain, mainly dependent on imported feedstock for conversion into lithium chemicals according to BMI.

Continental Brine Production

Continental brines form in seasonally flooded dry lakes, called salars. Volcanic and geothermal events or the eventual percolation of runoff containing high concentrations of ash created many of these brine aquifers. These events facilitate the leaching of minerals from the surrounding rock, particularly lithium chloride. Brine containing high concentrations of lithium is drawn from the aquifers using extraction wells. For example, at Allkem's Salar de Olaroz in Argentina, extraction of brine takes place from production wells which are spaced 1 km apart and are 200 m deep.

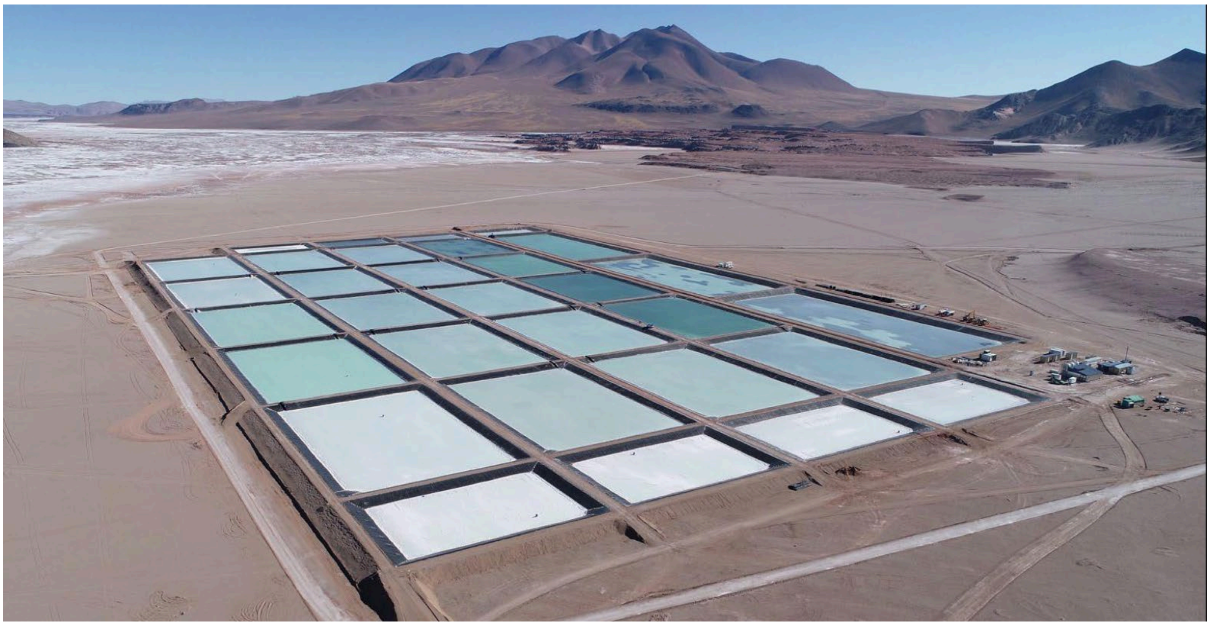
A major area of lithium brine deposits is in the Andes mountains in a region encompassing parts of Argentina, Chile and Bolivia. Brines can potentially contain economically viable concentrations of lithium and other minerals. The typical grade of a brine deposit is from 200-1,800 mg/l lithium, far lower than for a hard-rock deposit although the process of producing lithium from brines is generally much lower cost than that from hard-rock minerals.

In addition to lithium grade and quantity, other factors are important in determining the potential for commercial lithium production from a salar. The ratios of lithium to magnesium (Mg) and lithium to sulphate (SO_4) are equally important as they impact brine processing; low Mg and SO_4 relative to lithium is a favourable characteristic.

The main operators of lithium brine mines are based in South America. SQM is the largest producer and operates the Salar de Atacama in Chile. The second largest brine operation is the nearby Albemarle mine of the same name. The third largest is the Salar del Hombre Muerto in Argentina operated by Livent.

Outside of South America, China is the next largest brine producer from several salars, although they have high magnesium to lithium ratios. Its two largest primary sources of domestic brine production are in Qinghai and Tibet.

Figure 26. Brine Evaporation at Sal de Vida Project, Argentina



Source: Allkem

Production from Sedimentary Rocks

Several companies are exploring the extraction of lithium from sedimentary rocks and clay. Clay projects include Thacker Pass (American Lithium) and Sonora (Ganfeng Lithium) in Nevada. These sedimentary deposits are lower grade than hard rock deposits but are very large and more easily mineable. The shallow and massive nature of the deposit makes them amenable to open-pit mining methods. Drilling and blasting may or may not be necessary.

Production from Other Brines

Work is also underway assessing the potential to extract lithium from brines associated with geothermally active areas and oilfields, where brines are currently extracted as a waste product from underground formations, along with oil and gas, and usually reinjected underground. These deposits tend to have grades of 0.01-0.04% lithium. This requires the application of DLE (discussed below). Brine is pumped from a series of extraction wells to a processing unit.

