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CRITICAL MATERIALS FOR THE ENERGY TRANSITION:

LITHIUM

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BY DOLF GIELEN AND MARTINA LYONS

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ABBREVIATIONS

Al	aluminium
BNEF	Bloomberg New Energy Finance
CAGR	compound annual growth rate
CATL	Contemporary Amperex Technology Co. Ltd.
DLE	direct lithium extraction
DOE	US Department of Energy
EV	electric vehicle
Fe	iron
GWt	gigawatt hours
H_2SO_4	sulphuric acid
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
kt	thousand tonnes
kWh	kilowatt hours
LCE	lithium carbonate equivalent
LFP	lithium iron phosphate
Li	lithium
LIB	lithium–ion battery
Li_2O	lithium oxide
Li_2CO_3	lithium carbonate
Li-NMC	lithium–nickel–manganese–cobalt
LiOH	lithium hydroxide
Mt	million tonnes
NMC	nickel–manganese–cobalt
Pb	lead
PHEV	plug-in hybrid electric vehicle
ppm	parts per million
SMM	Shanghai Metals Market
SQM	Sociedad Química y Minera
tCO_2	tonnes of CO_2
tCO_2/t	tonnes of CO_2 per tonne
tLCE	tonnes of lithium carbonate equivalent
V	Volt
VW	Volkswagen
WETO	World Energy Transition Outlook
Wh	Watt hours
Zn	zinc

EXECUTIVE SUMMARY

Lithium is critical to the energy transition. The lightest metal on Earth, lithium is commonly used in rechargeable batteries for laptops, cellular phones and electric cars, as well as in ceramics and glass. Although sodium-based batteries are under development, it is likely that lithium will remain the metal of choice for the foreseeable future as requirements are relatively independent of specific battery composition.

Lithium prices have risen significantly in recent months to new record levels. This follows several years of low prices due to oversupply. It is likely that prices will remain high for some time as supply growth lags behind demand growth.

Lithium is produced from brine or from hard-rock ore. Whilst ore production dominates, both supply types are growing. Australia and Chile dominate today's mining, but new mines are being developed in many countries across the world. Brine resources are concentrated in the region where Argentina, Plurinational State of Bolivia (Bolivia) and Chile meet, as well as in China. Spodumene resources are spread more widely and other types of lithium minerals, clays and geothermal resources widen the resource base further.

The processing of the mined lithium ore is concentrated in China, which accounts for more than half of all processing, most notably of spodumene ore. However, new processing capacity is being developed outside China close to alternative mining sites.

Battery grade lithium carbonate and lithium hydroxide are the key products in the context of the energy transition. Lithium hydroxide is better suited than lithium carbonate for the next generation of electric vehicle (EV) batteries.

Batteries with nickel–manganese–cobalt NMC 811 cathodes and other nickel-rich batteries require lithium hydroxide. Lithium iron phosphate cathode production requires lithium carbonate. It is likely both will be deployed but their market shares remain uncertain.

Battery lithium demand is projected to increase tenfold over 2020–2030, in line with battery demand growth. This is driven by the growing demand for electric vehicles. Electric vehicle batteries accounted for 34% of lithium demand in 2020 but is set to rise to account for 75% of demand in 2030.

Bloomberg New Energy Finance (BNEF) projections suggest a 27.7% EV share in passenger car sales in 2030, comprising 19 million battery electric vehicles and 6.8 million hybrid electric vehicles. This is a conservative estimate, as 2021 sales exceed this trajectory. More recent estimates suggest nearly 40 million BEV and plug-in hybrid sales by 2030.

In this projection, total lithium demand will increase from 0.4 Mt of lithium carbonate equivalents (LCE) in 2020 to 1.6–2 Mt LCE in 2030, a four- to five-fold increase. Further but more moderate growth is projected thereafter. In later decades, recycling can mitigate the need for primary material, and the development of circular economy concepts for batteries with high material recovery rates should be actively pursued.

The total resource base is around 400 Mt LCE, which is adequate, and mining capacity is coming onstream that can meet the growing demand. However, it is likely that not all mined material yields battery grade carbonate or hydroxide. This is a significant source of uncertainty and may result in a shortfall for some time.

Battery grade lithium hydroxide demand is projected to increase from 75 000 tonnes (kt) in 2020 to 1 100 kt in 2030. This market segment grows faster than total lithium and lithium carbonate demand due to a projected shift to nickel-rich cathodes.

It takes two to three years to build and optimise a battery factory or an EV plant, but it takes between five and ten years to build and optimise a mine, and currently the EV sector (EV and battery manufacturing) is raising capital at much faster rates than the raw materials sector.

Efforts to develop additional lithium production and processing capacity will therefore be required this decade. The main issue in this regard is quality assurance between lithium suppliers and battery producers. The mining, processing and battery manufacturing segments are dominated by a limited number of companies, and car manufacturers are now seeking to take stakes in these companies.

New supply projects are coming onstream in different parts of the world, which will ease geopolitical concerns. However, market structures warrant continuous monitoring to avoid dominance by individual parties.

The environmental footprints of both types of supply differ significantly and will require careful management as energy use and CO_2 emissions in lithium supply rise, presenting an opportunity to deploy more low-carbon renewable energy. There is also a need for more transparency in this nascent industry to better understand potential supply risks; therefore, sufficient international co-operation amongst the key governments involved is required to ensure that lithium will not become a bottleneck for the energy transition.

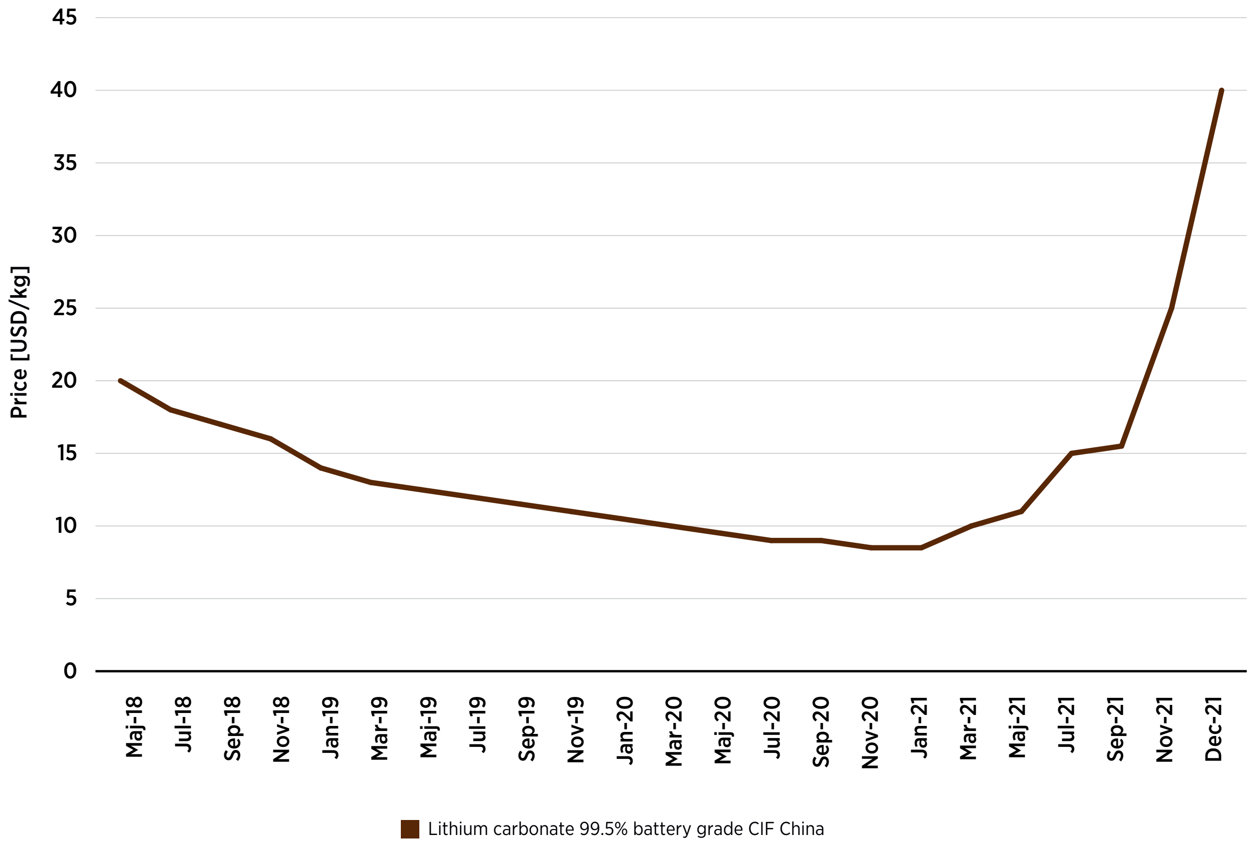
INTRODUCTION

An accelerated energy transition requires a growing supply of critical materials (Gielen, 2021) and IRENA's World Energy Transition Outlook (WETO) elaborates on the importance of batteries for the energy transition (IRENA 2021). As a key component in the transition, electromobility needs to become the dominant form of road transportation. Its success depends on the availability of affordable lithium-ion batteries. Stationary battery applications will also continue to grow; therefore, lithium supply needs to expand, and mining and materials processing industries need to be developed at an accelerated pace in way that is both environmentally and socially sound (IRENA, 2020).

Lithium prices have been rising sharply in recent months. This reflects rapidly growing demand due to the rapid growth in electromobility. This paper argues that this phenomenon will remain transient if the right enabling frameworks are put in place; lithium volumes are relatively small, compared to other commodities, and rising prices will result in new mining projects and new processing capacity. Only a few additional projects are required this decade to tilt the balance.

Following a prolonged slump, lithium carbonate prices have started to rise in recent months to around USD 40 per kilo, a four-fold increase over the past year (Fastmarkets, 2021). Prices of spodumene increased by 79% between July and September 2021 to a USD 2 240 per dry metric tonne (Lithium News, 2021).

Figure 1: Lithium carbonate price trends 2018–2021



Source: Fastmarkets, 2021.

Lithium is a critical material for the energy transition. Its chemical properties, as the lightest metal, are unique and sought after in the manufacture of batteries for mobile applications. Total worldwide lithium production in 2020 was 82 000 tonnes, or 436 000 tonnes of lithium carbonate equivalent (LCE) (USGS, 2021). Bloomberg NEF projects lithium consumption to range between 1.3 and 2.0 million tonnes LCE (240 000–375 000 of lithium) by 2030, a three- to five-fold increase from 2019 levels (BNEF, 2021a), primarily driven by rising demand from the EV industry (Kelly et al., 2021).

