Australia's National Science Agency

From minerals to materials

Assessment of Australia's critical mineral mid-stream processing capabilities

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Citation

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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 includes a complete list of the organisations that provided input into to this project.

The report benefitted greatly from comments and review from Chris Vernon, Andrew Jenkin, Joanne Loh, Robbie McDonald, Wensheng Zhang, Thomas Ruether, Gautam Das, Lyndsey Benson, Karl Bunney, Warren Bruckard, Greg Wilson, Jim Brosnan, Department of Industry Science and Resources (Critical Minerals Office), the Australian Nuclear Science and Technology Organisation (ANSTO), ITP Renewables and CRU.

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Foreword

Australia is a world leader in minerals exploration and mining, with a rich endowment of critical minerals essential for both our nation and our trading partners.

To capitalise on our rich mineral resources, build sovereign capability and create new jobs and wealth for future generations, we must develop new industries centred on the production of advanced chemicals and materials.

This shift will not only support Australia's manufacturing ambitions but also contribute to the growth of renewable energy technologies for the entire world.

This report, *From minerals to materials: Assessment of Australia's critical minerals mid-stream processing capabilities*, arrives at a crucial time.

It offers an overview of Australia's capabilities and strengths in downstream processing and looks at the many research and innovation opportunities coming in the future.

By exploring commercially mature technologies as well as new innovative processing methods for technologies such as lithium-ion batteries, rare earth magnets and solar panels, this report will equip decision-makers with the knowledge they need to drive the industry forward.

This report will also inform the ongoing work of the Australian Critical Minerals Research and Development Hub, established to bring together expertise from Australia's leading science agencies: CSIRO, Geoscience Australia and the Australian Nuclear Science and Technology Organisation (ANSTO).

By aligning our priorities with industry needs and global trends, we can accelerate the growth of Australia's critical minerals industry to the benefit of this country and our trading partners.

Madeleine King

Federal Minister for Resources
and the Minister for Northern Australia

Glossary

Abbreviations

ALD	Atomic layer deposition
CAGR	Compound annual growth rate
CAM	Cathode active material
C-SPG	Coated spherical purified graphite
C-Si-PV	Crystalline silicon solar photovoltaic
CVD	Chemical vapour deposition
ESG	Environmental, social and governance
EV	Electric vehicle
GWh	Gigawatt-hours
HPAL	High-pressure acid leaching
IP	Intellectual property
IX	Ion-exchange separation
LIB	Lithium-ion battery
MHP	Mixed hydroxide precipitate
MSP	Mixed sulphide precipitate
NMC	Nickel-manganese-cobalt CAM
Nd-Fe-B	Neodymium-Iron-Boron magnet
OEM	Original equipment manufacturer
PV	Photovoltaic
pCAM	Precursor cathode active material
R&D	Research and development
RD&D	Research, development and demonstration
RE	Rare earths
SPG	Spherical purified graphite
SX	Solvent extraction

Definitions

2N–11N	The level of purity of a product, for instance 2N corresponds to 99% purity and 11N to 99.999999999%.
Anode	The electrode component of lithium-ion batteries, that supplies electrons when the system is active, i.e. during discharge.
Baking	Heating an ore or concentrate at a temperature lower than that used for roasting (e.g. 200–600°C).
Black mass	Shredded and processed material from end-of-life lithium–ion batteries containing high value metals such as lithium, nickel, cobalt and manganese.
Bioleaching	Dissolving the metals in an ore using the biological processes or by-products of microorganisms.
Calcination	Heating a material in a low- or no-oxygen environment, without melting it, to remove impurities and potentially induce a change in physical properties or chemical composition.
Carbothermal reduction	A process to produce the metallic form of an element, with a carbon-containing compound as the reducing agent.
Cathode	The electrode component of lithium-ion batteries that receives electrons when the system is active, i.e. during discharge.
Chemical vapour deposition	A process that uses a gaseous precursor to deposit a thin layer of material over a surface, progressively generating a highly pure solid.
Crystallisation	A process that produces a solid crystal product from a dissolved compound using physical or chemical methods, like evaporation or precipitation.
Directional solidification	Refining process that controls the cooling rate and direction in which a molten metal solidifies to segregate impurities into a small section that can be removed.
Electrowinning	A process that passes an electric current through a solution, causing a dissolved metal of interest to be deposited as solid metal at the cathode.
Energy-related emissions	Emissions generated from electrical or thermal energy that is used to run facilities and processes.

Hydrogen reduction	A process to produce the metallic form of an element using hydrogen as the reducing agent.
Hydrometallurgy	The field and set of chemical processes focused on the extraction, modification and separation of metallic elements from ores.
Ion exchange	A process to separate an element of interest from a solution using resins covered in a highly selective extractant.
Leaching	Dissolving elements of interest from an initial feedstock (ore, concentrate or residue material) using an acid or alkaline agent.
Maturity level	Highest level of development that has been achieved by a technological process. This report uses three categories to represent maturity level: demonstration in a laboratory context; demonstration at intermediate scale in pilot projects; and large-scale deployment in commercial projects.
Metallothermic reduction	A process to produce the metallic form of an element using another metal as the reducing agent (e.g. calcium).
Molten salt electrolysis	A process that passes an electrical current through a molten salt, to deposit the metallic form of an element of interest at the cathode.
Precipitation	A process of bringing a compound out of solution into solid form. This can be done through a chemical reaction, saturation or change in pH (acidity/alkalinity).
Pyrolysis	Decomposing a carbon-containing material through heating at high temperature in an environment without oxygen.
Pyrometallurgy	The field and set of processes focused on heating ores, concentrates and residue materials at high temperatures in controlled environments to change their physical or chemical properties.
Polysilicon	A high-purity form of silicon used in solar cells and electronics.
Process-related emissions	Emissions arising from the chemical transformation of input materials.
Roasting	Heating a material at high temperature (above 600°C) in an environment with oxygen, to produce changes in its physical properties or chemical composition.
Smelting	Heating a complex material, like an ore, above its melting point in the presence of a reagent to modify its chemical composition and separate elements of interest from unwanted material.
Sol gel	A process used for producing advanced materials by dissolving metal salts alongside a reagent and heating the mixture to generate a gel.
Solvent extraction	Also known as liquid-liquid extraction. A chemical process to separate a metal compound from a mixture.
Solvo- and hydrothermal synthesis	A process used for producing advanced materials that dissolves metal salts in water (hydrothermal) or a solvent (solvothermal) and then applies heat.
Spray-based synthesis (spray drying, spray pyrolysis)	A process used for producing advanced materials by spraying fine droplets of a solution into a high-temperature environment.
Thermochemical reduction	A process to produce the metallic form of an element by heating a compound containing it in the presence of a suitable reducing agent.

Executive summary

The global shift towards a low carbon economy is reliant upon renewable energy technologies that require critical minerals, resulting in growing demand and foreign investment. However, supply chains face considerable environmental social and governance (ESG) concerns and are highly concentrated and thus vulnerable to global disruptions.

The energy transition and growth of clean energy technologies and electric vehicles (EVs) has doubled the demand for critical minerals over the past 5 years to USD$320 billion.[1] However, energy technology supply chains are highly concentrated, particularly in the mid-stream portion of the supply chain. Global diversification efforts face hurdles such as high capital costs, uneven access to relevant intellectual property (IP) and know-how, and ESG challenges.

Australia has a strong foundation – a rich mineral and renewable resource endowment, a strong industrial base, robust institutional structures, and a highly active research, development and demonstration (RD&D) sector – to supply the key minerals and the value-added products required for the global energy transition.

To develop a robust mid-stream processing industry and compete alongside global processing powerhouses, Australia will require a multifaceted approach, ranging from technological innovation and strategic collaboration to policy frameworks and investment. Given its comparative advantages, Australia is well placed to tackle the nuanced nature of the challenges at hand, including ensuring resilience and sustainability in renewable energy supply chains.

RD&D plays a key role in expanding mid-stream processing capabilities and unlocking competitive and sustainable production of value-added products.

Diversifying critical steps in the supply chain is technically and commercially challenging for Australia and its international partners. Focussed RD&D in mid-stream processing can deliver improvements and new pathways that are more efficient, less costly, integrate green energy, and reduce or eliminate the use of environmentally harmful reactants. This will enable competitive Australian exports of responsibly produced materials, strengthen Australia's economic resilience and complexity, and contribute to the broader goal of achieving a sustainable and low carbon future.

The opportunity for new suppliers to enter the critical minerals market is now, however insufficient coordination and understanding of existing capabilities and technology pathways could hinder Australia's progress.

To address this, the Australian Critical Minerals Research and Development (R&D) Hub was established in line with *Australia's Critical Minerals Strategy 2023–2030*.[2] Led by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Australian Nuclear Science and Technology Organisation (ANSTO) and Geoscience Australia (GA), the Hub's role is to foster greater collaboration within the Australian critical minerals ecosystem, to guide and prioritise critical minerals R&D, develop expertise, and to support international engagement.

As part of this initiative, the *From minerals to materials: Assessment of Australia's critical mineral mid-stream processing capabilities* supports the *Strategy's* key actions to analyse value chains for each priority technology and identify where Australia can be most competitive. This report series informs the Hub's RD&D and collaboration activities and broader government, industry, research and international audiences by:

- Communicating key mid-stream processing technologies, mature and emerging, that will underpin the production of value-added and recycled products for energy technology supply chains.
- Showcasing Australian capabilities across key technology areas.
- Summarising international capabilities across key mid-stream processing technologies, and strategic objectives across the supply chain.
- Synthesising opportunities for domestic RD&D and international collaboration in line with Australia's mineral resources, manufacturing ambitions, and export priorities and those of international partners.

1 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>

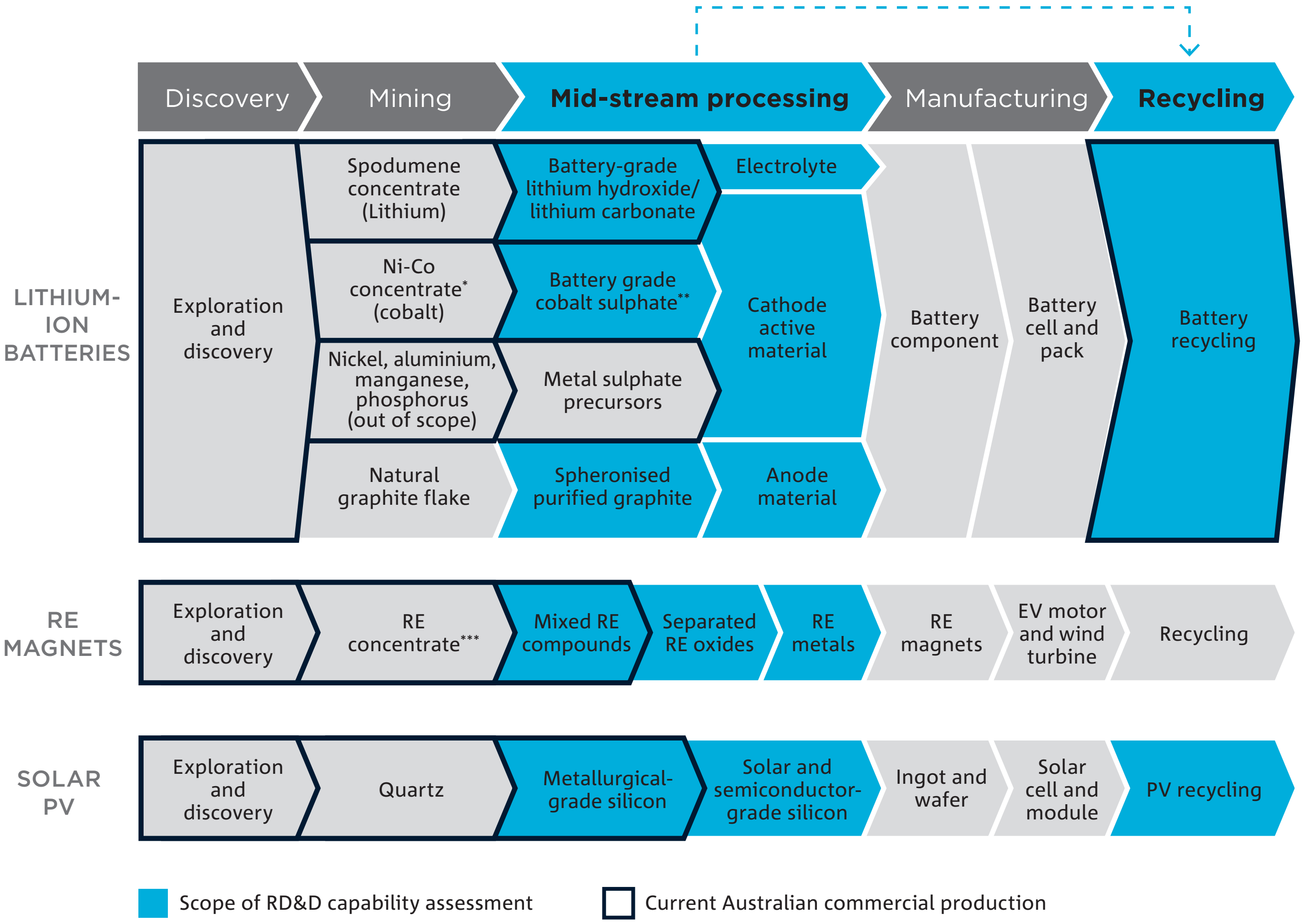
2 DISR (2023) Critical Minerals Strategy 2023-2030. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/sites/default/files/2023-06/critical-minerals-strategy-2023-2030.pdf>

The scope of this report series covers the mid-stream processing, namely the extraction of compounds from ores and the production of value-added materials.[3] The report series covers three key supply chains: lithium-ion batteries (LIBs), rare earth (RE) magnets (for wind turbines and EVs), and crystalline silicon solar photovoltaic (PV) (Figure 1). These technologies are part of Australia's priority technologies for critical minerals as stated in the *Strategy* and the *Critical Technologies Statement*.[4]

Mid-stream processing is also highlighted as a integral to national battery manufacturing and global diversification efforts in Australia's National Battery Strategy.[5]

By blending data driven insights, comprehensive technology analysis, and extensive industry and research consultations, this analysis identifies the challenges and opportunities for RD&D and international collaboration.

Figure 1: Scope of critical minerals RD&D capability assessment.



* Concentrate contains cobalt and nickel and can contain other metals depending on deposit type (e.g. copper and platinum group elements).

** Australia currently produces cobalt metal and mixed precipitate intermediates.

*** Concentrate is only applicable to hard rock deposits. Clay-hosted is leached and sold as mixed rare earth compounds.

EV, electric vehicle; Co, Cobalt; Ni, Nickel; PV, photovoltaic; RE, rare earth.

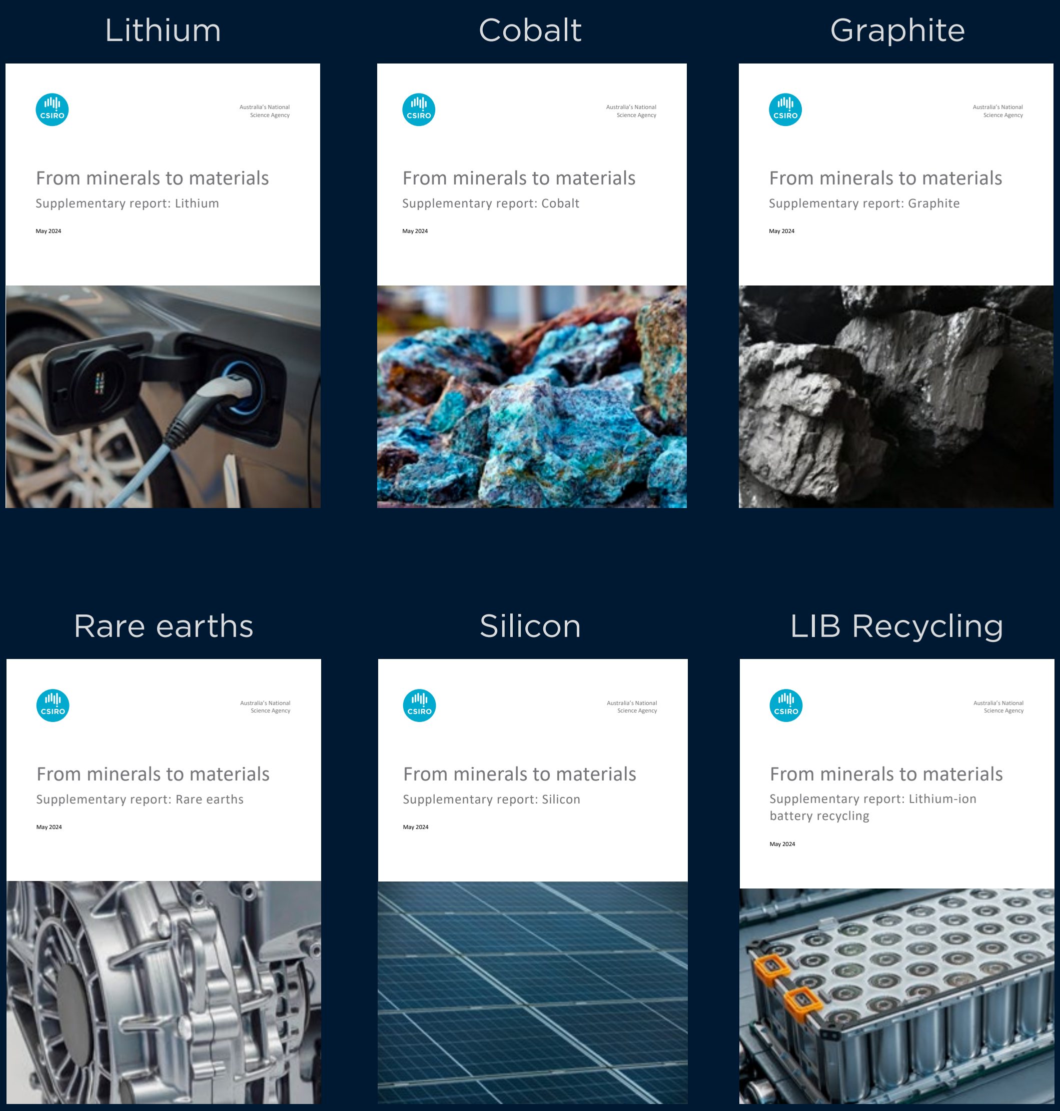
3 Mining and beneficiation is not covered.

4 DISR (2023) Critical Technologies Statement. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/publications/critical-technologies-statement>

5 DISR (2024) National Battery Strategy. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/publications/national-battery-strategy>

The technologies covered in this report series are highly technical, therefore a series of supplementary mineral reports (see Figure 2), have been produced to facilitate stakeholder understanding of the benefits and challenges, as well as the state of play globally and in Australia.

Figure 2: Supplementary mineral reports.

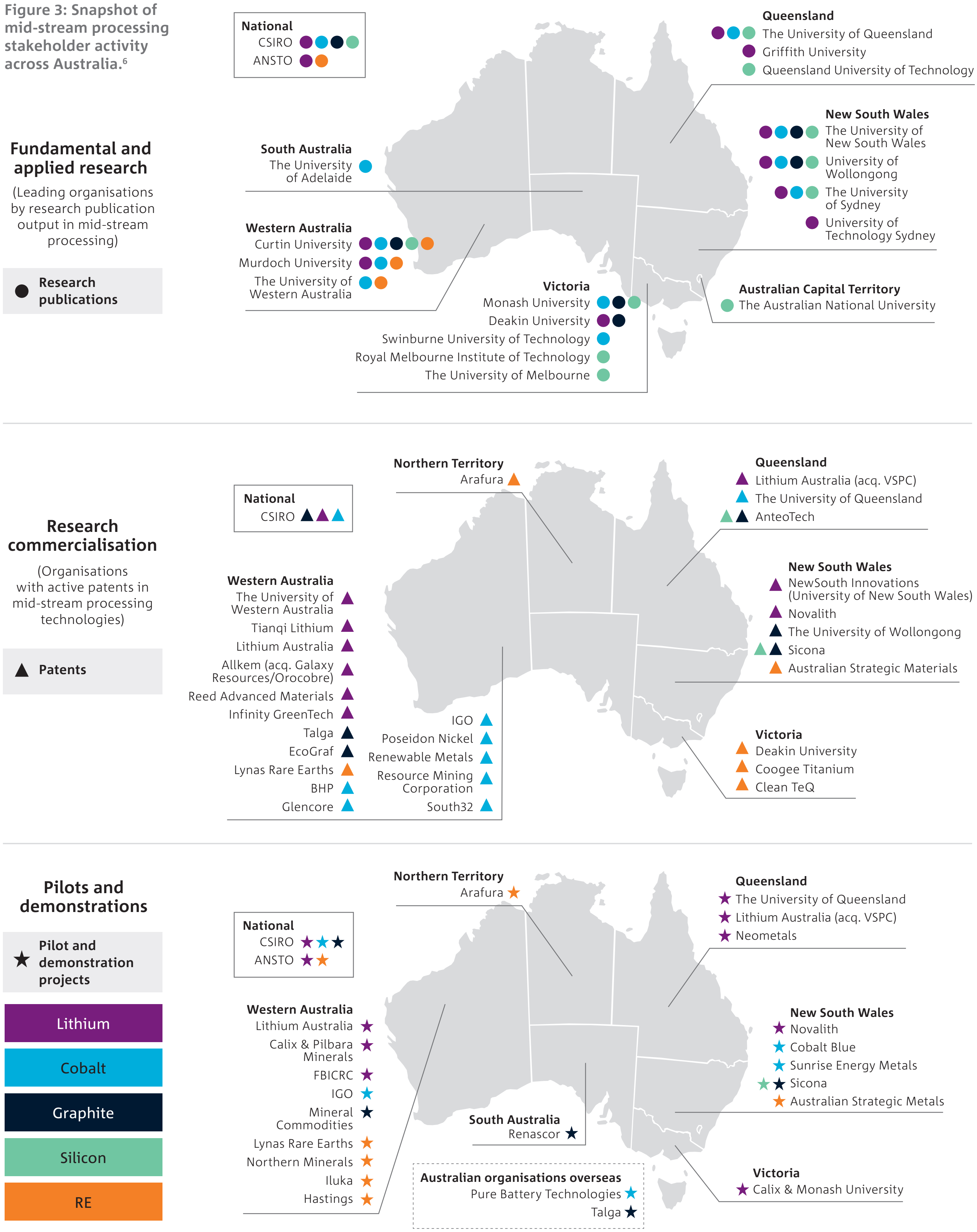


Key findings: Australia's RD&D capabilities

The Australian critical minerals RD&D ecosystem is large and diverse, with stakeholders across industry, research and government.

The capability assessment identified 17 universities and 32 industry organisations with high levels of RD&D activity as indicated by research publication output, patents or pilot projects (Figure 3).

Figure 3: Snapshot of mid-stream processing stakeholder activity across Australia.[6]



Acq., acquired

6 The accuracy of the research publication and patent data is 70% or above, see Appendices E and F for methodology.

Australia has significant RD&D strengths in mid-stream processing across several critical minerals, however some areas are more developed than others.

Australia has had strong activity in the first step of mid-stream processing (i.e. extractive metallurgy), whereas capabilities in the production of value-added intermediates are still developing. Lithium and cobalt have received high levels of RD&D activity in Australia relative to other minerals. Australia also has very strong patent activity in graphite, and research publication activity in photovoltaic (PV) recycling.

These findings (Figure 4) broadly align with the current state of industry development in Australia; the often-sequential nature of developing an integrated domestic supply chain, and the relative maturity of the domestic lithium and cobalt industries. There is growing recognition of the potential for value-adding in mid-stream processing and the development Australia's untapped critical mineral potential, warranting increased RD&D focus in developing areas.

Figure 4: Australia's research, development and demonstration (RD&D) activity levels in mid-stream processing.

*Extractive metallurgy does not apply to graphite (a non-metal).

LIB, lithium-ion battery; PV, photovoltaic.

Key actions for RD&D and international collaboration

Three RD&D themes were identified that represent the overarching priorities to enable sovereign critical minerals processing across various supply chains. The following themes (Figure 5) offer broad guidance on RD&D priorities for mid-stream processing across multiple supply chains.

Figure 5: Overarching research, development, and demonstration (RD&D) themes for the critical minerals sector.

Deliver continuous and step change improvements on cost and sustainability.	Maximise return on RD&D investment through cross-cutting capabilities and shared infrastructure.	Integrate research from adjacent fields to support innovation and decision making.
RD&D that unlocks continuous or step-change improvements in environmental and social outcomes and delivers costs reductions, will enhance competitiveness and improve industry resilience.	RD&D investment towards cross-cutting capabilities and RD&D infrastructure that can be applied across several critical minerals can maximise return on investment, streamline RD&D efforts and accelerate domestic projects.	Research in adjacent fields, including environment, modelling, traceability, and safety and social license can provide important information on the most efficient technology, policy or commercial pathways to develop greater mid-stream processing onshore.

Developing onshore processing and value-adding activity will require a set of RD&D and international engagement actions, and these differ across each mineral and technology area based on several complex factors.

Several considerations come into play when identifying mid-stream processing technology pathways, including opportunities to drive the development and commercialisation of Australian technologies and opportunities to support the adoption of mature technologies for near-term industry outcomes. These include the level of Australian RD&D activity (e.g. domestic patents), development timeframes (e.g. commercial maturity), opportunities to innovate (e.g. saturation of a technology area), and the potential to deliver continuous improvements or step-change disruptions. This report series has considered and assessed these complexities to synthesise a set of RD&D actions and international engagement actions based on the framework in Figure 6.

Figure 6: Framework for assessing research, development and demonstration (RD&D) and international engagement actions.

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.

Lithium

Mid-stream processing step	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
MINING & BENEFICIATION				
EXTRACTIVE METALLURGY (Lithium hydroxide, carbonate, and metal)			• 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.			
				• 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.			
	• Chlorination roasting	• Salt roasting		
	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.			
		• Acid and alkali leaching	• Acid and alkali leaching	
	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.			
		• Lithium metal production	• Lithium metal production	
	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.			
INTERMEDIATES AND ADVANCED MATERIALS (CAM and electrolytes)	• CAM (hydro- and solvothermal, combustion)		• CAM (spray-based)	• CAM (sol gel, solid state, coprecipitation)
	CAM synthesis is globally mature and represents a near term opportunity for Australia to value-add. Given Australia's R&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.			
		• Solid electrolytes	• Solid electrolytes • Liquid electrolytes	• Liquid 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 LiPF6 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.			
MANUFACTURING (components, cells)				

CAM, cathode active material; LiPF6, lithium hexafluorophosphate.

Cobalt

<table>
<tr><th>Mid-stream processing step</th><th>Establish new capability in emerging technologies</th><th>Accelerate emerging technologies and grow Australian IP</th><th>Pilot and scale up Australian IP</th><th>Support commercial deployment of mature technologies</th></tr>
<tr><td>MINING & BENEFICIATION</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="16">EXTRACTIVE METALLURGY
(MHP, MSP, cobalt sulphate, cobalt metal, pCAM)</td><td></td><td></td><td></td><td>• Roasting
• Smelting</td></tr>
<tr><td colspan="4">Roasting and smelting will likely continue to be relevant in Australia given existing domestic sulphide deposits, however its use for laterites is less prevalent. Australia's strong commercial and RD&D capabilities in this area can help improve sustainability, efficiency, and recovery rates to ensure continued activity into the future.</td></tr>
<tr><td></td><td></td><td></td><td>• Sulphuric acid (HPAL & AL)</td></tr>
<tr><td colspan="4">Sulphuric acid leaching methods are commonly used globally and in Australia to extract cobalt from sulphides and in particular laterites. However, sulphide ore grades are declining making them more difficult to leach, and laterite operations are costly to operate (high pressure acid leaching [HPAL]). Australia's strong RD&D capabilities in this area can help address the prevailing challenges of HPAL, and the scale up of cost-effective alternatives that can treat a range of ore types (e.g. atmospheric leaching [AL]).</td></tr>
<tr><td></td><td></td><td>• Chlorine leaching</td><td>• Ammonia leaching
• Chlorine leaching</td></tr>
<tr><td colspan="4">Cobalt extraction through ammonia leaching and chlorine gas are globally mature methods, efficient and versatile in terms of feedstock. However, both processes face an uncertain future: chlorine gas faces high costs and safety risks, and the use of ammonia leaching has been declining in industry. Nevertheless, these technologies can play a role as part of Australia's technology portfolio given their usefulness.</td></tr>
<tr><td></td><td>• AL with alternative acids</td><td>• AL with alternative acids</td><td></td></tr>
<tr><td colspan="4">Leaching with alternative acids has strong potential to improve environmental and cost outcomes compared with incumbent sulphuric acid processes, and to effectively leach cobalt from complex ore types. Given Australia's research capabilities, IP and existing pilot projects, there is an opportunity to continue progressing emerging options beyond the laboratory, as well as demonstrating and scaling-up Australian technologies.</td></tr>
<tr><td>• Bioleaching (laterite ores)</td><td></td><td></td><td>• Bioleaching (sulphide ores)</td></tr>
<tr><td colspan="4">Bioleaching can play a unique role in Australia's technology mix due to its ability to extract cobalt from low-grade sulphide ores and waste streams relatively cost-effectively and sustainably. However, RD&D is required to overcome technical challenges to scale-up.</td></tr>
<tr><td></td><td></td><td>• Precipitation
• Solvent extraction
• Ion exchange</td><td>• Precipitation
• Solvent extraction</td></tr>
<tr><td colspan="4">Separation and purification are key to producing cobalt intermediates (mixed hydroxide precipitate and mixed sulphide precipitate) and may provide a cost-effective pathway to the direct production of pCAM. Further, it is a requirement for downstream production of refined cobalt sulphate and cobalt metal. Australia has the capability to build upon its existing commercial activity in mixed precipitates and solvent extraction, while piloting and scaling-up novel Australian technology.</td></tr>
<tr><td>• Emerging crystallisation (eutectic freeze, antisolvent, membranes)</td><td></td><td></td><td>• Mature crystallisation (evaporative, cooling, reactive)</td></tr>
<tr><td colspan="4">Crystallisation is the final step to produce battery grade cobalt sulphate, and although many crystallisation methods are commercially mature, there are emerging technologies that could improve throughput, enhance control over end product characteristics, and increase energy efficiency In the near term, Australia can leverage its existing commercial capability producing similar products (e.g. nickel sulphate), while strong research capabilities can help deliver innovative improvements longer term.</td></tr>
<tr><td></td><td></td><td></td><td>• Cobalt metal (electrowinning)
• Cobalt metal (hydrogen reduction)</td></tr>
<tr><td colspan="4">Australia already produces cobalt metal, a versatile product that can be sold into multiple end markets, including the LIB market. The dominant ways of producing it, hydrogen reduction and electrowinning, have strong potential for renewable energy integration. Continued RD&D in this area can further drive the sustainability and productivity of the process, ensuring Australia's competitiveness in the long term.</td></tr>
<tr><td>INTERMEDIATES AND ADVANCED MATERIALS</td><td colspan="4">See CAM (Lithium)</td></tr>
<tr><td>MANUFACTURING
(components, cells)</td><td colspan="4"></td></tr>
</table>

MHP, mixed hydroxide precipitate; MSP, mixed sulphide precipitate; pCAM, precursor cathode active material; HPAL, high pressure acid leaching; AL, atmospheric leaching.