Geothermal brines with higher brine temperatures can be beneficial for reducing costs for some technologies (through the sale and use of intrinsic energy for processing). However, very hot brines like those at the Salton Sea in the US have much more challenging geochemistry because the higher temperatures cause higher concentrations of more problematic elements such as transition metals and silica.

Processing of Lithium Minerals

Lithium concentrates from hard-rock mining are transported offsite and processed elsewhere, while lithium brine is initially processed in evaporation ponds close to the site of the extraction wells.

Processing of Hard-rock Lithium Ore

In 2020, more than 95% of the conversion from spodumene-concentrates into lithium carbonate and/or lithium hydroxide took place in China. The most widely used process in the industry in China is the acid-roast process and the use of sulfuric acid. This process generates huge quantities of waste residue and is energy intensive as it requires high-temperature pre-treatment. In attempts to replace the acid-roast process, there are new technologies in development to recover lithium carbonate and lithium hydroxide directly from high quality spodumene concentrates as well as other types of lithium concentrates.

The acid leaching process involves high-temperature calcination of the concentrate at about 1,100 ^{o}C to improve the solubility of spodumene in acids, followed by acid digestion at 200-250 ^{o}C with sulfuric acid. Lithium from spodumene forms lithium sulphate, which is soluble in water; thus, a downstream water leaching step produces a solution of lithium sulphate. Impurities are removed by filtration, precipitation, and ion-exchange techniques. Finally, the recovery of lithium from the liquor is carried out by adding a carbonate donor like sodium carbonate (Na_2CO_3) at 80-100 ^{o}C to precipitate insoluble lithium carbonate (carbonation step). The purity of lithium carbonate can improve through a series of re-dissolution/precipitation/ion exchange steps to achieve up to 99.9% grade.

Industry-grade lithium carbonate generally has a purity of 98.5-99.0%, while battery-grade lithium carbonate must have a higher purity of at least 99.5%.

Other metallurgical methods for recovery of lithium from hard-rock ores include the autoclave carbonate leaching and the lime leaching method.

Evaporation Processing of Continental Brines

From the salar extraction wells, the brine is diverted to an evaporation pond system. Using solar evaporation, the lithium salts are concentrated in the brine and eventually routed to the next pond in the system. This step repeats multiple times, until the lithium concentration reaches a level high enough for extraction of lithium carbonate. During the evaporation process, the lithium concentration increases from about 200 ppm to up to 6% lithium in the final brine. The entire concentration process can take 12 to 18 months.

Salars are exposed to different weather conditions (such as evaporation rates, precipitation rates, wind patterns, and ambient temperatures), all of which influence the ability to economically recover lithium from the salar. The process may slow down due to rain or flooding, which is a common occurrence.

Lithium carbonate production from brine undergoes processing with the use of reagents at integrated facilities away from the salar and evaporation ponds. The lithium brine processing initially produces lithium carbonate, although it can be further processed to produce lithium hydroxide.

Brine processing methods vary considerably, depending on the overall chemistry. In the basic process, the concentrated lithium-rich brine is treated with sodium carbonate to precipitate a lithium carbonate slurry. After filtering, washing, and drying, a pure lithium carbonate product is obtained. Potassium, magnesium, and boron salts may be recovered as co-products.

Lithium chloride and lithium hydroxide can be produced via different processing routes. The chemical-grade mineral concentrates undergo additional processing in refining plants to produce a variety of higher-grade lithium chemicals (as required for batteries) or lithium metal. The main by-products are potash, used by the fertiliser industry, and bischofite, used for road paving.

DLE Processing of Continental Brines

A number of new projects are planning the use of DLE for lithium extraction from salars. DLE is already being used at some operations but on a small scale. Livent is currently using sorbent DLE to extract lithium chloride from its Catamarca brine operation in Argentina. In China, a significant amount of experimentation is reported to have occurred across the Qinghai lithium brinefield where DLE processes have been tested by different groups to produce lithium chloride from waste brines of evaporative brine facilities. Third-party DLE technology companies include Lilac, SunResin, IBAT, and Summit Nanotech.

While some success has been achieved at pilot-scale plants, many industry commentators point out that the economics of DLE for mainstream production at commercial scale are still uncertain and technical challenges remain, including freshwater consumption levels and brine reinjection.

Nevertheless, it is apparent that lithium extraction and recovery from geothermal brines is becoming technically possible and at least 45 different DLE technology solutions are under development which may be incorporated into new lithium brine projects in development. Many companies have developed their own proprietary extraction technologies, while adsorbent-type DLE technologies are commercially available from several suppliers. Meanwhile, a number of projects are advancing toward commercial production.

The three main types of DLE are adsorption, ion exchange, and solvent extraction. They are fundamentally different, and different technology solutions are being developed within each category.

