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From minerals to materials

Supplementary report: Cobalt

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Contents

Contents	3
Glossary	4
1 Executive summary	5
2 Objectives and scope	10
3 RD&D challenges and opportunities	11
3.1 Extraction of cobalt compounds from ores	14
3.2 Production of refined cobalt products	34

Glossary

Abbreviations

AL	Atmospheric leaching	LIB	Lithium-ion battery
CAM	Cathode active material	MHP	Mixed hydroxide precipitate
CAPEX	Capital expenditure	MSP	Mixed sulphide precipitate
CC	Cooling crystallisation	NAPL	Nitric acid pressure leaching
CoSO₄·7H₂O	Cobalt sulphate heptahydrate	Ni-Cu-(Co-PGE)	Nickel-copper-(cobalt-platinum group elements)
EC	Evaporative crystallisation	NMC	Nickel-manganese-cobalt CAM
EFC	Eutectic freeze crystallisation	NO_x	Nitrous oxide
EPAL	Enhanced pressure acid leaching	NPI	Nickel pig iron
EW	Electrowinning	OEM	Original equipment manufacturer
HL	Heap leaching	pCAM	Precursor cathode active material
HPAL	High-pressure acid leaching	RD&D	Research, development and demonstration
IX	Ion-exchange separation	RKEF	Rotary kiln-electric furnace
LCO	Lithium cobalt oxide	SAL	Selective acid leach
LFP	Lithium iron phosphate	SX	Solvent extraction

1 Executive summary

Lithium-ion batteries (LIBs) are expected to make up a large portion of the global EV market share for the near and medium term, generating significant demand for critical battery materials, including cobalt. However, the global LIB supply chain currently faces sustainability challenges, geographic concentration, and technical challenges.

The majority of the world's cobalt is mined in the Democratic Republic of Congo; however, some operations are associated with poor working conditions and human rights concerns. Indonesia is emerging as a large cobalt miner and refiner but is challenged by significant environmental impacts from coal-powered processing and large waste volumes. Finally, the mid-stream processing portion of the LIB supply chain is highly concentrated in China, particularly the production battery-grade cobalt compounds and cathode active materials.

On the supply side, sulphide deposits containing cobalt and nickel are depleting and ore grades are declining globally. This impacts the unit cost of production upstream, which then impacts the economics of mid-stream processing. Although laterite ores account for the majority of terrestrial nickel and cobalt, this deposit type is less economic to extract due to its complexity.

With Australia's resource endowment, there is an opportunity for the country to move down the supply chain into the production of battery grade cobalt compounds, and to position itself as an alternative and sustainable supplier. This also paves the way for integrating downstream cathode active material (CAM) manufacture onshore. Australia's strong research, demonstration and development (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 from overseas in the Australian context; demonstrating Australian IP at scale; progressing Australia's technologies beyond the lab; or growing emerging capabilities in step-change technologies (Figure 1 and Figure 2).

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

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

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

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

● 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 [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]).

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.

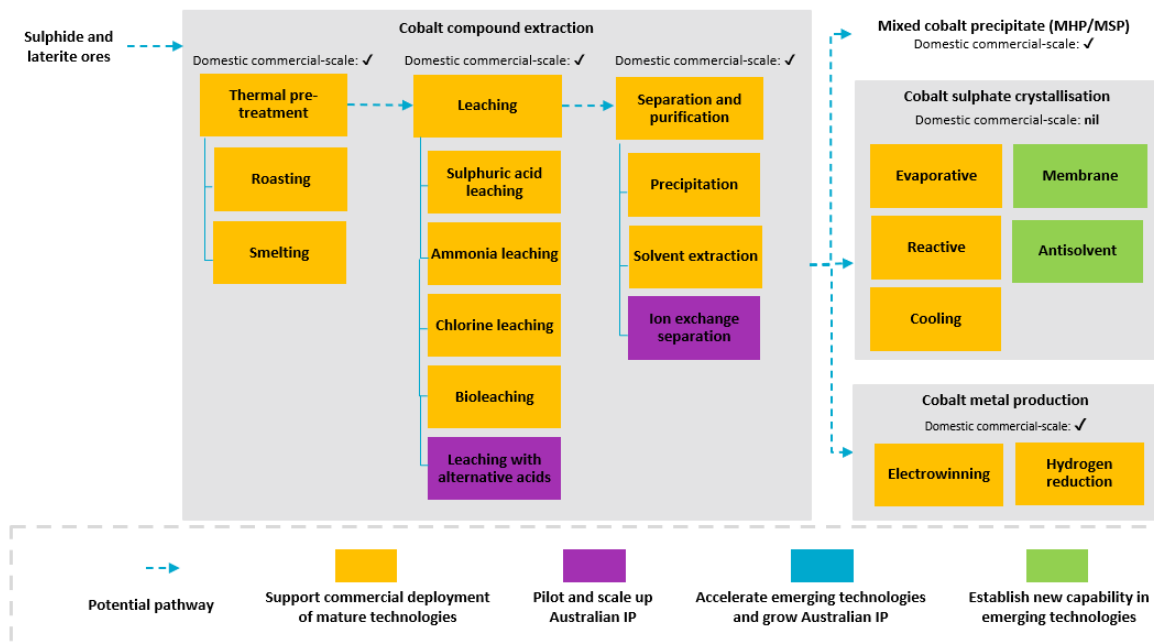
This area will require close international engagement with overseas battery manufacturers to ensure that Australian production meets their specifications and to de-risk commercial projects through off-take agreements.

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.

Figure 2: Australian RD&D opportunities across cobalt processing technologies.



NOTE: The type of RD&D opportunity is based on the highest known level of development for each process. However, each processing technology includes individual variants and approaches that may be more emerging, which could attract a different RD&D opportunity. A more detailed discussion of each technology can be found in its respective section of the report.

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

2 Objectives and scope

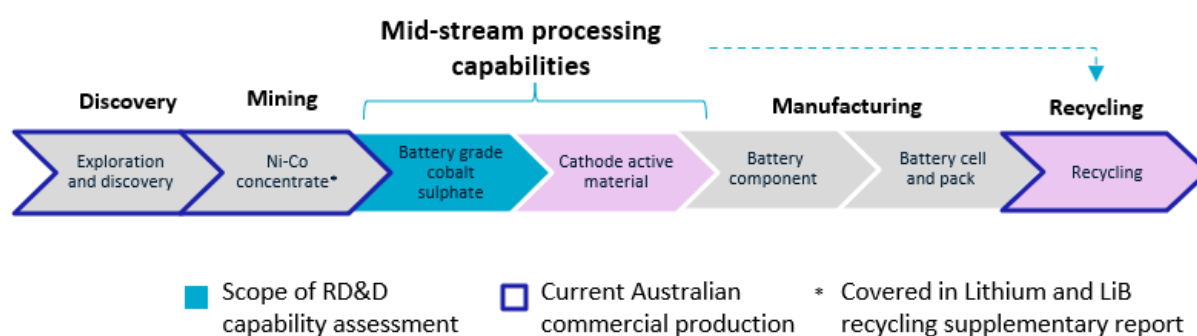
This supplementary report will focus on technologies used in the production of battery grade cobalt sulphate. The production of cathode materials and recycling are covered in the Lithium and LiB Recycling Chapters.

This chapter aims to:

- Introduce the main current and emerging technologies used in the extraction of cobalt from ores, the separation from other metals, and the production of both battery-grade cobalt sulphate and cobalt metal.
- Present the level of IP and research activity occurring in Australia and globally, for each emerging and mature technology area.
- Identify key challenges and opportunities for Australia to build domestic IP and collaborate with international partners, based on technological maturity, IP trends and research activity.

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

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



*Concentrate contains cobalt and nickel as well as other metals such as copper and platinum group elements

Ni, Nickel; Co, Cobalt; LiB, Lithium-ion battery.

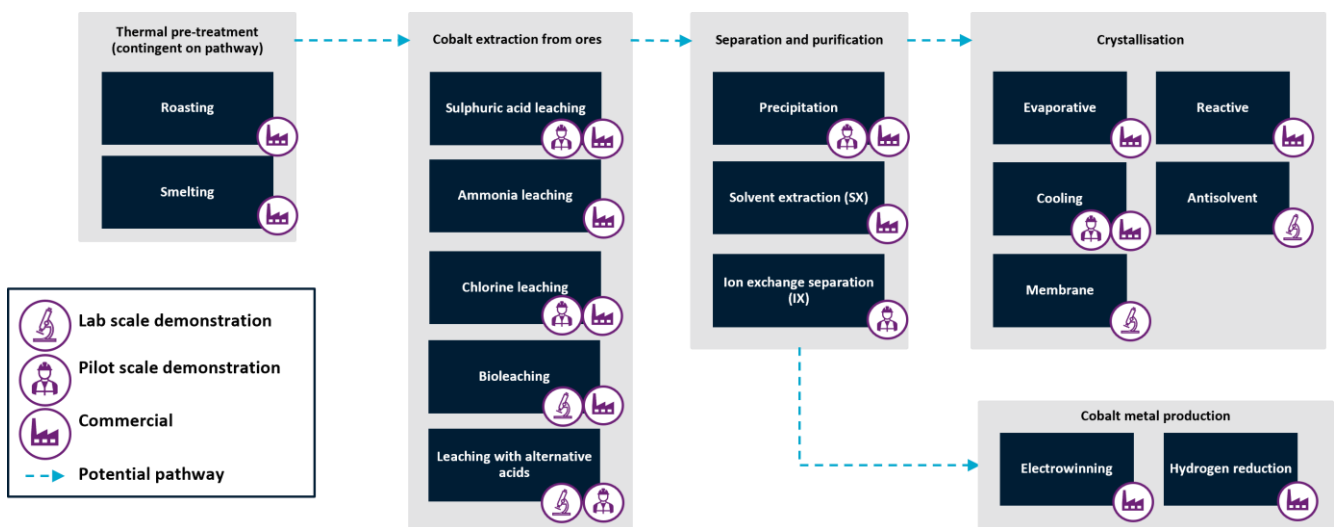
3 RD&D challenges and opportunities

The cobalt supply chain for lithium-ion batteries is commercially established globally, and underpinned by mature technologies in extraction, separation, purification, and recovery. However, there are several emerging technologies being developed globally to improve process efficiency and sustainability outcomes.

This supplementary report will discuss the RD&D challenges and opportunities related to mature and emerging technologies for extracting and separating cobalt compounds from Australian ores and for refining them to battery grade cobalt sulphate and high purity cobalt metal.

- Section 3.1 will cover the initial extraction and separation from cobalt-bearing laterite and sulphide ores to produce a cobalt-rich solution.
- Section 3.2.1 will cover the precipitation, separation and purification processes required to produce mixed precipitate intermediates and high purity, refined cobalt products.
- Section 3.2.2 will cover the crystallisation approaches to produce battery-grade cobalt sulphate.
- Section 3.2.3 will cover the methods to produce high purity cobalt metal.

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

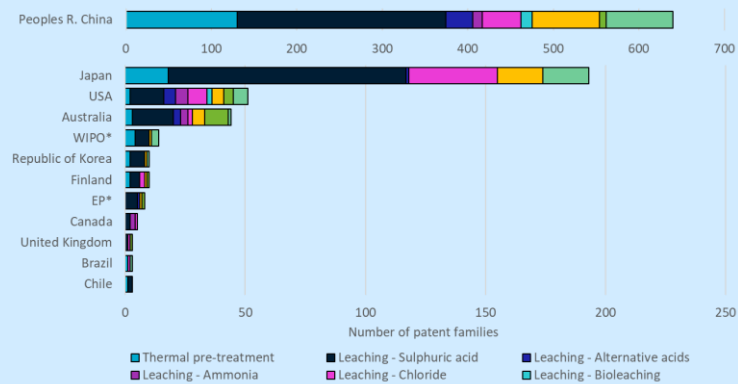


NOTE: Current status has been assigned based on the highest known level of development for each process, as applied specifically to the treatment of cobalt ores, cobalt compound separation and purification, cobalt sulphate crystallisation, or cobalt metal production. The development status of each process will vary when considering other applications and contexts.

Global R&D and commercialisation snapshot

Production of cobalt compounds and refined cobalt products

Figure 5: Patent output in cobalt mid-stream processing from 2007 to 2022, by country and processing technology.



*Applications filed under an entity other than a country.

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

Figure 5 shows the number of patents filed between 2007 and 2022 related to the cobalt processing technologies covered in this report. China represents 64% of all activity, followed by Japan (19%) and the United States (5%). Australian patents account for 4% of all filings in the analysis, with activity in almost all categories.

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

Figure 6: Research publication activity related to cobalt mid-stream processing from 2007 – 2023, by country and processing technology.

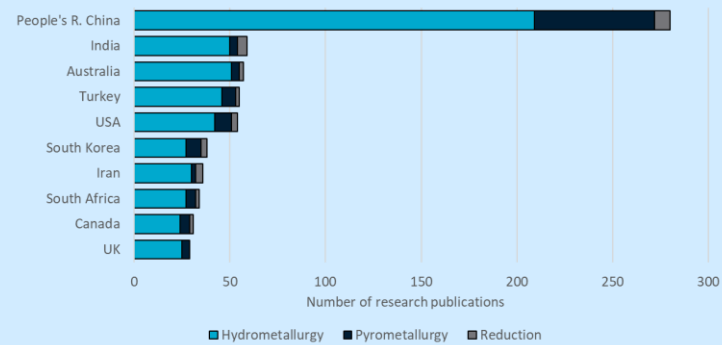
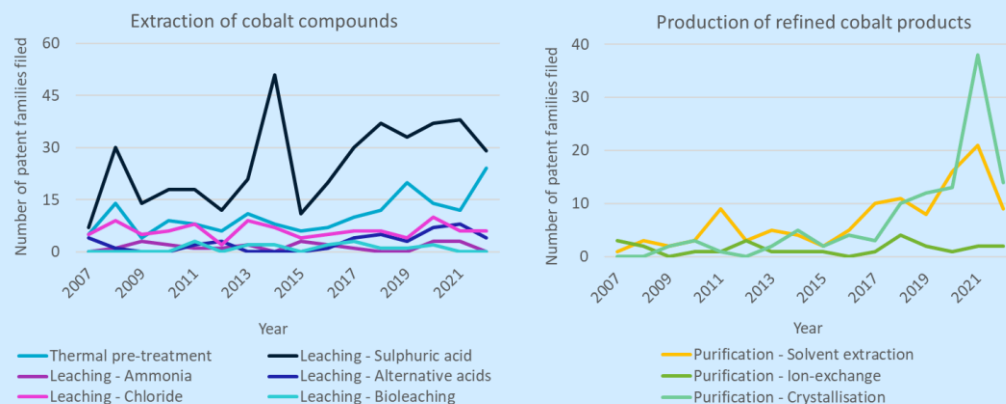


Figure 6 shows the number of research publications related to cobalt mid-stream processing that were identified by the analysis for the 2007 – 2023 period, by country and processing technology. China accounts for 28% of all publications, followed by India and Australia (13% each). The majority of the publications were related to hydrometallurgical processing (79%), followed by pyrometallurgical processing (15%), and reduction processes (5%).

Figure 7: Patent output in cobalt processing from 2007 to 2022, by technology.



The largest category overall was leaching with sulphuric acid, with 40.6% of all filings during the period. Meanwhile, thermal pre-treatment was the second largest category in the analysis (17%). The other extraction methods had lower proportions, including chlorine leaching (9.8%), leaching with alternative acids (4.2%), ammonia leaching (2.2%), and bioleaching (1.6%). In separation and purification, solvent extraction (11.2%) had the highest number of patents followed by ion-exchange (2.5%) and crystallisation (10.9%).

As shown in Figure 7, there have been large peaks of patent activity in leaching with sulphuric acid, as well as growth across thermal pre-treatment, leaching with alternative acids, solvent extraction, and crystallisation. Chloride leaching has a moderate and stable level of activity, while ammonia leaching, bioleaching and ion exchange separation have maintained a comparatively low baseline.

Table 1: Top 10 active organisations outside of China

By research publication output	By patent output
CSIR, India	Sumitomo metal mining, Japan
CSIRO, Australia	Cerro Matoso, Colombia
Istanbul Technical University, Turkey	Mitsubishi Materials, Japan
University of Johannesburg, South Africa	Korea Zinc, Republic of Korea
KU Leuven, Belgium	Metso Outotec, Finland
Bandung Institute of Technology, Indonesia	BHP Billiton SSM Development, Australia
CNRS, France	Kemco Korea Energy Materials, Republic of Korea
KIGAM, Republic of Korea	Vale, Brazil
Universidade de Sao Paolo, Brazil	CSIRO, Australia
University of Queensland, Australia	Freeport-McMoran, USA

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

3.1 Extraction of cobalt compounds from ores

Australia has the second largest cobalt reserves in the world, after the DRC, with the element found within two economically relevant deposit types: sulphide deposits and laterite deposits.¹ As such, this report focuses on extraction from these two ore types.

Sulphide ores have been mined for a long period of time, but high-grade deposits are becoming increasingly depleted. Laterite deposits are comparatively more complex in their composition and have received substantial commercial and RD&D interest.² Australian sulphide deposits are primarily found in Western Australia (WA), albeit there are some smaller deposits in the Northern Territory (NT), Tasmania (TAS), Queensland (QLD), and New South Wales (NSW). Laterite deposits are found across WA, QLD, NSW, South Australia (SA) and Tasmania (TAS).³ The difference in composition for laterite and sulphide ores directly influences their behaviour during extraction, determining the specific pathway and reagents to use.

The first stage of the processing pathway comprises a thermal pre-treatment step, including roasting, smelting or a combination of both. The use of thermal processes changes the ores into forms that are more amenable to leaching, while removing or minimising impurities. However, the use of a thermal pre-treatment depends on ore and deposit type. Currently, thermal pre-treatment is used for sulphide ores to produce matte. Other processing pathways do not require thermal pre-treatment and leaching can be directly performed as the initial stage.

Extraction of metals from the ore via leaching is the second stage following from the initial thermal step.⁴ Leaching is the process of dissolving the metals ores through the addition of a liquid leaching agent and the use of favourable temperature, pressure, and reaction conditions. This forms a solution from which elements of interest can be retrieved.⁵ Sulphuric acid, ammonia and chlorine gas are commonly used leaching agents, although alternatives like hydrochloric, nitric, phosphoric, and organic acids are also being explored for their potential to improve environmental or cost outcomes. The leaching may take place within an autoclave at high pressure and temperature or, alternatively, in tanks or heaps under atmospheric pressure.⁶

¹ Shedd KB (2023) Mineral commodity summaries 2023 – Cobalt. 60 – 61. United States Geological Survey, Reston, Virginia. <<https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf>>; Slack et al. (2017) Cobalt, chap. F. In *Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply*: U.S. Geological Survey Professional Paper 1802 (Eds. KJ Schulz, JH DeYoung Jr., RR Seal II, DC Bradley). U.S. Geological Survey, Reston, Virginia.