Graphite

Mid-stream processing step	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
MINING				
INTERMEDIATES AND ADVANCED MATERIALS (graphite anode materials, composite anode materials)				• Micronisation and spheronisation
	Micronisation and spheronisation technology is mature globally and off the-shelf equipment is accessible to Australian industry. Continued collaborations with equipment suppliers, and strong engagement with overseas battery OEMs will be key to growing onshore production.			
			• Alkali roasting • Alkali-acid method • Chlorination roasting • High temperature method	• High temperature method
	Diversifying graphite purification outside of China will require the development hydrofluoric (HF) acid-free methods due to its high risks, and Australia is well positioned to do so with strong RD&D and patent output to support piloting and scale-up.			
				• Coating processes
	There are significant barriers to entering the C-SPG market because coating technology is highly subject to trade secrets; however, there is an opportunity to develop formulations and coating methods in collaboration with international partners.			
		• Silicon-graphite compound materials	• Silicon-graphite compound materials	
	Australia has several active companies and research institutions working towards next generation silicon-graphite composite anodes. There is an opportunity to demonstrate Australian silicon-graphite anode materials in battery applications and pilot their production at scale, and to continue to develop novel compositions with increased performance.			
MANUFACTURING (components, cells)				

OEMs, original equipment manufacturer; C-SPG, coated spherical purified graphite.

LIB Recycling

Mid-stream processing step	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
END-OF-LIFE LIB WASTE				
RECYCLING (High purity metals, high purity graphite, electrolyte)				• Discharging
	Discharging technology will become increasingly important as EV uptake increases, and as LIB waste poses increasing safety risks across Australia's recycling system. Given the availability of off the shelf discharging equipment, there is an opportunity for Australia to implement discharging systems across the LIB recycling industry, while addressing key barriers such as standards and regulations.			
			• Dismantling and separation	• Dismantling and separation
	There is an opportunity to improve upon existing separation technologies used in Australian battery crushing and shredding operations. This can increase the quality and price of black mass product and facilitate improved extraction of materials in downstream processing.			
		• Graphite regeneration • Electrolyte recovery		
	Graphite regeneration and electrolyte recovery is emerging and gaining interest globally; Australia can leverage its RD&D leadership in this area to drive greater circularity and value recovery in domestic and global battery supply chains.			
		• Electrochemical metal recovery	• Pyro-and hydro-metallurgical metal recovery	• Pyro-and hydro-metallurgical metal recovery
	The recovery of high value metals using hydro- and pyrometallurgical techniques is commercial overseas, and global RD&D momentum continues to improve upon this technology. Given Australia's patent activity in this space, there is an opportunity to demonstrate Australian IP overseas or alongside emerging domestic battery plants.			
	• Bio-hydrometallurgy • Direct recycling			
	Direct recycling of cathode materials and biohydrometallurgy are emerging technologies that can provide step change improvements in battery recycling. Capabilities are nascent globally and in Australia and can be built through RD&D international collaboration.			
MANUFACTURING (components, cells)				

LIB, lithium-ion battery.

Rare earths

Mid-stream processing step	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
MINING & BENEFICIATION				
EXTRACTIVE METALLURGY (mixed rare earth compounds, separated rare earth oxides)			• Sulphuric acid roasting and baking	• Sulphuric acid roasting and baking
	Although sulphuric acid roasting or baking is globally mature and commercially used in Australia, it is still receiving substantial RD&D activity to improve the process. Australia's industry know-how and existing IP in sulphuric acid roasting and baking represents an opportunity to pilot Australian patents and to expand onshore commercial scale projects, with the support of international engagement.			
				• Alkaline baking
	Alkaline baking (also referred to as caustic digestion) has the potential to improve sustainability and cost outcomes but requires high grade monazite ores. Despite limited commercial applications globally, Australia may have the ore grades suitable for this process. The role of domestic RD&D is to assess the economic and technical viability of this process on Australian deposits, and if applicable, expand industrial know-how.			
	• Salt roasting • Chlorination roasting			
	Salt roasting and new approaches to chlorination are emerging extraction alternatives that have potential to bring about step change efficiencies compared with current processes. However global and Australian capabilities are nascent and will require a long-term RD&D effort and international collaboration to progress technology readiness and build capability.			
		• Desorption leaching (clay hosted deposits)		
	Extraction of rare earths from clay-hosted deposits is a strategic priority for Australia and many domestic operations have started to progress beyond exploration. RD&D will be essential to enhance understanding of Australian clays, identify suitable extraction mechanisms, compare process configurations and costs, and provide test work to support commercial pilots.			
				• Solvent extraction
	Solvent extraction is a commercially proven process widely used to produce separated RE oxides. Australia possesses industry know-how and companies are planning commercial operations onshore. The role of RD&D will be to continue supporting the development of domestic commercial projects through process validation and test work, and the expansion of industry skills. Similar to other mature areas, establishing large-scale plants will require engagement with overseas vendors.			
	• Membrane separation • Adsorption	• Ion exchange • Membrane separation • Adsorption	• Ion exchange	
	Emerging separation applications have the potential to bring about improvements in product purity, sustainability or cost relative to incumbent processes. However, RD&D is needed to overcome scalability barriers. International RD&D collaboration with partner organisations can help advance technology readiness and build new capability.			
INTERMEDIATES AND ADVANCED MATERIALS (rare earth metals and alloys)			• Molten salt electrolysis (light rare earth metals)	• Molten salt electrolysis (light rare earth metals)
	Molten salt electrolysis is mature globally and used commercially to produce light RE metals. Australian companies hold patents in this area and have deployed facilities overseas. There is an opportunity to pilot and demonstrate Australian IP domestically. Alternatively, Australia may consider engaging with overseas RE metal producers that have proven processes to establish commercial-scale projects onshore.			
		• Metallothermic reduction (heavy rare earth metals)	• Metallothermic reduction (heavy rare earth metals)	
	Metallothermic reduction is a versatile technology and particularly relevant for producing heavy RE metals. Given commercial-scale production is limited to China, there is an opportunity for Australia to diversify global capabilities by adapting its metallothermic reduction IP to RE metals.			
				• Metal purification
	RE metal purification is mature globally and the equipment is available off-the-shelf from overseas manufacturers. No single purification technique can fulfil all product specifications, and a suite of technologies is required instead. Strong engagement with overseas magnet manufacturers will be needed to meet specifications for RE metals produced domestically.			
MANUFACTURING (rare earth magnets)				

REs, rare earth.

Silicon

Mid-stream processing step	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
MINING & BENEFICIATION				
EXTRACTIVE METALLURGY (silicon metal)				• Carbothermal reduction
	Commercial production of metallurgical grade silicon is globally mature but faces strong pressure to decarbonise. The continued operation and expansion of this industry in Australia will require emissions reductions and RD&D infrastructure and facilities, namely industrial testing facilities for carbothermal reduction of Australian quartz.			
	• Electrolytic reduction • Gas based reduction			• Metallothermic reduction
	Emerging approaches to reducing quartz and produce metallurgical silicon, such as electrolytic, metallothermic, hydrogen or gas-based reduction, have the potential to offer cost-effective carbon neutral alternatives to carbothermal reduction. Despite their longer development timeframes and higher investment risk, these cross-cutting reduction techniques have spillover applications across other minerals and RD&D focus on this capability could support the development of other supply chains.			
INTERMEDIATES AND ADVANCED MATERIALS (solar grade polysilicon)				• Chemical vapour deposition (e.g. Siemens process)
	Polysilicon production using chemical vapor deposition techniques are commercially mature and are either highly proprietary or subject to high levels of know-how that are not easily replicated. Strong collaboration with overseas equipment providers will be required to produce polysilicon commercially in Australia.			
				• Metallurgical refining
	Metallurgical refining of solar-grade silicon is mature and can be used in conjunction with, or instead of, conventional chemical vapour deposition (CVD) processes. As an alternative to CVD, this can potentially reduce barriers to entry into polysilicon production and holds potential sustainability benefits. However lower product purities carry important market and techno-economic considerations.			
MANUFACTURING (wafers, cells, modules)				
PV RECYCLING			• Delamination • Hydrometallurgical metal recovery	
	The global PV industry has been dominated by low-cost bulk and low-purity processes due to the challenging economics of PV recycling. Australia's growing PV waste stream and RD&D processes targeting greater recovery of high-quality materials could improve the viability of domestic projects. Given the global momentum in this research area and Australia's RD&D activity, there is an opportunity to pilot and demonstrate domestic IP.			

CVD, chemical vapour deposition; PV; photovoltaic.

To fully realise Australia's critical mineral potential, innovation will be essential, including the development and implementation of new processing technologies, and the adoption and improvement of existing ones. Achieving this will require active participation from every part of the critical minerals ecosystem: industry, research and government. By fostering innovation and collaboration, Australia can solidify its position as a global leader in critical mineral processing.

1 Introduction

The global shift towards a low-carbon economy is reliant upon renewable energy technologies that require critical minerals, resulting in growing demand and foreign investment in the sector.

The demand for energy transition minerals has doubled in the past 5 years to USD$320 billion, led by the exponential growth of electric vehicles (EVs) and the continued deployment of solar and wind energy.[7] Despite this, the sector faces considerable challenges including supply chain concentration; poor environmental, social and governance (ESG) records; and prohibitive barriers to entry, such as access to intellectual property (IP) or high capital costs. These obstacles underscore the need for research, development and demonstration (RD&D) that enhances innovation and fosters diverse and sustainable supply chains.

With a rich endowment of critical minerals and a strategic focus to build sovereign processing capabilities, Australia is poised to be at the forefront of the global energy transition.

As a reliable exporter of energy, coupled with world leading experience in resource extraction, there is a significant economic opportunity for Australia to provide the raw minerals central to the energy transition. To capture maximum value and move further down the supply chain, domestic capability in critical minerals processing is required.[8]

Robust RD&D investment and international collaboration are essential to drive innovation and ensure that Australia realises the opportunity of developing integrated supply chains.

As competition intensifies, it is particularly important to develop the technological advancements that will reshape global supply chains.[9] There are RD&D investment opportunities across the entire technology development cycle from applied research to near-commercial scale pilot plants. Beyond this, increased investment and collaboration with strategic international partners can progress Australia's downstream processing capability. This two-pronged approach will help catalyse the development of diverse, resilient, and sustainable global supply chains.

7 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>

8 DISR (2023) Critical Minerals Strategy 2023-2030. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/sites/default/files/2023-06/critical-minerals-strategy-2023-2030.pdf>

9 Edler et al. (2023). Technology sovereignty as an emerging frame for innovation policy. Defining rationales, ends and means. Research Policy 52(6), 104765.

1.1 Australia's strategic objectives

Australia's *Critical Minerals Strategy 2023–2030*[10] has outlined four key objectives that relate to all critical minerals:

- Create diverse, resilient and sustainable supply chains through strong and secure international partnerships.
- Build sovereign capability in critical minerals processing (including recycling and reprocessing materials).
- Use our critical minerals to help become a renewable energy superpower.
- Extract more value onshore from our resources – creating jobs and economic opportunity, including for regional and Aboriginal and Torres Strait Islander communities.

Further, Australia has outlined critical technologies in the national interest in its *Critical Technologies Statement*.[11] Several of the technologies on the priority list rely on critical minerals, including batteries and battery components, rare earth (RE) permanent magnets, semiconductors for micro-chips and solar photovoltaic (PV). Australia's *National Battery Strategy* also highlights critical mineral processing as key objective and integral to national battery manufacturing and global supply chain diversification.[12]

Strategic objectives relating to mid-stream processing priorities in specific minerals or energy technology supply chains have been articulated in several national and state level reports (Figure 7).

Figure 7: Key Australian reports communicating mid-stream processing objectives.

FBICRC, Future Battery Industries Cooperative Research Centre; NSW, New South Wales; NT, Northern Territory; QLD, Queensland; WA, Western Australia.

10 DISR (2023) Critical Minerals Strategy 2023-2030. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/sites/default/files/2023-06/critical-minerals-strategy-2023-2030.pdf>

11 DISR (2023) Critical Technologies Statement. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/publications/critical-technologies-statement>

12 DISR (2024) National Battery Strategy. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/publications/national-battery-strategy>

1.2 The role of domestic RD&D and international collaboration

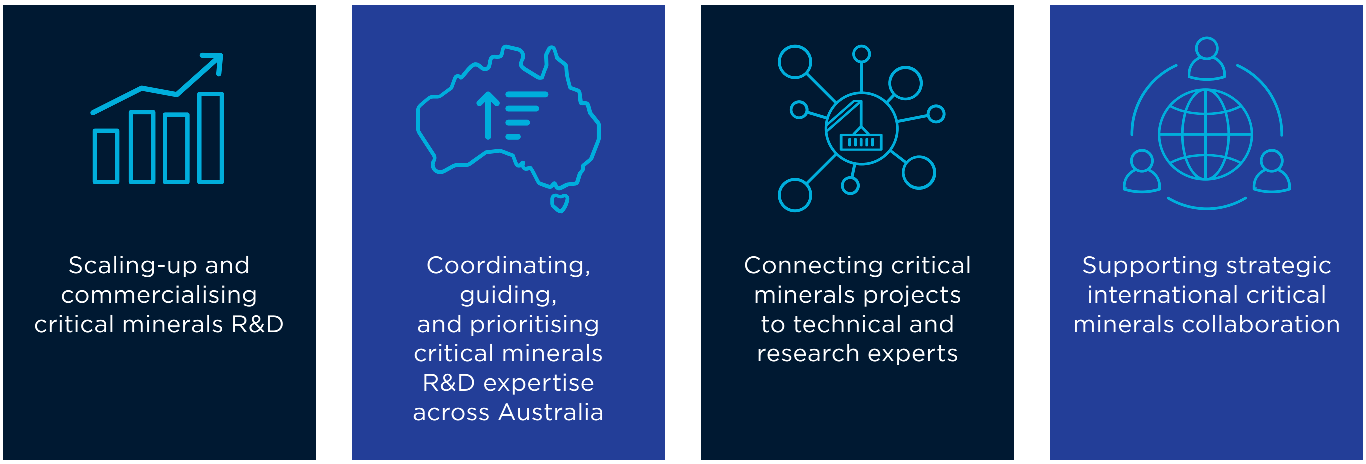
RD&D will play a vital role in enabling Australia's strategic objectives, alongside policy and commercial action. RD&D can support the expansion of Australia's developing value-adding sector and enable new activities along the critical minerals supply chain. In addition to positioning Australia as an additional supplier of critical minerals and materials, RD&D can also enhance Australia's competitiveness on a cost and sustainability basis by:

- Developing technology and processes in extractive metallurgy, chemicals refining and advanced materials production. Priorities include improvements to current technologies and the development of emerging alternatives, that drive reductions in costs, energy intensity, emissions intensity, chemicals intensity and waste.
- Development and optimisation of economically viable lithium-ion battery (LIB) and solar PV recycling technologies, including increasing the volumes and quality of critical materials recovered for improved circularity.
- Supporting the establishment of commercial operations onshore by strategically investing in cross-cutting mineral processing capabilities and RD&D infrastructure, and integrating research from adjacent fields (e.g. environment, scientific and economic modelling, traceability, safety and social license).

Collaboration between Australia and international supply chain partners is a key pillar of Australia's *Critical Minerals Strategy 2023–2030* and several other key strategy documents. Collaboration will be essential to enable the rapid development of diversified global critical minerals supply chains and value-added products. International collaboration on RD&D can accelerate progress by co-ordinating investment in mutually beneficial areas, avoiding duplication of RD&D efforts, and enhancing access to relevant IP and capabilities. Multilateral collaboration is also an opportunity for Australia to conduct science diplomacy, including facilitating science cooperation to improve international relations and inform and support decision-making in foreign and security policies.

To coordinate domestic RD&D and collaboration efforts, the Australian Critical Minerals Research and Development (R&D) Hub was launched. The Hub is hosted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in partnership with the Australian Nuclear Science and Technology Organisation (ANSTO) and Geoscience Australia (GA). The Hub's primary objective is to support clean energy and Australia's net zero policy agenda by addressing technical challenges and driving collaborative research across critical minerals supply chains from discovery to recovery (Figure 8).

Figure 8: Critical Minerals R&D Hub work streams.



1.3 Objectives, scope and approach

The primary goal of the *Critical Minerals RD&D Capability Assessment* is to assess Australia's RD&D capabilities across key critical minerals and provide guidance and information to government, industry and research decision-makers regarding RD&D investments and collaboration initiatives.

By providing a deep analysis into the technology landscape underpinning current and future mid-stream processing for renewable energy supply chains, this report series adds to existing Australian and international literature in this domain.

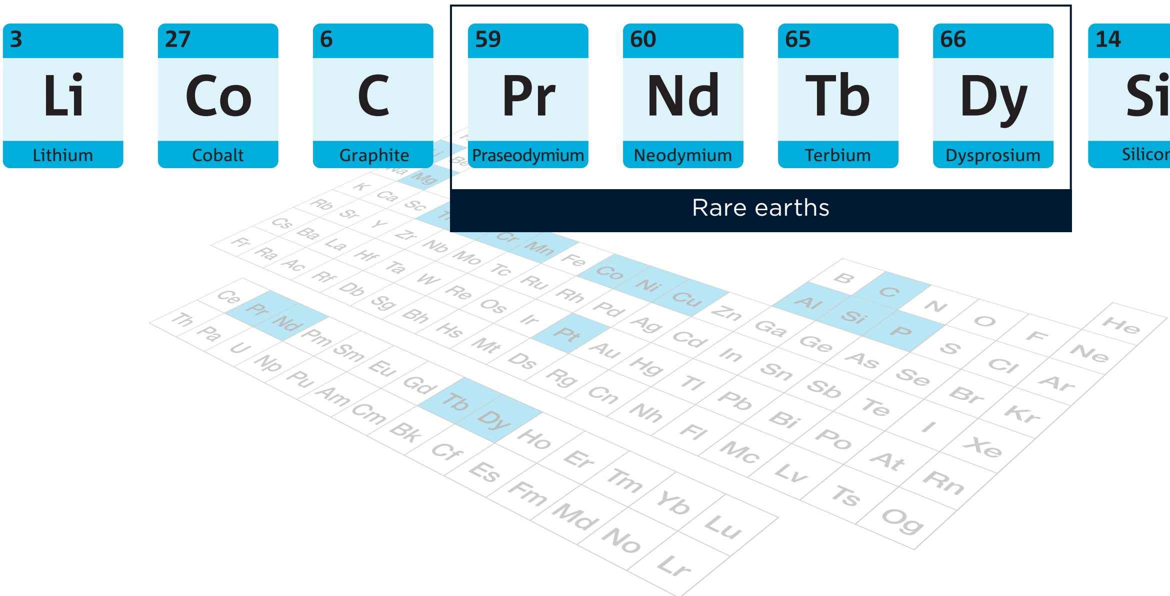
This effort aligns with Australia's objective to develop value-adding activities onshore, and international objectives to diversify the most highly concentrated portions of renewable energy supply chains.

The report series addresses the following objectives:

- Communicate key mid-stream processing technologies, mature and emerging, that will underpin the production of value-added products. This includes the production of intermediate products and advanced materials that are inputs into energy technology supply chains. Recycling of solar PV and LIBs is also included due to their importance and the overlapping capabilities with mid-stream processing.
- Showcase Australian capabilities across key technology areas, namely fundamental and applied research, IP development, and demonstrations.
- Summarise international capabilities across key technologies, and strategic objectives in upstream and downstream activities.
- Synthesise opportunities for Australia to grow domestic capability and to collaborate with international partners.

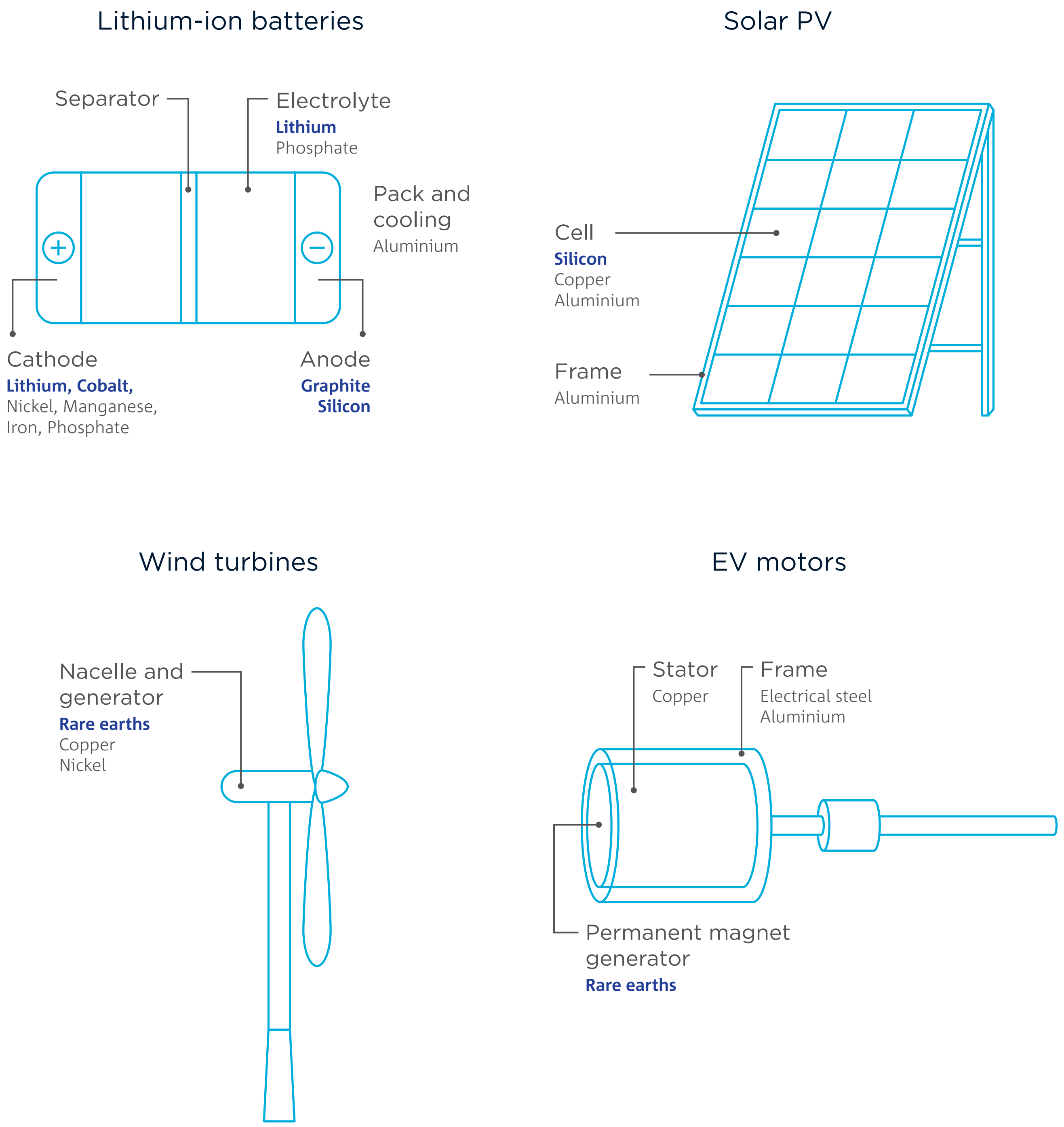
Five minerals have been selected for this analysis: lithium, cobalt, graphite, silicon, and REs (Figure 9). These were selected with input from stakeholder consultations and guided by criteria developed in the *2021 Critical Energy Minerals Roadmap*.[13] Their main uses in the energy transition are shown in Figure 10. The report series focuses on technologies that have either been demonstrated at laboratory, pilot or commercial scale to address both immediate needs, and long-term opportunities with cost and sustainability improvements.

Figure 9: Critical minerals in scope.



13 Bruce S, Delaval B, Moisi A, Ford J, West J, Loh J, Hayward J (2021) Critical energy minerals roadmap. CSIRO, Australia.

Figure 10: Uses of in-scope critical minerals in renewable energy technologies.

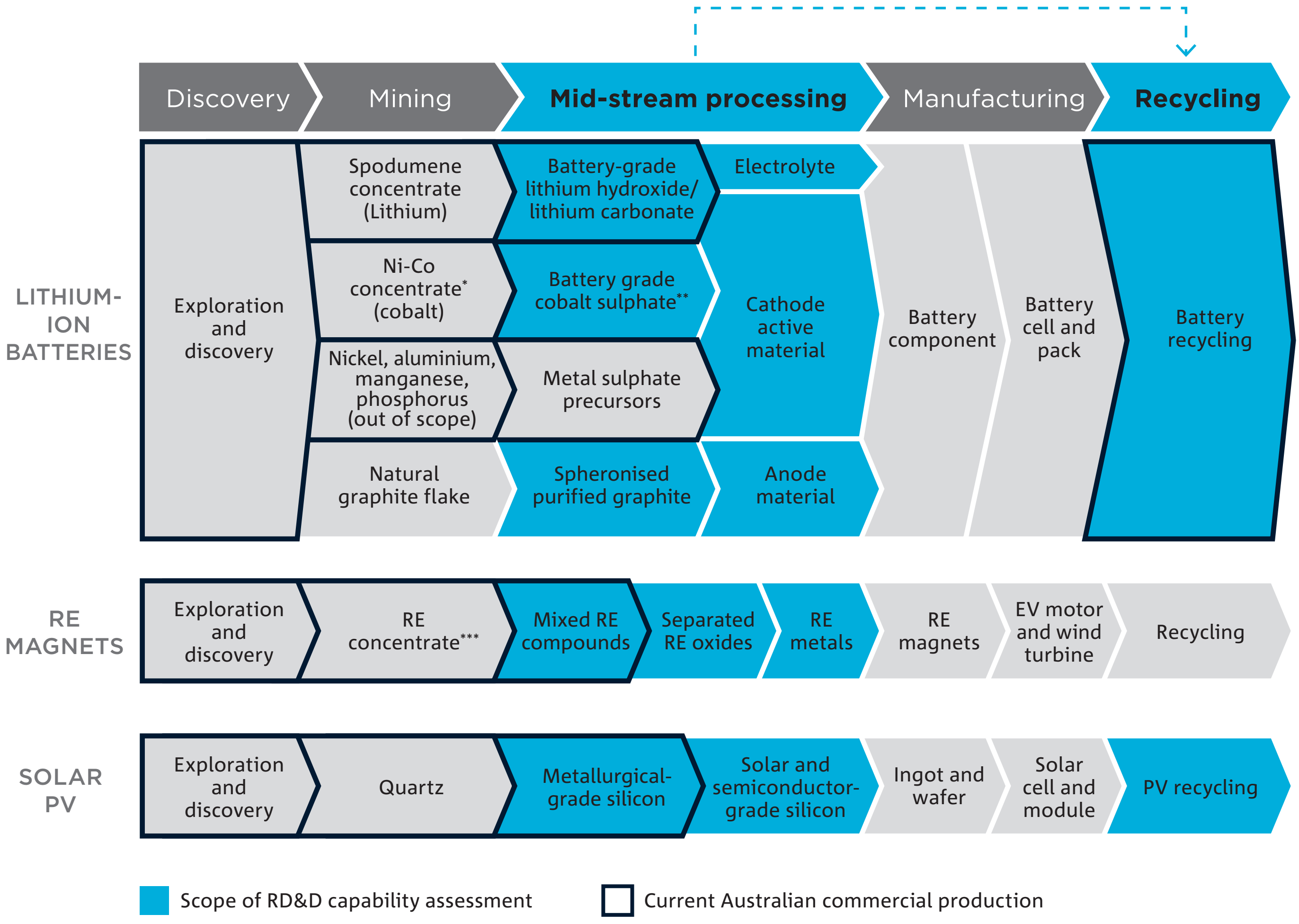


Critical minerals included in report scope

EV, electric vehicle; PV, photovoltaic.