Around 40% of global lithium carbonate production is from brine-based resources, which is supplemented by ore-based (spodumene) production, both of which are expanding rapidly.

Lithium reserves are estimated at 17 Mt, whilst total lithium resources are thought to be around 80 Mt (c. 400 Mt LCE) (USGS, 2020). These resources are concentrated in Argentina, Bolivia and Chile (brine-based), Australia, Canada, China and the United States of America (USA) (spodumene-based).

New resources continue to be identified, including most recently in Germany, where lithium ore reserves are being developed in Saxony and geothermal resources in the Upper Rhine valley (NS Energy, 2021a, 2021b). Many other projects are under consideration in Europe in countries such as Austria, Portugal, Spain, the United Kingdom of Great Britain and Northern Ireland (UK) and Serbia. Also, outside Europe new projects are being developed or considered. In the USA, the Salton Sea in California alone could produce 0.6 Mt of lithium per year – more than today's global production. In this case, geothermal energy could be deployed for evaporation (Cantú, 2021). Seawater also contains lithium; however, at this point it is not economically feasible to extract lithium from seawater, as the lithium concentration is too low.

DEMAND PROJECTIONS

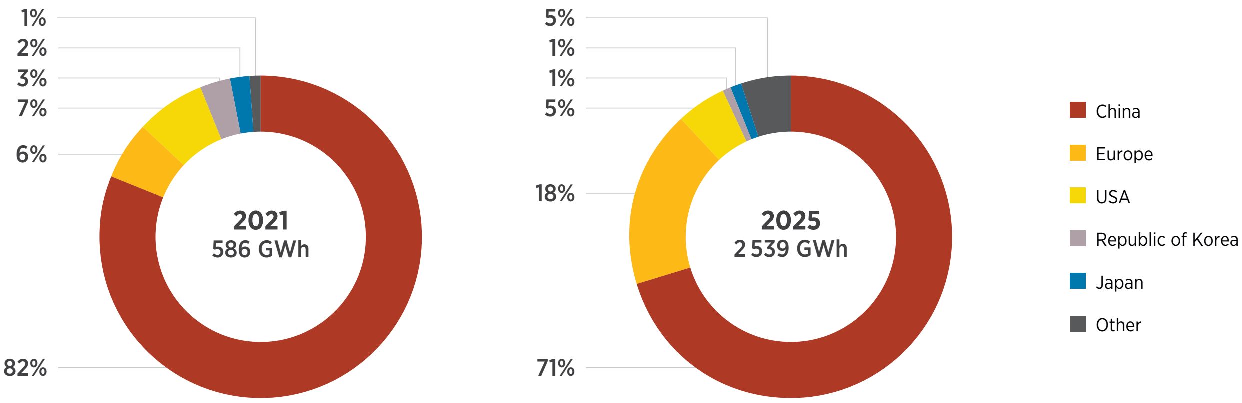
The global lithium compound market size reached a volume of 299 640 tonnes in the year 2020, or 0.4 Mt LCE. The market is expected to grow at a compound annual growth rate (CAGR) of 7.5% between 2021 and 2026 to reach a volume of 462 435 tonnes by 2026 (Research and Markets, 2021). The market consists of: lithium carbonate (Li_2CO_3); lithium hydroxide (LiOH);[1] lithium concentrate; lithium metal; lithium chloride; butyllithium and others. Lithium carbonate is the most popular compound on account of the huge demand for the product for the production of ceramics and glasses, battery cathodes and solid-state carbon dioxide detectors.

Although lithium markets vary by location, global end-use markets are estimated as follows: batteries, 71%; ceramics and glass, 14%; lubricating greases, 4%; continuous casting mould flux powders, 2%; polymer production, 2%; air treatment, 1%; and other uses, 6% (USGS, 2021). Battery demand includes laptops, mobile phones and EVs. Today's battery demand is still dominated by laptops and mobile phones, but electric vehicles will drive overall lithium demand this decade.

The best estimate for the lithium required is around 160g of Li metal per kWh of battery power, which equals about 850g of lithium carbonate equivalent (LCE) in a battery per kWh (Martin, 2017). This means a typical EV (with around 50 kWh battery capacity) will require around 40 kg of LCE. Therefore, a 2 000 GWh battery demand by 2030 (based on 40 million vehicles at 50 kWh/vehicle) would imply demand of 1.7 Mt LCE, to which 0.3 Mt of other demand must be added, yielding a total of 2 Mt LCE demand by 2030 – a four-fold increase from 2020 levels. Some sources quote much higher growth, but such numbers refer to battery applications alone, while mining requirements also need to be considered from resource perspectives.

Demand projections are uncertain due to the projected rapid growth of EV manufacturing (Figure 2). EV demand projections are rising fast. Whereas BNEF projected 1 769 GWh lithium-cell manufacturing capacity by 2030 in their 2020 outlook, it increased its projection to 2 538 GWh by 2030 in the latest projection (BNEF 2020, 2021). This means a four-fold increase in only four years, and lithium demand will rise in tandem with battery manufacturing. This strong growth is linked to EV sales projections of 32 million units by 2030 (BEV and plug-in hybrids). In this scenario, passenger cars and commercial EVs account for around 80% of vehicle battery sales (BNEF, 2020).

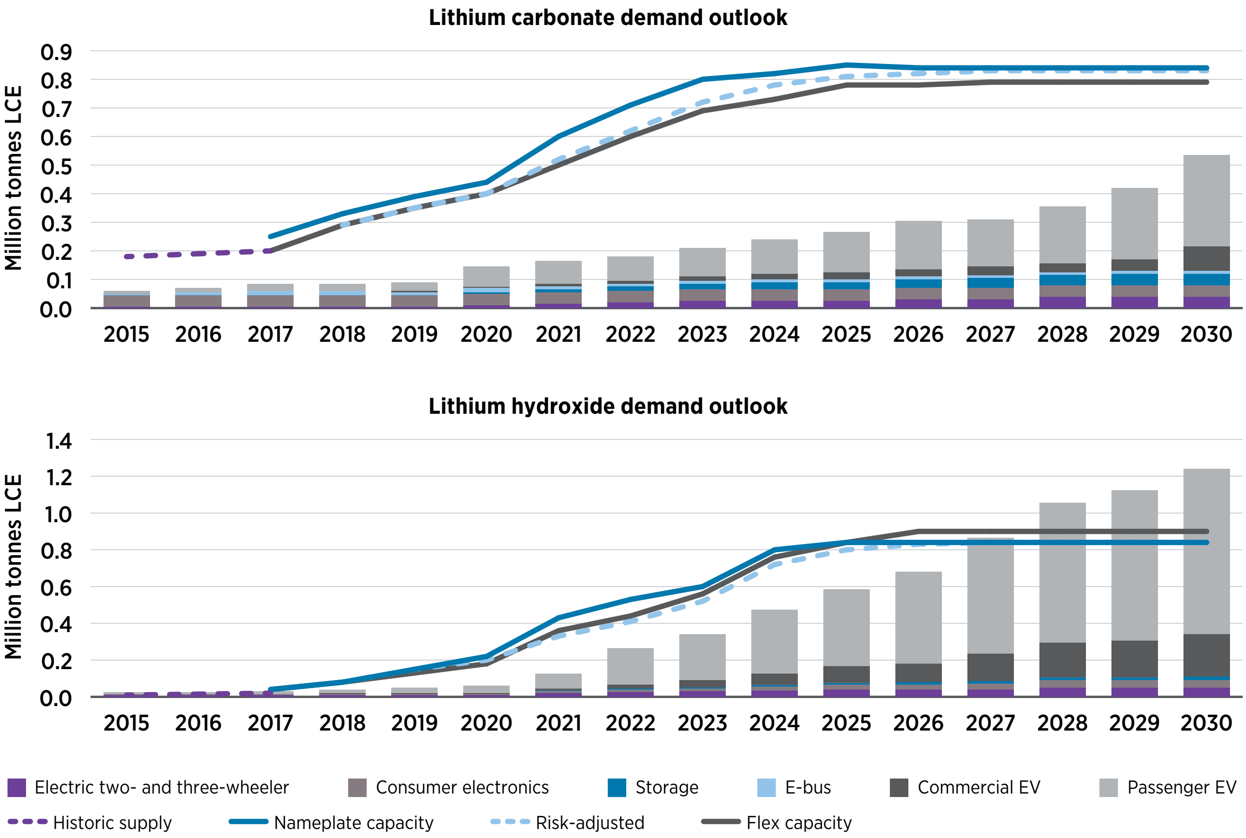
Figure 2: Lithium-cell manufacturing capacity by region of plant location



Source: BNEF, 2021.

1 Lithium hydroxide monohydrate ($LiOH \cdot H_2O$).

Figure 3: Lithium carbonate and lithium hydroxide demand outlook



Note: assumes 32 million passenger EV sales in 2030.

Source: BNEF, 2021.