² Mudd GM (2010) Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews* 38(1–2), 9–26; Dehaine Q, Tijsseling LT, Glass HJ, Törmänen T, Butcher AR (2021) Geometallurgy of cobalt ores: A review. *Minerals Engineering* 160, 106656.

³ Hughes et al. (2023) Australia's identified mineral resources 2022. Geoscience Australia, Canberra, ACT. <<https://www.ga.gov.au/digital-publication/aimr2022/australias-identified-mineral-resources>>; Geoscience Australia (2023) Nickel. *Australian Resource Reviews*. <<https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/nickel#>>

⁴ Dehaine et al. (2021) Geometallurgy of cobalt ores: A review. *Minerals Engineering* 160, 106656.

⁵ Crundwell et al. (2011) Extraction of Cobalt from Nickel Laterite and Sulfide Ores. In *Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals*. Elsevier.

⁶ Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Part I: Piloted Processes and Commercial Operations. *Mineral Processing and Extractive Metallurgy Review* 44(6), 407–435.

3.1.1 Thermal pre-treatment

Roasting

Roasting can entail direct roasting of the ore or roasting in the presence of an additive (e.g., sulphur dioxide, sulphates, chlorides, or chlorine gas).⁷ Roasting is used across three different processing pathways covered in subsequent sections:

- 1) As a preliminary step prior to smelting in an electric furnace, in the production of nickel-cobalt matte from sulphide ores.
- 2) To assist in the reduction of laterite ores, particularly prior to ammonia leaching.
- 3) In mixed roasting approaches where an additive (e.g., sulphate, chloride, or metal oxide) is used to transform the elements present in the ore and make them amenable to leaching.

Both reductive and mixed roasting can enhance metal extraction, because of the changes they induce in ore mineralogy. However, they are energy-intensive and are not used in all laterite ore leaching pathways.⁸

Smelting

Smelting can be applied after roasting to sulphide ores to produce a nickel-cobalt sulphide matte that can be separated from iron (a major impurity) and gangue material.⁹ This process conventionally uses an electric or flash furnace.¹⁰

Generally, smelting processes are useful for nickel recovery and to produce mixed products like ferronickel, but face challenges in lower recovery of cobalt, a portion of which is lost to slag, and high energy consumption.¹¹

Smelting is also used to produce nickel pig iron (NPI) using a rotary kiln-electric furnace (RKEF). NPI is a low-grade form of ferronickel useful as a less expensive feedstock for stainless steel production.¹² The RKEF pathway primarily focusses on extracting the nickel and iron present in the ore but there have been developments in recovering cobalt from the processes. For instance, NPI can be converted into a higher-grade nickel matte from which the lower amounts of cobalt remaining can be recovered.¹³ There is also

⁷ Dehaine et al. (2021) Geometallurgy of cobalt ores: A review. *Minerals Engineering* 160, 106656.

⁸ Dong et al. (2023) The effect of pre-roasting on atmospheric sulfuric acid leaching of saprolitic laterites. *Hydrometallurgy* 218, 106063; Li et al. (2009) Effect of pre-roasting on leaching of laterite. *Hydrometallurgy* 99(1–2), 84–88; Yang et al. (2019) Selective reduction of an Australian garnieritic laterite ore. *Minerals Engineering* 131, 79–89; Yang et al. (2016) Mechanistic and Kinetic Analysis of Na₂SO₄-Modified Laterite Decomposition by Thermogravimetry Coupled with Mass Spectrometry. *PLOS ONE* 11(6), e0157369.

⁹ Crundwell et al. (2011) Flash Smelting of Nickel Sulfide Concentrates, in *Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals*, Elsevier. doi:10.1016/B978-0-08-096809-4.10018-8.

¹⁰ Moats MS, Davenport WG (2014) Nickel and Cobalt Production. In *Treatise on Process Metallurgy*. (Ed. S Seetharam) 625-669. Elsevier.

¹¹ Dehaine et al. (2021) Geometallurgy of cobalt ores: A review. *Minerals Engineering* 160, 106656; Moats MS, Davenport WG (2014) Nickel and Cobalt Production. In *Treatise on Process Metallurgy*. (Ed. S Seetharam) 625-669. Elsevier.

¹² Rao et al. (2013) Carbothermic Reduction of Nickeliferous Laterite Ores for Nickel Pig Iron Production in China: A Review, *JOM*, 65(11):1573–1583, doi:10.1007/s11837-013-0760-7; Yildirim et al. (2013) Nickel Pig Iron Production From Lateritic Nickel Ores, in *The thirteenth International Ferroalloys Congress: Efficient technologies in ferroalloy industry*. <https://www.researchgate.net/publication/323177473_NICKEL_PIG_IRON_PRODUCTION_FROM_LATERITIC_NICKEL_ORES>

¹³ Sherritt (2021) Does Matte Matter? Is nickel pig iron the answer to EV battery demand?. <https://s2.q4cdn.com/343762060/files/doc_downloads/2021/Does-Matte-Matter-Sept-2021.pdf>

continued interest in recovering cobalt directly from the slag produced by the RKEF process,¹⁴ which may involve acid or alkaline roasting followed by leaching.¹⁵

While NPI production has been shown to be scalable and economically competitive, it faces challenges in its limitation to only process a portion of laterite ores (the saprolite portion).¹⁶ Further, the process experiences loss of cobalt to slag during smelting, high energy intensity, and significant carbon dioxide emissions.¹⁷



TECHNOLOGY STATE OF PLAY

Roasting and smelting processes to treat laterite and sulphide ores are highly mature around the world. In Australia, they have either been implemented in the past or remain in use at scale. Mixed roasting approaches remain under investigation at the laboratory scale.¹⁸ For instance, reduction of laterite ore concentrate through roasting was used at scale in the now-closed Yabulu refinery (Queensland Nickel).¹⁹ Smelting of sulphide ore concentrates to produce nickel-rich matte is currently performed by BHP Nickel West at the Kalgoorlie Nickel Smelter, which is equipped with a flash furnace.²⁰

Meanwhile, the RKEF pathway for producing NPI has been implemented at scale in both China and Indonesia.²¹ Multiple dedicated plants have been built in Indonesia, including by a collaboration between Chinese nickel and stainless-steel producer Tsingshan and Nickel Industries, an Australian company.²²

Thermal pre-treatment processes were the second highest technology area among extraction methods and accounted for 17% of all filings in the analysis of global activity from 2007 to 2022. This area has had a stable to growing trend over the past 15 years, showing an increase in activity particularly after 2015. This reflects the prevalence of this kind of processing across the industry and continuous innovation in the space. Activity from China was 76.5% of the total, followed by Japan with 10.6%, and Australia with 1.8%. Australian organisations with relevant patents include Glencore, LINICO Pty Ltd, and South32.²³

The following table summarizes the RD&D focus areas for thermal pre-treatment of sulphide and laterite ores:

¹⁴ Sudiby et al. (2021) Separation of cobalt from slag of nickel pig iron using solvent extraction method. AIP Conference Proceedings 2382, 050006.

¹⁵ Godirilwe et al. (2023) Establishment of a Hydrometallurgical Scheme for the Recovery of Copper, Nickel, and Cobalt from Smelter Slag and Its Economic Evaluation. Sustainability 15(13), 10496.

¹⁶ Rao et al. (2013) Carbothermic Reduction of Nickeliferous Laterite Ores for Nickel Pig Iron Production in China: A Review. JOM 65(11), 1573–1583.

¹⁷ Rao et al. (2013) Carbothermic Reduction of Nickeliferous Laterite Ores for Nickel Pig Iron Production in China: A Review. JOM 65(11), 1573–1583.

¹⁸ Dong et al. (2018) The Effect of Additives on Extraction of Ni, Fe and Co from Nickel Laterite Ores. JOM 70(10), 2365–2377.

¹⁹ Queensland Nickel (2014) Queensland Nickel Process Information. <https://www.qni.com.au/wp-content/uploads/2014/05/Yabulu-Process-flow_detail.pdf>; Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Part I: Piloted Processes and Commercial Operations. Mineral Processing and Extractive Metallurgy Review 44(6), 407–435.


²⁰ BHP (2022) Nickel West, What we do - Global locations - Australia - Western Australia. <<https://www.bhp.com/what-we-do/global-locations/australia/western-australia/nickel-west>>

²¹ Rao et al. (2013) Carbothermic Reduction of Nickeliferous Laterite Ores for Nickel Pig Iron Production in China: A Review. JOM 65(11), 1573–1583; Wood Mackenzie (2023) The rise and rise of Indonesian HPAL – can it continue? Opinion. <<https://www.woodmac.com/news/opinion/rise-of-indonesian-hpal/>>.

²² Nickel Industries (2021) About Nickel Industries - Our Story. About Us. <<https://nickelindustries.com/about-us/>>.

²³ Filings attributed to Glencore and its subsidiaries have been counted as Australian patents given Australia was listed as the earliest priority country.

Table 2: Global RD&D focus areas for thermal pre-treatment of sulphide and laterite ores.

 RD&D FOCUS AREAS	
Roasting	<ul style="list-style-type: none"> • Optimising reduction roasting parameters (reductant, additives, time, temperatures) to support ore upgrading and improve cobalt recovery during leaching.²⁴ • Optimising the composition and use of additives to increase the efficiency of downstream leaching processes. • Minimise energy intensity (e.g., roasting temperature required), and limit the generation of corrosive byproducts (like hydrochloric acid when using chloride additives).²⁵
Smelting	<ul style="list-style-type: none"> • Developing scalable strategies that recover the cobalt lost to slags during smelting.²⁶

3.1.2 Sulphuric acid leaching

Pressure oxidation processes

Extraction from sulphide ores is highly mature and can be done using pressure oxidation processes. In pressure oxidation, oxygen is added to a slurry (mix of ore and water) under high temperature and pressure. Some of the sulphur present in the ore generates sulphuric acid which supports the leaching.²⁷

Extraction through pressure oxidation is a rapid process and can be used on low grade sulphide ores that would be unsuitable for conventional nickel-cobalt matte production via smelting. The process itself generates sulphuric acid during leaching, which is a key advantage. Excess acid can be utilised for example, leaching highly acid-consuming ores, like laterites. However, without connected uses to consume it, the excess acid requires neutralisation with additional reagents and suitable waste handling, both of which could represent additional costs.²⁸

²⁴ Sun et al. (2021) Effects of temperature, CO content, and reduction time on the selective reduction of a limonitic laterite ore. *Minerals Engineering* 174, 107277; Sun et al. (2020) Efficient Synchronous Extraction of Nickel, Copper, and Cobalt from Low-Nickel Matte by Sulfation Roasting–Water Leaching Process. *Scientific Reports* 10(1), 9916; Zappala et al. (2023) Nickel Laterite Beneficiation and Potential for Upgrading Using High Temperature Methods: A Review. *Mineral Processing and Extractive Metallurgy Review*, 1–23.

²⁵ Dong et al. (2018) The Effect of Additives on Extraction of Ni, Fe and Co from Nickel Laterite Ores. *JOM* 70(10), 2365–2377.

²⁶ Godirilwe et al. (2023) Establishment of a Hydrometallurgical Scheme for the Recovery of Copper, Nickel, and Cobalt from Smelter Slag and Its Economic Evaluation. *Sustainability* 15(13), 10496; Crundwell et al. (2011) Extraction of Cobalt from Nickel Laterite and Sulfide Ores. In *Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals*. Elsevier.

²⁷ The Albion®, Intec Nickel, Activox®, CESL, PLATSOL™, and IGO processes are examples of pressure oxidation processes; Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Part I: Piloted Processes and Commercial Operations, *Mineral Processing and Extractive Metallurgy Review* 44(6), 407–435; McDonald et al. (2020) High Temperature Pressure Oxidation of a Low-Grade Nickel Sulfide Concentrate with Control of the Residue Composition. *Minerals* 10(3), 249.

²⁸ McDonald et al. (2020) High Temperature Pressure Oxidation of a Low-Grade Nickel Sulfide Concentrate with Control of the Residue Composition. *Minerals* 10(3), 249.

Pressure oxidation also relies on a supply of oxygen, which can become a significant operating cost. Oxygen consumption and its contribution to cost vary depending on the process, particularly those with elevated temperature that produce sulphates.²⁹

The other commercially mature method for extraction from sulphides ores is ammonia leaching (see Section 3.1.4).

High-pressure acid leaching (HPAL)

Current nickel and cobalt extraction from laterite ores is most frequently performed through high-pressure acid leaching (HPAL) with sulphuric acid. The advantages of using HPAL on laterite ores include high nickel and cobalt extractions, shorter processing times, and low extraction of iron (a major impurity). Minimising the presence of iron is relevant to operational efficiency and the simplification of downstream purification.³⁰

However, the major challenges for HPAL relate to the generation of large tailings volumes that may not be manageable in all locations and pose environmental concerns.³¹ Moreover, HPAL can face high capital expenditure due to expensive equipment and construction materials. Significant acid consumption and energy-intensity due to the high temperature and pressure conditions can also result in high operational costs.³²

Leaching at atmospheric pressure

Leaching with sulphuric acid at atmospheric pressure is used commercially to extract cobalt from laterite ores. However, its use in industry is less prevalent than HPAL. Acid leaching at atmospheric pressure includes atmospheric leaching in tanks at high temperature (AL) and heap leaching (HL). There are also mixed processes that incorporate both an atmospheric and a high-pressure step to treat different portions of the ore, for example, in enhanced pressure acid leaching (EPAL).

Leaching approaches at atmospheric pressure can enable cobalt extraction from low grade ores and tailings for which pressure leaching processes would not be economically feasible. Leaching at atmospheric pressure faces a lower capital expenditure (CAPEX) and energy consumption compared to high pressure processes (e.g. HPAL). However, AL with sulphuric acid can entail lower nickel and cobalt extractions, higher acid consumption, longer processing times, and difficulty in excluding metallic impurities (e.g., iron,

²⁹ Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates - A Historic and State-of-the-Art Review Part II: Laboratory Investigations into Pressure Leaching. *Mineral Processing and Extractive Metallurgy Review* 44(6), 451–473.

³⁰ Stanković et al. (2020) Review of the past, present, and future of the hydrometallurgical production of nickel and cobalt from lateritic ores. *Metallurgical and Materials Engineering* 26(2), 199–208; Dehaine et al. (2021) Geometallurgy of cobalt ores: A review. *Minerals Engineering* 160, 106656; Moats MS, Davenport WG (2014) Nickel and Cobalt Production. In *Treatise on Process Metallurgy*. (Ed. S Seetharam) 625-669. Elsevier.

³¹ Wood Mackenzie (2023) The rise and rise of Indonesian HPAL – can it continue? Opinion. <<https://www.woodmac.com/news/opinion/rise-of-indonesian-hpal/>>; Stanković S et al. (2020) Review of the past, present, and future of the hydrometallurgical production of nickel and cobalt from lateritic ores. *Metallurgical and Materials Engineering* 26(2), 199–208.

³² Ribeiro et al. (2021) Rising EV-grade nickel demand fuels interest in risky HPAL process. S&P Global Commodity Insights. <<https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/030321-nickel-hpal-technology-ev-batteries-emissions-environment-mining>>.

aluminium, chromium).³³ HL can also face challenges when ores become compressed during leaching, preventing effective extraction and making the heap less stable.³⁴



TECHNOLOGY STATE OF PLAY

Sulphuric acid in all its forms is commercially mature and have been deployed at scale globally. For instance, there are relevant examples of pressure oxidation processes in Australia, such as the pathway developed and piloted by IGO to treat sulphide concentrates. The IGO process transforms the metal sulphides present in the ore into metal sulphates using pressure oxidation, followed by a series of steps to remove impurities, separate nickel into its own purified stream, and retrieve cobalt as part of a mixed sulphide precipitate (MSP).³⁵

HPAL is used internationally at some of the largest plants for laterite ore processing, including Moa Nickel in Cuba (Sherritt and General Nickel Co.), Goro in New Caledonia (Prony Resources), Ramu Nickel in Papua New Guinea (China Metallurgical Group Corporation), Ambatovy in Madagascar (Sumitomo and KOMIR), Coral Bay Nickel and Taganito HPAL Nickel in the Philippines (Sumitomo), and 3 plants currently under construction in Indonesia.³⁶ Within Australia, HPAL is used at commercial scale in Murrin Murrin (Glencore) and Ravensthorpe (First Quantum Minerals), both in Western Australia.³⁷ It was implemented in the past at Bulong Nickel (Preston Resources) and Cawse Nickel (Centaur Mining & Explorations), also in WA.³⁸

In terms of leaching at atmospheric pressure, Brazil Nickel has established a commercial-scale, standalone heap leaching operation that uses dilute sulphuric acid to treat Ni-Co laterites and produce MHP in Northeast Brazil.³⁹ In Australia, First Quantum Minerals' Ravensthorpe operation uses the EPAL approach to treat the two ore fractions that compose Ni-Co laterite deposits: limonite (using HPAL) and saprolite (using atmospheric leaching). The two streams are later combined in a secondary atmospheric leach, prior to impurity removal and precipitation of MHP.⁴⁰

Sulphuric acid leaching in its different forms was the most active technology area across this cobalt extraction analysis. Patents related to leaching with sulphuric acid represent 40.6% of all filings identified in the analysis of the 2007 – 2022 period. China had the highest share of activity in leaching with sulphuric acid, making up 60.1% of global output. Japan held 24.4% of global output, followed by Australia with 4.2%.

³³ Zhao et al. (2022) Comprehensive Review on Metallurgical Upgradation Processes of Nickel Sulfide Ores. *Journal of Sustainable Metallurgy* 8(1), 37–50; Stanković et al. (2020) Review of the past, present, and future of the hydrometallurgical production of nickel and cobalt from lateritic ores. *Metallurgical and Materials Engineering* 26(2), 199–208; Luo et al. (2015) Atmospheric leaching characteristics of nickel and iron in limonitic laterite with sulfuric acid in the presence of sodium sulfite. *Minerals Engineering* 78, 38–44; Miettinen et al. (2019) Iron Control in Atmospheric Acid Laterite Leaching. *Minerals* 9(7), 404.

³⁴ Lupo JF (2012) Sustainable issues related to heap leaching operations. *The Journal of The Southern African Institute of Mining and Metallurgy*, 112, 1021–1030.

³⁵ IGO Limited (2019) Downstream Nickel Sulphate Study Update. <<https://www.igo.com.au/site/PDF/ae236a23-5880-454c-afc9-d2812c3f630b/DownstreamNickelSulphateStudyUpdate>>; IGO Limited (2023) Annual Report 2023. P. 25 – 29. <<https://www.igo.com.au/site/pdf/fc89acfe-4657-4317-9f4f-b3ce634dde76/2023-Annual-Report-to-Shareholders.pdf>>.

