Australia's National
Science Agency

# From minerals to materials

## Supplementary report: Rare earths

May 2024

## Citation

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## Acknowledgements

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

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

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# Contents

# Glossary

## Abbreviations

| | |
|---|---|
| **ANSTO** | Australian Nuclear Science and Technology Organisation |
| **CRP** | Carboxylate reduction process |
| **EV** | Electric vehicle |
| **FFC-Cambridge** | Fray-Farthing-Chen-Cambridge process |
| **HREE** | Heavy rare earth elements |
| **IP** | Intellectual property |
| **LREE** | Light rare earth elements |
| **Nd-Fe-B** | Neodymium-Iron-Boron |
| **PFC** | Perfluorocarbon |
| **RD&D** | Research, development and demonstration |
| **RE** | Rare earth |
| **REE** | Rare earth elements |
| **REO** | Rare earth oxide |
| **SSE** | Solid state electrotransport |

# 1 Executive summary

Rare earth elements (REEs) are a critical input for electric vehicle (EV) and wind supply chains, and therefore play an important role in the domestic and global energy transition. The market for rare earth (RE) products is a growing market, and supply chain concentration across all stages represents an opportunity for Australia to become an alternative supplier in mid-stream rare earth products.

Australia's research, development and demonstration (RD&D) capabilities can support the expansion of RE mid-stream processing activities onshore and the development of processing technologies more broadly in the global context. There are several opportunities for RD&D in RE processing, including supporting the commercial deployment of mature technologies 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. |

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.*

### Sulphuric acid roasting/baking

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

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

### Alkaline baking

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

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

### Salt roasting; Chlorination roasting

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

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

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

### Desorption leaching

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

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

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

### Solvent extraction

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

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

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

### Ion exchange; Membrane separation; Adsorption

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

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

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

### Molten salt electrolysis (light RE metals)

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

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

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

## Metallothermic reduction electrolysis (heavy RE metals)

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

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

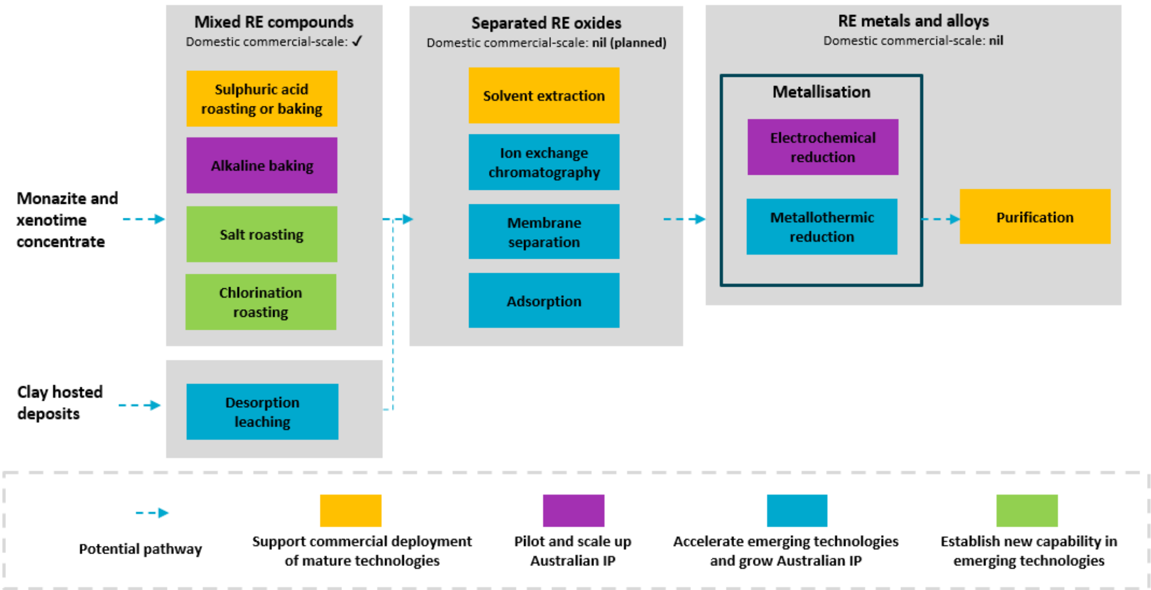
Given limited global capabilities outside of China, there may be opportunities for collaboration with partner countries to deploy Australian technologies. Engaging with upstream producers, such as EV and wind magnet manufacturers, will be essential to ensure the integration of Australian RE metal production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

## Purification

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

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

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




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

IP, intellectual property; RE, rare earth.

## 2 Objectives and scope

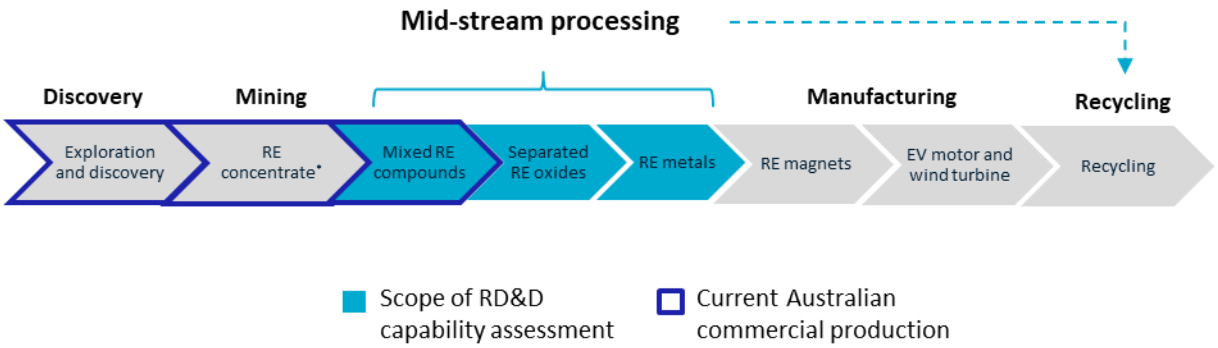
This supplementary report will focus on Australia's key rare earths supply chain gaps, and in particular the separation and metallisation of REEs (Figure 3).

This report aims to address several objectives:

- To communicate the key current and emerging technologies underpinning the production of mixed RE compounds, separated RE oxides and RE metals, with a strong focus on technologies that have been demonstrated at lab, pilot and commercial scales.
- To communicate where high levels of IP and research activity are occurring in Australia and globally, each emerging and mature technology area.
- To communicate key challenges and opportunities for Australia to build domestic IP and for collaboration with international partners.

The purpose of this analysis is to guide and inform government, industry and research sector 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 rare earths supplementary report and current commercial production in Australia.**




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

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

# 3 RD&D challenges and opportunities

The rare earth supply chain is commercially established globally, and underpinned by mature technologies in extraction, separation and metallisation.

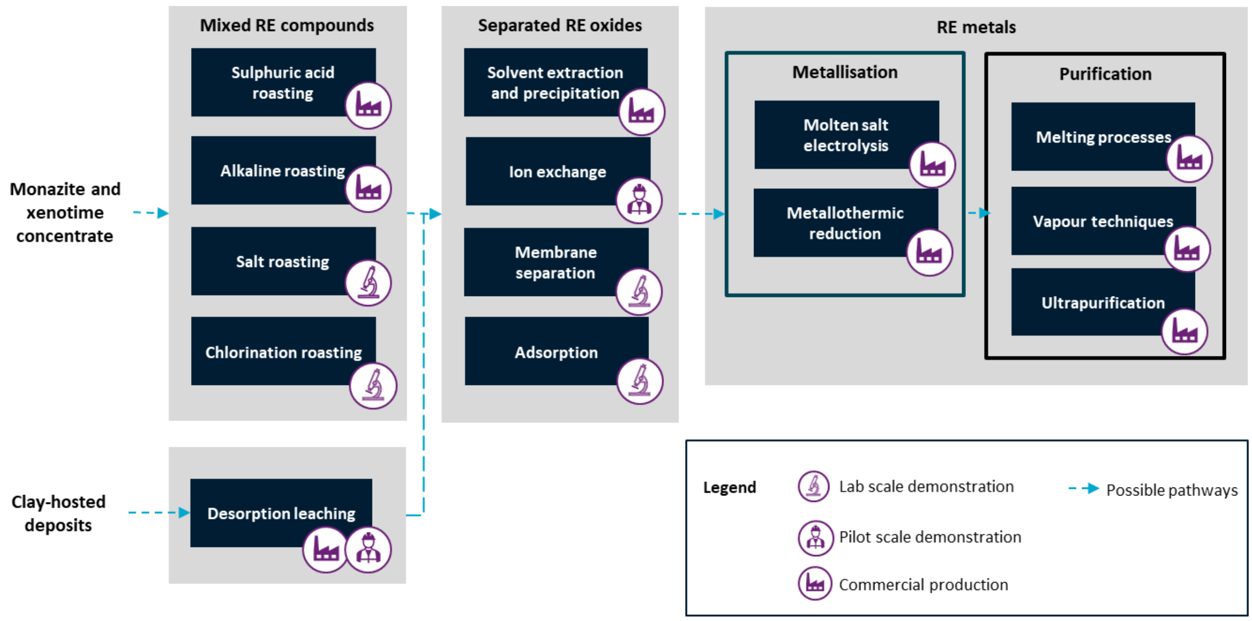
However, there are several emerging technologies being developed globally to improve process efficiency and sustainability outcomes.

This chapter will discuss the RD&D challenges and opportunities relating to mature and emerging technologies for extracting and separating REEs, and for refining RE metals.

- Section 3.1 will cover roasting and leaching technologies to produce mixed RE compounds from hard rock monazite and xenotime, as well as from clay-based ores.
- Section 3.2 will cover separation technologies to produce separated RE oxides, including solvent extraction, ion exchange chromatography, membrane separation and adsorption.
- Section 3.3 will cover techniques to refine RE oxides into metals, including electrochemical reduction and metallothermic reduction. It will also cover RE metal purification techniques including melting, vapour processes and ultrapurification.

The extraction of rare earths from tailings and waste materials such as coal waste, fly ash, red mud and spent RE magnets is an important RD&D area. In particular, spent RE magents have higher concentrations of rare earths compared to raw materials, making them a promising feedstock and an opportunity for resource circularlity. However, these areas have not been covered within the scope of this report.

**Figure 4: Taxonomy for rare earth processing technologies for the rare earth supply chain.**

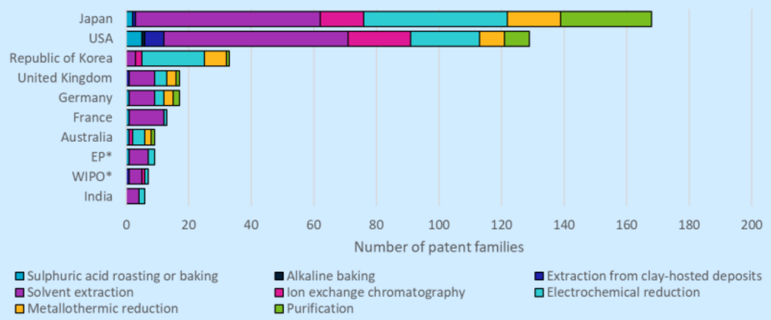



RE, rare earth.

# Global R&D and commercialisation snapshot

## Extraction and separation of rare earth compounds

**Figure 5: Patent output in rare earth mid-stream processing technologies from 2007 to 2022, by country.**




*Applications filed under an entity other than a country.

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

Figure 5 illustrates patent output in RE mid-stream processing technologies by country. In the 2007 – 2022 interval, China led patent activity on steps of the mid-stream processing supply chain, with 74% of patent families across all processes analysed. Japan, with 8.7%, and the US with 6.7% complete the top 3 of countries with the highest activity. Australia ranks 8th globally.

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

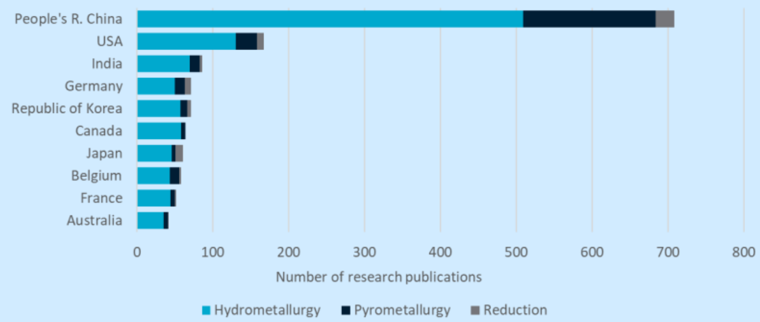
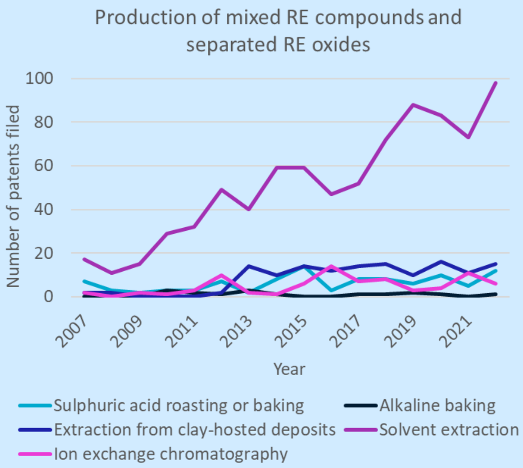


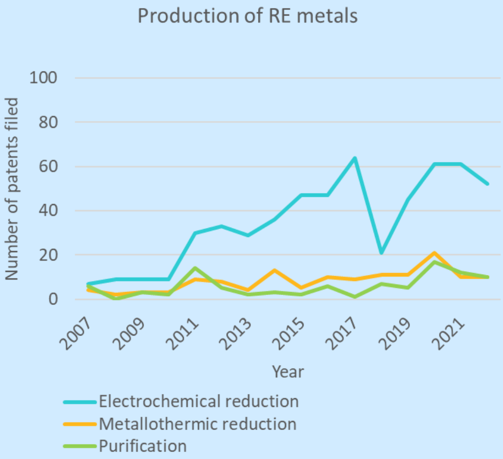

Figure 6 shows the output of research publications from 2007 to 2023 that are related to REEs, as distributed by country and processing technology. China accounts for 37.1% of the total, followed by the USA (8.7%), Russia (4.8%), and India (4.5%). Australia occupies the 11th position, with 2.2% of publications.

Most publications in the analysis were related to hydrometallurgical processes (77%), potentially reflecting the increased activity in separation technologies (i.e., solvent extraction and ion exchange chromatography) to produce RE oxides. This is followed by publications in pyrometallurgical processes (18.8%) related to roasting and baking processes to produce mixed RE compounds, and reduction (4.2%) related to RE metal refining processes.

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

**Figure 7: Global patent output in rare earth mid-stream processing technologies throughout the 2007 – 2022 period, by year and technology.**




The distribution of patent families across technologies from Figure 7 shows solvent extraction (42.5%) and electrochemical reduction (28.9%) as the areas of highest activity globally. This distribution of activity is also reflected in the overall trends for the 2007 – 2022 period (Figure 7), with solvent extraction and electrochemical reduction featuring increases that contrast with more stable baselines of activity for the other technologies. Most technologies show an uptick of activity after 2010.