The scope of mid-stream processes covered in this report series (Figure 11) includes the first two steps of mid-stream processing; the extraction of ores from Australia's mineral deposits, and value adding into materials, chemicals or alloys for the energy transition. Mid-stream processing capabilities are highly relevant for the extraction of critical minerals from waste streams, as such recycling is also covered for solar PV and LIBs.

Figure 11: Scope of critical minerals RD&D capability assessment.



* Concentrate contains cobalt and nickel and can contain other metals depending on deposit type (e.g. copper and platinum group elements).

** Australia currently produces cobalt metal and mixed precipitate intermediates.

*** Concentrate is only applicable to hard rock deposits. Clay-hosted is leached and sold as mixed rare earth compounds.

EV, electric vehicle; Co, Cobalt; Ni, Nickel; PV, photovoltaic; RE, rare earth.

Australia's capabilities span different stages of technology development from basic research to deployment at commercial scale. As a result, the analysis draws on three different indicators to assess Australia's activity; research publications, patents, and pilot projects (Figure 12) Consultations with government, research and industry stakeholders provided additional insight into and built consensus around key challenges and opportunities.

Actions for domestic RD&D and international collaboration

There are several considerations that come into play when identifying opportunities for RD&D investment and international collaboration. As such a framework has been developed based on the strength of Australia's RD&D activity and global technology maturity to synthesise key actions for each mineral. The concluding actions will be covered in *Section 5*.

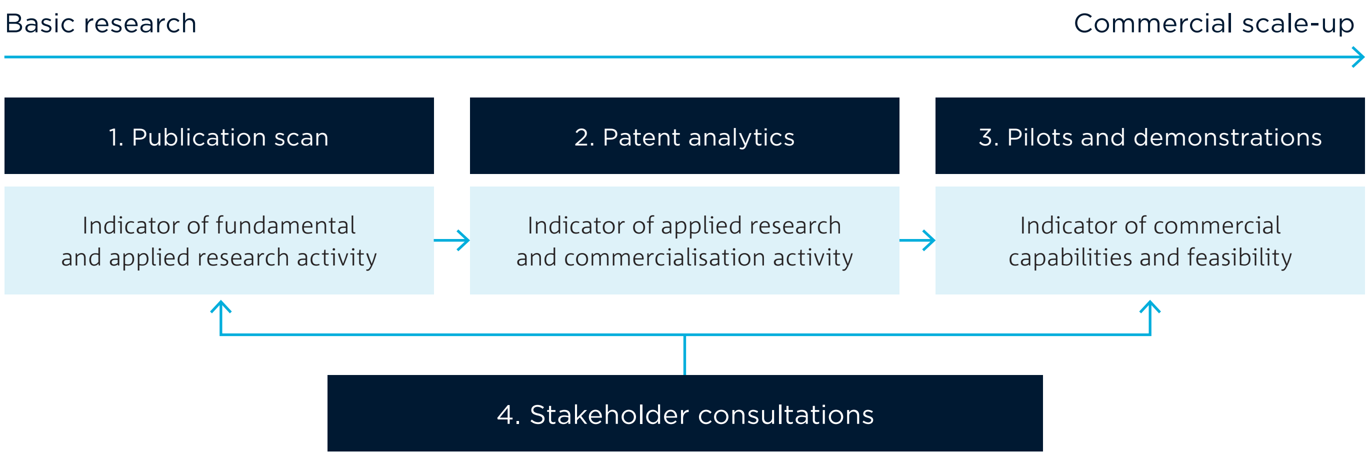
RD&D activity

Australian RD&D activity in a given technology, as measured by the level of publications, patents, and demonstration projects, is an indicator of Australia's RD&D strengths. RD&D investment in areas that leverage Australia's strengths can lead to growth in domestic IP or demonstrations of Australian technology. Areas with lower domestic activity may indicate the need for Australia to collaborate internationally to grow its RD&D capabilities or adopt mature technologies from overseas.

Technology maturity

Technology maturity can be used not only to assess whether a technology is ready to deploy commercially in the near term, but also to indicate whether there are opportunities for Australia to innovate. For highly mature technologies, the IP landscape may be highly saturated and it may be appropriate to adopt technologies from overseas (via licensing or foreign direct investment). Conversely a technology with lower maturity or with strong growth in global RD&D activity indicates an opportunity for innovation.

Figure 12: Approach to identifying capabilities, challenges and opportunities.



Actions for Australian RD&D and international collaboration, based on Australian activity and technology maturity, are synthesised into four categories as detailed below.

Support commercial deployment of mature technologies

Technologies in this category are commercially mature globally. Australia may already have industrial know-how and conducted commercial testing. In some cases, Australia may have significant RD&D activity (e.g. cobalt extraction) but in many cases Australia has comparatively low levels of research and patent activity and may need to adopt mature technologies from overseas.

There is potential to apply mature technologies on Australian feedstocks or to use them to produce innovative materials. The role of domestic RD&D is to support the commercial deployment of mature technologies by supporting plant optimisation, conducting cross-cutting RD&D (see *Section 3*) and supporting the expansion of industry know-how.

When adopting overseas technologies, the role of RD&D is to assess the technical and economic viability of integrating technologies into the Australian context. In these cases, expanding onshore activities will require strategic commercial collaborations and multilateral engagement. Examples include procuring off-the-shelf technologies from overseas technology developers, licensing patents, commissioning engineering services for large-scale plants, attracting foreign direct investment, and establishing relationships with offtakers.

Pilot and scale up Australian technology

Technologies in this category are characterised by strong Australian RD&D capability, coupled with high global maturity. There is an opportunity for Australia to demonstrate its IP at pilot and commercial scales.

International engagement with downstream offtakers will be required to de-risk domestic projects and to ensure offtaker product specifications are met. Alternatively, international engagement can enable demonstration and deployment of Australian technologies in offshore jurisdictions.

Accelerate emerging technology and grow Australian IP

In this technology category, Australia has shown strong research activity across its universities and research agencies. Given the emergence of this technology and the global momentum in RD&D activity, there is room to innovate. There is an opportunity to leverage Australia's strengths, grow domestic IP and progress technologies beyond the laboratory.

Long-term collaborations with industry, government, or research partners overseas may be beneficial to support sustained efforts on strategically important processing technologies. This includes co-funded or joint projects or with industry, government or research partners in mutually beneficial areas.

Establish new capability in emerging technologies

Technologies in this category are emerging globally, and capabilities are nascent both in Australia and internationally. These technologies have the potential to bring about step changes in sustainability and cost, or may provide solutions that are not currently met by incumbent technologies. There is an opportunity for Australia to grow its capability through RD&D, in order to realise longer-horizon objectives.

International collaboration in this area targets knowledge sharing, capability building and joint global RD&D projects between leading research institutions.

Other considerations

Additional considerations can be used to prioritise Australia's RD&D and collaboration efforts. This report series does not prioritise technologies but includes the following three considerations to inform decision makers.

- **Supply chain concentration:** All minerals supply chains discussed in this report series face a significant level of supply chain concentration in mid-stream processing. For some aspects and minerals, the concentration is higher than for others. This is a factor that should be considered in RD&D priority setting and is discussed in *Section 3.*
- **Vertical integration**: The decision to invest in technologies must also take into consideration the order in which a supply chain should be vertically integrated, from bottom up or top down. Individual supply chain steps cannot be deployed in isolation, but rather, should connect with existing domestic activities.

2 Australia's RD&D capabilities

Understanding Australia's RD&D capabilities across critical minerals processing is essential to support decision-making on integrating domestic and international supply chains. It provides a foundational understanding of where Australia can leverage its RD&D strengths, and areas that warrant further attention for capability building or international collaboration. Communicating Australia's mid-stream processing capabilities and showcasing active research and industry organisations can facilitate the development of a domestic stakeholder network. Importantly, it provides international organisations and governments with a greater understanding of the Australian landscape and its strengths.

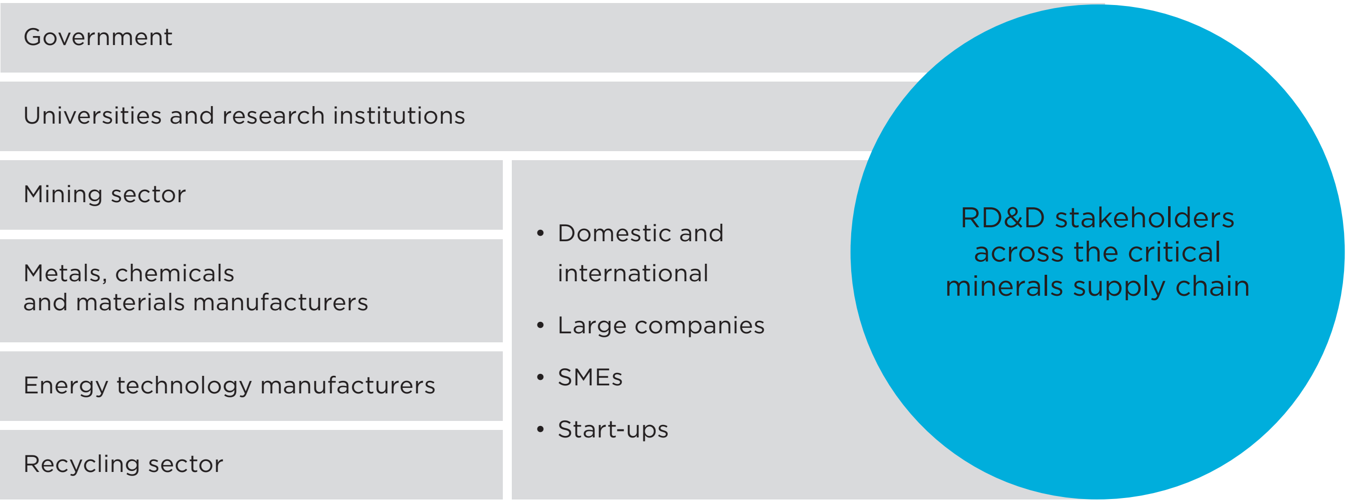
This section provides an overview of the key organisations in Australia's critical minerals RD&D ecosystem and an overview of R&D infrastructure and facilities. It also includes a summary of Australia's strengths in terms of RD&D activity in mineral processing activities across different parts of the innovation cycle. For more detailed information on Australian activity across each mineral processing technology, refer to the supplementary mineral reports on lithium, cobalt, graphite, LIB recycling, REs and silicon.

Australia’s RD&D ecosystem

Australia has a strong RD&D ecosystem made up of diverse stakeholders (Figure 13). This includes organisations that are active across different parts of the supply chain (e.g. extraction of metals and high purity compounds from primary sources or end-of-life waste, and the production of intermediates and advanced materials used in renewable energy technologies). It also includes organisations that are active at different stages of innovation, from applied research through to near-commercial demonstrations of Australian technologies (Figure 14).

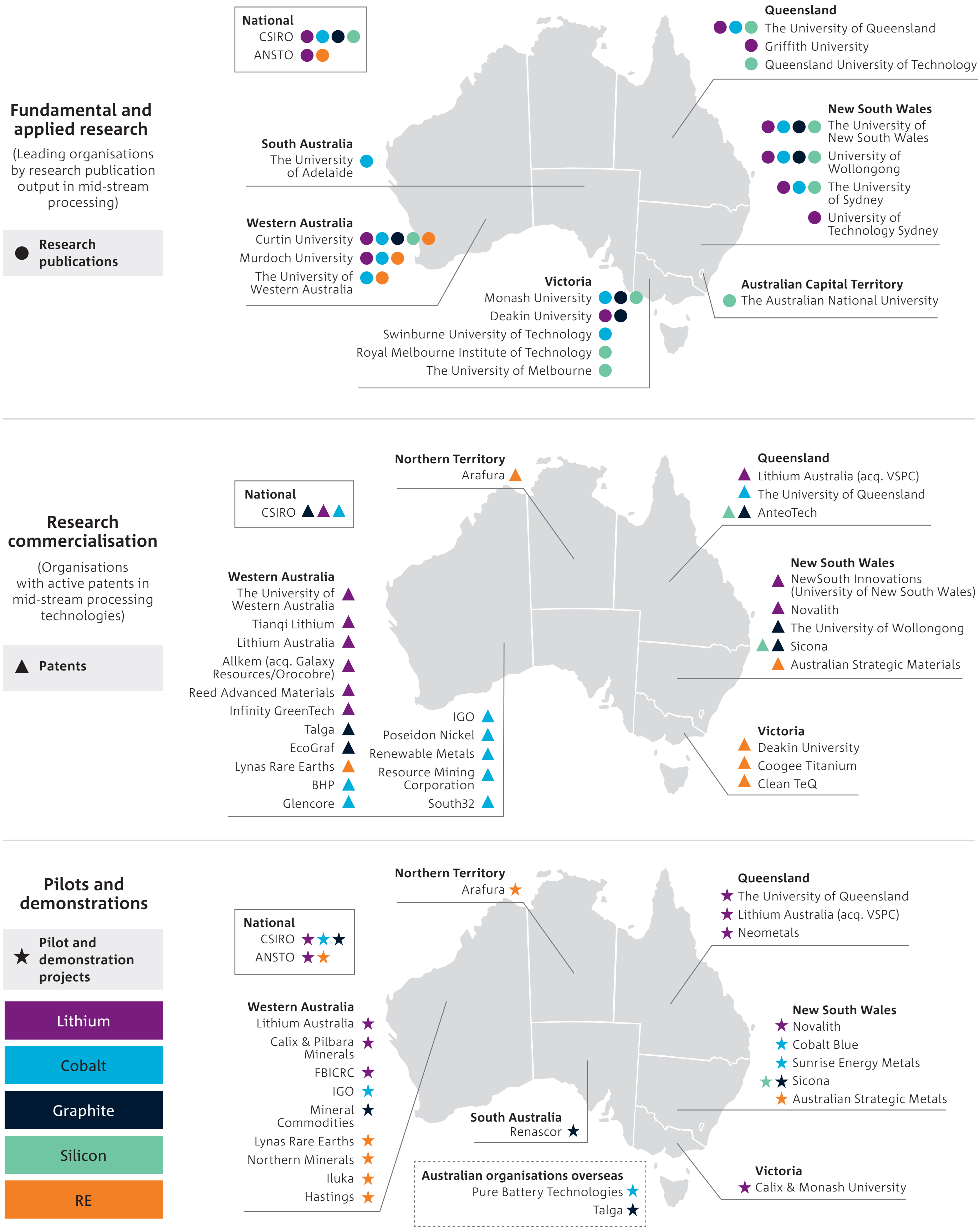
The establishment of new value-adding activities onshore requires strong collaboration between government, industry and research. This will ensure that the right policy settings and commercial enablers are in place to support technology deployment and a thriving industry.

Figure 13: Critical minerals research, development and demonstration (RD&D) ecosystem.



SMEs, small and medium enterprises.

Figure 14: Snapshot of critical minerals research, development and demonstration (RD&D) active organisations in Australia.[14]



Acq., acquired

14 Accuracy of the research publication and patent data is 70% or above. Only institutions with over 5 research publications were included in this diagram.

RD&D infrastructure and facilities

RD&D infrastructure and facilities, such as laboratories and shared user facilities can help reduce barriers for innovators and accelerate technology development. Many facilities of this type are being developed or already exist in Australia, including:

Table 1: RD&D infrastructure

RD&D INFRASTRUCTURE	DESCRIPTION
Queensland Resources Common User Facility	Located in Townsville, this will be a government-owned infrastructure for piloting critical mineral processing pathways at scale. It will provide training and generate and assess commercial end-products. The facility will be initially focussed on vanadium, with a planned start for operations in 2025, and could grow to include cobalt and REs in the future.[15]
Future Industries Hub FlexiLab	A planned common use facility in Queensland announced at the beginning of 2024, where industry will be able to test and demonstrate processing pathways for critical minerals including cobalt, silica, and REs.[16] The FlexiLab will complement the Queensland Resources Common User Facility.
ANSTO process development facilities	The national nuclear science and technology organisation offers process development services across lithium, REs, and other strategic metals, supported by pilot facilities for key pyro- and hydrometallurgical technologies.[17]
CSIRO Mineral Resources	The national science agency provides access to expertise and RD&D facilities for the processing of multiple critical minerals, from different locations throughout Australia. Capabilities are available to both research and industry, covering supply chain activities from discovery and exploration to refining and advanced manufacturing.[18]
Australian National Fabrication Facility (ANFF)	The ANFF is an Australia-wide network of research facilities that provides customers in industry and academia with access to micro- and nanofabrication capabilities, which are relevant to battery and energy storage applications.[19]
Melbourne Centre for Nanofabrication (MCN)	Part of the ANFF, the MCN is an advanced fabrication facility that provides access to equipment and expertise for material production, characterisation and testing. The MCN is a joint venture between CSIRO and several Victorian universities.[20]

15 Queensland Treasury (2023) Queensland resources common user facility. Queensland Government. <https://www.treasury.qld.gov.au/investment/investment-growth-stories/qrcuf/>

16 Stewart S (2024) Future of critical mineral processing unveiled in Mackay. Queensland Government. <https://statements.qld.gov.au/statements/99608>; The University of Queensland, Sustainable Minerals Institute (2024) State-of-the-art critical mineral processing plant concept unveiled. <https://smi.uq.edu.au/article/2024/02/state-art-critical-mineral-processing-plant-concept-unveiled>

17 ANSTO (2024) Capabilities. Services – Resources sector. <https://www.ansto.gov.au/services/resources-sector/minerals/consultancy/capabilities#content-facilities>; ANSTO (n.d.) Piloting Operations. <https://www.ansto.gov.au/sites/default/files/2019-12/Minerals%20Piloting%20Operations%20Capability%20Statement%20Dec19.pdf>

18 CSIRO (n.d.) Mining and resources. <https://www.csiro.au/en/work-with-us/industries/mining-resources>; CSIRO (n.d.) Manufacturing. <https://www.csiro.au/en/work-with-us/industries/manufacturing>; CSIRO (n.d.) Use our labs and facilities. <https://www.csiro.au/en/work-with-us/use-our-labs-facilities?start=0&count=6&tags=&content={CA271066-4B44-4736-A2F0-45642F877115}>

19 Australian National Fabrication Facility (ANFF) (2023) About ANFF. https://anff.org.au/about/; ANFF (2023) ANFF materials node. <https://anff.org.au/locations/materials-node/>

20 Melbourne Centre for Nanofabrication (n.d.) About us. https://nanomelbourne.com/about-us/; ANFF (2023) ANFF Victoria. <https://anff.org.au/locations/vic-node/>

Finally, there are several cross-cutting and collaborative programs of work within Australia that can also help accelerate development by bringing together Australia's best experts, streamlining investment and preventing duplicative efforts. Some of Australia's programs are listed below:

Table 2: Collaborative programs

COLLABORATIVE PROGRAMS	DESCRIPTION
Future Battery Industries Cooperative Research Centre (FBICRC)	Awarded a grant of $25 million from 2018–2025, the FBICRC is an independent research centre with RD&D programs across the LIB supply chain, from lithium and cobalt extraction to the production of cathode active material (CAM), anode materials and battery recycling. The FBICRC is supported by a national-scale partnership of industry, government and academic institutions.[21]
Australian Research Council (ARC) Centre of Excellence for Enabling Eco-Efficient Beneficiation of Minerals (COEMinerals)	COEMinerals is a joint research centre formed by nine universities from across Australia that is focused on the development of innovative processes that enhance the efficacy and sustainability of mineral beneficiation, including for REs. The centre's themes revolve around early rejection of waste material, minimising metal losses during beneficiation and enhancing water recovery to minimise the need for tailings dams.[22]
Mineral Exploration Cooperative Research Centre (MinEx CRC)	Awarded a grant of $50 million from 2018–2028, MinEx CRC is a cooperative centre with participants from government, industry and research dedicated to technologies that can advance exploration and mining, particularly in drilling. This includes projects on technological improvement, data capture and mapping regional geology.[23]
Australian Research Council (ARC) Industrial Transformation Research Hubs and Industrial Transformation Training Centres	These funding schemes from the ARC support, respectively, research into new technologies in priority areas by organisations and university–industry research partnerships for postgraduate training.[24] For example, the ARC Training Centre for Battery Recycling is focused on novel recycling, reuse and redesign approaches for batteries in the Australian context. The centre is a collaboration between The University of Adelaide, University of New South Wales, the University of Wollongong, four companies and ANSTO.[25]
ARC Linkage Infrastructure, Equipment and Facilities (LIEF)	LIEF is an ARC funding scheme for organisations, particularly higher education–industry collaborations, to secure access to research equipment, infrastructure and facilities.[26]
Powering Australia Industry Growth Centre	Awarded $14 million over 4 years from 2022–23, the Powering Australia Industry Growth Centre will fund activities and provide services to: help businesses manufacture renewable energy technologies and commercialise local ideas; encourage connections between critical minerals producers and renewable technology manufacturers; deliver First Nations advisory services to build First Nations business management capabilities.

21 Future Battery Industries CRC (FBICRC) (2024) Projects. https://fbicrc.com.au/projects/; FBICRC (2024) Participants. <https://fbicrc.com.au/participants/>

22 COEMinerals (n.d.) About. <https://coeminerals.org.au/about>

23 MinEx CRC (2024) About. https://minexcrc.com.au/about/; MinEx CRC (2024) Research programs. <https://minexcrc.com.au/programs/>

24 Australian Research Council (ARC) (2022) Industrial transformation research hubs. <https://www.arc.gov.au/funding-research/funding-schemes/linkage-program/industrial-transformation-research-program/industrial-transformation-research-hubs>; ARC (2022) Industrial transformation training centres. <https://www.arc.gov.au/funding-research/funding-schemes/linkage-program/industrial-transformation-research-program/industrial-transformation-training-centres>

25 ARC (2023) Grant IC230100042 – The University of Adelaide. <https://dataportal.arc.gov.au/NCGP/Web/Grant/Grant/IC230100042>

26 ARC (2022) Linkage infrastructure, equipment and facilities (LIEF). <https://www.arc.gov.au/funding-research/funding-schemes/linkage-program/linkage-infrastructure-equipment-and-facilities>

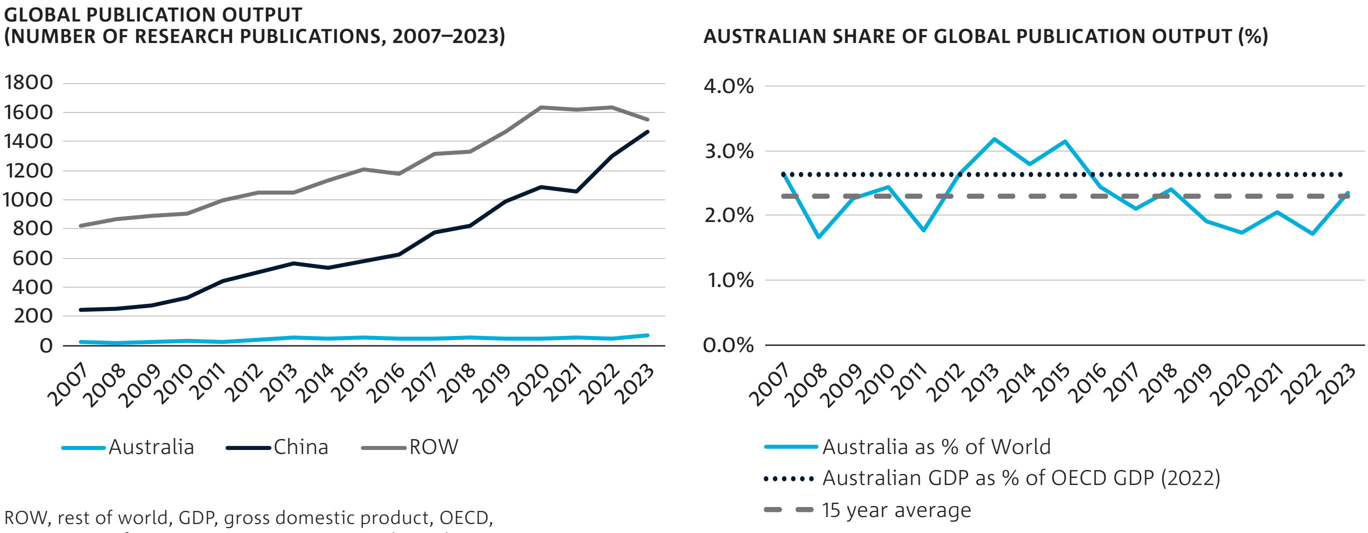
Research publications

Bibliometric data can be used as an indicator of activity in fundamental and applied research. Publications often cover emerging technologies that are at laboratory scale, or novel improvements in existing practices.

However, there are limitations to using publications as an indicator because they do not always reflect all the RD&D activities being undertaken at research institutions (e.g. research projects and pilots that don't involve academic publications).

Australia's research sector is highly active in terms of publication output, indicating strength in fundamental and applied research. On average, Australia's research publication output has been between 2% and 3% of global output (Figure 15). This is considered on par with the size of Australia's economy.[27]

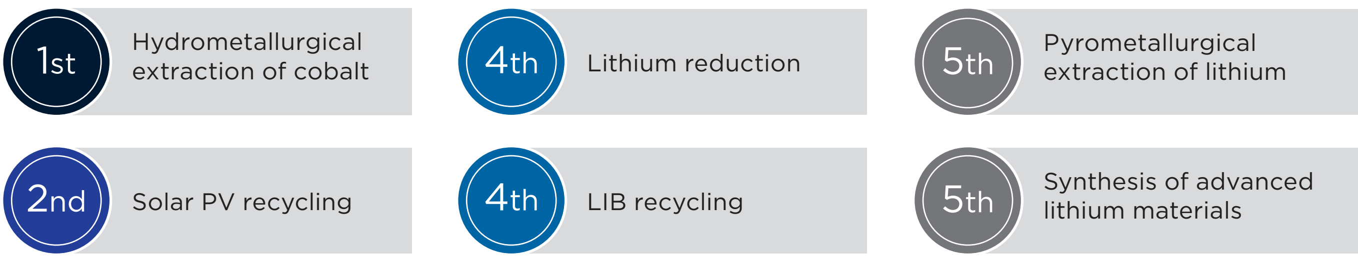
Figure 15: Output of research publications and patents in mid-stream processing of critical minerals.



ROW, rest of world, GDP, gross domestic product, OECD, Organisation for Economic Co-operation and Development.

A further breakdown shows that Australia is among the top countries in several areas related to cobalt, lithium and the extraction of critical materials from end-of-life waste (Figure 16).

Figure 16: Australia's research strengths as indicated by publication output (global ranking outside of China).



A detailed breakdown of Australian results and the methodology is available in Appendix B and C respectively. An explanation of the processing mentioned in this diagram can be found in *Section 5* and the series of supplementary mineral reports on lithium, cobalt, graphite, LIB recycling, REs and silicon.

27 The size of Australia's economy is measured against that of other Organisation for Economic Co-operation and Development (OECD) countries: Australia makes up roughly 3% of OECD gross domestic product; OECD (2024) Gross Domestic Product. OECD Data <https://data.oecd.org/gdp/gross-domestic-product-gdp.htm><https://data.oecd.org/gdp/gross-domestic-product-gdp.htm>

Patents

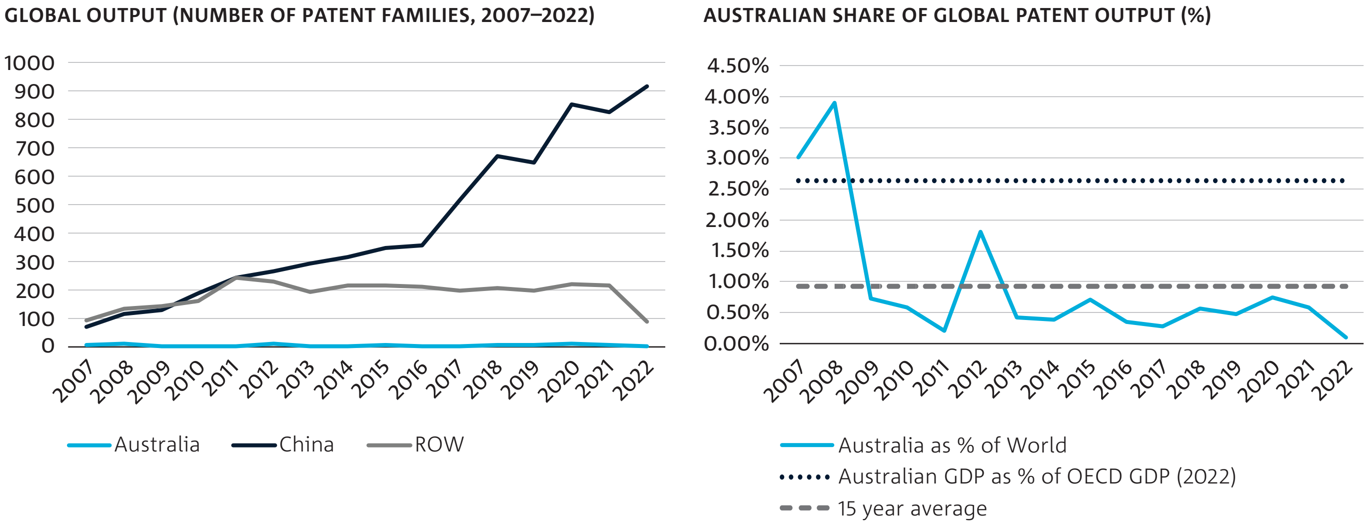
Patent data is a useful indicator of how innovation is being translated from the laboratory to commercial application. Recently patented technologies are usually emerging technologies or innovative improvements on existing technologies with potential for demonstration, scale up and commercialisation in the short to medium term.