- The most well-investigated and technologically advanced method for DLE from brines is **adsorption** by metal oxides and hydroxides.
- Processes based on precipitation and common **ion-exchange** resins can extract lithium from brines but are not specific to lithium and therefore are not practical for economical lithium extraction from geothermal brines, which have very complex chemistry.
- **Solvent extraction** of lithium from brines using lithium-selective solvents and sorption using organic polymer sorbents, including metal-imprinted polymers, are technologies that show promise.

Potential benefits of DLE for brine deposits compared with the evaporative processes include a significantly reduced physical footprint, up to 90% lithium recovery compared with 30-50% for conventional evaporation ponds, reduced water consumption, and a shorted expected lead time to production.

Evidence of DLE application for salar brines includes SQM moving to DLE technology at Salar de Atacama in Chile with a US$1.5bn investment. Eramet is constructing an adsorption brine project in Argentina at Centenario, and Rio Tinto acquired Rincon Mining for US$825m which owns the Rincon adsorption brine project, also in Argentina. Chile's recent National Lithium Policy calls for new lithium projects to implement DLE for environmental concerns.

A recent report on DLE from Goldman Sachs suggests that the higher upfront capital intensity of DLE compare with conventional evaporation ponds is offset by lower unit costs resulting from higher production on improved lithium recovery.

Processing Oilfield and Geothermal Brines

Geothermal and oilfield brines could become a major new source of lithium around the world. The development of technology to enable DLE from brines will be very important for the exploitation of these new lithium resources as they are lower grade than salar brines. The South-West Arkansas project in the United States has a grade of 310 mg/l lithium, Vulcan in Germany 181 mg/l, Lanxess in the United States 168 mg/l, Clearwater in Canada 75 mg/l, and Boardwalk in the United States just 68 mg/l.

At Clearwater's oilfield brine resource DLE ion-exchange technology will use a proprietary sorbent designed to be highly selective towards lithium ions. Lanxess, uses a stable, fine-grained solid adsorbent material to selectively extract lithium, and has been operating an industrial-scale fully integrated DLE demonstration plant since May 2020. Vulcan intends to use sorption technology and use low-cost energy from the geothermal operation. Recoveries are reported to be around 90%.

Processing Lithium Sedimentary Deposits

Generally, sedimentary lithium deposits are loosely bound and so do not always require calcination, allowing the lithium to be extracted using a chemical leach. Ore slurry can be processed in a leach circuit using sulfuric acid to extract the lithium from the lithium-bearing material. This is followed by an evaporation and crystallisation circuit, designed to concentrate lithium and remove sulphate salts and other impurities.

Lithium Hydroxide and Other Salts

To produce lithium hydroxide, in the typical processing route of acid leaching and before the carbonation step, the aqueous liquor after removal of impurities may undergo electrodialysis to produce a lithium hydroxide solution, and crystallisation to form a high-purity lithium hydroxide product. Alternatively, lithium hydroxide is produced by a chemical reaction between lithium carbonate and calcium hydroxide.

Lithium chloride is mainly produced in brine operations, by treating lithium carbonate with hydrochloric acid. Lithium bromide is produced from lithium carbonate after treatment with hydrobromic acid. Lithium metal is obtained by electrolysis of lithium chloride and potassium chloride mixture, in the form of ingots, rods, foils, granules, and powders. Finally, butyl-lithium and other organolithium compounds are produced from lithium metal.

Appendix 3 – Lithium-ion Battery Technology

This appendix provides an overview of lithium-ion battery technology and developments.

Batteries power everything from hand tools to electric vehicles (EVs). There are multiple battery chemistries, but lithium-ion batteries are currently the most widely used rechargeable batteries. Strong demand for these batteries is being driven by the growth in demand for EVs, which has resulted in significant innovation in battery technologies, leading to increased driving ranges and faster charging. The demand for energy storage systems (ESS) is also increasing battery demand.

EV Adoption and Growth

EV adoption is accelerating rapidly, with worldwide EV purchases increasing from around 1 million in 2017 to 10.4 million in 2022. In Europe and North America buyers are mainly affluent early adopters, but in China low-end models have attracted young, first-time car buyers. Sales increased by 55% in 2022 from 2021, despite supply chain disruptions, macro-economic and geopolitical uncertainty, and high commodity and energy prices and the growth in EV sales took place in the context of globally contracting auto markets.

EV sales are surging due to a combination of policy support, improvements in battery technology, the increased availability of charging infrastructure, and new compelling models from automakers. The use of batteries is also expected to increase in other sectors of road transport, and in air transport and stationary energy storage.

However, with the increase in adoption government policies are changing from giving financial support to implementation through tougher regulations. Many of the world's major cities have restricted zones for high polluting vehicles. Meanwhile, stringent fuel efficiency standards and challenging emissions targets for new cars also aim to drive people towards EVs. Countries representing over 50% of global car sales have expressed intent to be carbon neutral and phase out internal combustion engine (ICE) vehicles, although the deadlines for their ambitions vary. As examples, national bans on the purchase of ICE vehicles are planned in the UK and Germany by 2030, France by 2040, and California by 2035. Furthermore, increased long-term investment from auto manufacturers, and shifting consumer sentiment all suggest rapidly rising EV adoption. As at the end of 2020 there were 244 battery EVs and 126 plug-in hybrid vehicles models available globally, and by the end of 1H22 this had risen to 318 and 145 models, respectively.