**Table 1: Top 10 active organisations outside of China**

| By research publication output | By patent output |
|---|---|
| KU Leuven, **Belgium** | JX Nippon Mining and Metals, **Japan** |
| DOE, **United States** | Sumitomo Metal Mining, **Japan** |
| CSIR, **India** | Hitachi Metals, **Japan** |
| KIGAM, **Republic of South Korea** | Toshiba, **Japan** |
| CNRS, **France** | Yokohama National University, **Japan** |
| RWTH Aachen University, **Germany** | JAEA, **Japan** |
| CEA, **France** | AIST, **Japan** |
| IIT, **India** | Batelle Energy Alliance, **United States** |
| Montpellier University, **France** | Dowa Holdings, **Japan** |
| Virgina Polytechnic Institute, **United States** | KAERI, **Republic of Korea** |

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 Production of mixed rare earth compounds

### 3.1.1 Extraction from monazite and xenotime

Monazite and xenotime are two key REE resources in Australia with estimated reserves of 2.98 million tonnes.[1] Monazite and xenotime can be found in hard rock deposits like carbonatites, or mineral sands.[2] Monazite is typically rich in light REEs, whereas xenotime is rich in heavy REEs.[3] Once mined, monazite and xenotime are concentrated via physical and mechanical sorting to eliminate residual rock and increase the proportion of RE bearing mineral.

The mineral concentrate typically needs to be decomposed and leached using thermal and chemical processes to enable easier and more efficient REE extraction. Mature decomposition processes often involve roasting or baking solid RE concentrates with an acid or alkaline. Emerging salt and chlorination roasting processes are also being developed. The decomposed solid is then leached with an acid or alkaline solution, or water, to form a leach solution containing mixed RE compounds.

The mixed RE intermediates, such as mixed RE oxides and mixed RE carbonates can be sold as a product or used as a feedstock for the next stage, separation into individual RE compounds. This is the business model currently employed in Australia, with extraction plants and separation plants located in different jurisdictions. Alternatively, the leach solution can be purified and move on to the next stage directly, which can be done in an integrated plant. The next stage of the supply chain, separation into individual RE compounds, is covered in Section 3.2.

#### Sulphuric acid roasting or baking

Sulphuric acid roasting (above 600°C) or baking (between 200 and 600°C), followed by water leaching, is a mature pathway to decompose and solubilise monazite and xenotime concentrate into a leach solution containing mixed RE sulphate compounds.[4]

This process is applicable for a wide range of RE ore types including mixed and lower grade concentrates and can also achieve high RE extraction rate (above 95%).[5] Higher temperature processes (above 400°C) offer the advantage in impurity removal (e.g., iron, thorium, calcium, phosphate). However, it results in emissions of toxic gases (e.g., sulphur dioxide, hydrogen fluoride, fluorosilicic acid) and can slightly decrease the extractable RE content.[6] On the other hand, lower temperature processes (300°C or below)

[1] Reserves are reported in compliance with the Joint Ore Reserves Committee (JORC) Code; U.S. Geological Survey (2023) Mineral commodity summaries. Rare earths. <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-rare-earths.pdf>

[2] Geoscience Australia (2023) Rare earth elements. <https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/rare-earth-elements>

[3] Demol J, Ho E, Soldenhoff K and Senanayake G (2019b) The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. Hydrometallurgy 188, 123–139. DOI: 10.1016/j.hydromet.2019.05.015.

[4] Cheng S, Li W, Han Y, Sun Y, Gao P and Zhang X (2023) Recent process developments in beneficiation and metallurgy of rare earths: A review. Journal of Rare Earths DOI: 10.1016/j.jre.2023.03.017.

[5] Vaughan J, Tungpalan K, Parbhakar-Fox A, Fu W, Gagen EJ, Nkrumah PN, Southam G, van der Ent A, Erskine PD, Gow P. (2021) Toward Closing a Loophole: Recovering Rare Earth Elements from Uranium Metallurgical Process Tailings. JOM 73(1), 39–53. DOI: 10.1007/s11837-020-04451-7.

[6] Demol J, Ho E, Soldenhoff K and Senanayake G (2019b) The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. Hydrometallurgy 188, 123–139. DOI: 10.1016/j.hydromet.2019.05.015.

are reportedly easy to operate and yield consistent product quality. However, baking processes can take longer, and impurity removal can be a long and complex process.[7]

Despite its commercial maturity, the use of sulphuric acid faces several challenges in such as high waste levels (e.g., phosphorus and gypsum) and corrosion to equipment.[8] Industry consultations indicated that material behaviour during roasting and baking is also an operational challenge and can cause corrosion and process disruption.

## TECHNOLOGY STATE OF PLAY

Sulphuric acid roasting or baking is widely adopted by domestic and global producers to produce mixed RE compound solutions from monazite concentrate and is the only process that has been applied at commercial scales to process xenotime.[9] ANSTO has been providing process development and operational know-how in sulphuric acid roasting and baking to the majority of Australia's commercial operators.[10]

In late 2023, Lynas (Australia) commissioned a sulphuric acid roasting and leaching facility in Kalgoorlie (WA) to process monazite and xenotime from Mount Weld, in addition to its operating facility in Malaysia. Lynas's process is reportedly conducted at 600°C or higher.[11]

There are other Australian companies announcing plans to commercially process Australian monazite onshore using sulphuric acid processes in the next five years, namely Iluka,[12] Arafura,[13] Australian Strategic Materials (ASM),[14] and Hastings Technology Metals[15]. Northern Minerals operated a pilot plant for its xenotime deposit rich in heavy REEs in WA from 2018 to 2022,[16] and is planning to scale up and commence commercial production by 2026.[17]

Outside of Australia, sulphuric acid roasting is also the reported process used by producers in China to treat Baotou mixed RE concentrate of bastnaesite and monazite from Bayan Obo deposit (Mongolia).[18] The

[7] Roasting duration varies between ore types; Demol J, Ho E, Soldenhoff K and Senanayake G (2019b) The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. Hydrometallurgy 188, 123–139. DOI: 10.1016/j.hydromet.2019.05.015.

[8] Vaughan J, Tungpalan K, Parbhakar-Fox A, Fu W, Gagen EJ, Nkrumah PN, Southam G, van der Ent A, Erskine PD, Gow P. (2021) Toward Closing a Loophole: Recovering Rare Earth Elements from Uranium Metallurgical Process Tailings. JOM 73(1), 39–53. DOI: 10.1007/s11837-020-04451-7.

[9] Demol J, Ho E, Soldenhoff K and Senanayake G (2019) The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. Hydrometallurgy 188, 123–139. DOI: 10.1016/j.hydromet.2019.05.015.

[10] ANSTO (2020) Rare earth processing. <https://www.ansto.gov.au/sites/default/files/2020-07/G-7425%20Minerals%20Rare%20Earth%20Processing%20Capability%20Statement2%20%282%29.pdf>

[11] McNulty T, Hazen N and Park S (2022) Processing the ores of rare-earth elements. MRS Bulletin 47(3), 258–266. DOI: 10.1557/s43577-022-00288-4.

[12] Iluka Resources Limited (2022) Eneabba rare earth refinery – final investment decision. <https://iluka.com/media/srypf2vr/erer-fid-asx-release-final.pdf>

[13] Arafura Rare Earths Limited (2022) Nolans project update. <https://wcsecure.weblink.com.au/pdf/ARU/02597137.pdf>

[14] Australian Strategic Materials (2021) Dubbo project optimisation delivers strong financials. <https://asmd.irmau.com/site/PDF/7d89a7c9-fbde-4e03-b9e4-6856775b3985/DubboProjectOptimisationDeliversStrongFinancials>

[15] Hastings Technology Metals (2022) Onslow rare earth plant. Project update 1. <https://hastingstechmetals.com/wp-content/uploads/2022/10/202210-Oct-Onslow-Project-Update-1.pdf>

[16] de Klerk L and Jones R (2023) Developing a Commercial Heavy Rare Earth Processing Facility at Browns Range. Proceedings of the 61st Conference of Metallurgists, COM 2022. Springer International Publishing, Cham.

[17] Northern Minerals (n.d.) Browns Range project. <https://northernminerals.com.au/browns-range-project/>

[18] Cheng S, Li W, Han Y, Sun Y, Gao P and Zhang X (2023) Recent process developments in beneficiation and metallurgy of rare earths: A review. Journal of Rare Earths DOI: 10.1016/j.jre.2023.03.017; Demol J, Ho E, Soldenhoff K and Senanayake G (2019b) The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. Hydrometallurgy 188, 123–139. DOI: 10.1016/j.hydromet.2019.05.015.

Malaysian Rare Earth Corporation (Malaysia) and Megon Company (Norway), although no longer operational, once utilised sulphuric acid baking in their commercial operations.[19]

The global patent analysis for the 2007 to 2022 period identified 5.2% of patent families were related to sulphuric acid roasting and baking processes, and the global IP filing activity in this space has been consistently increasing since 2009. The top countries by output include China with 87.1% of patent families, the United States with 5%, and Japan and Russia with 2%. Australian companies producing patents in sulphuric acid processes include Arafura.

The following table summarizes the RD&D focus areas for sulphuric acid roasting and baking:

**Table 2: Global RD&D focus areas for sulphuric acid roasting and baking technologies**

| RD&D FOCUS AREAS | |
|---|---|
| **Sulphuric acid roasting and baking** | • Advancing current understanding of factors affecting the solubility of RE sulphate compounds and impurities in the final leach solution, such as temperature and acid concentration.[20]<br>• Reducing waste and improving circularity by investigating phosphoric acid recovery and wastewater recycling.<br>• Developing solutions to manage material behaviour during roasting and baking to prevent corrosion and process disruption.[21] |

### Alkaline baking

The conventional alkaline baking pathway (also referred to as caustic digestion) involves reacting the RE concentrate with a sodium hydroxide solution in an autoclave at temperatures between 140 and 160°C. The resulting mixture is leached with hydrochloric acid to obtain a solution containing RE chlorides.[22]

Compared to sulphuric acid processes, this pathway is less energy intensive due to the lower temperatures required and is less corrosive towards equipment which can potentially decrease capital costs. It prevents the formation of gypsum waste,[23] while also producing sodium phosphate that can be sold as fertiliser to offset the cost of reagents.[24] However, this pathway requires higher grade monazite concentrates, limiting its commercial use.[25] Further, this pathway often requires griding of the ore down to fine particles to

[19] Demol J, Ho E, Soldenhoff K and Senanayake G (2019) The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. Hydrometallurgy 188, 123–139. DOI: 10.1016/j.hydromet.2019.05.015.

[20] Demol J, Ho E, Soldenhoff K and Senanayake G (2019b) The sulfuric acid bake and leach route for processing of rare earth ores and concentrates: A review. Hydrometallurgy 188, 123–139. DOI: 10.1016/j.hydromet.2019.05.015.

[21] Industry consultation

[22] Cheng S, Li W, Han Y, Sun Y, Gao P and Zhang X (2023) Recent process developments in beneficiation and metallurgy of rare earths: A review. Journal of Rare Earths DOI: 10.1016/j.jre.2023.03.017.

[23] Stakeholder consultation

[24] Vaughan J, Tungpalan K, Parbhakar-Fox A, Fu W, Gagen EJ, Nkrumah PN, Southam G, van der Ent A, Erskine PD, Gow P (2021) Toward closing a loophole: recovering rare earth elements from Uranium metallurgical process tailings. JOM 73(1), 39–53. DOI: 10.1007/s11837-020-04451-7.

[25] Vaughan J, Tungpalan K, Parbhakar-Fox A, Fu W, Gagen EJ, Nkrumah PN, Southam G, van der Ent A, Erskine PD, Gow P (2021) Toward closing a loophole: recovering rare earth elements from Uranium metallurgical process tailings. JOM 73(1), 39–53. DOI: 10.1007/s11837-020-04451-7.

achieve greater breakdown efficiencies, and impurities such as silicon, aluminium and iron can consume much of the reagent and reduce filterability.[26]

## TECHNOLOGY STATE OF PLAY

Alkaline baking, or caustic digestion, is commercially mature for rare earths, however there are limited number of projects utilising this pathway. Currently, it is the main process for Indian Rare Earth Limited (India), who produced 5,048 tonnes of RE chlorides in the year 2019-20.[27] The plants continued operation in today's market environment may be partly attributable to the utilisation of existing facilities and mature technology, a relatively high RE and uranium content in Indian deposits, public ownership of the plant and other strategic aspects.[28] In the past, alkaline baking was reportedly used in commercial settings in the US and Brazil, however these are no longer operating.[29] It has also been commercially utilised by Solvay (France).[30]

In Australia, alkaline baking has not been deployed commercially, however ANSTO has process development and operational capabilities in this area.[31]

The global patent analysis for the 2007 to 2022 period identified 0.5% of patent families were related to alkaline baking processes. The global IP filing activity in this space began after 2010 and has followed a stable-to-declining trend. The two countries with alkaline baking patent outputs are China (93.8%) and the United States (6.2%).

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

**Table 3: Global RD&D focus areas for alkaline baking technologies**

| RD&D FOCUS AREAS | |
|---|---|
| **Alkaline baking/caustic digestion** | • Optimising the process (e.g., by integrating energy-efficient grinding processes during and after roasting) to improve baking rate and efficiency and minimise reagent consumption.[32] |

[26] Stakeholder consultations

[27] Indian Bureau of Mines (IBM) (2020) Indian Minerals Yearbook – 2019 Vol. III (Mineral reviews). <https://ibm.gov.in/writereaddata/files/10012020172151RareEarth_2019_AR.pdf>; Indian Bureau of Mines (IBM) (2022) Indian Minerals Yearbook – 2020 Vol. III (Mineral reviews). <https://ibm.gov.in/writereaddata/files/05132022180218Rare_Earths_2020.pdf>

[28] Stakeholder consultations

[29] Kumari A, Panda R, Jha MK, Kumar JR and Lee JY (2015) Process development to recover rare earth metals from monazite mineral: A review. Minerals Engineering 79, 102–115. DOI: 10.1016/j.mineng.2015.05.003.

[30] Stakeholder consultations

[31] ANSTO (2020) Rare earth processing. <https://www.ansto.gov.au/sites/default/files/2020-07/G-7425%20Minerals%20Rare%20Earth%20Processing%20Capability%20Statement2%20%282%29.pdf>

[32] Lucas J, Lucas P, Le Mercier T, Rollat A and Davenport W (2015) Extracting Rare Earth Elements from Concentrates. Rare Earths. Elsevier.

### Salt and chlorination roasting

Salt roasting has been developed as an alternative pathway to sulphuric acid roasting and baking. It is a four-step process of air roasting, acid leaching, salt roasting and acid leaching, with the commonly used salt being sodium carbonate, and the acid being sulphuric or hydrochloric acid.[33]

Salt roasting provides a more selective pathway to recover valuable elements and separate environmental contaminants, such as fluorine, phosphorus, thorium and cerium.[34] However, the main challenge restricting commercial implementation has been the build-up of melted salts during roasting, causing equipment damage.[35]

Chlorinating agents including chlorine gas can also be used to roast at 1000 – 1200°C and decompose various RE ore concentrates.[36] Chlorination roasting is a direct method to produce RE chlorides that does not require leaching and can be used to treat lower grade or complex mixed.[37] The key challenges of chlorination roasting include the corrosion of equipment and high energy intensity.[38]

Chloride salt roasting with chloride compounds like $CCl_4$, $NH_4Cl$, $ZnCl_2$ is a modification to the conventional chlorination roasting, requiring lower temperatures (i.e., 300 – 500°C).[39]

**TECHNOLOGY STATE OF PLAY**

Salt roasting has been applied at lab scale, mostly on Baotou mixed RE concentrate of bastnaesite and monazite in China.[40]

Although chlorination roasting processes are generally well understood, chlorination roasting processes are being investigated at lab scale, with some targeted Baotou mixed RE concentrate of bastnaesite and monazite.[41]

Global IP activity for salt and chlorination roasting were not included in this report due to the emergence of these technologies for mixed RE compound production and the limited number of patents being published in this area.

The following table summarizes the RD&D focus areas for salt and chlorination roasting:

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[33] Zhao J, Pan F and Liu H (2016) An environmental friendly Na2CO3-roasting decomposition strategy for the mixed rare earth concentrate. Separation and Purification Technology 168, 161–167. DOI: 10.1016/j.seppur.2016.05.036.