However, there are limitations to using patents as an indicator. First, not all patents are commercially implemented and scaled up to industrial scale. As such, patent volumes can overstate potential industry outcomes. Second, the ratio of publication output to patent output is not always reflective of a country's ability to translate research into IP. IP also includes unpatented technologies (also known as trade secrets), which can lead to understating research impact.

As a proportion of global activity, Australia's share of patent output is lower than its share of research publications, indicating that research is not always translated into patents. Australia's patent output relative to the rest of the world, and relative to the size of the Australian economy is illustrated (Figure 17). This may suggest that attention to translating science and technology into industry outcomes will be important.

A further breakdown shows that Australia is among the top countries with patent activity across several areas in cobalt, lithium, graphite, and rare earth processing (Figure 18).

Figure 17: Global patents in extraction and advanced material manufacturing.*



ROW, rest of world, GDP, gross domestic product, OECD, Organisation for Economic Co-operation and Development.

*Includes lithium, cobalt, graphite, REs and silicon.

Figure 18: Australia's patent strengths as indicated by patent filing output (global ranking outside of China).

	Lithium	Cobalt	Graphite	REs
1st	• Calcination • Alkaline leaching	• Ion exchange separation and purification		
2nd	• Mature and emerging leaching methods (sulphuric and alternative acids) • Separation and purification • Production of lithium metal	• Mature and emerging leaching methods (sulphuric acid, ammonia, and other acids) • Solvent extraction separation and purification	• Purification	
3rd-5th	• Salt roasting • Spray-based CAM synthesis • Electrolyte recovery in LIB recycling	• Chloride leaching • Roasting and smelting • Crystallisation of cobalt sulphate	• Micronisation and spheronisation • Carbon coating	• Sulphuric acid roasting • Production of rare earth metals (molten salt electrolysis) • Separation of REs by chromatography • Purification of RE metals

CAM, cathode active material; LIB, lithium-ion battery; RE, rare earth.

A detailed breakdown of Australian results and the methodology is available in Appendix B and D respectively. An explanation of the processing mentioned in this diagram can be found in *Section 5* and the series of supplementary mineral reports on lithium, cobalt, graphite, LIB Recycling, RE and, silicon.

Australia’s RD&D strengths and areas to monitor

Australia’s RD&D activity in mid-stream processing varies by mineral and by the type of RD&D activity. This section provides a comprehensive snapshot of Australia’s RD&D strengths and areas that may require monitoring and consideration.

Figure 19 summarises Australia’s RD&D activity across two mid-stream processing steps that are central to Australia’s strategy to undertaking more onshore value-adding activity:

- **Extractive metallurgy:** The extraction and refining of high purity compounds and metals from raw or waste materials using hydrometallurgical, pyrometallurgical, or reduction techniques. This includes the production of lithium compounds and metal, cobalt compounds, mixed and separated RE compounds, and metallurgical grade silicon.
- **Intermediate products and advanced materials:** Further refining to produce intermediate products and synthesis of advanced materials. This includes the production of cathode active materials (CAM) containing lithium and cobalt, graphite anode materials, RE metals and alloys, and solar-grade polysilicon.

Australian activity has been assessed against three indicators: publications, patents, and pilot and commercial examples (see *Section 1.3* for more information on the approach).

- Australian technologies that are classified as ‘**very strong**’ or ‘**strong**’ are areas where Australia has high levels of RD&D activity relative to the size of its economy in the global context. These are areas where Australia can leverage its strengths to grow mid-stream processing onshore and make significant contributions to science diplomacy and international supply chains.
- For areas classified as **‘moderate**,’ Australia may possess a solid foundation of domestic activity, however this is on par or slightly lower than what one would expect for an economy the size of Australia. These areas may benefit from further monitoring on progress.
- ‘**Limited’** areas are areas where Australia has a very small share of publications or patent activity, or where no pilots or demonstrations have been completed onshore. These areas will require consideration on whether to start building capability domestically or whether to partner with countries that are comparatively strong in this area.

It should be noted that although many innovations start with research and progress through to patents, demonstrations, and commercial deployment, not all technologies must follow this pathway. For example, some industries may benefit from directly piloting mature state-of-the-art technology from overseas, rather than progressing solutions from the lab. Another caveat is that some technologies are no longer protected by IP restrictions and there may not be a strong reason for producing patents. In this case organisations may freely use the technology to build internal know-how and ‘trade secrets’, which is not easily tracked and reported.

Figure 19: Australia's research, development and demonstration (RD&D) strengths and areas to monitor.

*Extractive metallurgy does not apply to graphite (a non-metal).

See Appendix B for the data underlying this figure and the key technologies included. For the research publication analytics and patent analytics methodologies refer to Appendix C and D respectively.

LIB, lithium-ion battery; PV, photovoltaic.

The variance in publications, patents, and pilot/commercial activity between the extraction and advanced material and intermediate product segments can be, in part, explained by the current state of the Australian critical minerals industry. Traditionally, domestic activity has been concentrated in mining and/or the initial steps of mid-stream processing. This emphasis was reflected in the data, with the highest level of activity evident in extraction technologies that predominantly relate to value-adding processes occurring directly after mining operations (See Figure 19). Given that initial mid-stream processing steps are a nearer term opportunity and the first step to greater value-adding, RD&D activity has been more focused on these technologies to date.

There have also been substantial challenges for Australia and other mining countries to move further up into mid-stream processing for. Challenges include strong cost-competition from China, access to IP, internal know-how and trade secrets, the significant capital and RD&D investment required, and ESG considerations.

3 Global supply chains and international RD&D capabilities

Global supply chains are highly concentrated across all energy technology supply chains, particularly in mid-stream processing. Although the mining of raw materials occurs across many countries, and most raw materials are exported to China for further processing into value-added materials. Supply chain disruptions experienced during COVID-19, natural disasters and other global shocks have highlighted the importance of diversifying global supply chains to support the global energy transition.

The rationale for Australia to move into the mid-stream processing of critical materials stems from the growing demand from the global renewable energy sector,[28] the current concentration risk of global supply chains, and the opportunities to export sustainably produced materials. The opportunity for Australia to enter the market as a major supplier of critical minerals and value-added materials is time critical.

Australia cannot tackle this challenge in isolation, and despite the competitiveness of the mid-stream processing space, the establishment of domestic operations will require collaborative efforts. RD&D collaboration entails co-ordinating RD&D efforts and investment to streamline development, enhancing access to IP, knowhow and capabilities outside of concentrated locations where possible, and strengthening RD&D partnerships that aim to connect downstream with upstream activity.

This section provides an introduction to the LIB, solar PV and RE magnet supply chains and the mid-stream activities involved. Next, it illustrates the degree of global supply chain concentration in commercial production, and in the levels of RD&D activity across different parts of the value chain. Finally, it provides a high-level overview of key countries, and where IP and knowhow could support global diversification efforts.

28 Kim et al. (2022) The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency, Paris. <https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf>

3.1 Supply chain overview

3.1.1 The LIB supply chain: Lithium, cobalt and graphite

The LIB supply chain (Figure 20) begins with the exploration, discovery and mining of battery minerals. Examples include hard-rock lithium-bearing ores, sulphide and laterite deposits containing cobalt, and natural graphite deposits. The scope of this report series covers two mid-stream processing steps that come after mining.

The first step is extraction and involves extracting the metals or compounds of interest from the ore usually via a series of thermal and/or chemical processes:

- **Lithium:** The processing of lithium-bearing ores involves extracting lithium compounds, the key product being battery-grade lithium hydroxide or lithium carbonate. These lithium compounds may also be recovered from waste streams, including from mine waste or LIB waste.[29]
- **Cobalt:** The processing of sulphide and laterite ores containing cobalt begins with a thermal pretreatment step, followed by leaching to obtain a cobalt-rich solution or mixed precipitate product (mixed hydroxide precipitate [MHP] or mixed sulphide precipitate [MSP]). These compounds can be further separated, purified, crystallised or metallised into various products, such as cobalt sulphate or cobalt metal, which are used for precursor cathode active material (pCAM) production.
- **Graphite:** Natural flake graphite ores are mined and then undergo a series of beneficiation steps including milling, shaping, and purification to battery-grade levels with the key product being spheronised purified graphite (SPG).

Although not included in the scope, other critical battery minerals are also expected to face strong demand, including manganese, phosphorus, fluorine, and aluminium.

The next mid-stream processing step of the LIB supply chain is the production of precursor or advanced materials for battery cell components:

- **Lithium, cobalt and other metals:** pCAM is made from cobalt and other metals such as nickel and manganese (in the case of nickel–manganese–cobalt batteries).[30] Next, lithium is added in order to produce a final CAM product using a range of synthesis techniques.
- **Lithium:** Lithium is also used to make the battery electrolyte. Current generation LIBs use liquid lithium electrolytes which comprises a lithium salt (e.g., lithium hexafluorophosphate – $LiPF_6$) in a liquid medium. Lithium is also used to make solid electrolytes for next generation lithium metal batteries. The lithium may also be used to produce lithium metal, which is used as the anode of next generation lithium metal batteries, also known as solid-state batteries.
- **Graphite:** Current generation batteries use graphite anode materials, also known as coated spherical purified graphite (C-SPG). Here the shaped and purified graphite is typically coated in a carbon layer and/or a proprietary composition of additives. Proponents are also developing silicon-graphite composite materials to improve anode and battery cell performance.[31]

The final stages of the supply chain, not covered within the scope, encompass battery cell manufacture, battery pack assembly and end-product integration (e.g., into an EV). After reaching the end of its life, the battery can be re-used in second life applications or recycled.

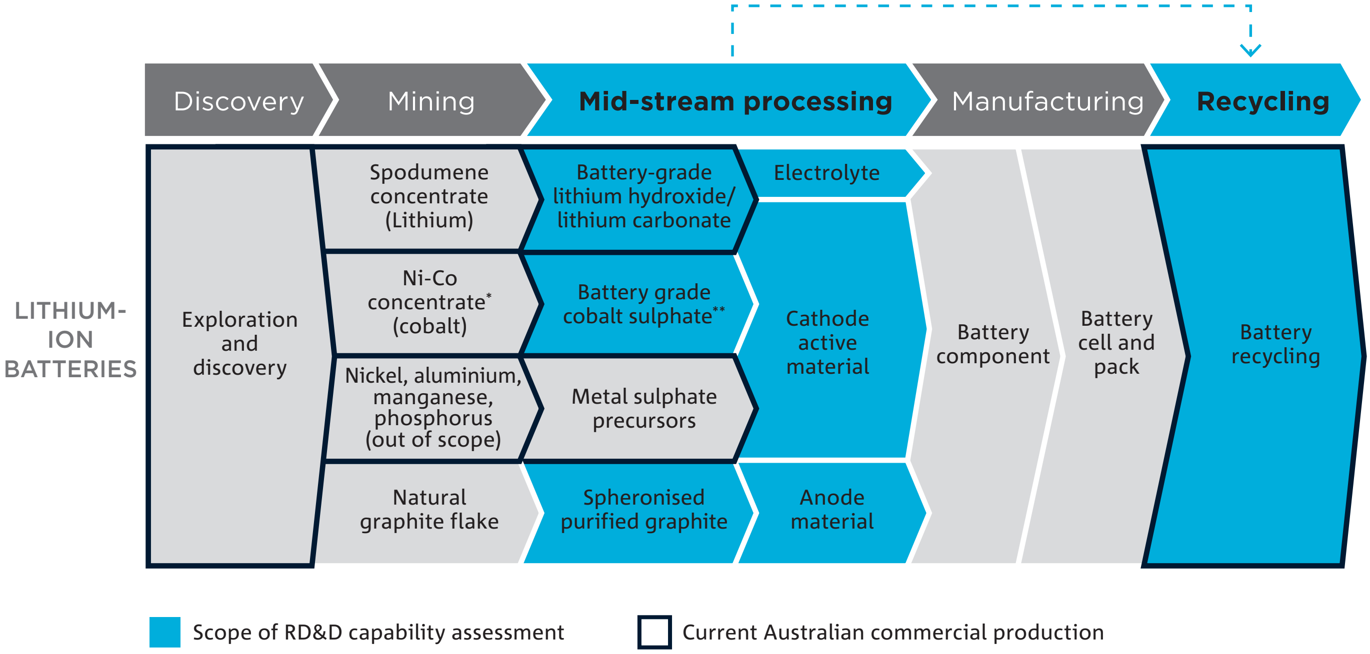
Section 5 describes in more detail the mature and emerging processing technologies for the two mid-stream processing steps and recycling. It also articulates key actions for Australian RD&D to expand and develop these areas domestically.

29 IEA (2021) The Role of Critical Minerals in Clean Energy Transitions. IEA, Paris. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>

30 Other battery chemistries like LFP (iron and phosphate) are not covered within the mineral scope of this report. The dominant battery chemistries for EVs include NMC, LFP, NCA, and LMO).

31 Moyassari E, Roth T, Kücher S, Chang C-C, Hou S-C, Spingler FB, Jossen A (2022) The Role of Silicon in Silicon-Graphite Composite Electrodes Regarding Specific Capacity, Cycle Stability, and Expansion. Journal of The Electrochemical Society 169(1), 010504.

Figure 20: Lithium-ion battery supply chain, scope and current commercial production in Australia.



*Concentrate contains cobalt and nickel and can contain other metals depending on deposit type (e.g. copper and platinum group elements).

**Australia currently produces cobalt metal and mixed precipitate intermediates.

Fremantle Ports, Western Australia

3.1.2 The rare earth magnet supply chain

RE magnets are used in a variety of applications including wind turbines and EV motors, and the supply chain begins with the exploration, discovery and mining stages. RE containing deposits found in Australia include carbonatites (e.g. Mt Weld), mineral sand deposits containing monazite and xenotime, and ion-adsorption clay deposits.[32] The scope of this report series covers the two mid-stream processing steps that follow the extraction of the ore or host sediment (Figure 21).

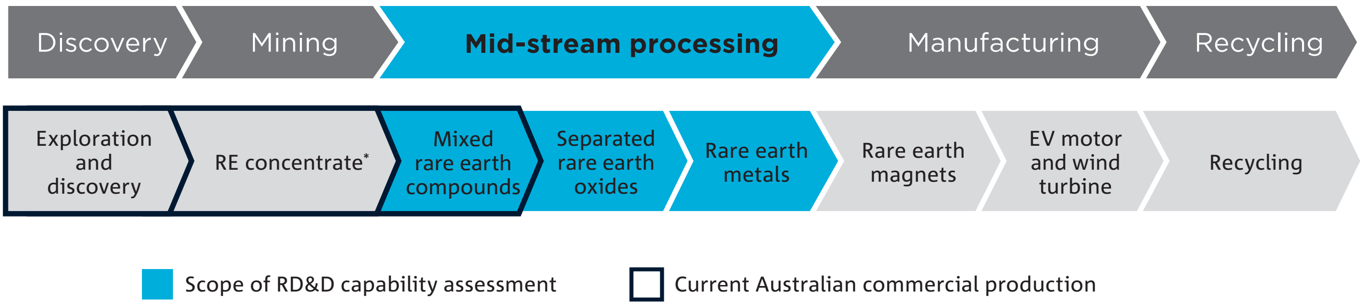
In the first mid-stream processing step, mixed RE compounds are extracted from hard rock ores or from clay hosted deposits found in Australia.[33] This usually involves a series of thermal and/or chemical steps. Extraction from hard rock ores (e.g. monazite and xenotime) generally follows a different process than that of extraction from clay-hosted deposits.

The next mid-stream processing step involves separating the mixed RE compounds into individual RE oxide products.[34] These can then be further refined into RE metals or alloys.

The downstream portion of the supply chain involves the manufacturing of permanent magnets from RE metals or alloys, then wind turbines and EV motors, and finally, use and recycling at end-of-life.[35]

Section 5 describes in more detail the mature and emerging processing technologies for the two mid-stream processing steps and recycling. It also articulates key actions for Australian RD&D to expand and develop these areas domestically.

Figure 21: Rare earth (RE) magnet supply chain, scope and current commercial production in Australia.



*Concentrate is only applicable to hard rock deposits. Clay-hosted is leached and sold as mixed rare earth compounds.

EV, electric vehicle; RD&D, research, development and demonstration; RE, rare earth element.

32 Liu et al. (2023) Global rare earth elements projects: New developments and supply chains. Ore Geology Reviews 157, 105428. <https://www.sciencedirect.com/science/article/pii/S0169136823001439>; Geoscience Australia (2023) Rare Earth Elements. <https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/rare-earth-elements>; Mineral Research Institute of Western Australia (2023) Characterisation of clay-hosted rare-earth element deposits in Western Australia. <https://www.mriwa.wa.gov.au/research-projects/project-portfolio/characterisation-of-clay-hosted-rare-earth-element-deposits-in-western-australia/>

33 Bruce et al. (2021) Critical energy minerals roadmap. CSIRO, Australia, Australia.

34 Bruce et al. (2021) Critical energy minerals roadmap. CSIRO, Australia, Australia.

35 Bruce et al. (2021) Critical energy minerals roadmap. CSIRO, Australia, Australia.

3.1.3 The solar PV supply chain: Silicon

The global solar PV supply chain begins with the exploration, discovery and mining of silica quartz. Although silica is the most abundant resource globally (e.g. sand), hard rock silica quartz deposits are not as common in nature and are important for the production of solar- and semiconductor-grade silicon (polysilicon).[36] The purity of the hard rock silica quartz is not as critical for the production of metallurgical silicon (eventually purified to solar and semiconductor-grade silicon). However, very-high-purity quartz is required for crucibles, which are a component used to manufacture polysilicon ingots (crucible production is out of scope). The scope of this report series covers the first two mid-stream processing steps that come after quartz mining and beneficiation (see Figure 22).

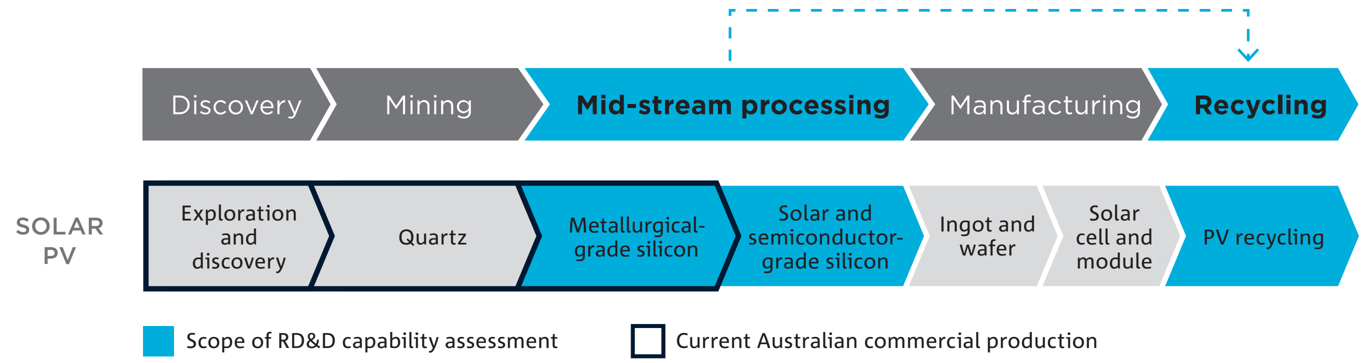
The first mid-stream processing step is the production of metallurgical-grade silicon. Once mined, silica quartz is carbothermically reduced to produce metallurgical-grade silicon. This product is a feedstock into polysilicon production, but is also used in other markets, for example in the chemicals and battery market (for silicon–graphite anodes).

The second mid-stream processing step is the production of solar or semiconductor-grade polysilicon. Here, the metallurgical-grade silicon is purified, usually by a chemical vapour deposition process (e.g. the Siemens process).

The downstream portion of these steps includes the manufacturing of ingots and wafers, solar cells and modules and then finally, recycling.

Section 5 describes in more detail the mature and emerging processing technologies for the two mid-stream processing steps and recycling. It also articulates key actions for Australian RD&D to expand and develop these areas domestically.

Figure 22: Solar photovoltaic supply chain, scope and current commercial production in Australia.



36 Geoscience Australia (2024) Critical minerals and their uses. <https://www.ga.gov.au/scientific-topics/minerals/critical-minerals/critical-minerals-and-their-uses>; Golev A (2024) Silica sand in focus: Abundant yet critical? Geoscience Queensland Open Data Portal. <https://geoscience.data.qld.gov.au/blog/silica-sand-focus-abundant-yet-critical>

3.2 International RD&D engagement to support supply chain diversification

Global supply chain concentration is a significant risk to the global energy transition and to energy security, in light of disruptions such as COVID-19 and natural disasters. By extending its activity into mid-stream processing, Australia can position itself as a supply chain diversification partner.

LIB, RE magnets and solar PV face the challenge of geographical concentration across the majority of their supply chains (Figure 23); however, concentration is particularly strong in the mid-stream processing portion.

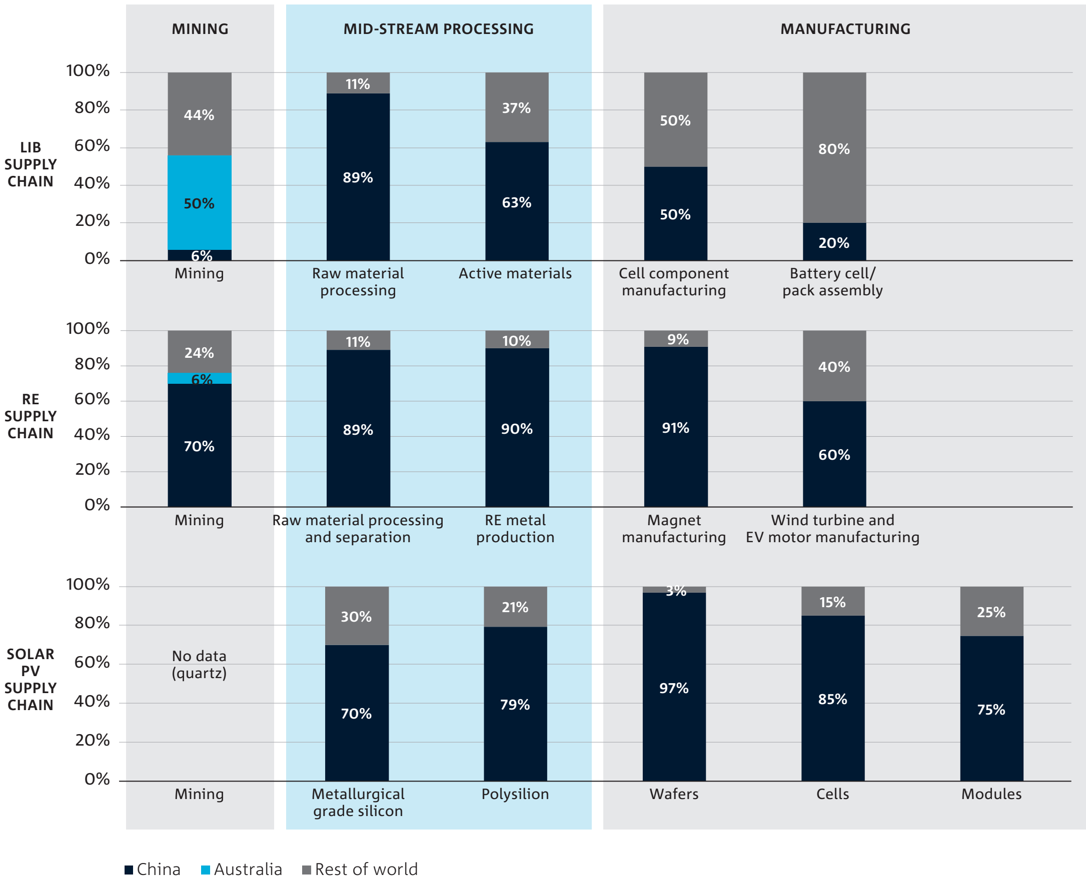
Mining activity faces moderate levels of concentration with operations for lithium, cobalt, REs and graphite taking place in a small number of countries.[37] Conversely hard rock quartz (for silicon) is relatively abundant, however limited data exists on its global mine production.[38]

Once mined, a large proportion of raw materials are shipped to China for mid-stream processing. Only in a few cases do mid-stream extractive processes occur in the country of origin. Some of the reasons for this are high barriers to entry (e.g. high capital expenditure and access to IP or capabilities), price volatility, and the environmental risks of energy or chemically intensive processes. These barriers are particularly salient for RE supply chains where knowledge and skills outside of China are very limited, and social license concerns exist around managing radioactivity.

Downstream manufacturing activity for LIBs, solar PV and rare earth magnets is comparatively less concentrated than mid-stream processing. Here China exports a portion of its intermediate products and advanced materials to countries that manufacture components and energy technologies. One exception is the wafer fabrication step of the silicon supply chain, which is the most highly concentrated part of the supply chain and is typically vertically integrated with polysilicon production.

With respect to recycling, a large portion of global LIB waste is sent to China to recover high value materials and metals (e.g. lithium and cobalt). High value metal recovery from solar PV (other than bulk materials) and RE products is an emerging area, therefore data has not been included in Figure 23.

Figure 23: Global supply chain concentration across the LIB, solar PV and RE supply chains.



Note where Australian production is not shown where it is below 1% of global.

Adapted from USGS (2023) Mineral Commodity Summaries, January 2023; IEA (2022) Executive summary of special report on solar PV global supply chains; BCG (2023) Five Steps for Solving the Rare-Earth Metals Shortage; US DOE (2022) Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment; Accenture (2021) Future Charge: Building Australia's Battery Industries, FBICRC

37 USGS data typically reports on silica sands, ferrosilicon and metallurgical silicon; U.S. Geological Survey (2023) Mineral commodity summaries 2023: U.S. Geological Survey, USGS, Reston, Virginia, USA. <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf>

38 USGS data typically reports on silica sands, ferrosilicon and metallurgical silicon; U.S. Geological Survey (2023) Mineral commodity summaries 2023: U.S. Geological Survey, USGS, Reston, Virginia, USA. <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf>

Although research activity is diversified globally, patent commercialisation in mid-stream processing remains highly concentrated.

Global research publications stemming from universities and public research institutes have followed an upward trend over the last 15 years and remain relatively diversified globally (Figure 24). However, over the last 15 years there has been a substantial increase in the quantity of patents from China, whereas patent activity across the rest of the world has remained relatively stable, even experiencing a drop in 2022 (Figure 25). This may indicate that the translation of research to commercial outcomes is a global challenge not unique to Australia.

It should be noted that while China has substantial innovation activity, subsidies and grants may have had a distortionary impact on the number of patent applications.[39] Reforms to IP incentives, with the goal of promoting high-impact patents, are expected to be implemented in China by 2025.[40]

Figure 24: Global research publication output in critical minerals (2007–2023).

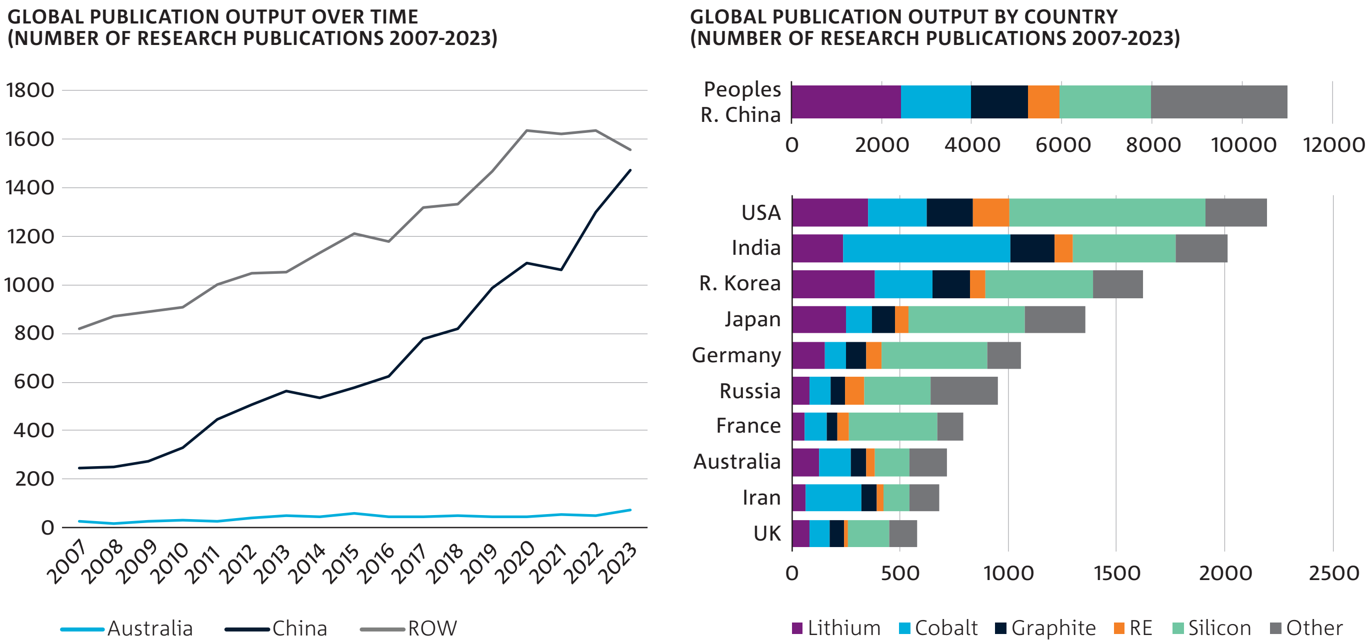
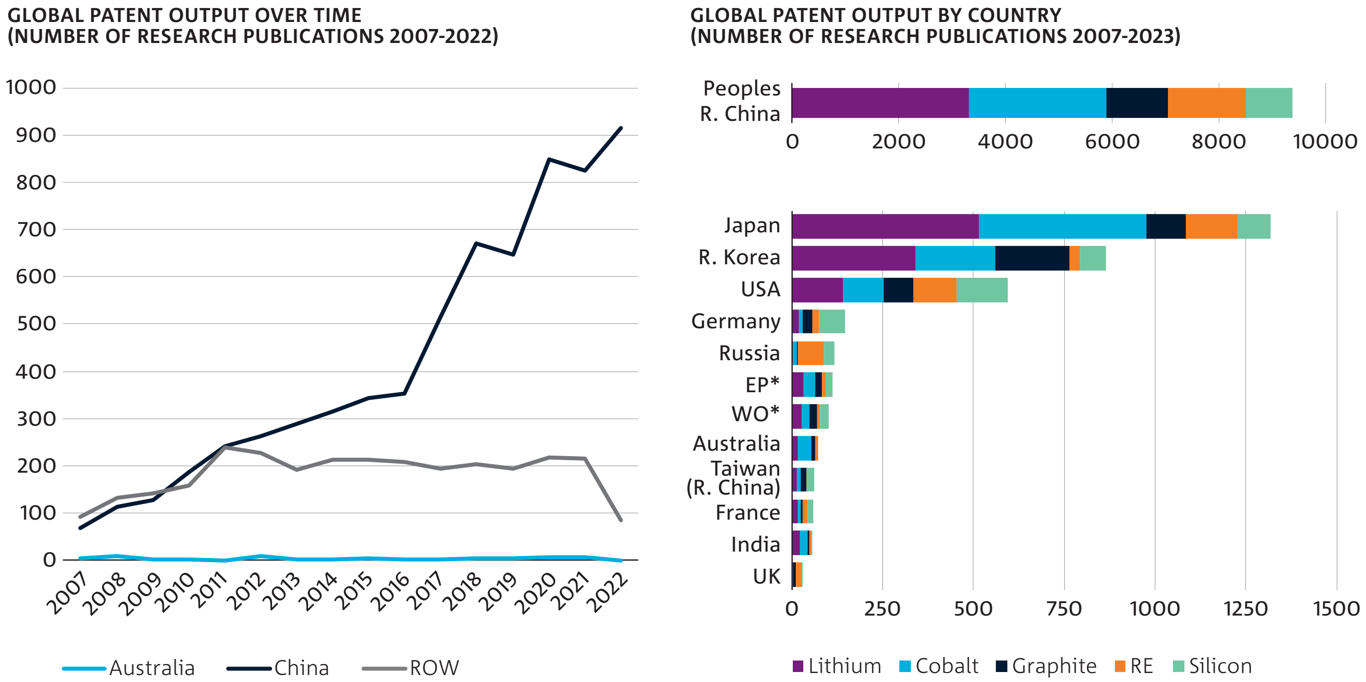


Figure 25: Global patent output in critical minerals (2007–2022).