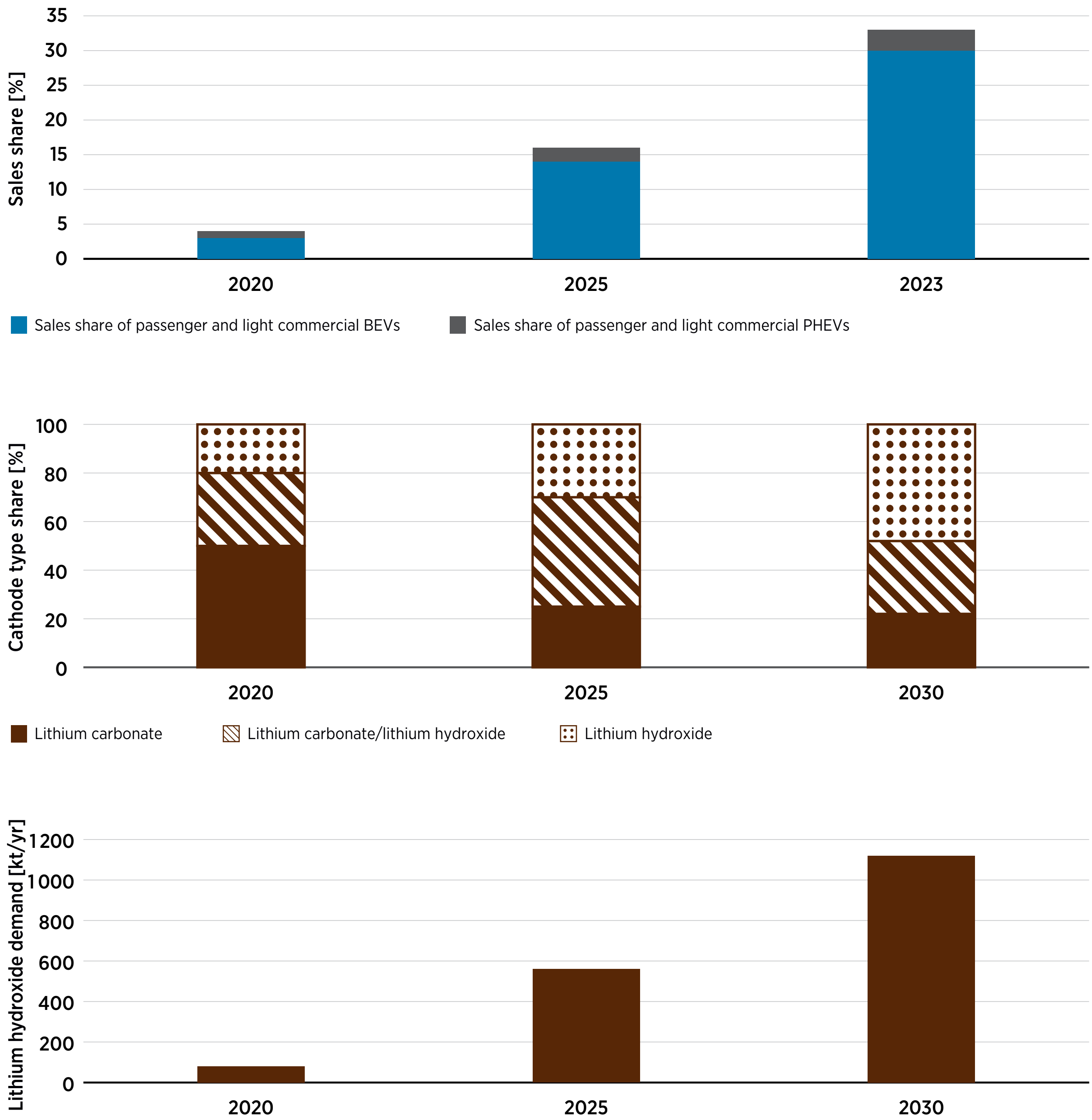
Already between 2020 and 2024, total lithium demand may grow 2.5-fold: total lithium metal production is expected to grow from 58.8 kt in 2020 to 134.7 kt in 2024 according to Global Data, driven by a quadrupling of EV production (2021); with the annual production of electric vehicles (EVs) set to grow from 3.4 million in 2020 to 12.7 million in 2024, and battery production growing from 95.3 GWh to 410.5 GWh over the same period, EV battery demand for lithium is expected to rise from a forecasted 47.3 kt in 2020 to 117.4 kt in 2024, at a 25.5% CAGR (Global Data, 2021).

Lithium carbonate and lithium hydroxide demand projections are shown in Figure 3. Around 0.75 Mt LCE is accounted for by carbonate demand and 1.25 Mt LCE by hydroxide demand for a total of 2 Mt LCE demand in 2030. This outcome depends on EV growth and battery technology assumptions, as high nickel cathode batteries require lithium hydroxide while lithium iron phosphate batteries require lithium carbonate. Cathode material created using lithium hydroxide requires less time and lower temperatures than that synthesised from lithium carbonate. The latter process also carries a higher risk of damage to the crystal structure of the cathode (Livent, 2021).

Figure 4 shows another projection from Livent, a lithium supplier. This suggests 1.1 Mt of lithium hydroxide demand by 2030, a twenty-fold increase form 2020 levels.[2] It should be noted that this projection implies the continued domination of high nickel cathodes; but this is balanced by a comparatively modest projection of 33% EV sales share in 2030.

2 Likely in LCE units, not specified.

Figure 4: Lithium hydroxide demand projection

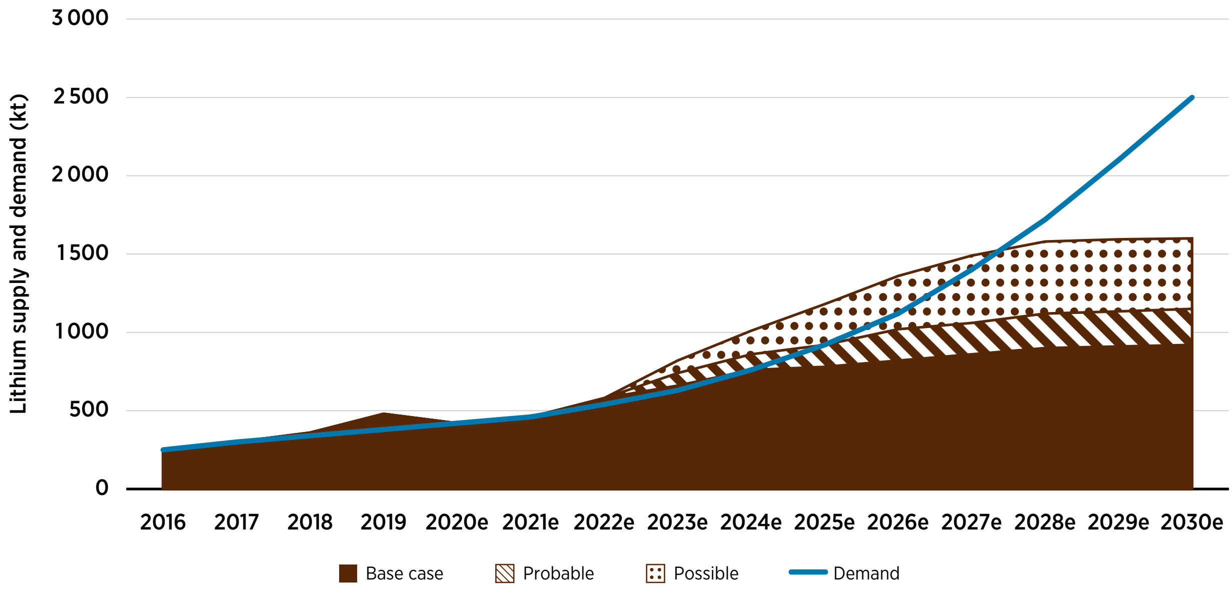


Source: Livent, 2021.

As industry shifts to high nickel cathodes, there will be a corresponding shift from lithium carbonate to lithium hydroxide. In 2020, around 50% of cathodes required lithium carbonate, 20% lithium hydroxide and 30% could employ either. The expectation is for a market that shifts to more high nickel cathodes (see also Figure 4). However, if Chinese and European markets favour lithium iron phosphate (LFP) due to the favourable cost structure and better safety, lithium carbonate may remain the dominant demand type. This uncertainty creates investment uncertainty (Barrera, 2019).

As Figure 5 illustrates, projects under development will yield around 1.7 Mt of supply by 2027. If EV sales develop as the latest projections suggest, there is a need to develop an additional 0.5–1 Mt of production capacity this decade. This investment is subject to uncertainty in terms of the type of lithium commodity that will be needed (carbonate of hydroxide) as well as the risk that EV sales do not develop accordingly.

Figure 5: Projected supply and demand balance for lithium



Source: Runkevicius, 2020, quoting UBS.

Note: e = estimated.

Box 1: Lithium specifications for processing

There are different purity requirements for lithium carbonate, ranging between 99.5% and 99.8%. Within that range, there is a significant spread of impurities; for instance, 150–650 ppm in sodium (Na), 30–300 ppm in chloride (Cl) and 150–500 ppm in sulphate (SO_4).

However, for some elements there is less variation. For instance, iron (Fe) is extremely deleterious in battery manufacture, with only 2–10 ppm allowable. Similarly, metals such as aluminium (Al), lead (Pb) and zinc (Zn) have very tightly-permitted concentrations.

The specification of the lithium output is agreed between the cathode maker and the lithium producer. The producer must go through an extended period of qualification and pre-production to ensure that they attain the specified levels of purity/impurities. This can take 12–18 months, before a cathode maker or battery producer (or their client) will sign off on an offtake agreement.

As a result, material from one lithium project is in no way directly fungible with material from another. Most cathode producers will use lithium from two to three suppliers to ensure that there are no supply issues if one of those suppliers goes down, but it will not be easy for them to bring a totally new supplier into the process if they have a different product specification (and could take months or years).

A fairly significant proportion of the lithium carbonate currently produced by Latin American brine producers is not suitable for use in batteries. Such material that is not battery grade at source either needs to be upgraded, with a commensurate drop in lithium recovery, or be set aside for other uses.

Probably as much as 50% of production from the first two years of production at greenfield project developments will not be battery grade.

Source: Fernley, 2021.