³⁶ Wood Mackenzie (2023) The rise and rise of Indonesian HPAL – can it continue? Opinion. <<https://www.woodmac.com/news/opinion/rise-of-indonesian-hpal/>>; Sherritt (2021) Moa JV. Operations. <<https://www.sherritt.com/English/operations/metals/Moa/default.aspx>>.

³⁷ Glencore (2023) Producing nickel and cobalt at Murrin Murrin. Who We Are. <<https://www.glencore.com.au/operations-and-projects/minara/who-we-are/producing-nickel-and-cobalt-at-murrin-murrin>>; Gray et al. (2022) Ravensthorpe Nickel Operations | NI 43-101 Technical Report, March 28, 2022. 109 – 112. <https://s24.q4cdn.com/821689673/files/doc_downloads/2022/Ravensthorpe-NI-43-101-Technical-Report.pdf>.

³⁸ Gabb J (2018) HPAL: Upping The Pressure. *Global Mining Research*. <<https://gigametals.com/site/assets/files/4861/2018-03-19-hpal.pdf>>.

³⁹ Brazilian Nickel PLC (2023) Nickel Heap Leaching. <<https://www.braziliannickel.com/nickel-heap-leaching/>>.


⁴⁰ Gray et al. (2022) Ravensthorpe Nickel Operations. NI 43-101 Technical Report, March 28, 2022. 109 – 112. <https://s24.q4cdn.com/821689673/files/doc_downloads/2022/Ravensthorpe-NI-43-101-Technical-Report.pdf>.

Australian organisations with relevant patents include BHP, Glencore, LINICO, Poseidon Nickel, and South32.⁴¹

Global filings in sulphuric acid leaching have been consistently high over the last 15 years, with some spikes in activity after 2013.

The following table summarizes the RD&D focus areas for leaching with sulphuric acid:

Table 3: Global RD&D focus areas for sulphuric acid leaching of sulphide and laterite ores.

 RD&D FOCUS AREAS	
High-pressure acid leaching	<ul style="list-style-type: none"> Developing cost-effective strategies to minimise waste generation and improve residue management. This includes recycling the large volumes of acid used and implementing safe tailings storage or reuse approaches.⁴²
Atmospheric pressure leaching	<ul style="list-style-type: none"> Assessing the viability at scale of using reducing agents and salt additives in atmospheric leaching, to increase nickel and cobalt recovery.⁴³ Optimising the removal of metallic impurities introduced because of the low selectivity of atmospheric leaching.⁴⁴
Pressure oxidation processes	<ul style="list-style-type: none"> Progressing cost-effective, scalable strategies that neutralise or reuse the excess sulphuric acid produced during pressure oxidation of sulphide ores (e.g., co-processing with laterite ores).⁴⁵
Supporting research domains	<ul style="list-style-type: none"> Developing cost-effective pre-concentration methods that upgrade laterite ores, to improve leaching economics.

3.1.3 Leaching with alternative acids

Leaching laterite ores at with alternative acids at atmospheric pressures is an emerging pathway. Leaching at atmospheric pressure proceeds at lower temperatures than those used in HPAL.⁴⁶ However, it can result in greater acid consumption, favouring the use of alternatives to sulphuric acid that are less expensive, reduce the introduction of impurities, or can be more easily regenerated after use. Some of these alternative acids can also leach both portions of laterite deposits simultaneously and enable the recovery of

⁴¹ Filings attributed to Glencore and its subsidiaries have been counted as Australian patents given Australia was listed as the earliest priority country.

⁴² Taylor et al. (2019) Alta 2019 Pressure Acid Leaching Panel Discussion. ALTA 2019 Panel Notes. <<https://www.altamet.com.au/wp-content/uploads/2019/10/ALTA-2019-Pressure-Acid-Leaching-Panel-Discussion.pdf>>; Fisher H, Grossi B (2023) Opinion: Overcoming mining waste issues will be key to Indonesia’s nickel ambitions. Benchmark Mineral Intelligence Limited. <<https://www.altamet.com.au/wp-content/uploads/2019/10/ALTA-2019-Pressure-Acid-Leaching-Panel-Discussion.pdf>>.

⁴³ McDonald RG, Whittington BI (2008) Atmospheric acid leaching of nickel laterites review. *Hydrometallurgy* 91(1–4), 35–55; Luo et al. (2015) Atmospheric leaching characteristics of nickel and iron in limonitic laterite with sulfuric acid in the presence of sodium sulfite. *Minerals Engineering* 78, 38–44.

⁴⁴ Zhao et al. (2022) Comprehensive Review on Metallurgical Upgradation Processes of Nickel Sulfide Ores. *Journal of Sustainable Metallurgy* 8(1), 37–50; Miettinen et al. (2019) Iron Control in Atmospheric Acid Laterite Leaching. *Minerals* 9(7), 404.

⁴⁵ McDonald RG, Li J (2020) The High Temperature Co-Processing of Nickel Sulfide and Nickel Laterite Sources. *Minerals* 10(4), 351.

⁴⁶ McDonald RG, Whittington BI (2008) Atmospheric acid leaching of nickel laterites review. *Hydrometallurgy* 91(1–4), 35–55.

economically relevant byproducts. Nitric, hydrochloric, phosphoric, and organic acids may be used and are actively being explored.

Nitric acid leaching is suitable for treating Ni-Co laterite ores (both the limonite and saprolite portions) and offers the advantage of regenerating the acid at the end of the process, which limits liquid waste. Moreover, it enables recovery of other metals present in the ore as saleable compounds (e.g., iron and aluminium).⁴⁷

However, using nitric acid generates nitrates as byproducts, requiring careful control to prevent water contamination.⁴⁸ The process also produces nitrous oxide (NO_x), which must be carefully controlled for environmental reasons and to enable acid regeneration.⁴⁹ Moreover, appropriate construction materials may be required given the potential to produce highly corrosive byproducts, increasing CAPEX. Alternatively, measures can be introduced to minimise the generation of corrosive byproducts, but this can also introduce additional cost considerations.

Meanwhile, the use of phosphoric acid for leaching laterite ores can reportedly attain high nickel and cobalt extraction at significantly lower temperatures and pressures than those used in HPAL. Moreover, the iron present in the ore is precipitated as iron phosphate, which is a saleable product relevant to the production of lithium-iron-phosphate (LFP) cathodes. Removing iron during leaching also facilitates downstream purification.⁵⁰

Despite these advantages, phosphoric acid leaches a large proportion of magnesium. This can increase acid consumption and makes the method less suitable for the saprolite portion of laterite ores.⁵¹ Additionally, phosphorus is critical to sectors like fertiliser production, posing future sustainability and scalability considerations to its use in mineral extraction and processing.⁵²

The use of organic acids (e.g., citric acid or oxalic acid) is also being trialled, particularly for cobalt recovery from secondary streams such as slags remaining from pyrometallurgical processes, spent lithium-ion batteries, or other high value metal-containing materials.⁵³ Interest in organic acids stems its multiple uses and extraction efficiency; they can serve as the leaching agent, reduce the cobalt itself into a more soluble

⁴⁷ Altilium Group Ltd (2023) THE DNI PROCESS™ FLOWSHEET. The DNI Process™. <<https://www.altiliiumgroup.com/the-dni-process-flowsheet/>>; Queensland Pacific Metals (2023) Detailed Process Flowsheet. <<https://qpmetals.com.au/detailed-process-flowsheet/>>.

⁴⁸ Carter (2014) Leaching laterites: Two new processes make progress. *Engineering and Mining Journal*. <<https://www.emj.com/departments/processing-solutions/leaching-laterites-two-new-processes-make-progress/>>.

⁴⁹ WorleyParsons (2018) Dutwa Nickel Project High Level Metallurgical Review. <https://www.harmony-minerals.com/wp-content/uploads/2019/04/Worley-Parsons_A-Dutwa-Ni-Review_0218.pdf>.

⁵⁰ Chen et al. (2024) Phosphoric Acid Leaching of Ni–Co–Fe Powder Derived from Limonitic Laterite Ore. *TMS 2024: Characterization of Minerals, Metals, and Materials 2024*. 269 – 278. The Minerals, Metals & Materials Series. Springer, Cham; Luo et al. (2021) Self-driven and efficient leaching of limonitic laterite with phosphoric acid. *Minerals Engineering* 169, 106979.

⁵¹ Chen et al. (2024) Phosphoric Acid Leaching of Ni–Co–Fe Powder Derived from Limonitic Laterite Ore. *TMS 2024: Characterization of Minerals, Metals, and Materials 2024*. 269 – 278; Luo et al. (2021) Self-driven and efficient leaching of limonitic laterite with phosphoric acid. *Minerals Engineering* 169, 106979.

⁵² Spears et al. (2022) Concerns about global phosphorus demand for lithium-iron-phosphate batteries in the light electric vehicle sector. *Communications Materials* 3(1), 14.

⁵³ Lim et al. (2023) Complexation leaching of critical and strategic metals from nickel converter slag using organic acids. *Minerals Engineering* 201, 108167; Nayaka et al. (2015) Recovery of valuable metal ions from the spent lithium-ion battery using aqueous mixture of mild organic acids as alternative to mineral acids. *Hydrometallurgy* 151, 73–77.

state, or reduce impurities themselves (e.g., manganese).⁵⁴ Some organic acids are also highly selective meaning similar elements won't be leached along with the metal of interest.⁵⁵

Leaching with organic acids has potential for less hazardous and energy intensive operations when used as part of a bioleaching approach.⁵⁶ Moreover, most organic acids are biodegradable on short timescales.⁵⁷ However, the use of organic acids is still challenged by long leaching times, low extractions, and a greater difficulty treating the limonite portion of laterite ores.⁵⁸

Finally, hydrochloric acid is being explored on its own and in combined solutions with chloride salts or chlorine gas. It is presented separately in Section 3.1.5.



TECHNOLOGY STATE OF PLAY

The maturity of leaching processes using alternative acids varies. Nitric acid applications have reached pilot scale, while phosphoric and organic acids remain at lab scale.

Nitric acid leaching has been tested and advanced in Australia. For example, the Direct Nickel process (owned by Altilium) has been piloted in the country and underpins operations at the Townsville Energy Chemicals Hub (TECH) project planned by Queensland Pacific Metals.⁵⁹ A variant that uses nitric acid leaching at high pressure (known as nitric acid pressure leaching, NAPL) has also been previously piloted in China by China Nickel Resources.⁶⁰

Leaching with alternative acids accounts for 4.2% of filing activity in the analysis of 2007 – 2022 but has experienced a growth in momentum since 2015, in line with efforts to develop alternative processing pathways. China accounted for most filings in leaching with alternative acids (76.2%), followed by the United States (11.9%) and Australia (7.1%). Australian organisations with relevant patents include Poseidon Nickel and Resource Mining Corp.

⁵⁴ Golmohammadzadeh et al. (2018) Recovery of lithium and cobalt from spent lithium ion batteries (LIBs) using organic acids as leaching reagents: A review. *Resources, Conservation and Recycling* 136, 418–435.

⁵⁵ Lim et al. (2023) Complexation leaching of critical and strategic metals from nickel converter slag using organic acids. *Minerals Engineering* 201, 108167.

⁵⁶ Kursunoglu S, Kaya M (2015) Dissolution behavior of Caldag lateritic nickel ore subjected to a sequential organic acid leaching method. *International Journal of Minerals, Metallurgy, and Materials* 22(11), 1131–1140.

⁵⁷ Pathak et al. (2021) Emerging role of organic acids in leaching of valuable metals from refinery-spent hydroprocessing catalysts, and potential techno-economic challenges: A review. *Critical Reviews in Environmental Science and Technology* 51(1), 1–43.


⁵⁸ Kursunoglu S, Kaya M (2015) Dissolution behavior of Caldag lateritic nickel ore subjected to a sequential organic acid leaching method. *International Journal of Minerals, Metallurgy, and Materials* 22(11), 1131–1140.

⁵⁹ Queensland Pacific Metals (2023) Project overview. TECH project. <<https://qpmetals.com.au/tech-project/project-overview/>>; Queensland Pacific Metals (2023) Detailed Process Flowsheet. <<https://qpmetals.com.au/detailed-process-flowsheet/>>.

⁶⁰ Ma et al. (2015) Pilot-scale plant study on the innovative nitric acid pressure leaching technology for laterite ores. *Hydrometallurgy* 155, 88–94.

The following table summarizes the RD&D focus areas for leaching with alternative acids:

Table 4: Global RD&D focus areas the leaching of sulphide and laterite ores using alternative acids.

 RD&D FOCUS AREAS	
Alternative acid leaching	<ul style="list-style-type: none"> For nitric and phosphoric acids, optimising regeneration approaches to minimise reagent loss, reduce energy intensity, and prevent release of harmful byproducts.⁶¹ For organic acids, optimising process conditions, assessing pathways for cost-effective processing after leaching, and implementing additives (salts, complexing agents, inorganic acids) to improve leaching efficiency, selectivity, and rate.⁶²
Supporting research domains	<ul style="list-style-type: none"> Developing cost-effective pre-concentration methods that upgrade laterite ores, to improve leaching economics. Optimising ore blends to enhance leaching, improve process economics, and expand the feedstock that can be treated.

3.1.4 Ammonia leaching

Ammonia-based leaching uses ammonia-ammonium salt solutions to dissolve the nickel and cobalt present in an ore and can take place under high pressure or atmospheric conditions.⁶³ Ammonia can be used to leach ores (both sulphides and laterites), matte or to re-leach mixed precipitate products (MSP and MHP) in order to extract cobalt and other metals.

Currently the most prevalent process for the extraction of cobalt from Ni-Cu-(Co-PGE) sulphide ores entails a mixed approach centred on smelting followed by ammonia leaching. The smelting process produces a matte, while the subsequent ammonia-based leaching produces a mixed metal solution containing nickel, copper, and cobalt. Afterwards, copper and nickel are separated before retrieving the cobalt and residual nickel as a mixed sulphide product.

Processing of Ni-Co laterites with ammonia solutions relies on conventional thermal pathways like reductive roasting followed by ammonia-based leaching at atmospheric pressure.⁶⁴

The main advantage offered by ammonia-based processes is greater selectivity in leaching, limiting the number of metallic impurities like iron, manganese and aluminium.⁶⁵ This makes downstream purification

⁶¹ Binnemans K, Jones PT (2023) The Twelve Principles of Circular Hydrometallurgy. *Journal of Sustainable Metallurgy* 9(1), 1–25.

⁶² Pathak et al. (2021) Emerging role of organic acids in leaching of valuable metals from refinery-spent hydroprocessing catalysts, and potential techno-economic challenges: A review. *Critical Reviews in Environmental Science and Technology* 51(1), 1–43.

⁶³ Zhao et al. (2022) Comprehensive Review on Metallurgical Upgradation Processes of Nickel Sulfide Ores. *Journal of Sustainable Metallurgy* 8(1), 37–50; Ilyas et al. (2020) Extraction of nickel and cobalt from a laterite ore using the carbothermic reduction roasting-ammoniacal leaching process. *Separation and Purification Technology* 232, 115971.

⁶⁴ Total Materia (2015) The Caron Process. Total Materia - Key to Metals AG. <<https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=372>>.

⁶⁵ Meng X, Han KN (1996) The Principles and Applications of Ammonia Leaching of Metals—A Review. *Mineral Processing and Extractive Metallurgy Review* 16(1), 23–61; Hu et al. (2022) Ammonia leaching process for selective extraction of nickel and cobalt from polymetallic mixed hydroxide precipitate. *Journal of Environmental Chemical Engineering* 10(6), 108936; Zhao et al. (2022) Comprehensive Review on Metallurgical Upgradation Processes of Nickel Sulfide Ores. *Journal of Sustainable Metallurgy* 8(1), 37–50.

less onerous. Ammonia can also be recycled and requires less heat for leaching.⁶⁶ Some byproducts of ammonia-based leaching can be sold depending on their purity (e.g. ammonium sulphate).

Conversely, there are several challenges for ammonia-based leaching. Pathways that require thermal treatment of the ore (smelting or reduction roasting) prior to leaching, increase the energy intensity of the process, and lead to loss of cobalt to slags (in the case of smelting). Second, it requires careful management of ammonia gas and ammonia byproducts for safety and environmental reasons. Finally, additional processing steps are required for cobalt recovery.⁶⁷

Ammonia leaching is also more readily applied to sulphide ores. The process is less efficient at leaching reduction roasted laterites (in terms of slow processing, lower overall recovery, and cobalt losses to waste streams), making it economically challenging.⁶⁸



TECHNOLOGY STATE OF PLAY

The smelting-ammonia leaching process used for sulphide ores is mature and implemented at scale around the world. Within Australia, this is the pathway used at commercial scale by BHP Nickel West in its Kwinana Nickel Refinery.⁶⁹ Internationally, the ammonia pressure leach pathway is only used by Sherritt in its Fort Saskatchewan (Canada) refinery to produce cobalt metal from both matte and MSP.⁷⁰

The reductive roasting-leaching pathway used for laterite ores is highly mature but its use at scale has declined globally. Roasting-leaching processes were implemented at commercial scale in refineries across Australia (Queensland Nickel), China, and the Philippines,⁷¹ but are no longer in use. Cuba is an exception, with the process still in use at the Punta Gorda plant in Moa.⁷²

Patents related to ammonia leaching account for 2.2% of all cobalt related filings identified in this analysis, from 2007 – 2022. The last 15 years have seen a low and stable baseline of yearly activity, in part reflecting the maturity of this technology. 50% of global patents in this area were filed in China, 22.7% in the United States, and 13.6% in Australia. Australian organisations with relevant patents in ammonia leaching include BHP.

⁶⁶ Hu et al. (2022) Ammonia leaching process for selective extraction of nickel and cobalt from polymetallic mixed hydroxide precipitate. *Journal of Environmental Chemical Engineering* 10(6), 108936.

⁶⁷ Total Materia (2015) The Caron Process. Total Materia - Key to Metals AG. <<https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=372>>; Dehaine et al. (2021) Geometallurgy of cobalt ores: A review. *Minerals Engineering* 160, 106656; Ma et al. (2013) Screening and reduction roasting of limonitic laterite and ammonia-carbonate leaching of nickel-cobalt to produce a high-grade iron concentrate. *Minerals Engineering* 50–51, 106–113; Oraby et al. (2023) Selective extraction of nickel and cobalt from disseminated sulfide flotation cleaner tailings using alkaline glycine-ammonia leaching solutions. *Minerals Engineering* 204, 108418; Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Part I: Piloted Processes and Commercial Operations. *Mineral Processing and Extractive Metallurgy Review* 44(6), 407–435.

⁶⁸ Dyer et al. (2012) Cobalt loss due to iron precipitation in ammoniacal carbonate solutions. *Hydrometallurgy* 125–126, 144–147.