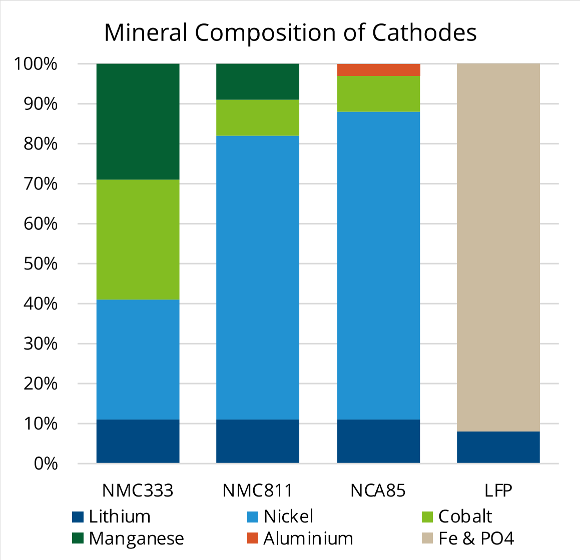
A variety of different types of hybrids and EVs are expected to become dominant in future transportation systems. These vehicles can use a range of battery technologies, with lithium- or nickel-based batteries providing propulsion functionality in full hybrids, plug-in hybrids, and full electric vehicles. Demand for lithium-ion batteries for EVs will be strongly influenced by the rate of growth of electric vehicle fleet sizes.

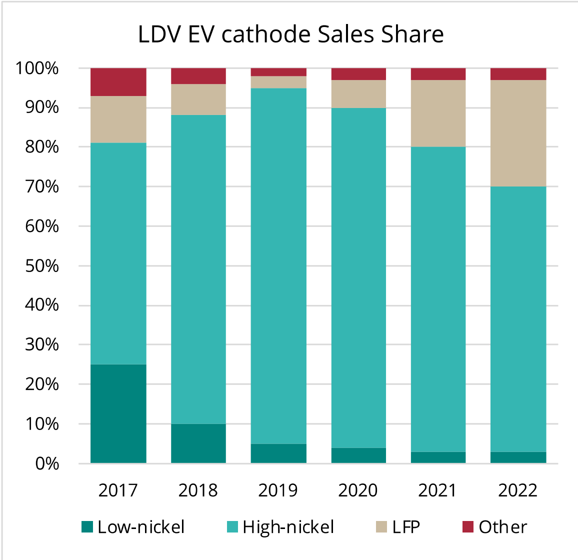
Lithium-ion Battery Basics

Lithium-ion batteries are high energy-density, re-chargeable power sources, especially important to all mobile applications and, importantly, are capable of high discharge rates to achieve powerful acceleration in EVs. The continued increase in production volume and improvements in technology of lithium-ion batteries, have allowed lithium-ion battery prices to decrease significantly over the past decade, although price increases did occur in 2022 following a sharp increase in commodity prices.

As the demand for lithium-ion batteries has grown, batteries have been developed that are not only cost-effective but also safe, reliable, fast charging, and with a long lifespan. The four main components of a lithium-ion cell are the cathode, anode, liquid electrolyte, and separator with the cathode material being one of the most critical components. This determines the battery's capacity, energy density, and cycle life. Lithium salts produced for batteries require a higher purity of product and usually designated as 'battery-grade'.

Figure 27. Mineral Composition of Different Battery Cathodes and Market Shares of Sales





Source: IEA – Global Supply Chains of EV Batteries July 2022.

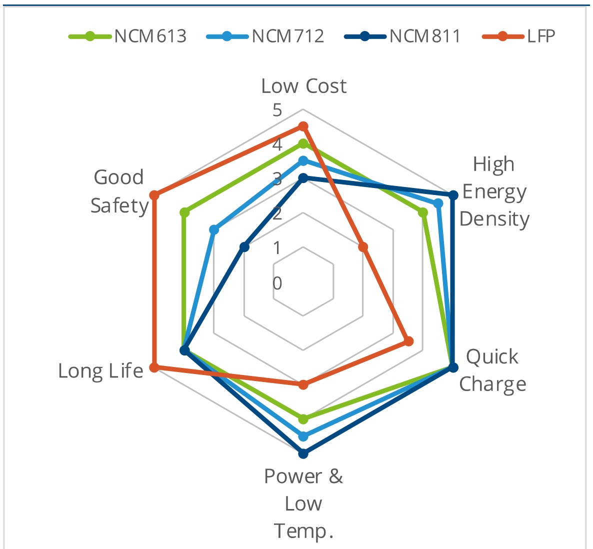
Lithium-ion batteries are often categorised by the chemistry of their cathodes. The most common lithium-ion battery types for EV applications are nickel manganese cobalt (NMC), lithium iron phosphate (LFP), nickel cobalt aluminium (NCA), and lithium manganese oxide (LMO). For mobile phones, laptops, and other handheld equipment, lithium cobalt oxide (CBO) batteries are generally used for their high specific energy. Figure 27 shows the mineral composition of different battery cathodes and market shares of sales.