ROW, Rest of world; WO, World Intellectual Property Organisation; EP, European Patent Office.
A deeper breakdown of international capabilities at the processing technology level is provided within the supplementary mineral reports on lithium, cobalt, graphite, LIB recycling, REs and silicon. Appendices D and E details the methodology.

39 Wininger A (2023) Shenzen proposes ending patent grant subsidies two years early. China IP Law Update. <https://www.chinaiplawupdate.com/2023/10/shenzhen-proposes-ending-patent-grant-subsidies-two-years-early/>

40 Wininger A (2023) Shenzen proposes ending patent grant subsidies two years early. China IP Law Update. <https://www.chinaiplawupdate.com/2023/10/shenzhen-proposes-ending-patent-grant-subsidies-two-years-early/>

Nevertheless RD&D can underpin the development of diversified supply chains by enhancing access to IP and capabilities. Australia can contribute to, and gain from, international RD&D engagement.

Australia has much to contribute to international diversification, with world leading expertise across several minerals (see *Section 2*). However, Australia's economy makes up less than 3% of the Organisation for Economic Co-operation and Development (OECD), and therefore Australia may have limited capacity to undertake RD&D across all priority areas and all critical minerals in isolation.[41] Furthermore, areas where Australia's capabilities are less developed will require engagement with key international supply chain partners.

International collaboration by stakeholders across the ecosystem will take on several forms and be interrelated; multilateral collaboration at government levels, research collaborations to share knowledge and accelerate technology readiness, and commercial engagement with overseas technology providers or product offtakers.

Australia's future role in international renewable energy technology supply chains, and opportunities to engage internationally will depend on the current upstream and downstream activity of partner countries, as well as their RD&D capabilities and priorities.

Despite concentration in commercial production and RD&D activity, several key countries have existing commercial plants, or hold patents in, the production of value-added materials, which could support the expansion of diversified mid-stream processing.

Many countries have detailed their strategic priorities with respect to upstream manufacturing of energy technologies, including the US, Japan, Korea, India, France, Germany, the UK and Canada. Countries with large mining sectors also have comprehensive mining strategies, including Australia and Canada. These key countries have communicated a general priority to support mid-stream processing or made large investments in the area (see Appendix E for public international documents and announcements). However, most have yet to develop specific priorities for mid-stream processing, both at a product or processing technology level.

Despite the high degree of global supply chain concentration (Figure 23), several countries have existing mid-stream production capacity despite not making up a significant portion of global market share. Importantly, several countries hold patents in the production of key mid-stream materials even if they are not currently producing at commercial levels. Table 3, Table 4 and Table 5 illustrate areas with existing production or existing patents across 10 key countries with respect to LIB, RE and Solar PV supply chains. It should be noted that this is a point-in-time assessment and subject to rapid change.

There is an opportunity to leverage international patents and capabilities to support diversification particularly in areas where there are gaps in mid-stream processing, or in areas where production is currently insufficient to mitigate supply chain risk. For Australia, there is an opportunity to contribute to global diversification efforts particularly in areas where Australia has a small existing industry, or strong levels of domestic IP that could underpin domestic projects. International collaboration will be key to secure project financing or offtake agreements, or for Australian innovators seeking to establish plants internationally.

In areas where Australia has limited levels of IP or industry know-how, international collaboration can help overcome access to IP or industrial capabilities. Several countries hold patents but are seeking attractive jurisdictions to set up mid-stream processing plants for economic reasons. Several countries have signalled intent to support companies establishing plants in upstream jurisdictions such as Australia. Australia may also be able to license overseas IP or establish joint ventures, to deploy domestic operations.

41 OECD (2024) Gross Domestic Product. OECD Data <https://data.oecd.org/gdp/gross-domestic-product-gdp.htm>

Table 3: LIB supply chain, current production and patents.

	MINING			LITHIUM AND/OR COBALT COMPOUNDS	ADVANCED MATERIALS			BATTERY CELL AND/OR PACK	RECYCLING*
				SCOPE OF PATENT ANALYSIS	SCOPE OF PATENT ANALYSIS	SCOPE OF PATENT ANALYSIS	SCOPE OF PATENT ANALYSIS		
	LITHIUM	COBALT	GRAPHITE (NATURAL OR SYNTHETIC)		CAM	ANODE MATERIAL	ELECTRO-LYTES		
China	■	■	■	■ ●	■ ●	■ ●	■ ●	■	■ ●
USA	■	■	■	■ ●	■ ●	■ ●	■ ●	■	■ ●
Canada	■	■	■	■ ●	●	●	●	■	●
Australia	■	■		■ ●	●	●		■	●
Japan			■	■	■ ●	■ ●	■ ●	■	■ ●
R. Korea			■	■ ●	■ ●	■ ●	■ ●	■	■ ●
Germany			■	■ ●	■ ●	●	■ ●	■	■ ●
France			■	■	●	■ ●	■ ●	■	■ ●
India			■	■	●	●		■	■ ●
UK				●		●		■	●

■ Commercial scale production (in country).
● Patents / potential to contribute IP for global supply chain diversification efforts.
CAM, cathode active materials. *End-to-end recycling including high value metal recovery from black mass.
See Appendix E for the reference documents underlying this table, and Appendix D for the patent analytics methodology.

Table 4: RE supply chain, current production and patents.

	MINING	MIXED RE COMPOUNDS	SEPARATED RE OXIDES	RE METALS	MAGNET MANUFACTURING	WIND TURBINE AND EV MOTOR MANUFACTURING	MAGNET RECYCLING
		SCOPE OF PATENT ANALYSIS	SCOPE OF PATENT ANALYSIS	SCOPE OF PATENT ANALYSIS			
China	■	■ ●	■ ●	■ ●	■	■	■
Australia	■	■ ●	●	●			
India	■	■	■ ●	●		■	
USA	■	■ ●	■ ●	●	■	■	■
Japan		●	■ ●	■ ●	■	■	■
UK		●	●	■ ●	■	■	■
R. Korea			●	■ ●	■	■	
Germany			●	●	■	■	■
France		●	●	●		■	
Canada						■	■

■ Commercial scale production (in country).
● Patents / potential to contribute IP for global supply chain diversification efforts.
EV, electric vehicle; RE, rare earth. See Appendix E for the reference documents underlying this table, and Appendix D for the patent analytics methodology.

Table 5: Solar PV current production and patents.

	MINING	METALLURGICAL-GRADE SILICON	POLYSILICON	INGOTS/WAFERS	CELLS AND/OR MODULES	RECYCLING*
		SCOPE OF PATENT ANALYSIS	SCOPE OF PATENT ANALYSIS			
China	■	■ ●	■ ●	■	■	■ ●
USA	■	■ ●	■ ●		■	■ ●
Germany	■	■ ●	■ ●	■	■	■ ●
Australia	■	■			■	
Canada	■	■			■	
France	■	■	●	■	■	■ ●
India	■			■	■	●
Japan	■	●	■ ● **	**	■	■ ●
R. Korea	■	●	■ ● **	**	■	●
UK	■				■	

■ Commercial scale production (in country).
● Patents / potential to contribute IP for global supply chain diversification efforts.
*End-to-end recycling including delamination and the recovery of silicon and silver. **Production is focused on the electronics semiconductor industry.
See Appendix E for the reference documents underlying this table, and Appendix D for the patent analytics methodology.

More detail on specific processing technologies and the relevant countries and organisations with patents and capabilities in these areas, see the supplementary mineral reports on lithium, cobalt, graphite, LIB recycling, REs and silicon.

4 Underpinning RD&D priorities across supply chains

Several key RD&D themes exist across all five critical minerals assessed in this project, as well as other critical and strategic minerals. These themes encapsulate the collective insights gained through extensive consultation with industry leaders and technical experts from each mineral domain. They represent the overarching RD&D challenges and opportunities that will advance the domestic critical minerals processing sector.

By synthesising the expertise and shared experiences of stakeholders across these mineral domains, this section offers broad guidance on the RD&D required to navigate the complexities of critical minerals processing, across multiple supply chains.

Theme 1: Deliver continuous and step-change improvements on cost and sustainability

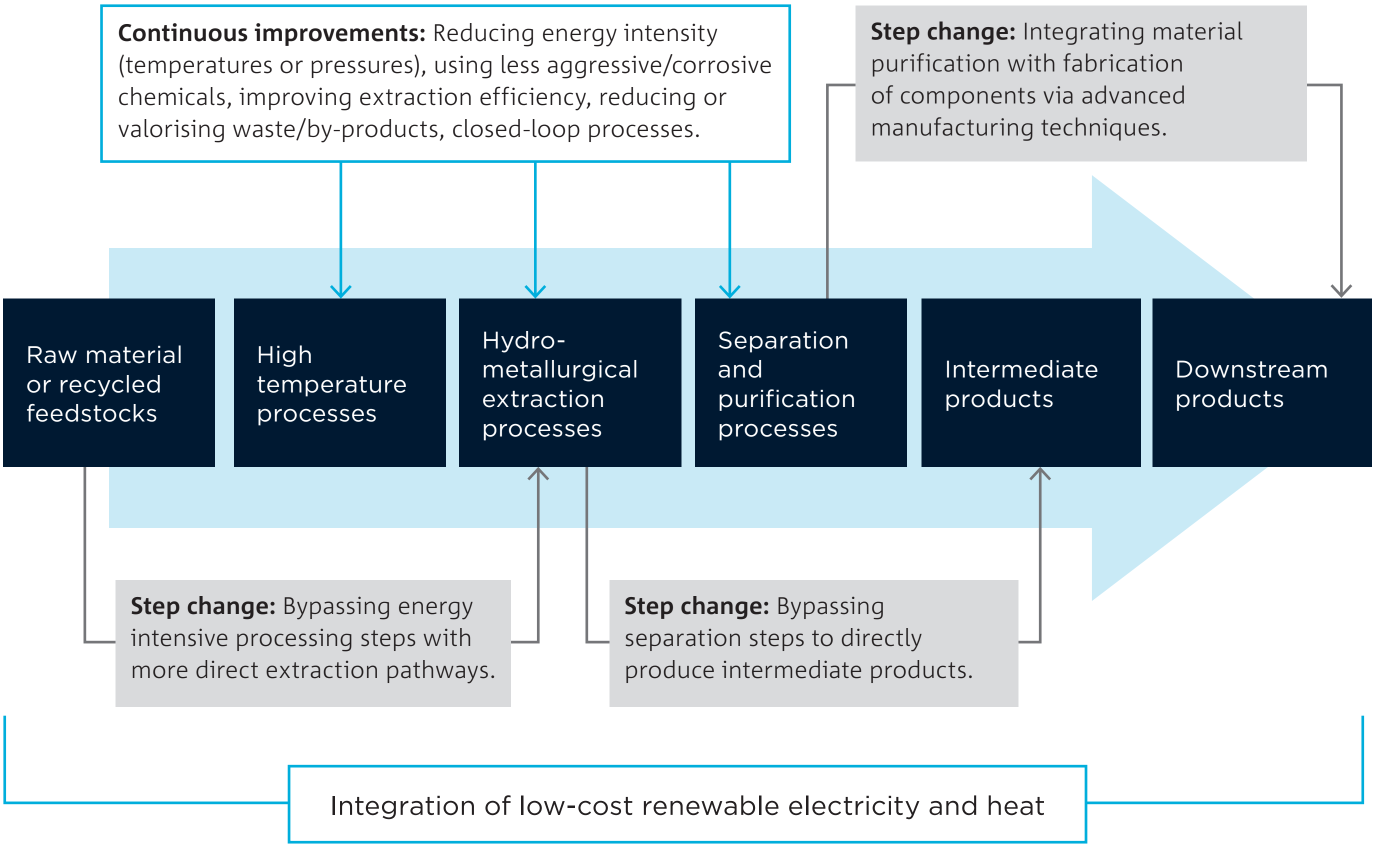
Diversifying international supply chains is a globally acknowledged strategic priority, however, the economics of projects will continue to influence investment in value-adding projects and whether they develop in Australia or elsewhere. Hence, RD&D that unlocks continuous improvements to drive cost reductions, will help ensure domestic projects remain competitive and resilient to the cyclical nature of the resources industry. Furthermore, the identification and development of technologies that provide step-change benefits could lead to breakthroughs that could change cost structures.

In addition to enhancing cost-competitiveness, many continuous and step-change improvements in mid-stream processing could also deliver more sustainable outcomes compared to incumbent processes. Improved environmental and social outcomes can improve the competitiveness of Australian exports to jurisdictions imposing sustainability requirements and taxes on imports (e.g. the EU carbon adjustment tax), and to companies voluntarily procuring responsible supply[42].

42 European Commission (2024) Carbon Border Adjustment Mechanism. Taxation and Customs Union. <https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en>

Figure 26 illustrates areas for continuous improvement, and step-change disruptions that reduce the complexity or number of processing steps in a given supply chain.

Figure 26: Continuous improvement and step change disruptions in mid-stream processing.



Note this diagram illustrates generic examples which may have varied applicability across different supply chains.

Many commercial mid-stream processing methods entail activities that are highly energy and chemically intensive, which can have adverse impacts on land, water, atmosphere, and human health. To enable a large-scale processing industry onshore, RD&D efforts will be essential to develop processes that reduce energy-related emissions and process emissions, use milder reagents and minimise, recycle or valorise waste.

- The integration of renewable energy into the mineral processing sector is an important solution to emissions-related challenges along various supply chains. There is potential for mid-stream processing technologies to incorporate renewable energy or heat to reduce carbon emissions and benefit from energy cost savings. These technologies include energy efficiency measures, energy recovery systems, renewable electricity and heat sources, and carbon capture technologies.[43]
- There is an opportunity to reduce process emissions by using feedstocks and processes that do not generate carbon. A key example is the reduction processes used for producing metals. Replacing carbothermal reduction processes with alternatives (e.g. hydrogen and electrolytic reduction) could reduce process emissions. Another avenue is to replace conventional carbon-based anodes with novel anodes or to use renewable sources of carbon.
- The development and adoption of processes that are more circular and maximise the value derived from resources will be key to reducing environmental impact and lowering costs. Examples include the ability to regenerate and re-use chemical reagents in a closed loop system which can reduce overall cost of reagents and waste management, therefore reducing environmental impacts. Further, some mid-stream processing technologies are highly applicable to extracting metals from tailings, slags, and low-grade ores that would otherwise not be economically mined.
- Using mid-stream processing capabilities to extract high value metals from end-of-life waste (e.g. PV panels and LIB) can decrease the volumes of waste going to landfill. This pathway has the potential to be less energy and process intensive than production from raw materials.

Step-change disruptions bypass energy- or chemically- intensive steps, changing the structure of supply chains and eliminating costs associated with incumbent multi-step processes. Examples can be found across several supply chains:

- In the case of mineral ores, novel leaching processes are being explored to bypass this energy-intensive thermal pre-treatment steps (e.g. alternative leaching agents for extracting lithium).
- Processes that avoid the need for intermediate products are also being explored. For example, emerging methods that can produce precursor CAM (pCAM) directly from a leach solution enable the conventional processing steps of making intermediate products (cobalt sulphate or cobalt metal) to be bypassed. Similarly, for the RE magnet supply chain, processes are being explored to directly produce master alloys, bypassing the need to produce individual RE metals beforehand.
- In the case of silicon, start-ups are investigating ways to use vapour deposition techniques to directly grow wafers instead of polysilicon ingots, which require further cutting and produce significant silicon waste.

Finally, expanding domestic supply chains, particularly in the mid-stream processing sector can carry social implications for workers and communities. Health and safety challenges vary depending on the mineral involved but broadly stem from processes involving high temperatures, chemical reagents, emissions, waste and, in the case of REs, radioactive isotopes.[44] Effective management of risks to health and safety will be essential to mitigate negative impacts to lives and livelihoods, and to enable the expansion of the industry to meet renewable energy sector demand.[45] Public transparency and community engagement regarding the risks and effectiveness of measures in place will be vital to social license for mid-stream processing.[46]

Collectively, these RD&D directions serve as overarching principles for enhancing resilience and commercial viability within Australia's critical minerals industry. Although the principles discussed are broadly applicable across critical minerals, each project has different process configurations, geographic locations, raw materials and chemical feedstocks, presenting unique opportunities and limitations. Tailored solutions will be needed for individual projects across different critical mineral supply chains.

43 Igogo et al. (2020) Integrating clean energy in mining operations: opportunities, challenges, and enabling approaches. Applied Energy 300, 117375.
44 Ali H (2014) Social and environmental impact of the rare earth industries. Resources, 3(1), 123-134.
45 Kim et al. (2022) The Role of Critical Minerals in Clean Energy Transitions. International Energy Agency, Paris.
46 Ali H (2014) Social and environmental impact of the rare earth industries. Resources, 3(1), 123-134.

Theme 2: Maximise return on critical minerals RD&D investment through cross-cutting capabilities and shared infrastructure.

There is an opportunity to increase efficiencies and maximise returns on RD&D investment by strategically allocating resources towards cross-cutting RD&D areas that benefit multiple supply chains. Although critical minerals have diverse properties and behave differently in certain conditions, there are a range of mid-stream processing techniques that can be applied across various minerals, metals, and materials. Capabilities applicable to one mineral can create innovation spillovers in other minerals.

Furthermore, RD&D infrastructure, such as shared user facilities offering laboratory and pilot scale services can help test the viability of Australian products and accelerate the deployment of domestic projects.

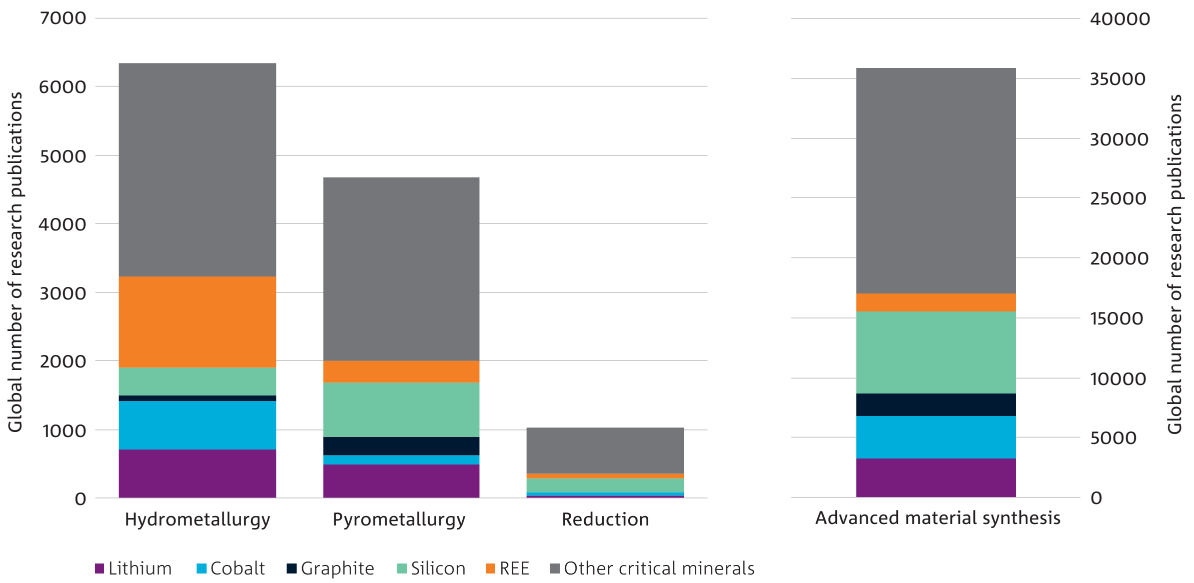
Twenty-one cross-cutting technological processes have been identified as applicable across various critical minerals. These can be grouped into four broad categories: reduction methods, pyrometallurgy, hydrometallurgy and advanced material manufacturing (Table 6).

These technologies can be applied, not only to the five minerals discussed, but potentially to the 31 other critical minerals identified in *Australia's Critical Minerals List.*[47] Figure 27 below illustrates global publications across cross-cutting techniques such as reduction, pyrometallurgy, hydrometallurgy and advanced material synthesis, and shows their applicability to multiple minerals.

Table 6: Cross-cutting processes.

REDUCTION	PYROMETALLURGY	HYDROMETALLURGY	ADVANCED MATERIALS MANUFACTURING
• Carbothermal reduction • Metallothermic reduction • Hydrogen and gas-based reduction • Electrowinning and electrolysis • Molten salt/high-temperature electrolysis	• Calcination • Roasting and baking • Pyrolysis • Directional solidification	• Acid and alkaline leaching • Solvent extraction • Ion-exchange separation • Precipitation • Crystallisation • Bioleaching	• Sol gel • Spray-based (spray drying, spray pyrolysis) • Coprecipitation • Chemical vapour deposition and atomic layer deposition • Milling and classification • Solvo- and hydrothermal synthesis

Figure 27: Global research publication output in cross-cutting processes, by mineral.



47 DISR (2024) Australia's Critical Minerals List and Strategic Materials List. Australian Government Department of Industry, Science and Resources. <https://www.industry.gov.au/publications/australias-critical-minerals-list-and-strategic-materials-list>

Theme 3: Integrate research from other fields to support commercial and policy decision-making.

There are several research fields that can provide important information on the most efficient technology, policy or commercial pathway to effectively develop greater mid-stream processing onshore. This can help commercial and policy decision-making, and support process development and innovation. These research domains include environment, modelling, robotics and automation and safety and social license (Figure 28).

Figure 28: Research domains to support decision-making.

Environment
Research in the land, water, atmospheric impacts of mid-stream processing to inform processing technology choices, support investment decisions, and enable ongoing monitoring of operations.

Modelling
Scientific/technical modelling to inform process/material development. Economic modelling to understand scenario outcomes and inform policy/commercial decisions.

Traceability frameworks and technologies
Studies into effective and cost-efficient traceability methodologies and technologies to enhance transparency and governance, and to enable monetisation of Australia's responsible products.

Safety and social license
Studies into best practice health and safety practices and on the social impacts of mid-stream processing activities to improve social outcomes and public understanding of mid-stream processing and its benefits and risks.

Environment

Research into land, water, and atmospheric impacts of mid-stream processing will be essential to inform commercial and policy decisions. Understanding the impacts can inform processing technology choices and help better understand the true costs of a project including social and environmental costs. Examples include lifecycle analysis of specific mid-stream processing technologies and end-to-end processes to determine the most sustainable outcomes and understand key areas for continued improvement. Environmental studies can support operations providing ongoing information and monitoring regarding planned and unforeseen impacts.

Modelling

There is a need for further modelling to understand the technical, commercial and policy complexities of mid-stream processing. By simulating different scenarios and assessing potential outcomes, decision-makers can leverage data-driven insights to identify optimal strategies.

There are various useful modelling techniques that provide different insights, including economic and technoeconomic analyses, scientific modelling, and supply chain modelling:

- **Economic modelling** can be conducted at different scales by organisations, peak bodies and government to understand the economic and commercial complexities of mid-stream processing. It can help industry identify effective business models or help policymakers create incentives for and remove barriers to mid-stream processing in Australia.
- **International supply chain modelling** can uncover key uncertainties regarding the development of integrated supply chains with key partner countries. This includes understanding which specific supply chain activities should be conducted in Australia (e.g. CAM production or RE metallisation), and the development of a clear and decisive action plan.
- **Technoeconomic analysis** can enhance understanding of the cost differences and cost drivers of different technology pathways for mid-stream processing, help identify opportunities for cost reduction and provide supporting evidence for project feasibility.
- **Scientific modelling** can significantly accelerate process and product development by reducing time, effort and resources needed. Examples include models that can replicate processes (e.g. computational fluid dynamics) or models that can simulate the characteristics and behaviours of materials (e.g. CAM). Models can also be used to optimise existing processes and materials.

Traceability frameworks and technologies

Traceability will be vital to Australia's ability to market its responsibly produced critical minerals and materials. However critical minerals supply chains are highly complex, making ESG information is difficult to track.

Collaborative studies into the most effective traceability frameworks will be key to ensuring globally harmonised regulations and methodologies.[48] There are several methodologies that can be used to trace materials ranging from ensuring the materials in an energy product originate from a single certified source, through to allowing blended certified and non-certified materials and disclosing content ratios.[49] An alternative to directly tracking provenance is the use of certificates and credit schemes.[50]

Studies into regulatory aspects must go hand-in-hand with research into fit-for-purpose and cost-effective traceability technologies. Possible technologies include mapping software, blockchain technology, and go-based fingerprinting.[51]

Safety and social license

The development of mid-stream processing capabilities in critical minerals is contingent upon the safety of workers and communities. This field of research increases understanding around the social impacts of mid-stream processing activities, both real and perceived, and identifies the most effective strategies to increase public understanding of mid-stream processing. Alongside this, continued research into best practice safety measures is crucial to reduce risks to the workforce and the surrounding communities from the potential hazards associated with mineral processing. This also includes limiting any social disruption due to land use change, which may manifest as water depletion, contamination and air pollution.[52]

48 DISR (2024) Joint Statement by Canada and Australia on Cooperation on Critical Minerals. Australian Government Department of Industry Science and Resources <https://www.industry.gov.au/publications/joint-statement-canada-and-australia-cooperation-critical-minerals>
49 Barbosa H et al (2022) Supply Chain Traceability: Looking Beyond Greenhouse Gases, RMI 2022 <https://rmi.org/insight/supply-chain-traceability-beyond-greenhouse-gases/>
50 Barbosa H et al (2022) Supply Chain Traceability: Looking Beyond Greenhouse Gases, RMI 2022 <https://rmi.org/insight/supply-chain-traceability-beyond-greenhouse-gases/>
51 IEA (2023) Sustainable and Responsible Critical Mineral Supply Chains: Guidance for policy makers. International Energy Agency.
52 IEA (2022) Sustainable and responsible development of minerals. International Energy Agency, Paris. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/sustainable-and-responsible-development-of-minerals>

5 Actions for RD&D and international engagement

The LIB, solar PV, RE magnet supply chains are well established globally and currently use mature and commercial mid-stream processing technologies, including extraction techniques and material synthesis techniques. However, in response to global supply chain concentration challenges and global ESG challenges, several emerging mid-stream processing technologies are being developed to provide a cost-competitive edge over incumbent technologies, circumvent IP barriers, and to overcome sustainability issues.

This chapter provides a deep dive into specific mature and emerging technologies relevant to the key mid-stream processing and recycling of lithium, cobalt, graphite, silicon and REs. It includes actions for Australian RD&D and for international engagement in specific technology areas.

The framework used to synthesise actions for Australia is summarised in Figure 29, and a full explanation is covered in *Section 1.3*.