⁶⁹ BHP Nickel West (2019) Attachment 2: BHP Nickel West Kwinana Licence L8437/2010/3 Process Description, 31 – 38. <https://www.der.wa.gov.au/images/documents/our-work/licences-and-works-approvals/Decisions/_W6275-2019-1_D.pdf>.


⁷⁰ Sherritt International (2017) How Sherritt Refines Metals. <https://s2.q4cdn.com/343762060/files/doc_downloads/2021/How-Sherritt-Refines-Metals-2017-Oct-21.pdf>.

⁷¹ Ma et al. (2013a) Screening and reduction roasting of limonitic laterite and ammonia-carbonate leaching of nickel-cobalt to produce a high-grade iron concentrate. *Minerals Engineering* 50–51, 106–113.

⁷² Foret et al. (2023) NI 43-101 Technical Report for the Mineral Resource and Mineral Reserve Estimate on the Moa Project, Province of Holguin, Cuba. Micon International Limited. 191. <https://s2.q4cdn.com/343762060/files/doc_downloads/whitepapers/NI-43-101-Moa-JV-Technical-Report-Final-Final.pdf>.

The following table summarizes the RD&D focus areas for ammonia leaching of sulphide and laterite ores:

Table 5: Global RD&D focus areas for the leaching of sulphide and laterite ores using ammonia.

 RD&D FOCUS AREAS	
Ammonia leaching	<ul style="list-style-type: none"> • Optimising process conditions and control over precipitates to minimise the loss of cobalt; or introducing strategies to recover and reintegrate it into the circuit.⁷³ • Assessing the use at scale of additives (such as reducing agents) to improve nickel and cobalt extraction and reaction rates.⁷⁴

3.1.5 Chloride leaching

In this report, three chlorine-based agents have been categorised under chloride leaching processes: leaching with chlorine gas, leaching with an acid in the presence of chloride salts (e.g., sodium chloride), and leaching with hydrochloric acid. These processes can be applied to multiple feedstocks including sulphide and laterite ores, nickel-cobalt matte produced through smelting, and MSP.⁷⁵

Interest in chloride leaching stems from its versatility compared to sulphuric acid-based pathways. This includes the potential to treat both the limonite and saprolite portions of laterite ores (in the case of leaching with hydrochloric acid), as well as the ability to regenerate and re-use chlorine-based agents.⁷⁶

However, chloride leaching processes face challenges, namely the high cost of materials and equipment due to corrosivity and the handling of chlorine gas. Additionally, it requires high energy input for acid regeneration (in the case of leaching with hydrochloric acid).⁷⁷ Despite its efficiency, chloride leaching has lower selectivity which brings other metallic impurities into the solution.⁷⁸

⁷³ Dyer et al. (2012) Cobalt loss due to iron precipitation in ammoniacal carbonate solutions. *Hydrometallurgy* 125–126, 144–147.

⁷⁴ Hu et al. (2022) Ammonia leaching process for selective extraction of nickel and cobalt from polymetallic mixed hydroxide precipitate. *Journal of Environmental Chemical Engineering* 10(6), 108936; Ma et al. (2021) A promising selective recovery process of valuable metals from spent lithium ion batteries via reduction roasting and ammonia leaching. *Journal of Hazardous Materials* 402, 123491.

⁷⁵ Li et al. (2020) Leaching Kinetics and Mechanism of Laterite with NH₄Cl-HCl Solution. *Minerals* 10(9), 754; Lakshmanan et al. (2017) A Mixed-Chloride Atmospheric Leaching Process for the Recovery of Base Metals from Sulphide Materials. *Transactions of the Indian Institute of Metals* 70(2), 463–470; Ning et al. (2019) Nickel leaching from low-grade nickel matte using aqueous ferric chloride solution. *Rare Metals* 38(12), 1199–1206; Sumitomo Metal Mining Co. Ltd. (2022) Niihama Nickel Refinery. Core facilities / group companies. <https://www.smm.co.jp/en/corp_info/location/domestic/nickel/>.

⁷⁶ Li et al. (2012) Physicochemical factors affecting leaching of laterite ore in hydrochloric acid. *Hydrometallurgy* 129–130, 14–18.

⁷⁷ McDonald RG, Whittington BI (2008) Atmospheric acid leaching of nickel laterites review. Part II. Chloride and bio-technologies. *Hydrometallurgy* 91(1–4), 56–69; Razika D (2022) Advanced study on the extraction of Nickel from its ores. Research Report - Oum El Bouaghi University. <<https://hal.science/hal-03637893/document>>; Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Part I: Piloted Processes and Commercial Operations. *Mineral Processing and Extractive Metallurgy Review* 44(6), 407–435.

⁷⁸ McDonald RG, Whittington BI (2008) Atmospheric acid leaching of nickel laterites review. Part II. Chloride and bio-technologies. *Hydrometallurgy* 91(1–4), 56–69; Razika D (2022) Advanced study on the extraction of Nickel from its ores. Research Report - Oum El Bouaghi University. <<https://hal.science/hal-03637893/document>>; Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Part I: Piloted Processes and Commercial Operations. *Mineral Processing and Extractive Metallurgy Review* 44(6), 407–435.



The maturity of chloride leaching varies depending on the specific mode of operation: Leaching with chlorine gas in solution is already used commercially, while the use of chlorides and hydrochloric acid, remain at pilot scale.

- For instance, leaching with chlorine gas in hydrochloric acid is used by Sumitomo Metal Mining in its Niihama Nickel Refinery (Japan) and by Glencore at the Nikkelverk plant (Finland).⁷⁹ Both facilities use nickel-cobalt matte instead of ores or concentrate as a feedstock (with Niihama also using MSP). After chloride leaching, the solution undergoes a series of separation and purification steps, followed by electrowinning to produce cobalt metal.
- Meanwhile, a pressure oxidation process that uses chloride brine during leaching has been piloted by Cobalt Blue at its Broken Hill Cobalt Project demonstration plant in New South Wales.⁸⁰ In the future, Cobalt Blue plans to use the MHP recovered at the end of this process to produce cobalt and nickel sulphate at a proposed refinery in Western Australia. Phase 1 of the proposed facility would have a capacity of 3,000 tonnes per annum of cobalt.⁸¹
- Finally, leaching laterite ores directly with hydrochloric acid has been piloted at small scale by Neomet Technologies (Canada).⁸²

Chloride leaching accounts is the third largest category among the methods used to extract cobalt from ores, with 9.8% of all between 2007 and 2022, likely due to its versatility in terms of leaching increasingly complex ore types in light of depletion of simple ore types. China activity represents 45.9% of global filings in this category, while Japan accounts for 37.8% and the United States for 8.2%. Australian filings were 2% of the total. Australian organisations with relevant patents include CSIRO and WildIP.

The analysis shows a moderate and overall stable level of filing activity related to chloride leaching over the last 15 years.

⁷⁹ Sumitomo Metal Mining Co. Ltd. (2022) Niihama Nickel Refinery. Core facilities / group companies. <https://www.smm.co.jp/en/corp_info/location/domestic/nickel/>; Glencore (2023) The Nikkelverk operations. Nikkelverk. <<https://www.nikkelverk.no/en/who-we-are/our-operations>>; Glencore (2016) General presentation Nikkelverk, February 2016. Hydrometallurgy in Norway 21–23. <https://hydromet.no/Prentasjoner/Kristiansand%20Odda%202016/Lecture%201%20-%202016%20GNN%20General%20presentation_Eng.pdf>.


⁸⁰ Cobalt Blue Holdings Limited (2018) Recovery of metals from pyrite (US20210156003A1). <<https://patents.google.com/patent/US20210156003A1/en?q=US+2021%2f0156003+A1>>; Cobalt Blue Holdings Limited (2021) Broken Hill Cobalt Project Scoping Report SSD 10426. 19 – 23. <<https://majorprojects.planningportal.nsw.gov.au/prweb/PRRestService/mp/01/getContent?AttachRef=SSD-10426%2120220118T020614.107%20GMT>>.

⁸¹ Cobalt Blue Holdings Limited (2023) COB to Progress Cobalt Nickel Refinery Project in 2024. ASX Announcement. <<https://cobaltblueholdings.com/assets/COB-Refinery-Study-Announcement-27Nov23-v4.pdf>>.

⁸² Harris B, White C (2013) Further Development of the Chloride Process for Base and Light Metals: Recent Miniplant and First Pilot Plant Data. 4th Annual Nickel-Cobalt-Copper Event, Perth, WA. Melbourne, VIC, Australia: ALTA Metallurgical Services.

The following table summarizes the RD&D focus areas for chloride leaching:

Table 6: Global RD&D focus areas for chloride leaching of sulphide and laterite ores.

 RD&D FOCUS AREAS	
Chloride leaching	<ul style="list-style-type: none"> Integrating scalable, economically viable acid regeneration approaches that are less energy-intensive and avoid the production of hazardous intermediates.⁸³ Integrating efficient precipitation strategies to remove metallic impurities (resulting from the lack of selectivity of hydrochloric acid) and facilitate the subsequent recovery of nickel and cobalt from solution.⁸⁴

3.1.6 Bioleaching

Bioleaching uses micro-organisms, or products created by micro-organisms, to help dissolve metal compounds present in an ore. This method is typically conducted in heap or tank conditions and utilises bacteria or fungi that are capable of withstanding high acidity and high temperature conditions.⁸⁵

Bioleaching continues to be explored as an alternative for the recovery of high value metals based on potential flexibility, simplicity, comparative environmental impacts, and economic implications. Bioleaching can enable extraction from low-grade ores that cannot be economically processed via conventional pathways.⁸⁶ The approach is also comparatively simple in terms of process and equipment, has low energy requirements,⁸⁷ and reduced CO₂ and SO₂ emissions as compared to pyrometallurgical processing.⁸⁸

However, RD&D is required to overcome long processing times (ranging from days to years depending on the method), low efficiency, and environmental risks (such as waste disposal and environmental contamination).⁸⁹ Additionally, to improve the resistance of organisms to aggressive operating conditions.⁹⁰

⁸³ Binnemans K, Jones PT (2023) The Twelve Principles of Circular Hydrometallurgy. *Journal of Sustainable Metallurgy* 9(1), 1–25.

⁸⁴ Mystrioti et al. (2018) Counter-Current Leaching of Low-Grade Laterites with Hydrochloric Acid and Proposed Purification Options of Pregnant Solution. *Minerals* 8(12), 599; Top et al. (2020) Effects of leaching parameters on the dissolution of nickel, cobalt, manganese and iron from Caldag lateritic nickel ore in hydrochloric acid solution. *Canadian Metallurgical Quarterly* 59(3), 368–376.

⁸⁵ Vera et al. (2022) Progress in bioleaching: fundamentals and mechanisms of microbial metal sulfide oxidation – part A. *Applied Microbiology and Biotechnology* 106(21), 6933–6952; Dusengemungu et al. (2021) Overview of fungal bioleaching of metals. *Environmental Advances* 5, 100083.

⁸⁶ Schippers et al. (2013) Biomining: Metal Recovery from Ores with Microorganisms; Kutschke et al. (2015) Bioleaching of Kupferschiefer blackshale – A review including perspectives of the Ecometals project. *Minerals Engineering* 75, 116–125.

⁸⁷ Saim AK, Darteh FK (2023) A Comprehensive Review on Cobalt Bioleaching from Primary and Tailings Sources. *Mineral Processing and Extractive Metallurgy Review* 1–27.

⁸⁸ Tuovinen et al. (2018) Behaviour of Metals during Bioheap Leaching at the Talvivaara Mine, Finland. *Geosciences* 8(2), 66.

⁸⁹ Törmänen T, Tuomela P (2021) Analysis of Finnish battery mineral deposits with special emphasis on cobalt. Geological Survey of Finland, Open File Research Report 29/2021. <https://tupa.gtk.fi/raportti/arkisto/29_2021.pdf>; Tuovinen et al. (2018) Behaviour of Metals during Bioheap Leaching at the Talvivaara Mine, Finland. *Geosciences* 8(2), 66.

⁹⁰ Saim AK, Darteh FK (2023) A Comprehensive Review on Cobalt Bioleaching from Primary and Tailings Sources. *Mineral Processing and Extractive Metallurgy Review* 1–27.



While cobalt extraction through bioleaching approaches only accounts for a small fraction of global output, the process is mature for sulphide ores and is currently implemented at scale by Terrafame in Finland.⁹¹ The company processes a cobalt-containing sulphide ore without prior pyrometallurgical steps, to produce MSP.⁹² In the past, commercial-scale bioleaching for cobalt recovery was also used in tanks by Mondo Minerals (Finland) and in heap format by the Kasese Cobalt Company (Uganda).⁹³

Within Australia, bioleaching was piloted and demonstrated by Western Areas (now owned by IGO) at its Cosmic Boy Nickel Concentrator for nickel and cobalt recovery from sulphide ore tailings.⁹⁴ The process is currently used to improve overall recovery from sulphide ore concentrate.⁹⁵

Bioleaching of laterite ores remains at laboratory scale.⁹⁶

Bioleaching accounts for 1.6% of cobalt related patent filings identified in this analysis, from 2007 – 2022, the smallest category overall. China had the largest proportion of patents with 81.3%, followed by the United States with 12.5%. This area has had a low and stable baseline of activity throughout the last 15 years.

⁹¹ Roberto FF, Schippers A (2022) Progress in bioleaching: part B, applications of microbial processes by the minerals industries. *Applied Microbiology and Biotechnology* 106(18), 5913–5928; Terrafame (n.d.) Our product journey. <<https://www.terrafame.com/offering/our-product-journey.html>>.

⁹² Faris et al. (2023) The Direct Leaching of Nickel Sulfide Flotation Concentrates – A Historic and State-of-the-Art Review Part I: Piloted Processes and Commercial Operations. *Mineral Processing and Extractive Metallurgy Review* 44(6), 407–435.

⁹³ Roberto FF, Schippers A (2022) Progress in bioleaching: part B, applications of microbial processes by the minerals industries. *Applied Microbiology and Biotechnology* 106(18), 5913–5928; Saim AK, Darteh FK (2023) A Comprehensive Review on Cobalt Bioleaching from Primary and Tailings Sources. *Mineral Processing and Extractive Metallurgy Review* 1–27.


⁹⁴ Törmänen T, Tuomela P (2021) Analysis of Finnish battery mineral deposits with special emphasis on cobalt. Geological Survey of Finland, Open File Research Report 29/2021. <https://tupa.gtk.fi/raportti/arkisto/29_2021.pdf>; GR Engineering Services Ltd (2018) Cosmic Boy – Mill Recovery Enhancement Project. Projects – Details. <<https://www.gres.com.au/projects/details/cosmic-boy-mill-recovery-enhancement-project.aspx>>.

⁹⁵ IGO Limited (2022) Fy22 Cosmos And Forrestania Resources And Reserves. <<https://www.igo.com.au/site/PDF/549915a8-ff6e-411d-9211-1e85fdf2e853/FY22CosmosandForrestaniaResourcesandReserves>>.

⁹⁶ Roberto FF, Schippers A (2022) Progress in bioleaching: part B, applications of microbial processes by the minerals industries. *Applied Microbiology and Biotechnology* 106(18), 5913–5928.

The following table summarizes the RD&D focus areas for bioleaching:

Table 7: Global RD&D focus areas for bioleaching of sulphide and laterite ores.

 RD&D FOCUS AREAS	
Bioleaching	<ul style="list-style-type: none"> • Characterising the ore phases most amenable to bioleaching to improve leaching speed and efficiency. • Optimising microorganism characteristics (including selection and modification of microorganisms and microbial communities), • Developing and optimising operation parameters and additives to improve leaching speed.⁹⁷
Supporting research domains	<ul style="list-style-type: none"> • Developing comprehensive models to predict bioleaching performance with different ore compositions, operating conditions, and microbial communities.⁹⁸

3.1.7 Implications for Australia

In its announced pledges scenario, the IEA estimates an increase in cobalt demand from 171.6 kt (thousand metric tons) in 2022 to 524.7 kt in 2050,⁹⁹ with a growing share from clean energy technologies.¹⁰⁰ Extraction of cobalt from ores represents the first step to produce the high purity cobalt compounds required for clean energy technologies, particularly the lithium-ion battery supply chain.

Current mine production is highly concentrated in the Democratic Republic of Congo, with 73% of global mine production in 2022. Alongside Indonesia (5% of global mine production), the country accounted for approximately 90% of the growth in cobalt supply between 2021 and 2022.¹⁰¹ Australia has the second largest cobalt reserves in the world, and therefore has an opportunity to diversify global supply. Australia's cobalt is distributed between sulphide ore (the most traditionally extracted due to their higher grade) and laterite ore deposits (lower in grade but more abundant). These deposits have different characteristics, processing pathways, and technical challenges.

With established mining and extraction operations and multiple planned projects, there is an opportunity for RD&D to support responsible, sustainable, and cost-effective use of Australian deposits, by enabling novel extraction processes and addressing the challenges faced by mature technologies. This can advance Australia's position as an international supplier and facilitate its expansion into high purity cobalt

⁹⁷ Saim AK, Darteh FK (2023) A Comprehensive Review on Cobalt Bioleaching from Primary and Tailings Sources. *Mineral Processing and Extractive Metallurgy Review*, 1–27.

⁹⁸ Sajjad W, Zheng G, Din G, Ma X, Rafiq M, Xu W (2019) Metals Extraction from Sulfide Ores with Microorganisms: The Bioleaching Technology and Recent Developments. *Transactions of the Indian Institute of Metals* 72(3), 559–579.

⁹⁹ IEA (2023) Critical Minerals Data Explorer. Cobalt – Announced Pledges Scenario. <<https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer>>.

¹⁰⁰ IEA (2023) Critical Minerals Review 2023. Implications. <<https://www.iea.org/reports/critical-minerals-market-review-2023/implications#abstract>>.

¹⁰¹ Benchmark Mineral Intelligence (2023) Cobalt Market Report 2022. 22 – 23. Cobalt Institute, Guildford. <https://www.cobaltinstitute.org/wp-content/uploads/2023/05/Cobalt-Market-Report-2022_final.pdf>.

compounds (particularly cobalt sulphate), which will be key to produce precursor cathode active materials in Australia.

This section discusses the opportunities for domestic RD&D and for international engagement in cobalt extraction from ores (summarised in Figure 8). More details on the framework used can be found in the main report *From minerals to materials: Assessment of Australia’s critical mineral mid-stream processing capabilities*.

Figure 8: Actions for Australian RD&D and international engagement in the extraction of cobalt from ores.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies	<ul style="list-style-type: none"> • Bioleaching (laterite ores) 	<ul style="list-style-type: none"> • AL with alternative acids 	<ul style="list-style-type: none"> • AL with alternative acids • Chloride leaching 	<ul style="list-style-type: none"> • Chloride leaching • Roasting • Smelting • Sulphuric acid (HPAL & AL) • Ammonia leaching • Bioleaching (sulphide ores)
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 off-takers 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.