In recent years, the most promising lithium battery technologies that have emerged are nickel cobalt manganese (NCM) and lithium iron phosphate (LFP). Both NCM and LFP batteries have their own unique strengths and limitations, and the choice of which type to use depends on the specific application, but these two are the main types of battery currently being produced and planned for future production for EVs. NCM chemistries are usually followed by three numbers which denotes the relative proportion of each of the three metals in the battery.

High nickel chemistry batteries, such as NCM811, have a higher energy density and usually use lithium hydroxide in the cathode. NCM622 cathodes use either lithium hydroxide or carbonate, while lower nickel-bearing NCM cathodes use lithium carbonate. LFP batteries, which have a lower energy density, use lithium carbonate in the cathode. Figure 28 shows a spider chart of NCM and LFP properties.

One of the key advantages of NCM batteries is their high specific energy, which refers to the amount of energy stored per unit of weight. NCM batteries have a specific energy of around 200-250 Wh/kg, which is higher than other types of lithium-ion batteries. LFP batteries have a specific energy of around 140-160 Wh/kg but have a high thermal stability and long cycle life and are lower cost.

Figure 28. Spider chart LFP and NCM



Source: The Battery Report 2023 – Volta Foundation

New Battery Technology

In recent years, there have been several significant developments in lithium-ion battery technology that have the potential to improve energy densities, charging times, and battery life. These newer technologies either involve new battery components or products, new manufacturing processes, or establishing new raw material supply chains. Their success will be determined by how easily they can be scaled up and integrated into current manufacturing technology and processes. At the same time, thrifting of raw materials is likely to occur.

One incremental new technology is a variant of the LFP battery, the lithium-manganese-iron-phosphate (LFMP) battery which could provide a higher density than conventional LFP. Mass production is expected to start in 2024.

Solid-State Lithium Battery

One of the most notable developments is the solid-state battery. Traditional lithium-ion batteries use a liquid electrolyte to facilitate the movement of lithium ions between the cathode and anode. Solid-state batteries, use a solid lithium electrolyte, and usually a lithium anode. These offer several advantages over traditional liquid electrolytes and could increase the longer-term demand for lithium.

Firstly, they are safer, as there is no risk of the electrolyte leaking or catching fire. Secondly, they have higher energy density. Thirdly, they have a longer lifespan, as the solid electrolyte is less prone to degradation than the liquid electrolyte.

BNEF estimates that 45 to 130% more lithium would be needed on a battery cell level if the solid-state electrolyte were to substitute both the liquid electrolyte and separator. Solid electrolytes contain more lithium due to slower diffusion of lithium ions through the solid electrolyte than a liquid one.

Companies such as QuantumScape, Solid Power, Factorial Energy, Bolloré, Panasonic, Samsung, ProLogium, and Hydro Québec are moving forward in their development, although they may see limited mainstream uptake initially due to cost and manufacturing limitations at present.

Silicon Anodes

Nearly all current commercial lithium-ion batteries use graphite as an anode material. Silicon is currently considered to be the most promising anode material to replace graphite due to its higher theoretical capacity. Silicon-based lithium-ion battery anodes could store ten times as much charge in each volume than graphite anodes if they could be applied. However, silicon undergoes significant volume changes during the electrochemical cycles that results in rapid capacity degradation of the battery.

In the past three years, battery makers have begun to use anodes made from carbon mixed with silicon which increases the specific capacity and energy density compared with pure graphite. This type of anode has already started to become more mainstream and the outlook by Benchmark MI is for silicon to comprise around 7% of anode materials by 2030.

Next Generation Battery Technology

Next generation battery technology is well advanced, with developments being led by the large Chinese battery companies. The two most recent developments are the sodium-ion battery and potentially game-changing condensed battery.

Sodium-ion Battery

Sodium-ion batteries typically have a cell energy density of 100 to 150 Wh/kg. However, in July 2021, CATL unveiled its first-generation sodium-ion battery, with a cell energy density of 160 Wh/kg. The battery is fast charging and operates well in low temperature environments. It added that CATL's next generation sodium-ion battery energy density would exceed 200 Wh/kg and that the company has already started industrial deployment of the sodium-ion battery. CATL also highlighted that existing lithium-ion battery manufacturing process and equipment could be used to produce the sodium-ion batteries.

Industry commentators suggest that while sodium-ion batteries have a lower power density than LFP, they could be in the order of 30% lower in cost due to the abundant resources of sodium. The cathode comprises a material called Prussian White ($Na_2Fe[Fe(CN)_6]$) and used in combination with a new hard carbon anode with a unique porosity structure better suited to sodium ions. CATL indicate that they could be used in mixed call packs in combination with lithium-ion cells which would improve the overall energy and power density of the battery pack but could be produced at a lower cost. We expect sodium-ion batteries to be used for small and compact EVs as well as for two- and three-wheel EV markets and energy storage systems and take market share from LFP batteries and are a negative for the lithium market.