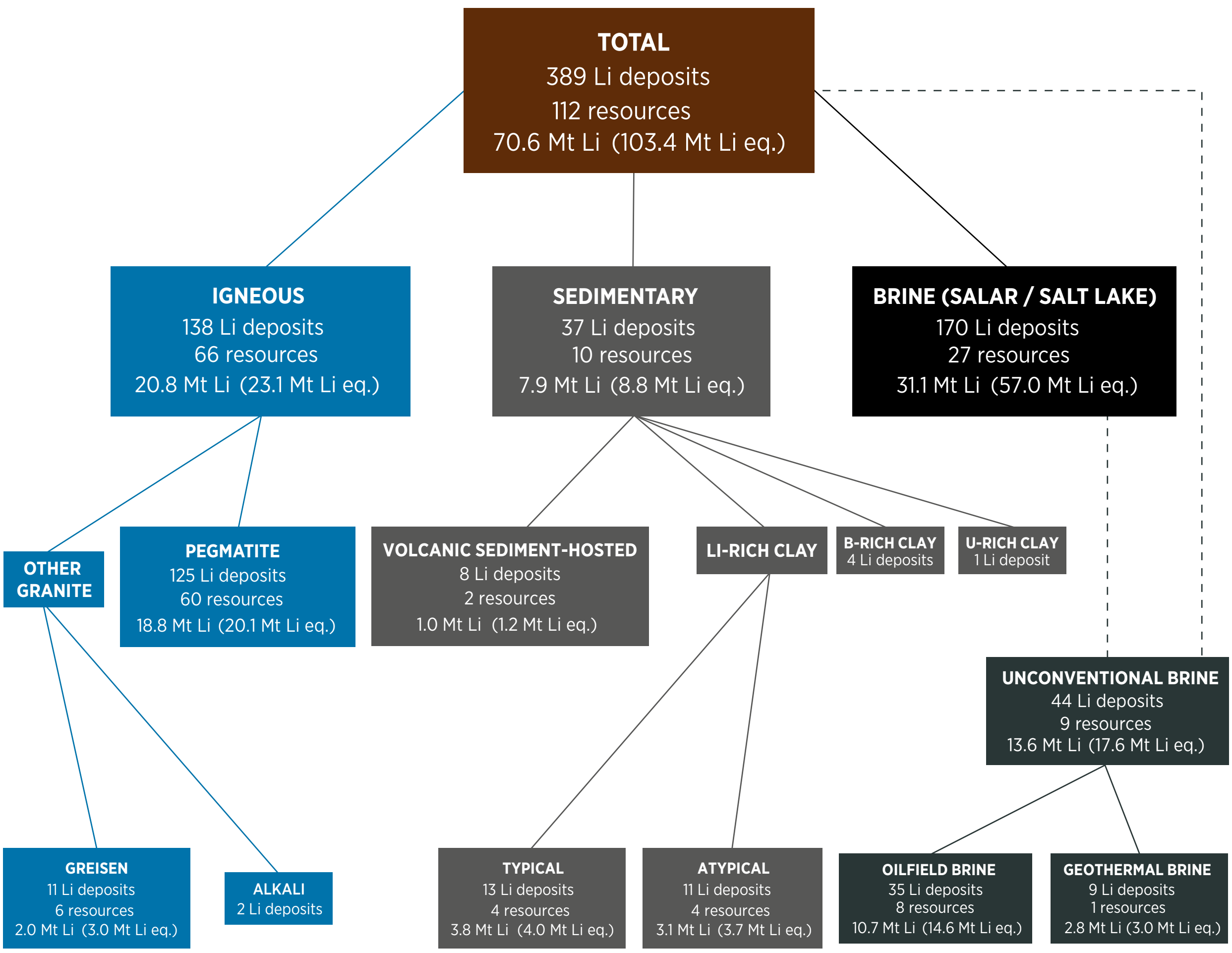
SUPPLY PROJECTIONS

Lithium is currently produced from two main different deposit types: brines and hard-rock. However, a much wider range of resources can be discerned (Figure 6).

PROCESSING FROM BRINE

The extraction of lithium from salars (brine reservoirs) in Chile, Bolivia and Argentina account for most of global production. The process involves using solar evaporation to extract lithium from salt-rich water pumped from below the surface. As the concentration of lithium increase over a period of months, potassium is also extracted to further refine the lithium content to reach anywhere between a few hundred parts per million (ppm) to as much as 7 000 ppm. At this point, any residual boron or magnesium is filtered out at a recovery plant, before the solution is treated with sodium carbonate to produce lithium carbonate. This is then used to create lithium hydroxide.

Figure 6: Breakdown of geological deposits and their lithium resource content



Source: Sykes et al., 2019.

Note: eq. = equivalent.

PROCESSING FROM SOLID ROCK ORE

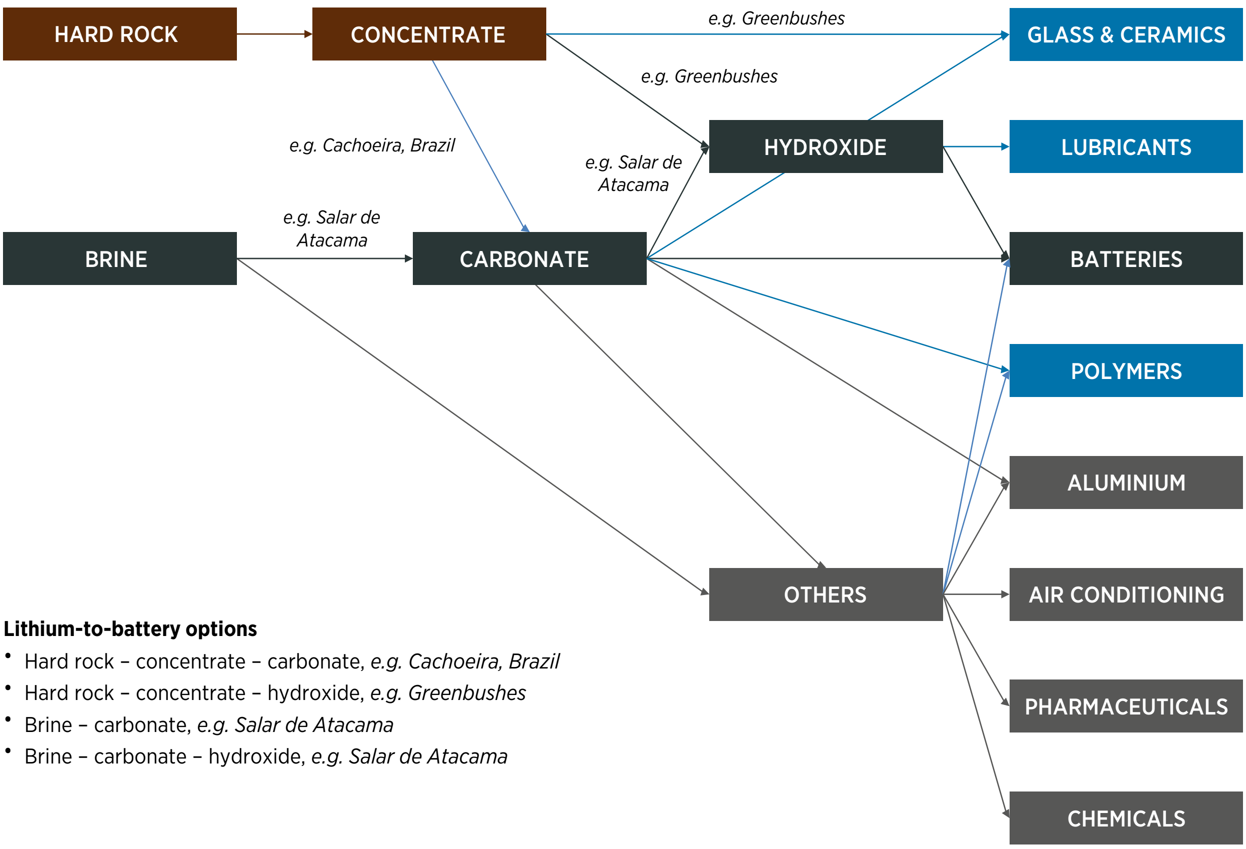
Lithium can also be produced from solid rock ore. Usually pegmatite deposits are mined using conventional mining techniques before being concentrated via crushing, dense media separation and sometimes flotation to produce a concentrate. Spodumene is the most widely occurring mineral but other types exist such as lepidolite, petalite, amblygonite and eucryptite. Spodumene has a theoretical lithium oxide (Li_2O) content of 8%. Due to its high lithium content, spodumene is considered the most important lithium ore mineral. A typical run of mine ore can contain 1–2% Li_2O, which is concentrated through flotation. A typical spodumene concentrate suitable for lithium carbonate production contains 6–7% Li_2O (75–87% spodumene) (SGS, 2011). Given the low lithium content, spodumene shipping adds substantially to the energy and financial cost of lithium supply: 7–8 tonnes of spodumene concentrate with 6% content equals one tonne of lithium carbonate or hydroxide once refined at conversion plants.

During processing, the temperature of the spodumene is raised to around 1100°C before being brought back to 65°C and then re-heated in combination with sulfuric acid and later sodium carbonate to create lithium carbonate. The chemicals used in processing therefore add to the overall costs of production.

PROCESSING FROM CLAY

In Nevada, American Lithium and Noram Ventures are among a number of companies exploring the feasibility of extracting lithium from clay. This requires alternative production processes such as sulfuric acid leaching, which are not yet proven at commercial scale.

Figure 7: Lithium processing routes and applications



Source: Sykes et al., 2019.

GLOBAL LITHIUM PRODUCTION

Worldwide production in 2020 decreased by 5% to 82 000 metric tonnes of lithium content from 86 000 tonnes of lithium content in 2019, in response to lithium production exceeding consumption and decreasing lithium prices (USGS, 2021). In terms of lithium content, Australia was by far the largest supplier of lithium in 2020 (40 000 tonnes; nearly half of total supply), ahead of Chile (18 000 tonnes), China (14 000 tonnes) and Argentina (6 200 tonnes). Australia has only gained a clear lead over Chile in recent years (Table 1). Australia largely mines spodumene, which is shipped to China for processing, but efforts are ongoing to process more spodumene close to the mining sites.

Twelve mines accounted for the majority of world lithium production in 2020: five mineral operations in Australia; two brine operations each in Argentina and Chile; and two brine and one mineral operation in China (USGS, 2021). However, going forward, the geographical diversity of supply will improve, with new mines coming into operation in Africa, Europe and North America.

Table 1: Lithium minerals and brine; world production, by country and locality (metric tonnes, gross weight)

COUNTRY OR LOCALITY[2]	2015	2016	2017	2018	2019
Argentina:					
Lithium carbonate	21 111	24 409	26 559	29 385 r	29 994
Lithium chloride	5 848	6 468	4 501	5 005	4 284
Australia, spodumene	439 514 r	522 181 r	1 706 618	1 965 944 r	1 616 764
Brazil, concentrate	5 781	8 804	10 547 r	41 000 r	85 000
Canada, spodumene	--	--	--	114 000	9 000
Chile:					
Lithium carbonate	50 418	70 831	73 563	87 029	99 300
Lithium chloride	2 069	1 775	2 535	3 826	3 000
Lithium hydroxide[3]	3 888	5 576	5 280	6 468	10 000
China, lithium carbonate equivalent[4]	20 470	25 400	37 300	37 800	57 500
Namibia, lepidolite	--	--	--	30 000 e	--
Portugal, lepidolite	17 120	25 758	52 741 r	76 818 r	77 000
United States of America, lithium carbonate	W	W	W	W	W
Zimbabwe, petalite, lepidolite	50 000 e	50 000 e	40 000	80 000 e	80 000 e

Note: e Estimated; r Revised; W Withheld to avoid disclosing company proprietary data; -- Zero.

1 Table includes data available through June 16, 2020. All data are reported unless otherwise noted. Estimated data are rounded to no more than three significant digits.

2 In addition to the countries and (or) localities listed, other nations may have produced small quantities of lithium minerals, but available information was inadequate to make reliable estimates of output.

3 Lithium hydroxide is produced from lithium carbonate, and therefore not included in world production total to avoid double counting.