AL, atmospheric leaching; HPAL, high-pressure acid leaching; IP, intellectual property.

Thermal pre-treatment

Thermal pre-treatment, such as roasting and smelting, is mature and commercially utilised in Australia. It will likely remain a relevant technology now and in the future. Thermal pre-treatment is necessary for producing matte, a feedstock into major commercial pathways for leaching sulphide ores. With sulphide deposits making up a large portion of current Australian production and lower global adoption of alternatives for processing sulphides, thermal pre-treatment will likely continue to be important for Australia.

Thermal pre-treatment is often essential to the economic viability of sulphide projects as it supports the efficiency of downstream leaching processes and can help maximise the recovery of co-occurring metals like nickel and copper. However, both roasting and smelting are energy intensive processes due to the high temperatures used. Improving cost and sustainability outcomes will be important to support the long-term viability of the industry in Australia.

Despite their high maturity, roasting and smelting have had high levels of patent activity over the past 15 years, indicating opportunities for innovation. These opportunities relate to optimising existing technologies: minimising temperatures while maintaining high recovery efficiency, minimising hazardous byproducts, increasing nickel and cobalt content, and producing intermediates that can be more directly transformed into battery-grade compounds. There are also opportunities to progress improvements such as mixed roasting approaches that use additives (e.g., chlorides, sulphates, carbonates, fluorides, alkaline compounds) to upgrade ores or improve cobalt recoveries. Recovering cobalt from waste residues is another key RD&D area, particularly in conventional smelting processes (e.g., when producing sulphide

matte) and in the RKEF pathway for nickel pig iron production. This could improve sustainability outcomes and maximise resource utilisation compared to international competitors.

Australia is well positioned to innovate in these areas, with established commercial-scale capability and existing patents in the thermal pre-treatment of sulphide and laterite ores. Given the maturity of roasting and smelting and the RD&D required, the opportunity for Australia lies in supporting existing operations to optimise their processes, and to support new commercial deployments which are driven by economic and sustainability considerations. The RD&D areas mentioned will require strong engagement with both domestic industry and overseas equipment manufacturers.

Sulphuric acid leaching

Sulphuric acid leaching is currently the major pathway to process laterite ores, an increasingly important source of cobalt globally and in Australia. While a significant proportion of Australian production of nickel and cobalt has come from its sulphide deposits and there have been recent sulphide discoveries in Australia,¹⁰² declining deposit sizes and sulphide ore grades are nevertheless a concern.¹⁰³ With the progressive exhaustion of large sulphide deposits globally, interest has grown in economically viable nickel and cobalt recovery from laterites,¹⁰⁴ and ways to address declining sulphide ore grades. Acid leaching is especially relevant for treating the limonite portion of laterite ores, which is not effectively treated through pyrometallurgical approaches at present.

The dominant and most commercially mature pathway for extracting cobalt from laterites is sulphuric acid at high temperatures and pressures (HPAL) or at atmospheric conditions (AL). In recent years the HPAL pathway has been prohibitively costly in Australia for private sector entrants due to the high capital and operating costs. Australia has not deployed a HPAL plant in since 2007.¹⁰⁵ Sulphuric acid in atmospheric conditions (AL) is less commonly used due to its technical drawbacks (see Section 3.1.2 Sulphuric acid leaching). However, it is well suited to treat tailings and low-grade ores and is therefore a useful technology in Australia's portfolio.

Pressure oxidation, which generates sulphuric acid in support of leaching, is a highly mature pathway for treating sulphide ores. However, it remains at pilot scale in Australia (e.g., IGO process). The incidental production of sulphuric acid and heat during pressure oxidation highlights an opportunity to treat sulphide and laterite ores simultaneously. This flexibility could be beneficial for process economics, compared to conventional approaches (like matte production followed by leaching).

Despite its maturity, leaching with sulphuric acid (HPAL, AL, and pressure oxidation processes) has multiple patent filings and shows a growing trend, suggesting there are opportunities to innovate. Australia is in a strong position to do so as it has commercial capability in both HPAL and atmospheric leaching of laterites using sulphuric acid. The country also has pilot activity in the pressure oxidation of sulphides and patents related to different forms of sulphuric acid leaching.

Australia's RD&D sector can support industry to address the prevalent challenges in commercial HPAL operations. There are RD&D opportunities for HPAL in the beneficiation step (out of scope for this report),

¹⁰² Government of Western Australia Department of Energy, Mines, Industry Regulation and Safety (n.d.) Nickel. Investor Information. <<https://www.dmp.wa.gov.au/Investors/Nickel-1477.aspx>>.

¹⁰³ Mudd GM (2010) Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews* 38(1–2), 9–26.

¹⁰⁴ It is estimated that 36% of land-based cobalt reserves are present in Ni-Co laterite deposits, compared to 15% in Ni-Cu-Co-(PGE) sulphide deposits; Slack et al. (2017) Cobalt, chap. F. In *Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply*: U.S. Geological Survey Professional Paper 1802. U.S. Geological Survey, Reston, Virginia.

¹⁰⁵ Wood Mackenzie (2023) The rise and rise of Indonesian HPAL – can it continue? Opinion. <<https://www.woodmac.com/news/opinion/rise-of-indonesian-hpal/>>.

particularly on widely applicable, cost-effective pre-concentration methods that can upgrade laterite ores to improve project economics. Other areas for improvement include strategies to reduce or manage waste streams (e.g., acidic tailings), and improved control over metallic impurities to facilitate downstream separation of cobalt.

On the other hand, piloting and scaling up improved sulphuric acid processes at atmospheric pressure could provide cost-effective and competitive alternatives to HPAL. RD&D opportunities for AL include addressing low recoveries and barriers to scale up through the use of additives, optimising the selectivity of the process, and addressing reagent consumption.

Pressure oxidation processes may also provide an alternative to ammonia and chlorine leaching for sulphide ores, in addition to enabling co-processing of laterites and sulphides in certain contexts. For pressure oxidation processes, work on optimised ore blends can facilitate leaching, improve process economics, and expand the feedstock that can be treated.

Leaching with alternative acids

Leaching using alternative acids is an emerging pathway with the potential to unlock other economically viable extraction pathways for laterites and enhance sustainability outcomes. As such, this topic is key to future cobalt production in Australia. Nitric and hydrochloric acids remain at pilot scale, while the use of phosphoric and organic acids is at lab scale. Although this area accounts for a smaller number of related patent filings, it has seen growing activity since 2007 and recent momentum.

Australia is well positioned to innovate in this area, with a number of patents on alternative acids, experience deploying pilot projects (e.g. Direct Nickel process), and strong capability in basic and applied hydrometallurgical research.

For leaching with alternatives like nitric acid, the opportunity lies in piloting and scaling up Australian technologies to support eventual large-scale deployment. Additional key RD&D includes energy-efficient acid regeneration strategies, as well as minimising corrosive and hazardous byproducts.

For organic and phosphoric acids, their emerging status represents an opportunity to develop and prove complete flowsheets, as well as establish new capabilities by engaging domestic and international research institutions in collaborative research.

Ammonia leaching

Ammonia leaching remains the prevalent pathway to treat the nickel matte produced from sulphide ores. Moreover, it can be applied to laterites and the mixed precipitate products (MHP and MSP) and is effective at removing metallic impurities. These characteristics make ammonia leaching a highly versatile technology option; it can accept multiple feedstocks and be used in purification steps providing a pathway that goes from extraction to the production of battery-grade cobalt sulphate.

Although ammonia leaching of mattes continues at commercial scale, its use in leaching laterite ores has declined over time as lower extraction makes it economically challenging. Patent activity over the last 15 years has been low and stable, in part reflecting the maturity of the process, its declining use for laterite ores, the stability of its feedstock (which in turn privileges a stable, conventional process), and the low recovery of cobalt from both ore and tailings.

Australia currently has commercial capability in ammonia leaching of mattes produced from sulphide ores and mixed sulphide precipitates and has had past industry experience utilising ammonia for leaching laterite ores. Further, Australia has a number of patents related to ammonia leaching, particularly to treat mixed precipitates (MHP and MSP).

Despite the high maturity of this area and low patent activity, there may be opportunities for Australia's RD&D sector to support commercial operations. This includes overcoming challenges of handling ammonia solutions, reducing the complexity of the process required to recover cobalt, and improving low extraction when treating laterite ores. Where relevant, there is an opportunity to pilot and demonstrate Australian IP to support the expansion of local operations into a wider range of ores and feedstocks and facilitate the cost-effective recovery of higher value cobalt compounds, not just nickel.

Chloride leaching

Chloride leaching is a versatile technology option useful for operations handling a range of different feedstocks. Leaching with chlorine gas in solution can be used for sulphide ores, matte and MSP, but despite its advantages it may be challenging to adopt commercially in Australia due to its high costs and due to risk-aversion. Leaching with hydrochloric acid, if paired with effective acid regeneration and re-use, is compatible with the entire profile of laterite ores (limonite and saprolite portions) and could potentially play a key role in Australia in the future.

Globally, leaching with chlorine gas in solution is mature and practiced at commercial scale, while leaching directly with hydrochloric acid or acidified chloride-containing solutions is at pilot scale. Despite commercial and pilot activity in this area, patent activity over the last 15 years has been moderate and experienced a small upwards trend.

Australia does not have commercial activity in leaching with chlorine gas in solution. Supporting the commercial deployment of proven overseas technologies could offer a pathway to implementing this technology onshore, with a role for RD&D in addressing the safety, sustainability and selectivity challenges faced by conventional chloride leaching processes. Opportunity areas are centred on managing the corrosivity of reagents and byproducts, the need for energy-efficient acid regeneration approaches, and addressing the low selectivity of chloride leaching (e.g., by implementing strategies to control metallic impurities). This would require strong international collaboration given the absence of domestic commercial activity.

Conversely, Australia has undertaken piloting activity on the use of chloride solutions. Furthermore, Australia has a small number of patents related to leaching with hydrochloric acid or chloride-containing solutions. Given strengths in this area, there is an opportunity to pilot and demonstrate relevant Australian IP on leaching laterite ores to support eventual commercial scale-up.

Bioleaching

Bioleaching plays a unique role in Australia's technology portfolio, due to its ability to extract nickel and cobalt from low grade or complex ores, and from secondary streams such as tailings and process waste.

In the context of recovery from waste and complex ores, bioleaching has been proven more economically viable than using conventional processes. It also has low energy requirements and produces fewer emissions. This addresses one of Australia's key strategic objectives to improve sustainability outcomes and to extract value from waste streams.

Bioleaching for nickel and cobalt recovery from sulphide ores is already used at commercial scale, as a main extractive method and a waste recovery approach. However, its use for recovery from laterite ores is technically challenging and remains at lab scale. Compared to other cobalt-related areas, bioleaching has the smallest volume of patents over the last 15 years.

Within Australia, bioleaching is already being used in a supporting capacity to facilitate nickel recovery from sulphide ores. However, the analysis of activity over the last 15 years (2007 – 2022) did not identify Australian patent filings related to bioleaching of laterite or sulphide ores.

Given the difference in maturity between ore types and limited IP activity, there are two complementary pathways for Australia. Firstly, there is an opportunity to support the commercial deployment of mature bioleaching approaches for challenging sulphide ores and waste streams. In this context, RD&D plays a role in addressing challenges to scale up, including improving the low and slow extraction, reducing the high variability in performance, and implementing adequate control measures to prevent environmental contamination. Secondly, there is an opportunity to engage internationally in the collaborative development of scalable, economically viable pathways for bioleaching laterite ores. However, given the substantial technical challenges of this area it is a long-term effort and higher risk RD&D investment.

3.2 Production of refined cobalt products

The next value-adding step in the cobalt supply chain is the production of refined cobalt products. In this step, producers can choose to produce three different products: a mixed intermediate (mixed hydroxide precipitate – MHP – or mixed sulphide precipitate – MSP), battery grade cobalt sulphate, or cobalt metal. Battery grade cobalt sulphate product is an input into the production of precursor cathode active material (pCAM) for lithium-ion batteries. Cobalt metal is a versatile product which can be sold to multiple end markets, including re-processing into battery-grade cobalt sulphate. Each product pathway has commercial and technical considerations which will be covered in this section.

First, the leach solution obtained from the initial extraction stage (containing cobalt, nickel, and other metals) must undergo separation and purification (see Section 3.2.1 Separation and purification).

To produce a mixed intermediate (MHP or MSP), precipitation is used as the main separation method; first by removing major metallic impurities (e.g., iron and aluminium), and then to produce MHP or MSP containing both nickel and cobalt. MHP and MSP are versatile products that can be sold to refineries for further processing. They can also be re-leached to produce cobalt sulphate or cobalt metal. Cobalt hydroxide (another battery precursor) can also be produced via precipitation.

Producing cobalt sulphate or cobalt metal from the leach solution involves several purification and separation techniques including precipitation, solvent extraction, and/or ion exchange. The objective of these methods is to remove metallic impurities and to separate cobalt from other metals, in order to produce a highly pure solution. This solution can then be used to produce battery-grade cobalt sulphate via crystallisation (see 3.2.2 Production of cobalt sulphate) or to produce cobalt metal (via electrowinning or hydrogen reduction (see 3.2.3 Production of cobalt metal)).

It is worth noting that, while the current supply chain uses highly pure cobalt sulphate for pCAM production, this could change in the future with the adoption of methods that directly produce pCAM or mixed metal sulphates (e.g., nickel-cobalt-manganese) from leach solutions. These methods could bypass the conventional separation and crystallisation stages, thus reducing the energy intensity of the overall production process.

3.2.1 Separation and purification

Precipitation

Cobalt may be separated from other metals through precipitation, from the solution obtained after leaching sulphide or laterite ores. Metallic impurities can be precipitated out of the solution. Cobalt is precipitated resulting in a cobalt compound (such as a cobalt sulphide, hydroxide, carbonate, or sulphate) by adding a reagent and modifying the pH of the solution.¹⁰⁶

However, the selectivity of cobalt recovery by precipitation is limited because other metals that behave similarly to cobalt (e.g. manganese, iron, and nickel) are also precipitated in the process. As such, this process is more frequently used to produce mixed precipitates (MHP and MSP) that are suitable for further refinement. For instance, the addition of magnesium oxide (MgO) precipitates nickel and cobalt as hydroxides (MHP), while the addition of hydrogen sulphide (H₂S) at high temperature and pressure precipitates a mixed sulphide (MSP).¹⁰⁷

Precipitation as MHP is comparatively simpler than the production of MSP as it does not require the use of hydrogen sulphide (a flammable and toxic reagent) at high pressures.¹⁰⁸ However, the MHP process is less selective, and can result in the presence of metallic impurities,¹⁰⁹ which must be adequately handled before precipitation or removed via downstream purification.

MSP production effectively excludes metallic impurities, making downstream processing simpler. MSP also has higher nickel content which increases the value of the product, and lower moisture which requires less drying time. This improves the overall economics of the extractive process and contributes to reducing transport costs.¹¹⁰ However, precipitating an MSP product can be complex given the hydrogen sulphide and high pressures involved (up to 1,000 kPa).¹¹¹

Precipitation can also be used to produce combined materials relevant to pCAM synthesis. For example, a recently developed process leaches MHP, producing two separate outputs: a concentrated nickel solution and a mixed precipitate (MHP) rich in cobalt and manganese. This approach is known as selective acid leach (SAL).¹¹²

¹⁰⁶ Shekarian et al. (2022) Development of a chemical-free process utilizing ozone oxidative precipitation for the recovery of cobalt and manganese from acid mine drainage. *Journal of Environmental Chemical Engineering* 10(5), 108533.

¹⁰⁷ Sole KC (2018) The Evolution of Cobalt–Nickel Separation and Purification Technologies: Fifty Years of Solvent Extraction and Ion Exchange. In *Extraction*, 1167–1191. The Minerals, Metals & Materials Series. Springer, Cham.

¹⁰⁸ Safitri et al. (2018) Recovery of nickel and cobalt as MHP from limonitic ore leaching solution: Kinetics analysis and precipitate characterization. *AIP Conference Proceedings* 1964, 020030.

¹⁰⁹ Cohen et al. (2018) Technological Advances, Challenges and Opportunities in Solvent Extraction from Energy Storage Applications In *Extraction*, 2033–2045. The Minerals, Metals & Materials Series. Springer, Cham.

¹¹⁰ Mubarak MZ, Lieberto J (2013) Precipitation of Nickel Hydroxide from Simulated and Atmospheric-leach Solution of Nickel Laterite Ore. *Procedia Earth and Planetary Science* 6, 457–464.

¹¹¹ Safitri et al. (2018) Recovery of nickel and cobalt as MHP from limonitic ore leaching solution: Kinetics analysis and precipitate characterization. *AIP Conference Proceedings* 1964, 020030; Ichlas et al. (2020) Processing mixed nickel-cobalt hydroxide precipitate by sulfuric acid leaching followed by selective oxidative precipitation of cobalt and manganese, *Hydrometallurgy* 191, 105185; Kyle (2010) Nickel laterite processing technologies – where to next? In *ALTA 2010 Nickel/Cobalt/Copper Conference*, 24 – 27 May, Perth, Western Australia.

¹¹² Williams et al. (2013) Selective leaching of nickel from mixed nickel cobalt hydroxide precipitate. *Hydrometallurgy* 138, 84–92; Byrne et al. (2017) Effect of key parameters on the selective acid leach of nickel from mixed nickel-cobalt hydroxide.

The two outputs generated by SAL may then be processed to produce highly pure separated nickel and cobalt solutions.¹¹³ Alternatively, these streams can be used as feedstock for pCAM production.¹¹⁴ In this case, the metallic impurities can be removed and the ratio of nickel, manganese, and cobalt can be adjusted to directly produce NMC pCAM. This effectively bypasses the conventional separation and crystallisation steps required to produce individual battery-grade sulphates that are eventually re-combined.¹¹⁵



TECHNOLOGY STATE OF PLAY

The use of precipitation to remove impurities and to produce mixed precipitate products is mature globally.

In Australia MHP is already produced as an end-product at the Ravensthorpe operation (First Quantum Minerals).¹¹⁶ Meanwhile, MSP is generated as an intermediate step at Murrin Murrin (Glencore) and produced as an end-product at the Kwinana Nickel Refinery (BHP Nickel West).¹¹⁷ MHP production is also present as an intermediate step in the planned flowsheets for the TECH (Queensland Pacific Metals) and Broken Hill (Cobalt Blue) projects.¹¹⁸ MSP is considered both an intermediate and an end-product in the piloted IGO process.¹¹⁹

There has also been relevant Australian activity on the use of selective leaching and precipitation for producing mixed materials for pCAM. The SAL process was developed by researchers at the University of Queensland and now underpins the NMC Direct process that has been piloted by Pure Battery Technologies at its plant in Hagen, Germany.¹²⁰ The company aims to increase commercial production capacity to 15,000 tonnes of pCAM per annum in Germany and establish a pCAM Hub in Western Australia to produce 50,000 tonnes per annum.¹²¹

¹¹³ Chong et al. (2013) Selective reductive leaching of oxidised cobalt containing residue. *Minerals Engineering* 54, 82–87.

