Australia's National
Science Agency

From minerals to materials

Supplementary report: Lithium

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Acknowledgements

CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past and present.

The project team would like to acknowledge the contributions of all stakeholders that provided input to this project from industry, government and academia. Appendix A of the main report 'From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities' includes a complete list of the organisations that provided input into to this project.

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Contents

Glossary

Abbreviations

CAM	Cathode active material
CSE	Composite solid electrolyte
FAST	Flame-assisted spray technology
FSP	Flame-assisted pyrolysis
IP	Intellectual Property
ISE	Inorganic solid electrolyte
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
LiFSI	Lithium bis(fluorosulfonyl)imide
$LiPF_6$	Lithium hexafluorophosphate
LiTFSI	Lithium bis(trifluoromethanesulfonyl)imide
LMO	Lithium Manganese Oxide
MoU	Memorandum of Understanding
NBTC	National Battery Testing Centre
NCA	Nickel Cobalt Aluminium Oxide
NMC	Nickel Manganese Cobalt Oxide
pCAM	Precursor Cathode Active Material
PVA	Polyvinyl Alcohol
SPE	Solid polymer electrolyte

1 Executive summary

Lithium-ion batteries (LIBs) are expected to make up a large portion of the global EV market share for the near and medium term, generating significant demand for critical battery materials including lithium, cobalt, and graphite. However, the global LIB supply chain currently faces geographic concentration and sustainability challenges at most stages, representing opportunities to enhance research, development and demonstration (RD&D) activity domestically and globally.

To date, Australian lithium extraction operations have been undertaken by a domestic miner in partnership with an overseas mid-stream processing technology partner. Australia has the RD&D capabilities to reduce its reliance on overseas technology partners in the production of battery grade lithium compounds, and to improve cost and sustainability outcomes.

There are several opportunities for RD&D related to lithium mid-stream processing, including supporting the implementation of mature technologies from overseas in the Australian context; demonstrating Australian intellectual property (IP) at scale; progressing Australia's technologies beyond the lab; or growing emerging capabilities in step-change technologies (Figure 1 and Figure 2).

This supplementary report is part of the report series *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*. The series adds to existing Australian and international literature on critical minerals and renewable energy technologies by providing a detailed picture into mid-stream processing, key areas for global risk reduction and capability development to support the energy transition in Australia.

Figure 1: Framework for assessing research, development and demonstration (RD&D) and international engagement actions.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

IP, intellectual property. For a full description and methodology of this framework, refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities.*

Calcination; Conversion and purification

The conventional pathway for lithium extraction from Australia's hard rock ores entails a three-step process: calcination; sulphuric acid roasting and leaching; and purification. Australia has world leading RD&D capabilities in both the calcination of spodumene and the purification of lithium compounds, providing a pathway for Australia to partially reduce its reliance on overseas technology providers.

Calcination is currently a necessary step to extract lithium from hard-rock ores like spodumene, because the process can make them more amenable to roasting or leaching. Despite the high global maturity, innovation in calcination is still highly relevant, particularly to lower energy intensity and greenhouse gas emissions. Given Australia's world-leading IP activity in this area and its cross-cutting capability from other metal industries, there is an opportunity to support Australian companies to pilot and demonstrate their processes onshore.

The conversion and purification of battery-grade lithium hydroxide and lithium carbonate is key to increasing the value of Australian exports and a step towards vertically integrating CAM production onshore. Despite being highly mature, there are also emerging purification methods (e.g. membrane electrodialysis) that could help diversify purification capability across multiple end products. Australia has world-leading IP activity in purification and is actively undertaking purification commercially in joint ventures with overseas companies. As such, there is an opportunity for RD&D to support the expansion of onshore operations, while also continuing to drive improvements in purification efficiency, product purity levels, operational costs and waste minimisation. International engagement will be key, because project financing and securing offtake agreements are critical to ensuring project success.

Sulphuric acid roasting

Sulphuric acid roasting is a step in the conventional process for lithium extraction and is globally mature and commercially used in Australia. Australia has limited IP in this area but is developing know-how through its industry operations conducted in partnership between an Australian miner and an overseas technology partner. There are multiple countries with strong sulphuric acid roasting capability, and international collaboration will continue to be beneficial to develop this capability in Australia.

Sulphuric acid roasting has relatively simple operational requirements and low costs, providing a more mature and lower risk near-term option for industry to adopt, compared with more emerging techniques. Despite not having high IP activity in sulphuric acid roasting, Australia has developed industrial capability as demonstrated by current and planned commercial projects in Western Australia.

The RD&D opportunity for Australia lies in providing a support role for existing operations and for the expansion of sulphuric acid roasting operations onshore. This will likely require collaboration with overseas technology providers (e.g. equipment providers and large-scale plant engineering). There are also RD&D opportunities to improve circularity and sustainability of the sulphuric acid roasting pathway, specifically reducing and managing waste and integrating renewable energy into operations where possible.

Salt roasting; Chlorination

Alternative roasting pathways such as salt roasting and chlorination can offer improved efficiency but are still emerging and require RD&D to overcome the technical challenges to implementation at scale. The opportunity is for Australia to grow its capabilities and develop technologies beyond the laboratory. RD&D collaboration with overseas organisations can support capability building and knowledge sharing.

Salt roasting has been developed as an alternative to sulphuric acid roasting to minimise equipment corrosion. It is commercialised and well established overseas in China (lepidolite deposits) with strong innovation momentum. However, its application to Australian lithium deposit types (i.e. spodumene) is more emerging, and there is limited IP activity in Australia. Direct salt roasting approaches (i.e. bypassing calcination) is a globally emerging variation with significant step-change potential for cost and sustainability, because it bypasses the energy intensive calcination step.

There is an opportunity for Australian RD&D to further develop salt roasting processes that are applicable for Australian lithium deposit types and to provide a pathway towards commercialisation. This can be further supported by international collaborations (e.g. joint RD&D projects).

Chlorination roasting can offer extraction efficiency advantages over sulphuric acid roasting. There is a role for RD&D to progress technology readiness by solving technical challenges to scale up, especially in relation to equipment corrosion and toxic gas emissions. Research collaborations with international RD&D partners can help build capability through knowledge sharing and joint projects.

Acid and alkali leaching; Bioleaching;

There are multiple emerging pathways that aim to bypass challenges associated with conventional lithium extraction operations. Acid and alkali leaching processes represent a step change opportunity for Australia's lithium industry to avoid the energy intensive steps of current calcination and sulphuric acid roasting processes. Piloting and scaling up these domestic technologies can help position Australia as a more sustainable and cost-effective supplier of lithium compounds for battery materials, and further decrease reliance on overseas technology partners.

Acid and alkaline leaching are emerging processes that have the potential to improve Australia’s competitiveness on cost and sustainability. Several Australian companies have been active in developing and patenting such processes. There is an opportunity for RD&D to pilot and scale up Australian technologies onshore, and to address factors impacting scale-up such as extraction times and reagent consumption.

Bioleaching is being explored by researchers for its potential to deliver significant cost and sustainability benefits, including the recovery of lithium from waste materials. However, despite being mature for other metals (e.g. cobalt), its application to lithium ores is nascent and highly challenging. Long term sustained RD&D efforts would be required to find a commercial solution, as well as international collaboration on knowledge sharing and capability building.

Lithium metal

Global demand for lithium metal is expected to grow with the emergence of next-generation lithium metal batteries. However, current production is highly concentrated and uses outdated and unsustainable molten salt electrolysis methods. Australia's RD&D strengths in alternative reduction processes represent an opportunity to grow domestic IP output and to pilot Australian technologies onshore, unlocking participation in the market for lithium metal.

Australia has demonstrated capability to develop alternative pathways for producing lithium metal namely thermochemical reduction. This method has the potential to disrupt prevailing production concentrated in China, which are well understood but are associated with chlorine gas emissions. Given the emergence of thermochemical reduction for lithium metal, there is an opportunity for Australia to pilot and scale up Australian technology. Continued RD&D to enhance understanding of process dynamics, and integrating sustainable thermal energy for high temperature requirements will be key.

An alternative pathway would be for RD&D to improve upon mature molten salt electrolysis pathways, namely chloride-free, lower-temperature methods.

Collaboration with international lithium-metal (i.e., solid-state) battery manufacturers will be essential due to the lack of domestic battery manufacturers, the emerging nature of lithium-metal batteries which increases investment risks and uncertainty, and the high costs required to test new technologies.

CAM (hydro/solvo-thermal); CAM (spray-based); CAM (sol gel, solid state, co-precipitation)

CAM synthesis is globally mature and represents a near term opportunity for Australia to value-add. Given Australia's RD&D foundation and past pilot projects, there is an opportunity to support scale-up of demonstrated Australian IP. Alternatively, Australia can engage with international partners to adopt overseas technologies (e.g. plant equipment and CAM formulations) for onshore production.

CAM synthesis is a well-established process with different technology options offering different benefits. Co-precipitation and spray-based methods are mature, low-cost, scalable, and precise. Having been piloted onshore, both technologies represent the opportunity to develop and scale up Australian IP. Alternatively, Australia may consider implementing existing mature technologies via international partners and commercial operators to expedite domestic production. For emerging CAM synthesis techniques, knowledge-sharing and collaborations with international institutions will likely be required.

Regardless of pathway, international collaboration will be essential to develop accepted CAM for offtake in the absence of a domestic cell manufacturer. Despite its maturity, CAM synthesis will benefit from ongoing RD&D to deliver improvements in manufacturing costs and sustainability, and CAM material properties for better battery performance.

Liquid electrolytes; Solid electrolytes

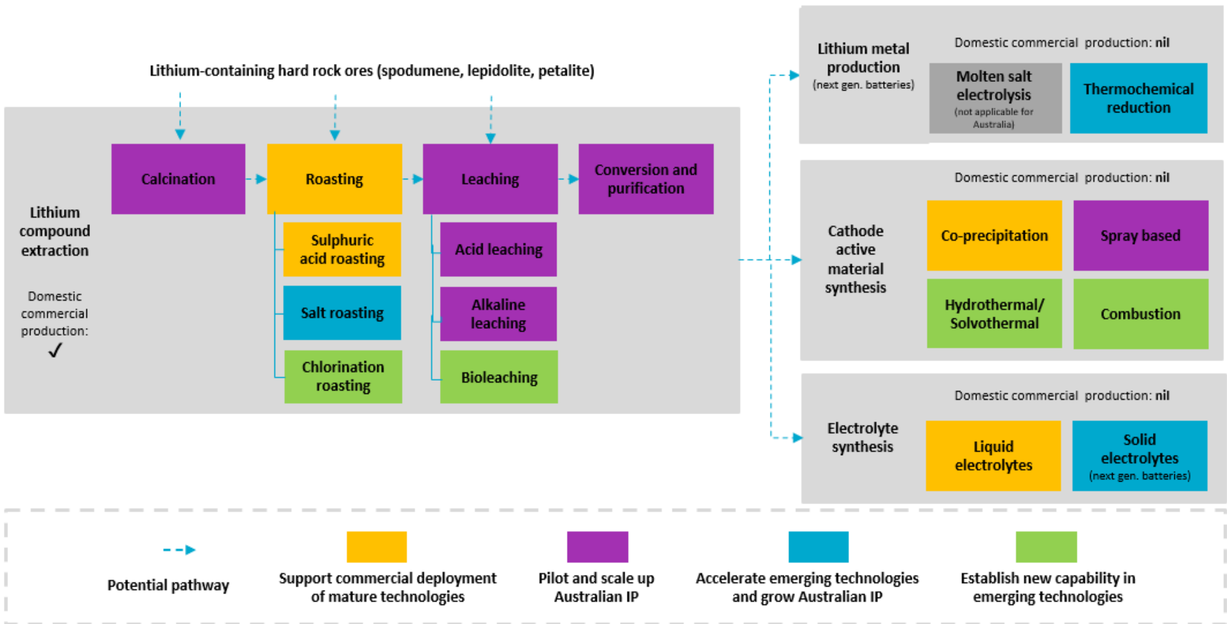
Current and next generation electrolytes are an important battery component not currently produced in Australia. Although Australian activity has been relatively low in liquid electrolyte synthesis (current generation), the global need for less toxic production pathways and the emergence of alternative salts to $LiPF_6$ are opportunities for innovation and collaboration. Solid electrolytes for next generation batteries are emerging globally, and Australia's significant investments in advanced manufacturing capabilities are an opportunity for Australia to participate in global technology development.

Despite the intrinsic challenges around safety, liquid electrolytes will remain an integral component of current-generation LIBs, with electrolyte salt $LiPF_6$ continuing to have prominent use in industry. The synthesis of liquid electrolytes and $LiPF_6$ salt is mature, geographically concentrated, and currently reliant on complex and hazardous synthesis processes.

Given Australia's low RD&D activity in this area to date, Australia's participation in the liquid electrolyte market can be built through international collaborations with emerging producers using sustainable practices, as well as domestic RD&D into alternative salts and fluorine-free synthesis pathways that support the performance and safety of current-generation batteries. Innovation in liquid electrolytes would benefit from technical and economic assessments to understand investment risks and returns given liquid electrolytes are an established market.

Solid electrolytes, made of polymer, inorganic or composite materials, are suitable candidates for next generation solid-state batteries due to their compatibility with lithium metal anodes, and improved safety, stability and energy density. The emerging status of solid electrolytes provides an opportunity for Australian RD&D to take on a greater role by leveraging its battery research base, cross-cutting activity in additive manufacturing and materials development to grow domestic IP. Establishing partnerships with international battery manufacturers will be key for commercialising Australian technologies, given the integrated nature of solid electrolyte production and solid-state battery cell assembly.

Figure 2: Australian RD&D opportunities across lithium mid-stream processing technologies.



Note: This diagram represents a simplified summary of research, development and demonstration (RD&D) actions and international engagement actions for Australia. However, some technologies and their variants cut across a range of maturity levels, therefore warranting multiple actions.

IP, intellectual property.

2 Objectives and scope

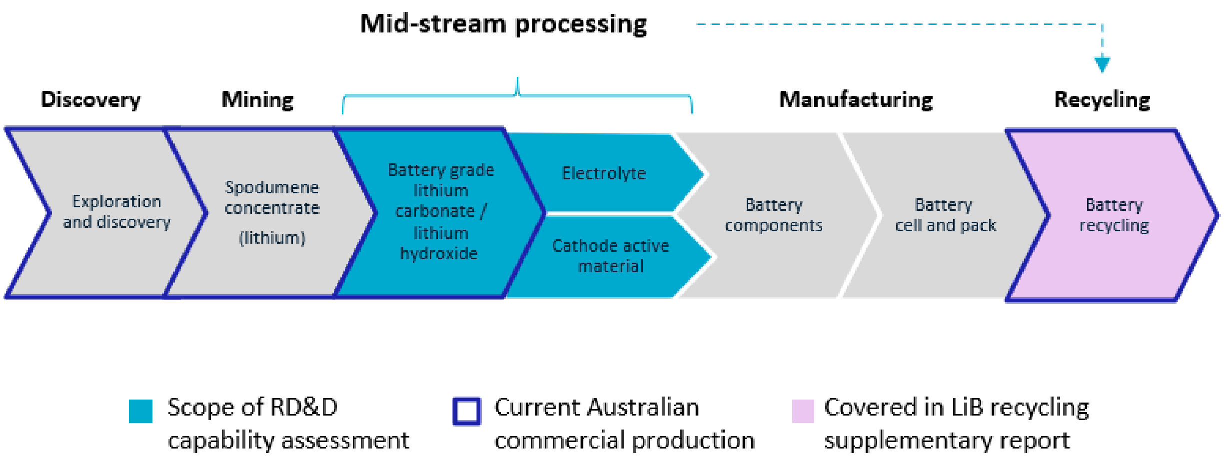
This supplementary report will focus on Australia's key LIB supply chain gaps. In particular, the first two steps of mid-stream value adding (production of lithium compounds and the manufacture of battery component precursors), as well as the recovery of high value metals from end-of-life LIBs (Figure 3).

This report aims to address several objectives:

- To communicate the key current and emerging technologies underpinning the extraction process and production of lithium compounds from hard rock ores, the production of electrode active materials (cathode and anode), and the synthesis of electrolytes, with a strong focus on technologies that have been demonstrated at lab, pilot and commercial scales.
- To communicate where high levels of IP and research activity are occurring in Australia and globally, each emerging and mature technology area.
- To communicate key challenges and opportunities for Australia to build domestic IP and for collaboration with international partners.

The purpose of this analysis is to guide and inform government, industry and research decision-making with respect to research, development and demonstration (RD&D) investment and collaboration efforts across critical minerals and renewable energy technology supply chain activity.

Figure 3: Scope of lithium supplementary report and current commercial production in Australia.



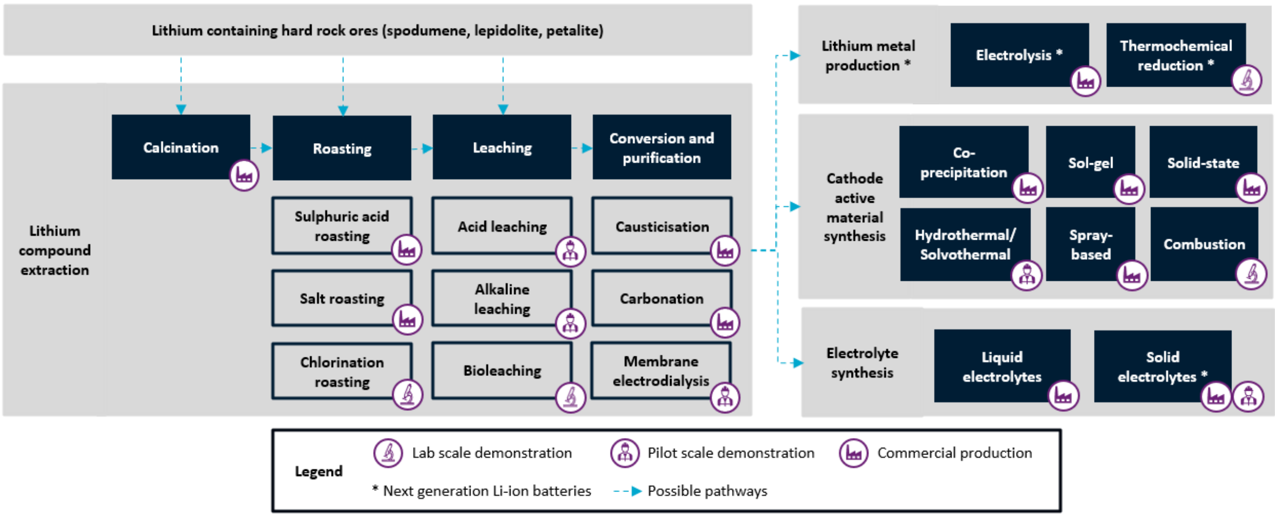
3 RD&D challenges and opportunities

The LIB supply chain is well established globally, and is underpinned by mature and commercial extraction technologies, mid-stream processing technologies and advanced materials manufacturing. However, there are several emerging technologies being developed globally to improve sustainability and cost outcomes as well as the production of next generation battery components such as solid electrolytes and lithium metal anodes for lithium metal (or solid-state) batteries (Figure 4).

This section will discuss the RD&D challenges and opportunities relating to mature and emerging technologies for extracting lithium compounds and lithium metal, and for the production of cathode active materials and electrolytes.

- Section 3.1 will cover technologies used to transform hard rock lithium-bearing ores found in Australia and produce compounds, including calcination and alternative techniques, as well as roasting methods, leaching techniques and purification processes.
- Section 3.2 will cover the production of lithium metal, including the conventional electrolysis method, as well as the emerging thermochemical reduction method.
- Section 3.3 will cover synthesis methods used to produce cathode active materials (CAM), focusing on advanced material synthesis techniques that can be applied across battery chemistries, rather than for specific CAM compositions (e.g., LFP, NMC, NCA and LMO).
- Section 3.4 will cover the synthesis of electrolytes, including current-generation liquid electrolytes, and next-generation solid electrolytes.

Figure 4: Taxonomy of lithium processing technologies for the lithium-ion battery supply chain.



Li, Lithium.

3.1 Production of lithium compounds

Globally, the two main natural sources of lithium are hard rock ores and salt lake brines, each requiring a different extraction pathway. Australia's primary source of lithium comes from hard rock spodumene, with a small portion from lepidolite and petalite.[1]

Mining hard rock ores involves a beneficiation step, where the lithium ores are concentrated via physical and mechanical sorting to eliminate other materials and obtain a lithium concentrate. Next, the extraction of lithium from lithium concentrate is a mature multi-step process. First, the ore concentrate is calcined to transform it to a more reactive state. The calcined ore can then be subjected to roasting, leaching, and purification processes to produce battery grade lithium compounds (lithium hydroxide or lithium carbonate). The production of lithium compounds faces an overarching challenge of improving recoveries and reducing waste generation. This is partially due to the low proportion of lithium in natural ores (approximately 4 to 8% lithium oxide) compared to other materials (e.g., aluminium and silicon).[2]

This section discusses mature and emerging processes used to produce lithium compounds. These include processes that can significantly reduce the energy intensity of calcination, or bypass it altogether, as well as alternative reagents used in roasting and leaching processes that can reduce the cost of feedstocks, energy use, or environmental toxicity. This section also discusses nuances in technology pathways, which can affect the number of treatment steps required and their complexity, and hence the efficiency of the overall process.