[34] Zhao J, Pan F and Liu H (2016) An environmental friendly Na2CO3-roasting decomposition strategy for the mixed rare earth concentrate. Separation and Purification Technology 168, 161–167. DOI: 10.1016/j.seppur.2016.05.036.

[35] Zhao J, Pan F and Liu H (2016) An environmental friendly Na2CO3-roasting decomposition strategy for the mixed rare earth concentrate. Separation and Purification Technology 168, 161–167. DOI: 10.1016/j.seppur.2016.05.036.

[36] Pomiro FJ, Gaviría JP, Fouga GG, Bohé AE and De Micco G (2021) A Panoramic Overview of Chlorination and Carbochlorination of Light Rare Earth Oxides, Including Thermodynamic, Reaction Mechanism, and Kinetic Aspects. Mining, Metallurgy & Exploration 38(6), 2467–2484. DOI: 10.1007/s42461-021-00490-z.

[37] Vaughan J, Tungpalan K, Parbhakar-Fox A, Fu W, Gagen EJ, Nkrumah PN, Southam G, van der Ent A, Erskine PD, Gow P et al. (2021) Toward closing a loophole: recovering rare earth elements from Uranium metallurgical process tailings. JOM 73(1), 39–53. DOI: 10.1007/s11837-020-04451-7.

[38] Vaughan J, Tungpalan K, Parbhakar-Fox A, Fu W, Gagen EJ, Nkrumah PN, Southam G, van der Ent A, Erskine PD, Gow P et al. (2021) Toward closing a loophole: recovering rare earth elements from Uranium metallurgical process tailings. JOM 73(1), 39–53. DOI: 10.1007/s11837-020-04451-7.

[39] Sadri F, Nazari AM and Ghahreman A (2017) A review on the cracking, baking and leaching processes of rare earth element concentrates. Journal of Rare Earths 35(8), 739–752. DOI: 10.1016/S1002-0721(17)60971-2.

[40] Zou D, Chen J, Hu J, Li K and Li D (2020) Thermal decomposition mechanism of low-content-fluorite Bayan Obo rare earth concentrate roasted with sodium carbonate and its consequent separation study. Journal of Rare Earths 38(9), 994–1002. DOI: 10.1016/j.jre.2019.09.015

[41] Xing Z, Cheng G, Yang H, Xue X and Jiang P (2020) Mechanism and application of the ore with chlorination treatment: A review. Minerals Engineering 154, 106404. DOI: 10.1016/j.mineng.2020.106404.

Table 4: Global RD&D focus areas for salt and chlorination roasting technologies

| RD&D FOCUS AREAS | |
|---|---|
| **Salt roasting** | • Developing pathways with no air roasting required to lower the energy intensity.[42]<br>• Developing strategies to mitigate the effect of melted salt build-up and avoid equipment damage and process discontinuity.[43] |
| **Chlorination roasting** | • Development of materials and plant equipment to protect against the corrosive nature of chlorinating agents.[44]<br>• Optimising reaction temperatures and utilising additional reducing agents (e.g., carbon) to improve roasting efficiency and minimise impurity.[45] |

### 3.1.2 Extraction from clay-hosted deposits

Clay-hosted deposits is another type of RE deposit, formed through the weathering of RE-hosted rock, during which mobilised REE ions are adsorbed onto the clay surface.[46] Clay-hosted deposits are a significant source of heavy REEs, accounting for 80% of the global heavy REEs production and 35% of China's total REEs production. Compared to light REEs, heavy REEs have higher economic value but are less abundant in nature. The processing of clay-hosted deposits typically involves desorption via leaching with a solution, followed by REE separation (see Section 3.2).

Clay-hosted deposits are most commonly found in Southern China. Recently, other deposits have also been discovered in Brazil, Laos, Madagascar, Malawi, Myanmar, the Philippines, Thailand, and the USA.[47] Australia has clay-hosted deposits located in WA[48], SA[49], Victoria[50], NSW,[51] Tasmania,[52] and there is

[42] Zou D, Chen J, Hu J, Li K and Li D (2020) Thermal decomposition mechanism of low-content-fluorite Bayan Obo rare earth concentrate roasted with sodium carbonate and its consequent separation study. Journal of Rare Earths 38(9), 994–1002. DOI: 10.1016/j.jre.2019.09.015.

[43] Ma R, Li J, Zhang X, Jia P, Liu Z, Wu J, Feng F and Xin W (2023) Decomposition of monazite in Bayan Obo rare earth ore by roasting of Na2CO3 pellets. Journal of Rare Earths DOI: 10.1016/j.jre.2023.09.014.

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

[45] Pomiro FJ, Gaviría JP, Fouga GG, Bohé AE and De Micco G (2021b) A Panoramic Overview of Chlorination and Carbochlorination of Light Rare Earth Oxides, Including Thermodynamic, Reaction Mechanism, and Kinetic Aspects. Mining, Metallurgy & Exploration 38(6), 2467–2484. DOI: 10.1007/s42461-021-00490-z.

[46] Anawati J and Azimi G (2023) Extraction of rare earth elements from a South American ionic clay. Journal of Rare Earths 41(9), 1408–1418. DOI: 10.1016/j.jre.2022.10.007.

[47] Borst AM, Smith MP, Finch AA, Estrade G, Villanova-de-Benavent C, Nason P, Marquis E, Horsburgh NJ, Goodenough KM, Xu C et al. (2020) Adsorption of rare earth elements in regolith-hosted clay deposits. Nature Communications 11(1), 4386. DOI: 10.1038/s41467-020-17801-5.

[48] Mineral's Research Institute of Western Australia (2023) Characterisation of clay-hosted rare-earth element deposits in Western Australia. <https://www.mriwa.wa.gov.au/research-projects/project-portfolio/characterisation-of-clay-hosted-rare-earth-element-deposits-in-western-australia/>

[49] Bromby R (2022) South Australia becoming the 'holy grail' of the rare earths space. Small Caps. <https://smallcaps.com.au/south-australia-becoming-holy-grail-rare-earths-space/>

[50] Resource Base (n.d.) Mitre Hill project. <https://resourcebase.com.au/projects/australian/mitre-hill-project/>; Australian Rare Earths (n.d.) Koppamurra project. <https://ar3.com.au/koppamurra-project-2/>

[51] Krakatoa Resources (2021) Ionic Clay Hosted Rare Earths Discovered at Rand Project, NSW. ASX Announcement. <https://company-announcements.afr.com/asx/kta/60693bb8-57a3-11ec-a10a-d2b929074954.pdf>

[52] ABx Group (n.d.) Rare earth elements. <https://www.abxgroup.com.au/site/projects/rare-earth-elements>.

prospective potential in Queensland[53] and the Northern Territory.[54] Research efforts are currently under way to better understand the composition and characteristics of Australian clays (e.g. physically or chemically adsorbed, and non-adsorbed REE clays).[55]

### Desorption leaching agents

Desorption is the process of leaching REEs from the surface of clay-hosted deposits, where the REEs are released into a solution. Clay hosted deposits differ from other minerals in that the grade of the deposit (proportion of REE content) can be misleading. The desorbable content (the proportion of REE that responds well to desorption leaching) is highly important. The remainder of the content may require further treatment to extract, leading to additional costs.

The choice of desorption leaching agent is strongly dependent on how the REEs are bound to the clay, which could either be physical or chemical adsorption.[56] Initial lab-scale characterisation is needed to identify the deposit characteristics and suitable desorption leaching agents.[57] Physical adsorption results in a weaker bond, and therefore only requires desorption leaching with a dilute sulphate or chloride salt solution (e.g., ammonium sulphate, sodium chloride, sodium sulphate, magnesium sulphate) at ambient temperature to extract REEs.[58] Chemical adsorption results in stronger bonds between REEs and the clay than physical adsorption, requiring stronger reagents such as (e.g. hydrochloric or sulphuric acid). [59] The portion of clay-hosted deposit that is non-desorbable requires high-temperature processes (e.g. acid baking, caustic digestion or calcination), making it less economical to extract.[60]

Many published studies and reports on desorption leaching are limited to clay-hosted deposits in China (predominantly physically adsorbed), with two commonly used reagents being ammonium sulphate and sodium chloride. Ammonium sulphate has high desorption efficiency with clay minerals. However, it can increase the impurity content in the final leaching solution and contaminate the environment with nitrogen.[61] It is also a driver of swelling in clay minerals in the ore body, resulting in landslides where in situ

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[53] ActivEX (2022) Rare earth opportunities in Queensland. ASX Announcement. <https://company-announcements.afr.com/asx/aiv/edf75622-54d8-11ed-8724-028fbfbe0152.pdf>; AR3 (2023) AR3 expands tenure in emerging Queensland are earths province. ASX Announcement <https://www.listcorp.com/asx/ar3/australian-rare-earths-limited/news/ar3-expands-tenure-in-queensland-rare-earths-province-2921678.html>

[54] Northern Territory Government (2023) Critical Minerals in the Northern Territory 2023.

[55] MRIWA (2023) Characterisation of clay-hosted rare-earth element deposits in Western Australia. Government of Western Australia < https://www.mriwa.wa.gov.au/research-projects/project-portfolio/characterisation-of-clay-hosted-rare-earth-element-deposits-in-western-australia/>

[56] Anawati J and Azimi G (2023) Extraction of rare earth elements from a South American ionic clay. Journal of Rare Earths 41(9), 1408–1418. DOI: 10.1016/j.jre.2022.10.007.

[57] Industry consultations

[58] Anawati J and Azimi G (2023) Extraction of rare earth elements from a South American ionic clay. Journal of Rare Earths 41(9), 1408–1418. DOI: 10.1016/j.jre.2022.10.007.

[59] Anawati J and Azimi G (2023) Extraction of rare earth elements from a South American ionic clay. Journal of Rare Earths 41(9), 1408–1418. DOI: 10.1016/j.jre.2022.10.007; Bradbury M and Bayens B (2002) Sorption of Eu on Na- and Ca-montmorillonites: experimental investigations and modelling with cation exchange and surface complexation. Geochimica et Cosmochimica Acta, 66(13). <https://doi.org/10.1016/S0016-7037(02)00841-4>; Moldoveanu GA and Papangelakis VG (2012) Recovery of rare earth elements adsorbed on clay minerals: I. Desorption mechanism. Hydrometallurgy 117-118(2012). <https://doi.org/10.1016/j.hydromet.2012.02.007>

[60] Ji B and Zhang W (2021) Rare earth elements (REEs) recovery and porous silica preparation from kaolinite. Powder Technology 391(2021) <https://doi.org/10.1016/j.powtec.2021.06.028>

[61] Xu Z, Li G, Yang H, Sha A, He Z, Tang Y, Wu M and Qu J (2023) Development Review on Leaching Technology and Leaching Agents of Weathered Crust Elution-Deposited Rare Earth Ores. Minerals 13(9), 1223. DOI: 10.3390/min13091223.

leaching is practised.[62] Sodium chloride has also been used as an alternative, however it has low leaching efficiency and is often required in higher concentrations which compromises soil fertility.[63]

For clay-hosted deposits from other countries, a combination of reagents may be required depending on the deposit type. For example, a study found leaching of a South American clay requires both ammonium sulphate and sulphuric acid.[64]

### Desorption leaching techniques

Desorption leaching can be done ex-situ where the clay is mined and then leached in heaps or tanks. In heap leaching, the leaching agent is applied on top of a pile of clay. After a few weeks, the REEs-enriched leaching agent can be collected at the bottom of the pile via a pre-built diversion system.[65] Advantages include simple operation and low capital costs.[66] Tank leaching utilises stirring tanks, which increases operation control and efficiency and minimises pollution and wastage, however there is a higher capital outlay. Ex-situ leaching techniques are associated with the biological, environmental and social implications of mining, including ecosystemic and biodiversity losses, pollution and landscape degradation, and health impacts.[67]

Desorption leaching can be done in-situ by vertically injecting the leaching agent into the soil where the clay-hosted deposit is located. As in situ leaching doesn't require physically removing the clay off the ground, it has lower damage to surface vegetation and labour intensity compared to ex-situ leaching.[68] However, in situ leaching may lead to groundwater contamination and loss of structural integrity in the terrain (which in turn can result in mine collapses and landslides).[69] It also has poor recovery rate of REEs (70 to 80%) and significant leaching agent consumption.[70] The process takes approximately 4-13 months to complete.[71] Implementing in situ leaching requires a comprehensive geological assessment of the mining area structure, characteristics and ore quantity.[72]

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[62] Chen Z, Zhang Z, Liu D, Chi X, Chen W and Chi R (2020) Swelling of clay minerals during the leaching process of weathered crust elution-deposited rare earth ores by magnesium salts. Powder Technology 367, 889–900. DOI: 10.1016/j.powtec.2020.04.008.

[63] Vahidi E, Navarro J and Zhao F (2016) An initial life cycle assessment of rare earth oxides production from ion-adsorption clays. Resources, Conservation and Recycling 113, 1–11. DOI: 10.1016/j.resconrec.2016.05.006.

[64] Anawati J and Azimi G (2023) Extraction of rare earth elements from a South American ionic clay. Journal of Rare Earths 41(9), 1408–1418. DOI: 10.1016/j.jre.2022.10.007.

[65] Li LZ and Yang X (2016) China's Rare Earth Resources, Mineralogy, and Beneficiation. Rare Earths Industry. Elsevier.

[66] Yang XJ, Lin A, Li X-L, Wu Y, Zhou W and Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environmental Development 8, 131–136. DOI: 10.1016/j.envdev.2013.03.006.

[67] Yang XJ, Lin A, Li X-L, Wu Y, Zhou W and Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environmental Development 8, 131–136. DOI: 10.1016/j.envdev.2013.03.006.

[68] Xu Z, Li G, Yang H, Sha A, He Z, Tang Y, Wu M and Qu J (2023b) Development Review on Leaching Technology and Leaching Agents of Weathered Crust Elution-Deposited Rare Earth Ores. Minerals 13(9), 1223. DOI: 10.3390/min13091223.

[69] Yang XJ, Lin A, Li X-L, Wu Y, Zhou W and Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environmental Development 8, 131–136. DOI: 10.1016/j.envdev.2013.03.006.

[70] Burcher-Jones C, Mkhize S, Becker M, Ram R and Petersen J (2018) Study of the Deportment of REEs in Ion Adsorption Clays Towards the Development of an In Situ Leaching Strategy; Wang G, Xu J, Ran L, Zhu R, Ling B, Liang X, Kang S, Wang Y, Wei J, Ma L et al. (2022) A green and efficient technology to recover rare earth elements from weathering crusts. Nature Sustainability 6(1), 81–92. DOI: 10.1038/s41893-022-00989-3.

[71] Yang XJ, Lin A, Li X-L, Wu Y, Zhou W and Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environmental Development 8, 131–136. DOI: 10.1016/j.envdev.2013.03.006.

[72] Yang XJ, Lin A, Li X-L, Wu Y, Zhou W and Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environmental Development 8, 131–136. DOI: 10.1016/j.envdev.2013.03.006.

Bioleaching, or the use of microorganisms for compound extraction, is an emerging pathway with potential sustainability benefits. While the interest for applying bioleaching so far has been for material recovery from e-wastes,[73] there have been recent attempts to apply it to primary RE sources including ion-adsorption clay.[74]

## TECHNOLOGY STATE OF PLAY

Extraction and processing projects involving clay-hosted deposits are commercially operational in China and recent pilots have begun in South American countries (e.g., Aclara in Chile).