¹¹⁴ Hawker W, Vaughan JW, Hodge HM, Weng F, Mann D (2021) Precipitation of Metals. Patent AU2022229686B2. Pure Battery Technologies Pty Ltd. <<https://patents.google.com/patent/AU2022229686B2/en?q=AU+2022%2f229686+B2>>.

¹¹⁵ CHEManager (2023) Von der Mine bis zum batteriefertigen Material. *Chemie & Life Sciences*. <<https://www.chemanager-online.com/news/von-der-mine-bis-zum-batteriefertigen-material>>.

¹¹⁶ Gray et al. (2022) Ravensthorpe Nickel Operations. NI 43-101 Technical Report, March 28, 2022. 109 – 112. <https://s24.q4cdn.com/821689673/files/doc_downloads/2022/Ravensthorpe-NI-43-101-Technical-Report.pdf>.

¹¹⁷ Minara Resources Limited (2023) Murrin Murrin Process and Technology Flow Chart. Glencore - Producing nickel and cobalt at Murrin Murrin. <https://www.glencore.com.au/dam/jcr:cc613626-0b0d-46d0-8d47-ffa175447c1b/MR_1147_flowchart_process2.pdf>; BHP Nickel West (2019) Attachment 2: BHP Nickel West Kwinana Licence L8437/2010/3 Process Description, 31 – 38. <https://www.der.wa.gov.au/images/documents/our-work/licences-and-works-approvals/Decisions_/W6275-2019-1_D.pdf>.

¹¹⁸ Queensland Pacific Metals (2023) Detailed Process Flowsheet. <<https://qpmetals.com.au/detailed-process-flowsheet/>>; Cobalt Blue (n.d.) Mining and processing. Broken Hill Cobalt Project. <<https://cobaltblueholdings.com/broken-hill/broken-hill-cobalt-project/>>.

¹¹⁹ IGO Limited (2019) Downstream Nickel Sulphate Study Update. <<https://www.igo.com.au/site/PDF/ae236a23-5880-454c-afc9-d2812c3f630b/DownstreamNickelSulphateStudyUpdate>>; IGO Limited (2019) IGO Maximises Value of its Nova Concentrate Through Offtake Agreements. ASX Release 1 November 2019. <<https://www.igo.com.au/site/PDF/770b3f12-1246-4577-991c-9955d345f24a/IGOmaximisesvalueofNovathroughnewofftakeagreements>>.

¹²⁰ HENDY (2022) Battery technology wins award for research commercialisation. *Australian Financial Review*, Nov 4. <<https://www.afr.com/work-and-careers/education/battery-technology-wins-award-for-research-commercialisation-20221027-p5bti7>>; Pure Battery Technologies (2022) Eine sichere Rohstoffversorgung steht auf zwei Füßen – Beispiel Pure Battery Technologies. BGR – GERRI Rohstoffkonferenz 2022, 5 – 6 July 2022. Federal Institute for Geosciences and Natural Resources (BGR) - German Research Network for Natural Resources – German Resource Research Institute (GERRI). <https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Veranstaltungen/Rohstoffkonferenz_2022_Rohstoffversorgung_Deutschlands/Zikarsky.pdf?__blob=publicationFile&v=3>.

¹²¹ Pure Battery Technologies (n.d.) Current Operations. <<https://purebatterytech.com/>>.

Solvent extraction (SX)

Solvent extraction selectively extracts cobalt out of a solution where other metals are present (e.g., aluminium, calcium, copper, iron, nickel, manganese, zinc) by using a reagent.¹²² Reagents based on organophosphorus acids have been the most used in commercial operations to separate cobalt.¹²³ Other examples include carboxylic acids, organophosphorus acids, and nitrogen-containing compounds (oximes and amines).¹²⁴

Conventional SX processes face several challenges that could benefit from RD&D efforts. These include the number of cycles required to achieve adequate purity, low stability of the reagent, trade-offs between selectivity and yield, and cross-contamination during other purification steps.¹²⁵ Moreover, the use of significant amounts of volatile or otherwise hazardous organic solvents in conventional SX poses risk- and environmental-related challenges.

There are emerging variations in SX with potential to overcome challenges found in commercially mature SX techniques. These variations explore alternative reagents, extractant combinations, or novel operation modes. For instance, liquid membranes are being explored due to their potential for greater efficiency, low energy input, and low solvent and extractant requirements.¹²⁶



TECHNOLOGY STATE OF PLAY

SX is one of the most commercially mature and widely used methods for the separation and purification of cobalt.¹²⁷ In Australia, Glencore uses SX at commercial scale for nickel and cobalt separation at its Murrin Murrin operation,¹²⁸ and Cobalt blue has used it at pilot scale in its Broken Hill Demonstration Plant.¹²⁹ SX was also tested as part of the piloted IGO process and is part of Queensland Pacific Metals' planned

¹²² CSIRO (n.d.) Solvent extraction to recover metals. Mining and Resources – Processing. <<https://www.csiro.au/en/work-with-us/industries/mining-resources/processing/solvent-extraction-to-recover-metals>>; Ecott C (2021) Refining of Mixed Sulphide Precipitate to Produce Battery Grade Metals Using Outotec Pressure Oxidation Process; Sole KC (2008) Solvent Extraction in the Hydrometallurgical Processing and Purification of Metals: Process Design and Selected Applications. In Solvent extraction and liquid membranes: Fundamentals and applications in new materials. (Eds. M Aguilar, JL Cortina) 141 – 200. CRC Press, Boca Raton.

¹²³ Sole KC (2018) The Evolution of Cobalt–Nickel Separation and Purification Technologies: Fifty Years of Solvent Extraction and Ion Exchange. In Extraction 2018. (Eds. B Davis, M Moats, S Wang) 1167–1191. The Minerals, Metals & Materials Series. Springer, Cham.

¹²⁴ Fischmann et al. (2013) Hydrometallurgical Nickel Laterite Processing: A Review of Current SX Flowsheets and Industry Trends. In Ni-Co 2013. (Eds T Battle, M Moats, V Cocalia, H Oosterhof, S Alam, A Allanore, R Jones, N Stubina, C Anderson, S Wang) 391 – 403. Springer International Publishing, Cham; Cohen et al. (2018) Technological Advances, Challenges and Opportunities in Solvent Extraction from Energy Storage Applications.

¹²⁵ Sole KC (2018) The Evolution of Cobalt–Nickel Separation and Purification Technologies: Fifty Years of Solvent Extraction and Ion Exchange. In Extraction 2018. (Eds. B Davis, M Moats, S Wang) 1167–1191. The Minerals, Metals & Materials Series. Springer, Cham; Cohen et al. (2018) Technological Advances, Challenges and Opportunities in Solvent Extraction from Energy Storage Applications.

¹²⁶ Parhi PK (2013) Supported Liquid Membrane Principle and Its Practices: A Short Review. Journal of Chemistry 2013, 1–11. Kislik VS (2016) Liquid Membrane Separation. In Encyclopedia of Membranes. (Eds E Drioli, L Giorno) 1105 – 1107. Springer Berlin Heidelberg. Berlin, Heidelberg.

¹²⁷ Sole KC (2018) The Evolution of Cobalt–Nickel Separation and Purification Technologies: Fifty Years of Solvent Extraction and Ion Exchange. In Extraction, 1167–1191, The Minerals, Metals & Materials Series. Springer, Cham; Cohen et al. (2018) Technological Advances, Challenges and Opportunities in Solvent Extraction from Energy Storage Applications.

¹²⁸ Minara Resources Limited (2023) Murrin Murrin Process and Technology Flow Chart. Glencore - Producing nickel and cobalt at Murrin Murrin. <https://www.glencore.com.au/dam/jcr:cc613626-0b0d-46d0-8d47-ffa175447c1b/MR_1147_flowchart_process2.pdf>.

¹²⁹ Cobalt Blue (n.d.) Mining and processing. Broken Hill Cobalt Project. <<https://cobaltblueholdings.com/broken-hill/broken-hill-cobalt-project/>>.

flowsheet for its TECH project.¹³⁰ Moreover, multiple relevant solvent extraction systems have been developed and piloted by CSIRO.¹³¹

In recent years, solvent extraction accounts for 11.2% of cobalt related filings identified in this analysis of 2007 – 2022, however it has faced a very strong uptick in patent activity since 2015, reflecting the importance of purification and high-purity compounds for battery applications. Filing activity in this area is led by China, with 70.5% of global output, followed by Japan (17%), and both Australia and the United States (4.5% each). Australian organisations with relevant patents include CSIRO, IGO, Renewable Metals, and South32.

Ion exchange separation (IX)

Ion exchange separation (IX) can be used either as an alternative to, or in conjunction with SX. IX relies on beads made from synthetic resins. The beads have a porous structure and contain compounds that selectively interact with the metals present in a solution under specific pH conditions. This allows the metals of interest to be separated from the leach solution, with the captured metals released afterward using an appropriate reagent (e.g., sulphuric acid). The resins then undergo a process of regeneration before re-use.¹³²

The potential of IX in cobalt processing is twofold. First, it can be used for the purification of cobalt-containing solutions (by extracting the impurities or the cobalt itself). This produces highly pure cobalt solutions suitable for electrowinning (to produce cobalt metal) or crystallisation (to produce battery-grade compounds like cobalt sulphate).¹³³ Secondly IX can support cobalt recovery from waste streams, namely the slurry of already leached material to capture any residual cobalt.¹³⁴ This approach can also maximise extraction from low-grade or complex ores to improve project economics.¹³⁵

IX separation benefits from its high selectivity, minimal waste byproducts, low energy intensity, and capacity to recover even small amounts of dissolved metals. However, it faces challenges related to cost, limited processing capacity, slow release of captured metals, and the progressive degradation of resins over multiple uses.¹³⁶ There are emerging areas of research on techniques similar to IX, looking at improving selectivity by using specially designed compounds (e.g., molecular recognition technology, MRT).¹³⁷

¹³⁰ IGO Limited (2019) Downstream Nickel Sulphate Study Update. <<https://www.igo.com.au/site/PDF/ae236a23-5880-454c-afc9-d2812c3f630b/DownstreamNickelSulphateStudyUpdate>>; Queensland Pacific Metals (2023) Detailed Process Flowsheet. <<https://qpmetals.com.au/detailed-process-flowsheet/>>.

¹³¹ Cheng et al. (2016) Recovery of nickel, cobalt, copper and zinc in sulphate and chloride solutions using synergistic solvent extraction. *Chinese Journal of Chemical Engineering* 24(2), 237–248.

¹³² van Deventer J (2011) Selected Ion Exchange Applications in the Hydrometallurgical Industry. *Solvent Extraction and Ion Exchange* 29(5–6), 695–718; Sole et al. (2018) Ion Exchange in Hydrometallurgical Processing: An Overview and Selected Applications. *Separation & Purification Reviews* 47(2), 159–178.

¹³³ Sole et al. (2018) Ion Exchange in Hydrometallurgical Processing: An Overview and Selected Applications. *Separation & Purification Reviews* 47(2), 159–178.

¹³⁴ Harrison et al. (2019) 2019 - The Clean Teq Sunrise Project – Pilot Demonstrated Upgrade Of Pressure Acid Leach Discharge Through Use Of Continuous Resin In Pulp Technology. <<https://www.cleanteqwater.com/wp-content/uploads/2020/10/2019-pilot-demonstrated-upgrade-PAL-discharge-CRIP.pdf>>.

¹³⁵ van Deventer J (2011) Selected Ion Exchange Applications in the Hydrometallurgical Industry. *Solvent Extraction and Ion Exchange* 29(5–6), 695–718.

¹³⁶ El Ouardi et al. (2023) The recent progress of ion exchange for the separation of rare earths from secondary resources – A review. *Hydrometallurgy* 218, 106047; Chen et al. (2022) Recent advances in selective separation technologies of rare earth elements: a review. *Journal of Environmental Chemical Engineering* 10(1), 107104.

¹³⁷ Mohanty et al. (2017) Mechanistic Aspects of Host–Guest Binding in Cucurbiturils: Physicochemical Properties. In *Comprehensive Supramolecular Chemistry II* 2017. 435 – 457, Elsevier; Huang F, Anslyn EV. (2015) Introduction: Supramolecular Chemistry. *Chemical Reviews*



The use of IX for purification of nickel and cobalt is mature globally, being used at scale by ERG Africa at its Chambishi Metals Refinery (Zambia) and by Vale at its Port Colborne Refinery (Canada).¹³⁸

In Australia, IX separation has been previously implemented at scale at the Bulong Nickel project for copper removal and used in conjunction with SX for separation of nickel-cobalt, as part of the purification process. The operation then produced cobalt metal by electrowinning.¹³⁹

IX is also part of the flowsheet used by Cobalt Blue in its demonstration plant at Broken Hill.¹⁴⁰ Moreover, IX use has been piloted by Clean Teq (now Sunrise Energy Metals) as part of demonstration activities for its Sunrise project.¹⁴¹

Ion-exchange separation forms a smaller patent category, with related patents representing 2.5% of all cobalt related filings identified in this analysis from 2007 – 2022. Australia accounts for 40% of the total, followed by China (32%), and the United States (16%). Australian organisations with relevant patents include BHP, CSIRO, Glencore, South32, and the University of Queensland.¹⁴²

Overall, the area maintained a low and stable baseline of filing activity between 2007 and 2022.

The following table summarizes the RD&D focus areas for separation and purification:

Table 8: Global RD&D focus areas for separation and purification technologies.

RD&D FOCUS AREAS	
Precipitation	<ul style="list-style-type: none"> Implementing strategies that enhance precipitation selectivity (i.e., minimise the co-precipitation of metallic impurities), increase the grade of cobalt in mixed precipitates, or reduce reagent use.¹⁴³

115(15), 6999–7000; Izatt et al. (2015) Industrial applications of molecular recognition technology to separations of platinum group metals and selective removal of metal impurities from process streams. *Green Chemistry* 17(4), 2236–2245.

¹³⁸ Sole et al. (2018) Ion Exchange in Hydrometallurgical Processing: An Overview and Selected Applications. *Separation & Purification Reviews* 47(2), 159–178; Gauld et al. (2021) Technical Report Summary - Sudbury Property - Ontario Operations – Canada. 165. <https://minedocs.com/22/Sudbury__TR_04072022.pdf>.

¹³⁹ Sole et al. (2018) Ion Exchange in Hydrometallurgical Processing: An Overview and Selected Applications. *Separation & Purification Reviews* 47(2), 159–178.

¹⁴⁰ Cobalt Blue Holdings Limited (2022) Demonstration Plant Transitioning to Operations. <<https://cobaltblueholdings.com/assets/2410364.pdf>>; Cobalt Blue Holdings Limited (2021) Broken Hill Cobalt Project Scoping Report SSD 10426. 19 – 23. <<https://majorprojects.planningportal.nsw.gov.au/prweb/PRRestService/mp/01/getContent?AttachRef=SSD-10426%2120220118T020614.107%20GMT>>

¹⁴¹ Harrison et al. (2019) 2019 - The Clean Teq Sunrise Project – Pilot Demonstrated Upgrade Of Pressure Acid Leach Discharge Through Use Of Continuous Resin In Pulp Technology. <<https://www.cleanteqwater.com/wp-content/uploads/2020/10/2019-pilot-demonstrated-upgrade-PAL-discharge-CRIP.pdf>>.

¹⁴² Filings attributed to Glencore and its subsidiaries have been counted as Australian patents given Australia was listed as the earliest priority country.

¹⁴³ Sethurajan et al. (2022) Hydrometallurgical leaching and recovery of cobalt from lithium ion battery. *Environmental Technology & Innovation* 28, 102915; Harvey et al. (2011) Selective precipitation of mixed nickel–cobalt hydroxide. *Hydrometallurgy* 105(3–4), 222–228; Kim et al. (2021) Selective cobalt and nickel electrodeposition for lithium-ion battery recycling through integrated electrolyte and interface control. *Nature Communications* 12(1), 6554.

	<ul style="list-style-type: none"> Assessing the viability at scale of leaching and precipitation techniques that help bypass downstream separation and purification steps.¹⁴⁴
Solvent extraction	<ul style="list-style-type: none"> Developing cost-effective strategies to directly separate nickel and cobalt from a complex leach solution. This may include combinations of existing extractants (synergistic SX) or development of new ones.¹⁴⁵ Developing alternative solvents to address the safety and environmental challenges of organic solvents (e.g., use of non-aqueous solvents).¹⁴⁶ Characterising the alternative operation modes that can be used for SX (e.g., supported liquid membranes), optimising their performance for selective recovery of cobalt, and assessing their viability at scale.
Ion exchange separation	<ul style="list-style-type: none"> Optimising physical aspects of the resins, which includes enhancing resin durability and reuse, minimising fouling, and increasing throughput. Optimising and assessing the viability of integrating IX resins in direct cobalt recovery from leach solutions and waste streams (e.g. resin-in-leach and resin-in-pulp approaches).¹⁴⁷
Supporting research domains	<ul style="list-style-type: none"> Developing models for predicting the behaviour and performance of new SX approaches.¹⁴⁸

Implications for Australia

Separation and purification technologies are key to producing high-grade intermediates and the high purity, refined products used in advanced materials. This includes mixed precipitates like MSP and MHP (common saleable intermediates to refineries), cobalt sulphate for use in pCAM production for lithium-ion batteries, and cobalt metal for a suite of alloys.

Global production of refined cobalt products was estimated at 165 kt in 2022, 80% of which corresponds to compounds and 20% to metal.¹⁴⁹ This segment is heavily concentrated in China, which accounted for 76%

¹⁴⁴ Vaughan et al. (2013) Engineering aspects of the selective acid leaching process for refining mixed nickel-cobalt hydroxide. 4th Annual Nickel-Cobalt-Copper Event, Perth, WA, Australia 25 May-1 June 2013. Melbourne, VIC, Australia: ALTA Metallurgical Services; Ichlas et al. (2020) Processing mixed nickel-cobalt hydroxide precipitate by sulfuric acid leaching followed by selective oxidative precipitation of cobalt and manganese. *Hydrometallurgy* 191, 105185.

¹⁴⁵ Cheng et al. (2016) Recovery of nickel, cobalt, copper and zinc in sulphate and chloride solutions using synergistic solvent extraction. *Chinese Journal of Chemical Engineering* 24(2), 237–248.