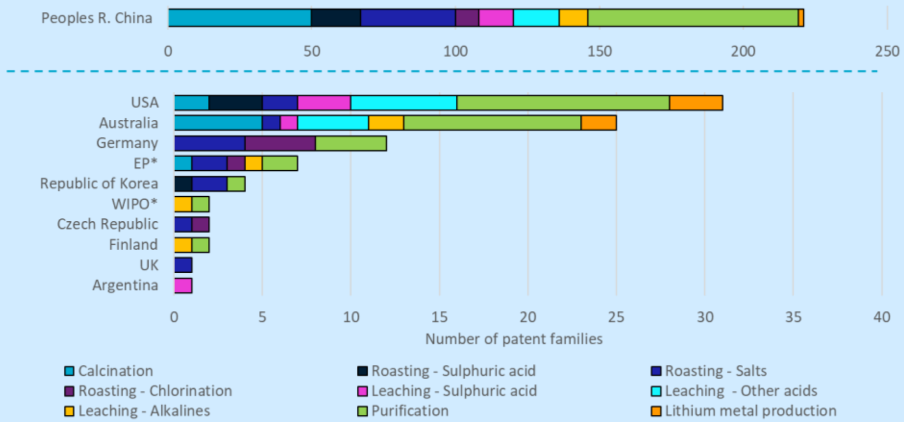
[1] Champion D (2019) Australian resource reviews: lithium. Geoscience Australia, Canberra.

[2] For spodumene, petalite and lepidolite. Liu Y, Ma B, Lü Y, Wang C and Chen Y (2023) A review of lithium extraction from natural resources. International Journal of Minerals, Metallurgy and Materials 30(2), 209–224. DOI: 10.1007/s12613-022-2544-y.

Global R&D and commercialisation snapshot

Production of lithium compounds and lithium metal

Figure 5: Patent output in lithium compound extraction and lithium metal production technologies from 2007 to 2022, by country and processing technology.



*Applications filed under an entity other than a country.

Peoples R. China, Peoples Republic of China; WIPO, World Intellectual Property Organisation; EP, European Patent Office

Figure 5 illustrates patent output in lithium extraction technologies by country. In the 2007 – 2022 interval, China led patent activity on the production lithium compounds and lithium metal, with 71.5% of patent families across all processes analysed. The USA, with 10%, and Australia with 8.1% complete the top 3 of countries with the highest activity.

Figure 6: Research publication activity related to lithium extraction and metal production from 2007 – 2023, by country and processing technology.

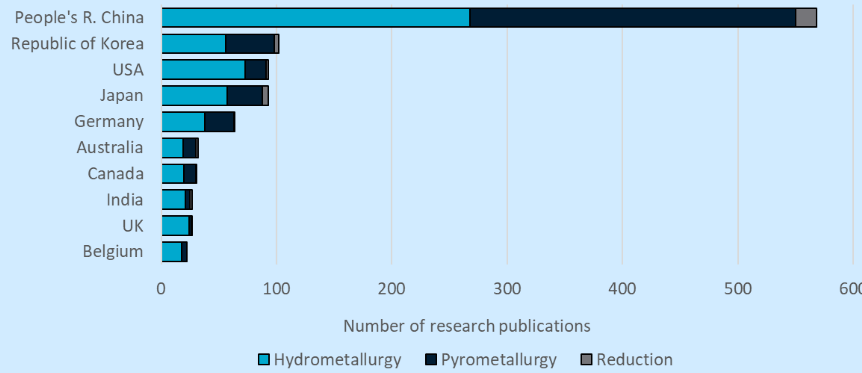
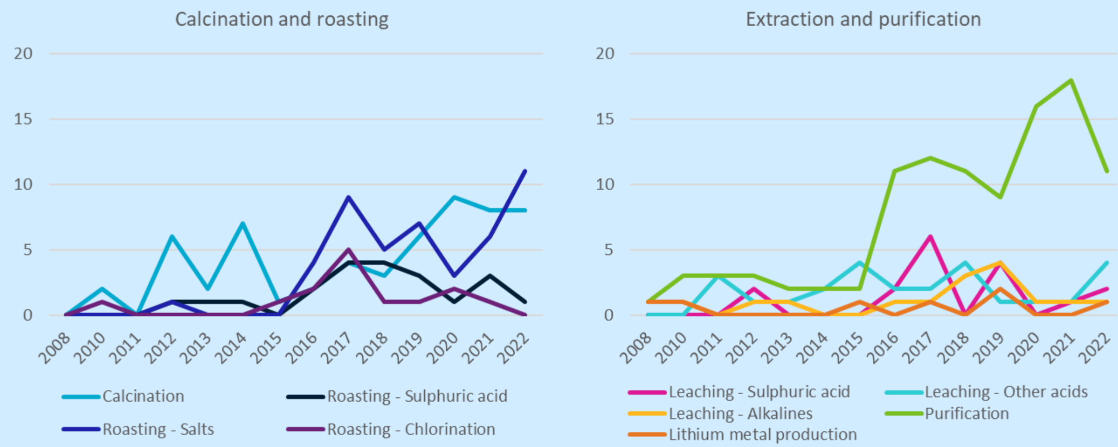


Figure 6 shows the output of research publications from 2007 to 2023 that are related to lithium extraction, by country and processing technology. China accounts for 41% of the total, followed by South Korea (7.3%), the US and Japan (each 67%). Australia occupies the 7th position, with 2.3% of publications.

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 7: Global patent output in lithium extraction and lithium metal production 2007 – 2022 period, by year and technology.



The distribution of patent families across technologies from Figure 7 shows purification (33.7%), calcination (18.8%), and lithium extraction via salt roasting (14.9%) as the areas of highest activity globally. This distribution of activity is also reflected in the overall trends for the 2007 – 2022 period (Figure 7), with purification, calcination and salt roasting featuring increases that contrast with more stable baselines of activity for the other technologies. Moreover, most technologies show an uptick of activity after 2015, except for lithium metal production.

Table 1: Top 10 active organisations outside of China

By research publication output	By patent output
• DOE, **United States**	• Reed Advanced Materials, **Australia**
• Delft University of Technology, **Netherlands**	• Metso Outotec, **Finland**
• Vrije Universiteit Brussels, **Belgium**	• SMS Group, **Germany**
• Chonnam National University, **Republic of South Korea**	• Frontier Lithium, **Canada**
• Helmholtz Association, **Germany**	• Lithium Australia, **Australia**
• CONICET, **Argentina**	• Tianqi Lithium Kwinana, **China/Australia**
• Hanyang University, **Republic of South Korea**	• American Battery Technology, **United States**
• AIST, **Japan**	• Novalith, **Australia**
• Argonne National Laboratory, **United States**	• Orbite (acquired by AEM Canada), **Canada**
• CNRS, **France**	• St Georges Eco Mining, **United States**

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

3.1.1 Calcination

All of Australia's lithium production is from hard rock ores, including spodumene, lepidolite and petalite.[3] Naturally occurring spodumene, specifically α-spodumene, is resistant to conventional extraction processes and current processing pathways require an initial thermal process to convert it into a more reactive form, β-spodumene. Lepidolite and petalite also require an initial thermal process.[4]

Initial thermal processing of hard rock lithium-containing ores includes mature methods such as high temperature calcination and emerging processes such as microwave irradiation or mechanical activation.

Calcination is a technique commonly used across many industries, where mineral ores or compounds are subjected to high temperatures in order to transform them, making them more amenable to extraction or helping remove impurities.[5] It is typically done in a rotary kiln, a cylindrical vessel in which the feedstock is heated and mixed, and is an energy-intensive process powered by natural gas.[6]

Other techniques that can be used to improve energy and efficiency include microwave irradiation and mechanical activation. Mechanical activation such as ball milling can lower the calcination temperature required to transform ores into a reactive state.[7] Meanwhile, subjecting partially calcined ores to microwave irradiation could shorten the total processing time and potentially reduce energy costs and energy-related emissions.[8]

TECHNOLOGY STATE OF PLAY

Calcination is the dominant method used to treat hard rock lithium-bearing ores.[9] It is an integral part of most lithium hydroxide refineries, including the three commercial scale projects in WA; the Tianqi-IGO refinery in Kwinana, a joint venture between Tianqi (China) and IGO (Australia);[10] the Albemarle refinery in Kemerton;[11] and the Covalent Lithium refinery in Kwinana, a joint venture between Wesfarmers (Australia) and SQM (Chile) targeted to commence production in 2024.[12]

[3] Champion D (2019) Australian resource reviews: lithium 2018. Geoscience Australia, Canberra, Australia. <http://dx.doi.org/10.11636/9781925848281>

[4] Tran T, Luong VT (2015) Chapter 3 – Lithium production processes. In Lithium Process Chemistry. (Eds. A Chagnes, J Światowska). Elsevier.

[5] Messing G L (2021) Calcination and Phase Transformations, Encyclopedia of Materials: Technical Ceramics and Glasses; Gasafi E, Pardemann R (2020) Processing of spodumene concentrates in fluidized-bed systems. Minerals Engineering 148:106205.

[6] Gasafi E, Pardemann R (2020) Processing of spodumene concentrates in fluidized-bed systems. Minerals Engineering 148:106205.

[7] Abdullah AA, Oskierski HC, Altarawneh M, Senanayake G, Lumpkin G, Dlugogorski BZ (2019) Phase transformation mechanism of spodumene during its calcination. Minerals Engineering 140, 105883.

[8] Rezaee M, Han S, Sagzhanov D, Vaziri Hassas B, Slawecki TM, Agrawal D, Akbari H, Mensah-Biney R (2022) Microwave-assisted calcination of spodumene for efficient, low-cost and environmentally friendly extraction of lithium. Powder Technology 397:116992.

[9] Abdullah AA, Oskierski HC, Altarawneh M, Senanayake G, Lumpkin G and Dlugogorski BZ (2019) Phase transformation mechanism of spodumene during its calcination. Minerals Engineering 140, 105883.

[10] IGO Limited (2022) Kwinana lithium hydroxide refinery site visit presentation. <https://www.igo.com.au/site/pdf/5689dd29-0fec-480d-8bc1-3cab878469ea/Kwinana-Site-Visit-Presentation.pdf>

[11] Albemarle (2023) Albemarle to double lithium hydroxide output in Australia. <https://www.albemarle.com/news/albemarle-to-double-lithium-hydroxide-output-in-australia>; GHD (2017) Albemarle Kemerton Plant Air Quality Impact Assessment - Part A. Albemarle Lithium. <https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/CMS17244%20-%20Appendix%20F%20-%20Albemarle%20Kemerton%20Plant%20Air%20Quality%20Impact%20Assessment%20Part%20A%20from%20Albemarle%207%20November%202017%20%28DWERDA-013528%29.pdf>

[12] Covalent Lithium (n.d.) Refinery. <https://www.covalentlithium.com/refinery>; The Government of Western Australia (2022) New battery and critical minerals prospectus to power investment. <https://www.wa.gov.au/government/media-statements/McGowan-Labor-Government/New-

Innovators in the calcination space are looking to optimise the energy efficiency of the process and to utilise sustainable energy sources. International examples include Metso (Finland), piloting the use of a circulating fluidised bed furnace for calcination, which is an alternative to the conventional rotary kiln with potential benefits across energy efficiency and maintenance.[13] In Australia, Calix is planning a demonstration of its flash calcination process with Pilbara Minerals (Australia). The plant is expected to process 27,000 tonnes of calcined spodumene per annum and be powered by renewable energy.[14]

Calcination processes using renewable energy are also being demonstrated in other metal industries domestically. For example, Alcoa is leading the Renewable Powered Electric Calcination Pilot project in WA and Rio Tinto has completed a feasibility study on hydrogen calcination in 2022, both aiming to decarbonise the alumina refining process.[15]

Emerging pre-treatment methods, microwave irradiation and mechanical activation, have been demonstrated at laboratory scale.[16]

An analysis of global patent filing activity from 2007 to 2022 found 18.8% of patent families were related to the initial calcination of lithium-containing ores. Patent activity for calcination shows strong momentum in the last 5 years, aligning with the increased demand in lithium and the central role that calcination plays in commercial extraction processes. Australia is second in patent families for calcination, with 8.6% filed during the period analysed, compared with 86.2% from China and 3.5% from the USA. Australian companies that have patent activity in calcination include Reed Advanced Materials, Tianqi Lithium Energy Australia, Allkem (formerly Galaxy Resources) and Novalith.

battery-and-critical-minerals-prospectus-to-power-investment-20220622>; WA Environmental Protection Authority (2021) Covalent Lithium Hydroxide Refinery. WA Environmental Protection Authority, Perth, Australia. <https://www.epa.wa.gov.au/sites/default/files/EPA_Report/EPA%20Report%201700_Covalent%20Lithium%20Hrdroxide%20Refinery_assessment%20report.pdf>

[13] von Garnier A, Beisheim T (n.d.) How to increase energy efficiency of spodumene calcination applying CFB technology. Metso. <https://www.metso.com/insights/webinars/how-to-increase-energy-efficiency-of-spodumene-calcination-applying-cfb-technology/>

[14] Export Finance Australia (n.d.) Calix. Customer stories. <https://www.exportfinance.gov.au/customer-stories/calix/>; Walsh M (2022) Calix and Pilbara Minerals Mid-Stream Project Update. Calix. <https://calix.global/sustainable-processing/pilbara-minerals-mid-stream-project-scoping-study/>

[15] ARENA (2022) Alcoa Renewable Powered Electric Calcination Pilot, Australian Renewable Energy Agency. <https://arena.gov.au/projects/alcoa-renewable-powered-electric-calcination-pilot/>; Balachandran S (2022) Rio Tinto Pacific Operations Hydrogen Program, Rio Tinto Aluminium Ltd. <https://arena.gov.au/assets/2022/11/hydrogen-feasibility-study-report.pdf>

[16] Salakjani NK, Singh P, Nikoloski AN (2019) Production of lithium – a literature review part 1: pretreatment of spodumene. Mineral Processing and Extractive Metallurgy Review 41(5), 335–348.

The following table summarizes the key RD&D areas of focus in the calcination of lithium hard rock ores:

Table 2: Global RD&D focus areas for calcination of hard rock lithium ores technologies

RD&D FOCUS AREAS	
Calcination of hard rock lithium ores	• Advancing calciner design to improve process efficiency. • Integrating renewable energy into the calcination process e.g. electric calciners or hydrogen calciners.[17] • Developing cost- and energy-efficient pathways that combine mechanical activation and microwave irradiation.[18]

3.1.2 Roasting

In the roasting process, ore is reacted with a chemical reagent in the presence of oxygen in a high temperature environment. Roasting processes are commonly used across several mineral resource industries including copper, zinc, gold, and are often designed to produce byproducts that can be utilised or sold for other processes.

Sulphuric acid roasting

The most commercially mature lithium extraction method used in industry is to roast calcined ores with sulphuric acid (in the case of spodumene at a temperature between 200 and 300°C, in a process alternatively referred to as sulphuric acid baking).[19] The roasted mixture is then water-leached to obtain a lithium sulphate solution which undergoes further purification and conversion into lithium hydroxide or carbonate (See Section 3.1.4).[20]

In addition to its maturity, this method is the preferred option in industry due to its relatively low processing and operating costs with little to no requirements for specialised anti-corrosive equipment. However, the biggest challenges of sulphuric acid roasting are the high energy consumption and the need to manage toxic gases and large volumes of waste residues.[21]

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[17] Srinivasan V, Delaval B, Dollman R, Towns A, Charnock S, Palfreyman D, Hayward J, Graham P, Foster J, Reedman L, Tourbier D (2023) Renewable Energy Storage Roadmap. CSIRO, Canberra, Australia, <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy-and-Resources/Renewable-Energy-Storage-Roadmap>.

[18] Abdullah AA, Oskierski HC, Altarawneh M, Senanayake G, Lumpkin G, Dlugogorski BZ (2019) Phase transformation mechanism of spodumene during its calcination. Minerals Engineering 140, 105883.

[19] Salakjani NKh, Singh P, Nikoloski AN (2021) Production of Lithium –A Literature Review. Part 2. Extraction from Spodumene. Mineral Processing and Extractive Metallurgy Review 42(4), 268–283; Rioyo J, Tuset, Grau R (2022) Lithium Extraction from Spodumene by the Traditional Sulfuric Acid Process: A Review. Mineral Processing and Extractive Metallurgy Review 43(1), 97–106;

[20] Karrech A, Azadi MR, Elchalakani M, Shahin MA, Seibi AC (2020) A review on methods for liberating lithium from pegmatites. Minerals Engineering 145, 106085.

[21] Liu H, Azimi G (2021) Process analysis and study of factors affecting the lithium carbonate crystallization from sulfate media during lithium extraction. Hydrometallurgy, 199:105532; Li H, Eksteen J and Kuang G (2019) Recovery of lithium from mineral resources: State-of-the-art and perspectives – A review. Hydrometallurgy, 189:105129.

TECHNOLOGY STATE OF PLAY

Sulphuric acid roasting is commonly used in countries with large spodumene resources, which include Australia, China and the USA. Both Tianqi-IGO and Albemarle refineries mentioned previously in this report currently undertake sulphuric acid roasting at the commercial scale plant in WA.[22] The Covalent Lithium plant will also use the sulphuric acid roasting pathway.[23]

Sulphuric acid roasting represents 6.8% of patent families identified globally between 2007 and 2022. This technology area area shows an overall stable to declining trend and peaking from 2016 to 2019, in part reflecting the maturity of this method and its common use in commercial operations. The trend of activity may indicate a shift towards patenting alternative extraction methods. Australia had no patent activity related to sulphuric acid roasting in the period analysed. The top countries by output include China with 81% of patent families, the USA with 14.3% and The Republic of Korea with 4.8%.

Salt and chlorination roasting

Alternative roasting pathways are being developed to overcome some of the drawbacks of sulphuric acid roasting. These include salt roasting (using sodium-, calcium- or potassium- carbonate or sulphate), and chlorination roasting (using chlorine gas or chloride salts). The roasted product is then leached using water or acid to obtain corresponding lithium compounds (e.g. lithium carbonate, lithium sulphate, or lithium chloride), which would undergo further processing and purification (see Section 3.1.4).

Compared to sulphuric acid roasting, salt roasting (non-chloride salts) has the advantage of being less corrosive to equipment.[24] However, similar to sulphuric acid it also suffers from efficiency challenges, with low lithium recoveries and high waste volumes.[25]

Meanwhile, chlorination roasting is generally a more efficient reaction with high lithium recoveries (consistently above 90 percent) and minimal waste and residue generation.[26] However, chlorination roasting is energy intensive, as it requires temperatures 850°C or above, compared to the average acid

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[22] IGO Limited (2022) Kwinana lithium hydroxide refinery site visit presentation. <https://www.igo.com.au/site/pdf/5689dd29-0fec-480d-8bc1-3cab878469ea/Kwinana-Site-Visit-Presentation.pdf>; Albemarle (2018) Albemarle and Western Australia. <https://www.albemarle.com/storage/wysiwyg/alb_kemerton_literature_051618_a4_fnl.pdf>; GHD (2017) Albemarle Kemerton Plant Air Quality Impact Assessment - Part A. Albemarle Lithium. <https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/CMS17244%20-%20Appendix%20F%20-%20Albemarle%20Kemerton%20Plant%20Air%20Quality%20Impact%20Assessment%20Part%20A%20from%20Albemarle%207%20November%202017%20%28DWERDA-013528%29.pdf>.

[23] Covalent Lithium (2021) Lithium Hydroxide Refinery Project: Covalent Lithium Greenhouse Gas Management Plan. Covalent Lithium. <https://straueconnhubpublic1.blob.core.windows.net/env/Refinery%20Greenhouse%20Gas%20Management%20Plan.pdf>; Martinick Bosch Sell (2023) Kwinana lithium refinery process residues geochemical assessment. Covalent Lithium. <https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/Kwinana%20Lithium%20Refinery%20Process%20Residues%20Geochemical%20Assessment.pdf>.

[24] Tian-ming G, Na F, Wu C, Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[25] Tian-ming G, Na F, Wu C, Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[26] Tian-ming G, Na F, Wu C, Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153; Liu Y, Ma B, Lü Y, Wang C and Chen Y (2023) A review of lithium extraction from natural resources. International Journal of Minerals, Metallurgy and Materials 30 (2), 209–224.

roasting temperature of 250°C.[27] Other prominent challenges of chlorination roasting include equipment corrosion and the health and safety risks associated with the use and emission of chlorine gas.[28]

TECHNOLOGY STATE OF PLAY

Salt roasting methods were first proposed in the 1960s and have since been commercially applied in industry to process lepidolite.[29] In particular, lepidolite roasting with a mixture of potassium sulphate, calcium carbonate and sodium sulphate is a well-established process for large-scale refineries in China.[30]

There are many lab-scale research projects investigating the potential to apply salt roasting directly to naturally occurring ores (e.g, α-spodumene) without calcination, as this approach can potentially decrease energy and reagent consumption and increase lithium extraction efficiency.[31]

Chlorination roasting with chloride compounds has been demonstrated at commercial scale, whereas the application of chlorine gas is still limited to laboratory scales.[32] Although the project is no longer operating, chloride salt roasting was once commercialised by Ganfeng Lithium (China) to extract lithium from lepidolite.[33]

The patent analysis identified that 14.9% of patent families from 2007 to 2022 were related to salt roasting. Patent activity in this processing technology has been increasing and has surpasses the activity for all other extractive processes (both roasting and leaching-based). This may be attributed to its prevalent use to extract lithium from Chinese ores. China had 71.7% of the total, followed by Germany with 8.7%, and the USA and the Republic of Korea with 4.4% each. Other countries with relevant patent filings include Australia, the Czech Republic and the UK with 2.2% of the total each. Australian companies that have patent activity in salt roasting include Tianqi Lithium Energy Australia.

Meanwhile, 4.5% of patent families were related to chlorination roasting within the analysed period, with only 21.4% of activity within the area occurring in the last 3 complete years. This matches an overall stable to declining trend after a peak in activity between 2016 and 2018, potentially linked to the technical difficulties associated with the corrosivity and hazardous by-products generated in the process. China accounted for 57.1% of patent family filings, followed by Germany with 28.6%, and the Czech Republic with 7.1%.