As discussed previously, the majority of China's deposits utilise two common reagents (ammonium sulphate and sodium chloride) to extract from physically adsorbed clay hosted deposits. Heap leaching was widely used in China until 2011 when the Chinese Government introduced a ban on this technique due to the impact of mining and began implementing in situ leaching.[75] In situ leaching is currently the main technique in China to process clay-hosted deposits.[76] Currently, heap leaching is still practised by some miners globally, such as Texas Mineral Resources (US) for their Round Top Mountain deposit,[77] with the leaching agent being dilute sulphuric acid.[78]

Tank leaching has recently been piloted by Aclara (Chile). The company's patented "Circular Mineral Harvesting" process includes many sustainability practices, such as returning leached and washed clays back to mining site and recycling used water and reagents (mainly ammonium sulphate).[79] Within three months of operation, the pilot processed 120 tonnes of clays, producing 107 kilograms of high-purity heavy RE concentrate.[80]

Most clay-based projects in Australia have progressed beyond the exploration stage and are currently engaging with testing labs (e.g., ANSTO, Strategic Metallurgy (WA)) to conduct lab-scaled characterisation and desorption leaching test works. The most progressed domestic project is Australian Rare Earths (AR3) in SA. In March 2023, the company successfully processed 800 kg of clays into mixed RE compounds using ANSTO's existing equipment and simple processes operating at ambient temperature and pressure. Other

[73] Brown RM, Mirkouei A, Reed D and Thompson V (2023) Current nature-based biological practices for rare earth elements extraction and recovery: Bioleaching and biosorption. Renewable and Sustainable Energy Reviews 173, 113099. DOI: 10.1016/j.rser.2022.113099.

[74] Barnett M, Palumbo-Roe B and Gregory S (2018) Comparison of Heterotrophic Bioleaching and Ammonium Sulfate Ion Exchange Leaching of Rare Earth Elements from a Madagascan Ion-Adsorption Clay. Minerals 8(6), 236. DOI: 10.3390/min8060236; Yin S, Chen W, Fan X, Liu J and Wu L (2021) Review and prospects of bioleaching in the Chinese mining industry. International Journal of Minerals, Metallurgy and Materials 28(9), 1397–1412. DOI: 10.1007/s12613-020-2233-7.

[75] Yang XJ, Lin A, Li X-L, Wu Y, Zhou W and Chen Z (2013) China's ion-adsorption rare earth resources, mining consequences and preservation. Environmental Development 8, 131–136. DOI: 10.1016/j.envdev.2013.03.006.

[76] Li LZ and Yang X (2016) China's Rare Earth Resources, Mineralogy, and Beneficiation. Rare Earths Industry. Elsevier.

[77] This is a rhyolite deposit. However, it can be processed in a similar way to clay.

[78] E. Pingitore Jr. N, W. Clague J and Gorski D (2018) Remarkably Consistent Rare Earth Element Grades at Round Top Yttrofluorite Deposit. Advances in Materials Physics and Chemistry 08(01), 1–14. DOI: 10.4236/ampc.2018.81001; Texas Mineral Resources (2019) Texas Mineral Resources and USA Rare Earth report significantly upgraded resource and confirm prior potential economics in updated round top preliminary economic assessment. <https://tmrcorp.com/news/press_releases/2019/index.php?content_id=203>

[79] Aclara (n.d.) Penco Module. <https://www.aclara-re.com/pencomodule-our-process>

[80] Aclara (2023) Aclara successfully completes semi-industrial scale piloting for the Penco Module. <https://uploads-ssl.webflow.com/6267a587be31507747a1c8b6/64f78afbe40d7f3c700fcced_Aclara%20-%20PP%20Completed_VF.pdf>

domestic organisations include but are not limited to Taruga[81] (SA), iTech Minerals (SA)[82], Godolphin[83] (NSW), ABx[84] (Tasmania), Krakatoa[85] (WA), Heavy Rare Earths[86] (WA), Resource Base[87] (Victoria). In 2024, ANSTO received $13.9 million of funding through the Australian Critical Minerals R&D Hub for a two-year project focusing on processing clay-hosted deposits.[88]

Australia also has cross-cutting capabilities from other metallurgical industries that can potentially be applied and bring step changes in terms of cost efficiency and sustainability for clay-based operations. Heap, tank and in-situ leaching are commercially used techniques in low-grade copper, silver, gold and uranium mining industries.[89] Australia has been a global leader in developing in situ recovery best practices, both from the regulatory and innovation perspectives.[90] For example, EnviroCopper, in partnership with CSIRO and the University of Adelaide, has been developing and demonstrating environmentally friendly strategies for in-situ copper extraction.[91]

Out of all the extractive processes, extraction from clay-hosted deposits attracted the highest level of patent activity in this analysis. For the period analysed (2007 to 2022) 7.1% of patent families were related to the production of mixed RE compounds from clay-based ores. This area experienced a very strong uptick in activity after 2011, reflecting the demand for rare earths and the emergence of clay resources as an economically viable source. China (91.2%) is the dominant player in this space, followed by the United States (4.4%). Other countries with one patent each include Japan, Russia, South Africa, the United Kingdom and Finland.

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[81] Taruga (2022) ANSTO metallurgical extractions up to 70% of magnet rare earths. <https://announcements.asx.com.au/asxpdf/20221215/pdf/45jvt81s65x7gh.pdf>.

[82] iTech Minerals (2023) Breakthrough in REE metallurgy at Caralue Bluff clay hosted REE prospect. <https://www.itechminerals.com.au/investorarticles/breakthrough-in-ree-metallurgy-at-caralue-bluff-clay-hosted-ree-prospect/>

[83] Godolphin (2024) ANSTO leach tests continue to deliver exceptional REE recoveries at Narraburra rare earths project. <https://godolphinresources.com.au/downloads/announcements/grl_2024021901.pdf>

[84] ABx Group (2023) Widespread high extractions of ionic adsorption clay rare earths. <https://www.abxgroup.com.au/site/pdf/1a141255-94bf-4408-bf5e-3293748e2f91/WideSpread-High-Extractions-of-Ionic-Adsorption-Clay.pdf>

[85] Krakatoa Resources (2023) Positive metallurgical results demonstrate pathway to production at Tower deposit. <https://wcsecure.weblink.com.au/pdf/KTA/02622956.pdf>

[86] Heavy Rare Earths Limited (2023) Metallurgical program delivers two-fold grade increase and up to 91.3% extraction of magnet rare earths. <https://wcsecure.weblink.com.au/pdf/HRE/02685825.pdf>

[87] Resource Base (2023) Extractions up to 70% of magnet rare earths at Mitre Hill. <https://www.investi.com.au/api/announcements/rbx/72b464d9-df0.pdf>

[88] ANSTO (2024) ANSTO welcomes $13.9M critical minerals funding. <https://www.ansto.gov.au/news/ansto-welcomes-139m-critical-minerals-funding>

[89] Thenepalli T, Chilakala R, Habte L, Tuan LQ and Kim CS (2019) A Brief Note on the Heap Leaching Technologies for the Recovery of Valuable Metals. Sustainability 11(12), 3347. DOI: 10.3390/su11123347.

[90] The Government of South Australia (n.d.) In situ recovery (ISR) mining. <https://www.energymining.sa.gov.au/industry/minerals-and-mining/mining/major-projects-and-mining-activities/in-situ-recovery-ISR-mining>

[91] EnviroCopper (n.d.) EnviroCopper leading ISR technology. <https://www.envirocopper.com.au/isr-technology>

The following table summarizes the RD&D focus areas for the extraction technologies for clay-based ores:

**Table 5: Global RD&D focus areas for the extraction technologies for clay-based ores.**

| RD&D FOCUS AREAS | |
|---|---|
| **Desorption leaching agents** | • Developing and demonstrating ammonia-free or low-ammonia leaching agents to avoid nitrogen pollution to the environment.[92]<br>• Developing impurity and swelling inhibition leaching agents to improve product purity and leaching efficiency.[93] |
| **Desorption leaching techniques** | • Developing methods to improve in situ leaching efficiency (e.g., application of surfactants[94] or electric field[95]).<br>• Developing integrated method of heap leaching and vegetation restoration (e.g., horizontal liquid injection).[96]<br>• Developing mitigation strategies for ammonium contamination in the environment, including nitrogen removal technology.[97] |

### 3.1.3 Implications for Australia

Monazite and xenotime deposits are rich in light and heavy REEs, and prospective deposits have been found across many Australian states. In recent years, many discoveries of clay-hosted deposits have also been made in Australia, which have the ability to be mined at extracted at comparatively low costs. In light of highly concentrated global supply, there is a strategic opportunity for Australia to expand its activity in extraction and mid-stream processing of RE compounds.

This section discusses the opportunities for domestic RD&D and for international engagement in RE extraction from hard rock deposits, and from clay-hosted deposits (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*.

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[92] Xu Z, Li G, Yang H, Sha A, He Z, Tang Y, Wu M and Qu J (2023b) Development Review on Leaching Technology and Leaching Agents of Weathered Crust Elution-Deposited Rare Earth Ores. Minerals 13(9), 1223. DOI: 10.3390/min13091223.

[93] Xu Z, Li G, Yang H, Sha A, He Z, Tang Y, Wu M and Qu J (2023b) Development Review on Leaching Technology and Leaching Agents of Weathered Crust Elution-Deposited Rare Earth Ores. Minerals 13(9), 1223. DOI: 10.3390/min13091223.

[94] Zhou F, Zhang L, Wang Z, Zhang Y, Chi R and Wu X (2024) Application of surfactant for improving leaching process of weathered crust elution-deposited rare earth ores. Journal of Rare Earths 42(1), 181–190. DOI: 10.1016/j.jre.2022.11.002.

[95] Zhou L, Yang J, Kang S, Wang X, Yu H and Wan Y (2024) Enhancing leaching efficiency of ion adsorption rare earths by ameliorating mass transfer effect of rare earth ions by applying an electric field. Journal of Rare Earths 42(1), 172–180. DOI: 10.1016/j.jre.2023.03.019; Wang G, Xu J, Ran L, Zhu R, Ling B, Liang X, Kang S, Wang Y, Wei J, Ma L et al. (2022) A green and efficient technology to recover rare earth elements from weathering crusts. Nature Sustainability 6(1), 81–92. DOI: 10.1038/s41893-022-00989-3.

[96] Ju W, Yang J, Yao C, Zhang X, Ye Z and Liu D (2022) Experimental Study on the Permeability of Rare Earths with Different Particle Composition for a Novel Heap Leaching Technology. Applied Sciences 12(22), 11368. DOI: 10.3390/app122211368.

[97] Xu Z, Li G, Yang H, Sha A, He Z, Tang Y, Wu M and Qu J (2023b) Development Review on Leaching Technology and Leaching Agents of Weathered Crust Elution-Deposited Rare Earth Ores. Minerals 13(9), 1223. DOI: 10.3390/min13091223.

**Figure 8: Actions for Australian RD&D and international engagement in the production of mixed rare earth compounds.**

| Opportunity area | Establish new capability in emerging technologies | Accelerate emerging technologies and grow Australian IP | Pilot and scale up Australian IP | Support commercial deployment of mature technologies |
|---|---|---|---|---|
| **Applicable Technologies** | • Salt roasting<br>• Chlorination | • Desorption leaching (clay hosted deposits) | • Sulphuric acid roasting and baking | • Sulphuric acid roasting and baking<br>• Alkaline baking |
| **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.

Sulphuric acid roasting and baking will likely play a role in current and future Australian RE extraction projects from hard rock ores, due to its commercial maturity and versatility. Sulphuric acid roasting and baking pathways are highly compatible with different mineralogies. New centralised processing plants maybe be able to accept RE concentrates from miners across multiple locations, optimising functionality, efficiency and potential profit. However, this could be challenging if ore grades differ significantly between different deposits, as plant operating parameters are often narrowly calibrated for a relatively homogeneous feedstock. This may be overcome by mixing ores from different locations at proportions consistent to suit the plant parameters.[98]

Despite its commercial maturity, sulphuric acid roasting and baking has received consistent IP activity over the past 15 years, suggesting opportunities to innovate still exist. Industry consultations have highlighted the need to better understand and manage material behaviour during roasting and baking, which is a current challenge for commercial operations outside of China. Other RD&D opportunities include improving reagent recycling and waste management to improve sustainability and lower operating costs.

Sulphuric acid roasting and baking is no longer subject to high levels of IP restrictions.[99] As such, Australia's existing industry know-how can support the expansion of commercial operations onshore. Australia also possesses patents (e.g. Arafura) in sulphuric acid roasting representing an opportunity to pilot and demonstrate Australian IP onshore.

While Australia's strengths are an opportunity to accelerate onshore commercial activity with less reliance on overseas partners, international engagement will be beneficial. Commercial arrangements such as obtaining equipment from overseas manufacturers and large-scale engineering of plants will be required. There is also an opportunity for Australia to provide its expertise and services to prospective organisations overseas, supporting international supply chain diversification efforts.

Alkaline baking (or caustic digestion) is an alternative to sulphuric acid processes and represents an opportunity to improve sustainability outcomes in the decomposition and leaching stages (e.g. lower

[98] Stakeholder consultation

[99] Stakeholder consultation

energy intensity). There is also potential to reduce costs depending on the operation configuration, for example by recovering and selling phosphate.

Despite its potential benefits, alkaline baking is an extraction technology that has been used in limited commercial application due to the need for high grade ores. This is reflected in the relatively low IP activity over the last 15 years. With existing industry know-how at ANSTO, the role of RD&D is likely to help understand the technical and economic viability of alkaline baking in the Australian context and, if applicable, support commercial deployment of the technology onshore. Given alkaline baking has only been commercially deployed overseas, international collaboration with extensive industry know-how may be beneficial, as well as engagement with overseas equipment vendors.

Salt roasting and chlorination roasting are emerging alternatives to sulphuric acid and alkaline processes, with potential to deliver step changes in efficiency over a longer development horizon. Salt roasting benefits from efficient impurity removal, potentially simplifying subsequent separation and purification steps. Chlorination roasting is highly efficient and enables bypassing the leaching step to directly produce RE chlorides for REE separation.

Given the emergence of salt and chlorination roasting technologies globally, RD&D will be required to overcome technical challenges and build greater capability domestically. This can be supplemented with knowledge sharing and research collaborations with international institutions. An RD&D area for salt roasting is managing material behaviour and melted salt build-up during roasting, as it can cause corrosion and process discontinuity. Additionally, low energy salt roasting processes, such as one with no preliminary air roasting required, is a more sustainable option to be investigated.[100] For chlorination roasting, RD&D would need to overcome existing challenges related to energy intensity, corrosion and safety.

Extraction from clay-hosted deposits represents a strategic opportunity for Australia to diversify and capitalise on this concentrated step of the global RE supply chain. Despite being relatively lower grade than hard rock deposits, extracting RE compounds from clay-hosted deposits is economically attractive due to the low cost of mining (relative to hard rock deposits), low processing costs (for desorption leaching), low levels of radioactive elements (thorium and uranium), and the heavy rare earth content.[101] Further, the majority of global heavy rare earths are extracted from ionic clays in southern China, and clay projects in other countries have only reached pilot stages.[102]

There are several challenges facing this emerging industry. Firstly, there is limited processing knowledge and skills for clay-hosted deposits outside of China. This challenge is amplified by the fact that each deposit has distinct chemical and mineralogical characteristics, requiring a tailored desorption approach, representing an RD&D cost burden for producers.

Given the growing number of clay-hosted RE discoveries in Australia and their economic potential, Australia has already made RD&D investments in this space. Continued RD&D support can help overcome the technical and financial barriers of prospective producers in Australia. Due to supply chain concentration and limited capabilities outside of China, the processing of clay-hosted deposits is experiencing high levels

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[100] Zou D, Chen J, Hu J, Li K and Li D (2020b) Thermal decomposition mechanism of low-content-fluorite Bayan Obo rare earth concentrate roasted with sodium carbonate and its consequent separation study. Journal of Rare Earths 38(9), 994–1002. DOI: 10.1016/j.jre.2019.09.015.