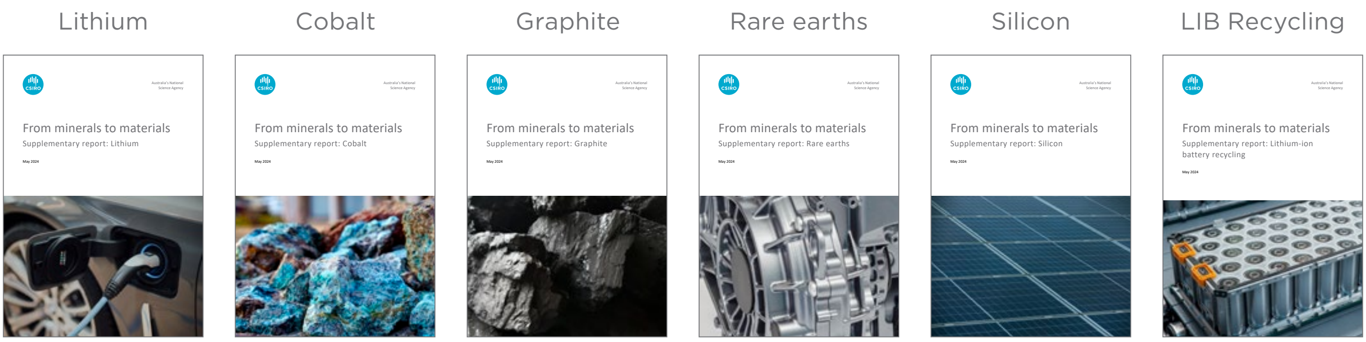
Figure 29: Framework for synthesising research, development and demonstration (RD&D) actions and international engagement actions.

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.

Because the technology areas discussed in this section are highly nuanced, a series of supplementary mineral reports have been produced to introduce these technologies, their benefits and challenges, as well as to summarise their maturity levels and their state of play in Australia (Figure 30). These reports also include detailed statistics on RD&D trends and activity by country.

Figure 30: Supplementary mineral reports.

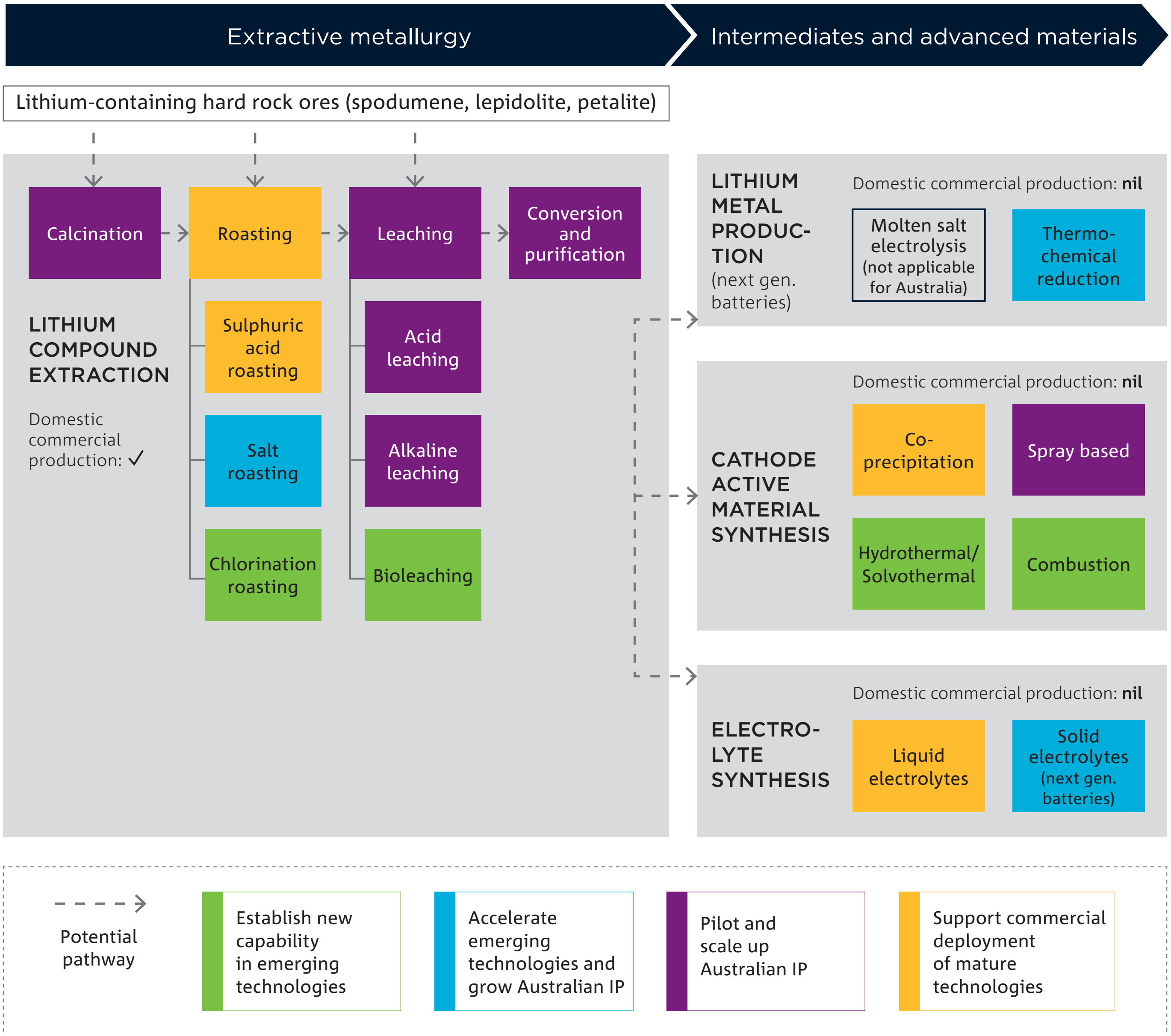


5.1 Lithium

LIBs are expected to make up a large portion of the global EV and stationary storage market shares from now to 2050, 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 RD&D activity both domestically and globally.

Australia's RD&D capabilities can support both the expansion of lithium mid-stream processing activities onshore and support the development of technologies more broadly in the global context. There are several opportunities for RD&D related to the mid-stream processing of lithium, including supporting the implementation of mature technologies in the Australian context, piloting and scaling up Australian technology, accelerating emerging technologies and growing the Australian IP or establishing new capabilities in emerging technologies (Figure 31).

Figure 31: Actions for research, development and demonstration (RD&D) and international engagement in 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, and therefore warrant multiple actions. A more nuanced discussion of each technology can be found below and within the supplementary mineral reports.

IP, intellectual property.

Extractive metallurgy

● **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.

Intermediates and advanced materials

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 LiPF6 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.

MagSonic carbothermal reduction pilot plant, CSIRO Clayton, Victoria

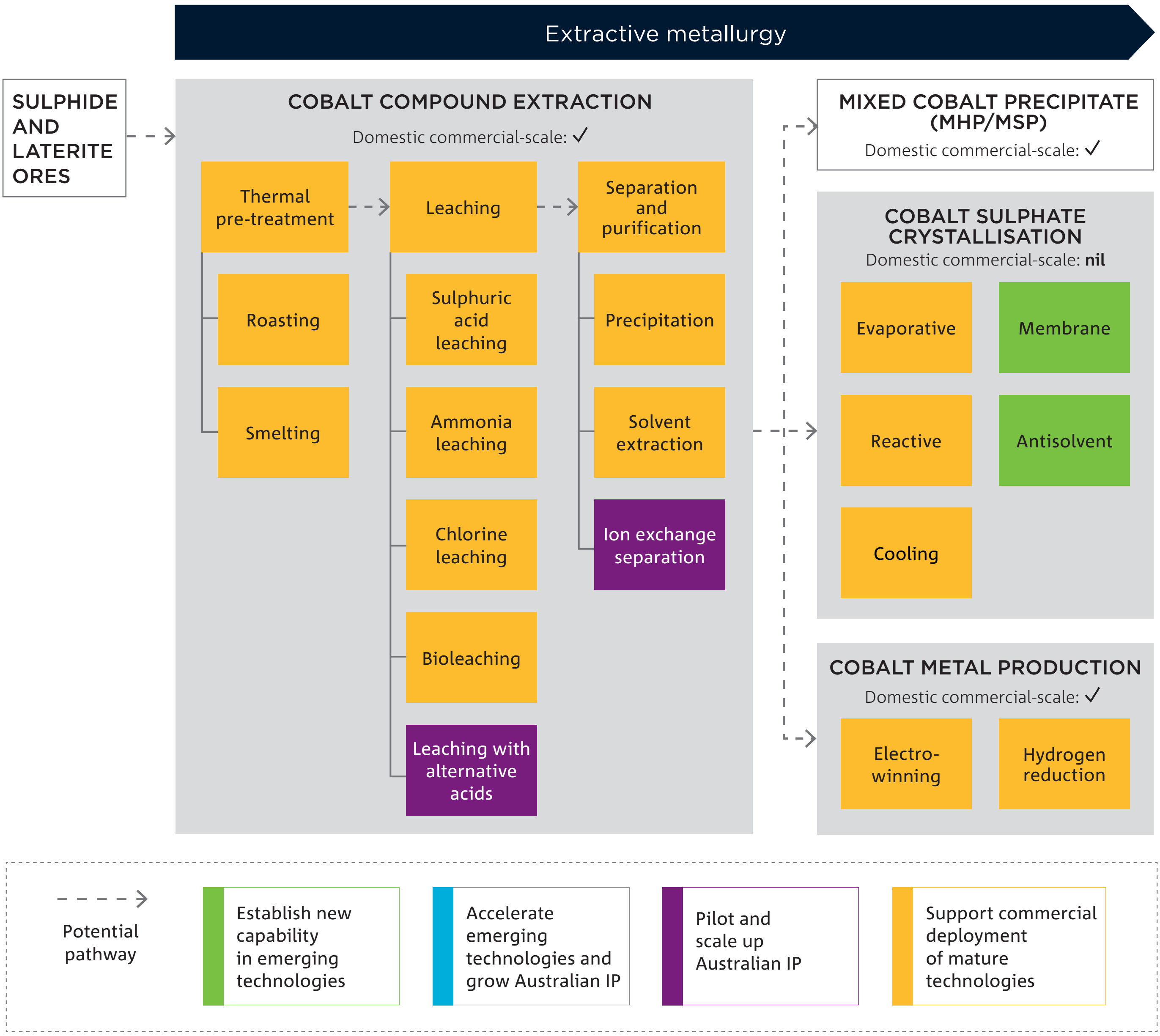
5.2 Cobalt

Cobalt supply chains are subject to several global challenges, including supply chain concentration across the LIB supply chain, and environmental and social issues. The mid-stream processing portion of the supply chain remains highly concentrated in China, particularly the production of battery-grade cobalt compounds and CAMs.

Given Australia's resource endowment, there is an opportunity for domestic industry to expand its activities in mid-stream processing by building on the existing production of cobalt metal and cobalt intermediates (MHP and MSP) or undertaking new production of battery intermediates products such as cobalt sulphate and the direct production of pCAM. This also paves the way for integrating upstream CAM manufacture onshore. Australia's strong RD&D capabilities are well positioned to tackle the processing of declining and complex ore grades, recover cobalt from waste streams and reduce energy intensity, emissions and chemical-based impacts.

There are several opportunities for RD&D related to cobalt mid-stream processing, including supporting the implementation of mature technologies in the Australian context; piloting and scaling up Australian technology; accelerating emerging technologies and growing Australian IP; or establishing new capabilities in emerging technologies (Figure 32).

Figure 32: Actions for research, development and demonstration (RD&D) and international engagement in cobalt 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. A more nuanced discussion of each technology can be found below and within the supplementary mineral reports.

IP, intellectual property; MHP, mixed hydroxide precipitate; MSP, mixed sulphide precipitate.

● Roasting; ● Smelting

Roasting and smelting will likely continue to be relevant in Australia given existing domestic sulphide deposits, however its use for laterites is less prevalent. Australia's strong commercial and RD&D capabilities in this area can help improve sustainability, efficiency, and recovery rates to ensure continued activity into the future.

Roasting and smelting are mature processes conventionally used on sulphide deposits to improve the downstream recovery of cobalt and other relevant metals (e.g. copper and nickel). Despite the depletion of sulphide ore grades and growing importance of laterites, a portion of Australian cobalt production still comes from sulphide ores. Conventional roasting and smelting processes are energy-intensive and suffer losses of metal to waste streams, highlighting opportunities for RD&D to improve the sustainability and competitiveness of operations.

● Sulphuric acid leaching

Sulphuric acid leaching methods are commonly used globally and in Australia to extract cobalt from sulphides and in particular laterites. However, sulphide ore grades are declining making them more difficult to leach, and laterite operations are costly to operate (high pressure acid leaching). Australia's strong RD&D capabilities in this area can help address the prevailing challenges of high-pressure acid leaching (HPAL), and the scale up of cost-effective alternatives that can treat a range of ore types.

Laterite ore deposits represent the majority of Australian cobalt reserves, making them an important source for continued cobalt supply into the future. They are conventionally treated using sulphuric acid at high temperature and pressure (i.e. HPAL) and to a lesser extent using atmospheric pressure processes.

However, HPAL projects have faced high economic barriers in Australia and produce large volumes of acid tailings. There are opportunities for Australian RD&D to address these challenges and support domestic operations, through strategies that upgrade laterite ores, reduce waste streams, and increase control over impurities.

Cost-effective alternatives, such as atmospheric pressure leaching, and pressure oxidation, are mature and available. RD&D in these areas can further improve overall process economics and versatility.

● Ammonia leaching; ●● Chlorine leaching

Cobalt extraction through ammonia leaching and chlorine gas are globally mature methods, efficient and versatile in terms of feedstock. However, both processes face an uncertain future: chlorine gas faces high costs and safety risks, and the use of ammonia leaching has been declining in industry. Nevertheless, these technologies can play a role as part of Australia's technology portfolio given their usefulness.

Both ammonia solutions and chlorine gas in solution can be used to leach a variety of feedstocks including ores, matte and mixed precipitate products. Ammonia solutions in particular provide an advantage for purification, making downstream purification less onerous. However, ammonia processes are currently used for nickel production and require additional processes to recover cobalt, whereas chloride-based methods face impurity challenges. Given the usefulness of these technologies, there is an opportunity for Australian RD&D to support existing ammonia operations and the deployment of chlorine in gas solutions where applicable.

● Alternative acids (nitric, hydrochloric, chlorides);
● Alternative acids (phosphoric acid, organic acids)

Leaching with alternative acids has strong potential to improve environmental and cost outcomes compared with incumbent sulphuric acid processes, and to effectively leach cobalt from complex ore types. Given Australia's research capabilities, IP and existing pilot projects, there is an opportunity to continue progressing emerging options beyond the laboratory, as well as demonstrating and scaling-up Australian technologies.

Nitric, hydrochloric, phosphoric, and organic acids are emerging solutions to conventional sulphuric acid pathways, with potential to improve process economics, maximise resource utilisation, and reduce hazardous byproducts. Nitric and hydrochloric acid are closer to commercialisation. Piloting and scaling can support their commercial deployment in Australia. Although phosphoric and organic acids are less mature, there is an opportunity to develop and demonstrate complete flowsheets and to develop capabilities by engaging in international collaborative research.

● **Bioleaching (sulphide ores);**
● **Bioleaching (laterite ores)**

Bioleaching can play a unique role in Australia's technology mix due to its ability to extract cobalt from low-grade sulphide ores and waste streams relatively cost-effectively and sustainably. However, RD&D is required to overcome technical challenges to scale-up.

Given Australia's prior experience in cobalt bioleaching from sulphide ores, and the maturity of bioleaching for cobalt relative to other critical minerals, there is an opportunity for RD&D to improve the commercial prospects and scalability of the technology. This includes developing microorganisms or operation modes to support higher recovery rates, speed up processing time, and reduce variability in performance. This could help Australian operations recover cobalt from complex or low-grade sulphide ores and tailings that could not be treated economically via other means.

● **Precipitation;** ● **Solvent extraction;** ● **Ion exchange**

Separation and purification are key to producing cobalt intermediates (MHP and MSP) and may provide a cost-effective pathway to the direct production of pCAM. Further, it is a requirement for downstream production of refined cobalt sulphate and cobalt metal. Australia has the capability to build upon its existing commercial activity in mixed precipitates and solvent extraction, while piloting and scaling-up novel Australian technology.

Mid-stream processing plants can be designed to produce a number of cobalt intermediates for battery supply chains, including mixed precipitates (MHP and MSP), cobalt sulphate (a direct input into CAM production) or cobalt metal (an intermediate that can be sold to multiple end markets). The Australian cobalt industry and research sector has extensive experience using precipitation, solvent extraction (SX) and ion exchange (IX) to produce these products. Although these are mature technologies, there is an opportunity for RD&D to deliver improvements on existing processes to increase product grades and value.

There is also an opportunity to pilot and scale emerging approaches such as the direct production of pCAM. This has the potential to bypass conventional steps of precursor production, minimising the energy intensity and cost of the overall process, and providing a pathway to domestic supply chain integration. Innovation areas include precipitation to directly produce pCAM, and ion exchange to directly recover cobalt from waste streams.

● **Crystallisation (evaporative, reactive, cooling);**
● **Crystallisation (membrane, antisolvent)**

Crystallisation is the final step to produce battery-grade cobalt sulphate, and although many crystallisation methods are commercially mature, there are emerging technologies that could improve throughput, enhance control over end product characteristics, and increase energy efficiency. In the near term, Australia can leverage its existing commercial capability producing similar products (e.g. nickel sulphate), while strong research capabilities can help deliver innovative improvements longer term.

The current structure of global supply chains involves producing highly pure cobalt sulphate, which is a key feedstock into CAM production. Battery-grade cobalt sulphate is not currently produced at commercial scale in Australia, but it is part of multiple planned projects. RD&D can support the commercial deployment and improvement of onshore crystallisation. This includes increasing the energy efficiency of temperature-based methods, the throughput and control of reagent-based methods, and the durability of membrane-based methods.

This area will require close international engagement with overseas battery manufacturers to ensure that Australian production meets their specifications and to de-risk commercial projects through off-take agreements.

● **Cobalt metal (electrowinning, hydrogen reduction)**

Australia already produces cobalt metal, a versatile product that can be sold into multiple end markets, including the LIB market. The dominant ways of producing it, hydrogen reduction and electrowinning, have strong potential for renewable energy integration. Continued RD&D in this area can further drive the sustainability and productivity of the process, ensuring Australia's competitiveness in the long term.

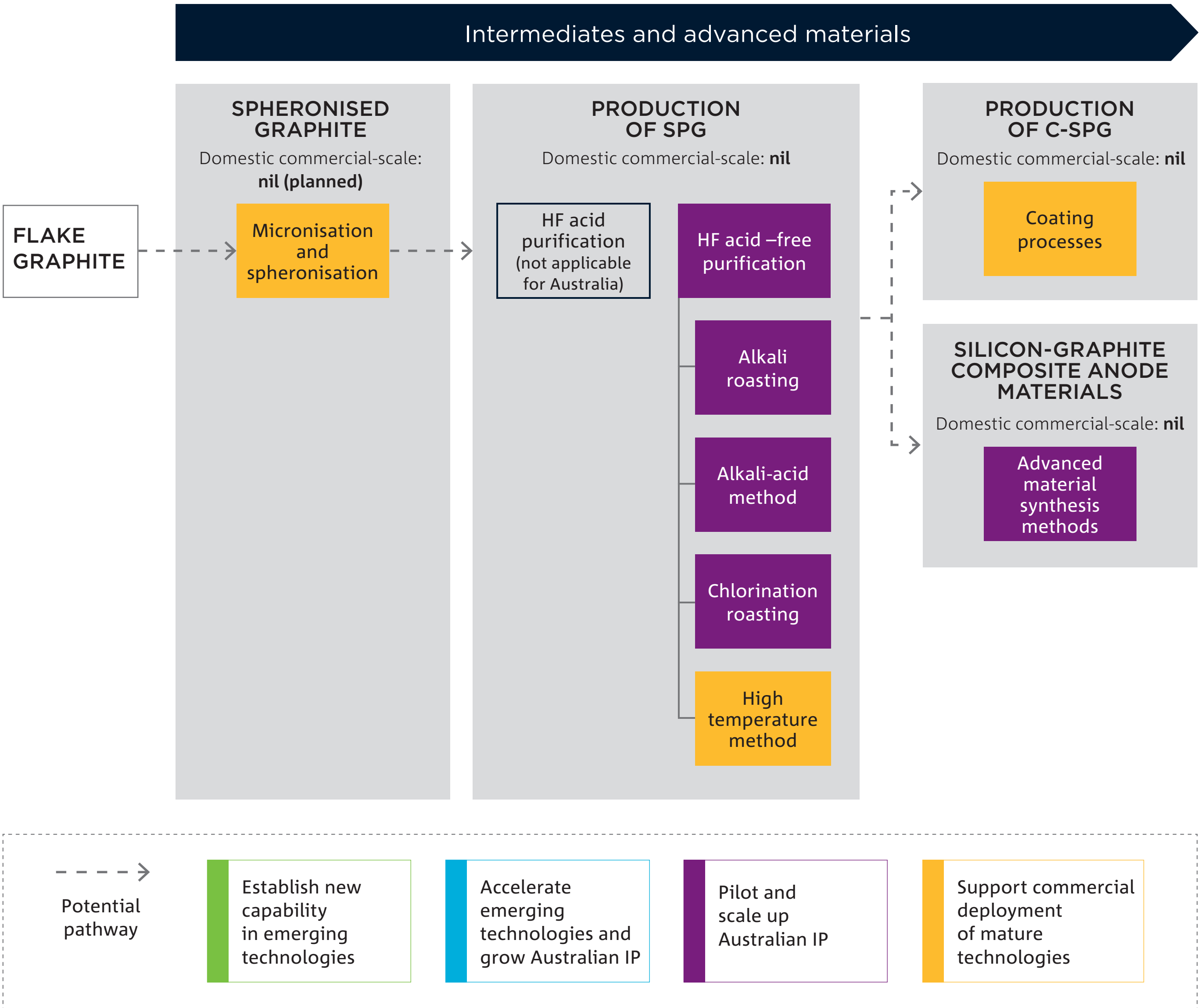
Cobalt metal production is a less direct pathway to produce CAM, but has benefits in terms of purity, transport, and saleability into markets other than LIBs. RD&D efforts to increase sustainability and productivity of the metal production processes can support existing Australian producers and reduce the overall energy intensity and emissions embodied in final CAM produced with cobalt sulphate derived from cobalt metal.

5.3 Graphite

The growing lithium ion battery market is driving demand for synthetic and natural graphite for current generation and state-of-the-art high performance anodes. This offers an economic opportunity for Australia if operations can undertake these activities competitively in terms of cost and sustainability. Given the high supply chain concentration in China, particularly in raw material processing and active anode material production, Australia can position itself as a supply chain diversification partner for battery manufacturing partners.

Australia has no commercial scale production of graphite materials; however, several companies have conducted tests and pilots, and plan to vertically integrate from their natural graphite deposits. There are several opportunities for RD&D across the graphite supply chain to support the growth of an onshore industry, including supporting the implementation of mature technologies in the Australian context; piloting and scaling up Australian technology; accelerating emerging technologies and growing Australian IP; or establishing new capabilities in emerging technologies (Figure 33).

Figure 33: Actions for RD&D and international engagement in graphite 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. A more nuanced discussion of each technology can be found below and within the supplementary mineral reports.

C-SPG, coated spherical purified graphite; SPG, spherical purified graphite.

Micronisation and spheronisation

Micronisation and spheronisation technology is mature globally and off the-shelf equipment is accessible to Australian industry. Continued collaborations with equipment suppliers, and strong engagement with overseas battery original equipment manufacturers (OEMs) will be key to growing onshore production.

Despite the use of overseas technology, there is a role for Australian RD&D to optimise the operation of commercial equipment, with the goal of improving yields and efficiency. Although this doesn't fall under the purview of traditional RD&D activities, it could be a crucial for enhancing the performance of the domestic industry, especially considering the variability in equipment and ore characteristics.

HF acid-free purification

Diversifying graphite purification outside of China will require the development hydrofluoric (HF) acid-free methods due to its high risks, and Australia is well positioned to do so with strong RD&D and patent output to support piloting and scale-up.

Australia has developed patents across several alternatives to HF-acid, such as chlorination roasting and alkaline roasting or leaching pathways. Continued R&D efforts are required to scale up alternative purification pathways (that are HF-acid-free) beyond the laboratory and pilot scales. Given Australian companies hold graphite deposits in Australia and internationally, Australian purification technologies could support value-adding operations onshore and offshore, unlocking greater global diversification.

Coating processes

There are significant barriers to entering the C-SPG market because coating technology is highly subject to trade secrets; however, there is an opportunity to develop formulations and coating methods in collaboration with international partners.

Coating technologies are mature globally, and Australia can leverage its strong RD&D capabilities in advanced materials (e.g. thin films), to support commercial production of C-SPG onshore. C-SPG attracts a significantly high price compared to uncoated material. Collaborations with global battery cell manufacturers will be essential to capturing this value through the co-development of coating formulas tailored to specific manufacturers products.

Graphite composite materials (advanced material synthesis)

Australia has several active companies and research institutions working towards next generation silicon-graphite composite anodes. There is an opportunity to demonstrate Australian silicon-graphite anode materials in battery applications and pilot their production at scale, and to continue to develop novel compositions with increased performance.

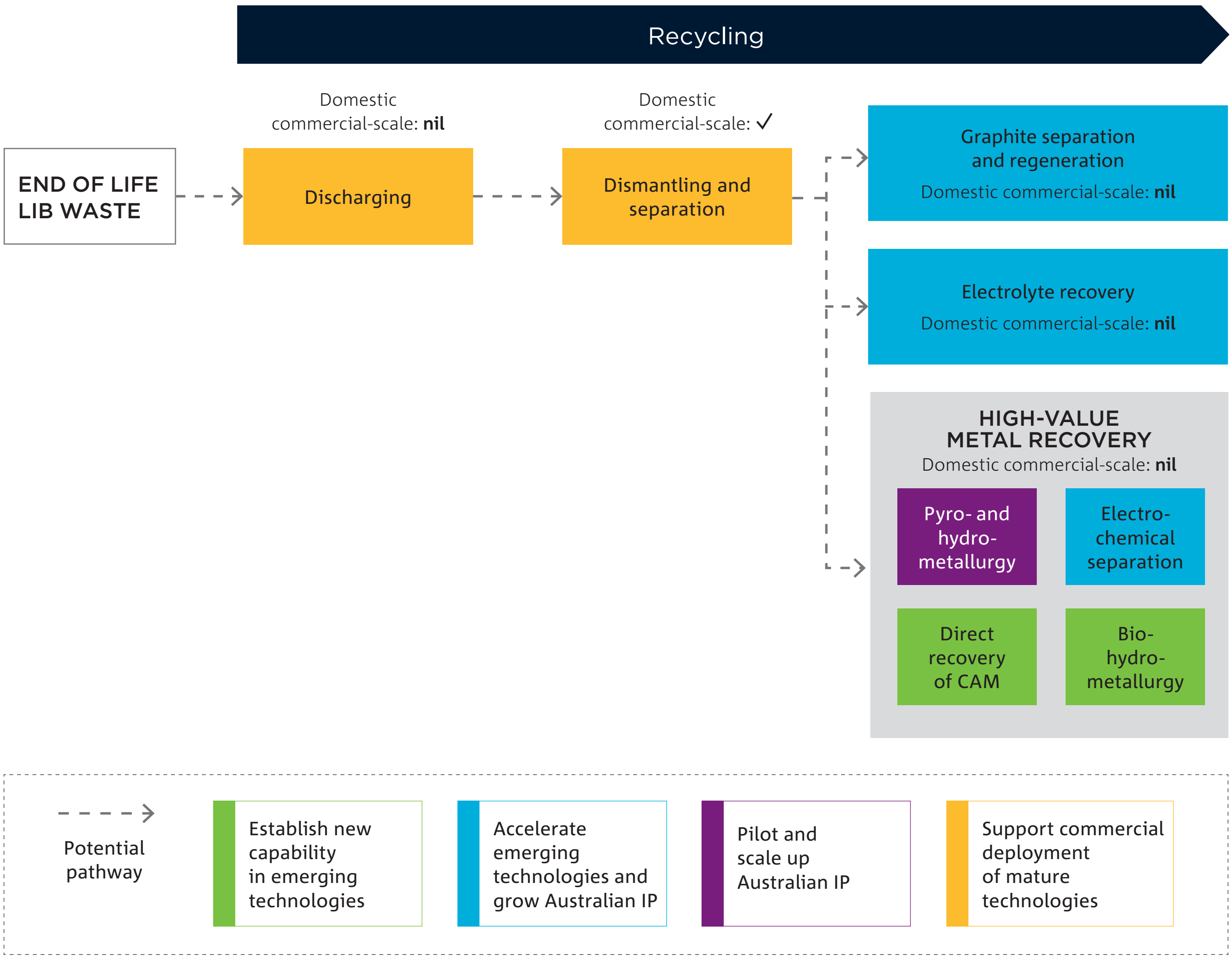
Increasing proportions of silicon are being used in commercial LIBs and are achieving breakthroughs in performance, representing a significant opportunity for Australian technology developers. Demonstrating Australian anode materials and strong engagement with international LIB manufacturers will be required for Australian technology to capture anode market share.

5.4 LIB recycling

Increasing the recovery of high value metals, such as cobalt and lithium, has been the economic driver for commercial activity and RD&D in LIB recycling to date. This is shifting and now supply chain concentration for critical energy minerals and international circular economy policies are driving efforts to recover more materials from LIB waste, including lithium electrolytes and graphite.

Australia's RD&D capabilities can support the expansion of LIB recycling activities onshore and support the development of recycling technologies more broadly in the global context. There are several opportunities for RD&D related to LIB recycling, including supporting the implementation of mature technologies in the Australian context; piloting and scaling up Australian technology; accelerating emerging technologies and growing Australian IP; or establishing new capabilities in emerging technologies (Figure 34).