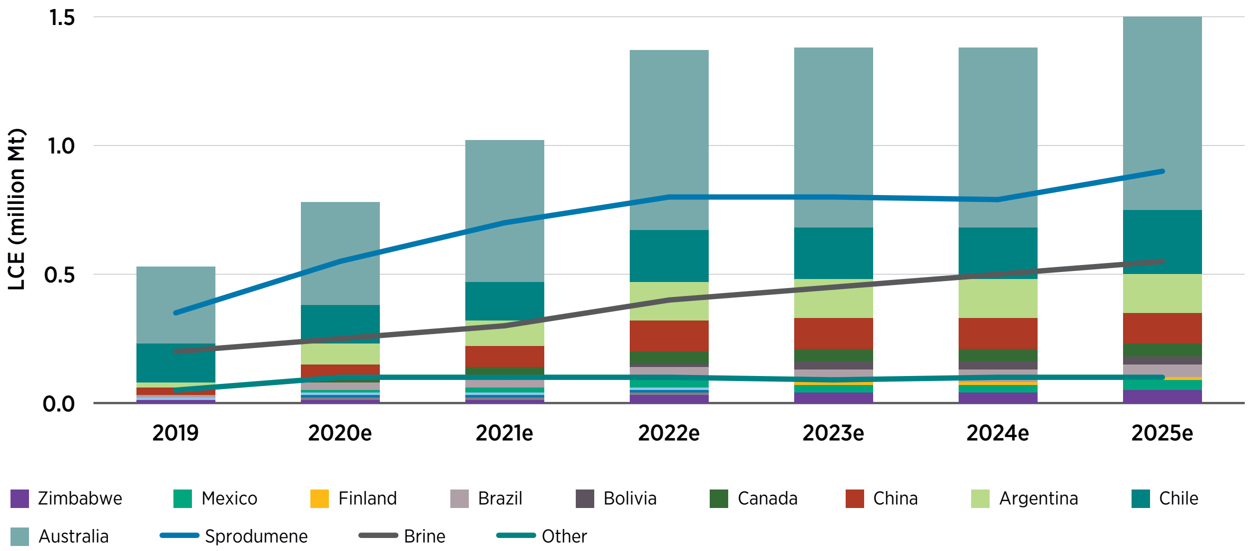
4 Produced from subsurface brine and domestic concentrates.

Source: USGS, 2021.

LITHIUM SUPPLY OUTLOOK BY 2025

Lithium supply is projected to triple by 2025, compared to 2019 levels (from 0.5 to 1.5 Mt LCE) (Figure 8). Apart from a doubling of supply from Australia and Chile, new entrants such as Bolivia, Mexico and Zimbabwe will add supply. The USA and European supply will not play a significant role in this timeframe, with new mines coming on stream thereafter.

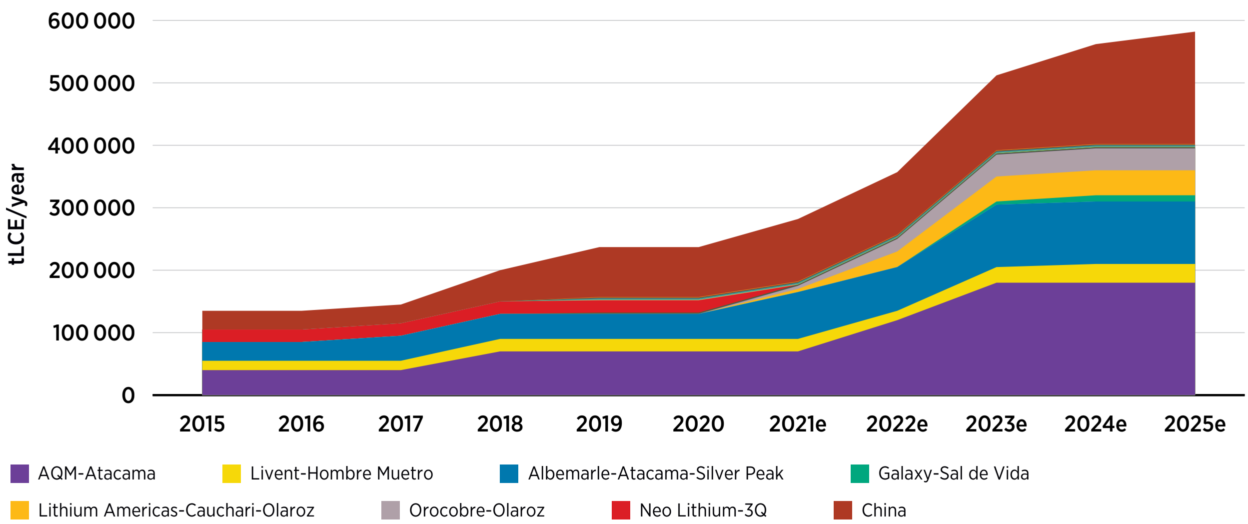
Figure 8: Lithium supply projections 2019–2025



Source: S&P Global Market Intelligence, 2020.

Figure 9 shows the projected growth of salt lake lithium extraction. More than a doubling of production is expected between 2020 and 2025, with three quarters being located in South America and one quarter in China. This will take salt lake extraction from 250 kt LCE to 560 kt LCE by 2025 (Figure 9).

Figure 9: Global lithium brine production output forecast (2009–2025E)



Source: Jephcott, 2021.

Based on proven and probable reserves, the ten biggest lithium ore mines in the world are presented below (Powell, 2020). This list includes several mines that have not yet started production, for which the target commissioning year is indicated; these mines will add to the geographical spread of lithium supply.

- Sonora Lithium Mine (Mexico, 2025)
- Thacker Pass Lithium Mine (USA, post-2025)
- Wodgina Lithium Mine (Australia, operational)
- Pilgangoora Lithium-Tantalum Lithium Mine (Australia, operational)
- Earl Grey Lithium Mine (Australia, proposal)
- Greenbushes Lithium Mine (Australia, operational)
- Whabouchi Lithium Mine (Canada, 2025)
- Altura's Pilgangoora Lithium Mine (Australia, operational)
- Goulamina Lithium Mine (Mali, final investment decision in December 2021)
- Arcadia Lithium Mine (Zimbabwe, operational)

Many other projects are under consideration (Mining, 2021). These include: an old lithium mining site in North Carolina (Gaston County), as well as the Salton Sea in California in the USA (Boraks, 2021; Cantu, 2021); a large project proposed close to Caceres in Spain; projects in Serbia close to the Jadar river, and in Cornwall in the UK; and smaller projects in Austria and Germany (Jadar resources 2021). However, many of the European projects face local opposition, and therefore their prospects are not always clear. Also, some of these use new types of resources such as lithium borate (Serbia) or geothermal resources (German Vulcan project). A kilogram of geothermal lithium was produced for first time in France this year (Eramet, 2021). Also, the processing of clay in Nevada is not yet commercially proven.

Lithium processing is also important, most notably for hard rock mining. Spodumene processing is currently concentrated in China, with the Qinhai, Jinxi and Sichuan provinces being the main centres of processing, with a combined annual output of around 240 Mt in 2021 (SMM, 2021). In most cases, lithium carbonate is used as a precursor to lithium hydroxide, which requires an extra processing step that is reflected in its relatively higher price.

Although capital-intensive, the cost differential between chemical and concentrate plants is often sufficient to inspire the construction of conversion plants. (S&P Global Market Intelligence, 2021b). This is driving Australian miners to venture into downstream activities.

Capacity is also expanding elsewhere; Galp has partnered with Northvolt – a Swedish start-up – to offset reliance on China by increasing European processing capacity through a EUR 700 million lithium hydroxide plant in Portugal. The new plant, which is scheduled to begin operation in 2026, will have an annual production capacity of up to 35 000 tonnes of battery-grade lithium hydroxide, which is sufficient to meet the needs of around 700 000 EVs (Benchmark Mineral Intelligence, 2021).

Box 2: A need to accelerate mine expansions

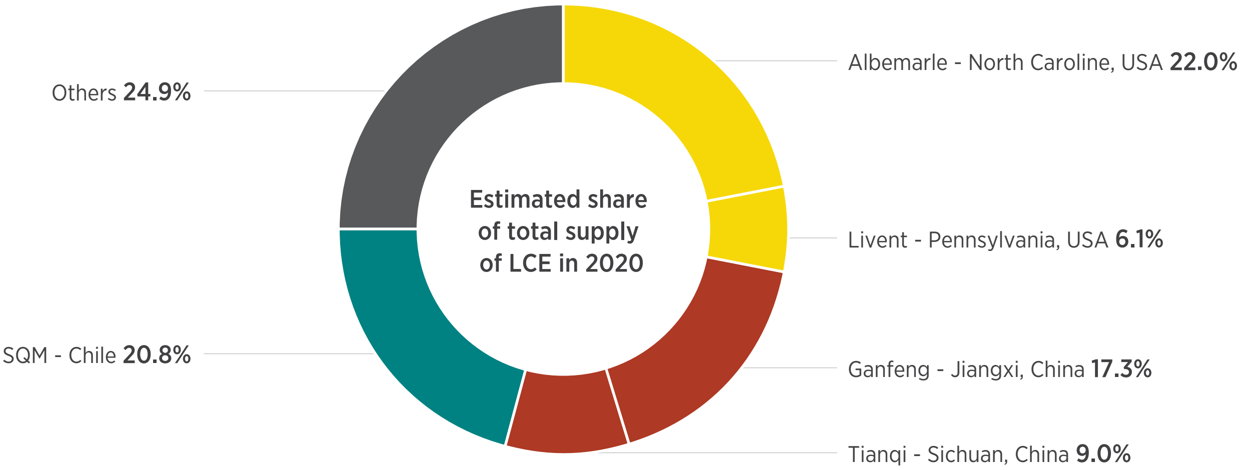
The mining sector operates at different timescales to the battery and car industries. It takes two to three years to build and optimise a battery factory or an EV plant; but it takes between five and ten years to build and optimise a lithium mine. Currently, the EV sector is raising capital at rates of over 10 times the rate that the raw materials sector is raising capital. Seven new projects the size of the largest lithium operations in the world must be funded within the next 18 months, with two more each year after that. These numbers illustrate the challenge ahead.

Source: Fernley, 2021.

GLOBAL LITHIUM INDUSTRY STRUCTURE

A limited number of companies dominate global lithium supply (Figure 10). The largest seven will be discussed here (Mining Technology, 2021; Yahoo, 2021).

Figure 10: Lithium supply by company



Source: Palandrani, 2020.

Jiangxi Ganfeng Lithium Co. Ltd.

Market capitalisation: USD 38.6 billion.

Jiangxi is the world's leading lithium metal producer and third largest producer of lithium compounds (including fluorides and chlorides), with resource holdings in Australia, Argentina and Mexico. Jiangxi reported USD 839.26 million in revenue in 2020, up from USD 432.11 in 2016, and has interests in Bacanora Lithium plc. And the Sonora Lithium project in Mexico. The company has a supply MoU with Volkswagen and a long-term supply agreement with BMW.

Albemarle

Market capitalisation: USD 26.8 billion.