In China, sodium-ion batteries are being used on a limited test basis in an electric car manufactured by Hina in a joint venture with JAC and Volkswagen Anhui. The battery pack uses sodium-ion cells with an energy density of 140 Wh/kg. In April 2023, CATL announced that its first sodium-ion battery would be used to power Chery EV models.

Condensed Battery

In April 2023, at Auto Shanghai, CATL launched its latest high energy battery, the condensed battery, which it states will open up a new scenario of electrification centred on high level of safety and light weight. With an energy density of up to 500 Wh/kg, it can achieve high energy density and high level of safety at the same time in a "creative manner". It is currently being aimed at opening up the electrification market for passenger aircraft. In addition, CATL will also launch an automotive-grade version of condensed batteries, which are expected to be put into mass production within this year.

The company released limited details of the battery and only gave a somewhat superficial and jargon-filled description of the technology. CATL stated; "the condensed battery leverages highly conductive biomimetic condensed state electrolytes to construct a micron-level self-adaptive net structure that can adjust the interactive forces among the chains, thus improving the conductive performance of the cells and in turn the efficiency of lithium ion transporting while boosting stability of the microstructure. In addition, the condensed battery integrates a range of innovative technologies, including the ultra-high energy density cathode materials, innovative anode materials, separators, and manufacturing processes, offering excellent charge and discharge performance as well as good safety performance." A key positive takeaway for the lithium market is that this new battery will be a lithium-ion battery. We expect the condensed battery will be used for autos at the top end of the market.

Appendix 4 – Lithium Mines & Projects

Table 11. Current Lithium Mines – Forecast Production Un-Risked.

	Project	Country	Owner/ Operating Company	Forecast Prodn LCE 2025 kt/y	Forecast Prodn LCE 2030 kt/y	Resource LCE Mt	Grade % Li_2O mg/l Li
1	Greenbushes	Australia	Albemarle/Tinaqi/IGO	253,433	376,885	10.745	1.68
2	Salar de Atacama	Chile	SQM	210,000	210,000	49.423	1,840
3	Mount Marion	Australia	Ganfeng/Mineral Res.	120,000	120,000	1.840	1.45
4	Pilgangoora	Australia	Pilbara Minerals	100,898	140,961	8.655	1.15
5	Wodgina	Australia	Albemarle/Mineral Res	110,000	110,000	5.239	1.15
6	Grota do Cirilo	Brazil	Sigma Lithium	95,619	105,276	3.033	1.43
7	Salar de Atacama	Chile	Albemarle	84,000	84,000	0.018	0.46
8	Sd Hombre Muerto	Argentina	Livent	65,000	100,000	11.818	740
9	Olaroz	Argentina	Allkem/Toyota Tsusho/ Jujuy	25,000	42,500	20.662	648
10	Cauchari-Olaroz	Argentina	Ganfeng/Lithium Americas/ Jujuy	40,000	40,000	24.574	592
11	Tanco	Canada	Sinomine Res.	16,322	37,095	0.151	3.15
12	Bikita	Zimbabwe	Bikita Minerals	34,000	34,000	1.128	1.13
13	NA Lithium	Canada	Sayona Mining/ Piedmont Lithium	30,000	30,000	1.766	1.23
14	Chaerhan Lake	China	Qinghai Salt Lake	24,854	24,854	13.849	-
15	Arcadia	Zimbabwe	Zhejiang Huayou	21,800	21,800	1.997	1.11
16	Finniss	Australia	Core Lithium	23,123	20,130	0.997	1.31
17	Mibra	Brazil	AMG Critical Materials	19,289	19,289	-	-
18	Zulu	Zimbabwe	Premier African Min.	6,352	12,464	0.527	1.06
19	East Taijinair	China	Western Mining	10,250	10,250	0.484	-
20	Qinghai Yiliping	China	China Minmetals	10,000	10,000	-	-
21	Silver Peak	USA	Albemarle	10,000	20,000	-	-
22	Rincon	Argentina	Argosy Minerals	7,000	10,000	0.245	325
23	Yichun	China	Yichun Tantalum	9,787	9,787	-	-
24	Qarhan Lake	China	Zangge Mining	9,400	9,400	-	-
25	Jiajika	China	Youngy Investment	6,098	6,098	-	-
26	Cachoeira	Brazil	Co. Brasileira de Lítio	5,700	5,700	-	-
27	West Taijinair	China	CITIC Guoan	5,000	5,000	2.349	-
28	Zhabuye	China	Tibet Mineral Dev.	5,000	5,000	1.620	-
29	Alvarroes	Portugal	Grupo Mota	1,800	1,800	0.126	0.87
30	Jintaier Lake	China	Qinghai Hengxin	1,000	1,000	-	-
31	Mt Cattlin	Australia	Allkem	30,000	-	0.411	1.30
	Total			1,390,725	1,623,289	**162.701**	

Source: RFC Ambrian, company data.