Figure 34: Actions for research, development and demonstration (RD&D) and international engagement in lithium-ion battery recycling 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. A more nuanced discussion of each technology can be found below and within the supplementary mineral reports.

CAM, cathode active material; LIB, lithium-ion battery.

● Discharging

Discharging technology will become increasingly important as EV uptake increases, and as LIB waste poses increasing safety risks across Australia's recycling system. Given the availability of off the shelf discharging equipment, there is an opportunity for Australia to implement discharging systems across the LIB recycling industry, while addressing key barriers such as standards and regulations.

Australia currently undertakes the initial processing steps for LIB waste (crushing and shredding) prior to shipping black mass. Without discharging this can be an unsafe activity for workers and pose a risk to facilities. Given this activity is likely to grow there is a need to state of the art discharging practices within Australia's recycling infrastructure; systems that are safe and do not contaminate materials for subsequent recovery

RD&D can support the development of regulations and standards that currently make electrical discharging (the safest discharging option, and compatible with high quality material recovery) difficult. Further, RD&D in adjacent fields such as robotics and automation can help overcome issues with handling and throughput.

●● Dismantling and separation

There is an opportunity to improve upon existing separation technologies used in Australian battery crushing and shredding operations. This can increase the quality and price of black mass product and facilitate improved extraction of materials in downstream processing.

Given Australia's current commercial and patent activity, there is an opportunity to demonstrate Australian IP in separation technology onshore, and to continue to drive reductions in cost, energy, and reagent use while increasing revenues from the export of black mass.

Although separation technology is mature and available for industry, improved separation technologies can enable more efficient recovery of high value metals through hydro-metallurgical processes (the subsequent step in processing), as well as the recovery of electrolytes and graphite, which is not currently practiced at scale globally.

● Graphite regeneration; ● Electrolyte recovery

Graphite regeneration and electrolyte recovery is emerging and gaining interest globally; Australia can leverage its RD&D leadership in this area to drive greater circularity and value recovery in domestic and global battery supply chains.

Global battery recyclers are yet to adopt graphite regeneration (as opposed to downcycling) and electrolyte recovery. Given the emergence of this technology and Australia's RD&D activity in this space, there is an opportunity to build on existing capabilities to develop the technology beyond the laboratory and to grow domestic IP.

● Pyro- and hydrometallurgical recovery;
● Electrochemical recovery

The recovery of high value metals using hydro- and pyrometallurgical techniques is commercial overseas, and global RD&D momentum continues to improve upon this technology. Given Australia's patent activity in this space, there is an opportunity to demonstrate Australian IP overseas or alongside emerging domestic battery plants.

Australia does not currently undertake high value metal recovery and instead ships black mass for processing offshore. Despite projected growth, the scale of Australia's LI-B waste stream is currently small and geographical dispersion results in challenging economics. Australia's IP in hydro- and pyro-metallurgical recovery can be demonstrated overseas or alongside eventual domestic CAM and battery cell manufacturing plants.

Alternatively, Australia may choose to implement commercially proven technologies from overseas to manage investment risk and accelerate implementation timelines. RD&D in supporting fields may be beneficial, such as assessing the economic viability of overseas technologies in the Australian context.

● Direct recycling; ● Biohydrometallurgy

Direct recycling of cathode materials and biohydrometallurgy are emerging technologies that can provide step change improvements in battery recycling. Capabilities are nascent globally and in Australia and can be built through RD&D international collaboration.

Direct recovery of CAM has the potential to reduce the number of steps, inputs and costs compared with commercial processing that targets separated metals. Where applicable, bio-metallurgy has the potential to reduce capital costs, energy consumption and environmental impact.

However, these technologies are at low maturity and several technical challenges will need to be resolved through RD&D to deliver these outcomes.

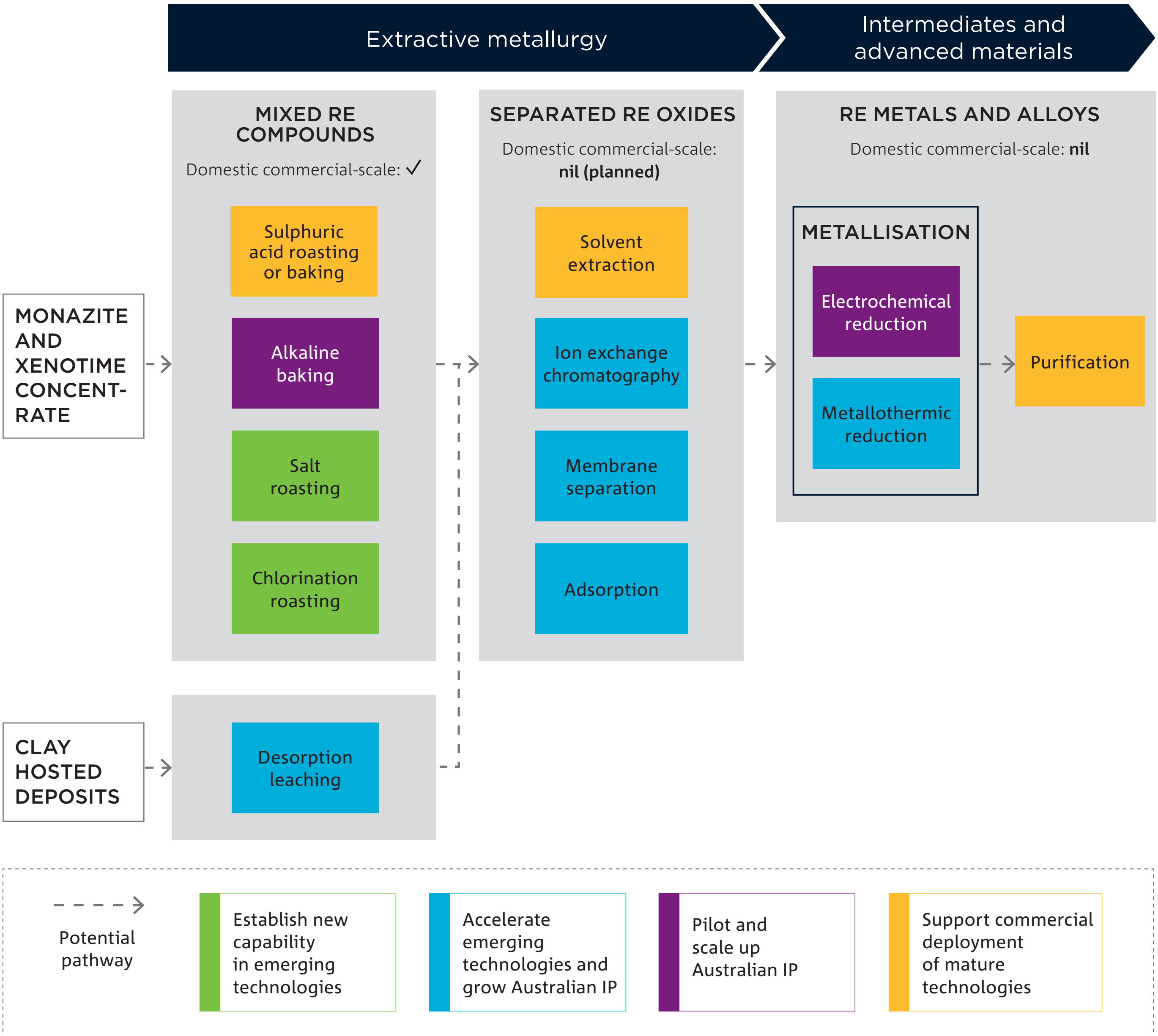
Australia and partner countries can grow their capabilities in this space through RD&D and engaging in knowledge sharing and joint projects.

5.5 Rare earths

REs are a critical input for EV and wind turbine supply chains, and therefore play an important role in the domestic and global energy transition. The market for RE products is a growing market, and supply chain concentration across all stages represents an opportunity for Australia to become an alternative supplier of mid-stream RE products.

Australia's RD&D capabilities can support the expansion of RE mid-stream processing activities onshore and the development of processing technologies more broadly in the global context. There are several opportunities for RD&D in RE processing, including supporting the implementation of mature technologies in the Australian context, piloting and scaling up Australian technology, accelerating emerging technologies and growing Australian IP or establishing new capabilities in emerging technologies (Figure 35).

Figure 35: Actions for RD&D and international engagement in RE 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. A more nuanced discussion of each technology can be found below and within the supplementary mineral reports.

IP, intellectual property; RE, rare earth.

Extractive metallurgy

Sulphuric acid roasting/baking

Although sulphuric acid roasting or baking is globally mature and commercially used in Australia, it is still receiving substantial RD&D activity to improve the process. Australia's industry know-how and existing IP in sulphuric acid roasting and baking represents an opportunity to pilot Australian patents and to expand onshore commercial scale projects, with the support of international engagement.

The compatibility of sulphuric acid roasting or baking with different mineralogies makes it a versatile technology, and its proven use in industry makes it a lower risk technology for adoption. No longer subject to high levels of IP protection, sulphuric acid roasting or baking can be applied to Australian ores with the support of the RD&D sector for commercial testing. Further, there is an opportunity to demonstrate Australian IP in this area. Although this reduces reliance on overseas partners, Australia will nevertheless need engagement with overseas equipment manufacturers and large-scale engineering services in order to enable the construction of large-scale processing projects.

Alkaline baking

Alkaline baking (also referred to as caustic digestion) has the potential to improve sustainability and cost outcomes but requires high grade monazite ores. Despite limited commercial applications globally, Australia may have the ore grades suitable for this process. The role of domestic RD&D is to assess the economic and technical viability of this process on Australian deposits, and if applicable, expand industrial know-how.

Alkaline baking has had limited deployments globally due to the requirement for high grade monazite. Although sulphuric acid baking is the preferred commercial route in Australia, domestic high grade monazite resources may be amenable to alkaline baking. Alkaline baking represents an opportunity to improve competitiveness on cost and sustainability of associated operations (subject to plant configuration). Potential benefits include lower corrosivity to equipment and the ability to recover phosphorus, a valuable by-product. RD&D will be required to assess the technology viability, and to optimise processes. Given this process is not commercially utilised in Australia, international engagement with organisations that have commercially deployed the technology overseas may be beneficial.

Salt roasting; Chlorination roasting

Salt roasting and new approaches to chlorination are emerging extraction alternatives that have potential to bring about step change efficiencies compared with current processes. However global and Australian capabilities are nascent and will require a long-term RD&D effort and international collaboration to progress technology readiness and build capability.

Salt roasting provides a more selective pathway to recover valuable elements and separate environmental contaminants, whereas chlorination roasting offers the ability to bypass the leaching step and directly produce RE chlorides.

There is an opportunity for RD&D to solve technical challenges and progress technology readiness, especially in relation to process continuity, energy intensity, corrosion and safety. Research collaborations with international RD&D partners can help build capability through knowledge sharing and joint projects.

Desorption leaching

Extraction REs from clay-hosted deposits is a strategic priority for Australia and many domestic operations have started to progress beyond exploration. RD&D will be essential to enhance understanding of Australian clays, identify suitable extraction mechanisms, compare process configurations and costs, and provide test work to support commercial pilots.

Clay-hosted deposits are a significant source of heavy REs, however mining and processing activity outside of China are limited to a few pilot scale projects. Given Australia's domestic know-how and ongoing commercial development activities, there is an opportunity to support Australian companies to pilot and demonstrate their processes onshore and continue to grow domestic capabilities. Additionally, enhancing sustainability and cost effectiveness are opportunities to position Australia as a responsible and competitive global producer.

Opportunities for international engagement include establishing research partnerships for knowledge sharing and capability building and leveraging Australian RD&D expertise to provide service and support overseas commercial operations.

Solvent extraction

Solvent extraction is a commercially proven process widely used to produce separated RE oxides. Australia possesses industry know-how and companies are planning commercial operations onshore. The role of RD&D will be to continue supporting the development of domestic commercial projects through process validation and test work, and the expansion of industry skills. Similar to other mature areas, establishing large-scale plants will require engagement with overseas vendors.

Solvent extraction is an effective and scalable process for separating REs; however, its high complexity is a key barrier for aspiring domestic producers. RD&D plays an essential role in providing services such as commercial test work and resolving complex technical challenges. Further, ongoing RD&D in process improvement can help position Australia as a competitive and sustainable producer of RE oxides in the long term.

International engagement will be needed with regard to enabling piloting and scale-up, namely obtaining plant equipment from overseas manufacturers, and engineering large-scale plants. Given Australia does not currently have integrated RE metal production, relationships with offtakers will also be critical to de-risk and finance projects.

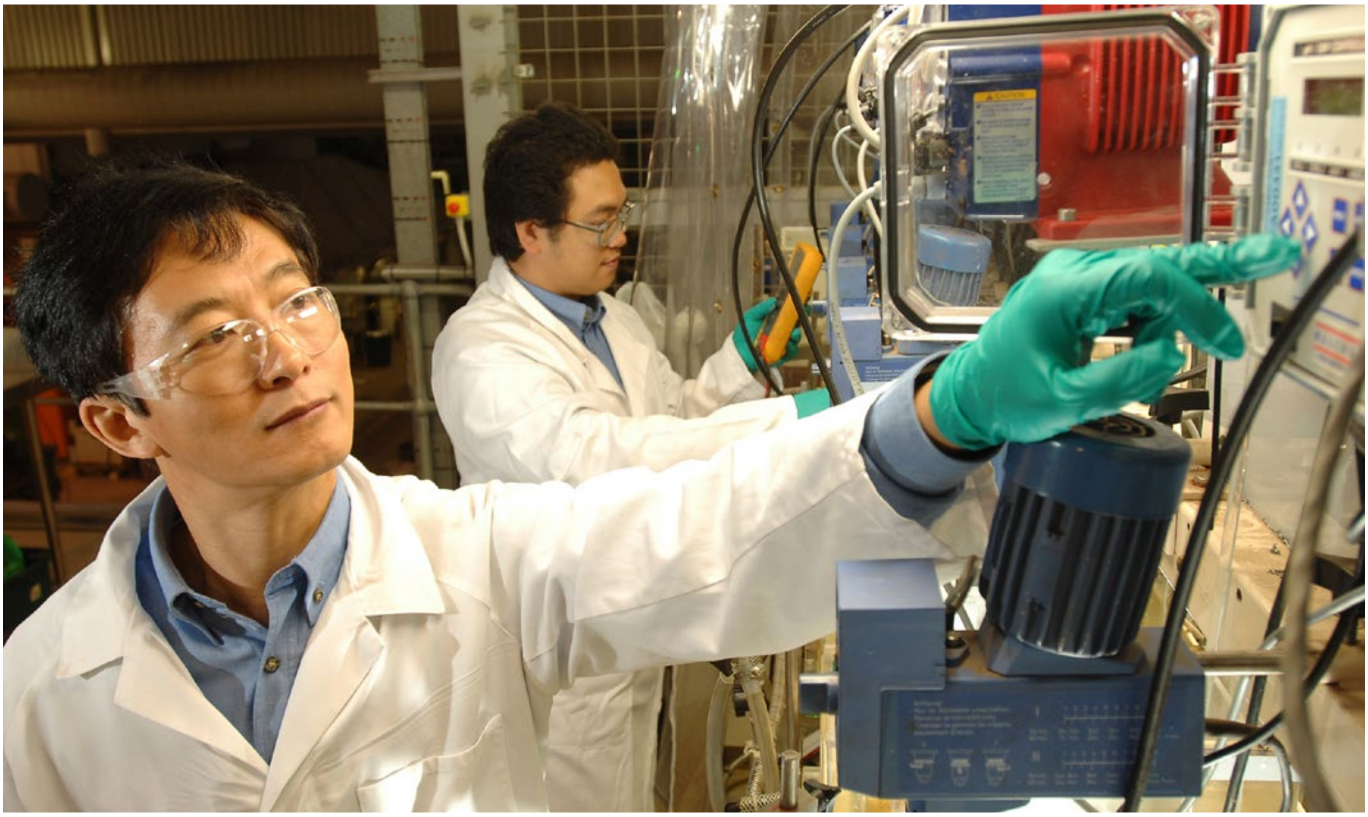
Ion exchange; Membrane separation; Adsorption

Emerging separation applications have the potential to bring about improvements in product purity, sustainability or cost relative to incumbent processes. However, RD&D is needed to overcome scalability barriers. International RD&D collaboration with partner organisations can help advance technology readiness and build new capability.

Technologies that fall under this category include novel approaches to ion exchange and the more emerging membrane separation and adsorption methods. Australia possesses patents in ion exchange, and there is a role for RD&D to support piloting and demonstrations. Across all emerging areas, there is a role for RD&D in developing advanced materials and continuous processes to enable scalability.

International engagement will be needed to de-risk pilot projects through funding or offtake agreements, and for more emerging areas, to support knowledge sharing and capability building.

CSIRO researchers monitoring the solvent extraction rig at the Australian Minerals Research Centre in Waterford, Western Australia



Intermediates and advanced materials

Molten salt electrolysis (light RE metals)

Molten salt electrolysis is mature globally and used commercially to produce light RE metals. Australian companies hold patents in this area and have deployed facilities overseas. There is an opportunity to pilot and demonstrate Australian IP domestically. Alternatively, Australia may consider engaging with overseas RE metal producers that have proven processes to establish commercial-scale projects onshore.

Molten salt electrolysis is the prevalent pathway to produce light RE metals, and its commercial use is concentrated in China, with a few exceptions. Aside from piloting Australian IP domestically, RD&D can enhance Australia's competitiveness by improving energy efficiency, increasing throughput, reducing greenhouse gas emissions, mitigating hazardous by-products, ensuring safety and making the process compatible with the direct production of magnet-relevant alloys.

As an alternative pathway, Australia could collaborate with partner countries that already use electrochemical reduction methods commercially. In this case RD&D can support process optimisation, as well as economic and technical assessments of the technologies in the Australian context.

Metallothermic reduction electrolysis (heavy RE metals)

Metallothermic reduction is a versatile technology and particularly relevant for producing heavy RE metals. Given commercial-scale production is limited to China, there is an opportunity for Australia to diversify global capabilities by adapting its metallothermic reduction IP to RE metals.

The versatility of metallothermic reduction could be useful for a comprehensive downstream expansion of the magnet supply chain outside of China, because high-performance magnets require both light and heavy RE metals. Aside from adapting domestic IP to RE applications, RD&D opportunities include developing alternative metal reductants and continuous processing approaches to address throughput and feedstock constraints.

Given limited global capabilities outside of China, there may be opportunities for collaboration with partner countries to deploy Australian technologies. Engaging with upstream producers, such as EV and wind magnet manufacturers, will be essential to ensure the integration of Australian RE metal production into global supply chains.

Purification

RE metal purification is mature globally and the equipment is available off-the-shelf from overseas manufacturers. No single purification technique can fulfil all product specifications, and a suite of technologies is required instead. Strong engagement with overseas magnet manufacturers will be needed to meet specifications for RE metals produced domestically.

A range of purification methods are typically used in tandem in order to meet the purity requirements of high-performance magnets used in EVs and wind turbines. Aside from procuring off-the-shelf equipment and collaborating with offtakers, there is a role for RD&D to support the deployment of existing technologies onshore through process optimisation. This includes limiting the reintroduction of impurities from the equipment, reducing the number of cycles needed to reach adequate purity levels and integrating different technologies in series.

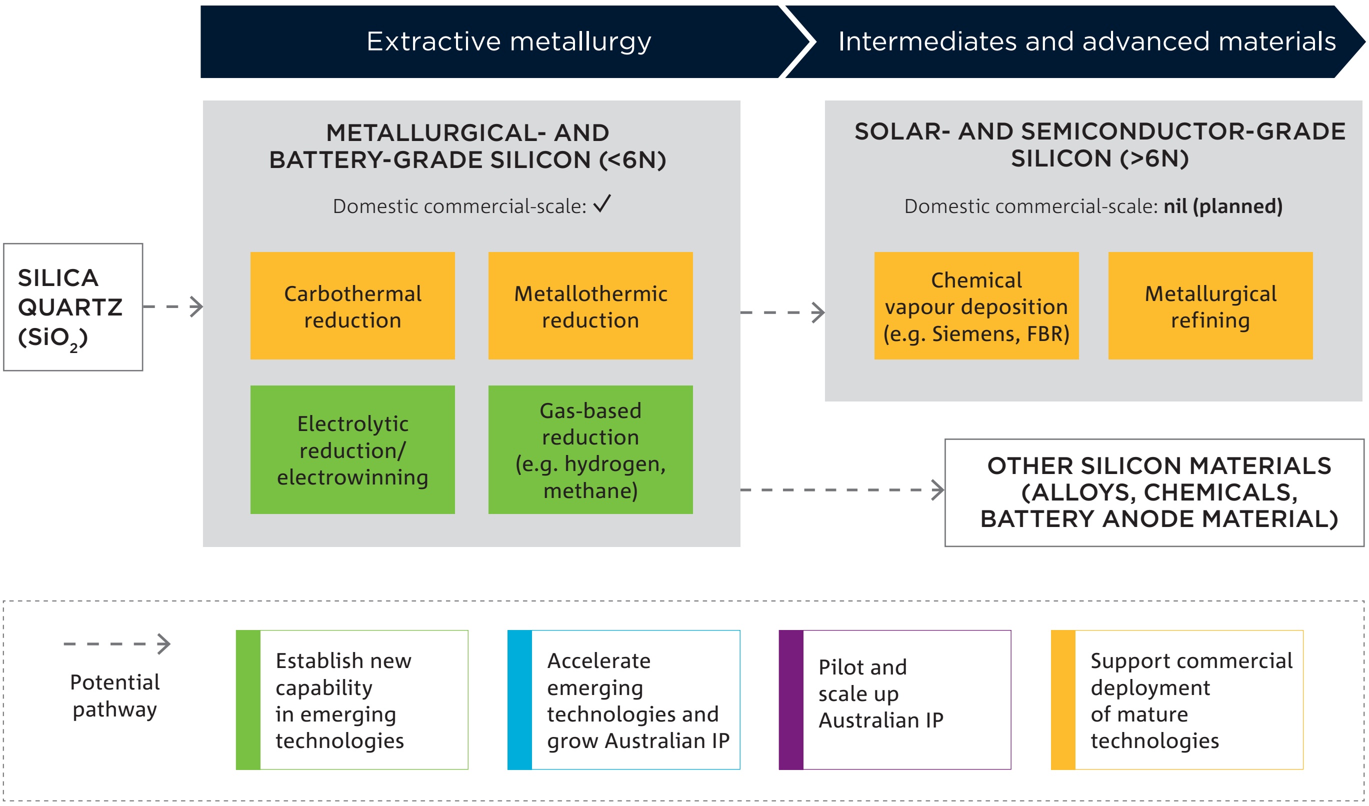
5.6 Silicon

Australia has a history of strong RD&D in downstream solar PV activities, including the development of the passivation emitter rear contact (PERC) solar cell and solar PV recycling research. However, RD&D in mid-stream activities, such as the production of metallurgical silicon and polysilicon, has historically been lower in Australia, despite existing industrial production of metallurgical silicon in Western Australia.

Despite the recent oversupply of polysilicon in the global market, the global energy transition will require a 10 to 12-fold increase on current production capacity,[53] and supply chains are highly vulnerable to disruptions due to concentration.

Australia can play a role in diversifying the global silicon supply chain; however, in light of modest domestic RD&D activity in this area to date, international collaboration and RD&D efforts will be required to deliver near-term commercial outcomes and to develop the capabilities for long-term step-change innovations. This includes supporting the implementation of mature technologies in the Australian context, piloting and scaling up Australian technology, accelerating emerging technologies and growing Australian IP or establishing new capabilities in emerging technologies (Figure 36).

Figure 36: Australian research, development and demonstration (RD&D) opportunities across silicon 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. A more nuanced discussion of each technology can be found below and within the supplementary mineral reports.

53 Hallam et al. (2022) A Polysilicon Learning Curve and the Material Requirements for Broad Electrification with Photovoltaics by 2050. Solar RRL 6(10), 2200458.

Extractive metallurgy

Carbothermal reduction

Commercial production of metallurgical grade silicon is globally mature but faces strong pressure to decarbonise. The continued operation and expansion of this industry in Australia will require emissions reductions and RD&D infrastructure and facilities, namely industrial testing facilities for the carbothermal reduction of Australian quartz.

Australia currently produces metallurgical silicon, but despite its industrial capability, RD&D in this area is limited. Given carbothermal reduction is highly mature, collaboration with overseas equipment manufacturers will be required to deploy state of the art furnaces with low particulate emissions and energy intensity. It is also important to collaborate with research groups specialising in biocarbon (instead of coal-based) reductants for metallurgical processing to build greater domestic capability. Finally, testing the reduction of Australian quartz with various carbon reductants cannot currently be done onshore, and access to such facilities will be essential to accelerate domestic projects.

Metallothermic reduction; Electrolytic reduction; Hydrogen reduction

Emerging approaches to reducing quartz and produce metallurgical silicon, such as electrolytic, metallothermic, hydrogen or gas-based reduction, have the potential to offer cost-effective Zerocarbon neutral alternatives to carbothermal reduction. Despite their longer development timeframes and higher investment risk, these cross-cutting reduction techniques have spillover applications across other minerals and RD&D focus on this capability could support the development of other supply chains.

Partnering with international research organisations that have expertise in emerging quartz reduction techniques will be essential for knowledge sharing and capability building in Australia. Further, Australia has expertise in applying these techniques across other metals, which could be leveraged to develop domestic silicon capability. Studies are required to understand the comparative costs and lifecycle impacts of these emerging processes, and importantly, the level and type of impurities in the final product.

Intermediates and advanced materials

Chemical vapour deposition (e.g. Siemens process)

Commercial production of solar-grade silicon (polysilicon) using chemical vapor deposition techniques are commercially mature and are either highly proprietary or subject to high levels of know-how that are not easily replicated. Strong collaboration with overseas equipment providers will be required to produce polysilicon commercially in Australia.

Stakeholder consultations have indicated that the viability of polysilicon production in Australia will also depend on international offtake agreements or on the integration of domestic ingot and wafer manufacturing. Enabling RD&D areas play a role in supporting the development of an integrated supply chain.

Metallurgical refining

Metallurgical refining of solar-grade silicon is mature and can be used in conjunction with, or instead of, conventional chemical vapour deposition (CVD) processes. As an alternative to CVD, this can potentially reduce barriers to entry into polysilicon production and holds potential sustainability benefits. However, lower product purities carry important market and techno-economic considerations.

Reducing the purity (and solar cell efficiency gap) with CVD-produced polysilicon, while keeping the process comparatively simple and cost-effective, can help de-risk metallurgical refining and increase its viability as a competitive option for Australia. This will require research and collaboration projects to unlock technical improvements, as well as future technoeconomic and market analyses to assess the viability of onshore production.

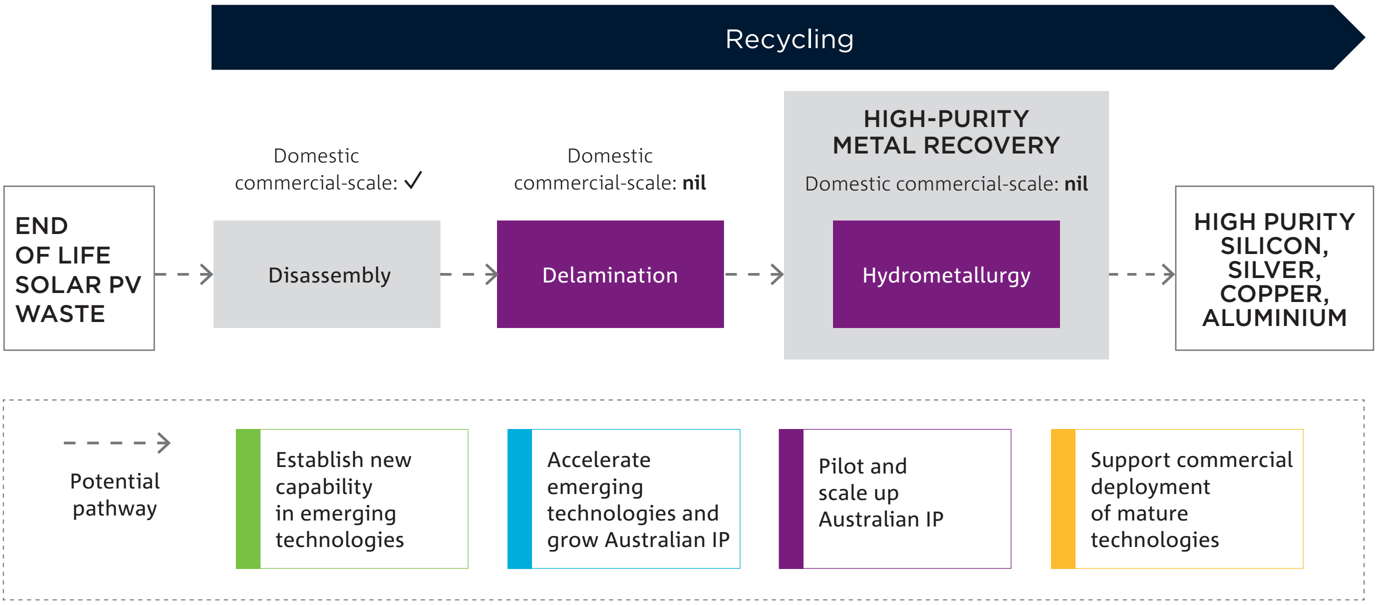
Recycling

● **Solar PV Recycling (delamination, hydrometallurgical high purity metal recovery)**

The global PV industry has been dominated by low-cost bulk and low-purity processes due to the challenging economics of PV recycling. Australia's growing PV waste stream and RD&D processes targeting greater recovery of high-quality materials could improve the viability of domestic projects. Given the global momentum in this research area and Australia's RD&D activity, there is an opportunity to pilot and demonstrate domestic IP.