[101] Feng J et al. (2023) Leaching behavior of rare earth elements and aluminium from weathered crust elution-deposited rare earth ore with ammonium formate inhibitor. Minerals, 13(10), 1245. https://doi.org/10.3390/min13101245; Chai X et al. (2020) Leaching kinetics of weathered crust elution-deposited rare earth ore with compound ammonium carboxylate. Minerals, 10(6), 516 < https://doi.org/10.3390/min10060516>; Murakami H and Ishihara S (2008) REE mineralisation of weathered crust and clay sediment on granitic rocks in the Sanyo Belt, SW Japan and the Southern Jiangxi Province, China. Resource Geology, 58(4) < https://doi.org/10.1111/j.1751-3928.2008.00071.x>

[102] Anawati J and Azimi G (2023) Extraction of rare earth elements from a South American ionic clay. Journal of Rare Earths 41(9), 1408–1418. DOI: 10.1016/j.jre.2022.10.007.

of RD&D activity. The recent piloting of novel processes with sustainable practices outside of China and the consistently high IP activity since 2013 suggests this is a growth area in terms of innovation.

Given the existing capabilities at ANSTO and ongoing commercial development activities, there is an opportunity to support Australian companies to pilot and demonstrate their processes onshore and to continue to grow domestic IP and enhance industry know-how. The primary focus of RD&D will be to enhance understanding of Australian clays, identify suitable extraction mechanisms, compare process configurations and costs, and to provide test work for commercial projects.

Additionally, establishing best practices in sustainability and optimising operating costs are opportunities to position Australia as a responsible and competitive supplier of heavy REEs from clay-hosted deposits. To achieve these objectives, it is important to develop and demonstrate environmentally friendly leaching agents that have high leaching efficiency and swelling and impurity inhibition properties when used on clays, and low environmental impact. Australia can also leverage existing capabilities and best practices from other industries (e.g., mining and extraction of gold, silver, copper and uranium), or explore alternative processing pathways (e.g., bioleaching). Together, these strategies would help optimise reagent consumption and reduce costs for waste treatment and waste mitigation measures.

In light of the global effort to better understand clay-hosted deposits and diversify this step of the supply chain, there are opportunities for international engagement. Establishing long-term commercial or research partnerships with overseas organisations active in extraction from clay-hosted deposits could support knowledge sharing and capability growth for Australia. Further, there is an opportunity for Australian processing experts to provide their RD&D services to support overseas commercial operations.

## 3.2 Production of separated rare earth oxides

The next stage in the supply chain is for mixed RE concentrates (e.g. RE oxides and RE carbonates) or a leach solution containing these compounds, to undergo a series of separation steps. The separation step yields a mixed light or heavy RE oxide, or separated oxide salt of each RE element.[103]

Commercial separation operations utilise solvent extraction as the key technology. Ion exchange chromatography is also a mature technology; however, it is often incorporated in certain steps of the separation process to target specific REEs and is overall less utilised commercially. Emerging technologies such as membrane separation or adsorption are being developed to lower the costs and improve efficiency and sustainability.

These technologies can also be used to separate and remove radioactive elements present in RE ores, such as thorium and, less commonly, uranium.[104] This section does not discuss this aspect in detail, however discussion on radioactivity management and social license can be found in the main report.

[103] Xie F, Zhang TA, Dreisinger D and Doyle F (2014) A critical review on solvent extraction of rare earths from aqueous solutions. Minerals Engineering 56, 10–28. DOI: 10.1016/j.mineng.2013.10.021.

[104] Zhu Z, Pranolo Y and Cheng CY (2015) Separation of uranium and thorium from rare earths for rare earth production – A review. Minerals Engineering 77, 185–196. DOI: 10.1016/j.mineng.2015.03.012.

### 3.2.1 Solvent extraction

Solvent extraction is a liquid-based method that uses solubility differences to separate components of a liquid mixture.[105] The separation of REEs involves many solvent extraction circuits (up to 100 per circuit),[106] each separating one element or impurity from the mixture into a concentrated solution.[107]

Solvent extraction is considered one of the most appropriate techniques for REE separation given its high and continuous throughput and its selectivity.[108] It is also effective in separating radioactive elements like uranium and thorium, and has been integrated in current flow sheets in industry.[109]

The main disadvantages of solvent extraction include low efficiency due to requiring multiple circuits, and significant solvent consumption and wastage. These challenges were highlighted during stakeholder consultations as key challenge for aspiring commercial operators Australia.

The solvent extraction process involves a chemical reagent functioning as an extractant, and an acidic solution functioning as a medium to dissolve the mixed RE compound. Currently, organic phosphorus acids such as P507 (2-ethylhexyl phosphonic acid mono-2-ethylhexyl ester) are the most commonly used reagents for solvent extraction in industry.[110] However, the use of organic solvents is also oftentimes considered unsustainable due to secondary environmental pollution concerns.[111]

Alternative reagents such as ionic liquids and deep eutectic solvents are being investigated for solvent extraction. Ionic liquids have low flammability and volatility, are highly selective and can enhance REE extraction and efficiency.[112] However, some families of ionic liquids are toxic and expensive, limiting their commercial application.[113] Deep eutectic solvents are an extended class of ionic liquids with biodegradable and non-toxic properties, and comparable costs to conventional solvents.[114] Deep eutectic solvents have been highlighted during the consultation process as a sustainable and high potential pathway to separate REEs.

For the acidic solution medium, chloride solutions especially hydrochloric acid are widely used in industry due to the high solubility of REEs and ability to minimise co-extraction of impurities, improving extraction

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[105] Liu T and Chen J (2021b) Extraction and separation of heavy rare earth elements: A review. Separation and Purification Technology 276, 119263. DOI: 10.1016/j.seppur.2021.119263.

[106] Zhang R and Azimi G (2023b) Separation of Praseodymium and Neodymium from Heavy Rare Earth Elements Using Extractant-Impregnated Surfaces Loaded with 2-Ethylhexyl Phosphonic Acid-mono-2-ethylhexyl Ester (PC88A). Industrial & Engineering Chemistry Research 62(33), 13117–13132. DOI: 10.1021/acs.iecr.3c01547.

[107] McNulty T, Hazen N and Park S (2022b) Processing the ores of rare-earth elements. MRS Bulletin 47(3), 258–266. DOI: 10.1557/s43577-022-00288-4.

[108] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

[109] Talan D and Huang Q (2022) A review of environmental aspect of rare earth element extraction processes and solution purification techniques. Minerals Engineering 179, 107430. DOI: 10.1016/j.mineng.2022.107430.

[110] Kostanyan AE, Belova V V, Tsareva Y V, Petyaeva MM (2023) Separation of Rare Earth Elements in Multistage Extraction Columns in Chromatography Mode: Experimental Study and Mathematical Simulation. Processes 11(6), 1757. DOI: 10.3390/pr11061757.

[111] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

[112] Okamura H and Hirayama N (2021) Recent Progress in Ionic Liquid Extraction for the Separation of Rare Earth Elements. Analytical Sciences 37(1), 119–130. DOI: 10.2116/analsci.20SAR11.

[113] Entezari-Zarandi A and Larachi F (2019) Selective dissolution of rare-earth element carbonates in deep eutectic solvents. Journal of Rare Earths 37(5), 528–533. DOI: 10.1016/j.jre.2018.07.015.

[114] Entezari-Zarandi A and Larachi F (2019) Selective dissolution of rare-earth element carbonates in deep eutectic solvents. Journal of Rare Earths 37(5), 528–533. DOI: 10.1016/j.jre.2018.07.015.

selectivity and efficiency. However, using chloride solutions can cause degradation to certain organic reagents and affect the separation efficiency and cost.

Potential alternatives to chloride include sulphate and nitrate solutions. Sulphate solutions such as sulphuric acid offer a highly soluble environment for REEs, however it is corrosive to equipment and can also cause reagent degradation. Nitrate solutions such as nitric acid are generally more environmentally benign. They offer high extraction selectivity and produce nitrate by-products (e.g., ammonium nitrate) that can be easily managed or sold as fertilisers for additional revenue. However, there are current challenges with finding compatible reagents with nitrate solutions.[115]

## TECHNOLOGY STATE OF PLAY

Solvent extraction is commercially mature and used at scale in China,[116] and fewer commercial operations in other parts of the world (Malaysia[117], the US[118], and India[119]). Solvent extraction is being considered for many upcoming commercial scale operations in Australia.

- Lynas (Australia) utilises solvent extraction at their commercial separation plant in Malaysia to produce separated RE oxides from their Kalgoorlie (WA) RE carbonate.[120] The company also has plans to build another separation facility in Texas (US) to produce RE oxides, becoming operational by 2025.[121]
- In 2022, Iluka received $1.2 billion federal government loan to build Australia's first integrated refinery (including sulphuric acid roasting and solvent extraction) in Eneabba (WA), commencing in 2025.[122]
- In the NT, Arafura is scaling its 2020 pilot demonstration into a commercial-scale refinery (including sulphuric acid roasting and solvent extraction), targeting first production in 2025.[123] In March 2024, the Australian Government announced a $840 million loan to support the refinery construction.[124]
- Australian Strategic Materials (ASM) has developed and demonstrated a solvent extraction process at pilot scales in collaboration with ANSTO. The project's most recent milestone (October 2023) is

[115] Merroune A, Ait Brahim J, Berrada M, Essakhraoui M, Achiou B, Mazouz H and Beniazza R (2024) A comprehensive review on solvent extraction technologies of rare earth elements from different acidic media: Current challenges and future perspectives. Journal of Industrial and Engineering Chemistry DOI: 10.1016/j.jiec.2024.04.042.

[116] Xie F, Zhang TA, Dreisinger D and Doyle F (2014) A critical review on solvent extraction of rare earths from aqueous solutions. Minerals Engineering 56, 10–28. DOI: 10.1016/j.mineng.2013.10.021.

[117] Lynas Rare Earths (n.d.) Lynas Malaysia, Kuantan, Malaysia. <https://lynasrareearths.com/about-us/locations/kuantan-malaysia/>

[118] Easley M (2023) Special report: U.S. begins forging rare earth supply chain. National Defense Magazine. <https://www.nationaldefensemagazine.org/articles/2023/2/10/us-begins-forging-rare-earth-supply-chain>; MP Materials (2024) MP Materials reports fourth quarter and full year 2023 results. <https://s25.q4cdn.com/570172628/files/doc_news/2024/MP-4Q23-Earnings-Release-FINAL.pdf >

[119] Balachandran G (2014) Extraction of Rare Earths for Advanced Applications. Treatise on Process Metallurgy. Elsevier; The Government of India Department of Atomic Energy (2023) Mining of rare earth elements. <https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1914305>.

[120] Lynas Rare Earths (n.d.) Lynas Malaysia, Kuantan, Malaysia. <https://lynasrareearths.com/about-us/locations/kuantan-malaysia/>

[121] Lynas Rare Earths (2023) Lynas USA FAQ. <https://lynasrareearths.com/wp-content/uploads/2023/11/Lynas-USA-FAQ-November-2023.pdf>

[122] Iluka Resources Limited (2022) Eneabba rare earth refinery – final investment decision. <https://iluka.com/media/srypf2vr/erer-fid-asx-release-final.pdf>

[123] Arafura Rare Earths Limited (2022) Nolans project update. <https://wcsecure.weblink.com.au/pdf/ARU/02597137.pdf>.

[124] Arafura Rare Earths Limited (2024) Commonwealth Government supports the Nolans project with US$533 million finance package. <https://wcsecure.weblink.com.au/pdf/ARU/02784883.pdf>

the successful separation and production of high-purity terbium and dysprosium oxide.[125] ASM has plans to commence a commercial scale separation plant in Dubbo (NSW) by 2027.[126]

- Northern Minerals in WA will partner with Iluka to undertake separation of their RE carbonates.[127]
- Australia's commercial developments are supported by ANSTO's process development and operational capabilities in solvent extraction.[128]

Emerging approaches to solvent extraction are being developed internationally. For example, Ucore in collaboration with Kingston Processing Metallurgy Inc have developed RapidSX™, a compact and streamlined plant design that doesn't require electrically powered mixing. The approach reduces costs compared to conventional solvent extraction plants, significantly shortens processing times, and is adaptable to diverse feedstocks.[129]

Alternative reagents (i.e., ionic liquids and deep eutectic solvents) and acid solution mediums (i.e., sulphate and nitrate solutions) are being developed at lab scale,[130] however there is industry interest in cross-cutting applications and demonstrations. For example, Ionic Technologies (UK) is demonstrating a REE separation process from used magnets using ionic liquids.[131] Iluka has proposed utilising nitric acid instead of hydrochloric acid in their separation process development.[132]

Solvent extraction processes attracted the highest level of IP activity across the entirety of this rare earths analysis, with 42.5% of patent families over the 2007 – 2022 period. The IP activity has been increasing steadily throughout the analysis period, despite its high commercial maturity. This partly reflects the continued work in this space to overcome technical challenges and inherent complexity of this process. IP activity was driven strongly by China (72.1%), followed by the United States and Japan (7.2%), Russia (6.6%) and France (1.3%).

[125] Australian Strategic Materials (2023) Excellent heavy rare earth oxide results from Dubbo Project pilot plant testing. <https://asmd.irmau.com/site/pdf/864019ab-4697-456c-a2af-2f72a8a13e0d/Excellent-heavy-rare-earth-oxide-results-from-Dubbo-Project.pdf>

[126] Currently subject to final investment decision in late 2024. Australian Strategic Materials (2023) Annual report 2023. <https://asmd.irmau.com/site/pdf/298e5dee-6427-4403-9ff4-c4a9d332bc2c/Annual-Report-to-shareholders.pdf>; Australian Strategic Materials (2021) Dubbo project optimisation delivers strong financials. <https://asmd.irmau.com/site/PDF/ad9dcf23-41ca-4ebb-a779-b2cbc200217e/DubboProjectOptimisationDeliversStrongFinancials>

[127] Iluka Resources (2022) Strategic partnership with Northern Minerals rare earths concentrate supply. <https://iluka.com/media/fgajciyc/iluka-resources-asx-strategic-partnership-with-northern-minerals.pdf>

[128] ANSTO (2020) Rare earth processing. <https://www.ansto.gov.au/sites/default/files/2020-07/G-7425%20Minerals%20Rare%20Earth%20Processing%20Capability%20Statement2%20%282%29.pdf>.

[129] Ucore™ (2024) RapidSX™ <https://ucore.com/rapidsx/>

[130] Arrachart G, Couturier J, Dourdain S, Levard C and Pellet-Rostaing S (2021) Recovery of Rare Earth Elements (REEs) Using Ionic Solvents. Processes 9(7), 1202. DOI: 10.3390/pr9071202; Merroune A, Ait Brahim J, Berrada M, Essakhraoui M, Achiou B, Mazouz H and Beniazza R (2024) A comprehensive review on solvent extraction technologies of rare earth elements from different acidic media: Current challenges and future perspectives. Journal of Industrial and Engineering Chemistry DOI: 10.1016/j.jiec.2024.04.042.

[131] Ionic Technologies (n.d.) Process. <https://ionictechnologies.com/process/>.

[132] Stakeholder consultations; Iluka Resources Limited (2022) Eneabba rare earths refinery – final investment decision presentation. <https://iluka.com/media/jyzjypkg/erer-fid-presentation-final.pdf>

The following table summarizes the RD&D focus areas for solvent extraction technologies:

**Table 6: Global RD&D focus areas for solvent extraction separation technologies.**

| RD&D FOCUS AREAS | |
|---|---|
| **Solvent extraction separation** | • Optimising solvent extraction efficiency and sustainability through the development of novel extractive solvents and processes.[133] |

### 3.2.2 Ion exchange chromatography

Chromatography is a group of separation techniques that involves passing a solution mixture through an adsorbing column. During the chromatography process, atoms, ions, or molecules from the solution adhere to the surface of the resin material and are then reacted with a chemical to yield a concentrated solution containing the target metal.