Table 12. Lithium Projects - Under Construction – Forecast Production Un-Risked.

	Project	Country	Owner/ Operating Company	Forecast Prodn LCE 2025 kt/y	Forecast Prodn LCE 2030 kt/y	Resource LCE Mt	Grade % Li_2O mg/l Li
1	Goulamina	Mali	Ganfeng/Leo Lithium	96,951	107,724	7.149	1.37
2	Kathleen Valley	Australia	Liontown Res.	81,194	90,215	5.174	1.34
3	Thacker Pass	USA	Lithium Americas	-	76,000	19.141	0.44
4	Sal de los Angeles	Argentina	Tibet Summit Res.	20,000	50,000	2.049	490
5	Sal de Vida	Argentina	Allkem	10,000	44,654	6.845	0.16
6	Mt Holland	Australia	Wesfarmers/SQM	39,747	44,163	6.719	1.52
7	Centenario-Ratones	Argentina	Eramet/Tsingshan	9,600	24,000	9.929	436
8	Tres Quebradas	Argentina	Zijin Mining	20,000	20,000	7.723	790
9	Keliber	Finland	Sibanye Stillwater	6,600	13,200	0.370	1.03
10	Mariana	Argentina	Ganfeng Lithium	8,500	17,000	8.116	315
11	Fort Cady	USA	5E Advanced Mats	-	4,989	0.307	0.07
	Total			**292,592**	**491,946**	**73.422**	

Source: RFC Ambrian, company data.

Table 13. Lithium Projects – Construction Planned – Forecast Production Un-Risked.

	Project	Country	Owner/ Operating Company	Forecast Prodn LCE 2025 kt/y	Forecast Prodn LCE 2030 kt/y	Resource LCE Mt	Grade % Li_2O mg/l Li
1	Uyuni Salt Flat	Bolivia	CM de Bolivia	-	50,000	96.447	400
2	James Bay	Canada	Allkem	41,131	45,701	1.395	1.40
3	Sonora	Mexico	Ganfeng Lithium	-	20,000	8.809	0.64
4	Nemaska	Canada	Livent/Quebec Prov.	-	31,477	1.724	1.30
5	Rose	Canada	Critical Elements	-	31,196	0.759	0.90
6	Pastos Grandes	Argentina	Lithium Americas	-	9,420	5.258	439
7	Vulcan	Germany	Vulcan Energy	-	21,120	26.584	181
8	Maricunga	Chile	Lithium Power Int.	6,080	13,680	2.886	953
9	Karibib	Namibia	Lepidico	-	1,531	153.7	0.51
10	Lijiagou	China	Sichuan Dexin Mining	-	26,708	-	-
	Total			**47,211**	**224,125**	**144.016**	

Source: RFC Ambrian, company data.

Table 14. Lithium Projects – Feasibility Completed – Forecast Production Un-Risked.

	Project	Country	Owner/ Operating Company	Forecast Prodn LCE 2025 kt/y	Forecast Prodn LCE 2030 kt/y	Resource LCE Mt	Grade % Li_2O mg/l Li
1	Manono	DRC	AVZ Minerals/La CEM	-	103,866	16.530	1.62
2	Salar del Rincon	Argentina	Rio Tinto	1,500	50,000	8.337	393
3	Bougouni	Mali	Kodal Minerals	7,419	41,917	0.585	1.11
4	Carolina Lithium	USA	Piedmont Lithium	-	26,400	1.175	1.08
5	Rhyolite Ridge	USA	Ioneer	-	24,000	3.331	0.37
6	Paradox	USA	Anson Resources	-	13,074	1.039	0.03
7	Zinnwald	Germany	Zinnwald Lithium	-	10,570	0.757	0.76
8	Wolfsberg	Austria	European Lithium	-	7,744	0.319	1.00
	Total			**8,919**	**277,571**	**32.072**	

Source: RFC Ambrian, company data.

Table 15. Lithium Projects – PEA/PFS Completed – Forecast Production Un-Risked.