¹⁴⁶ Li et al. (2021) Nonaqueous Solvent Extraction for Enhanced Metal Separations: Concept, Systems, and Mechanisms. *Industrial & Engineering Chemistry Research* 60(48), 17285–17302; Lei et al. (2017) Introduction: Ionic Liquids. *Chemical Reviews* 117(10), 6633–6635; Smith et al. (2014) Deep Eutectic Solvents (DEEs) and Their Applications. *Chemical Reviews* 114(21), 11060–11082; El Achkar et al. (2021) Basics and properties of deep eutectic solvents: a review. *Environmental Chemistry Letters* 19(4), 3397–3408; Hansen et al. (2021) Deep Eutectic Solvents: A Review of Fundamentals and Applications. *Chemical Reviews* 121(3), 1232–1285.

¹⁴⁷ Littlejohn P, Vaughan J (2013) Recovery of nickel and cobalt from laterite leach tailings through resin-in-pulp scavenging and selective ammoniacal elution. *Minerals Engineering* 54, 14–20; Oraby et al. (2023) Selective extraction of nickel and cobalt from disseminated sulfide flotation cleaner tailings using alkaline glycine-ammonia leaching solutions. *Minerals Engineering* 204, 108418.

¹⁴⁸ Van Eygen et al. (2021) Efficient membrane-based affinity separations for chemical applications: A review. *Chemical Engineering and Processing - Process Intensification* 169, 108613; Li et al. (2021) Nonaqueous Solvent Extraction for Enhanced Metal Separations: Concept, Systems, and Mechanisms. *Industrial & Engineering Chemistry Research* 60(48), 17285–17302.

¹⁴⁹ Benchmark Mineral Intelligence (2023) Cobalt Market Report 2022. 26 – 27. Cobalt Institute, Guildford. <https://www.cobaltinstitute.org/wp-content/uploads/2023/05/Cobalt-Market-Report-2022_final.pdf>

of global production in 2022, followed by Finland (10%) and Canada (2%).¹⁵⁰ With the adoption of clean energy technologies driving demand for refined cobalt products, Australian RD&D will be necessary in three distinct ways. First, to support the deployment of proven technologies in new onshore projects. Second, to ensure existing operations remain competitive through increasingly efficient, sustainable and cost-effective separation and purification. Finally, to demonstrate innovative methods at scale that can provide time, cost and energy intensity benefits, positioning Australia as a reliable supplier compatible with the low emissions requirements of battery and EV OEMs. This triple role can help leverage Australia advance its strategic objective of moving downstream in the supply chain, towards onshore production of cobalt sulphate and pCAM.

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

Figure 9: Actions for Australian RD&D and international engagement in the separation and purification of cobalt.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies			<ul style="list-style-type: none"> • Ion-exchange • Precipitation • Solvent Extraction 	<ul style="list-style-type: none"> • Precipitation • Solvent Extraction
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.

Precipitation

Precipitation underpins the production of MHP and MSP, which have become widespread commercial intermediates. Mixed precipitates provide an opportunity to move downstream from the production and export of concentrate, without requiring a comprehensive pathway that goes all the way to cobalt sulphate or cobalt metal. Moreover, their increased nickel and cobalt contents make them more economically favourable for transportation than ores or concentrates.

Novel leaching and precipitation methods can also be used to directly produce NMC pCAM from MHP. This approach enables shorter flowsheets that bypass conventional cobalt sulphate production, to generate pCAM. This process intensification can enhance competitiveness on both cost and environmental metrics. Lastly, precipitation also enables downstream separation and purification to produce cobalt sulphate and cobalt metal.

¹⁵⁰ Benchmark Mineral Intelligence (2023) Cobalt Market Report 2022. 26 – 27. Cobalt Institute, Guildford. <https://www.cobaltinstitute.org/wp-content/uploads/2023/05/Cobalt-Market-Report-2022_final.pdf>

Australia currently has commercial capability in both MHP and MSP production and relevant IP in novel approaches such as the direct production of combined materials for pCAM synthesis (e.g., NMC Direct process). For mixed MHP and MSP production, there is an opportunity for RD&D to support expanded commercial deployment of mature technologies. There is also an opportunity to improve the selectivity of the process, both to maximise nickel and cobalt recovery and to minimise the presence of impurities that can complicate downstream processing. This can help reduce costs while increasing industry revenues through higher-grade, higher purity end-products. For the direct production of combined materials for pCAM, there is an opportunity to pilot and scale up existing IP domestically to deliver economic, emissions, and energy intensity benefits.

In both cases, engagement with battery manufacturers interested in mixed precipitates as feedstock will be essential to de-risk domestic projects and obtain offtake.¹⁵¹ Additional RD&D opportunities include improving the handling of metallic impurities and privileging the recovery of metals of interest.

Solvent extraction (SX)

Solvent extraction is a core technology across many separation and purification processes and is a commercially viable pathway to making cobalt sulphate and cobalt metal for the LiB supply chain. SX is a high throughput process suitable for large scale operations, and its maturity across cobalt and other industries makes it a near-term technology option with comparatively low investment risk. Further innovations in SX can enhance the competitiveness of Australian operators from a cost and sustainability standpoint.

Despite being implemented at commercial scale around the world, there is still room for innovation in the area. Solvent extraction has had consistently high patent activity over the last 15 years and has experienced a growing trend with multiple peaks in activity. RD&D opportunities include direct solvent extraction approaches to reduce the number of process steps, synergistic solvent extraction strategies to enhance recovery, and liquid membranes to enable continuous separation. Developing new reagents for SX is also possible. However, this represents a higher risk proposition given the resources required for development, the environmental approvals required, and the need to minimise cost to ensure a new reagent is competitive.

Australia currently has established capabilities for SX separation of nickel and cobalt, distributed across multiple commercial projects and pilot plants. Moreover, Australia has several relevant patents in the area. Given the maturity of solvent extraction and Australia's capabilities, there is an opportunity for the RD&D sector to support the expansion of commercial deployment. This may involve process optimisation or process intensification to simplify existing pathways and enhance separation efficiency. Additionally, there is an opportunity to pilot and scale Australian IP in emerging SX approaches that provide throughput or purity benefits over conventional SX processes, or that enable a more direct recovery of high value metals from complex solutions.

Ion exchange separation

IX is particularly relevant in flowsheets that aim to produce battery-grade cobalt sulphate or cobalt metal through electrowinning, two key value-added products for Australia. Ion exchange (IX) can be used instead of, or in conjunction with, solvent extraction (SX) to produce highly pure solutions, a pre-requisite for cobalt sulphate and cobalt metal production. IX's high selectivity and ability to produce highly pure solutions make

¹⁵¹ Milewski A (2021) Mixed hydroxide precipitate – the new class one nickel. Mining.com. <<https://www.mining.com/mixed-hydroxide-precipitate-the-new-class-one-nickel/>>.

it an essential part of Australia's technology portfolio. Furthermore, IX resins can be used to recover cobalt from leaching waste streams. This aligns with Australia's strategic and sustainability objectives around maximising resource recovery.

IX separation is a mature process used at commercial scale globally to remove impurities from cobalt solutions. It represents a small portion of all filings identified in the patent analysis with low and stable activity over the past 15 years. This can, in part, be attributed to the high maturity of the technology and a greater focus on SX for applications with large volumes.

Australia has established capabilities in IX separation, illustrated by past commercial projects (e.g. Bulong Nickel), pilot demonstrations (e.g. Cobalt Blue), and relevant IP (e.g. Sunrise Energy Metals). Australia also has several patents related to the use of IX separation in the purification of nickel and cobalt solutions. There is an opportunity for the RD&D sector to support the expansion of IX in the commercial production of highly pure cobalt sulphate onshore. Other than providing process engineering services and plant optimisation there is an opportunity for enhancing resin durability, optimising recovery strategies from residue streams, and increasing throughput. There is also an opportunity to pilot and scale Australian IX technologies for direct cobalt recovery from waste streams.

3.2.2 Production of cobalt sulphate

Once purified and separated, the recovered cobalt undergoes a process of crystallisation and final drying to produce a highly pure compound. The crystallisation process uses controlled temperatures or solvent compositions to induce solidification of a crystal, usually in powder form. Cobalt sulphate heptahydrate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$) is a common end-product suitable for use in pCAM manufacture, but other compounds like cobalt hydroxide may also be produced.¹⁵² Approaches to crystallisation include thermal approaches, chemical approaches, and membrane crystallisation which employs elements of both.

Thermal approaches

In evaporative crystallisation, the solution obtained after purification is heated to evaporate the solvent, resulting in the formation of crystals once the temperature decreases.¹⁵³ Advantages include high growth rates for the crystals and high control over their characteristics through process parameters (e.g., temperature, mixing speed).¹⁵⁴ However, in its conventional format it faces limited control over the impurities into the final product and significant energy consumption linked to heating.¹⁵⁵ This has led to the development of approaches that maximise the recovery and reuse of heat produced in other processes.¹⁵⁶

Cooling crystallisation uses evaporation coupled with lower temperatures to induce the formation and growth of cobalt sulphate crystals from a solution.¹⁵⁷ Cooling crystallisation and its related variants are less

¹⁵² Ma et al. (2020) Precipitation and Crystallization Used in the Production of Metal Salts for Li-Ion Battery Materials: A Review. *Metals* 10(12), 1609.

¹⁵³ Hipple J (2017) Evaporation and Crystallization. In *Chemical Engineering for Non-Chemical Engineers*, 203-219. American Institute of Chemical Engineers, Inc.

¹⁵⁴ Choi KH, Azimi G (2023) Crystallization of nickel sulfate and its purification process: towards efficient production of nickel-rich cathode materials for lithium-ion batteries. *RSC Advances* 13(41), 28501–28512; Zhang et al. (2022) Semi-batch evaporative crystallization and drying of cobalt sulphate hydrates. *Hydrometallurgy* 208, 105821.

¹⁵⁵ Xuan et al. (2022) Antisolvent Precipitation for Metal Recovery from Citric Acid Solution in Recycling of NMC Cathode Materials. *Metals* 12(4), 607.

¹⁵⁶ Lu et al. (2017) Crystallization techniques in wastewater treatment: An overview of applications. *Chemosphere* 173, 474–484.

¹⁵⁷ Cool Separations (n.d.) CC Technology - How it works. Cooling Crystallization Technology. <<https://www.coolseparations.nl/cc-technology-how-it-works/>>.

susceptible to equipment corrosion caused by byproducts due to the lower temperatures used, relative to evaporative crystallisation.¹⁵⁸ However, it requires careful control of impurities in the feed solution which can affect the crystallisation temperature and end-product characteristics (e.g., crystal size and form).¹⁵⁹ There are emerging variations on this process, such as eutectic freeze crystallisation, which may enable further reduction of energy intensity, corrosion and better recovery of product from the frozen solvent.¹⁶⁰ However, operational challenges include, for example, separating the crystals from internal surfaces.¹⁶¹

Chemical approaches

Chemical approaches use a reagent to induce crystallisation, and do not rely on temperature changes thereby reducing the energy consumption associated with evaporative or cooling methods.

Reactive crystallisation involves introducing suitable reagent to generate a crystalline product, which can then be precipitated out of the solution and recovered. This approach offers control over product characteristics, and limits the waste generated.¹⁶² However, reactive crystallisation produces a large number of small crystals which can be prone to clustering, affecting the quality of the final product.¹⁶³

Antisolvent crystallisation relies on the addition of a liquid agent to significantly reduce solubility, triggering crystallisation of the metal compound of interest.¹⁶⁴ This method differs from reactive crystallisation; rather than reacting with the metal present to form a compound, it alters the capacity of the solvent to keep the metal in a dissolved state. The change in solubility is fast and does not depend on temperature changes, making the process suitable for the crystallisation of a broader range of compounds.¹⁶⁵ However, the use of antisolvents faces challenges related to additional reagent use and the processes required to recover them.¹⁶⁶

Membrane crystallisation

Membrane crystallisation uses membranes to facilitate crystallisation and solvent separation. This approach uses the core principles of thermal and chemical approaches, and can be used to improve energy efficiency, control over crystal size, and waste generation of conventional processes.¹⁶⁷ Challenges for this area include membrane degradation over time, which can impact performance and increase costs (given the need to restore or replace the membrane). Further, impurities can significantly impact the yield and quality of crystals.

¹⁵⁸ Lu et al. (2017) Crystallization techniques in wastewater treatment: An overview of applications. *Chemosphere* 173, 474–484; Ma et al. (2020) Precipitation and Crystallization Used in the Production of Metal Salts for Li-Ion Battery Materials: A Review. *Metals* 10(12), 1609.

¹⁵⁹ Han et al. (2019) Purification of Nickel Sulfate by Batch Cooling Crystallization. *Chemical Engineering & Technology* 42(7), 1475–1480.

¹⁶⁰ Cool Separations (n.d.) EFC TECHNOLOGY – HOW IT WORKS. Eutectic Freeze Crystallization. <<https://www.coolseparations.nl/efc-technology-how-it-works/>>.

¹⁶¹ Ma et al. (2020) Precipitation and Crystallization Used in the Production of Metal Salts for Li-Ion Battery Materials: A Review. *Metals* 10(12), 1609.

¹⁶² McDonald et al. (2021) Reactive crystallization: a review. *Reaction Chemistry & Engineering* 6(3), 364–400.

¹⁶³ Karpiński PH, Baldyga J. (2019) Precipitation Processes. In *Handbook of Industrial Crystallization*. (Eds. Myerson AS, Erdemir D, Lee AY) 216-265. Cambridge University Press, UK.

¹⁶⁴ Dighe et al. (2022) Three-Step Mechanism of Antisolvent Crystallization. *Crystal Growth & Design* 22(5), 3119–3127.

¹⁶⁵ Takiyama H (2020) Anti-solvent Crystallization Method for Production of Desired Crystalline Particles. (Eds M Sakamoto, H Uekusa) 53 – 70. Springer Singapore, Singapore; Jia et al. (2022) Recent progress in antisolvent crystallization. *CrystEngComm* 24(17), 3122–3135.

¹⁶⁶ Genck W (2010) Make The Most of Antisolvent Crystallization. *Chemical Processing*. <<https://www.chemicalprocessing.com/processing-equipment/powder-solids/article/11372856/make-the-most-of-antisolvent-crystallization-chemical-processing>>.

¹⁶⁷ Jiang et al. (2021) Membrane Crystallization for Process Intensification and Control: A Review. *Engineering* 7(1), 50–62.



Evaporative methods are mature and employed widely to crystallise battery-grade compounds globally and in Australia. In Australia, EC is being used at commercial scale by BHP to produce nickel sulphate hexahydrate from the nickel metal powder generated by the Kwinana Nickel Refinery.¹⁶⁸ This type of crystallisation is also used by both BHP and Glencore to recover the ammonia used in their processes as ammonium sulphate, which can be sold as a fertiliser.¹⁶⁹ Production of cobalt sulphate heptahydrate via EC has been performed at pilot scale by Cobalt Blue at its Broken Hill Cobalt Project demonstration plant.¹⁷⁰ The crystallisation circuit at BHP's nickel sulphate plant was designed and delivered by JordProxa, an Australian-South African joint venture specialising in crystallisation processes.¹⁷¹ The company will also deliver the corresponding crystallisation technology for Queensland Pacific Metals' TECH project.¹⁷²

Reactive crystallisation is already used at scale globally for intermediate steps throughout the separation and extraction from ores. Within Australia, its use in the generation of a final battery-grade cobalt product remains under investigation. For example, IGO's direct crystallisation (DXTL™) approach to produce nickel sulphate has been tested at the pilot scale and could be considered a form of reactive crystallisation.

The conventional form of cooling crystallisation is mature globally. While not currently used at commercial scale in Australia, it has been proposed as part of the sulphate refinery flowsheet for Queensland Pacific Metals' TECH project.¹⁷³ Meanwhile, eutectic freeze crystallisation has been tested at the laboratory scale to produce cobalt sulphate heptahydrate, including from leached and purified solution from recycled lithium-ion batteries.¹⁷⁴ EFC has also been piloted by Cool Separations (Netherlands) for the removal of magnesium sulphate, sodium sulphate, and sodium bicarbonate from various waste streams, including acid mine drainage.¹⁷⁵ Moreover, researchers at TU Delft (Netherlands) have also conducted a small-scale pilot of EFC for recovering nickel sulphate from an industrial stream.¹⁷⁶

Both antisolvent crystallisation and membrane crystallisation remain at the laboratory scale for nickel and cobalt sulphate production.¹⁷⁷

¹⁶⁸ BHP (2021) BHP delivers first crystals from Kwinana nickel sulphate plant. Media Centre. <<https://www.bhp.com/news/media-centre/releases/2021/10/bhp-delivers-first-crystals-from-kwinana-nickel-sulphate-plant>>.

¹⁶⁹ BHP Nickel West (2019) Attachment 2: BHP Nickel West Kwinana Licence L8437/2010/3 Process Description, 17 July 2019. 31 – 38. <https://www.der.wa.gov.au/images/documents/our-work/licences-and-works-approvals/Decisions_/W6275-2019-1_D.pdf>; Minara Resources Limited (2023) Murrin Murrin Process and Technology Flow Chart. Glencore - Producing nickel and cobalt at Murrin Murrin. <https://www.glencore.com.au/dam/jcr:cc613626-0b0d-46d0-8d47-ffa175447c1b/MR_1147_flowchart_process2.pdf>.

¹⁷⁰ Cobalt Blue Holdings Limited (2020) Broken Hill Cobalt Project (BHCP) Project Update 2020. ASX Announcement. 58. <<https://cobaltblueholdings.com/assets/BHCP-Project-Update-16July20-READY.pdf>>.

¹⁷¹ JordProxa (n.d.) Nickel Sulphate Crystalliser in Australia. Case Studies. <<https://jordproxa.com/nickel-sulphate-plant/>>.

¹⁷² Queensland Pacific Metals (2022) June 2022 Quarterly Report. <<https://wcsecure.weblink.com.au/pdf/QPM/02546972.pdf>>.

¹⁷³ Pure Minerals Limited (2020) TECH PROJECT – A Diversified Value-Add Business for all Commodity Cycles: Updated PFS to include HPA Delivers Significant Returns. ASX Release. 21. <<https://announcements.asx.com.au/asxpdf/20200407/pdf/44gs5m886dfpm0.pdf>>.

¹⁷⁴ Ma et al. (2022) Eutectic freeze crystallization for recovery of NiSO₄ and CoSO₄ hydrates from sulfate solutions. *Separation and Purification Technology* 286, 120308; Zhang J, Louhi-Kultanen M (2023) Determination of nucleation kinetics of cobalt sulfate by measuring metastable zone width and induction time in pure and sulfuric acid solution. *Powder Technology* 422, 118463; Ma et al. (2023) Eutectic Freeze Crystallization for Recovery of Cobalt Sulfate in the Recycling of Li-Ion Batteries.

¹⁷⁵ Cool Separations (n.d.) History. About Us. <<https://www.coolseparations.nl/history-timeline/>>.