Many variations of chromatography have been applied for RE separation at lab scales. The most widely used chromatography technique is ion exchange. Other variations include ion-pair reverse-phase chromatography, extraction chromatography and centrifugal partition chromatography.[134]

Ion exchange is done in columns filled with a resin (e.g., copolymer or organic material) which adsorbs REEs based on particle charge differences.[135] The two most important factors for this process include the selection of resins and the operating condition.[136] The advantages of ion exchange include the ability to separate many REEs in one step and achieve high purity levels, while maintaining low pollution.[137] However, ion exchange has a relatively low processing throughput, restricting commercial scalability. Some resin materials have limited reusability and require regular replacement, reducing process efficiency and increasing operating costs. [138]

**TECHNOLOGY STATE OF PLAY**

Ion exchange is a highly mature technology and was previously the only commercial RE separation process up until the 1960s. Commercial operations have since moved to solvent extraction techniques.[139] Although commercial scale ion exchange operations have ceased, advancements in continuous systems have strong scalability potential and are being piloted globally. Rainbow Rare Earths (UK) and K-Technologies (US),

[133] Traore M, Gong A, Wang Y, Qiu L, Bai Y, Zhao W, Liu Y, Chen Y, Liu Y, Wu H et al. (2023) Research progress of rare earth separation methods and technologies. Journal of Rare Earths 41(2), 182–189. DOI: 10.1016/j.jre.2022.04.009; Sui N and Huang K (2019b) Separation of rare earths using solvent extraction consisting of three phases. Hydrometallurgy 188, 112–122. DOI: 10.1016/j.hydromet.2019.06.012.

[134] Chen B, He M, Zhang H, Jiang Z and Hu B (2017) Chromatographic Techniques for Rare Earth Elements Analysis. Physical Sciences Reviews 2(4). DOI: 10.1515/psr-2016-0057.

[135] El Ouardi Y, Virolainen S, Massima Mouele ES, Laatikainen M, Repo E and Laatikainen K (2023b) The recent progress of ion exchange for the separation of rare earths from secondary resources – A review. Hydrometallurgy 218, 106047. DOI: 10.1016/j.hydromet.2023.106047.

[136] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022b) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

[137] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022b) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

[138] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022b) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

[139] El Ouardi Y, Virolainen S, Massima Mouele ES, Laatikainen M, Repo E and Laatikainen K (2023b) The recent progress of ion exchange for the separation of rare earths from secondary resources – A review. Hydrometallurgy 218, 106047. DOI: 10.1016/j.hydromet.2023.106047.

supported by test work from ANSTO, are piloting a continuous ion exchange and continuous ion chromatography technology to process a high-grade deposit from South Africa (i.e., gypsum stacks).[140] The continuous system has many advantages over solvent extraction, such as fewer steps, non-hazardous reagents and lower costs.[141] The use of ionic liquids in ion exchange operations are also being developed at lab scale to reduce the costs and environmental impact of the process.[142]

Although ion exchange is not utilised commercially in Australia, ANSTO has process development and operational capabilities in ion exchange applications in rare earth separation.[143]

A global patent analysis of the 2007 to 2022 period identified 4.1% of patent families were related to ion exchange and chromatography techniques for separating REEs. The IP activity in this space experienced an upward trend since 2010. 26.3% of patents were filed between 2020 and 2022, with the most recent peak in activity in 2021. China accounted for 43.8% of the patent family filings, followed by the United States (25%) and Japan (17.5%). Australian patent-active organisations include Clean Teq.

The following table summarizes the RD&D focus areas for ion exchange technologies:

**Table 7: Global RD&D focus areas for ion exchange chromatography separation technologies.**

| RD&D FOCUS AREAS | |
|---|---|
| **Ion exchange chromatography separation** | • Developing new ion exchange materials with improved selectivity and separation efficiency.[144]<br>• Optimising current process design to reduce reagent consumption, recover solvents and improve sustainability.[145] |

### 3.2.3 Membrane separation and adsorption

#### Membrane separation

Membrane separation technologies achieve separation by using a membrane as a separation medium, and by leveraging pressure or differences in concentration.[146] In general, membrane separation technology is simple to operate, can achieve high selectivity with minimal solvent consumption and has no thermal

[140] Rainbow Rare Earths Limited (2023) Annual report 2023. <https://www.rainbowrareearths.com/wp-content/uploads/2023/10/RRE-2023-Annual-Report_Final.pdf>

[141] Rainbow Rare Earths Limited (2022) Technical report on the Phalaborwa processing flow sheet development. <https://www.rainbowrareearths.com/wp-content/uploads/2022/03/2022-02-Technical-Report-on-Phalaborwa-processing-flow-sheet-development_FINAL.pdf>

[142] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

[143] ANSTO (2020) Rare earth processing. <https://www.ansto.gov.au/sites/default/files/2020-07/G-7425%20Minerals%20Rare%20Earth%20Processing%20Capability%20Statement2%20%282%29.pdf>.

[144] El Ouardi Y, Virolainen S, Massima Mouele ES, Laatikainen M, Repo E and Laatikainen K (2023b) The recent progress of ion exchange for the separation of rare earths from secondary resources – A review. Hydrometallurgy 218, 106047. DOI: 10.1016/j.hydromet.2023.106047.

[145] El Ouardi Y, Virolainen S, Massima Mouele ES, Laatikainen M, Repo E and Laatikainen K (2023b) The recent progress of ion exchange for the separation of rare earths from secondary resources – A review. Hydrometallurgy 218, 106047. DOI: 10.1016/j.hydromet.2023.106047.

[146] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

treatment requirement.[147] However, some membranes have limited lifetime due to the solid accumulation issue on surface (i.e., fouling) and the materials can have low stability in harsh conditions (e.g., high pH). This results in the need to regularly replace the membranes, which is costly and inefficient at large scale operations.[148]

Pressure-driven membrane separation (e.g., nano-, ultra- or micro-filtration) has mostly been used for impurity removal. Concentration-driven membrane separation is an emerging technology for REE separation.[149] Liquid membranes have been investigated over the past few decades; however, current efforts are being focused on non-liquid membranes and materials to achieve efficient REE separation, low costs and low environmental impacts (e.g. polymer inclusion membranes).[150]

Membranes can also be integrated into solvent extraction processes to improve cost and sustainability outcomes. Compared to conventional solvent extraction, installing membranes into solvent extraction circuits has higher separation efficiency and lower reagent consumption and waste levels. It also recycles reagents and water, requires low capital and operating costs, and is highly scalable. However, this method faces the challenge of declining extraction rate over time.[151]

### Adsorption separation

In adsorption separation methods, adsorbent materials are introduced to the mixed RE leach solutions to selectively bind with RE and impurity metal ions.[152] Common adsorbents include activated carbon, silica gel, activated alumina, zeolites and synthetic polymeric resins. Additionally, bio-adsorbents derived from natural materials like cellulose or starch, as well as advanced nanomaterials like graphene and magnetic nanoparticles have also been applied.[153]

Adsorption is a simple, efficient, low-cost and environmentally friendly method to separate RE elements. It can also be used to treat low concentration RE leach solutions.[154] However, current adsorbent materials are unable to simultaneously ensure high adsorption capacity and high selectivity. Some materials also have low stability in acidic environments.[155]

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[147] Bashiri A, Nikzad A, Maleki R, Asadnia M and Razmjou A (2022) Rare Earth Elements Recovery Using Selective Membranes via Extraction and Rejection. Membranes 12(1), 80. DOI: 10.3390/membranes12010080.

[148] Kujawa J, Al Gharabli S, Szymczyk A, Terzyk AP, Boncel S, Knozowska K, Li G and Kujawski W (2023) On membrane-based approaches for rare earths separation and extraction – Recent developments. Coordination Chemistry Reviews 493, 215340. DOI: 10.1016/j.ccr.2023.215340.

[149] Bashiri A, Nikzad A, Maleki R, Asadnia M and Razmjou A (2022) Rare Earth Elements Recovery Using Selective Membranes via Extraction and Rejection. Membranes 12(1), 80. DOI: 10.3390/membranes12010080.

[150] Kujawa J, Al Gharabli S, Szymczyk A, Terzyk AP, Boncel S, Knozowska K, Li G and Kujawski W (2023) On membrane-based approaches for rare earths separation and extraction – Recent developments. Coordination Chemistry Reviews 493, 215340. DOI: 10.1016/j.ccr.2023.215340.

[151] Islam SZ, Wagh P, Jenkins JE, Zarzana C, Foster M and Bhave R (2022) Process Scale-Up of an Energy-Efficient Membrane Solvent Extraction Process for Rare Earth Recycling from Electronic Wastes. Advanced Engineering Materials 24(12). DOI: 10.1002/adem.202200390; Oak Ridge National Laboratory (2023) Revolutionizing resource renewal: scaling up sustainable recycling for critical materials. <https://www.ornl.gov/news/revolutionizing-resource-renewal-scaling-sustainable-recycling-critical-materials>

[152] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022b) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

[153] da Costa TB, da Silva MGC and Vieira MGA (2020) Recovery of rare-earth metals from aqueous solutions by bio/adsorption using non-conventional materials: a review with recent studies and promising approaches in column applications. Journal of Rare Earths 38(4), 339–355. DOI: 10.1016/j.jre.2019.06.001.

[154] Chen Z, Li Z, Chen J, Kallem P, Banat F and Qiu H (2022b) Recent advances in selective separation technologies of rare earth elements: a review. Journal of Environmental Chemical Engineering 10(1), 107104. DOI: 10.1016/j.jece.2021.107104.

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Concentration-driven membrane separation has been demonstrated at lab and pilot scales,[156] however, there haven't been any reported commercial scale applications of this technology in industry.[157] Membrane assisted solvent extraction was originally developed for the recovery of REEs from the permanent magnets found in e-waste and has been demonstrated at a pilot scale plant by researchers from the Oak Ridge National Laboratory (US). In 2023, the Laboratory shifted its focus to applying the technology for REE separation from ores.[158] Adsorption methods are being demonstrated at lab scales, mostly limited to batch systems.[159]

Australia has several research initiatives looking at membrane technologies for REE separation, and for other relevant applications and minerals. Examples include a study between Northern Minerals and the University of Melbourne, looking at polymer inclusion membrane materials. The University of NSW hosts the UNESCO Centre for Membrane Science and Technology. The Centre conducts fundamental and applied research in membrane technologies for various applications and facilitates collaboration between domestic and international universities and industry.[160]

Global patent activity for membrane separation and adsorption was not included in this report due to the emergence of these technologies for separating REEs and the limited number of patents being published in this area.

[156] Alemrajabi M, Ricknell J, Samak S, Rodriguez Varela R, Martinez J, Hedman F, Forsberg K and Rasmuson ÅC (2022) Separation of Rare-Earth Elements Using Supported Liquid Membrane Extraction in Pilot Scale. Industrial & Engineering Chemistry Research 61(50), 18475–18491. DOI: 10.1021/acs.iecr.2c03268.

[157] Kujawa J, Al Gharabli S, Szymczyk A, Terzyk AP, Boncel S, Knozowska K, Li G and Kujawski W (2023) On membrane-based approaches for rare earths separation and extraction – Recent developments. Coordination Chemistry Reviews 493, 215340. DOI: 10.1016/j.ccr.2023.215340.

[158] Oak Ridge National Laboratory (2023) Revolutionizing resource renewal: scaling up sustainable recycling for critical materials. <https://www.ornl.gov/news/revolutionizing-resource-renewal-scaling-sustainable-recycling-critical-materials>

[159] Anastopoulos I, Bhatnagar A and Lima EC (2016) Adsorption of rare earth metals: A review of recent literature. Journal of Molecular Liquids 221, 954–962. DOI: 10.1016/j.molliq.2016.06.076; da Costa TB, da Silva MGC and Vieira MGA (2020) Recovery of rare-earth metals from aqueous solutions by bio/adsorption using non-conventional materials: a review with recent studies and promising approaches in column applications. Journal of Rare Earths 38(4), 339–355. DOI: 10.1016/j.jre.2019.06.001.

[160] UNESCO Centre for Membrane Science and Technology (n.d.) About CMST. <https://www.membrane.unsw.edu.au/about-cmst>; University of New South Wales (n.d.) Membrane technology with a global legacy. <https://www.unsw.edu.au/engineering/our-research/impact-stories/membrane-technology-with-a-global-legacy-for-a-thirsty-world>

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

**Table 8: Global RD&D focus areas for membrane separation and adsorption separation technologies.**

| RD&D FOCUS AREAS | |
|---|---|
| **Membrane separation** | • Improving thermal and chemical stability and developing cost-effective strategies to synthesise polymer membranes.[161]<br>• Developing advanced membrane materials with improved efficiency, stability, selectivity and lower costs (e.g., ion-imprinted, metal-organic frameworks, nanocomposite and filtration).[162]<br>• Developing strategies to overcome fouling and improve efficiency at large-scale operations.[163]<br>• Developing strategies to prevent solvent loss and improve extraction efficiency of the membrane solvent extraction process.[164] |
| **Adsorption** | • Demonstrating adsorption in continuous fixed-bed systems and developing methods to regenerate adsorbents as the next steps for scaling up.[165]<br>• Developing and evaluating multicomponent adsorbent mixtures to improve adsorption capacity and selectivity.[166] |
| **Supporting research domains** | • Applying artificial intelligence to optimise the design of membrane materials and test their application in different flow sheets.[167] |

### 3.2.4 Implications for Australia

Separation of REEs is a critical step in the RE supply chain with significant market potential and importance for global supply chain security. Demand for RE oxides is projected to grow from 171,300 tonnes in 2022 to 238,700 tonnes by 2030.[168] However, global shortages of key RE oxides are forecasted in the medium term (by 2040). Specifically, NdPr oxide undersupply is forecasted to be 90,000 tonnes per year by 2040, while

[161] Kujawa J, Al Gharabli S, Szymczyk A, Terzyk AP, Boncel S, Knozowska K, Li G and Kujawski W (2023) On membrane-based approaches for rare earths separation and extraction – Recent developments. Coordination Chemistry Reviews 493, 215340. DOI: 10.1016/j.ccr.2023.215340.

[162] Kujawa J, Al Gharabli S, Szymczyk A, Terzyk AP, Boncel S, Knozowska K, Li G and Kujawski W (2023) On membrane-based approaches for rare earths separation and extraction – Recent developments. Coordination Chemistry Reviews 493, 215340. DOI: 10.1016/j.ccr.2023.215340.

[163] Kujawa J, Al Gharabli S, Szymczyk A, Terzyk AP, Boncel S, Knozowska K, Li G and Kujawski W (2023) On membrane-based approaches for rare earths separation and extraction – Recent developments. Coordination Chemistry Reviews 493, 215340. DOI: 10.1016/j.ccr.2023.215340.

[164] Islam SZ, Wagh P, Jenkins JE, Zarzana C, Foster M and Bhave R (2022) Process Scale-Up of an Energy-Efficient Membrane Solvent Extraction Process for Rare Earth Recycling from Electronic Wastes. Advanced Engineering Materials 24(12). DOI: 10.1002/adem.202200390

[165] da Costa TB, da Silva MGC and Vieira MGA (2020) Recovery of rare-earth metals from aqueous solutions by bio/adsorption using non-conventional materials: a review with recent studies and promising approaches in column applications. Journal of Rare Earths 38(4), 339–355. DOI: 10.1016/j.jre.2019.06.001.

[166] Salfate G and Sánchez J (2022) Rare Earth Elements Uptake by Synthetic Polymeric and Cellulose-Based Materials: A Review. Polymers 14(21), 4786. DOI: 10.3390/polym14214786.