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[27] Tian-ming G, Na F, Wu C and Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[28] Tian-ming G, Na F, Wu C and Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[29] Tian-ming G, Na F, Wu C and Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[30] Tian-ming G, Na F, Wu C and Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[31] Zhang Y, Ma B, Lv Y, Wang C, Chen Y (2023) An effective method for directly extracting lithium from α-spodumene by activated roasting and sulfuric acid leaching. Journal of Industrial and Engineering Chemistry, 122, 540-550; Fosu AY, Kanari N, Bartier D, Vaughan J, Chagnes A (2022) Novel extraction route of lithium from α-spodumene by dry chlorination. RSC Advances 12(33), 21468–21481; Braga PFA, França SCA, Pinto CP, Rosales GD (2020) Recovery of lithium from spodumene by chlorination roasting, IMPC 2020: XXX International Mineral Processing Congress, Cape Town, South Africa, 18–22 October 2020. <https://cetem.gov.br/antigo/images/congressos/2020/CAC00040020.pdf>

[32] Tian-ming G, Na F, Wu C and Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[33] Tian-ming G, Na F, Wu C and Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

The following table summarizes the key RD&D areas of focus in roasting technologies:

Table 3: Global RD&D focus areas for roasting of hard rock lithium ores technologies.

	RD&D FOCUS AREAS
General	• Developing and scaling up alternative, energy efficient roasting mechanisms (e.g., microwave-assisted heating) to reduce energy and reagent consumption.[34]
Sulphuric acid roasting	• Developing treatment processes for residues to optimise lithium recovery and minimise waste.[35]
Salt roasting	• Piloting and scaling up methods for spodumene ores to improve extraction and energy efficiency.[36] • Developing solutions to minimise and treat any waste residues.[37] • Designing and optimisation at commercial scale, including improving control of reaction conditions (e.g., ore-to-salt ratio, roasting temperatures and duration).[38]
Chlorination roasting	• Development of materials and plant equipment to protect against the corrosive nature of chlorinating agents.[39] • Implementing closed-loop system design and using adsorbents (e.g., calcium hydroxide) capture the chlorine gas byproduct.[40]

3.1.3 Leaching

In the conventional commercial pathway, leaching is typically done after the calcination and roasting steps to form either solid or soluble lithium compounds. However, new approaches are being developed to leach ores after, or even without, calcination or roasting. By using acids and alkali solutions there is the potential to bypass the energy-intensive calcination or roasting steps.[41]

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[34] Salakjani NKh, Singh P, Nikoloski AN (2019) Acid roasting of spodumene: Microwave vs. conventional heating. Minerals Engineering 138, 161–167.

[35] Wang X, Hu H, Liu M, Li Y, Tang Y, Zhuang L, Tian B (2021) Comprehensive utilization of waste residue from lithium extraction process of spodumene. Minerals Engineering, 170 106986; Yelatontsev D, Mukhachev A (2021). Processing of lithium ores: Industrial technologies and case studies–A review. Hydrometallurgy, 201, 105578.

[36] Tian-ming G, Na F, Wu C, Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology, 6 137-153

[37] Xu W, Haisheng H, Meitang L, Yunfei L, Yong T, Lun Z, Benjun T, (2021) Comprehensive utilization of waste residue from lithium extraction process of spodumene. Minerals Engineering, 170, 106986. <https://doi.org/10.1016/j.mineng.2021.106986>.

[38] Tian-ming G, Na F, Wu C, Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137–153.

[39] Xing Z, Cheng G, Yang H, Xue X, Jiang P (2020) Mechanism and application of the ore with chlorination treatment: A review. Minerals Engineering, 154 106404.

[40] Lv Y, Liu Y, Ma B, Wang C, Qiu Z, Chen Y (2023) Emission reduction treatment of chlorine-containing waste gas during the chlorination roasting process of lepidolite: thermodynamic analysis and mechanism investigation. Separation and Purification Technology, 315, 123686.; Liu Y, Lv Y, Ma B, Wang C, Chen Y (2023) An environmentally friendly improved chlorination roasting process for lepidolite with reduced chlorinating agent dosage and chlorinated waste gas emission. Separation and Purification Technology, 310, 123173.

[41] Karrech A, Azadi MR, Elchalakani M, Shahin MA, Seibi AC (2020) A review on methods for liberating lithium from pegmatites. Minerals Engineering; Gao T, Fan N, Chen W, Dai T (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology.

Acid leaching

In this process an acid is mixed with the calcined or natural ore and heated to a temperature suitable for the leaching reaction. Several leaching agents are being considered, including sulphuric, hydrochloric, hydrofluoric or nitric acid.[42] Pathways that allow efficient leaching at comparatively lower temperatures represent an area of research interest given the potential for reductions in energy intensity and, consequently, process cost.

TECHNOLOGY STATE OF PLAY

Sulphuric acid leaching has been demonstrated at pilot scale, whereas hydrochloric, hydrofluoric and nitric acid leaching processes are still at laboratory scale. For example, Lithium Australia has developed and patented the SiLeach® process which directly uses sulphuric acid in the presence of fluoride (i.e. without the need for calcination and roasting). The process results in a lithium solution that can be used to produce lithium phosphate or carbonate. The company has conducted two rounds of testing between 2015 and 2018 at ANSTO's pilot facility in NSW having the capacity to process 27,600 tonnes of feedstock per year and demonstrate the effectiveness of the technology. [43]

Laboratory demonstrations have shown that hydrofluoric acid can directly leach lithium from β-spodumene (calcined spodumene), or it can leach lithium from α-spodumene (untreated spodumene) when combined with sulphuric acid.[44]

From the extractive processes analysed, 13.9% of patent families were related to acid leaching processes from 2007 – 2022 period; 5.5% for processes involving sulphuric acid and 8.4% for leaching with other acids. There is a low-baseline, stable trend of activity for both areas relative to other extractive processes, in part reflecting the low number of innovators in this space, and low number of countries with hard rock lithium deposits. Australia ranked 3rd in patents related to acid leaching, with particularly strong activity in the use of alternative acids (15% of global patents). China (70.6%) and the USA (17.6%) were the only other countries with activity in sulphuric acid leaching, and were also active in the use of other acids (USA with 23.1% and China with 61.5%). Australian companies that have patent activity in acid leaching processes include Reed Advanced Materials, Lithium Australia and Novalith.

Alkaline leaching

Alkaline solutions such as sodium- or calcium-based hydroxides and carbonates are also being considered for the leaching of lithium ores. The reaction is often conducted in the high-pressure, high-temperature environment of an autoclave or pipeline reactor. The products of the leaching process include a solution

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Karrech A, Azadi MR, Elchalakani M, Shahin MA, Seibi AC (2020) A review on methods for liberating lithium from pegmatites. Minerals Engineering; Gao T, Fan N, Chen W, Dai T (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology.

[43] Griffith CS, Griffin AC, Roper A, Skalski A (2018) Development of SiLeach® Technology for the Extraction of Lithium Silicate Minerals. In Extraction 2018, The Minerals, Metals & Materials Series. Springer International Publishing, Cham; Lithium Australia (2022b) About SiLeach. Lithium Chemicals <https://www.lithium-au.com/about-sileach/>; Lithium Australia (2021) Lithium Australia granted Australian patent for lithium extraction technology. ASX Announcement Li chemicals. <https://vspc.com/wp-content/uploads/2020/01/03062021-LIT-granted-Australian-patent-for-Li-extraction-technology.pdf>.

[44] Rosales GD, Ruiz MDC, Rodriguez MH (2014) Novel process for the extraction of lithium from β-spodumene by leaching with HF. Hydrometallurgy 147–148, 1–6; Guo H, Yu H, Zhou A, Lü M, Wang Q, Kuang G, Wang H (2019) Kinetics of leaching lithium from α-spodumene in enhanced acid treatment using HF/H2SO4 as medium. Transactions of Nonferrous Metals Society of China 29(2), 407–415; Guo H, Kuang G, Wang H, Yu H, Zhao X (2017) Investigation of Enhanced Leaching of Lithium from α-Spodumene Using Hydrofluoric and Sulfuric Acid. Minerals 7(11), 205.

containing lithium compounds which can undergo further purification and product recovery (see Section 3.1.4), and solid waste residues.[45]

TECHNOLOGY STATE OF PLAY

Several alkali leaching processes have been patented and are being piloted domestically and globally. For example, Metso (Finland) has developed a two-stage leaching process using sodium carbonate and calcium hydroxide to produce lithium hydroxide.[46] The company has commercialised the technology, with plans to construct refineries in Canada under way.[47]

In Australia, Lithium Australia and ANSTO co-developed and patented LieNa®, a two-step leaching process that is particularly effective for processing fine particles of α-spodumene, which are conventionally lost as mining waste (tailings). The tailings are first leached with sodium hydroxide in an autoclave, the solids produced then leached with hydrochloric acid and the leach liquor purified through precipitation with trisodium phosphate to form lithium phosphate.[48] In 2023, Mineral Resources (Australia) committed $4.5 million in funding to help Lithium Australia pilot this technology.[49]

Novalith, an Australian start-up, has developed and patented a leaching process using carbonated water made up of CO_2 captured from industrial sources. The technology is being demonstrated and improved at a pilot plant in Sydney.[50]

Alkaline solutions can also be used to process the waste residues from the roasting and leaching process. The waste residue is reacted with sodium hydroxide at elevated temperatures and pressures to form adsorbents and catalytic materials (e.g., zeolite).[51]Although waste processing is a relatively emerging research space,[52] Australia has made substantial progress in terms of technology development and piloting.

Neometals (Australia) and CSIRO have co-developed a process to convert leach residue from lithium extraction processing into zeolite in Australia.[53] Neometals is partnering with the Queensland University of

[45] Karrech A, Azadi MR, Elchalakani M, Shahin MA and Seibi AC (2020) A review on methods for liberating lithium from pegmatites. Minerals Engineering, 145:106085.

[46] Metso (2019) The Metso alkaline leach concept: a direct leach process for producing battery-grade lithium salts. Mining and Metals Blog < https://www.metso.com/insights/blog/mining-and-metals/the-metso-alkaline-leach-concept/>

[47] Metso (2019) Metso and Avalon sign Memorandum of Understanding for potential partnership to advance the building of first battery-grade lithium facility in Ontario, Canada <https://www.metso.com/corporate/media/news/2023/7/metso-and-avalon-sign-memorandum-of-understanding-for-potential-partnership-to-advance-the-building-of-first-battery-grade-lithium-facility-in-ontario-canada/>

[48] Lithium Australia (2022) About LieNa. Lithium Chemicals. <https://www.lithium-au.com/about-liena/>.

[49] Lithium Australia (2023) Lithium Australia signs landmark joint development agreement with Mineral Resources. <https://wcsecure.weblink.com.au/pdf/LIT/02694707.pdf>.

[50] Novalith (2023) Novalith Technologies Raises AU$23 Million In Series A Funding To Revolutionise Lithium Production. <https://www.novalith.com.au/news/novalith-technologies-raises-au-23-million-in-series-a-funding-to-revolutionise-lithium-production>

[51] Outram J, Collins F, Millar G, Couperthwaite S, Beer G (2023) Process optimisation of low silica zeolite synthesis from spodumene leachate residue. Chemical Engineering Research and Design 189, 358-370. <https://doi.org/10.1016/j.cherd.2022.11.015>

[52] Yingwei L, Baozhong M, Yubo L, Chengyan W, Yongqiang C (2022) Adsorption behavior and mechanism of mixed heavy metal ions by zeolite adsorbent prepared from lithium leach residue. Microporous and Mesoporous Materials, 329, 111553. <https://doi.org/10.1016/j.micromeso.2021.111553>

[53] Argus Media (2018) Neometals produces zeolite from lithium residue. <https://www.argusmedia.com/en/news/1748172-neometals-produces-zeolite-from-lithium-residue>

Technology and the Innovative Manufacturing Cooperative Research Centre to advance and demonstrate the technology at pilot scale.[54]

Patent activity for extractive processes involving alkaline leaching account for 5.2% of patent families filed from 2007 to 2022. Like the other leaching processes, the trend over this period was stable, with a low baseline, peaking between 2018 and 2020. Australia ranked 2nd for the period with 12.5% of patent families, coming in after China which had 62.5%, and ahead of Finland with 6.3%. Australian companies that have patent activity in alkaline leaching include Lithium Australia and Tianqi Lithium Energy Australia.

Bioleaching

Bioleaching is an emerging extraction technology that uses micro-organisms, or leaching agents created by micro-organisms, to transform minerals into forms that are soluble and easy to extract. A number of bacteria and fungi are able to decompose lithium-containing hard rock minerals to extract lithium. Depending on the particle size of the ore and the engineering design, the extraction period can vary from a few days up to several months.[55]

Due to its low energy consumption, toxic waste generation and capital expenditure (CAPEX), bioleaching has been commercially applied to extract other metal compounds (e.g., copper, gold) from ores. It is also considered a strong technology candidate for material recovery from low-grade ores, mining tailings and e-waste.[56]

TECHNOLOGY STATE OF PLAY

The application of bioleaching for lithium extraction from hard rock ores, is still limited to laboratory scale.[57] CSIRO is developing comprehensive capabilities in bioleaching of e-wastes such as used Li-ion batteries and printed circuit boards.[58] Outside of Australia, Rio Tinto's Nuton venture (USA) is demonstrating an elevated temperature bioleaching process on low-grade copper resources, including mining wastes and tailings.[59]

Global IP activity for bioleaching was not included in this report due to the emergence of this technology for lithium-containing materials and the limited number of patents being published in this area.

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[54] IMCRC (2019) $2.57 million collaborative research project to commercialise zeolite process. <https://www.imcrc.org/neometals_announcement/>

[55] Sedlakova-Kadukova J, Marcincakova R, Luptakova A, Vojtko M, Fujda M, Pristas P (2020) Comparison of three different bioleaching systems for Li recovery from lepidolite. Scientific Reports, 10(1):14594.

[56] Rendón-Castrillón L, Ramírez-Carmona M, Ocampo-López C, Gómez-Arroyave L (2023) Bioleaching Techniques for Sustainable Recovery of Metals from Solid Matrices. Sustainability, 15(13):10222; Kaksonen AH, Deng X, Bohu T, Zea L, Khaleque HN, Gumulya Y, Boxall NJ, Morris C and Cheng KY (2020) Prospective directions for biohydrometallurgy. Hydrometallurgy 195, 105376. DOI: 10.1016/j.hydromet.2020.105376.

[57] Sedlakova-Kadukova J, Marcincakova R, Luptakova A, Vojtko M, Fujda M, Pristas P (2020) Comparison of three different bioleaching systems for Li recovery from lepidolite. Scientific Reports, 10(1):14594.

[58] CSIRO (2022) Microbes to mine metals from e-waste?. <https://www.csiro.au/en/work-with-us/industries/mining-resources/Resourceful-magazine/Issue-25/Biomining>.

[59] Reuters (2022) Miners turn to bacteria and other new ways to leach copper from waste rock. <https://www.reuters.com/markets/us/miners-turn-bacteria-other-new-ways-leach-copper-waste-rock-2022-05-11/>

The following table summarizes the key RD&D areas of focus in lithium extraction using acid, alkaline, and bioleaching pathways:

Table 4: Global RD&D focus areas for leaching of hard rock lithium ores technologies.

RD&D FOCUS AREAS	
Acid and alkaline leaching	• Developing closed loop systems for reagent recovery and regeneration.60 • Developing and scaling up technologies to minimise and treat any waste residues.61
Bioleaching	• Increasing the efficiency and flexibility of bioleaching, which includes designing processes to target low-grade ores and developing microorganisms with improved tolerance and effectiveness. • Designing large-scale bioreactors with automated and streamlined operations to improve efficiency and reduce cost.

3.1.4 Conversion and purification

Once extracted, lithium compounds and lithium-containing liquors will contain impurities (e.g., sulphate, magnesium, or chloride ions) and will require purification before use in battery applications.[62] Lithium compounds must possess a purity level above 99.95 % to be classified as battery-grade or ultra-pure.[63] Battery-grade lithium compounds are then used for the synthesis of cathode active materials (CAM), which is discussed in Section 3.3.

The conversion and purification process typically involves multiple steps and varies depending on the processing route used and the type of impurities present. While the main target end-products have traditionally been lithium hydroxide and lithium carbonate, others like lithium sulphate and lithium phosphate are increasingly relevant as they can be used to directly produce other cathode chemistries of interest (e.g., LFP through lithium phosphate).

Key conversion and purification methods for lithium carbonate and lithium hydroxide include causticisation, membrane electrodialysis, and carbonation.

Causticisation is used to produce battery-grade lithium hydroxide. Roasting and leaching processes typically produce a lithium sulphate, carbonate or chloride compound. Causticisation involves reacting these compounds with a hydroxide compound (usually sodium based, but can also be barium or calcium hydroxide), to produce battery-grade lithium hydroxide.[64]

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[60] Yelatontsev D, Mukhachev A (2021) Processing of lithium ores: Industrial technologies and case studies–A review. Hydrometallurgy, 201, 105578.

[61] Wang X, Hu H, Liu M, Li Y, Tang Y, Zhuang L, Tian B (2021) Comprehensive utilization of waste residue from lithium extraction process of spodumene. Minerals Engineering 170:106986.

[62] Cai W, Chen R, Yang Y, Yi M, Xiang L (2018) Removal of SO_4^{2-} from Li2CO3 by Recrystallization in Na2CO3 Solution. Crystals 8(1):19. < https://doi.org/10.3390/cryst8010019>

[63] Linneen N, Bhave R, Woerne D (2019) Purification of industrial grade lithium chloride for the recovery of high purity battery grade lithium carbonate. Separation and purification technology 214, 168-173.

[64] Liu H, Azimi G (2022) Production of battery grade lithium hydroxide monohydrate using barium hydroxide causticizing agent. Resources, Conservation and Recycling 179, 106115.

Membrane electrodialysis is an alternative approach to causticisation to produce battery-grade lithium hydroxide. Rather than the addition of sodium hydroxide in causticisation, this method involves electrolysis of water to generate OH^- ions.[65]

Carbonation is used to produce battery-grade lithium carbonate. In this process, a lithium hydroxide solution is first reacted with carbon dioxide to obtain lithium carbonate, rejecting contaminants in the process.[66] Alternatively, when lithium is present in a sulphate solution it can be precipitated as lithium carbonate through sodium carbonate addition, with a by-product of the reaction being sodium sulphate which has low value.[67] While sodium sulphate could potentially be regenerated into sodium hydroxide and sulphuric acid for reuse, this is a challenging process.[68]

Purification and conversion are areas of ongoing development, and advanced treatment processes in addition to mature methods are being developed at laboratory scale to target a wider range of impurities, improve the purification efficiency, and ultimately increase the purity of the lithium compounds. An example of these advanced treatment processes involves using various ion-exchange resins to remove metallic impurities (e.g., calcium, magnesium, copper, nickel, and zinc) to produce >99.9% lithium carbonate.[69]

TECHNOLOGY STATE OF PLAY

Causticisation is commercially mature and the standard method of many domestic and international refiners who extract lithium via the conventional sulphuric acid roasting pathway. Causticisation is used in current and upcoming commercial-scale lithium hydroxide refining joint ventures in Australia. Tianqi-IGO, Albemarle and Covalent Lithium all use sodium hydroxide to convert and purify lithium sulphate into battery-grade lithium hydroxide.[70]

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[65] Grageda M, Gonzalez A, Quispe A, Ushak S (2020) Analysis of a process for producing battery grade lithium hydroxide by membrane electrodialysis. Membranes 10(9), 198.

[66] Kim S, Yoon H, Min T, Han B, Lim S, Park J (2023) Carbon dioxide utilization in lithium carbonate precipitation: A short review. Environmental Engineering Research 29(3), 230553–0; Milyutin VV, Nekrasova NA, Rudskikh VV, Volkova TS (2020) Preparation of High-Purity Lithium Carbonate Using Complexing Ion-Exchange Resins. Russian Journal of Applied Chemistry 93, 549-553.

[67] Liu H, Azimi G (2021) Process analysis and study of factors affecting the lithium carbonate crystallization from sulfate media during lithium extraction. Hydrometallurgy 199, 105532.

[68] Stakeholder consultations

[69] Milyutin VV, Nekrasova NA, Rudskikh VV, Volkova TS (2020) Preparation of High-Purity Lithium Carbonate Using Complexing Ion-Exchange Resins. Russian Journal of Applied Chemistry 93, 549-553; Milyutin VV, Kaptakov VO, Nekrasova NA, Rudskikh VV, Volkova TS (2020) Deep Purification of Lithium Compounds to Remove Chemical and Radioactive Impurities. Radiochemistry 62, 331-334.