¹⁷⁶ Lu X (2014) Novel Applications of Eutectic Freeze Crystallization. PhD Thesis. Department of Biotechnology, Faculty of Applied Sciences, Delft University of Technology. <<https://doi.org/10.4233/uuid:6633e264-9839-4b25-b737-5126bf35e4f0>>.

¹⁷⁷ Aktas et al. (2013) Investigation of cobalt sulfate precipitation by alcohol and influencing factors. *Mining, Metallurgy & Exploration* 30(3), 174–179; Demirel et al. (2022) Antisolvent crystallization of battery grade nickel sulphate hydrate in the processing of lateritic ores. *Separation and*

In recent years, the crystallisation of cobalt sulphate has become the second largest area of patent activity behind leaching. It represents 10.9% of all filings in this analysis of global activity between 2007 and 2022, and has had a significant ramp up in patent activity since 2017, reflecting the demand for cobalt sulphate stemming from the battery market. China accounts 71.6% of filings in this category, followed by Japan with 17.4%, and the United States with 5.5%. Australian activity accounts for less than 1% of global output. Australian organisations with relevant patents include CSIRO.

The following table summarizes the RD&D focus areas for crystallisation of battery-grade cobalt compounds.

Table 9: Global RD&D focus areas for the crystallisation of battery-grade cobalt compounds.

 RD&D FOCUS AREAS	
Evaporative crystallisation	<ul style="list-style-type: none"> Integrating strategies to increase the energy efficiency of the process (e.g., by recycling heat) and minimise or remove impurities incorporated into the final crystal product (e.g., magnesium).¹⁷⁸
Reactive crystallisation	<ul style="list-style-type: none"> Characterising in detail the influence of additives and mixing and implementing strategies that use them to control end-product characteristics.¹⁷⁹
Cooling crystallisation	<ul style="list-style-type: none"> Developing mechanisms to increase crystallisation efficiency, reduce energy consumption, enhance control over end-product properties, and (in the case of EFC) streamline the separation of salt crystals from ice and solvent.¹⁸⁰
Antisolvent crystallisation	<ul style="list-style-type: none"> Optimising antisolvent, addition rate, seeding, antisolvent addition point, mixing and other crucial parameters specifically for the crystallisation of cobalt sulphate and assessing the viability of the process at scale.¹⁸¹ Developing cost-effective strategies for recovering and recycling antisolvents at scale.
Membrane crystallisation	<ul style="list-style-type: none"> Implementing scalable, cost-effective measures to prevent and reverse membrane degradation.¹⁸²

Purification Technology 286, 120473; Madsen et al. (2019) Novel membrane percrystallisation process for nickel sulphate production. Hydrometallurgy 185, 210–217.

¹⁷⁸ Lu et al. (2017) Crystallization techniques in wastewater treatment: An overview of applications. Chemosphere 173, 474–484; Choi KH, Azimi G (2023) Crystallization of nickel sulfate and its purification process: towards efficient production of nickel-rich cathode materials for lithium-ion batteries. RSC Advances 13(41), 28501–28512.

¹⁷⁹ Teychené et al. (2020) Reactive crystallization: From mixing to control of kinetics by additives. Current Opinion in Colloid & Interface Science 46, 1–19.

¹⁸⁰ Randall DG, Nathoo J (2015) A succinct review of the treatment of Reverse Osmosis brines using Freeze Crystallization. Journal of Water Process Engineering 8, 186–194; Han et al. (2019) Purification of Nickel Sulfate by Batch Cooling Crystallization. Chemical Engineering & Technology 42(7), 1475–1480.

¹⁸¹ Peters et al. (2022) Impact of process parameters on product size and morphology in hydrometallurgical antisolvent crystallization. CrystEngComm 24(15), 2851–2866.

¹⁸² Shen et al. (2023) Recent advances in membrane crystallization. CrystEngComm 25(17), 2503–2517; Jiang et al. (2021) Membrane Crystallization for Process Intensification and Control: A Review. Engineering 7(1), 50–62.

- Developing detailed models of membrane materials, designs, and key processes to improve efficiency, performance, and control over crystal properties.¹⁸³

Implications for Australia

Crystallisation is a key technology underpinning the final step to produce cobalt sulphate, a high-grade saleable solid and direct input into pCAM. It represents a strategic opportunity for Australia given strategic ambitions to produce pCAM and CAM onshore.

Bridging the gap between existing extraction activity and cobalt sulphate production also represents a potential economic opportunity for Australia given the market size for cobalt sulphate and pCAM, if Australia is able to produce cost-competitively. The global cobalt sulphate and CAM markets were valued at US\$1.3 billion and US\$24.8, respectively, in 2022.¹⁸⁴

Figure 10: Actions for Australian RD&D and international engagement in the production of cobalt sulphate.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies	<ul style="list-style-type: none"> • Emerging crystallisation (Eutectic freeze, antisolvent, membrane) 		<ul style="list-style-type: none"> • Ion-exchange • Precipitation • Solvent Extraction 	<ul style="list-style-type: none"> • Precipitation • Solvent Extraction • Mature crystallisation (evaporative, cooling & reactive)
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.

Crystallisation is an area with strong levels of research activity, as indicated by levels of patent filing trends and recent momentum. This reflects high levels of global activity in battery intermediate products, and the need for high performance materials. The maturity of the different crystallisation techniques varies, as does their global deployment to produce cobalt sulphate. Evaporative, cooling, and reactive crystallisation are the most mature and currently used at commercial scale globally due to their simplicity, scalability, and ability to meet product characteristics. Eutectic freeze, antisolvent, and membrane crystallisation of cobalt sulphate remain at lab scale.

Despite its apparent simplicity, crystallisation parameters can influence crystal purity, size and hydrate form, affecting suitability of the product for pCAM production. There is space for RD&D across both mature and emerging crystallisation processes. For instance, increasing energy efficiency is relevant for

¹⁸³ Shen et al. (2023) Recent advances in membrane crystallization. *CrystEngComm* 25(17), 2503–2517; Jiang et al. (2021) Membrane Crystallization for Process Intensification and Control: A Review. *Engineering* 7(1), 50–62.

¹⁸⁴ Global Industry Analysts, Inc (2024) Cobalt Sulfate: Global Strategic Business Report. <<https://www.researchandmarkets.com/reports/5139659/cobalt-sulfate-global-strategic-business-report>>; Frost & Sullivan (2023) Global Lithium-ion Battery Materials Market Growth Opportunities. <<https://store.frost.com/global-lithium-ion-battery-materials-market-growth-opportunities.html>>.

evaporative, cooling, and eutectic freeze crystallisation, which rely on temperature control as a central mechanism. For chemical-based methods such as reactive and antisolvent crystallisation, improving control over crystal characteristics by optimising the reagents used and how they are introduced is a shared area of interest. So is reducing, recovering, and recycling reagents (e.g., antisolvent) where possible. Adoption of membrane crystallisation will require additional RD&D into preventing and reversing membrane degradation, which is currently a barrier to scale-up.

Australia has established commercial capabilities in evaporative crystallisation, through commercial operations (BHP's Kwinana Nickel Refinery for nickel sulphate production), pilot projects (Cobalt Blue), and equipment providers (JordProxa). However, Australian patents related to this area are limited.

Opportunities for Australia vary according to the crystallisation process. For evaporative, cooling, and reactive crystallisation, global maturity and local activity highlight an opportunity for RD&D to support commercial deployments of existing technologies. Simultaneously, there is an opportunity to develop local capabilities across the more emerging crystallisation approaches, which could offer throughput, end-product control, and energy efficiency benefits with adequate development.

3.2.3 Production of cobalt metal

Besides crystallisation to produce a high-purity compound, cobalt may also be retrieved as a metal, after the separation and purification stage. This can occur via hydrogen reduction to produce cobalt metal in powder form or through electrowinning to deposit cobalt metal at the cathode. The cobalt metal produced may be sold directly or leached in an acid solution to produce cobalt salts suitable for pCAM manufacture.

Hydrogen reduction

Introducing hydrogen gas to a cobalt-containing solution, at appropriate temperature and partial pressure, can be used to produce metallic cobalt powder. The process first entails the addition of ammonia to the solution for pH control and the removal of sulphate as a byproduct (ammonium sulphate). The process is also assisted by the presence of added cobalt particles that provide a support for metal deposition.¹⁸⁵

Hydrogen reduction contends with the economic, logistical, and environmental considerations of sourcing sufficient quantities of hydrogen gas to be used as a reductant. It also faces challenges in reactor design to maximise throughput and an intrinsically lower reductive capacity of hydrogen as compared to carbon. Relevant to this challenge, hydrogen plasma is a stronger reductant than hydrogen gas and research into its use for metal reduction could represent an opportunity for process improvement.¹⁸⁶

Electrowinning (EW)

Electrowinning passes an electric current between two electrodes to reduce the cobalt ions present in a purified or recycled solution, depositing them in metallic form as a layer over the cathode.¹⁸⁷

¹⁸⁵ Moats MS, Davenport WG (2014) Nickel and Cobalt Production. In *Treatise on Process Metallurgy*. (Ed. S Seetharam) 625-669. Elsevier.

¹⁸⁶ Rukini et al. (2022) Metals Production and Metal Oxides Reduction Using Hydrogen: A Review. *Journal of Sustainable Metallurgy* 8(1), 1–24.

¹⁸⁷ Lumitos (2023). Electrowinning. CHEMEUROPE.COM – Encyclopedia.
<https://www.chemeurope.com/en/encyclopedia/Electrowinning.html#_note-copper/>.

Cobalt metal production via electrowinning finds advantages in being compatible with both sulphide and chloride solutions and in the extensive characterisation of its key parameters.¹⁸⁸ However, the process is limited by the simultaneous production of hydrogen, co-deposition alongside nickel and copper (which requires their prior removal from solution), and intrinsic metal stress that leads to premature delamination of the cathode.¹⁸⁹

Recent areas of research interest focus on process optimisation to increase end-product quality, limit energy consumption, increase selectivity, and control the formation of byproducts that affect the process (e.g., hydrogen, impurities that are incorporated in the metal and introduce stress, or corrosive agents that reduce the durability of the equipment).¹⁹⁰



TECHNOLOGY STATE OF PLAY

Hydrogen reduction of cobalt is a highly mature process implemented at industrial scale in multiple refineries across the world.¹⁹¹ For instance, it is used in the production of nickel metal powder at BHP's Kwinana Nickel Refinery and for both nickel and cobalt metal powder production at Glencore's Murrin Murrin operation.¹⁹²

Electrowinning is also highly mature and has been widely implemented at scale to produce cobalt metal.¹⁹³ For instance, cobalt metal is produced using electrowinning at Vale's Port Colborne Refinery (Canada) and Sumitomo's Niihama Nickel Refinery (Japan).¹⁹⁴

In Australia, cobalt metal is primarily produced using hydrogen reduction. While there are no current commercial scale operations for cobalt electrowinning, it was used in the past at the Bulong Nickel plant in WA.¹⁹⁵ Moreover, there is local capability in the process for other metals. For instance, electrowinning is used at BHP's Olympic Dam operation to produce copper metal from the solution resulting from tailings leaching.¹⁹⁶

¹⁸⁸ Sharma et al. (2005) Electrowinning of cobalt from sulphate solutions. *Hydrometallurgy* 80(1–2), 132–138; Subagja et al. (2022) Effect of Technological Parameters on the Electrowinning of Cobalt from Cobalt(II) Chloride Solutions. *International Journal of Electrochemical Science* 17(9), 220959.

¹⁸⁹ Mulaudzi N, Kotze MH (2013) Direct cobalt electrowinning as an alternative to intermediate cobalt mixed hydroxide product. In *Base Metals Conference 2013*. The Southern African Institute of Mining and Metallurgy, Johannesburg.

¹⁹⁰ Mafra Passos et al. (2023) Statistical study of the influence of some variables on cobalt electrowinning. *Mineral Processing and Extractive Metallurgy Review* 44(7), 481–491; Moats MS, Davenport WG (2014) Nickel and Cobalt Production. In *Treatise on Process Metallurgy*, 625–669. Elsevier; Kim et al. (2021) Selective cobalt and nickel electrodeposition for lithium-ion battery recycling through integrated electrolyte and interface control. *Nature Communications* 12(1), 6554.

¹⁹¹ Minara Resources Limited (2023) Murrin Murrin Process and Technology Flow Chart. Glencore - Producing nickel and cobalt at Murrin Murrin. <https://www.glencore.com.au/dam/jcr:cc613626-0b0d-46d0-8d47-ffa175447c1b/MR_1147_flowchart_process2.pdf>; Sherritt International (2017) How Sherritt Refines Metals. <https://s2.q4cdn.com/343762060/files/doc_downloads/2021/How-Sherritt-Refines-Metals-2017-Oct-21.pdf>.

¹⁹² Minara Resources Limited (2023) Murrin Murrin Process and Technology Flow Chart. Glencore - Producing nickel and cobalt at Murrin Murrin. <https://www.glencore.com.au/dam/jcr:cc613626-0b0d-46d0-8d47-ffa175447c1b/MR_1147_flowchart_process2.pdf>; BHP Nickel West (2019) Attachment 2: BHP Nickel West Kwinana Licence L8437/2010/3 Process Description, 17 July 2019. 31 – 38. <https://www.der.wa.gov.au/images/documents/our-work/licences-and-works-approvals/Decisions_/W6275-2019-1_D.pdf>.

¹⁹³ Lu et al. (2018) Cobalt electrowinning – A systematic investigation for high quality electrolytic cobalt production. *Hydrometallurgy* 178, 19–29.


¹⁹⁴ Gauld et al. (2021) Technical Report Summary - Sudbury Property - Ontario Operations – Canada. 165. <https://minedocs.com/22/Sudbury__TR_04072022.pdf>; Sumitomo Metal Mining Co. Ltd. (2022) Niihama Nickel Refinery. Core facilities / group companies. <https://www.smm.co.jp/en/corp_info/location/domestic/nickel/>.

¹⁹⁵ Sole et al. (2018) Ion Exchange in Hydrometallurgical Processing: An Overview and Selected Applications. *Separation & Purification Reviews* 47(2), 159–178.

¹⁹⁶ Ehrig et al. (2019) Olympic Dam – is it really complex? AusIMM Adelaide Branch Technical Meeting. 22–23. <<https://www.ausimm.com/globalassets/communities/branches/adelaide/ehrig-et-al-feb2019-ausimm-adelaide-branch-presentation.pdf>>.

The following table summarizes the RD&D focus areas for cobalt metal production:

Table 10: Global RD&D areas for cobalt metal production technologies.

 RD&D FOCUS AREAS	
Electrowinning	<ul style="list-style-type: none"> Increasing the selectivity of cobalt electrodeposition over elements with similar properties (e.g., nickel), to enable direct electrochemical recovery approaches that minimise or bypass the need for conventional, reagent-driven purification.¹⁹⁷
Hydrogen reduction	<ul style="list-style-type: none"> Optimising reactor designs to increase the throughput of conventional hydrogen reduction and reduce maintenance and operational costs.¹⁹⁸ Assessing the viability at scale of hydrogen plasma as a reducing agent.¹⁹⁹

Implications for Australia

The production of cobalt metal represents an opportunity for Australia. It is a high-purity and stable product that may be used directly or converted into specific compounds, including cobalt sulphate for pCAM production. Moreover, as a condensed form of cobalt it is easy and competitive to transport. Due to this versatility, cobalt metal can be sold to multiple markets, making it an attractive option for Australian producers. The overall value of the cobalt market was estimated at US\$9.48 billion in 2022 and has been projected to reach US\$17.68 billion by 2028.²⁰⁰

Converting cobalt metal into cobalt sulphate is a less direct pathway that can entail higher overall energy intensity (and therefore greenhouse gas emissions). However, it provides a near-term alternative, leveraging a feedstock already available in Australia. Strategic and technoeconomic comparisons with other pathways that produce battery grade cobalt compounds can be beneficial to assess viability over different timescales.

¹⁹⁷ Kim et al. (2021) Selective cobalt and nickel electrodeposition for lithium-ion battery recycling through integrated electrolyte and interface control. *Nature Communications* 12(1), 6554.

¹⁹⁸ Rukini et al. (2022) Metals Production and Metal Oxides Reduction Using Hydrogen: A Review. *Journal of Sustainable Metallurgy* 8(1), 1–24.

¹⁹⁹ Sabat et al. (2015) Reduction of Cobalt Oxide (Co3O4) by Low Temperature Hydrogen Plasma. *Plasma Chemistry and Plasma Processing* 35(2), 387–399.

²⁰⁰ Daedal Research (2023) Global Cobalt Market. <<https://www.researchandmarkets.com/report/cobalt>>.

Figure 11: Actions for Australian RD&D and international engagement in the production of cobalt metal.

Opportunity area	Establish new capability in emerging technologies	Accelerate emerging technologies and grow Australian IP	Pilot and scale up Australian IP	Support commercial deployment of mature technologies
Applicable Technologies				<ul style="list-style-type: none"> Cobalt metal (electrowinning) Cobalt metal (hydrogen reduction)
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.

Hydrogen reduction is a prevalent method globally for producing cobalt metal powder at large scale and will therefore be a part of any near-term commercial solutions in Australia. Its use of hydrogen currently poses a supply challenge, but also offers the possibility of greater sustainability if using green hydrogen, particularly if also paired with renewable energy sources to generate the heat required.

Australia has established commercial capability for hydrogen reduction of both nickel (BHP’s Kwinana Nickel Refinery) and cobalt (Glencore’s Murrin Murrin operation). Given the maturity of the area, there is an opportunity to support the commercial deployment of existing technology and to engage with local and overseas industry partners. Beyond reactor improvements to increase throughput, RD&D into the cost-effective use of hydrogen plasma could facilitate cobalt reduction.

There are also opportunities to leverage Australia’s existing knowhow in the production of nickel sulphate from nickel powder to develop production of battery grade cobalt sulphate from Australia’s cobalt metal output. Both cobalt sulphate and nickel sulphate are feedstocks into NMC pCAM synthesis.

Electrowinning (EW) is another highly mature and commercially deployed metal production method suitable for large scale operations. Electrowinning is compatible with both cobalt sulphate and cobalt chloride feedstocks. This versatility makes the process capable of handling the output of multiple leaching methods, while the technological maturity helps de-risk extraction pathways that go beyond the mixed precipitates and into cobalt metal production.

Despite its high maturity, cobalt metal production through electrowinning still faces challenges related to low selectivity (as a result of the similar electrochemical behaviour of nickel), which leads to lower purity metal. RD&D into increased selectivity can go beyond marginal improvements in the performance of the conventional process, also opening the possibility of EW as a strategy for separation earlier in a flowsheet and not just metal production at the end.

Australia has established capability for EW of other metals, but no current commercial operations use it for cobalt production. While the area is highly mature, research into increased selectivity is more emerging and will require engagement with both local equipment manufacturers and research institutions to develop materials that preferentially interact with cobalt over nickel and other metals.

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