RD&D focus areas include delamination technologies and hydrometallurgical recovery of high purity materials (Figure 37). Given many technologies have been piloted overseas, collaboration will be essential to ensure Australia's effort and investment are not duplicative.

Figure 37: Australian research, development and demonstration (RD&D) opportunities across solar photovoltaic recycling 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. A more nuanced discussion of each technology can be found below and within the supplementary mineral reports.

Appendix A: Stakeholder groups consulted

Industry, government and research

ABx

ANSTO

Australian Photovoltaic Institute (APVI)

Avenira

Bright Dimension

Silicon & Ferroalloy Consulting

Curtin University

Department of Industry, Science and Resources

Exawatt, CRU Group

EcoGraf

Envirostream

Glencore Nickel

Green Li-ion

IGO

Iluka Resources

ITP Renewables

Lynas

Magnis Energy Technologies

Metso

Neometals

Northern Graphite

Northern Minerals

NTNU, Norway

Pure Battery Technologies

Queensland Pacific Metals

Queensland University of Technology

ReCell Center

Renascor Resources

Sicona

Novalith

Simcoa

SINTEF, Norway

Solquartz

Swinburne University of Technology

Syrah Resources

Tesla

The Cobalt Institute, UK

The Faraday Institution, UK

The University of Newcastle

The University of Melbourne

The University of New South Wales

The University of Queensland

VSPC (subsidiary of Lithium Australia)

Wacker Chemie, Germany

Geoscience Australia

KIGAM, Republic of Korea

Edith Cowan University

University of Toronto, Canada

CSIRO

Robbie McDonald

Marzi Bargamadi

Thomas Ruether

Keith Barnard

Adam Best

Joanne Loh

Jason Czapla

Dongmei Liu

Warren Bruckard

Anna Kaksonen

Goutam Das

Wensheng Zhang

Allan Costine

Nawshad Haque

Suzanne Neville

Lyndsey Benson

Mark Styles

Tim Jones

Daniel Liang

Bruno Vicari Stefani

Gregory Wilson

Tony Hollenkamp

Appendix B: Research publication, patent and pilots metrics

The following data was used to populate the information contained in *Section 2*.

LEGEND	PUBLICATIONS AND PATENTS (%)	PILOTS AND PROJECTS (COUNT)
Very strong	>5	>4
Strong	>3	>3
Monitor	2–3	1 to 3
Limited	<2	<1

*Half point for uncompleted or overseas

Research publications

MINERAL	SUMMARY STEP	TECHNOLOGY	AUSTRALIA AS % OF GLOBAL (EXCLUDING CHINA)	RANKING (EXCLUDING CHINA)
Cobalt	Extraction	**Hydrometallurgy**	8.73	1st
		Pyrometallurgy	4.40	7th
		Reduction	4.35	7th
	Advanced material synthesis	**Advanced material synthesis**	2.64	10th
Graphite	Advanced material synthesis	**Hydrometallurgy**	3.51	7th
		Pyrometallurgy	3.13	11th
		Advanced material synthesis	3.37	8th
Lithium	Extraction	**Hydrometallurgy**	3.47	9th
		Pyrometallurgy	4.38	5th
		Reduction	7.14	4th
	Advanced material synthesis	**Advanced material synthesis**	4.87	5th
	Recycling	**LIB recycling**	4.85	4th
RE	Extraction	**Hydrometallurgy**	3.64	10th
		Pyrometallurgy	3.26	7th
	Advanced material synthesis	**Reduction**	1.79	11th
Silicon	Extraction	**Reduction**	2.82	11th
	Advanced material synthesis	**Advanced material synthesis**	2.02	14th
	Recycling	**PV recycling**	8.87	2nd

LIB, lithium battery; PV, photovoltaic; RE, rare earth elements.

Patents

MINERAL	SUMMARY STEP	TECHNOLOGY	AUSTRALIA AS % OF GLOBAL (EXCLUDING CHINA)
Cobalt	Extraction	**Leaching and purification**	12.26
		Smelting and roasting	7.50
		Hydrogen reduction and electrowinning	No data
	Advanced material synthesis	**CAM synthesis**	0.49
Graphite	Advanced material synthesis	**Purification**	25.00
		Micronisation/spheronisation, coating, composites	1.36
Lithium	Extraction	**Leaching and purification**	33.00
		Calcination, roasting, chlorination	19.00
		Lithium metal	40.00
	Advanced material synthesis	**CAM synthesis**	0.49
		Electrolyte synthesis	
	Recycling	**LIB recycling**	1.16
RE	Extraction	**Extraction from clays, SX, chromatography, purification**	0.60
		Roasting	7.14
	Advanced material synthesis	**Metallothermic, molten salt electrolysis**	3.80
Silicon	Extraction	**Metallurgical silicon**	0.00
	Advanced material synthesis	**Polysilicon**	0.00
	Recycling	**PV recycling**	0.00

CAM, cathode active material; LIB, lithium battery; PV, photovoltaic; RE, rare earth elements; SX, solvent extraction.

Pilots and commercial projects

MINERAL	SUMMARY STEP	TECHNOLOGY	NO. PROJECTS IDENTIFIED
Cobalt	Extraction	**Leaching and purification**	10
		Smelting and roasting	2
		Hydrogen reduction and electrowinning	2
	Advanced Mat.	**CAM synthesis**	1.5
Graphite	Advanced Mat.	**Purification**	0
		Micronisation/spheronisation, coating, composites	2
Lithium	Extraction	**Leaching and purification**	5.5
		Calcination, Roasting, Chlorination	4
		Lithium metal	0.5
	Advanced Mat.	**CAM synthesis**	1.5
		Electrolyte synthesis	0
	Recycling	**LIB recycling**	2.5
RE	Extraction	**Leaching, SX, chromatography, purification**	3.5
		Roasting	2
	Advanced Mat.	**Metallothermic, molten salt electrolysis**	0.5
Silicon	Extraction	**Metallurgical silicon**	1
	Advanced Mat.	**Polysilicon**	0
	Recycling	**PV recycling**	1

CAM, cathode active material; LIB, lithium battery; PV, photovoltaic; RE, rare earth elements; SX, solvent extraction.

Appendix C: Bibliometric analysis methodology

The bibliometric analysis presented within this report series was conducted according to the following methodology.

Data sources

Web of Science

The Web of Science (WoS) is the publication and citation index from Clarivate. It indexes around 20,000 peer-reviewed journals each year, as well as a selection of conference proceedings, datasets and books. The journals are divided into four indices: core journals in the Science Index (SCI), Social Science Index (SSCI) and Arts & Humanities Index (AHCI), along with the Emerging Sources Citation Index (ESCI). The ESCI includes newer journals that have yet to establish a reputation. This index was excluded from the analysis.

Publication metadata is indexed at an article level, making it possible to analyse publication counts by a range of fields, such as subject area, institution, publication type, author, country and year.

WoS is divided into 250 subject areas, allowing for highly granular reporting. Allocation to subject areas takes place at a journal, rather than individual article, level.

A corollary of this is that there is no existing structure that will allow for the analysis of critical minerals publications specifically. Instead, a custom search strategy is required, which groups publications by their metadata, including words appearing in title, abstract and keywords, often with filters based on journal or subject area.

Search strategy

A search strategy was developed to determine the publications to include in the analysis. The strategy generally consisted of a list of topic keyword combinations to include and exclude, as well as a list of WoS subject areas to exclude that were clearly irrelevant. The search matches topic keywords against article titles, abstract text, author-provided keywords and Keywords Plus (keywords determined by Clarivate through an algorithm). A keyword-based strategy was required because there was no clear WoS subject area definition that included critical minerals mid-stream processing and recycling.

To build the search strategy, 20 cross-cutting technology areas were identified that are relevant across all evaluated minerals. These technologies were divided into four categories (Table 7).

Table 7: Cross cutting capabilities across critical minerals processing

REDUCTION	PYROMETALLURGY	HYDROMETALLURGY	ADVANCED MATERIAL SYNTHESIS
• Carbothermal • Metallothermic • Hydrogen and gas-based reduction • Electrowinning/electrolytic • Molten salt/high temperature electrolysis	• Calcination • Roasting • Pyrolysis • Directional solidification	• Acid leaching • Alkaline leaching • Solvent extraction • Ion exchange • Crystallisation	• Ball milling and classification • Co-precipitation • Sol-gel • Spray-based • Chemical vapour deposition • Solvothermal/hydrothermal

Terms associated with each technology were sourced from the literature and stakeholder consultations and aggregated to build a keyword list for each of the four categories. The keyword lists were used to search the WoS Core Collection database, for each mineral.

Search scripts including relevant keywords were developed for the minerals assessed. The minerals included lithium, cobalt, graphite, silicon, REs and all other critical minerals.

- The REs search was restricted to the keywords dysprosium, neodymium, praseodymium and terbium and the general term ‘rare earth’
- All other critical minerals included high purity alumina, antimony, beryllium, bismuth, chromium, gallium, germanium, hafnium, indium, magnesium, manganese, niobium, platinum, palladium, rhodium, ruthenium, iridium, osmium, rhenium, scandium, tantalum, titanium, tungsten, vanadium and zirconium.

Dataset filters

To improve accuracy, a filter was applied to the results to include only research areas that are relevant to mineral processing and advanced material synthesis (e.g., Metallurgical engineering, Electrochemistry, Materials Science).

The results of the search were restricted to those research areas and limited to the 2007 – 2023 period.

Quality assessment and data cleaning

The results were exported and pre-processed in Excel and manually assessed and cleaned to improve the rate of accuracy:

- The raw data extracts were ordered by WoS relevance order (this is based on the WoS algorithm considering how many relevant search terms are found in each record).
- The project team assessed samples of at least five publications at each percentile of the dataset to determine the point at which results became consistently inaccurate (where the accuracy dropped below 60% in the sample). This determined the cut-off point, with all publications falling outside of the cut-off point removed from the analysis.
- As such it is expected that the final dataset may contain a proportion of non-relevant results. Significant variability in natural language can result in keyword combinations matching articles from areas that are out of scope.
- It is also expected that a small proportion of relevant articles may have been excluded from the dataset, particularly where articles use uncommon terminology or keywords not used in the search, or when a relevant article is part of an excluded research area.

The resulting dataset was uploaded to PowerBI and further processed to remove duplicates, prevent instances of double counting, extract countries and organisations, and generate summary graphs.

Some instances of duplication were allowed to ensure collaborative output and cross-cutting research were captured:

- A publication may be counted multiple times if it was written collaboratively by organisations in multiple countries (e.g. Australia and the UK will both receive a publication count if a journal article written collaboratively by an Australian and a UK university).
- A publication may be counted multiple times if it covers more than one mineral (e.g. a publication discussing a CAM formulation containing lithium and cobalt will be counted once for lithium and once for cobalt).

Publication metrics

Publication count

The publication count is a measure of output volume and represents the number of publications in the given data source for the stated organisation or country in the stated year range. The criteria by which the publication count and all associated citation statistics were acquired are usually stated in figure headings or in a note under the table, as appropriate. Please note that most bibliometric analyses look only at articles, reviews and, where the necessary citation data exist for them, conference proceedings, and omit smaller documents that do not tend to contain research output, such as book reviews and editorials.

Appendix D: Patent analytics methodology

The patent analysis presented within this report series was conducted according to the following methodology.

The methodology for patent analytics involved three stages: technology taxonomy development; database searching; and quality control and assessment.

First, a literature review and stakeholder consultation were performed for each critical mineral to identify the in-scope technologies used for mid-stream processing. This covers the steps occurring after beneficiation, up to and including the production of high-purity metals or specific compounds.

- Highly representative terms were sourced from the literature and stakeholder consultations to build individual search term lists.
- Where possible, International Patent Classification (IPC) or Cooperative Patent Classification (CPC) codes matching each technology were also identified and compiled into individual lists.

Second, each list of terms and codes was used as part of a search script in the Orbit Intelligence (Questel) database to identify patent filings related to the corresponding mineral and processing technology.

- The final search scripts are not publicly available.

Finally, a sample from the raw dataset was assessed by the testing team to estimate the accuracy of the results against the defined technology category. ChatGPT was used to process patent claims and abstract and rapidly identify relevant and irrelevant patents. A minimum threshold of 70% was established for acceptance and further analysis.

Where a dataset did not meet the minimum threshold, up to two additional iterations of the search were performed refining the search strategy, with a final step of manual clean-up if necessary.

- Manual clean-up involved using filters to select for highly relevant codes or keywords and removing unmatched patents from further analysis.
- In technologies with a lower number of filings, the clean-up entailed a complete review to manually exclude unrelated results.
- Emerging technologies with very low patent counts were excluded from the results.
- The resulting dataset was processed in Excel and Power BI to extract countries and organisations, and to generate summary graphs.

Patent search limitations

A patent search strategy will include the use of keywords and/or patent classifications; however, it is not possible to guarantee that all relevant patents have been discovered and searched or that patents will be correctly classified.

- It is expected that up to 30% of patents identified in the results may be moderately relevant or not relevant to the technology category. The following are examples of instances where this may occur:
  - where search terms and code combinations match patent areas that are not relevant to the scope of the analysis, introducing irrelevant patents into the results
  - where patents have been incorrectly classified by the applicants during the filing process
  - where patent abstracts and claims use natural language; this can introduce irrelevant results if a non-relevant patent has used a search term in its abstract and claim.
- It is expected that some relevant patents may have been missed and are therefore not included in the results. The following are examples of where this may occur:
  - Although the search scripts have used known search terms and patent codes, it is not possible to identify all possible combinations, or all variants in natural language use. Furthermore, some search terms can introduce a high proportion of irrelevant results compared with the proportion of relevant results and have therefore been omitted from the search strategy.
  - Some patent claims and abstracts may deliberately use obscure or general language, which have not been included in the search strategy.
  - There may be instances where relevant patents for a given mineral have been filed under a different mineral.

The search strategy will be implemented in an appropriate database. Each database has respective limitations as to its patent coverage and the level of information available for patent records. There is no single database that has complete coverage of all patent data. The same keyword search in one database will not necessarily provide the same results in another database.

Regardless of the database used, patent information is not published in databases when a patent is first filed (i.e. at the priority date). The first publication of information for a patent may not occur for at least 18 months in most cases. Therefore, it is likely that any searching results for more recent years do not yet include all patent applications.

Disclaimer

CSIRO advises that the information contained in this publication comprises general statements based on patent information research. The reader is advised and needs to be aware that such information may be incomplete for reasons such as the abovementioned patent search limitations, or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, CSIRO (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses, and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Appendix E: International supply chain activity references

The following documents were used to inform Section 3 of the report. It should be noted that the list below is a point-in-time assessment as of 21 April 2024. This is a rapidly evolving space and therefore subject to change.

Source documents for public funding and national strategies

	PUBLIC FUNDING/NATIONAL STRATEGIES SOURCE DOCUMENTS
Global	• European Commission (2022) REPowerEU: Affordable, secure and sustainable energy for Europe. <https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en>
Canada	• Government of Canada (2024) The battery value chain. Canadian Automotive Industry. <https://ised-isde.canada.ca/site/canadian-automotive-industry/en/battery-value-chain>
France	• European Commission (2022) REPowerEU: Affordable, secure and sustainable energy for Europe. <https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en> • European Commission (n.d.) Important projects of common European interest (IPCEI). <https://competition-policy.ec.europa.eu/state-aid/legislation/modernisation/ipcei_en> • Global Trade Alert (2023) France: Launch of investment fund in critical minerals and metals. <https://www.globaltradealert.org/intervention/119806/capital-injection-and-equity-stakes-including-bailouts/france-launch-of-investment-fund-in-critical-minerals-and-metals> • Ministry of the Economy, Finance and Industrial and Digital Sovereignty (2022) [France 2030: An investment plan for France]. <https://www.economie.gouv.fr/france-2030> • Aguesse F et al (2023) Inventing the Sustainable Batteries of the Futures: Research Needs and Future Action. Battery 2030. <https://battery2030.eu/wp-content/uploads/2023/09/B-2030-Science-Innovation-Roadmap-updated-August-2023.pdf> • Solvay (2021) Solvay and its partner Veolia set up demo plant for recycling battery metals <https://www.solvay.com/en/press-release/solvay-and-its-partner-veolia-set-demo-plant-recycling-battery-metals> • Grudzien P (2024) Transforming end-of-life battery backs into commodity-grade materials: recycling at TES. Batteryverse <https://www.battereverse.eu/blog/transforming-end-of-life-battery-packs-into-commodity-grade-materials-recycling> • Sibanye Stillwater (2024) Sandouville nickel refinery <https://www.sibanyestillwater.com/business/europe/sandouville-france/> • Choose France (2024) Conversion: France for Batteries. Business France <https://franceforbatteries.fr/conversion/>
Germany	• European Commission (2022) REPowerEU: Affordable, secure and sustainable energy for Europe. <https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en> • European Commission (n.d.) Important projects of common European interest (IPCEI). <https://competition-policy.ec.europa.eu/state-aid/legislation/modernisation/ipcei_en> • Kowalcze K, Nienaber M, Burton M (2023) Germany draws up €2 billion state fund to secure key commodities. Mining.com • Saatkamp M (2023) Europe expands recycling of lithium-ion batteries: Focus on capacity development, demand analysis and market players. Fraunhofer ISI <https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-kapazitaeten-bedarf-akteure-markt-analyse.html>
India	• IEA (2023) Faster adoption and manufacturing of hybrid and electric vehicles (FAME) scheme – Phase I & II. <https://www.iea.org/policies/12517-faster-adoption-and-manufacturing-of-hybrid-and-electric-vehicles-fame-scheme-phase-i-ii> • IEA (2023) Global EV outlook 2023. <https://www.iea.org/reports/global-ev-outlook-2023>

	PUBLIC FUNDING/NATIONAL STRATEGIES SOURCE DOCUMENTS
Japan	• Ministry of Economy, Trade and Industry (2022) Battery industry strategy- Interim Summary <https://www.meti.go.jp/english/report/pdf/0520_001a.pdf> • Ministry of Economy, Trade and Industry (2021) Outline of strategic energy plan. <https://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/6th_outline.pdf> • IEA (2021) Japan 2021. <https://www.iea.org/reports/japan-2021> • Mining.com (2023) Japan to subsidize half the costs of lithium, critical minerals projects – report. <https://www.mining.com/japan-to-subsidize-half-the-costs-of-lithium-critical-minerals-projects-report/>
Republic of Korea	• The Ministry of Economy and Finance (2020) Korean new deal: National strategy for a great transformation. <https://www.mofa.go.kr/eng/brd/m_22747/view.do?seq=35&srchFr=&amp%3BsrchTo=&amp%3BsrchWord=&amp%3BsrchTp=&amp%3Bmulti_itm_seq=0&amp%3Bitm_seq_1=0&amp%3Bitm_seq_2=0&amp%3Bcompany_cd=&amp%3Bcompany_nm=&page=1&titleNm=> • Invest Korea (2021) Endless opportunities for collaborations. KOTRA, Seoul. • STIP Compass (2023) The 2030 K-Battery development strategy. <https://stip.oecd.org/stip/interactive-dashboards/policy-initiatives/2023%2Fdata%2FpolicyInitiatives%2F99997435> • Batteries Europe (2023) Battery innovation system of South Korea. <https://batterieseurope.eu/wp-content/uploads/2023/06/Battery-Innovation-South-Korea_rev6.pdf> • OCI (2023) The joint venture of OCI and POSCO Future M completed the construction of a plant to produce high-softening-point pitch, a core material for anode materials for rechargeable batteries. Newsroom. <https://www.oci.co.kr/en/newsroom/news/22>
UK	• GOV.UK (2020) The Ten Point Plan for a Green Industrial Revolution. HM Government. <https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution> • National Audit Office (2023) Decarbonising the power sector. Department for Energy Security and Net Zero. <https://www.nao.org.uk/reports/decarbonising-the-power-sector/> • Department for Business, Energy & Industrial Strategy (2022) British energy security strategy. <https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy>
USA	• The White House (2022) Building a clean energy economy: A guidebook to the Inflation Reduction Act's investments in clean energy and climate action. <https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf> • The White House (2022) Fact sheet: Biden–Harris administration driving U.S. battery manufacturing and good-paying jobs. <https://www.whitehouse.gov/briefing-room/statements-releases/2022/10/19/fact-sheet-biden-harris-administration-driving-u-s-battery-manufacturing-and-good-paying-jobs/> • The White House (2022) Fact sheet: CHIPS and science act will lower costs, create jobs, strengthen supply chains and counter China. <https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/> • Zhang J, Liang C and Dunn JB (2023) Graphite Flows in the U.S.: Insights into a Key Ingredient of Energy Transition. Environmental Science & Technology 57(8), 3402-3414

Source documents for production

	GLOBAL SOURCE DOCUMENTS
Mining (graphite, lithium and cobalt)	• Accenture (2021) Future Charge: Building Australia's battery industries. Future Battery Industries Cooperative Research Centre. <https://fbicrc.com.au/wp-content/uploads/2021/06/Future-Charge-Report-Final.pdf> • U.S. Department of the Interior; U.S. Geological Survey (2023) Mineral commodity summaries 2023. <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf> • Government of Canada (n.d.) Lithium facts. <https://natural-resources.canada.ca/our-natural-resources/minerals-mining/mining-data-statistics-and-analysis/minerals-metals-facts/lithium-facts/24009> • World Integrated Trade Solution (2022) Graphite; artificial exports by country in 2022. <https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2022/tradeflow/Exports/partner/WLD/product/380110>
Lithium hydroxide/ carbonate	• World Integrated Trade Solution (2021) Lithium oxide and hydroxide exports by country in 2021. <https://wits.worldbank.org/trade/comtrade/en/country/ALL/year/2021/tradeflow/Exports/partner/WLD/product/282520#> • Mordor Intelligence (2023) Lithium hydroxide market size & share analysis – growth trends & forecasts (2024–2029). <https://www.mordorintelligence.com/industry-reports/lithium-hydroxide-market> • Mordor Intelligence (2023) Lithium carbonate market size & share analysis – growth trends & forecasts (2024–2029). <https://www.mordorintelligence.com/industry-reports/lithium-carbonate-market>
Refined cobalt	• Cobalt Institute (2022) Cobalt market report 2021. <https://www.cobaltinstitute.org/resource/state-of-the-cobalt-market-report-2021/>

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Cathode active materials	• BCC Research (2023) Next-generation advanced batteries: Global markets. <https://www.bccresearch.com/market-research/fuel-cell-and-battery-technologies/next-generation-advanced-battery-market.html> • BCC Research (2019) 2019 Fuel cell and battery research review. <https://www.bccresearch.com/market-research/fuel-cell-and-battery-technologies/2019-fuel-cell-and-battery-research-review-market-report.html> • Emergen Research (2023) Cathode active materials industry overview < https://www.emergenresearch.com/industry-report/cathode-active-materials-market> • Novonix (2024) Piloting production for cathode materials. <https://www.novonixgroup.com/cathode-materials/>
Anode materials	• POSCO (2024) POSCO Group, the sole player in anode materials, is shaping the futures. POSCO Newsroom <https://newsroom.posco.com/en/3-minute-recap-youtube-posco-group-the-sole-player-in-anode-materials-is-shaping-the-future/> • POSCO (2020) POSCO FUTURE M Rechargeable Battery Anode Material Plant, Sejong. POSCO <https://www.poscoenc.com:446/en/business_areas/project.aspx?brpt=210> • Business France (n.d.).Tokai COBEX. The battery show Europe 2024. <https://event.businessfrance.fr/the-battery-show-europe-2024/tokai-cobex/>
Lithium electrolytes	• Business Research Insights (2023) Lithium-ion battery electrolyte market report overview. <https://www.businessresearchinsights.com/market-reports/lithium-ion-battery-electrolyte-market-104831> • Federal Consortium for Advanced Batteries (2021) National blueprint for lithium batteries 2021–2030. <https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf> • LANXESS (2021) LANXESS enters battery chemistry business: electrolyte production for lithium-ion batteries in Leverkusen, Germany. Press release (30/03/2021). <https://lanxess.com/en/Media/Press-Releases/2021/03/LANXESS-enters-battery-chemistry-business-electrolyte-production-for-lithium-ion-batteries-in-Leverkusen-Germany> • Business France (n.d.). Solvay. Company directory - Components – Electrolyte salts. <https://franceforbatteries.fr/solvay-4/>
Cell component manufacturing **Battery pack assembly** **Reuse and recycling**	• Accenture (2021) Future charge: Building Australia's battery industries. Future Battery Industries Cooperative Research Centre. <https://fbicrc.com.au/wp-content/uploads/2021/06/Future-Charge-Report-Final.pdf> • AusTrade (2018) The lithium-ion battery supply chain: New economy opportunities for Australia. <https://apo.org.au/node/210341> • Roskill (2020) Tables 18–21 and Chapter 14. In Lithium-ion Batteries: Outlook to 2029. Roskill in Accenture (2021) Future Charge: Building Australia’s Battery Industries. FBICRC. • Saatkamp M (2023) Europe expands recycling of lithium-ion batteries: Focus on capacity development, demand analysis and market players. Fraunhofer ISI <https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-kapazitaeten-bedarf-akteure-markt-analyse.html> • Cobalt Institute (2022) Cobalt Market Report 2022. Cobalt Institute <https://www.cobaltinstitute.org/wp-content/uploads/2023/05/Cobalt-Market-Report-2022_final-1.pdf> • Tees Valley Lithium (2023) Establishing Tees Valley Lithium to Supply Europe’s Burgeoning Battery Market [Investor Presentation] Alkemy Capital Investments PLC <https://teesvalleylithium.co.uk/wp-content/uploads/2023/11/Alkemy-IR-Presentation_November2023-1.pdf> • British Lithium (2023) Imerys British Lithium: on track to become Europe’s first commercial battery-grade lithium carbonate producer. Imerys <https://imerysbritishlithium.com/joint-venture/> • Green Lithium (2024) FAQs Green Lithium Teeside Project. Green Lithium <https://greenlithium.co.uk/teesside-project-faqs> • The Faraday Institution (2022) UK electric vehicle and battery production potential to 2040 <https://www.faraday.ac.uk/ev-economics-study-2022/> • Lion Electric (2023) Lion Electric Announces Successful Final Certification of its LionBattery MD Battery Pack. Press release (07/12/2023) https://thelionelectric.com/documents/en/Press_Release_MD_Lion_Battery_Certification_ENG.pdf • SNAM (n.d.) Expertise. Produits. https://www.snam.com/expertise/produits/ • LOHUM (n.d.) Our solutions. Lithium battery recycling with LOHUM. <https://lohum.com/battery-recycling/>

Rare earth magent supply chain (wind and electric vehicles)

Source documents for public funding and national strategies

	PUBLIC FUNDING/NATIONAL STRATEGIES SOURCE DOCUMENTS
Canada	• Government of Canada (2024) Rare earth elements facts. <https://natural-resources.canada.ca/our-natural-resources/minerals-mining/mining-data-statistics-and-analysis/minerals-metals-facts/rare-earth-elements-facts/20522>
France	• Gauß R, Burkhardt C, Carencotte F, Gasparon M, Gutfleisch O, Higgins I, Karajić M, Klossek A, Mäkinen M, Schäfer B, Schindler R and Veluri B (2021) Rare earth magnets and motors: A European call for action. A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance. <https://eit.europa.eu/sites/default/files/2021_09-24_ree_cluster_report2.pdf> • Tenerrdis (n.d.) MAGNOLIA – MAGNets on pilOt LIne Ambition. <https://www.tenerrdis.fr/en/projects/magnolia-magnets-on-pilot-line-ambition/>
Germany	• Gauß et al. (2021) Rare earth magnets and motors: A European call for action. A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance. <https://eit.europa.eu/sites/default/files/2021_09-24_ree_cluster_report2.pdf>
India	• Confederation of Indian Industry (2021) Australian economic strategy for mining sector. <https://aes2020.in/wp-content/uploads/2021/01/MINING-SECTOR.pdf> • Government of India Ministry of Mines (2023) Critical minerals for India. Report of the Committee on Identification of Critical Minerals. <https://mines.gov.in/admin/storage/app/uploads/649d4212cceb01688027666.pdf>
Japan	• Fujioka K (2023) Japan to subsidize half of costs for lithium and key mineral projects. Nikkei Asia. <https://asia.nikkei.com/Economy/Japan-to-subsidize-half-of-costs-for-lithium-and-key-mineral-projects> • The Japanese Government Cabinet Secretariat (2022) National security strategy of Japan. [Provisional translation] <https://www.cas.go.jp/jp/siryou/221216anzenhoshou/nss-e.pdf> • Nikkei Asia (2021) Japan to boost public funding for rare earth exploration. <https://asia.nikkei.com/Business/Markets/Commodities/Japan-to-boost-public-funding-for-rare-earth-exploration> • Vekasi K (2023). Securing supply chain resiliency for critical rare earth metals. In Critical Minerals, the Climate Crisis and the Tech Imperium. Archimedes, Vol. 65. (Ed. S Kalantzakos) 45–68. Springer, Cham. <https://doi.org/10.1007/978-3-031-25577-9_3> • Burke SE, Hughes L, Phung QH, Vekasi K, Wu YH (2022) Critical minerals: Global supply chains and Indo-Pacific geopolitics. The National Bureau of Asian Research. <https://www.nbr.org/wp-content/uploads/pdfs/publications/sr102_criticalminerals_dec2022.pdf>
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