[70] IGO Limited (2022) Kwinana lithium hydroxide refinery site visit presentation. <https://www.igo.com.au/site/pdf/5689dd29-0fec-480d-8bc1-3cab878469ea/Kwinana-Site-Visit-Presentation.pdf>

Covalent Lithium (2021) Lithium Hydroxide Refinery Project: Covalent Lithium Greenhouse Gas Management Plan. Covalent Lithium, Australia. <https://straueconnhubpublic1.blob.core.windows.net/env/Refinery%20Greenhouse%20Gas%20Management%20Plan.pdf>; Martinick Bosch Sell (2023) Kwinana lithium refinery process residues geochemical assessment. Covalent Lithium, Perth, Australia. <https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/Kwinana%20Lithium%20Refinery%20Process%20Residues%20Geochemical%20Assessment.pdf>

Albemarle (2018) Albemarle and Western Australia. Albemarle Lithium, Perth, Western Australia. <https://www.albemarle.com/storage/wysiwyg/alb_kemerton_literature_051618_a4_fnl.pdf>; GHD (2017) Albemarle Kemerton Plant Air Quality Impact Assessment - Part A, Albemarle Lithium. <https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/CMS17244%20-%20Appendix%20F%20-%20Albemarle%20Kemerton%20Plant%20Air%20Quality%20Impact%20Assessment%20Part%20A%20from%20Albemarle%207%20November%202017%20%28DWERDA-013528%29.pdf>

Membrane electrodialysis is a less mature and less commonly used technology to produce battery-grade lithium hydroxide compared to causticisation.[71] Nemaska Lithium (Canada) demonstrated the technology at pilot scale in 2017 and will integrate it into a commercial-scale facility that is expected to be operational by 2025.[72] The company is currently co-owned by Livent (USA) and Investissement Québec, the Québec Government's investment agency.[73]

Carbonation is also a mature process and the industry-standard method to produce battery-grade lithium carbonate.[74]

The global patent analysis found 33.7% of filings between 2007 and 2022 were related to the conversion and purification of lithium compounds. This area has seen a significant increase in patent activity post-2015. This aligns with the increased demand for highly purified, battery grade lithium compounds stemming from the global energy transition. Australia was 3rd with 9.6% of total activity, while the USA was 2nd and accounted for 11.5% of filings. China had the largest proportion of patent filings during the period with 70.2%. Other active countries include Germany, Finland and the Republic of Korea. Australian companies with patent activity in conversion and purification processes include Reed Advanced Materials, Lithium Australia, Infinity Greentech, Novalith, and Tianqi Lithium Kwinana.

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[71] Gmar S, Chagnes A (2019) Recent advances on electrodialysis for the recovery of lithium from primary and secondary resources. Hydrometallurgy 189, 105124.

[72] Nemaska Lithium (2016) How to profit from the booming lithium markets. <http://www.chemwinfo.com/private_folder/Uploadfiles2016_May/Nemaska_lithium.pdf>; Nemaska Lithium Inc (2017) Nemaska Lithium Processes Whabouchi Concentrate at the Phase 1 Plant and Provides Project Financing Update, GlobeNewswire News Room <https://www.globenewswire.com/news-release/2017/10/10/1470488/0/en/Nemaska-Lithium-Processes-Whabouchi-Concentrate-at-the-Phase-1-Plant-and-Provides-Project-Financing-Update.html>; Nemaska Lithium Inc (2023) Bécancour Conversion Facility. What we do. <https://nemaskalithium.com/en/becancour-conversion-facility/>.

[73] BioAge Group (2022) Livent to double its ownership stake in Nemaska Lithium to 50%. Green Car Congress. <https://www.greencarcongress.com/2022/05/20220508-livent.html>.

[74] Milyutin VV, Kaptakov VO, Nekrasova NA, Rudskikh VV, Volkova TS (2020) Deep Purification of Lithium Compounds to Remove Chemical and Radioactive Impurities. Radiochemistry 62, 331-334.

The following table summarizes the key RD&D areas of focus in the purification of lithium compounds:

Table 5: Global RD&D focus areas for conversion and purification technologies to produce battery grade lithium compounds.

RD&D FOCUS AREAS	
Causticisation	• Improving the efficiency of causticisation, including reducing the cost and energy requirement for post-treatment (e.g. evaporative crystallisation).[75]
Membrane electrolysis	• Optimising the design of the membrane reactor for closed-looped reactions (to reduce toxic gas emissions) and efficient large-scale application.[76]
Carbonation	• Developing advanced treatment processes to improve efficiency, minimise waste and decrease CO_2 consumption of the carbonation process.[77]

3.1.5 Implications for Australia

The production of high-purity, battery-grade, lithium compounds is essential to the global energy transition, and in particularly lithium-batteries which store renewably produced electricity, and power electric vehicles. However, supply shortages are expected, particularly by 0.1 million tonnes in 2030 and increasing to 1.1 million tonnes in 2035.[78] Australia's resources and existing industrial capability provides the foundation for a thriving export market in lithium compounds to meet the needs of the global energy transition. Australia has world leading lithium reserves and mining activity, accounting for 48% of global production in 2023.[79] Australia's Tianqi refinery in Western Australia currently produces 88,000 tons of lithium compounds per year.[80] However, despite its maturity, the production of lithium compounds continues to face several technical, cost, and sustainability challenges. This is an area of strong innovation momentum globally, and Australia's capabilities in this area can be leveraged to support the development of state-of-the-art domestic projects.

This section discusses the opportunities for domestic RD&D and international engagement in the production of lithium compounds from hard rock ores (summarised in Figure 8). More details on the

[75] Liu H, Azimi G (2022) Production of battery grade lithium hydroxide monohydrate using barium hydroxide causticizing agent. Resources, Conservation and Recycling 179, 106115.

[76] Grageda M, Gonzalez A, Quispe A, Ushak S (2020). Analysis of a process for producing battery grade lithium hydroxide by membrane electrodialysis. Membranes, 10(9), 198.

[77] Wang J, Hu H (2020) Microbubble-assisted pressure carbonation for preparation of high purity lithium carbonate. Journal of Materials Research and Technology, 9(5), 9498-9505; Milyutin VV, Nekrasova NA, Rudskikh VV, Volkova TS (2020) Preparation of High-Purity Lithium Carbonate Using Complexing Ion-Exchange Resins. Russian Journal of Applied Chemistry, 93(4):549–553.

[78] Wurzbacher C, Gilbert M, McAdoo M, Niese N, Smilkstins A and Reed E (2022) The lithium supply crunch doesn't have to stall electric cars. BCG. <https://www.bcg.com/publications/2022/the-lithium-supply-crunch-doesnt-have-to-stall-electric-cars>.

[79] Tabelin CB, Dallas J, Casanova S, Pelech T, Bournival G, Saydam S and Canbulat I (2021) Towards a low-carbon society: A review of lithium resource availability, challenges and innovations in mining, extraction and recycling, and future perspectives. Minerals Engineering 163, 106743. DOI: 10.1016/j.mineng.2020.106743; U.S. Geological Survey (2024) Mineral commodity summaries. Lithium. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-lithium.pdf; Alyabyev S, Edstein M, Krauze A, Jensen MY (2023) Australia's potential in the lithium mining market. McKinsey & Company. <https://www.mckinsey.com/industries/metals-and-mining/our-insights/australias-potential-in-the-lithium-market>

[80] Tianqi Lithium (2023) 2023 Annual Report < https://newsfile.futunn.com/public/NN-PersistNoticeAttachment/7781/20240429/11185912-0.pdf>

framework used can be found in the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 8: Opportunities for Australian RD&D and international engagement in the production of lithium compounds.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies	• Chlorination roasting	• Acid and alkali leaching • Salt roasting	• Calcination • Purification • Acid and alkali leaching • Salt roasting	• Sulphuric acid roasting
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

IP, intellectual property.

Calcination

Calcination is currently a necessary step in commercial operations to extract lithium from hard-rock ores like spodumene, since the process can make the ores more amenable to leaching.[81] Given Australia's lithium reserves are based on hard-rock ores and the growing interest in these sources as an alternative to brines, calcination is an important activity for current and upcoming Australian lithium hydroxide refining projects.

Calcination is a mature process but remains an area with high levels of innovation. It was the second most active area of the lithium compound production supply chain in terms of IP activity over the past 15 years, with the trend also showing momentum in recent years. This could reflect its role across different lithium extraction pathways, which may use different roasting-leaching combinations but still rely on an initial thermal step. The high energy intensity of the process remains a key challenge, warranting innovation. Addressing it may require RD&D in areas such as novel hybrid processes and integration of renewables (including electrification and hydrogen).

There is a role for RD&D to support the piloting and scaling up of domestic IP, especially those with high efficiency and sustainability outcomes, which can position Australia as a competitive global producer.[82] Australia emerges second after China in terms of IP activity and currently has commercial capabilities through partnerships with foreign technology partners, helping derisk future pilots and demonstrations. Furthermore, Australia is active in sustainable calcination projects in other metals industries, resulting in cross-cutting capabilities that can be leveraged across the mineral resources sector, including lithium.

[81] Abdullah AA, Oskierski HC, Altarawneh M, Senanayake G, Lumpkin G, Dlugogorski BZ (2019) Phase transformation mechanism of spodumene during its calcination. Minerals Engineering 140, 105883.

[82] Alyabyev S, Edstein M, Krauze A, Jensen MY (2023) Australia's potential in the lithium mining market. McKinsey & Company. <https://www.mckinsey.com/industries/metals-and-mining/our-insights/australias-potential-in-the-lithium-market>

Roasting

Sulphuric acid roasting is already commercially deployed in Australia due to its high maturity level, simpler operational requirements and lower costs relative to other pathways and will remain important in Australia going forward. The high maturity level and stable-to-declining IP activity trend in sulphuric acid roasting suggests that RD&D opportunities lie in improvements of existing technology and cross-cutting research, supported by domestic and international collaboration. Australia has not had high IP activity in sulphuric acid roasting, which could in part be due to the maturity of the technology and the access to overseas IP and know-how via international partners. As such, the opportunity for Australia lies in strategic international engagement to enable commercial scale projects, which is aligned with current activity (i.e., partnerships between Australian miner and international technology developers).

Challenges with sulphuric acid roasting still exist which could warrant further RD&D efforts, including the integration of renewable energy and waste residues processing. RD&D in waste processing technologies represents an opportunity to improve circularity and sustainability, potentially reduce operating costs, and generate additional revenues from the recovered materials. Like calcination, cross-cutting capabilities in integrating renewable energy and decarbonisation can be leveraged across the mineral sector, including roasting processes.

Salt roasting can play a role in Australia's technology portfolio, due to the potential to minimise equipment corrosion, and to directly process naturally occurring ores without calcination, a variation that could offer a step-change improvement terms of cost and sustainability.

Since Australia has limited relevant IP activity, a potential pathway for commercial deployment of salt roasting in Australia would likely involve engaging with international partners to access and deploy existing mature technologies, supported by RD&D on its applicability to Australian ores and contexts.

There is strong potential for innovation in salt roasting illustrated by patent trends over the last 15 years and the recent work being done in this area. Salt roasting patent activity surpasses the activity for all other extractive processes (both roasting and leaching-based). With the global emergence of direct salt roasting of naturally occurring ores, there is an opportunity for Australia to develop domestic capability and via RD&D. Other RD&D areas include advancing processes for spodumene ores, optimising operation control at scale, and minimising waste.

Chlorination roasting, with chlorine gas or chloride salts, can offer extraction efficiency advantages over sulphuric acid roasting. However, it faces significant challenges in equipment corrosion and safety due to the use and emission of chlorine gas, potentially resulting in the limited commercial activity and declining IP activity trend globally as well as the lack of IP in Australia. By collaborating with international institutions for knowledge sharing, there might be an opportunity for RD&D to improve the process and enable scaling up.

Leaching

Acid and alkali leaching processes represent a step change opportunity to bypass energy intensive steps of current commercial processes. Leaching processes are being demonstrated at pilot scales domestically and globally. To progress projects to the commercial scale, RD&D in efficiency and cost optimisation will be required. This, for example, includes reducing extraction time and improving extractions, or reducing reagent consumption and waste production.[83]

With the world-leading IP activity and active commercial development, Australia is well placed to undertake RD&D to scale up novel leaching methods without significant technology support from overseas partners. Supporting domestic RD&D in this space can help position Australia as a sustainable and competitive lithium compound producer and a global technology innovator. This can also provide opportunities to license Australian IP overseas, or opportunities for Australian proponents to partner with overseas project developers and expand extraction projects in other jurisdictions.

Bioleaching is a less mature technology in the context of lithium but may offer cost and sustainability benefits in the long-term however this area is very nascent. The development of bioleaching for lithium would require R&D targeting efficiency, process optimisation, and improved microorganisms. Bioleaching is well studied in other minerals, being a commercially ready process to extract copper from natural resources. Australia could collaborate with relevant foreign institutions and companies to develop lithium applications by leveraging its existing experience and sharing knowledge on bioleaching of wastes and other ore bodies.

Purification

The growing demand for battery active materials is a driving factor for the rise in purification RD&D and commercial activity. Diversifying purification capability across mature and emerging technology options will be necessary to meet the future demand and specifications of lithium hydroxide and lithium carbonate, as well as adapt to the outputs of diverse extraction pathways (which produce different lithium compounds).

Patent filings related to conversion and purification methods accounted for over a third of all activity identified in our analysis, being the largest category within the production of lithium compounds supply chain. Moreover, the area shows a growing trend and recent momentum, potentially reflecting the importance of achieving battery-grade purity in the lithium compounds produced.

While Australia has already undertaken purification commercially in joint ventures with overseas companies, many Australian companies are developing their own IP. This represents the opportunity to pilot and demonstrate domestic processes onshore and reduce reliance on overseas technology partners.

Ongoing RD&D efforts would be required to enhance purity levels, process efficiency and energy consumption, which could increase product value and decrease costs. International collaboration for project financing and offtakers, in addition to technology support, is necessary for commercial production of lithium compounds in Australia. This is due to the global demand for lithium precursors being significantly higher than domestic demand.

International collaboration will be required across the majority of technologies discussed in this section. Demonstration projects and first-of-a-kind commercial projects often require high CAPEX investment, especially those utilising calcination and roasting.[84] For example, the construction costs of Calix and Pilbara Minerals' demonstration plant to produce lithium compounds, which includes an electric calciner, are

[83] Karrech A, Azadi MR, Elchalakani M, Shahin MA, Seibi AC (2020) A review on methods for liberating lithium from pegmatites. Minerals Engineering, 145:106085; Tian-ming G, Na F, Wu C, Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137-153.

[84] Alyabyev S, Edstein M, Krauze A, Jensen MY (2023) Australia's potential in the lithium mining market. McKinsey & Company. <https://www.mckinsey.com/industries/metals-and-mining/our-insights/australias-potential-in-the-lithium-market>

estimated to be $104.9 million.[85] Similarly, emerging leaching pathways face higher investment risk relative to incumbent processes. Although operational expenditure (OPEX) costs may be reduced due to fewer processing steps, specialised equipment may be required.[86] Finally, for conversion and purification, continuous engagement with end users and product offtakers is also important for determining a suitable process to meet product specifications.

3.2 Production of lithium metal

High purity lithium metal is essential for next generation lithium-metal batteries, where it is used as an anode material. Lithium metal is highly reactive and is therefore not found in nature in elemental form. Metal production and storage must be conducted in a vacuum or an inert environment to prevent the lithium metal from reacting with air and/or water.[87]

This section covers the production of lithium metal from lithium compounds such as lithium chloride, hydroxide or carbonate using techniques such as electrolysis and thermochemical reduction.

3.2.1 Molten salt electrolysis

The most commercially mature method for producing lithium metal is by electrolysing the lithium chloride component of a molten salt mixture (containing lithium and potassium chloride) at high temperatures. This method is mature and well understood, however, key challenges of electrolysis include the requirement for highly pure and expensive lithium chloride as the feedstock and the production of toxic chlorine gas.

To overcome the challenges associated with chlorine gas emissions and to reduce costs, variations of the electrolysis process are being developed that use more accessible lithium compounds such as lithium hydroxide and carbonate. [88]

3.2.2 Thermochemical reduction

Thermochemical reduction processes use a reductant (e.g. a reactive metal, element, gas or compound) and high temperatures to reduce an ore (or compound) into a metal. Several reductants can be used for the thermochemical reduction of lithium compounds (lithium oxide, hydroxide or carbonate) into lithium metal. These include carbon, magnesium, aluminium, silicon, hydrogen, iron and calcium carbide.[89]

Thermochemical reduction is being investigated as an alternative to molten salt electrolysis as advantages for this technique include flexibility in the use of various reagents and having no toxic gas emissions.

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[85] Plibera Minerals, Calix Limited (2023) Final Investment Decisions for Mid-stream Demonstration Plant. <https://announcements.asx.com.au/asxpdf/20230802/pdf/05s7wrfrwdrrrd.pdf>

[86] Tian-ming G, Na F, Wu C, Tao D (2023) Lithium extraction from hard rock lithium ores (spodumene, lepidolite, zinnwaldite, petalite): Technology, resources, environment and cost. China Geology 6(1), 137-153.

[87] Acebedo B, Morant-Miñana MC, Gonzalo E, Ruiz De Larramendi I, Villaverde A, Rikarte J, Fallarino L (2023) Current Status and Future Perspective on Lithium Metal Anode Production Methods. Advanced Energy Materials, 13(13):2203744.

[88] Zhang Xin, Han A, Yang Y (2020) Review on the production of high-purity lithium metal. Journal of Materials Chemistry A, 8(43):22455–22466.

[89] Zhang Xin, Han A, Yang Y (2020) Review on the production of high-purity lithium metal. Journal of Materials Chemistry A, 8(43):22455–22466.

However, it is a challenging reaction to successfully achieve due to its high temperature requirements and lithium reactivity.[90]

TECHNOLOGY STATE OF PLAY

Molten salt electrolysis was commercialised in the 1920s and remains the sole method for commercial lithium metal producers globally.[91] Ganfeng Lithium is the largest lithium metal producer in the world, with an annual capacity of 2,150 tonnes in 2021. It is planning to add another 7,000 tonnes per annum in the upcoming years.[92]

Emerging molten salt electrolysis methods using lithium hydroxides and carbonates (instead of chlorides) are being developed at laboratory and pilot scales to reduce costs and avoid chlorine gas emissions. For example, in mid-2023, Li-metal (Canada) successfully patented and piloted lithium metal production via lithium carbonate electrolysis.[93]

Thermochemical reduction of lithium is at laboratory and pilot scale. For example, CSIRO has developed and patented a carbothermal reduction process, called LithSonic™, to produce lithium metal, where supersonic flow is applied to rapidly cool and stabilise the lithium metal produced.[94] The process has been successfully demonstrated at laboratory scale and is in the final stages of technical improvements to prepare for mini-plant demonstration (pre-pilot scale).

IP activity in lithium metal production was consistently low throughout the 2007 – 2022 period. The analysis identified 2.3% of patent families filed globally as related to the process. This reflects the nascency of lithium metal battery technologies. The patent families were distributed between the USA with 42.9%, China with 28.6%, and Australia with 28.6%.

[90] Shi L, Zhang H, Qu T, Deng Y, Liu D, Xu B, Yang B, Dai Y (2020) Preparation of lithium using vacuum carbothermal reduction of $LiAlO_2$. Materials Research Express 7(11), 116517.

[91] CSIRO (n.d.) LithSonic lithium metal production. Commercialisation marketplace. <https://www.csiro.au/en/work-with-us/ip-commercialisation/marketplace/lithsonic-lithium-metal-production>

[92] Ganfeng Lithium Group Co (2021) 2021 Annual Report. https://www1.hkexnews.hk/listedco/listconews/sehk/2022/0426/2022042602622.pdf (accessed 27 September 2023); Ganfeng Lithium Group Co (2022) Fengcheng project officially started. <https://www.ganfenglithium.com/new_detail_en/id/47.html>; Daly T (2021) China's Ganfeng eyes solid-state battery market with lithium metal project. Reuters, 8 April.

[93] Li-Metal Corp (2023) Scalable Technologies for Next-Generation Batteries. <https://s201.q4cdn.com/317034825/files/doc_presentation/2023-06-27-LIM-Investor-Deck-June-FINAL-web.pdf>

[94] CSIRO (n.d.) LithSonic lithium metal production. Commercialisation marketplace. <https://www.csiro.au/en/work-with-us/ip-commercialisation/marketplace/lithsonic-lithium-metal-production>

The following table summarizes the key RD&D areas of focus in lithium metal production.

Table 6: Global RD&D focus areas for lithium metal production technologies.

RD&D FOCUS AREAS	
Electrolysis	• Designing and scaling up non-chloride, low temperature processes.[95]
Thermochemical reduction	• Investigating sustainable heat sources and heating techniques to achieve the high temperature requirement.[96]
Supporting research domains	• Applying advanced modelling to enhance the understanding of reduction chemistry and the dynamics of thermochemical reduction.

3.2.3 Implications for Australia

This section discusses the opportunities for domestic RD&D and international engagement in the production of lithium metal (summarised in Figure 9). More details on the framework used can be found in the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 9: Opportunities for Australian RD&D and international engagement in the production of lithium metal.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies		• Lithium metal production	• Lithium metal production	
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

IP, intellectual property.

The expected growth of the lithium metal market, the concentration of its supply chain, and the sustainability issues of current lithium metal production, all represent opportunities for Australia to seize a role through local RD&D. The current global lithium metal market is small (approximately 5,000 tonnes per annum), however the commercialisation of solid-state lithium batteries is expected to quadruple lithium metal demand from 2025 to 2030.[97] Current commercial production of lithium metal using molten salt

[95] Xia S, Zhang Yingjie, Dong P, Zhang Y (2014) Synthesis cathode material $LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$ with two step solid-state method under air stream. The European Physical Journal-Applied Physics 65(1), 10401.

[96] Zhang Xin, Han A, Yang Y (2020) Review on the production of high-purity lithium metal. Journal of Materials Chemistry A, 8(43):22455–22466.

[97] Maximize Market Research (2023) Lithium Metal Market: Global Industry Analysis and Forecast (2022-2029) Trends, Statistics, Dynamics, Segmentation by Source, Application, and End-Users. <https://www.maximizemarketresearch.com/market-report/lithium-metal-market/201117/>

electrolysis is concentrated in China and faces challenges such as having high costs and managing chlorine gas emissions.

Low IP activity in the last 15 years for lithium metal production could, in part, reflect the high maturity of molten salt electrolysis and the limited and currently saturated lithium metal market dominated by molten salt electrolysis production in China. However, Australia has demonstrated capability to develop alternative pathways of lithium metal production and overcome technical challenges. This represents the opportunity to progress reduction technologies beyond the laboratory and pilot domestic IP onshore, which can help position Australia as an innovative and responsible producer in the emerging market of lithium metal production for next generation solid state batteries.