North Carolina-based Albemarle is the world's second-biggest miner of lithium, and the largest provider of lithium to the EV battery market. Albemarle also produces bromine specialities and catalysts. The company posted revenue of USD 3.128 billion in 2020. It maintains lithium brine operations in the USA and Chile, and a 49% stake in the Greenbushes mine.

Tianqi Lithium

Market capitalisation: USD 24.39 billion.

China's Tianqi Lithium is the largest producer of hard-rock lithium in the world, with resources in Australia, Chile and China, controlling around 46% of global production. The company posted revenues of USD 140 million in 2021, owns a 23.77% share in Sociedad Química y Minera (SQM) and has a lithium hydroxide plant in Western Australia.

Sociedad Química y Minera de Chile (SQM)

Market capitalisation: USD 14.03 billion.

SQM's lithium production has almost doubled over the past decade, having produced 72 200 tonnes of lithium carbonate from its Salar de Atacama mine in 2020, compared to 38 000 tonnes in 2011, from its Salar del Carmen plant in Chile. This is used to produce lithium hydroxide for batteries and colorants. In Australia, the company is developing the Mount Holland project through a JV with Wesfarmers; and through a JV announced with Lithium Americas in 2016, the company revealed plans to develop the Cauchari–Olaroz project in Argentina.

Mineral Resources Ltd.

Market capitalisation: USD 6.98 billion.

With revenues of USD 1.6 million in 2019, Mineral Resources operates lithium hydroxide processing facilities, as well as open-pit mining for lithium and iron ore in Australia. In a JV with Neometals Ltd. and Jiangxi Ganfeng Lithium Co. Ltd., the company is a partner in the Mt. Marion Lithium project, with an estimated production of 450 000 tons per annum over its expected 20-year lifetime.

Pilbara Minerals

Market capitalisation: USD 6.8 billion.

With reported revenues of USD 61 million in 2020, Pilbara Minerals' lithium and tantalum project subsidiaries include Sturt Resources Ltd., Tabba Tabba Tantalum Pty. Ltd., Pilgangoora Operations Pty. and Pilbara Lithium Pty. Ltd. Pilbara is the sole owner of the largest, independent hard-rock lithium operation in the world, located in Western Australia, and operates the Pilgangoora Lithium–Tantalum Project through a consortium including Ganfeng Lithium, General Lithium, Great Wall Motor Company, POSCO, Contemporary Amperex Technology Co. Ltd. (CATL) and Yibin Tianyi.

Livent

Market capitalisation: USD 3.26 billion.

With a 60+ year history in the lithium industry, the Philadelphia-based Livent Corporation is a lithium chemicals producer and distributor, serving battery producers and auto industry clients around the world, including Tesla. The company produced around 6 400 Mt of lithium carbonate from its brine resource operations in Argentina in 2019.

LITHIUM SUPPLY COST

The following discussion is based on S&P's Lithium Sector: Production Costs Outlook (S&P Global Market Intelligence, 2019). The mining and processing of brine and hard-rock deposits to produce lithium carbonate and lithium ore concentrate, respectively, incur vastly different costs, with lithium from brine being almost double the cost of that from hard-rock sources. Yet the average value of the concentrates produced at hard-rock mines is around USD 6 250/tLCE lower than lithium carbonates from brine operations.

At USD 5 386/tLCE, the 2019 average margin for brine production was almost twice that of hard-rock production. Hence, Australian producers are seeking to locate their conversion facilities closer to mining operations to reduce costs.

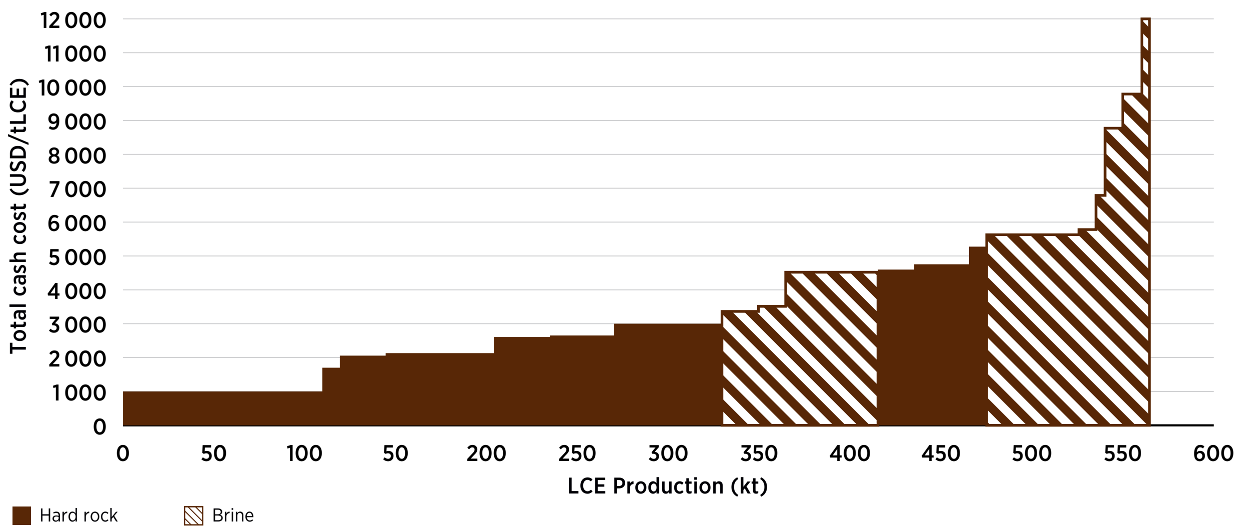
In 2019, products from brine operations were priced USD 6 250/tLCE higher, on average, than those for concentrates from hard-rock mines, whilst average costs at brine operations were USD 3 040/tLCE higher than hard-rock mines.

Total average cash costs among 11 hard-rock producers in 2019 were USD 2 540/tLCE, compared to the average among nine brine operations, at USD 5 580/tLCE. The range is very broad, from a low of USD 1 000 per tonne to a high of USD 12 000 per tonne (Figure 11). The majority of projects have cash costs in the USD 2 000–5 500 per tonne range.

Given the relatively higher wages paid at hard rock mines in Australia, where most hard-rock production is based, labour accounts for around 30% of costs, compared to 9% at brine operations.

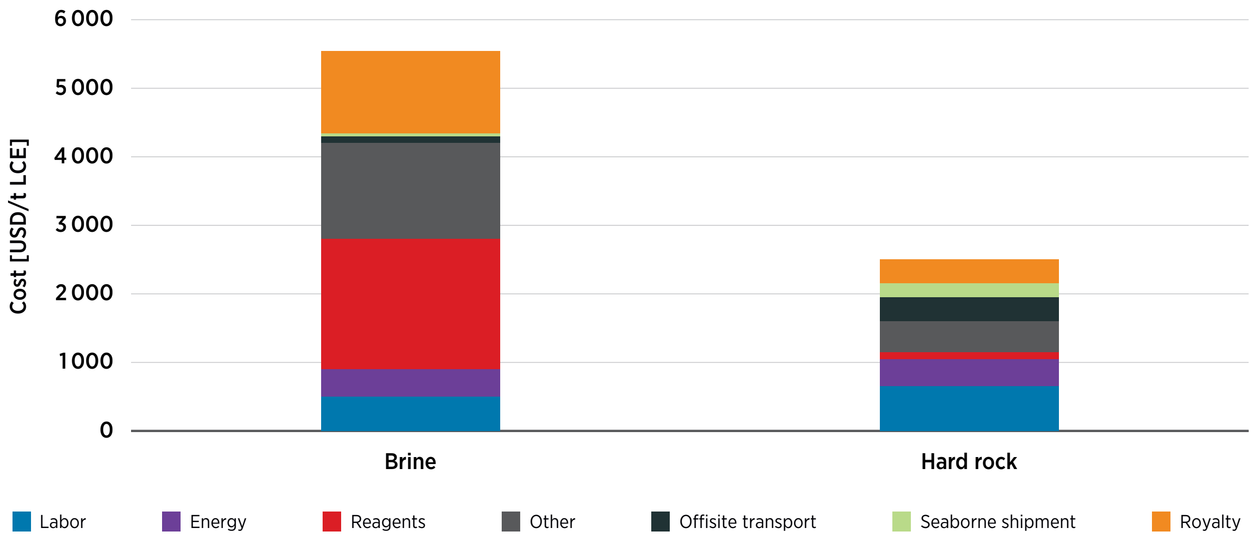
Meanwhile, downstream processing reagents – primarily sodium carbonate and lime – account for the majority of costs incurred at brine assets, at around 36%; and Royalties represent around 23% of cash costs at brine operations – for example, at the Salar de Atacama in Chile, royalties were USD 1 835/tLCE in 2019.

Figure 11: Lithium hard rock and brine operations, cash cost distribution



Source: S&P Global Market Intelligence, 2019.

Figure 12: Breakdown of lithium production cash cost



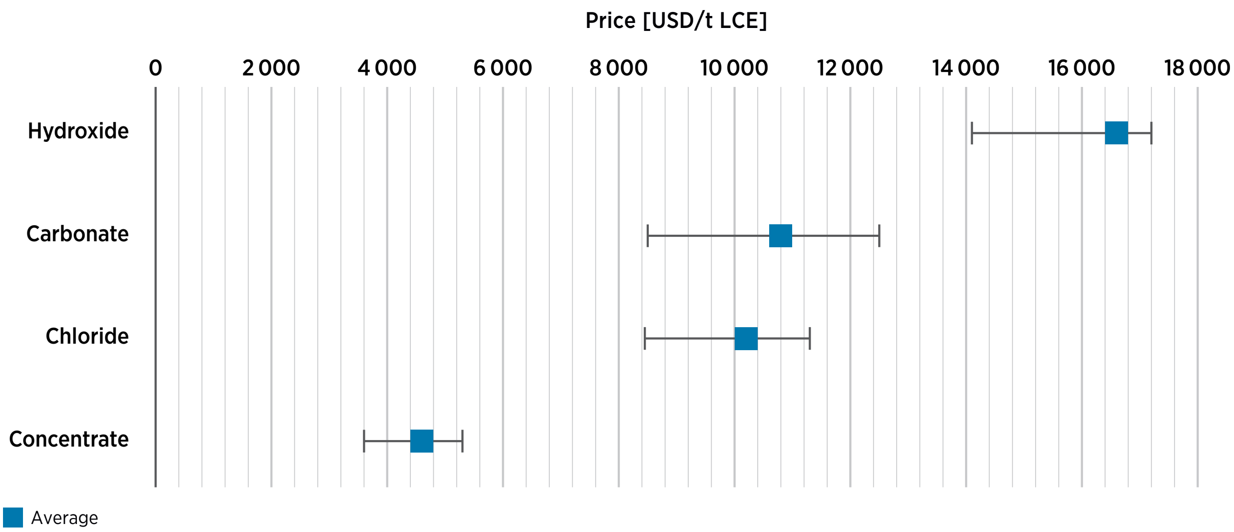
Source: S&P Global Market Intelligence, 2019.