[167] Maleki R, Shams SM, Chellehbari YM, Rezvantalab S, Jahromi AM, Asadnia M, Abbassi R, Aminabhavi T and Razmjou A (2022) Materials discovery of ion-selective membranes using artificial intelligence. Communications Chemistry 5(1), 132. DOI: 10.1038/s42004-022-00744-x.

[168] Khan Y (2023) The U.S. wants a rare-earths supply chain. Here's why it won't come easily. WSJ. <https://www.wsj.com/articles/the-u-s-wants-a-rare-earths-supply-chain-heres-why-it-wont-come-easily-dfc3b632>

that of Dy and Tb oxide are 1,800 and 450 tonnes per year respectively.[169] There is an opportunity for Australia to meet growing global demand representing a potentially significant economic opportunity. Key bilateral partners such US, Canada, Germany and Japan are amongst the countries with the strongest forecasted compound annual growth rate over the 2022-2030 period. [170] Overall, the value of the global RE oxide market is estimated to be US$ 11.3 billion by 2030.[171]

This section discusses the opportunities for domestic RD&D and for international engagement in RE separation (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 production of separated rare earth oxides.**

| 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 | • Membrane separation<br>• Adsorption | • Membrane separation<br>• Adsorption<br>• Ion exchange | • Ion exchange | • 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.

Solvent extraction is widely employed in industry globally, due to its maturity and proven effectiveness for separating REEs, high processing capacity and scalability. However, the process can be highly complex which is a key barrier for new domestic producers.

For the last 15 years, IP activity in solvent extraction has surpassed all other RE mid-stream processing technologies, suggesting that there is strong RD&D momentum for solvent extraction globally. Australia's existing industry know-how can support the development and expansion of commercial operations onshore. Due its maturity, solvent extraction technology is no longer highly protected by IP restrictions, and although no Australian patents were found, domestic know-how is well established at ANSTO, and several Australian companies have announced plans establish commercial operations onshore.

The role of Australian RD&D in this space will be to support the development of domestic projects, by providing services such as mineral process validation and test-work. Further, ongoing RD&D in process improvement can help position Australia as a competitive and sustainable producer of RE oxides in the long-term. Key RD&D focus areas include reducing the complexity and number of solvent extraction circuits

[169] Adamas Intelligence (2023) NEW REPORT: Rare Earth Magnet Market Outlook to 2040. <https://www.adamasintel.com/rare-earth-magnet-market-outlook-to-2040/>

[170] Research and Markets (2024) Rare earth metals - global strategic business report. <https://www.researchandmarkets.com/reports/5139969/rare-earth-metals-global-strategic-business>

[171] Research and Markets (2024) Rare earth metals – global strategic business report. <https://www.researchandmarkets.com/reports/5139969/rare-earth-metals-global-strategic-business>

and developing and applying non-polluting and cost-effective reagents such as ionic liquids and deep eutectic solvents.

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

Ion exchange (and other chromatography methods), membrane separation and adsorption are emerging applications for RE separation and have the potential to deliver step-changes in RE oxide production in the longer term. Ion exchange can increase the purity of RE oxides produced, and although the technique dates back to the 1960s, recent innovations in the process are overcoming key barriers such as process continuity. Membrane and adsorption techniques have potential efficiency, cost and sustainability advantages relative to the current solvent extraction pathway, however, are mainly applicable to impurity removal; rare earth separation with membranes faces longer development timeframes.

Global patent activity may not be a good indicator of innovation potential of these technologies. Ion exchange is highly mature and no longer subject to high levels of IP protection,[172] and current efforts are on modifying the existing process. On the other hand, membrane and adsorption technologies are still being developed in the lab and have yet to be patented. Instead, relying on current activities can shed light on the potential for innovation. Australian activity is evident from its research projects at universities, patents (e.g. Clean Teq) and industry know-how (e.g. ANSTO).

There is an opportunity for Australia to leverage its existing capabilities and research strengths to grow domestic capabilities and IP in these areas, and in some cases support pilot projects. For ion exchange there is a role for Australian RD&D to pilot and demonstrate patented Australian technologies, and for international collaboration to derisk projects through funding or offtake agreements. Further, there is an opportunity to further improve technology efficiency, sustainability and scalability. Some notable innovation areas include developing high-performing ion exchange materials, including the utilisation of ionic liquids, and optimising the design and operation of continuous systems.

With respect to membrane separation and adsorption, domestic RD&D will be needed to advance technology readiness and build local capability. Opportunities include developing stable and selective membrane and adsorbent materials, overcoming membrane fouling and technical challenges of membrane assisted solvent extraction, and implementing continuous and recyclable systems. International collaboration in emerging separation approaches can accelerate capability building through joint RD&D projects and knowledge sharing.

## 3.3 Production of rare earth metals

Rare earth oxides (REOs) obtained after separation are processed into metals prior to their use in alloy production for magnet manufacture. This can be done at scale using two methods: electrowinning in a molten medium and metallothermic reduction. Electrowinning in a molten medium is more commonly used for light rare earth elements (LREEs), whereas metallothermic reduction is more prevalent for the heavy rare earth elements (HREEs).

[172] Stakeholder consultation.

### 3.3.1 Electrochemical reduction

In electrochemical reduction an electric current is passed between two electrodes immersed in a REE solution. This reduces the REE of interest, depositing it on the cathode in metal or alloy form. The conventional and commercially mature process is molten salt electrolysis, but there are emerging approaches that do not use molten salts.

Molten salt electrolysis dissolves rare earth oxides (REOs) in fluoride or chloride salts that are melted at high temperature.[173] Molten salt electrolysis can be a continuous process, facilitating larger scale operations with higher output, and has lower temperature and energy requirements as compared to metallothermic reduction (see Section 0).[174] It is especially suited to light REEs given their lower melting points and the comparatively lower cost of the process.[175] However, molten salt electrolysis faces challenges including harmful gas emissions (e.g. chlorine, hydrogen fluoride or perfluorocarbons),[176] corrosion, constrained yield (due to low solubility of REOs in molten fluorides), and the introduction of impurities into the metal.[177]

Importantly, aspects of the process can be modified to directly produce master alloys relevant for magnet manufacture, reducing the number of process steps towards magnet manufacturing. For instance, new research looks at directly producing neodymium-iron master alloy, a direct precursor to neodymium-iron-boron (Nd-Fe-B) permanent magnets.[178]

There are other electrochemical methods besides molten salt electrolysis. These are focused on production at lower temperatures (e.g. using ionic liquids instead of molten salts) or direct metal production by removing oxygen from REOs (e.g., the FFC-Cambridge process).[179] However, they are not widely implemented in the production of RE metals.

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[173] Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals 10(10), 1376.

[174] Pérez-Cardona JR, Huang T-Y, Zhao F, Sutherland JW, Atifi A, Fox R V, Baek DL (2022) Molten salt electrolysis and room temperature ionic liquid electrochemical processes for refining rare earth metals: Environmental and economic performance comparison. Sustainable Energy Technologies and Assessments, 54:102840. doi:10.1016/j.seta.2022.102840.

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[178] Tripathy PK, Mondal K and Khanolkar AR (2021) One-step manufacturing process for neodymium-iron (magnet-grade) master alloy. Materials Science for Energy Technologies, 4:249–255, doi:10.1016/j.mset.2021.07.001.

[179] Pérez-Cardona JR, Huang T-Y, Zhao F, Sutherland JW, Atifi A, Fox R V, Baek DL (2022) Molten salt electrolysis and room temperature ionic liquid electrochemical processes for refining rare earth metals: Environmental and economic performance comparison. Sustainable Energy Technologies and Assessments, 54:102840. doi:10.1016/j.seta.2022.102840; Elliott BJ (2023) Ionic Liquid-based Electrowinning for Refining of Rare Earth Oxides/Salts. United States. <https://www.osti.gov/biblio/1970362>; Larochelle T (2024) Rare Earth Element Reduction to Metals. In Rare Earth Metals and Minerals Industries. 257–269. Springer International Publishing.

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Molten salt electrolysis is a mature process implemented at scale outside Australia for metallisation of REs, particularly from light REE. Molten fluorides are the most commonly used salt in industry. Chloride salts are mature, however less utilised due to technical challenges (corrosion and efficiency and chlorine gas emissions). [180]

Australian Strategic Materials (ASM) opened a commercial-scale facility (the Korean Metals Plant) in 2022.[181] The facility is currently focussed on the production of neodymium metal and Nd-Fe-B alloy, with a view of expanding to titanium, zirconium, hafnium and niobium in the future.[182] It is unclear from publicly available information which process underpins the company's commercial operations. ASM owns an electrolytic process, originally developed by Ziron Tech (South Korea) that can be used to produce titanium, zirconium, hafnium, and rare earth metals.[183] The process reduces metal oxides using a liquid metal cathode, to produce an intermediate alloy which can be separated to produce a highly pure metal.[184] ASM has also piloted a metallisation and refining technology developed by Ziron Tech since 2019.[185]

Molten salt electrolysis has been used at commercial scale by Chinese companies in Baotou and Ganzhou.[186] Molten salt electrolysis is also being used by Less Common Metals (United Kingdom) to commercially produce neodymium metal and neodymium-praseodymium alloy.[187] In 2023, LCM received funding from Innovate UK as part of The Critical Materials for Magnets opportunity. The company has been provided a fraction of the £6.6m investment intended to develop a supply chain of REs in the UK.[188] Finally,

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[180] Takeda O, Uda T, Okabe TH (2014) Rare Earth, Titanium Group Metals, and Reactive Metals Production. In Treatise on Process Metallurgy, 995-1069; Guo S, Zhang J, Wu W, Zhou W (2018) Corrosion in the molten fluoride and chloride salts and materials development for nuclear applications. Progress in Materials Science 97, 448–487; Cvetković VS, Feldhaus D, Vukićević NM, Barudžija TS, Friedrich B, Jovićević JN (2020) Investigation on the Electrochemical Behaviour and Deposition Mechanism of Neodymium in NdF3–LiF–Nd2O3 Melt on Mo Electrode. Metals 10(5), 576; Sahoo DK, Anitha M, Mondal S, Singh DK, Mishra R, Kain V (2017) Taguchi optimisation of process parameters for electrowinning of praseodymium metal in molten salt electrolysis. Mineral Processing and Extractive Metallurgy, 126(4), 231–237; Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals, 10(10), 1376.

[181] Australian Strategic Materials (2022) ASM's first high purity critical metals plant officially opens in South Korea. ASX Announcement. <https://asmd.irmau.com/site/pdf/c58bb814-476d-4e12-8d4f-52a51261d6d8/High-purity-critical-metals-plant-officially-opens-in-Korea.pdf>

[182] Australian Strategic Materials (n.d.) Products. Korean Metals Plant. <https://asm-au.com/korean-metals-plant/overview/>

[183] Australian Strategic Materials (2019) Alkane invest in clean, high purity processing technology. ASX Announcement. <https://asm-au.com/alkane-invests-in-clean-high-purity-processing-technology/>; Australian Strategic Materials (2020) ASM completes acquisition of Ziron Tech. ASX Announcement. <https://asm-au.com/asm-completes-acquisition-of-ziron-tech/>

[184] Yoo et al. (2018) Minimising oxygen contamination through a liquid copper-aided group IV metal production process. Scientific Reports 8(1), 17391; Lee et al. (2017) Refining Method of Metal Using Electroreduction and Electrorefining process. Patent number: KR101793471B1.

[185] Australian Strategic Materials (2019) Alkane invest in clean, high purity processing technology. ASX Announcement. <https://asm-au.com/alkane-invests-in-clean-high-purity-processing-technology/>; Australian Strategic Materials (2020) ASM'S JV produces titanium metal alloy with 45% power saving. ASX Release. <https://asm-au.com/asms-jv-produces-titanium-metal-alloy-with-45-power-saving/>; Australian Strategic Materials (2020) JV produces high quality neodymium metal alloy. ASX Release. <https://asm-au.com/jv-produces-high-quality-neodymium-metal-alloy/>; Australian Strategic Materials (2020) High-quality neodymium metal produced. ASX Release. <https://asm-au.com/high-quality-neodymium-metal-produced/>; Australian Strategic Materials (2020) Neodymium Praseodymium production and permanent magnet samples. ASX Announcement. <https://asm-au.com/neodymium-praeseodymium-production-and-permanent-magnet-samples/>.

[186] Okabe TH (2017) Bottlenecks in rare metal supply and the importance of recycling – a Japanese perspective. Mineral Processing and Extractive Metallurgy, 126(1–2):22–32, doi:10.1080/03719553.2016.1268855; Okabe T (2019) Current status of rare earth production in China and recycling in Japan. REE4EU Exploitation Workshop - Presentation in the exploitation workshop with external industry and EU-policy participation, REE4EU, Brussels. < https://www.ree4eu.eu/wp-content/uploads/2019/05/UOT_PPT-pt-3.pdf>; Baotou Research Institute of Rare Earths (n.d.) Molten salt electrolysis of rare earth. Metallic Material Researches. <https://en.brire.com/picture/show-10.html> (accessed 23 November 2023).

[187] Less Common Metals (2021) How we control our neodymium metal making process. Company news. <https://lesscommonmetals.com/how-we-control-our-neodymium-metal-making-process/>; Nyanin KA (2019) REE Opportunities from the European Industry Perspective. Less Common Metals. <https://www.ree4eu.eu/wp-content/uploads/2019/05/LCM_PPT.pdf>; Less Common Metals (2022) Less Common Metals Celebrates 30 Years in Business. <https://lesscommonmetals.com/less-common-metals-celebrates-30-years-in-business/>

[188] UK Research and Innovation (2023) Projects secure £6.6m to strengthen UK supply of critical materials. <https://www.ukri.org/news/projects-secure-6-6m-to-strengthen-uk-supply-of-critical-materials/>

Santoku Corporation (Japan) recycles RE magnet materials and produces REOs that are reduced into metal using molten salt electrolysis, as part of their process to produce magnet alloys.[189]

Analysis of patent filing activity across the rare earths supply chain from 2007 to 2022 found 28.9% of patents were related to molten salt electrolysis. This proportion makes it the second largest category, after RE separation via solvent extraction. This area saw a continued growth in activity after 2010, eventually reaching relative stability after 2017. This reflects its prevalence across commercial processes and the increased demand for rare earth metals for various applications including EVs. China represented 80.4% of all filings, followed by Japan with 8.2% and the USA with 3.9%. Australian patents accounted for less than 1% of global activity. Australian organisations with relevant patents include Lynas Rare Earths Ltd., CSIRO, and Deakin University.

[189] Santoku Corporation (2016) About the company: Santoku Corporation. Hyogo 'Only-one' Companies. <https://web.pref.hyogo.lg.jp/sr07/onlyone/documents/santokucorporation.pdf>; Koen Binnemans (2016) Rare Earth Recycling and the Balance Problem. <http://summerschool.etn-demeter.eu/wp-content/uploads/2016/12/03_BinnemansBalanceProblemRecycling2016.pdf>

The following table summarizes the RD&D focus areas for electrowinning REOs into RE metals:

**Table 9: Global RD&D focus areas for rare earth metal production using electrochemical reduction.**

| RD&D FOCUS AREAS | |
|---|---|
| **Electrochemical reduction** | • Reducing greenhouse gas emissions ($CO_2$, perfluorocarbons), limiting energy input, and increasing yield by optimising molten salt processes and advancing alternative mediums (e.g. ionic liquids).[190]<br>• Trialling alternative anode materials with greater stability and reusability (e.g., inert alternatives to consumable graphite anodes).[191]<br>• Developing and piloting closed systems equipped with monitoring and automation mechanisms that support continuous production, contain gas emissions (e.g., hydrogen fluoride, chlorine), and increase process efficiency.[192]<br>• Implementing strategies to bypass the limited solubility of REOs in fluoride melts and minimising the formation of oxyfluorides, both of which limit process throughput.[193]<br>• Limiting the introduction of atmosphere and equipment-derived impurities into the final product.[194]<br>• Exploring and scaling process variants that enable the direct production of alloys usable in magnet manufacture. |
| **Supporting research domains** | • Automating process steps to reduce labour cost drivers and improve safety.[195] |

[190] Schreiber A, Marx J, Zapp P, Kuckshinrichs W (2020) Comparative Life Cycle Assessment of Neodymium Oxide Electrolysis in Molten Salt. Advanced Engineering Materials 22(6); Zhu H (2014) Rare Earth Metal Production by Molten Salt Electrolysis. In Encyclopedia of Applied Electrochemistry (Eds. G Kreysa, K Ota, RF Savinell) 1765–1772. Springer, New York.