Additionally, given the low maturity level of thermochemical reduction currently, RD&D efforts will be required to better understand the reaction chemistry and dynamics, achieve the high temperature requirement, and scale up the process. For molten salt electrolysis to be implemented in Australia, non-chloride, low-temperature pathways would need to be developed and advanced to manage risks, potentially in collaboration emerging producers from countries with high sustainability standards (e.g., Canada) for knowledge sharing.

Securing offtake and expediting domestic RD&D in this area will require collaboration with emerging international lithium-metal (i.e., solid-state) battery manufacturers. This is due to the lack of domestic battery manufacturers, the emerging nature of lithium-metal (i.e., solid-state) batteries which increases investment risks and uncertainty, and the high costs required to develop and test new technologies. For instance, further growth in lithium metal production will likely be linked to successfully stabilising its use in solid-state batteries, something that will benefit from complementary RD&D into lithium metal anode – solid electrolyte interfaces.

3.3 Synthesis of cathode active materials (CAM)

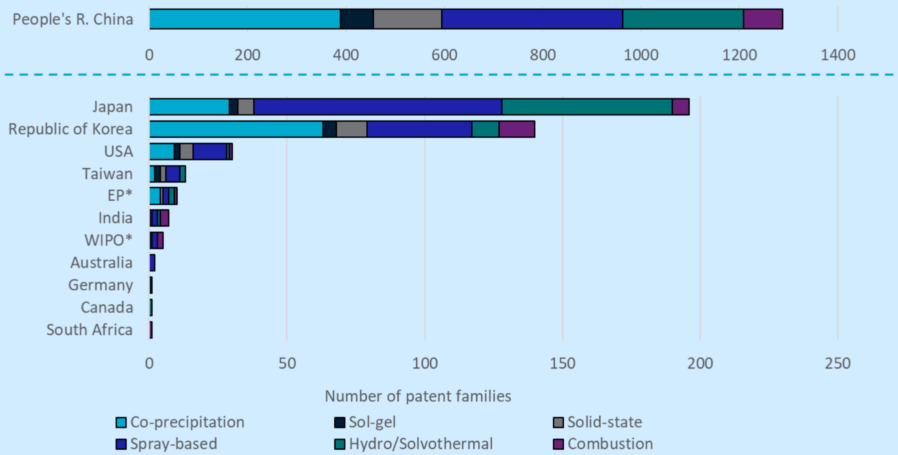
The synthesis of cathode active materials (CAM) is an active area of advanced materials research. The choice of production methods of CAM influences the size, shape, structure, and properties of the material. Advances in this area can lead to substantial improvements in battery performance.

This section covers the mature and emerging methods of producing CAM. It should be noted that there can be overlap between the different methods, and more than one technique can be used in the materials synthesis process. Although the synthesis methods discussed can be applied to producing NMC (Nickel Manganese Cobalt Oxide), NCA (Nickel Cobalt Aluminium Oxide) and LFP (Lithium Iron Phosphate) cathodes, manufacturers may choose a particular synthesis route based on what works best for a particular cathode chemistry.

Global R&D and commercialisation snapshot

Synthesis of cathode active materials

Figure 10: Patent output in CAM synthesis methods from 2007 to 2022, by country.



*Applications filed under an entity other than a country.

WIPO, World Intellectual Property Organisation; EP, European Patent Office; ROW, rest of the world.

Figure 10 shows patent output for CAM synthesis methods by country, from 2007 to 2022. China had the highest activity for the period across all methods analysed (75.9%). The top 3 is completed by Japan with 11.5% and South Korea with 8.2%.

Figure 11: Research publication activity related to CAM throughout the 2007-2023 period, by country

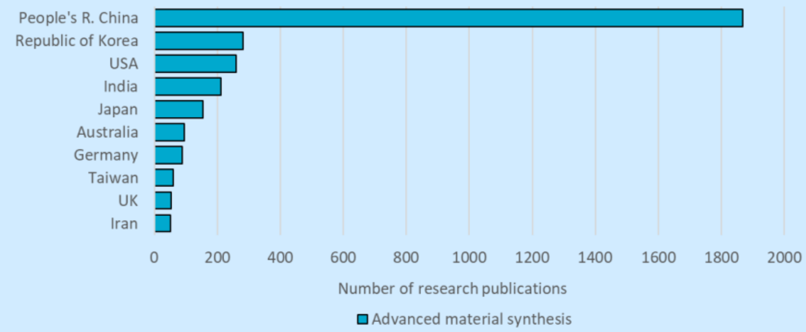
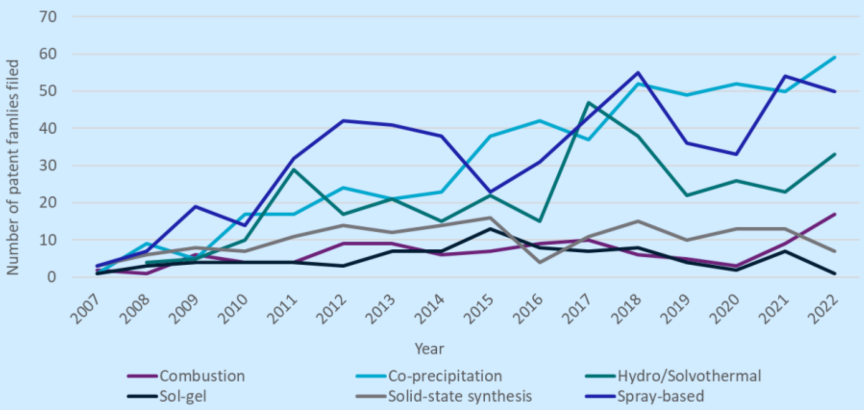


Figure 11 shows the output of research publications from 2007 to 2023 related to advanced materials using lithium (including CAM and electrolytes) as distributed by country and processing technology. China accounted for 49% of publications in this area followed by the republic of Korea (7.38%) and the US (6.78%).

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 12: Global patent output in CAM synthesis throughout the 2007 – 2022 period, by year and method.



Patent output across the CAM synthesis methods indicate that the highest activity was focussed on spray-based methods (30.7% of the total), co-precipitation (29.2%), and hydrothermal/solvothermal (19.3%). This trend is reflected in the number of annual filings in these categories (Figure 12). Moreover, they have maintained an increasing trend from the beginning of the analysis period that contrasts with the lower, more stable baselines for solid-state, sol-gel, and combustion synthesis methods.

CAM, cathode active materials.

Table 7: Top 10 active organisations outside of China

By research publication output (CAM and Electrolytes)	By patent output (CAM only)
DOE, **United States**	LG Chem, **Republic of South Korea**
University of Wollongong, **Australia**	Sumitomo Metal Mining, **Japan**
Helmholtz Association, **Germany**	Samsung SDI, **Republic of South Korea**
KIST, **Republic of Korea**	JX Nippon Mining and Metals, **Japan**
CSIR, **India**	RIST, **Republic of South Korea**
CNRS, **France**	Tokyo Metropolitan University, **Japan**
Hanyang University, **Republic of Korea**	KIST, **South Korea**
IIT, **India**	Sumitomo Chemical, **Japan**
Karlsruhe Institute of Technology, **Germany**	Toyota Motor, **Japan**
Korea University, **Republic of Korea**	Umicore, **Belgium**

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

3.3.1 Co-precipitation

Co-precipitation is a widely used method to synthesise various advanced materials. In simplified terms the process involves mixing a metal salt solution with a precipitation reagent. A chemical reaction occurs, resulting in the formation of the desired material, which can then be separated out of the liquid. To control the particle size and shape of the resulting crystals, manufacturers use multiple mixing agents. This can help meet specific commercial specifications.[98]

The co-precipitation method in CAM synthesis involves two steps. First, the non-lithium metal salts (e.g. compounds containing nickel, manganese, cobalt, iron or potassium) are reacted with a precipitation reagent (e.g., a basic compound like sodium hydroxide) to produce a solid precursor cathode active material (pCAM). After the pCAM is washed and dried, it is mixed with a lithium compound (lithium carbonate or hydroxide) and thermally treated (sintered) to form the CAM.[99] Mixing agents used include various acids, bases as well as polymers such as polyvinyl alcohol (PVA). [100]

TECHNOLOGY STATE OF PLAY

Co-precipitation processes are mature and widely used across the global battery industry for producing CAM at commercial scale due to their low cost, scalability and precision. [101] In 2022, the FBICRC launched a pCAM pilot plant in Western Australia, with a view to co-locate commercial scale NMC CAM production in Australia in the future.[102] The use of co-precipitation for this facility was explicitly recommended in the FBICRC's Li-ion battery cathode manufacture in Australia report.[103]

Co-precipitation made up 29.2% of all patent families related CAM synthesis from 2007 and 2022. Patent activity in co-precipitation had consistently increasing trend across the full analysis period. China accounted for 78.4% of patent families, followed by the Republic of Korea with 12.7% and Japan with 5.8%. Other active countries include the USA and Taiwan.

[98] Bajaj NS, Joshi RA (2021) Energy materials: synthesis and characterization techniques. In Energy Materials (Eds. SJ Dhoble, NT Kalyani, B Vengadaesvaran, AK Arof) 61–82. Elsevier.

[99] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

[100] Duvigneaud PH, Segato T (2004) Synthesis and characterisation of LiNi1−x−yCoxAlyO2 cathodes for lithium-ion batteries by the PVA precursor method. Journal of the European Ceramic Society, 24(6):1375–1380; Purwanto A, Yudha CS, Ubaidillah U, Widiyandari H, Ogi T, Haerudin H (2018) NCA cathode material: synthesis methods and performance enhancement efforts. Materials Research Express, 5(12):122001.

[101] QUT (2020) Li-ion battery cathode manufacture in Australia: A scene setting project. Future Battery Industries CRC, Australia. <https://fbicrc.com.au/wp-content/Tuploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

[102] Miller T (2022) Cathode facility officially launched. Future Battery Industries CRC. <https://fbicrc.com.au/cathode-facility-officially-launched/>

[103] QUT (2020) Li-ion battery cathode manufacture in Australia: A scene setting project. Future Battery Industries CRC, Australia. <https://fbicrc.com.au/wp-content/Tuploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

The following table summarizes the key RD&D areas of focus in the co-precipitation CAM synthesis methods:

Table 7: Global RD&D focus areas for co-precipitation CAM synthesis methods.

RD&D FOCUS AREAS	
Co-precipitation CAM synthesis	• Designing and optimising the co-precipitation process at scale, which requires precise control of reaction parameters.[104] • Reagent recovery and waste-water recovery and treatment.[105]

3.3.2 Sol-gel

Sol-gel processes are widely employed in the preparation of advanced materials. In this method a liquid precursor solution, or a "sol", is transformed in a series of chemical steps into a final product in the form of a "gel" material with the desired structure. The gel is then washed, dried and thermally treated (sintered) to form the final product. For the synthesis of CAM, the "sol" can be prepared by combining the metal salts with a gelling agent (citric acid, glycine, starch, gelatine).[106]

Benefits of this method include scalability, low-energy requirements, ability to produce CAM with desirable physical and chemical properties, resulting in high performance.[107]

TECHNOLOGY STATE OF PLAY

Sol-gel synthesis is commercially used in the battery industry and was identified in a FBICRC report as another viable mature option (alongside co-precipitation), for CAM production in Australia.[108] Examples of commercial sol-gel CAM production include LFP CAM manufacture in China and Vietnam.[109]

Sol-gel synthesis methods accounted for 4.9% of patent families identified within the 2007 – 2023 period, with a low baseline of activity. While sol gel patent activity increased up until 2015, this technology area experienced a decrease in activity over the last several years. This reflects the maturity of this method and its displacement by other methods. China led in this area with 80.7% of filings, followed by the Republic of Korea with 6% and Japan with 3.6%. Other countries with relevant activity include Germany, India, Taiwan and the USA.

[104] Xia S, Zhang Yingjie, Dong P, Zhang Y (2014) Synthesis cathode material LiNi0. 80Co0. 15Al0. 05O2 with two step solid-state method under air stream. The European Physical Journal-Applied Physics 65(1), 10401.

[105] Wang L, Shi Q, Zhan C, Liu G (2023) One-Step Solid-State Synthesis of Ni-Rich Cathode Materials for Lithium-Ion Batteries. Materials 16(8), 3079.

[106] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

[107] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

[108] QUT (2020) Li-ion battery cathode manufacture in Australia: A scene setting project. Future Battery Industries CRC, Australia. <https://fbicrc.com.au/wp-content/Tuploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>

[109] Lithium Australia (2021) ASX Announcement: Lithium Australia PFS vindicates high-value potential of LFP battery materials. Lithium Australia, Perth, Australia. <https://announcements.asx.com.au/asxpdf/20210414/pdf/44vj6k04n7gspp.pdf>

The following table summarizes the key RD&D areas of focus in the sol-gel CAM synthesis methods:

Table 8: Global RD&D focus areas for sol-gel CAM synthesis methods.

	RD&D FOCUS AREAS
Sol-gel CAM synthesis	• Designing and optimising the sol-gel process at scale, to address the significant volume of reagents required and ensure precise control of reaction parameters.[110]

3.3.3 Solid-state methods

Solid-state methods for producing CAM involve ball-milling or grinding of lithium and other metal compounds together before being pressed into pellets and thermally treated (calcination, then sintering) to form the powdered CAM.[111] Solid-state methods are some of the earliest and most widely used to prepare CAM,[112] as solid-state methods are relatively simple and easy to scale.[113]

However, the industry has shifted towards synthesis methods that can provide more precise and homogenous end products, which are faster and less energy intensive to produce (e.g. co-precipitation).[114] To overcome the limitations of solid-state technology, several emerging variations of the process are being demonstrated at pilot and commercial scale by global manufacturers.

Innovations in controlled solid-state methods can produce ultra fine particles to better control product characteristics.[115] Hybrid approaches, such as using infrared and plasma technologies, can be used during the sintering step after solid-state and other CAM synthesis methods. If powered by renewable electricity this provides an efficient and carbon-neutral alternative to the combustion of natural gas and other fossil fuels associated with conventional sintering processes.[116]

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[110] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

[111] Malik M, Chan KH, Azimi G (2022) Review on the synthesis of LiNixMnyCo1-x-yO2 (NMC) cathodes for lithium-ion batteries. Materials Today Energy, 28:101066.

[112] Zhang J, Singh G, Xu S, Hamad K, Ratner A, Xing Y (2020) A scalable approach of using biomass derived glycerol to synthesize cathode materials for lithium-ion batteries. Journal of Cleaner Production, 271:122518.

[113] Purwanto A, Yudha CS, Ubaidillah U, Widiyandari H, Ogi T, Haerudin H (2018) NCA cathode material: synthesis methods and performance enhancement efforts. Materials Research Express, 5(12):122001.

[114] Malik M, Chan KH, Azimi G (2022) Review on the synthesis of LiNixMnyCo1-x-yO2 (NMC) cathodes for lithium-ion batteries. Materials Today Energy, 28:101066.

[115] Obrovac N, Zheng L, Garayt L (2020) Engineered particle synthesis by dry particle microgranulation. Cell Reports Physical Science 1(6); Novonix (2023) Cathode Materials - Piloting production for cathode materials. <https://www.novonixgroup.com/cathode-materials/>.

[116] Purwanto A, Yudha CS, Ubaidillah U, Widiyandari H, Ogi T, Haerudin H (2018) NCA cathode material: synthesis methods and performance enhancement efforts. Materials Research Express, 5(12):122001.

TECHNOLOGY STATE OF PLAY

Solid-state synthesis is a highly mature method and has declined in in use, however there are some emerging players employing novel approaches to solid-state methods which are at pilot scale.

For example, NOVONIX (USA) has developed a controlled solid-state process to produce a uniform and ultra-fine NMC CAM at low cost and with zero waste.[117] The company is commissioning a 10 tonnes per annum sized pilot production to validate and improve the process.[118]

6K (USA) has developed a microwave plasma process called UniMelt® that can rapidly convert the starting solid materials to high quality CAM.[119] The company has received funding to construct a commercial scale demonstration plant with an expected combined production capacity of 3,000 tonnes for NMC and LFP CAM per annum in 2025. 6K is also partnering with Aqua Metals to further advance the technology and apply it to recycled materials.[120]

Solid state synthesis methods made up 9.7% of patent families related to CAM globally between 2007 and 2022. This area has followed a stable patent activity trend to date, but its baseline remains low relative to popular methods (co-precipitation, spray-based and hydro-/solvo-thermal). China accounted for 84.8% followed by the Republic of Korea (6.7%), and Japan (3.7%). The USA and Taiwan complete the list of countries active in this area.

The following table summarizes the key RD&D areas of focus in the solid-state CAM synthesis methods:

Table 9: Global RD&D focus areas for solid-state CAM synthesis methods.

	RD&D FOCUS AREAS
Solid-state CAM synthesis	• Lowering the time required for synthesis and increasing CAM particle homogeneity.[121] Greater control over particle characteristics could be enabled by improved mill designs and techniques that produce ultra-fine CAM competitively at commercial scale.[122] • Developing and demonstrating single-step, non-fossil fuel thermal treatment methods, [123] for example plasma- and microwave-assisted synthesis.[124]

[117] Obrovac N, Zheng L, Garayt L (2020) Engineered particle synthesis by dry particle microgranulation. Cell Reports Physical Science 1(6); Novonix (2023) Cathode Materials - Piloting production for cathode materials. <https://www.novonixgroup.com/cathode-materials/>.

[118] Novonix (2023) NOVONIX Commissions Zero-Waste Cathode Pilot Line. <https://www.novonixgroup.com/novonix-commissions-zero-waste-cathode-pilot-line/>

[119] 6K Inc (n.d.) UniMelt Microwave-Based Plasma Technology. <https://www.6kinc.com/6k-inc-unimelt-metal-powders/unimelt-microwave-based-plasma-technology/>

[120] 6K Inc (2023) Aqua Metals and 6K Energy sign strategic supply agreement to establish North America's first sustainable lithium battery supply chain. < https://www.6kinc.com/news/press-release/aqua-metals-and-6k-energy-sign-strategic-supply-agreement-to-establish-north-americas-first-sustainable-lithium-battery-supply-chain/>

[121] Xia S, Zhang Y, Dong P and Zhang Y (2014) Synthesis cathode material LiNi0. 80Co0. 15Al0. 05O2 with two step solid-state method under air stream. The European Physical Journal-Applied Physics 65(1), 10401.

[122] Obrovac MN, Zheng L, Garayt MDL (2020) Engineered particle synthesis by dry particle microgranulation. Cell Reports Physical Science, 1(6).

[123] Wang L, Shi Q, Zhan C, Liu G (2023) One-Step Solid-State Synthesis of Ni-Rich Cathode Materials for Lithium-Ion Batteries. Materials 16(8), 3079.

[124] Joseph J, Murdock AT, Seo DH, Han ZJ, O'Mullane AP, Ostrikov K (2018) Plasma Enabled Synthesis and Processing of Materials for Lithium-Ion Batteries. Advanced Materials Technologies 3(9), 1800070; Liu S, Yan P, Li H, Zhang X, Sun W (2020) One-Step Microwave Synthesis of Micro/Nanoscale LiFePO4/Graphene Cathode with High Performance for Lithium-Ion Batteries. Frontiers in Chemistry 8(104).

3.3.4 Spray-based methods

Spray-based techniques for synthesising materials involve spraying a precursor solution (containing the relevant transition metal salts and lithium compounds) into a high temperature reactor, where the precursor undergoes evaporation, precipitation and reaction with the surrounding gas, resulting in a powder with the desired material properties. Spray-based methods are increasingly used in industry due to their single-step operation, scalability and capacity to produce uniform and ultra-fine particles at low cost.[125]

There are two general spray-based methods for CAM production, namely spray pyrolysis (which involves the direct application of heat within a furnace to decompose the droplets) and spray drying (where the solvent evaporates by contact of the droplets with a heated surface). [126]

TECHNOLOGY STATE OF PLAY

Spray-based methods are commercially mature in industry. For example, Aleees (Taiwan) has developed a spray drying process to produce LFP CAM. The company has licensed its technology to three international partners, including Australian phosphate miner Avenira, for commercial production. Avenira, Aleees and the Northern Territory Government have signed a MoU to develop a LFP CAM manufacturing plant in Darwin which will have an initial capacity of 10,000 tonnes per annum.[127]

Spray-based methods are also being demonstrated at pilot scale domestically. VSPC has piloted a patented spray-drying process to produce LFP CAM at a facility in Brisbane with a capacity of up to 4 tonnes per annum. The pilot has demonstrated the technology's cost-competitiveness and ability to process a range of lithium feedstocks, including lithium carbonate, hydroxide and phosphate.[128]

Spray-based methods had the largest proportion of identified patent filings among CAM synthesis methods between 2007 and 2022, with 30.7% of the total. This technology has experienced strong patent activity, reflecting it's use across commercial settings and in CAM innovation. The top three active countries in IP activity for these methods are China with 70.4% of the total, Japan with 17.3%, and the Republic of Korea with 7.3%. Additional countries with relevant patent filings include the USA, Taiwan, India, Australia, and France.

[125] Zhang J, Singh G, Xu S, Hamad K, Ratner A, Xing Y (2020) A scalable approach of using biomass derived glycerol to synthesize cathode materials for lithium-ion batteries. Journal of cleaner production 271, 122518.

[126] Zhu Y, Choi SH, Fan X, Shin J, Ma Z, Zachariah MR, Choi JW, Wang C (2017) Recent progress on spray pyrolysis for high performance electrode materials in lithium and sodium rechargeable batteries. Advanced Energy Materials 7(7), 1601578.