	Project	Country	Owner/ Operating Company	Forecast Prodn LCE 2025 kt/y	Forecast Prodn LCE 2030 kt/y	Resource LCE Mt	Grade % Li_2O mg/l Li
1	Jadar	Serbia	Govt. of Serbia	-	52,200	6.383	1.80
2	Kachi	Argentina	Lake Resources/Lilac	-	35,000	8.112	211
3	Pozuelos (PPG)	Argentina	Gangeng Lithium	20,000	50,000	1.651	489
4	TLC	USA	American Lithium	-	36,500	10.688	0.17
5	Falchani	Peru	American Lithium	-	36,154	11.623	1.46
6	Ewoyaa	Ghana	Atlantic Lithium	-	33,534	1.090	1.25
7	Bonnie Claire	USA	Iconic/Nevada Lithium	-	32,300	18.369	0.22
8	Zeus	USA	Noram Lithium	-	31,900	6.265	0.20
9	Manna	Australia	Global Lithium	-	29,923	0.819	1.01
10	Boardwalk	Canada	LithiumBank Res.	-	27,588	6.205	68
11	Clayton Valley	USA	Century Lithium	-	27,400	7.237	0.19
12	Pioneer Dome	Australia	Essential Metals	-	27,272	0.319	1.16
13	SW Arkansas	USA	Standard Lithium	-	26,400	1.195	310
14	Barroso	Portugal	Savannah Res.	-	25,979	0.721	1.04
15	Cinovec	Czechia	CEZ/European Metals	-	25,860	7.394	0.42
16	Lanxess	USA	Standard Lithium	8,360	20,900	3.140	168
17	HMW/Candelas	Argentina	Galan Lithium	4,000	38,000	7.260	946
18	Laguna Verde	Chile	CleanTech Lithium	-	20,000	1.512	206
19	Pakeagama Lake	Canada	Frontier Lithium	-	18,378	2.178	1.50
20	Clearwater	Canada	E3 Lithium	-	17,600	16.920	75
21	San Jose	Spain	Infinity Lithium	-	17,160	1.682	0.61
22	Georgia Lake	Canada	Rock Tech Lithium	-	13,222	0.335	0.91
23	Sirmac	Canada	Vision Lithium	-	11,907	0.011	1.33
24	Clayton Valley	USA	Schlumberger	-	9,064	0.218	123
25	Separation Rapids	Canada	Avalon Adv. Materials	-	8,987	0.351	1.39
26	Trelavour	UK	Cornish Lithium	-	6,600	0.303	0.24
27	Hombre Muerto North	Argentina	Lithium South Dev./Sino Lithium	-	5,000	0.571	756
	Total			**32,360**	**679,828**	**122,552**	

Source: RFC Ambrian, company data.

Table 16. Lithium Projects – Resource >100 kt LCE

	Project	Country	Owner/ Operating Company	Forecast Prodn LCE 2025 kt/y	Forecast Prodn LCE 2030 kt/y	Resource LCE Mt	Grade % Li_2O mg/l Li
1	McDermitt	USA	Jindalee Resources	NA	NA	21.480	0.29
2	Prairie Lithium	Canada	Prairie Lithium	NA	NA	4.100	111
3	Salar de Tolillar	Argentina	Alpha Lithium	NA	NA	3.279	221
4	Kings Mountain	USA	Albemarle	NA	NA	2.752	1.24
5	Salar de Arizaro	Argentina	Lithium Chile	NA	NA	2.587	296
6	Rio Grande	Argentina	Pluspetrol Res.	NA	NA	2.190	374
7	St Austell	UK	British Lithium	NA	NA	2,150	0.54
8	Clayton Valley	USA	Spearmint Res.	NA	NA	2.092	0.18
9	Moblan	Canada	Sayona Mining/SOQUEM	NA	NA	2.007	1.15
10	Fox Creek	Canada	Empire Metals	NA	NA	1.926	88
11	Laguna Verde Salar	Chile	CleanTech Lithium	NA	NA	1.500	206
12	Colina	Brazil	Latin Resources	NA	NA	1.498	1.34
13	Salar Ollague	Chile	Lithium Chile	NA	NA	1.441	180
14	Viewfield & Mansur	Canada	EMP Metals	NA	NA	1.158	143
15	Bald Hill	Australia	Alita Resources	NA	NA	0.655	1.00
16	Sal de la Puna	Argentina	Arena Min./Ganfeng	NA	NA	0.564	460
17	Marble Bar	Australia	Global Lithium Res.	NA	NA	0.445	1.00
18	Salinas	Brazil	Latin Resources	NA	NA	0.396	1.21
19	Buldania	Australia	Liontown Res.	NA	NA	0.359	0.97
20	Bitterwasser	Namibia	Private Interest	NA	NA	0.327	0.13
21	Big Sandy	USA	Arizona Lithium	NA	NA	0.321	0.40
22	Thompson Bros	Canada	Snow Lake Res.	NA	NA	0.273	1.00
23	Seymour Lake	Canada	Green Tech Metals	NA	NA	0.256	1.04
24	Salta Lithium	Argentina	Power Minerals	NA	NA	0.249	198
25	Sutti	Mexico	Silver Valley Metals	NA	NA	0.242	0.08
26	Sd Salinas Grandes	Argentina	Pluspetrol Res.	NA	NA	0.239	795
27	Mavis Lake	Canada	Critical Resources	NA	NA	0.213	1.08
28	Burro Creek	USA	Anglo Design Hold.	NA	NA	0.185	0.18
29	Manono Tailings	DRC	Tantalex Lithium	NA	NA	0.178	0.59
30	Alberta II	Spain	Can. GoldCamps	NA	NA	0.134	0.44
31	Uis Tailings	Namibia	Montero Mining	NA	NA	0.132	0.31
32	Reung Kiet	Thailand	Pan Asia Metals	NA	NA	0.113	0.44
33	Root Lake	Canada	Green Tech. Metals	NA	NA	0.111	1.00
	Total					**55.554**	

Source: RFC Ambrian, company data.

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