Whilst the relative costs for hard-rock producers are lower than those for brine producers, the prices for end products such as spodumene concentrate are well below those attracted by lithium carbonate, chloride and hydroxide from brine. Average prices for lithium concentrates were 57% lower than for lithium carbonate in 2019, at USD 4 619/tLCE, partly owing to additional costs and material losses incurred during processing.

The premium commanded by lithium hydroxide over lithium carbonate stands at around USD 2 500/t, and increases on an equivalent basis owing to the lower LCE content of lithium hydroxide (Figure 13).

Lithium prices vary widely by product type, with forecast lithium carbonate prices ranging from USD 8 552/tLCE to USD 12 500/tLCE for nine brine operations in 2019 (Figure 13). Lithium products tend to be supplied via long-term contracts, hence prices fluctuate widely.

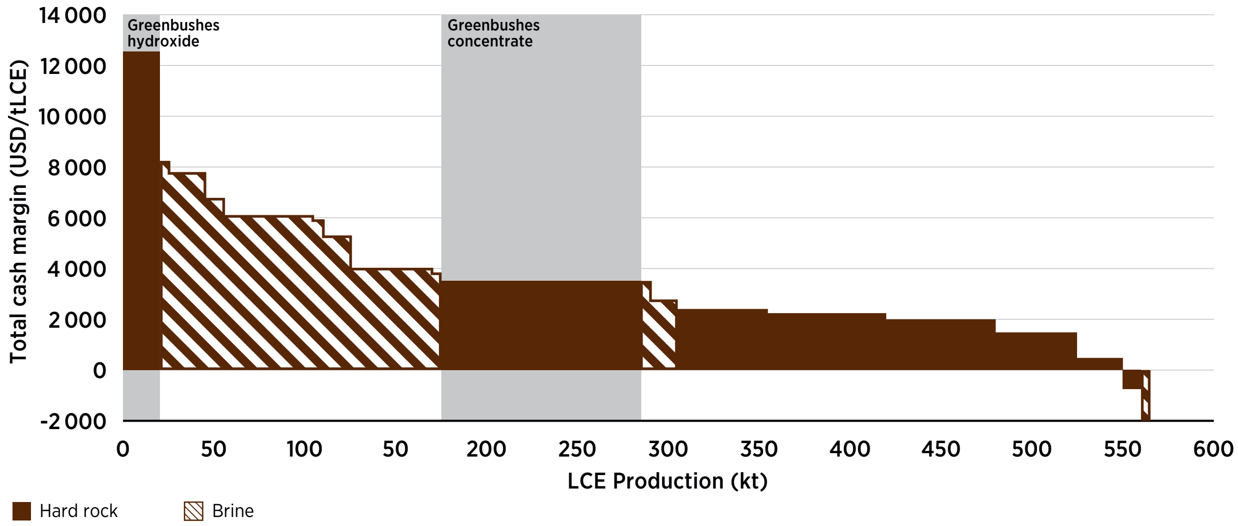
Figure 13: Product price variations



Source: S&P Global Market Intelligence, 2019.

The economic benefits of integrating processing operations can be illustrated by the case of lithium hydroxide at Greenbushes – an Australian hard-rock mine that produces a spodumene concentrate – where facilities now convert some of the spodumene to lithium hydroxide. The additional costs incurred in 2019 as a result were c. USD 2 456/tLCE. These were offset, however, by the higher value of the lithium hydroxide (USD 4 587/tLCE for spodumene concentrate; USD 17 274/tLCE for lithium hydroxide), making Greenbushes the most profitable operation of its kind around the world (Figure 14). This potential is inspiring other hard-rock producers in Australia, such as Mineral Resources Ltd., to consider the economic feasibility of similar moves.

Figure 14: Profitability of lithium projects



Source: S&P Global Market Intelligence, 2019.

INNOVATIONS TO REDUCE DEMAND GROWTH

Lithium demand depends on the number of EVs that are sold each year, as well as the size of the batteries and their composition. Recycling can help to reduce primary materials demand. Innovation is largely focused on the development of new battery materials.

Today all electric vehicle batteries are of the lithium-ion type. The choice of lithium can be explained by the fact that it's the lightest metal in existence. The theoretical minimum is about 70 grams of lithium/kWh for a for a 3.7 volts (V) nominal Li-NMC battery, or 80 g/kWh for a 3.2 V nominal LFP battery. In practice, lithium content is about twice as high (Martin, 2017).

One line of research aims to replace lithium with sodium. Sodium-based batteries exist today but only for stationary applications. CATL plans to continue developing its standalone sodium-ion battery for electric vehicles, with the goal of increasing its energy density from the current 160 Watt-hours (Wh) per kilo to 200 Wh/kg. This battery would be heavier or will have a lower drive range – today's Li-ion batteries have an estimated energy density of 250 Wh/kg (Houser, 2021). However, scientific results suggest that it is possible to produce sodium batteries with a higher energy density than lithium-ion batteries (Lewis, 2020). In theory, such sodium batteries offer the prospect of lithium elimination.

Solid state batteries using pliable polymers are less vulnerable to overheating, and offer enhanced battery life and charging performance. They therefore represent safer, more efficient alternatives that could deliver as much as 2.5 times more energy density than lithium-ion equivalents. Lithium–sulphur batteries, for example, offer more than double the energy density of lithium-ion batteries, reaching as much as 600 Wh/kg (Hanley, 2021). However, the lithium savings will be more modest given the theoretical requirements outlined above.

In conclusion, battery research continues and can impact lithium demand significantly; but these new battery designs are not yet proven at a commercial scale and are more than a decade away. In the meantime, lithium-ion is the only option available.

Battery recycling is also widely quoted as an alternative supply option. However, the number of batteries in use will rising rapidly in the coming years. If a vehicle battery lasts ten years, the number of waste batteries that enters end-of-life stage will lag ten years behind demand. Therefore, recycling is not an option to reduce primary lithium supply needs significantly.

ENERGY USE AND CO_2 EMISSIONS OF LITHIUM PRODUCTION

Ore-based production energy use and CO_2 intensity are considerably higher than for brine-based production. The CO_2 intensity of representative supply chains is illustrated in Figure 15. The CO_2 intensity ranges from 5-15 tCO_2/t lithium hydroxide. Hard-rock based production is nearly three times as CO_2 intensive as brine-based production.

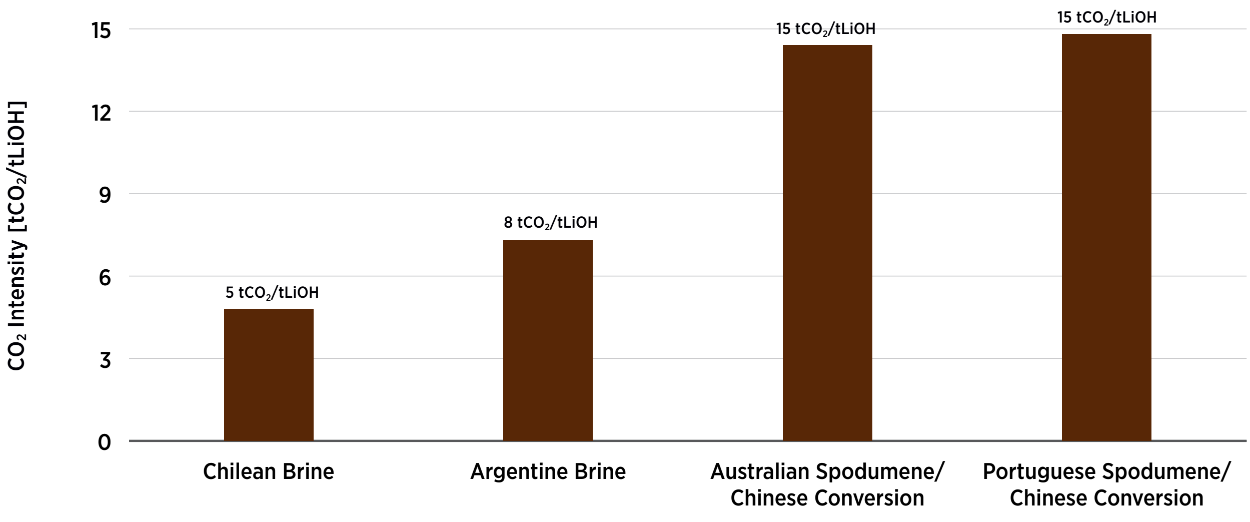
Kelly et al. (2021) conclude that lithium hydroxide products made from spodumene resources are almost seven times more CO_2 intense to produce than lithium carbonate from brine, largely owing to the energy required for mining and processing. Chinese LiOH products are the most CO_2-intense available, given the high CO_2 intensity of spodumene concentrate processing.

The CO_2 intensity of technical grade LiOH production from Chilean brine operations is approximately twice that of SQM's historical lithium carbonate (Li_2CO_3) products, owing to the causticisation and energy intense crystallisation steps involved in its production. It would take even more energy to double crystallise the LiOH, therefore increasing the CO_2 intensity still further.

Meanwhile, LiOH production from the brine operation in Argentina is more CO_2 intense than technical grade Chilean production, as significant quantities of natural gas are required during their lithium extraction process – although alternative technologies may reduce this intensity going forward.

LiOH production from spodumene concentrate in China, as well as the general industry shift towards the use of lithium hydroxide in high-nickel cathode materials, are significantly increasing the CO_2 intensity of lithium batteries.

Figure 15: CO_2 intensity of different lithium hydroxide supply chains



Source: Kelly et al, 2021.

Total CO_2 emissions for lithium supply will be below 30 Mt per year by 2030. This is small compared to the emissions savings that accrue due to the switch to EVs. Yet opportunities exist to reduce these emissions further.

Given these developments, CO_2 emissions from lithium-ion battery production are likely to grow from 4% to somewhere in the region of 20–30% under current conditions.

Options to reduce emissions exist and include:

- Geothermal–lithium projects: the use of low CO_2-intensity geothermal energy in combination with advanced lithium extraction technologies that do not require mining or fossil fuel use, could lead to negative CO_2 intensities, as low CO_2 intense power sold to the grid displaces coal-fired generation. There are projects in the USA and Germany looking to do this that have been discussed above.

- Lithium extraction from unconventional resources: extraction from sedimentary materials that require sulphuric acid (H_2SO_4) rather than roasting, employing low CO_2-intensity on-site burning of sulphur to produce H_2SO_4, power and heat to support lithium processing.