[127] Avenira Limited (n.d.) LFP Project. <https://avenira.com/lfp-project/>

[128] Lithium Australia (2021) ASX Announcement: Lithium Australia PFS vindicates high-value potential of LFP battery materials. Lithium Australia, Perth, Australia. https://announcements.asx.com.au/asxpdf/20210414/pdf/44vj6k04n7gspp.pdf; Lithium Australia (2018) ASX Announcement: Lithium Australia/VSPC to resume production of lithium-ion cathode powder. <https://announcements.asx.com.au/asxpdf/20180418/pdf/43t91nk4709003.pdf>

The following table summarizes the key RD&D areas of focus in the solid-state CAM synthesis methods:

Table 10: Global RD&D focus areas for spray-based CAM synthesis methods.

RD&D FOCUS AREAS	
Spray-based CAM synthesis	• Improving control over the multiple physical and chemical processes occurring in single step approaches. • Designing and optimising spray-based processes at scale so that minimal reagents are used and wasted.[129] • Developing different solvents for spray-based methods to reduce material costs, environmental impact and pyrolysis temperatures.[130]

3.3.5 Hydrothermal/Solvothermal

Hydrothermal and solvothermal methods involve the use of water or a solvent, specific pressures and temperatures to induce a reaction, resulting in the formation of a solid product. To produce CAM, a solution containing the transition metals and, optionally, a lithium compound is heated and pressurised in a reactor or autoclave to produce a solid pCAM. The pCAM is then mixed with additional lithium compound and thermally treated (sintered) to produce the CAM product.[131] Solvothermal methods use organic solvents (e.g., ethanol or ethylene glycol) rather than the distilled water of hydrothermal methods.[132]Some variations on the process use microwave- or infrared-assisted reactions to reduce reaction time and increase energy efficiency.[133]

Hydro- and solvothermal processes can deliver high yields, however, may have higher costs at larger scales depending on pressure and temperature requirements.[134]

TECHNOLOGY STATE OF PLAY

Hydrothermal and solvothermal processes are being demonstrated on pilot scales by global manufacturers. Nano One (Canada) has patented a 'metal direct to cathode' technology that is a 'one-pot' process which reduces the energy, cost and number of steps required for CAM synthesis. The company is commissioning a

[129] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

[130] Zhang J, Singh G, Xu S, Hamad K, Ratner A, Xing Y (2020) A scalable approach of using biomass derived glycerol to synthesize cathode materials for lithium-ion batteries. Journal of cleaner production 271, 122518.; You B, Sun J, Jing Y, Yan G, Guo H, Wang Z, Wang D, Peng W, Li Q, Wang J (2023) A Fresh One-Step Spray Pyrolysis Approach to Prepare Nickel-Rich Cathode Material for Lithium-Ion Batteries. ACS Applied Materials & Interfaces 15(11), 14587-14595.

[131] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

[132] Ye N, Yan T, Jiang Z, Wu W, Fang T (2018) A review: conventional and supercritical hydro/solvothermal synthesis of ultrafine particles as cathode in lithium battery. Ceramics International 44(5), 4521-4537.

[133] Kang S, Wang C, Chen J, Meng T, EJ (2023) Progress on solvo/hydrothermal synthesis and optimization of the cathode materials of lithium-ion battery. Journal of Energy Storage, 67:107515; Hsieh C-T, Hsu H-H, Hsu J-P, Chen Y-F, Chang J-K (2016) Infrared-assisted Synthesis of Lithium Nickel Cobalt Alumina Oxide Powders as Electrode Material for Lithium-ion Batteries. Electrochimica Acta, 206:207–216.

[134] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

LFP CAM pilot production in Canada with an initial capacity of 200 tonnes per annum and a maximum capacity of 10,000 tonnes per annum when fully commercialised.[135] In Australia, Calix has developed an all-electric reactor, named BATMn, that is capable of producing LMO (Lithium Manganese Oxide) CAM with an advanced nanostructure at low cost, with reduced waste and in fewer steps.[136]

Hydrothermal and solvothermal processes account for 19.3% of patent families identified between 2007 and 2022. The overall trend throughout the period has been increasing, with a peak of activity in 2017 – 2018. These methods have experienced a rapid growth in activity, just behind co-precipitation and spray-based techniques. China ranked 1st in this area with 75.5% of total activity, followed by Japan (19%) and the Republic of Korea (3.1%). Countries with relevant patent filings also include Taiwan, Canada, India, and the USA.

The following table summarizes the key RD&D areas of focus for hydro- and solvothermal CAM synthesis methods:

Table 11: Global RD&D focus areas for hydro- and solvothermal CAM synthesis methods.

	RD&D FOCUS AREAS
Hydro- and solvothermal CAM synthesis methods	• Advancing and demonstrating low-energy and alternative processes like low temperature synthesis and reactions at supercritical conditions (i.e., temperatures and pressures above a critical point which change the behaviour of the system).[137] • Improving process efficiency and the structure and consistency of the final product.[138] • Adapt and optimise the process to an industrial scale (e.g., through continuous flow approaches).[139] • Reagent and waste-water recovery.[140]

[135] Nano One Materials Corp. (2023a) Technology. https://nanoone.ca/technology/technology/; Nano One Materials Corp. (2023b) Nano One Advances its Commercial LFP Plans at Québec Facility, Secures Six New Patents. News Releases. <https://nanoone.ca/news/news-releases/nano-one-advances-its-commercial-lfp-plans-at-quebec-facility-secures-six-new-patents/>

[136] Boot Handford M (2020) Calix's advanced battery material development program. Calix. <https://calix.global/advanced-batteries-focus-area/calixs-advanced-battery-material-development-program/>; Bourdareau J (2020) VIDEO: BATMn Reactor, a game-changer for advanced battery research. Calix. <https://calix.global/advanced-batteries-focus-area/video-calix-batmn-reactor/>; Walsh M (2023) Advanced Batteries: Performance improvements, commercial testing and new chemistries. Calix <https://calix.global/news/advanced-batteries-performance-improvements-commercial-testing-new-chemistries/>; Deakin University (n.d.) Kickstarting next-generation battery production in Australia. <https://www.deakin.edu.au/research/impact-stories/kickstarting-next-generation-battery-production-in-australia>; Boot-Handford M (2022) Nano-active Electrode Materials for High Power Applications. Calix, Advanced Battery. <https://calix.global/advanced-batteries-focus-area/nano-active-electrode-materials-for-high-power-applications/>

[137] Benedek P, Wenzler N, Yarema M, Wood VC (2017) Low temperature hydrothermal synthesis of battery grade lithium iron phosphate. RSC advances 7(29), 17763-17767.; Ye N, Yan T, Jiang Z, Wu W, Fang T (2018) A review: conventional and supercritical hydro/solvothermal synthesis of ultrafine particles as cathode in lithium battery. Ceramics International 44(5), 4521-4537.

[138] Kang S, Wang C, Chen J, Meng T, EJ (2023) Progress on solvo/hydrothermal synthesis and optimization of the cathode materials of lithium-ion battery. Journal of Energy Storage, 67:107515.

[139] Xu Y, Farandos N, Rosa M, Zielke P, Esposito V, Vang Hendriksen P, Jensen SH, Li T, Kelsall G, Kiebach R (2018) Continuous hydrothermal flow synthesis of Gd-doped CeO 2 (GDC) nanoparticles for inkjet printing of SOFC electrolytes. International Journal of Applied Ceramic Technology 15(2), 315–327.

[140] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy, 5(2):022002.

3.3.6 Combustion

Combustion synthesis involves heating a liquid or a solid precursor containing transition metals, a lithium salt, and fuel to produce CAM. Examples of ignition fuels include nitrate/urea mixtures, sucrose, glycine/urea mixtures, or hexamethylene tetramine.[141] Combustion can be combined with mature and high-throughput methods (e.g., spray pyrolysis), with the heat generated helping to shorten the post-annealing time and the need for additional energy inputs.

TECHNOLOGY STATE OF PLAY

Combustion methods are mostly being developed at laboratory scale. For example, a US government-funded research successfully synthesised NMC CAM using flame-assisted spray technology (FAST) with glycerol, a low-cost and abundant by-product of biodiesel production, as an ignition fuel instead of fossil fuels.[142] This easy-to-scale process was piloted by Storagenergy (a US government-funded technology development company),[143] is reportedly compatible with materials recovered from used batteries, [144] and may consume 61% less electricity than the more conventional carbonate co-precipitation pathway, based on techno-economic modelling.[145]

Combustion synthesis methods were present in 6.3% of patent families in our 2007 – 2022 analysis. While the trend of activity is low relative to the dominant methods, there has been a surge in activity post-2020. The leading countries in filing activity related to combustion synthesis are China with 73.8%, the Republic of Korea with 12.1% and Japan with 5.6%. India, Chile, South Africa, and the USA also emerged in the analysis with relevant patent families.

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[141] Malik M, Chan KH, Azimi G (2022) Review on the synthesis of LiNixMnyCo1-x-yO2 (NMC) cathodes for lithium-ion batteries. Materials Today Energy, 28:101066; Purwanto A, Yudha CS, Ubaidillah U, Widiyandari H, Ogi T, Haerudin H (2018) NCA cathode material: synthesis methods and performance enhancement efforts. Materials Research Express, 5(12):122001.

[142] Zhang J, Singh G, Xu S, Hamad K, Ratner A and Xing Y (2020) A scalable approach of using biomass derived glycerol to synthesize cathode materials for lithium-ion batteries. Journal of Cleaner Production 271, 122518.

[143] Storagenergy Technologies (2023) About Us. <https://storagenergy.com/, https://storagenergy.com/about-us/>.

[144] Storageneregy (n.d.) FAST Synthesis and Recycling of Battery Materials. <https://storagenergy.com/fast-synthesis-recycling-battery-materials/>; Batteries News (2022) How Storagenergy Technologies Is Developing New Flame-Assisted Spray Technology (FAST) for Battery Cathode Synthesis and Recycling. <https://batteriesnews.com/how-storagenergy-technologies-is-developing-new-flame-assisted-spray-technology-fast-for-battery-cathode-synthesis-and-recycling/>.

[145] Zang G, Zhang J, Xu S, Xing Y (2021) Techno-economic analysis of cathode material production using flame-assisted spray pyrolysis. Energy 218, 119504.

The following table summarizes the key RD&D areas of focus in the combustion CAM synthesis methods:

Table 12: Global RD&D focus areas for combustion CAM synthesis methods.

RD&D FOCUS AREAS	
Combustion CAM synthesis	• Trialling different fuel combinations to optimise the structural characteristics of the final product and minimise the process complexity, material costs and environmental impact.[146] • Investigating hybrid methods (e.g., co-precipitation process assisted with combustion) to enhance the product quality.[147] • Development of facilities and procedures to conduct the combustion safely at large scale, which includes handling highly reactive materials and limiting toxic gas emissions.[148]
Supporting research domains	• Increasing experimental and theoretical research into combustion reaction mechanisms, its controllable parameters, combinations and impacts in resulting CAM attributes.[149]

3.3.7 Implications for Australia

The growing global market for CAM and Australia's battery minerals resource base present an opportunity for integrating upstream mining capabilities with domestic, large-scale CAM production. This can build a greater participation in global supply chains and enable an end-to-end Australian battery industry.[150]

CAM synthesis brings together the battery-grade compounds from multiple supply chains (e.g., lithium, nickel, cobalt, manganese, iron, phosphate) into a single, value-adding step. The process is the bridge between upstream extraction and downstream battery component and cell manufacture and therefore of strategic importance to Australia.

Economically, the cathode accounts for the highest proportion of cost among lithium-ion battery components when considering both raw materials and processing and is heavily influenced by its specific chemistry.[151] Global cathode demand in 2030 for EV batteries alone is estimated to increase sixfold

[146] Karami M, Masoudpanah SM, Rezaie HR (2021) Solution combustion synthesis of hierarchical porous LiFePO4 powders as cathode materials for lithium-ion batteries. Advanced Powder Technology 32(6), 1935–1942.

[147] Prettencia L, Soundarrajan E, Shanmugharaj AM, Kalaivani RA, Raghu S (2022) Combustion-assisted synthesis of Mn-rich cathode for high performance Li-ion batteries. Journal of Energy Storage 48, 104054.

[148] Deganello F, Tyagi AK (2018) Solution combustion synthesis, energy and environment: Best parameters for better materials. Progress in Crystal Growth and Characterization of Materials 64(2), 23–61.

[149] Mathew V, Sambandam B, Kim S, Kim S, Park S, Lee S, Lee J, Park S, Song J, Kim J (2020) High-voltage cathode materials by combustion-based preparative approaches for Li-ion batteries application. Journal of Power Sources 472, 228368.

[150] Accenture (2023b) Charging Ahead: Australia's battery powered future. Future Battery Industries CRC. https://fbicrc.com.au/wp-content/uploads/2023/03/Charging-Ahead_Final-Report_Full-17-March-2023-1.pdf; Bruce S, Delaval B, Moisi A, Ford J, West J, Loh J, Hayward J (2021) Critical Energy Minerals Roadmap. CSIRO, Australia.

[151] Wentker M, Greenwood M, Leker J (2019) A Bottom-Up Approach to Lithium-Ion Battery Cost Modelling with a Focus on Cathode Active Materials. Energies 12(3), 504; Orangi S, Strømman AH (2022) A Techno-Economic Model for Benchmarking the Production Cost of Lithium-Ion Battery Cells. Batteries 8(8), 83.

compared to production levels in 2021, under the IEA's Stated Policies Scenario model.[152] Further, lithium battery demand from the Asia-Pacific region is expected to provide a large end user market within geographical proximity to Australia.[153] Current and expected cathode chemistries are also aligned with Australia's minerals resource base and CAM pilot projects performed to date. NMC and LFP cathodes accounted for the majority of EV batteries sold in 2022, continuing the trend of growing market share for high-nickel (e.g., NMC811) and LFP chemistries.[154] Furthermore, the IEA has projected this shift will continue into 2030 under its base case scenario.[155]

CAM synthesis is a well-established process, with differences in maturity based on the specific method. Despite its general maturity, CAM synthesis requires ongoing RD&D to deliver technical improvements in manufacturing costs, sustainability, and CAM material properties. This is reflected in the continued growth in global IP activity.

This section discusses the opportunities for domestic RD&D and international engagement in the synthesis of CAM (summarised in Figure 13). More details on the framework used can be found in the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 13: Opportunities for Australian RD&D and international engagement in the synthesis of cathode active materials (CAM).

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies	• Hydrothermal / Solvothermal • Combustion		• Co-precipitation	• Co-precipitation • Sol-gel • Spray-based methods • Solid state methods
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

IP, intellectual property.

[152] IEA (2022) Global Supply Chains of EV Batteries. International Energy Agency, Paris, France. <https://iea.blob.core.windows.net/assets/4eb8c252-76b1-4710-8f5e-867e751c8dda/GlobalSupplyChainsofEVBatteries.pdf>

[153] Accenture (2023b) Charging Ahead: Australia's battery powered future. Future Battery Industries CRC. <https://fbicrc.com.au/wp-content/uploads/2023/03/Charging-Ahead_Final-Report_Full-17-March-2023-1.pdf>; Accenture (2021) Future Charge, Building Australia's Battery Industries. <https://fbicrc.com.au/wp-content/uploads/2021/06/Future-Charge-Report-Final.pdf>; O'Farrell K, Kinrade P, Jones P, Roser L (2020) Australian Battery Market Analysis. Battery Stewardship Council, Victoria, Australia. <https://bsc.org.au/wp-content/uploads/2020/06/R02-05-A21602-Australian-battery-market-analysis-Project-report-Published.pdf>; Frye C (2019) FCB028H Lithium Batteries: Markets and Materials. bccResearch, 113. <https://www.bccresearch.com/market-research/fuel-cell-and-battery-technologies/lithium-batteries.html>

[154] IEA (2023) Critical Minerals Market Review 2023. International Energy Agency, Paris. <https://iea.blob.core.windows.net/assets/c7716240-ab4f-4f5d-b138-291e76c6a7c7/CriticalMineralsMarketReview2023.pdf>; IEA (2022) Global Electric Vehicle Outlook 2022. International Energy Agency, Paris. <https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf>.

[155] IEA (2022) Global Electric Vehicle Outlook 2022. International Energy Agency, Paris. <https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf>.

The majority of synthesis methods discussed in this section also involve an energy-intensive, high-temperature step (e.g., sintering) to produce a final CAM product. The integration of renewable energy into high temperature thermal processes and RD&D in advanced techniques like plasma or infrared heating could yield cross-cutting benefits across several CAM manufacturing techniques.

The synthesis techniques that have seen the most growth in IP activity globally over the last 15 years are co-precipitation, spray-based, hydro/solvothermal, and combustion methods. Co-precipitation and spray-based methods are mature, low-cost, scalable, and precise.[156] However, they can benefit from further optimisation at scale, improved precision, and through the recovery of reagents and waste (see RD&D tables in Sections 3.3.1 and 3.3.4). Co-precipitation and spray-based methods represent an area of opportunity given Australia's demonstrated capability evidenced by the pilot projects performed to date. Spray-based methods also offer the potential to further reduce process steps and costs. For example, one techno-economic analysis showed that flame-assisted spray pyrolysis (FSP) could reduce the price of NMC CAM by 17 percent compared to co-precipitation, due to lower labour and energy requirements, and less waste treatment.[157]

Less mature CAM synthesis processes such as hydro- and solvothermal methods (pilot scale) and combustion synthesis (laboratory scale), may be able to help deliver high yields of CAM product. However, RD&D is required to overcome CAPEX and OPEX costs related to the specialised equipment required to handle high pressure and temperature requirements at large scale. These methods can also benefit from improvements in the precision of the process, in the resulting structure and consistency of the CAM material, and in overcoming challenges to scale-up. Combustion synthesis methods are emerging. However, their simplicity, potentially lower energy consumption, and cost could make them an area to consider for longer-term sustained RD&D efforts.

Despite lower levels of global IP activity, innovation in sol-gel and solid-state methods could also be considered. Sol-gel synthesis was identified by a FBICRC report as another viable option for CAM production in Australia (alongside co-precipitation) given its maturity, scalability, low energy requirements and high performing end-product.[158] However RD&D is required to overcome the large volumes of reagent required. Solid-state methods can provide a low-complexity and scalable pathway to CAM production in Australia. While industry has moved away from conventional solid-state synthesis, RD&D into advanced solid-state production and hybrid approaches could help further reduce the energy consumption of this method. [159]

The opportunity for Australia in CAM synthesis is two-fold: supporting commercial deployment of mature technologies in collaboration with global partners, or piloting and scaling up Australian IP in improved CAM synthesis techniques.

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[156] QUT (2020) Li-ion battery cathode manufacture in Australia: A scene setting project. Future Battery Industries CRC. <https://fbicrc.com.au/wp-content/uploads/2020/07/Li-ion-Battery-Cathode-Manufacturing-in-Aust-1.pdf>; Pardikar K, Entwistle J, Ge R, Cumming D and Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modelling. Journal of Physics: Energy 5(2), 022002.

[157] Zang G, Zhang J, Xu S and Xing Y (2021) Techno-economic analysis of cathode material production using flame-assisted spray pyrolysis. Energy 218, 119504.

[158] Pardikar K, Entwistle J, Ge R, Cumming D, Smith R (2023) Status and outlook for lithium-ion battery cathode material synthesis and the application of mechanistic modeling. Journal of Physics: Energy 5(2), 022002.

[159] Dunn JB, Gaines L, Kelly JC, James C, Gallagher KG (2015) The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy & Environmental Science 8(1), 158–168; Dunn JB, James C, Gaines L, Gallagher K (2014) Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries. Argonne, Illinois. <https://publications.anl.gov/anlpubs/2014/11/108520.pdf>

pCAM and CAM manufacturing pilots have already been undertaken domestically, paving the way for commercial scale up. The FBICRC and VSPC have demonstrated co-precipitation and spray-drying synthesis processes for NMC and LFP CAM production respectively, with VSPC aiming to scale up.[160] Commercial-scale CAM synthesis will require strong collaboration with international offtake partners and technology providers, given Australia's comparatively limited IP and workforce capacity in this space, and the current absence of a large-scale battery cell manufacturer. Relationships with technology providers will be crucial for technology transfer, building industrial capability, and obtaining manufacturing plant components that cannot be sourced domestically. Despite the highly proprietary nature of CAM chemistries, knowledge-sharing and technology transfer can diversify global manufacturing knowhow outside of concentrated locations. Further, in the current absence of a large-scale Australian battery manufacturer, establishing CAM manufacturing will require offtake from overseas battery OEMs.

Finally, there is also a role for ongoing cross-cutting RD&D to support these commercial efforts. This includes testing facilities, economic and techno-economic assessments, and export pilots. The National Battery Testing Centre (NBTC) represents one instance of support for local commercial efforts, for example. It was established for the testing, validation, and certification of battery systems within Australia to international standards, and is critical for quality control and ensuring Australian products are in high demand.[161]

3.4 Synthesis of electrolyte materials

The electrolyte component of an LIB transfers ions (charged particles) between the battery electrodes (anode and cathode), as the battery goes through its charge-discharge cycle. The focus of this report is on lithium, and as such discussion is limited to lithium-containing electrolytes for lithium-ion and lithium metal batteries.

The following section covers the synthesis of various lithium-based electrolytes including current-generation and next-generation electrolyte materials. The current-generation lithium-ion batteries uses liquid electrolytes, consisting of organic solvents as the medium for ion transfer. Solid electrolytes containing glass, ceramics or polymer materials are being developed for next-generation batteries (e.g. lithium metal batteries) due to their potential to deliver improvements in safety and battery lifetime.[162]

[160] VSPC (2021b) Next-generation cathode materials for lithium-ion batteries. <https://vspc.com/wp-content/uploads/2021/07/VSPC-A4-Flyer.pdf>; VSPC (2021c) VSPC - path to commercialisation. R&D and pilot plant facilities. <https://vspc.com/rd-and-pilot-plant-facilities/>

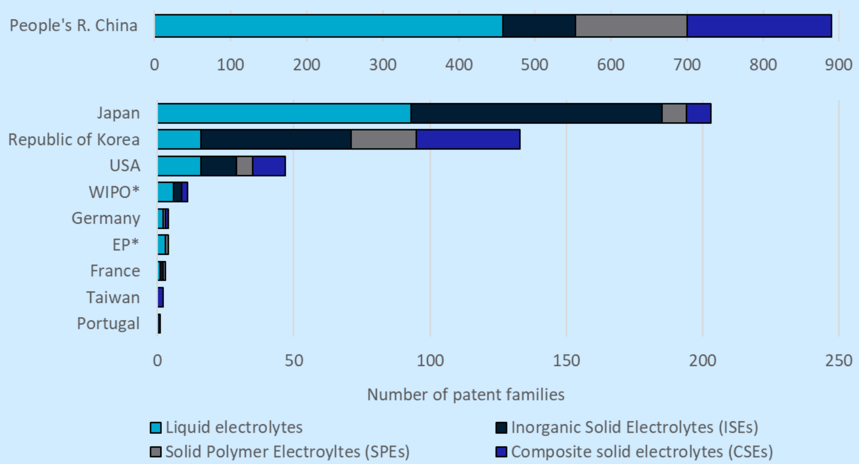
[161] Queensland Government Department of Environment and Science (2023) National Battery Testing Centre. Queensland science capability directory. <https://science.des.qld.gov.au/research/capability-directory/national-battery-testing-centre>

[162] Zhang D, Li L, Zhang W, Cao M, Qiu H and Ji X (2023) Research progress on electrolytes for fast-charging lithium-ion batteries. Chinese Chemical Letters 34(1), 107122.

Global R&D and commercialisation snapshot

Synthesis of electrolyte material

Figure 14: Patent output in electrolyte synthesis methods from 2007 to 2022, by country.

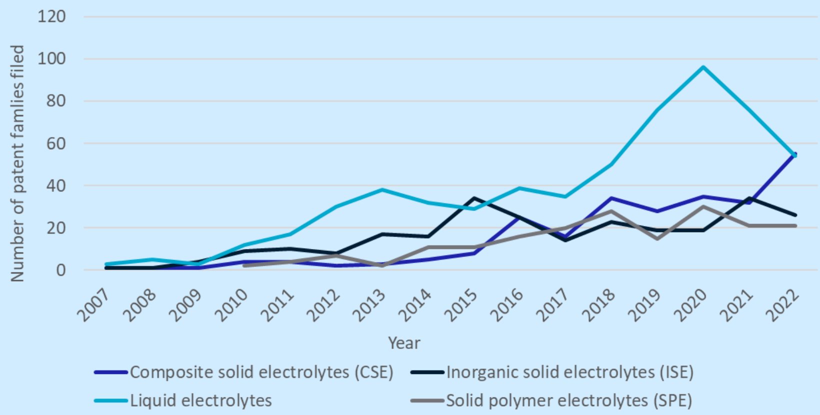


*Applications filed under an entity other than a country.

People's R. China, People's Republic of China; WIPO, World Intellectual Property Organisation patent application; EP, European patent application; ROW, rest of the world.

Figure 14 illustrates the global patent output for electrolyte synthesis processes by country, between 2007 and 2022. China had the highest proportion of filing activity, across all electrolyte types. The country's patent families account for 68.6% of global activity, followed by Japan's 15.6%, and the Republic of Korea's 10.3%.

Figure 15: Global patent output in electrolyte synthesis throughout the 2007 – 2022 period, by year and electrolyte type.



Liquid electrolytes synthesis featured the largest activity of the 4 technology areas (45.8% of the total), consistent with this electrolyte's role in current generation batteries. Conversely, inorganic solid electrolytes (ISEs, 20%), composite solid electrolytes (CSEs, 19.6%) and solid polymer electrolytes (SPEs, 14.6%) are closer in proportion and lower overall, reflecting their more nascent role in battery manufacturing, particularly for next-generation solid-state batteries. This contrast between larger and still growing activity in liquid electrolyte synthesis and more slowly emerging alternatives is also evident in the trends formed by patent filings per year (Figure 15).

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Table 13: Top 10 active organisations outside of China

By research publication output (CAM and Electrolytes)	By patent output (Electrolytes only)
DOE, **United States**	Toyota Motor, **Japan**
University of Wollongong, **Australia**	Samsung Electronics and Samsung SDI, **Republic of South Korea**
Helmholtz Association, **Germany**	NEC Corporation, **Japan**
KIST, **Republic of Korea**	Furukawa, **Japan**
CSIR, **India**	KITECH, **Republic of South Korea**
CNRS, **France**	LG Energy Solutions, **Republic of South Korea**
Hanyang University, **Republic of Korea**	AGC, **Japan**
IIT, **India**	Hyundai Motor, **Republic of South Korea**
Karlsruhe Institute of Technology, **Germany**	Seiko Epson, **Japan**
Korea University, **Republic of Korea**	Fujifilm, **Japan**

The bibliometric and patent data presented in this report is subject to limitations and has an estimated accuracy of 70% or above. For a full description of the methodology and limitations refer to the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

3.4.1 Liquid electrolytes

Current generation lithium-ion batteries use liquid electrolytes. Liquid electrolytes comprise a lithium electrolyte salt and additives dissolved in a mixture of solvents. The significant advantages of liquid electrolytes include high conductivity and good contact with the electrodes.[163] However, its application is limited by safety concerns regarding the flammability of current solvents (organic carbonates), and the low cycling efficiency which affects battery longevity.[164]

Lithium hexafluorophosphate ($LiPF_6$) is the most prevalent electrolyte salts in current-generation lithium-ion batteries. To synthesise $LiPF_6$, lithium fluoride and phosphorus pentachloride are reacted together in the presence of hydrogen fluoride.[165] The synthesis of $LiPF_6$ is a complex process involving many hazardous and expensive chemicals.[166] $LiPF_6$ is at high risk of degrading and releasing toxic hydrogen fluoride when exposed to moisture, requiring adequate storage conditions (e.g., humidity, temperature, container material) after being synthesised and during transport.[167]

There is increasing RD&D interest in alternative lithium electrolyte salts with improved conductivity and stability compared to $LiPF_6$. These salts can also be used as an additive or as the main conductive salt in both liquid and solid electrolytes.[168] Alternatives to $LiPF_6$ include other salts like lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) and lithium bis(fluorosulfonyl)imide (LiFSI).[169] LiTFSI and LiFSI have high conductivity, thermal stability and anode compatibility, which enhances battery performance and safety.[170] Compared to $LiPF_6$, they are also more stable and less prone to release toxic hydrogen fluoride when exposed to moisture, which improves their longevity and safety.[171] However, both salts are corrosive to the aluminium foil in batteries, affecting battery longevity. The synthesis of these salts also requires expensive and hazardous chloro- and fluoro-based chemicals.[172]

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[163] Niu H, Wang L, Guan P, Zhang N, Yan C, Ding M, Guo X, Huang T and Hu X (2021) Recent Advances in Application of Ionic Liquids in Electrolyte of Lithium Ion Batteries. Journal of Energy Storage 40, 102659.

[164] Niu H, Wang L, Guan P, Zhang N, Yan C, Ding M, Guo X, Huang T and Hu X (2021) Recent Advances in Application of Ionic Liquids in Electrolyte of Lithium Ion Batteries. Journal of Energy Storage 40, 102659.

[165] Susarla N and Ahmed S (2019) Estimating Cost and Energy Demand in Producing Lithium Hexafluorophosphate for Li-Ion Battery Electrolyte. Industrial & Engineering Chemistry Research 58(9), 3754–3766.

[166] Susarla N and Ahmed S (2019) Estimating Cost and Energy Demand in Producing Lithium Hexafluorophosphate for Li-Ion Battery Electrolyte. Industrial & Engineering Chemistry Research 58(9), 3754–3766.

[167] Xia C (2023) Important factors for the reliable and reproducible preparation of non-aqueous electrolyte solutions for lithium batteries. Communications Materials, 4(10). <https://doi.org/10.1038/s43246-023-00338-7>

[168] Mauger A, Julien CM, Paolella A, Armand M, Zaghib K (2018) A comprehensive review of lithium salts and beyond for rechargeable batteries: Progress and perspectives. Materials Science and Engineering: R: Reports 134, 1–21; Xing J, Bliznakov S, Bonville L, Oljaca M and Maric R (2022) A Review of Nonaqueous Electrolytes, Binders, and Separators for Lithium-Ion Batteries. Electrochemical Energy Reviews 5(4), 14.

[169] Mauger A, Julien CM, Paolella A, Armand M, Zaghib K (2018) A comprehensive review of lithium salts and beyond for rechargeable batteries: Progress and perspectives. Materials Science and Engineering: R: Reports 134, 1–21; Xing J, Bliznakov S, Bonville L, Oljaca M and Maric R (2022) A Review of Nonaqueous Electrolytes, Binders, and Separators for Lithium-Ion Batteries. Electrochemical Energy Reviews 5(4), 14.

[170] Ahmed F, Rahman MdM, Chandra Sutradhar S, Siraj Lopa N, Ryu T, Yoon S, Choi I, Kim J, Jin Y, Kim W (2019) Synthesis of an imidazolium functionalized imide based electrolyte salt and its electrochemical performance enhancement with additives in li-ion batteries. Journal of Industrial and Engineering Chemistry 78, 178–185.

[171] Ahmed F, Rahman MdM, Chandra Sutradhar S, Siraj Lopa N, Ryu T, Yoon S, Choi I, Kim J, Jin Y, Kim W (2019) Synthesis of an imidazolium functionalized imide based electrolyte salt and its electrochemical performance enhancement with additives in li-ion batteries. Journal of Industrial and Engineering Chemistry 78, 178–185.

[172] Ahmed F, Rahman MdM, Chandra Sutradhar S, Siraj Lopa N, Ryu T, Yoon S, Choi I, Kim J, Jin Y, Kim W (2019) Synthesis of an imidazolium functionalized imide based electrolyte salt and its electrochemical performance enhancement with additives in li-ion batteries. Journal of Industrial and Engineering Chemistry 78, 178–185. DOI: 10.1016/j.jiec.2019.06.016; Cai Y, Zhang H, Cao Y, Wang Q, Cao B, Zhou Z, Lv F, Song W, Duo D and Yu L (2022) Synthesis, application and industrialization of LiFSI: A review and perspective. Journal of Power Sources 535, 231481.

TECHNOLOGY STATE OF PLAY

$LiPF_6$ production is highly mature, and the majority of global supply currently comes from China. However, in recent years there has been a lot of interest and development from the USA, Japan, and some European countries to establish their own production.[173] In early 2023, Koura (USA) signed a technology licensing agreement with Kanto Denka Kogyo (Japan) to access their $LiPF_6$ production technology and industry expertise.[174] Koura is looking to produce up to 10,000 tonnes per year, making it the first domestic large-scale $LiPF_6$ producer in the USA.[175] In 2021, LANXESS (Germany), a manufacturer of hydrofluoric acid and phosphorus chemicals, partnered with Tinci Materials Technology (China) to produce $LiPF_6$ for European battery cell manufacturers.[176]

$LiPF_6$ alternative salts have been commercialised in the past decade and are now produced by a few chemical companies in the USA, Japan, Korea, China and Europe. LiTFSI was first commercialised by 3M (USA) in 2012.[177] Currently, Solvay (Belgium) is the largest producer of LiTFSI in the world.[178] Nippon Shokubai (Japan) was the first company to commercialise the production of LiFSI back in 2013. It now produces 3,000 tonnes per annum, accounting for 13 percent of the global production volume (22,600 tonnes).[179] The company partnered with Arkema (France) on a pilot line in 2021 and will commission a commercial scale plant that will reach mass production by the end of 2025.[180]

Australia currently has no commercial activity in liquid electrolyte synthesis, however there are relevant domestic research and innovation capabilities. For example, a joint research project between Monash University and Calix successfully synthesised two lithium borate ester salts that outperform both $LiPF_6$ and LiFSI in terms of stability and battery performance enhancement.[181]

45.8% of patent families identified globally for the 2007 – 2022 interval were related to liquid electrolytes. Continued growth in patent activity for this technology is in line with the continued role of liquid electrolytes in current generation batteries. China had 77% of global output during the analysis period.

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173 ChemAnalyst (2023) Lithium hexafluorophosphate market analysis. <https://www.chemanalyst.com/industry-report/lithium-hexafluorophosphate-market-730>

174 Koura (2023) Koura Signs Technology Licensing Agreement with Kanto Denka Kogyo to Supply Critical Electrolyte Salt to North American Battery Market. <https://www.kouraglobal.com/north-american-lithium-ion-battery-supply-chain-boosted-through-localization-of-lithium-hexafluorophosphate-lipf6-production/>

175 Koura (2022) Orbia's Fluorinated Solutions Business Koura Receives $100M U.S. Department of Energy Award. <https://www.kouraglobal.com/orbias-fluorinated-solutions-business-koura-receives-100m-u-s-department-of-energy-award/>

176 LANXESS (2021) LANXESS enters battery chemistry business: electrolyte production for lithium-ion batteries in Leverkusen, Germany. <https://lanxess.com/en/Media/Press-Releases/2021/03/LANXESS-enters-battery-chemistry-business-electrolyte-production-for-lithium-ion-batteries-in-Leverkusen-Germany>

177 3M (2012) 3M™ Battery Electrolyte HQ-115. <https://multimedia.3m.com/mws/media/829379O/3mtm-battery-electrolyte-hq-115.pdf>; Xiao A, Eberman KW, Lamanna B, Jain G, Ye H, Burns JC, Sinha NN and Dahn J (2014) 3M HQ-115 (LiTFSI) Electrolyte Additive Dramatically Improves Battery Performance in Electrolytes Containing Trace Amounts of Water. ECS Meeting Abstracts MA2014-02(7), 516–516.

178 24ChemicalResearch (2023) LiTFSI Market Size, Share Global Outlook and Forecast 2023-2029. <https://www.24chemicalresearch.com/reports/202393/global-litfsi-market-2023-2029-633>

179 Cai Y, Zhang H, Cao Y, Wang Q, Cao B, Zhou Z, Lv F, Song W, Duo D, Yu L (2022) Synthesis, application and industrialization of LiFSI: A review and perspective. Journal of Power Sources 535, 231481; Tycorun Energy (2022) LiFSI industry research - LiFSI presents high growth space. <https://www.takomabattery.com/lifsi/>

180 Arkema (2022) Nippon Shokubai and Arkema: a strategic partnership to mass-produce LiFSI electrolyte salts for a European battery supply chain. <https://www.arkema.com/global/en/media/newslist/news/non-global/countries/japan/2022/20220531-nippon-shokubai-and-arkema-a-strategic-partnership-01/>

181 Roy B, Cherepanov P, Nguyen C, Forsyth C, Pal U, Mendes TC, Howlett P, Forsyth M, MacFarlane D, Kar M (2021) Lithium Borate Ester Salts for Electrolyte Application in Next-Generation High Voltage Lithium Batteries. Advanced Energy Materials 11(36).

Japan ranks 2nd with 15.6%, while the Republic of Korea and the USA are joint 3rd with 2.7% each. Germany and France also have limited patent activity in this area.

The following table summarizes the key RD&D areas of focus in liquid electrolyte and electrolyte salt synthesis:

Table 14: Global RD&D focus areas for liquid electrolyte and electrolyte salt synthesis.

RD&D FOCUS AREAS	
Liquid electrolytes	• Developing and testing alternatives to organic carbonate solvents (e.g., ionic liquids) to improve battery safety.[182] • Investigating different salt combinations and ratios to optimise electrolyte cycling efficiency and battery longevity.[183]
Lithium electrolyte salts	• Developing reduced fluorine materials and chlorine-free synthesis pathways; this includes investigating alternative reagents, to reduce costs and environmental risks and impacts.[184] • Develop alternative electrolyte salts with reduced fluorine content • Optimising $LiPF_6$ synthesis at scale, which requires precise control of reaction parameters and storage conditions.[185]

3.4.2 Solid electrolytes

Solid electrolytes have been developed to eliminate the need for solvents, which significantly improves battery safety. They are suitable candidates for next-generation batteries due to their compatibility with lithium metal anodes and high energy density and thermal stability.[186] There are three main types: solid polymer electrolytes (SPE), inorganic solid electrolytes (ISE), and composite solid electrolytes (CSE).

[182] Niu H, Wang L, Guan P, Zhang N, Yan C, Ding M, Guo X, Huang T, Hu X (2021) Recent Advances in Application of Ionic Liquids in Electrolyte of Lithium Ion Batteries. Journal of Energy Storage 40, 102659.

[183] Mauger A, Julien CM, Paolella A, Armand M, Zaghib K (2018) A comprehensive review of lithium salts and beyond for rechargeable batteries: Progress and perspectives. Materials Science and Engineering: R: Reports 134, 1–21.

[184] Liu J, Cai Y, Pang H, Cao B, Luo C, Hu Z, Xiao C, Zhang H, Lv F, Cao Y, Yu L (2022) Chloro-free synthesis of LiPF6 using the fluorine-oxygen exchange technique. Chinese Chemical Letters 33(8), 4061–4063; Liu J, Cai Y, Xiao C, Zhang H, Lv F, Luo C, Hu Z, Cao Y, Cao B and Yu L (2019) Synthesis of LiPF6 Using CaF2 as the Fluorinating Agent Directly: An Advanced Industrial Production Process Fully Harmonious to the Environments. Industrial & Engineering Chemistry Research 58(44), 20491–20494. DOI: 10.1021/acs.iecr.9b04958; Cai Y, Zhang H, Cao Y, Wang Q, Cao B, Zhou Z, Lv F, Song W, Duo D and Yu L (2022b) Synthesis, application and industrialization of LiFSI: A review and perspective. Journal of Power Sources 535, 231481. DOI: 10.1016/j.jpowsour.2022.231481.

[185] Xia C (2023) Important factors for the reliable and reproducible preparation of non-aqueous electrolyte solutions for lithium batteries. Communications Materials, 4(10). <https://doi.org/10.1038/s43246-023-00338-7>

[186] Wang L, Li J, Lu G, Li W, Tao Q, Shi C, Jin H, Chen G, Wang S (2020) Fundamentals of Electrolytes for Solid-State Batteries: Challenges and Perspectives. Frontiers in Materials 7.

Solid polymer electrolytes

Solid polymer electrolytes consist of polymer matrices containing lithium salts and potentially additional fillers, which can alter the physical properties or conductivity of the electrolyte.[187] The polymer matrix is a physically flexible material used as a base structure. It enhances the thermal stability and cycling efficiency of the electrolyte, improving battery longevity and safety.[188] However, the key limitation of SPEs is their low conductivity, especially at room temperatures, which can affect battery performance.[189]

There are three common pathways to prepare SPEs: solution casting, hot pressing and extrusion processing.[190] Solution casting involves dissolving the polymer and lithium salt in an organic solvent, then casting the mixture thinly onto a plate and allowing the solvent to evaporate. An improved variation of this method involves dissolution of the lithium salt in the molten or liquid polymer, reducing the risk of contamination and the need for toxic and expensive solvents. Hot pressing involves pressing the powdered mixture of lithium salt and polymer under high temperature and pressure. Extrusion processing involves forcing the lithium salt and polymer mixture through a heated chamber.

Inorganic solid electrolytes

Inorganic solid electrolytes (ISEs) are comprised of ceramic, glass or hybrid materials.[191] ISEs can achieve high ionic conductivity, energy density and chemical stability across a wide range of temperatures, which are all advantageous for battery performance.[192] Due to the mechanical properties of its inorganic materials, ISEs face challenges related to brittleness, low stability, and limited contact with the electrodes (which affects battery cycling efficiency), making large-scale manufacturing difficult.[193]

The common methods to prepare ISEs include melt-quenching, solid-state processing and wet-chemistry synthesis.[194] Melt-quenching involves melting and rolling the precursor ingredients into sheets, which are then rapidly cooled. Solid-state processing is a simplified version of melt-quenching, where the precursor ingredients are milled, pressed into pellets and sintered without melting. Wet chemistry synthesis involves dissolving the initial compounds with a solvent and precipitating the solid precursors, which are then sintered at high temperatures. Sol-gel techniques (discussed in Section 3.3.2) can also be employed to improve homogeneity.[195]

Composite solid electrolytes

Composite solid electrolytes (CSEs) are hybrid versions of liquid and solid electrolytes, or two types of solid electrolytes combined. CSEs are designed to achieve an optimised balance between conductivity, stability,

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[187] Chen A, Qu C, Shi Y, Shi F (2020) Manufacturing Strategies for Solid Electrolyte in Batteries. Frontiers in Energy Research, 8:571440; Verdier N, Foran G, Lepage D, Prébé A, Aymé-Perrot D, Dollé M (2021) Challenges in Solvent-Free Methods for Manufacturing Electrodes and Electrolytes for Lithium-Based Batteries. Polymers 13(3), 323.

[188] Sashmitha K, Rani MU (2023) A comprehensive review of polymer electrolyte for lithium-ion battery. Polymer Bulletin 80(1), 89–135.

[189] Sashmitha K, Rani MU (2023) A comprehensive review of polymer electrolyte for lithium-ion battery. Polymer Bulletin 80(1), 89–135.

[190] Verdier N, Foran G, Lepage D, Prébé A, Aymé-Perrot D, Dollé M (2021) Challenges in Solvent-Free Methods for Manufacturing Electrodes and Electrolytes for Lithium-Based Batteries. Polymers 13(3), 323.

[191] Chen A, Qu C, Shi Y, Shi F (2020) Manufacturing Strategies for Solid Electrolyte in Batteries. Frontiers in Energy Research, 8.

[192] Wang Y-A, Yin L, Luo C-W, He G-H (2023) Advances in Inorganic Solid Electrolytes: A Mini Review. JOM.

[193] Wang Y-A, Yin L, Luo C-W, He G-H (2023) Advances in Inorganic Solid Electrolytes: A Mini Review. JOM.