- Use of solar, wind, geothermal, hydroelectric of nuclear power for mining or chemical conversion processes, where possible.

However, given that the majority of brine-based production currently occurs in desert areas in South America, the expansion of production activities may be undermined by the significant groundwater drainage requirements of the process.

THE ROLE OF GOVERNMENTS IN DE-RISKING LITHIUM SUPPLY

Electromobility is in many countries seen as a key industry of the future. EV production depends on access to batteries and lithium. Mining is dominated by Australia and Chile (with a combined mining share of around 70%). Processing is concentrated in China (55–60% share). As elaborated above, Chinese suppliers are actively acquiring mines worldwide to assure access, whereas the USA and Europe are developing their own resources. Europe is aiming for lithium self-sufficiency by 2025 (Willuhn, 2020). Also, the USA is actively expanding its national production (DOE, 2021); however, the goal is not to attain self-sufficiency.

The analysis in this paper has shown that lithium resources are widely spread and the geographical spread of supply will improve in the coming years. There could be merit in tracking the ownership of these mines more systematically. The current structure is oligopolistic; it is unclear how this will develop going forward as the market will expand rapidly. However, the main supply challenge is not related to mining but to processing. Processing of spodumene ore is currently concentrated in China; but from an economic perspective (high transportation cost for spodumene), there is an incentive to move the processing close to the mines. Recent trends suggest a move in this direction.

Two schools of thought exist in this regard. One is to leave it to market forces to find the balance of supply and demand. Market players have more and better information and therefore make better decisions. The IMF estimates that a 10% price shock will result in a 16.9% growth of lithium supply in the same year. After 20 years, the same price shock yields a supply growth of 25.5% (Boer et al., 2021).

The second school of thinking is that only governments have the long-term perspective that is needed to gauge supply risks and understand the full economic consequences of potential supply disruptions. Active development of national resources or investment support for sustainable mining abroad are among the responses. At the same time, from a business perspective, economies of scale and low supply costs are important benefits, and usually outweigh political efforts to 'desinicise' supply chains, particularly in those countries with the most significant strategic resources (Kalantzakos, 2020a).

There is also a rising trend of resource nationalism. It includes royalties, ensuring operations don't get shut down and jobs are kept, and sustainability of operations. Government can facilitate the buildout of mining through streamlined permitting; but various government actors have a role to play across the whole supply chain (Barrera, 2021).

The era of stable competition for resources is coming to a close, as the concentrations of minerals critical to carbon-free pathways and highly digitised economies become more concentrated geographically. Governments in the geographies concerned, largely in the Global South, have demonstrated a willingness to secure exclusive deals with China that effectively displace traditional Western competitors (Kalantzakos, 2020a). The European Commission unveiled in December 2021 the Global Gateway – a plan to invest 300 billion euros (USD 340 billion) globally by 2027 in infrastructure, digital and climate projects. Whereas such government investment frameworks do not have a specific critical materials aim, they could be used for this purpose.

A global transparent market would clearly be the best way forward. China is the world's largest consumer of critical materials and has recognised supply as a strategic issue. This has resulted in efforts to expand national supply (Chen, 2021; Fu, 2021) and to gain access to foreign supply. China has demonstrated its increasing economic power by systematically forging a global network of partners.

Other consumers could begin to build a new framework for co-operation. Therefore, they must build new avenues of trust and co-operation with developing countries. Sustainable mining that creates local benefits and aids the producing country will be critical. As this analysis has shown in the case of lithium, it makes sense to locate processing close to mining sites.

The question remains as to what strategies governments should pursue to enhance supply security for lithium. Options include the following:

- Increase market transparency (see also Annex):
    - Track current supply in more detail.
    - Develop scenarios for future demand.
    - Assess mining developments and their likely commissioning date and supply contribution.
    - Public prices and future prices of key lithium products.
    - Ensure international quality standards and certification to facilitate market formation.
- Deepen the international dialogue regarding critical materials:
    - Consumer countries must build new avenues of trust and co-operation with developing countries.
    - Deeper state and industry investments in the areas of exploration, recycling, substitution, and supply chain diversification, complemented by appropriate legislation, the prioritisation of critical materials and further promotion of innovation (Kalantzakos, 2020b).
- Align geopolitical affairs to better meet the challenges of the new era:
    - The lack of coordination and cooperation in securing critical minerals remains a challenge. A new critical minerals approach is required, combining economic, strategic and security-related factors – China's state-capitalist model may offer useful lessons in this regard (Kalantzakos, 2020b).
    - The geographic concentration of both extractive and processing activities must be addressed – not only ownership and control of critical minerals mines, but also processing facilities.
- Invest in mining, processing, infrastructure and human capital:
    - Streamline the permitting process for new mines while adhering to stringent compliance measures in the areas of environment, society and transparency/anti-corruption regulations, regardless of whether they are operating domestically or internationally (Wood et al., 2021). This requires a level playing field that also involves the governments of the mining nations.
    - Private sector cooperation to lessen perceived investment risks in mining, including through long-term supply contracts, and both human capital and technology investments to generate expertise and lower technology costs (Wood et al., 2021).

- Ensure that supply is diversified:
  - Resources are widely distributed; the development of mines in different parts of the world and diversified ownership can help to create competitive deep markets.
- Build critical materials stocks:
  - Countries maintain various types of strategic stockpiles, including some metals (Siripurapu, 2020). Opinions differ as to whether strategic stockpiles constitute an effective response. Whereas stocks of lithium can help in the case of short-term emergencies, these do not present an alternative for a supply shock similar to oil stocks, as the level of concentration in lithium supply is currently much higher and the response time to develop new supply is much longer. Contrary to fossil fuels, the issue is consumer competition, not supplier behaviour. At the same time, as the world's largest processor of lithium, China is also the world's largest consumer of lithium. Japan maintains a stockpile of minerals that it qualifies as rare/critical and new stockpiles are being discussed in the USA.

Box 3: China's role as key player in the global lithium market

Electromobility and battery technology constitute core industries for Chinese economic growth and the government is actively developing these industries. Among the 136 lithium-ion battery plants that were scheduled for construction worldwide as of 2019, 101 are due to be opened in China. The country is also home to the largest manufacturer of electric vehicle batteries – Contemporary Amperex Technology Co. Ltd. (CATL) – which accounted for 27.9% of the market in 2019, whilst Chinese chemical companies produced 80% of the raw materials used for advanced battery manufacturing.

In terms of acquisitions, 6.4 million tonnes of lithium reserves and resources were secured by Chinese miners and battery companies in 2021 (to October 18), out of a global total of 6.8 Mt, and USD 1.58 billion in development-stage lithium projects (S&P Global Market Intelligence, 2021a).

Tianqi Lithium owns 51% of the world's largest lithium reserve in Australia, and is holds the second-largest stake in Chile's biggest producer, Sociedad Química y Minera; and an existing LTA provides Ganfeng Lithium with the ability to underwrite lithium produced at the world's second- largest high-grade lithium reserve, Mount Marion, in Australia.

Zijin Mining Group Co. Ltd. is seeking to acquire the Toronto-based Neo Lithium Corporation, which owns the Tres Quebradas (3Q) project in Argentina; CATL has already acquired Millennial Lithium Corporation, another Canadian concern that runs the Pastos Grandes lithium project in Argentina; and Ganfeng Lithium signed two acquisition deals 2021, valued at USD 272.5 million (S&P Global Market Intelligence, 2021a).

These acquisitions of largely development-stage assets require significant investments to become major producers, but offer significant potential for development.

Meanwhile, at home, the need to import large amounts of lithium for industrial production is seen as a supply risk and significant efforts have focused on the identification and development of own national lithium supply (Fu, 2021).

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ANNEX: OUTLINE OF AN OBSERVATORY FOR CRITICAL MATERIALS

There is an opportunity to enhance transparency in the maturing lithium market. This can help to reduce risks for suppliers and consumers. This case study for lithium shows that there is a need for multiple indicators to understand the supply outlook for lithium.

DEMAND TRENDS

- Lithium demand growth is directly related to EV outlook. Battery electric vehicles, plug-in hybrids and hybrid-electric vehicles need to be understood. Passenger cars, delivery vans, other commercial vehicles and buses, as well as two-wheeler developments need to be accounted for.

- Demand depends on the battery size and battery type for different types of vehicles. Therefore, a lithium tracking system must be combined with an EV and battery manufacturing tracking system. The battery type determines whether lithium carbonate or lithium hydroxide is required.

- Battery composition trends need to be understood better, given their potential impact on the demand for various lithium commodities.

- The product quality, standards and certification need to be understood in more detail in light of battery manufacturing needs.

SUPPLY TRENDS

- On the supply side, sourcing needs to be monitored (national level and mine level; existing and new brine projects, and ore mines). The types of products from these projects need to be understood better and calculation methods are needed to express them in a single unit – likely LCE (spodumene concentrate, lithium carbonate, lithium hydroxide).

- A better understanding is needed of national- and company-level processing capacity and activity (from spodumene concentrate to carbonate and hydroxide; and from brine derived carbonate to hydroxide).

- Spodumene, lithium carbonate and lithium hydroxide prices and forward contracts should be tracked, as an indicator of scarcity.

MARKET STRUCTURE TRENDS

- Trade flows can be tracked in order to enhance the understanding of market power.
- The ownership of key assets can also be tracked (mines and processing capacity and well as battery manufacturing capacity).

START FROM EXISTING INFORMATION SOURCES

A lot of information is gathered but remains fragmented, and large parts are proprietary. Making essential information available in the public domain to enhance market transparency is a key role for governments. A number of commercial parties provide market information. These include, amongst others:

- Roskill Lithium market report: https://roskill.com/market-report/lithium/
- IHS Markit Lithium & Lithium minerals market research https://ihsmarkit.com/products/lithium-lithium-minerals-chemical-economics-handbook.html
- Shanghai Metals Market (SMM): www.metal.com/Lithium
- S&P Global Platts: www.spglobal.com/platts/en/
- BNEF electric vehicle outlook: www.bnef.com

Also, government agencies and international non-profit organisations collect valuable information regarding lithium supply including:

- EU Joint Research Centre: https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6
- European lithium institute: https://lithium-institute.eu/
- German Geological Survey: www.bgr.bund.de/EN/Themen/Min_rohstoffe/min_rohstoffe_node_en.html;jsessionid=8884997B8715996E0F882FA43219D213.1_cid321
- UK Geological Survey: www.bgs.ac.uk/geology-projects/critical-raw-materials/
- US Geological Survey: www.usgs.gov/

IRENA
International Renewable Energy Agency

www.irena.org