[194] Kundu S, Kraytsberg A, Ein-Eli Y (2022) Recent development in the field of ceramics solid-state electrolytes: I—oxide ceramic solid-state electrolytes. Journal of Solid State Electrochemistry 26(9), 1809–1838.

[195] Chen A, Qu C, Shi Y, Shi F (2020) Manufacturing Strategies for Solid Electrolyte in Batteries. Frontiers in Energy Research, 8.

electrode compatibility, and safety features.[196] A common liquid-solid hybrid approach involves introducing an organic solvent to a polymer matrix to improve conductivity, stability and safety.[197] The strategies for combining solid electrolyte materials include polymer-polymer, glass-polymer, and polymer-ceramics, all of which involve adding solid materials as fillers to an existing polymer matrix.[198] Since all four types of CSE contain a polymer matrix as a base structure, the methods to produce CSEs are similar to those used for SPEs.[199]

TECHNOLOGY STATE OF PLAY

SPEs have gathered high levels of commercial interest and activity, accounting for 63 percent of the global solid electrolyte market in 2021.[200] Blue Solutions (France) is the first company to commercially produce all-solid-state LFP lithium metal batteries in 2012. The key component of Blue Solutions' battery is a SPE prepared via an extrusion process.[201] Hydro-Québec (Canada) has partnered with Mercedes-Benz since 2020 to develop and trial SPE for their electric vehicles' battery cells and modules, which could be commercialised as early as 2026.[202]

Historically, the ISE market was dominated by a limited number of manufacturers from the USA and Japan.[203] Within the past five years, there has been increasing interest from companies based in the USA, Europe, Korea, and Japan to establish pilot production of ISEs. QuantumScape (USA) has developed a wet-chemistry-based technology to produce a ceramic ISE that is compatible with lithium metal anodes.[204] The ceramic electrolyte is the key component to QuantumScape's solid-state battery, which is being produced at pilot scale through a joint venture with Volkswagen since 2021.[205] In 2021, Solid Power (USA) established a pilot production of a glass-type ISE with a capacity of 30 tonnes per annum. Once fully commercialised in 2028, it is expected to produce 40,000 tonnes of products per annum.[206] Solid Power has also signed a

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[196] Tan S-J, Zeng X-X, Ma Q, Wu X-W, Guo Y-G (2018) Recent Advancements in Polymer-Based Composite Electrolytes for Rechargeable Lithium Batteries. Electrochemical Energy Reviews, 1(2):113–138.

[197] Tan S-J, Zeng X-X, Ma Q, Wu X-W, Guo Y-G (2018) Recent Advancements in Polymer-Based Composite Electrolytes for Rechargeable Lithium Batteries. Electrochemical Energy Reviews, 1(2):113–138.

[198] Tan S-J, Zeng X-X, Ma Q, Wu X-W, Guo Y-G (2018) Recent Advancements in Polymer-Based Composite Electrolytes for Rechargeable Lithium Batteries. Electrochemical Energy Reviews, 1(2):113–138.

[199] Chen A, Qu C, Shi Y and Shi F (2020) Manufacturing Strategies for Solid Electrolyte in Batteries. Frontiers in Energy Research, 8:571440.

[200] Maximise Market Research (2023) Solid Electrolyte Market. <https://www.maximizemarketresearch.com/market-report/solid-electrolyte-market/147478/>

[201] Werwitzke C (2021) "Actually, we are the pioneer of solid-state battery". electrive. <https://www.electrive.com/2021/03/03/actually-we-are-the-pioneer-of-solid-state-battery/>; Blue Solutions (n.d.) Battery Technology. <https://www.blue-solutions.com/en/battery-technology>

[202] Berman B (2020) Work on Goodenough's breakthrough solid-state EV battery moves forward. Electrek. <https://electrek.co/2020/04/23/work-on-goodenoughs-breakthrough-solid-state-ev-battery-moves-forward/>; Hydro-Québec (2020) Hydro-Québec partners with Mercedes-Benz on Development of Solid-State Battery Technologies. <http://news.hydroquebec.com/en/press-releases/1580/hydro-quebec-partners-with-mercedes-benz-on-development-of-solid-state-battery-technologies/>; Hydro-Québec (n.d.) Solid-electrolyte batteries. <https://www.hydroquebec.com/ce-transportation-electrification-energy-storage/solid-electrolyte-batteries.html>.

[203] Mordor Intelligence (2023) Solid Electrolyte Market. <https://www.mordorintelligence.com/industry-reports/solid-electrolyte-market>

[204] QuantumScape (2022) Ceramics 101: The QuantumScape Separator in Context. <https://www.quantumscape.com/resources/blog/ceramics-101-the-quantumscape-separator-in-context/>

[205] Businesswire (2021) QuantumScape and Volkswagen Sign Agreement to Select Location for Joint Venture Pilot-Line Facility. <https://www.quantumscape.com/press-release/quantumscape-and-volkswagen-sign-agreement-to-select-location-for-joint-venture-pilot-line-facility/>

[206] Solid Power (2021a) Solid Power to Quadruple Production Footprint with Second Denver-Area Facility. News Release. <https://ir.solidpowerbattery.com/news-releases/news-release-details/solid-power-quadruple-production-footprint-second-denver-area>

Memorandum of Understanding (MoU) with SK Innovation (Korea) to license the electrolyte technology and further advance all-solid-state battery production.[207]

Due to the complex chemistry and structural design, CSEs are currently being pursued by a small number of companies and start-ups. Blue Current (USA) is piloting the production of a glass-polymer electrolyte for a silicon-anode all-solid-state battery.[208] The company is partnering with Umicore (Belgium) to improve the technology and accelerate commercialisation.[209] In early 2022, NEI Corporation (USA), a major battery materials producer, announced that it now offers different varieties of polymer-ceramics CSE materials, demonstrating the ability to customise CSE formulations at scale.[210]

Solid electrolytes have experienced a stable and growing trend in patent activity from 2007 onwards, and in aggregate, surpass patent trends for liquid electrolytes. This reflects development in the innovation sector towards next generation solid state batteries with improved performance and safety. From 2007 to 2022, 14.6% of patent families were related to SPE synthesis, 20% ISE synthesis, and 19.6% CSE synthesis. China is particularly active in SPEs and CSEs with 77.8% and 74.% of patents in those areas. In ISEs, China and Japan are both highly active with 36.5% and 35.4% share respectively. The Republic of Korea was particularly strong in SPEs and CSEs with 12.7% and 15% of patent activity in those areas.

Australia does not currently have commercial activity in solid electrolyte synthesis, however there are domestic cross-cutting capabilities in advanced manufacturing and materials that could potentially be leveraged. Australia has strong levels of activity in additive manufacturing. Researchers from the University of New South Wales (UNSW) successfully 3D printed a SPE that has high conductivity and strength. These superior properties were achieved thanks to the ability to customise the electrolyte structure via 3D printing.[211] Lab22 Innovation Centre, one of Australia's leading centres in additive manufacturing, works with a wide range of materials and complex structures and is developing solutions for the space, defence and medical industries.

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[207] Solid Power (2021b) Solid Power Partners with SK Innovation to Jointly Produce All-Solid-State Batteries. News Release. <https://ir.solidpowerbattery.com/news-releases/news-release-details/solid-power-partners-sk-innovation-jointly-produce-all-solid>

[208] Blue Current (2023) Technology. <https://bluecurrent.com/technology/>; Businesswire (2022) Solid-State Battery Innovator Blue Current Announces New CEO and Pilot Plant Investment <https://www.businesswire.com/news/home/20220405005965/en/Solid-State-Battery-Innovator-Blue-Current-Announces-New-CEO-and-Pilot-Plant-Investment>.

[209] Umicore (2023) Umicore steps up solid-state battery technology development with investment in Blue Current. GlobeNewswire. <https://www.globenewswire.com/news-release/2023/03/30/2637979/0/en/Umicore-steps-up-solid-state-battery-technology-development-with-investment-in-Blue-Current.html>

[210] NEI Corporation (2022) NEI Corporation Expands Selection of Materials for Lithium-ion & Sodium-ion Batteries. <https://www.neicorporation.com/news/2022/01132022_Li-ion_Na-ion_Expansion_Press_Release.pdf>

[211] Lee K, Shang Y, Bobrin VA, Kuchel R, Kundu D, Corrigan N and Boyer C (2022) 3D Printing Nanostructured Solid Polymer Electrolytes with High Modulus and Conductivity. Advanced Materials 34(42).

The following table summarizes the key RD&D areas of focus in solid electrolyte synthesis:

Table 15: Global RD&D focus areas for solid polymer electrolyte preparation.

	RD&D FOCUS AREAS
Solid polymer electrolytes	• Developing and scaling up additive manufacturing (i.e., 3D printing) techniques to enhance the interfacial compatibility between the SPE and the electrodes and reduce cost and material wastage.[212] • Developing different polymer combinations to improve the conductivity of SPEs.[213] • Advancing SPEs' physical (e.g., thinness) and mechanical properties and introducing additional structural components to improve battery safety and durability.[214] • Investigating the feasibility of using biopolymer materials.[215]
Inorganic solid electrolytes	• Advancing manufacturing techniques, including additive manufacturing (i.e., 3D printing), to process and handle brittle and unstable inorganic materials and reduce cost and material wastage.[216] • Developing coating or structural engineering solutions to facilitate the interaction between electrodes and ISEs.[217]
Composite solid electrolytes	• Optimising the chemical and structural design of CSEs.[218] • Advancing the manufacturing techniques to reduce energy and cost and improve product quality and process efficiency.[219] • Investigating low-cost fillers and biopolymers.[220] • Advancing the understanding of ion transport mechanisms and the behaviour of the various phases comprising a CSE within batteries (e.g., in terms of stability, interactions, performance).[221]

[212] Chen A, Qu C, Shi Y, Shi F (2020) Manufacturing Strategies for Solid Electrolyte in Batteries. Frontiers in Energy Research, 8:571440.

[213] Sashmitha K, Rani MU (2023) A comprehensive review of polymer electrolyte for lithium-ion battery. Polymer Bulletin 80(1), 89–135.

[214] Wu Y, Li Y, Wang Y, Liu Q, Chen Q, Chen M (2022) Advances and prospects of PVDF based polymer electrolytes. Journal of Energy Chemistry 64, 62–84; Barbosa JC, Gonçalves R, Costa CM, Lanceros-Méndez S (2022) Toward Sustainable Solid Polymer Electrolytes for Lithium-Ion Batteries. ACS Omega 7(17), 14457–14464.

[215] Lizundia E, Kundu D (2021) Advances in Natural Biopolymer-Based Electrolytes and Separators for Battery Applications. Advanced Functional Materials 31(3).

[216] Chen A, Qu C, Shi Y, Shi F (2020) Manufacturing Strategies for Solid Electrolyte in Batteries. Frontiers in Energy Research, 8.

[217] Li C, Wang Z, He Z, Li Y, Mao J, Dai K, Yan C, Zheng J (2021) An advance review of solid-state battery: Challenges, progress and prospects. Sustainable Materials and Technologies, 29:e00297.

[218] Fan LZ, He H, Nan CW (2021) Tailoring inorganic–polymer composites for the mass production of solid-state batteries. Nature Reviews Materials, 6(11):1003–1019.

[219] Baade P, Wood V (2021) Ultra-high throughput manufacturing method for composite solid-state electrolytes. iScience, 24(2):102055.

[220] Maurya DK, Dhanusuraman R, Guo Z, Angaiah S (2022) Composite polymer electrolytes: progress, challenges, and future outlook for sodium-ion batteries. Advanced Composites and Hybrid Materials, 5(4):2651–2674.

[221] Fan LZ, He H, Nan CW (2021) Tailoring inorganic–polymer composites for the mass production of solid-state batteries. Nature Reviews Materials, 6(11):1003–1019.

3.4.3 Implications for Australia

This section discusses the opportunities for domestic RD&D and international engagement in the synthesis of CAM (summarised in Figure 16). More details on the framework used can be found in the main report *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities*.

Figure 16: Opportunities for Australian RD&D and international engagement in the synthesis of electrolyte materials.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies		• Solid electrolytes	• Solid electrolytes • Liquid electrolytes	• Liquid electrolytes
RD&D actions	Build capability in emerging technology areas via fundamental and applied research projects.	Leverage Australia's strengths to progress technologies beyond the lab and grow Australian IP.	Deploy Australian IP in pilot-scale and commercial-scale demonstrations.	Support the deployment of mature technologies domestically at commercial scale, through commercial testing and validation, and cross-cutting RD&D.
International engagement actions	Engage with research institutions on capability building and knowledge sharing (e.g. joint research programs).	Partner with overseas industry, research or government on mutually beneficial sustained technology development efforts (e.g. co-funded or joint projects).	Engage with upstream offtakers to de-risk and finance pilot projects. Alternatively, demonstrate Australian technologies overseas.	Engage on commercial arrangements e.g. international technology providers, license overseas patents, attract foreign direct investment, and secure offtake agreements.

IP, intellectual property.

Despite the intrinsic challenges around safety, liquid electrolytes will remain an integral component of current generation lithium-ion batteries. As such, the market for liquid electrolytes and for the electrolyte salt feedstock supporting it are expected to face strong growth in demand over the coming years.

The global market for battery electrolytes is forecasted to increase from US$ 7.6 billion in 2022 to US$ 16.8 billion by 2027, with liquid electrolytes holding the largest market segment throughout the forecasted period.[222] $LiPF_6$ is likely to remain an important electrolyte salt for the near future, with the global market projected to grow from US$ 3.02 billion in 2022 to US$ 5.63 billion in 2029 due to the demand from the EV and transportation industries.[223] The demand for alternative electrolyte salts is also expected to increase. By 2025, the demand for LiFSI is forecasted to reach 33,500 tonnes globally.[224] The global LiTFSI market is projected to grow from US$ 203.1 million in 2022 to US$ 357.8 million in 2028, with a compound annual growth rate of 9.9 percent.[225]

[222] MarketsandMarkets (2022) Battery Electrolyte Market by Battery Type (Lead-Acid and Lithium-Ion), Electrolyte Type (Liquid, Gel, Solid), End-Use (EV, Consumer Electronics, Energy Storage) and Region (APAC, North America, Europe, South America and MEA) - Global Forecast to 2027. <https://www.marketsandmarkets.com/Market-Reports/battery-electrolyte-market-78609093.html>

[223] 24 Chemical Research (2023) LiPF6 Market 2023 forecast to 2030 - Capacity, Production, Capacity Utilization Rate, Ex-Factory Price, Revenue, Demand & Supply, Import and Export, Cost, Gross Margin Analysis. Reagents Market Research Report. <https://www.24chemicalresearch.com/reports/210681/lipf-market-2023-2030-887>

[224] Everbright Securities (2021) Everbright Securities: lithium hexafluorophosphate sustainable prosperity new lithium salt ushered in new opportunities. SMM. <https://news.metal.com/newscontent/101515160/everbright-securities-lithium-hexafluorophosphate-sustainable-prosperity-new-lithium-salt-ushered-in-new-opportunities>

[225] Business Research Insights (2023) LiTFSI Market Size, Share, Growth, and Industry Analysis, by Type (LiTFSI powder and LiTFSI solution), by Application (Electrolyte Salt, Antistatic Agent and Others), Regional Forecast to 2028. Chemicals and Materials. <https://www.businessresearchinsights.com/market-reports/litfsi-market-105845>

The synthesis of liquid electrolytes is mature, geographically concentrated, and currently reliant on complex and hazardous synthesis processes for existing technologies. [226] Nearly half of the patent filings identified in the IP analysis of the last 15 years were related to liquid electrolytes, with the top 4 countries accounting for 98% of them. Moreover, the global supply of $LiPF_6$ is currently dominated by a limited number of large-scale producers in China.

While Australia currently does not have established liquid electrolyte production capabilities or identifiable patent activity, the need to diversify electrolyte supply chains and lower its environmental footprint could represent a pathway for participation in the market. Australia has demonstrated strong research and innovation capabilities in the production of electrolyte salts, as discussed in the example of Monash University and Calix's development of high-performance alternative lithium salts (see Section 3.4.1). Australia's participation in the liquid electrolyte market can be built through collaborations with international partners for knowledge sharing and capability building.

There is also an opportunity for domestic RD&D to improve current $LiPF_6$ synthesis pathways and advance alternative technologies. Specifically, to enable responsible liquid electrolyte production in Australia, RD&D efforts are required to enhance the safety of conventional $LiPF_6$ synthesis and storage, and to develop alternative $LiPF_6$ synthesis methods using low cost and low environmental impact reagents. Another potential strategy to enable safe and sustainable $LiPF_6$ production in Australia is by partnering with producers from countries with high sustainability standards like Japan, the US, and Germany (see examples in Section 3.4.1) to deploy existing mature technologies.

Developing $LiPF_6$ alternatives with improved conductivity and stability is also important for performance enhancement and to improve the safety of current-generation batteries. The applicability of alternative electrolyte salts to next-generation batteries provides an additional addressable market in the medium to long term, de-risking RD&D investment. Given the emerging applicability of $LiPF_6$ alternatives (including but not limited to LiFSI and LiTFSI) in the battery industry, supporting technical, economic and market assessment will be important to understand long-term demand and inform strategic investments.

Australia has the potential to capture market share in the emerging solid-state battery market by producing materials and components including solid electrolytes. Solid electrolytes are a key component of next generation batteries, having high thermal stability and compatibility with lithium metal anodes, helping increase energy density.[227] The market for solid-state batteries is projected to grow to $US 13.15 billion by 2030, mostly due to their expected improvement in performance, durability and safety with regards to current-generation lithium-ion batteries with liquid electrolytes.[228]

Solid electrolytes are an emerging area of growing IP activity globally, with each type (ISE, SPE and CSE) facing benefits and challenges in manufacturing and performance. The current stage of their development provides an opportunity for Australian RD&D to become more integrated in international electrolyte development and commercialisation. SPEs show good all-round characteristics (electrochemical and thermal stability, safety, and performance). They are the more mature and easier to manufacture of the

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[226] 24 Chemical Research (2023) LiPF6 Market 2023 forecast to 2030 - Capacity, Production, Capacity Utilization Rate, Ex-Factory Price, Revenue, Demand & Supply, Import and Export, Cost, Gross Margin Analysis. Reagents Market Research Report. <https://www.24chemicalresearch.com/reports/210681/lipf-market-2023-2030-887>; Everbright Securities (2021) Everbright Securities: lithium hexafluorophosphate sustainable prosperity new lithium salt ushered in new opportunities. SMM. <https://news.metal.com/newscontent/101515160/everbright-securities-lithium-hexafluorophosphate-sustainable-prosperity-new-lithium-salt-ushered-in-new-opportunities>

[227] Chandler (2022) Toward batteries that pack twice as much energy per pound. MIT News. <https://news.mit.edu/2022/solid-state-batteries-interface-stability-0308>

[228] Straits Research (2021) Solid-State Battery Market. <https://straitsresearch.com/report/solid-state-battery-market/>

three types of solid electrolyte. As a result, SPEs have already been commercially produced by some companies. However, there is room for improvement on compatibility with the electrodes and performance at room temperatures, which can potentially impact the battery's durability.[229] A pathway to consider is the use of natural biopolymers instead of synthetic ones. R&D in biopolymers is required to enable sustainable resource utilisation and green chemical manufacturing, and material recycling.[230]

ISEs are produced at pilot scale internationally. These show greater electrochemical and thermal stability and have the potential to enhance battery durability, but their brittleness makes them harder to manufacture and their structural design can be improved to enhance compatibility with the electrodes and the battery overall performance. RD&D is required for manufacturing strategies that can overcome issues posed by brittle materials (e.g. additive manufacturing) and that are also cost- and energy-efficient and scalable.

CSEs are also at pilot scale internationally, and combine the characteristics of both SPEs and ISEs, balancing performance, durability and safety.[231] The variety and flexibility of CSEs offer many commercial propositions, with many possibilities to combine materials. Continued RD&D efforts are required to understand the effect of different combinations and identify the optimal ones in terms of effectiveness, cost and environmental impact. RD&D will also be required to scale advanced manufacturing techniques to produce high quality product at reduced energy and cost.

Given the still emerging status of solid-state batteries, there is an opportunity to partner with international battery manufacturers to leverage Australian cross-cutting capabilities for the next generation of solid electrolytes. Australia does not currently have identifiable patents or commercial production of solid electrolytes, but it possesses both active research and advanced manufacturing capabilities that are directly relevant to the area. Using existing domestic capabilities in additive manufacturing for the battery industry can help overcome the engineering challenges of ISEs and lower the cost of production, positioning Australia as a collaborator in the emerging global market. Similarly, leveraging Australia's cross-cutting capabilities in biopolymers (stemming from the medical sector) and applying it to battery applications could create a step change in operational costs and sustainability, helping Australia prepare for the future sustainable manufacturing requirements from the global industry.

Securing offtake and expediting domestic RD&D in solid electrolyte synthesis will require collaboration with emerging international lithium-metal (i.e., solid-state) battery manufacturers. This is due to the lack of domestic battery manufacturers, the emerging nature of lithium-metal (i.e., solid-state) batteries which increases investment risks and uncertainty, and the high costs required to develop and test new technologies. Further, co-locating solid electrolyte production with battery cell assembly is important due to the close technical integration required between the two steps.

[229] Sashmitha K and Rani U (2023) A comprehensive review of polymer electrolyte for lithium-ion battery. Polymer Bulletin 80(1), 89-135.

[230] Lizundia E and Kundu D (2021) Advances in natural biopolymer-based electrolytes and separators for battery applications. Advanced Functional Materials 31(3), 2005646.

[231] Zhang Z, Wang X, Li X, Zhao J, Liu G, Yu W, Dong X, Wang J (2023) Review on composite solid electrolytes for solid-state lithium-ion batteries. Materials Today Sustainability, 100316.

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