[191] Chen GZ (2020) Interactions of molten salts with cathode products in the FFC Cambridge Process. International Journal of Minerals, Metallurgy and Materials 27(12), 1572–1587; Schreiber A, Marx J, Zapp P and Kuckshinrichs W (2020) Comparative Life Cycle Assessment of Neodymium Oxide Electrolysis in Molten Salt. Advanced Engineering Materials 22(6).

[192] EuRare Project (2022) Metal production by salt electrolysis. EURARE sustainable European REE exploitation technologies. <https://www.eurare.org/technologies/REE-metal-production.html>

[193] Abbasalizadeh A, Malfliet A, Seetharaman S, Sietsma J, Yang Y (2017) Electrochemical Extraction of Rare Earth Metals in Molten Fluorides: Conversion of Rare Earth Oxides into Rare Earth Fluorides Using Fluoride Additives. Journal of Sustainable Metallurgy 3(3), 627–637; Ciumag M, Gibilaro M, Massot L, Laucournet R, Chamelot P (2016) Neodymium electrowinning into copper-neodymium alloys by mixed oxide reduction in molten fluoride media. Journal of Fluorine Chemistry 184, 1–7.

[194] Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals 10(10), 1376.

[195] Stakeholder consultations.

### 3.3.2 Metallothermic reduction

Metallothermic reduction can be used to produce rare earth metals, and to directly produce rare earth alloys used in permanent magnets, like samarium-cobalt, samarium-iron, or neodymium-iron-boron.[196] Metallothermic reduction can technically be used for all REEs, however it is more commonly used for the metallisation of yttrium and HREEs.[197]

In metallothermic reduction, a RE compound is reduced into RE metal by reacting with an active metal at a high temperature.[198] Alkaline and alkaline earth metals like lithium, sodium, potassium, and calcium can be used as the reductant metal in the process. The use of calcium and lithium metal is particularly prominent.[199] Directly producing an alloy requires combining a RE compound with the reductant (e.g., calcium) and an alloying metal or compound.

The ability to go beyond the production of individual RE metals and to directly produce alloys is a significant advantage for producers seeking to vertically integrate. However, challenges include the high cost of equipment (e.g. tantalum crucibles), availability of sufficient high-purity reductants, vulnerability to impurities leading to further purification steps, and batch operation which can hinder scalability.[200]

Other reduction techniques, such as gas-based reduction, are being developed as an alternative to metallothermic or electrothermic reduction.

**TECHNOLOGY STATE OF PLAY**

Metallothermic reduction is a highly mature technology used at commercial scale, however its use remains highly concentrated in China to produce HREE. For instance, Fujian Changting Golden Dragon Rare-Earth Co (GDRE) uses calciothermic and lanthanothermic reduction for the metallisation of certain REEs, as part of an integrated supply chain that covers mining through to alloy production.[201] The company's operations, formerly controlled by Xiamen Tungsten Co, are now part of a joint venture with the Chinese Rare Earth Group, the largest producer of REEs in the world.[202]

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[196] Balachandran G (2014) Extraction of Rare Earths for Advanced Applications. In Treatise on Process Metallurgy, Elsevier, doi:10.1016/B978-0-08-096988-6.09983-1; Chen C-Q, Kim D, Choi C (2014) Influence of Ca amount on the synthesis of Nd2Fe14B particles in reduction–diffusion process. Journal of Magnetism and Magnetic Materials 355, 180–183; Galkin V, Kuchi R, Kim S, Jeong J-R, Kim T, Baek Y, Kim D (2023) Nd-Fe-B particles with reduced oxygen content and enhanced magnetic properties prepared through reduction-diffusion and novel washing process. Journal of Magnetism and Magnetic Materials 578, 170832.

[197] Liu H, Zhang Y, Luan Y, Yu H and Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals, Metals, 10(10):1376, doi:10.3390/met10101376; Takeda O, Uda T and Okabe TH (2014) Rare Earth, Titanium Group Metals, and Reactive Metals Production. In Treatise on Process Metallurgy, Elsevier, doi:10.1016/B978-0-08-096988-6.00019-5.

[198] Krishnamurthy N and Gupta CK (2015) Extractive Metallurgy of Rare Earths. CRC Press. P.333 – 339, doi:10.1201/b19055.

[199] Habashi F (2013) Extractive metallurgy of rare earths. Canadian Metallurgical Quarterly, 52(3):224–233, doi:10.1179/1879139513Y.0000000081.

[200] Balachandran G (2014) Extraction of Rare Earths for Advanced Applications. In Treatise on Process Metallurgy 3, 1291 – 1340. Elsevier; Liu H, Zhang Y, Luan Y, Yu H and Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals 10(10), 1376; Krishnamurthy N, Gupta CK (2015) Extractive Metallurgy of Rare Earths. CRC Press. 333 – 368; Takeda O, Uda T, Okabe TH (2014) Rare Earth, Titanium Group Metals, and Reactive Metals Production. In Treatise on Process Metallurgy, 995-1069. Elsevier.

[201] Golden Dragon Rare-Earth (2018) About Us. <https://en.gdre.com.cn/intro/1.html>; Golden Dragon Rare-Earth (n.d.) About Us. <http://www.rare-earth-metal.com/aboutus.html>

[202] David Merriman (2023) Xiamen Tungsten and China Rare Earth Group continue consolidation of Chinese rare earth industry. Project Blue. <https://projectblue.com/blue/news-analysis/614/xiamen-tungsten-and-china-rare-earth-group-continue-consolidation-of-chinese-rare-earth-industry>

For alternative, gas-based reduction processes, the "Carboxylate Reduction Process" (CRP) being patented and demonstrated at small scale by Hela Novel Metals (United States) uses a gas mix to reduce RE compounds into metal powders and magnet-relevant alloys.[203]

In our patent filing analysis of the 2007 – 2022 interval, 6.9% of patents globally were related to metallothermic reduction. This area has seen an overall rising trend in yearly filings since 2010 but remains modest as compared to the largest categories. This reflects the currently small number of global innovators in this space. China accounts for the largest proportion of patents (63.9%). Japan was second, followed by the USA in third position (6%). Australian activity was 1.5% of the total for the area. Local organisations with related metallothermic reduction patents include Coogee Titanium and CSIRO.

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

**Table 10: Global RD&D focus areas for rare earth metal production using metallothermic reduction.**

| **RD&D FOCUS AREAS** | |
|---|---|
| **Metallothermic reduction** | • Trialling and implementing methods for REE extraction from the slag residue generated by metallothermic reduction processes, to maximise resource utilisation.[204]<br>• Optimising direct alloy production methods (e.g., reduction-diffusion) to facilitate downstream magnet manufacturing.[205]<br>• Developing and trialling setups that allow metallothermic reduction to operate in a semicontinuous or continuous mode, to surpass the limited production associated with batch processing.[206]<br>• Assessing the viability at scale of using alternative reductants at scale (e.g., less expensive, or more readily available).[207]<br>• Optimising the amount of reductant used and the preparation of the RE compound feedstock (fluorides or chlorides) to minimise the introduction of impurities.[208] |

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[203] Larochelle T (2024) Rare Earth Element Reduction to Metals. In Rare Earth Metals and Minerals Industries. (Eds. YV Murty, MA Alvin, JP Lifton) 257–269. Springer International Publishing; Hela Novel Metals LLC (2024) Discover HELA's Story. Company. <https://hlnovelmetals.com/discover-helas-story/>

[204] Huang M, Liu K, Zhang H, Zhang X, Li J, Xie Y, Lai Y, Huang Z and Qi T (2023) A Novel Process for the Recovery of Rare Earth and Fluoride Compounds from Calciothermic Reduction Slag JOM 75(9), 3577–3586.

[205] Takeda O, Uda T, Okabe TH (2014) Rare Earth, Titanium Group Metals, and Reactive Metals Production. In Treatise on Process Metallurgy. (Ed. S Seetharaman) 995-1069. Elsevier.

[206] Lucas J, Lucas P, Le Mercier T, Rollat A, Davenport W (2015) Metallothermic Rare Earth Metal Reduction. In Rare Earths, 109-122. Elsevier; Takeda O, Uda T, Okabe TH (2014) Rare Earth, Titanium Group Metals, and Reactive Metals Production. In Treatise on Process Metallurgy. (Ed. S Seetharaman) 995-1069. Elsevier.

[207] Balachandran G (2014) Extraction of Rare Earths for Advanced Applications. In Treatise on Process Metallurgy 3, 1291 – 1340. Elsevier.

[208] Liu H, Zhang Y, Luan Y, Yu H and Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals, 10(10):1376; Krishnamurthy N, Gupta CK (2015) Extractive Metallurgy of Rare Earths. CRC Press. 333 – 368.

### 3.3.3 Purification

The processes of RE extraction, separation and metallisation may introduce trace impurities into the final product, which can impact the performance of permanent magnets.[209] Standard RE processing often results in a purity greater than 95.50%,[210] but further purification is critical to reach commercial purity levels higher than 99.90% for EV motors and wind turbines.[211] The most effective method of purification depends on which RE metal is being purified and which impurities are present. Purification methods covered in this report include melting processes, vapour techniques and ultrapurification.

Melting processes subject RE metals to high temperatures in a vacuum or inert atmosphere to vaporise and remove impurities.[212] Melting processes are used for RE elements with a low vapour pressure, such as neodymium, praseodymium and terbium.[213] Examples of melting processes include vacuum induction melting, electron beam melting and vacuum arc remelting. Melting processes vary in terms of heating method, crucible material and specialised components. These differences carry trade-offs across energy efficiency, equipment cost, durability, and potential for contamination of the final product.[214] These processes are not mutually exclusive and can be used in tandem, with multiple cycles of each potentially being required to achieve higher purity levels.

Vapour techniques separate the REE and impurities by converting the RE metal into a vapour and then distilling the vapour pack into a liquid or solid metal. As a result, they are particularly used for the more volatile REEs (including dysprosium). Examples of vapour techniques include vacuum distillation and vacuum sublimation.[215] Vapour techniques have large-scale production capacity, high yield, and can be used to remove both metallic and interstitial impurities (e.g., carbon, nitrogen, oxygen). They can also be directly integrated with metallothermic reduction, serving as a subsequent purification step.[216] However, these methods can result in metal losses if adequate measures are not in place to collect the vapour. Moreover, vapour techniques are not as effective at removing fluoride impurities from scandium, dysprosium, holmium, and erbium.[217]

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[209] Judge WD, Azimi G (2020) Recent progress in impurity removal during rare earth element processing: A review. Hydrometallurgy 196, 105435.

[210] Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals 10(10).

[211] Tripathy PK, Mondal K, Khanolkar AR (2021) One-step manufacturing process for neodymium-iron (magnet-grade) master alloy. Materials Science for Energy Technologies 4, 249–255; Wu B, Ding X, Zhang Q, Yang L, Zheng B, Hu F, Song Z (2018) The dual trend of diffusion of heavy rare earth elements during the grain boundary diffusion process for sintered Nd-Fe-B magnets. Scripta Materialia 148, 29–32.

[212] Zhan YZ, Du Y, Zhuang YH (2007) Chapter Four - Determination Of Phase Diagrams Using Equilibrated Alloys. Methods for Phase Diagram Determination, 108–150; Zhang Z, Jia Q, Liao W (2015) Chapter 277 - Progress in the Separation Processes for Rare Earth Resources. Handbook on the Physics and Chemistry of Rare Earths 48, 287-376.

[213] Zhang Z, Jia Q, Liao W (2015) Chapter 277 - Progress in the Separation Processes for Rare Earth Resources. Handbook on the Physics and Chemistry of Rare Earths 48, 287-376.

[214] Zanner FJ (2004) Vacuum Melting. Encyclopedia of Materials: Science and Technology, 1–6; Xi'an Hani Tech Co., Ltd (2023) Electric Induction Furnace VS Electric Arc Furnace. <https://www.hanmetallurgy.com/electric-induction-furnace-vs-electric-arc-furnace/>; Zhan YZ, Du Y, Zhuang YH (2007) Chapter Four - Determination Of Phase Diagrams Using Equilibrated Alloys. Methods for Phase Diagram Determination, 108–150; Otubo J, Rigo OD, Neto CM, Mei PR (2006) The effects of vacuum induction melting and electron beam melting techniques on the purity of NiTi shape memory alloys. Materials Science and Engineering A 438–440, 679–682; Bellot JP, Jourdan J, Kroll-Rabotin JS, Quatravaux T, Jardy A, Jean I (2021) Thermal Behavior of Ti-64 Primary Material in Electron Beam Melting Process materials. Materials 14(11), 2853; Karimi-Sibaki E, Kharicha A, Wu M, Ludwig A, Bohacek J (2020) A Parametric Study of the Vacuum Arc Remelting (VAR) Process: Effects of Arc Radius, Side-Arcing, and Gas Cooling. Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science 51(1), 222–235.

[215] Krishnamurthy N and Gupta CK (2015) Extractive Metallurgy of Rare Earths. CRC Press. 448 – 478.

[216] Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals, 10(10); Shanghai Gehang Vacuum Technology Co (2021) Vacuum Distillation Technology. In The Purification Of Rare Earth Metals. <https://www.vacfurnace.com/vacuum-furnace-news/vacuum-distillation-technology-in-the-purification-of-rare-earth-metals/>

[217] Krishnamurthy N, Gupta CK (2015) Extractive Metallurgy of Rare Earths. CRC Press. 448 – 478.

Ultrapurification techniques redistribute impurities (e.g. move them to the sides of the ingot) rather than removing them, hence they are often the final step when producing high purity RE metals. [218] These methods must take place under ultra-high vacuum or inert atmospheres, to eliminate potential contaminants from the atmosphere. Examples of ultrapurification techniques include zone refining and solid state electrotransport (SSE). Zone refining and SSE are limited to REEs with low and medium vapour pressures (such as neodymium, praseodymium and terbium).[219]Due to their effectiveness at removing different impurities, they can be used together due to their complementarity.[220] Despite the high purity that they enable, ultrapurification techniques have low throughput, require long processing times, and rely on specialised set-ups.

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Melting, vacuum, and ultrapurification processes are all currently being used on a commercial scale for RE metal purification outside Australia.

- For instance, the China-based Fujian Changting Golden Dragon Rare-Earth Co (GDRE) uses vacuum melting, vacuum distillation, zone refining, and solid state electrotransport to purify RE metals as part of their commercial offerings.[221]
- The UK-based company Less Common Metals (LCM) utilises vacuum induction melting for RE ingots, including Nd-Fe-B alloys, using two 600kg strip cast furnaces.[222]LCM can individually produce neodymium, praseodymium, dysprosium and terbium ingots to a purity of greater than 99%.[223]
- Similarly, Shin-Etsu Chemical (Japan) also uses vacuum induction melting to produce Nd-Fe-B magnets, as part of an RE 'mine to metal alloy' pipeline.[224] RE magnet production occurs at Takefu Plant in Fukui, Japan and the Shin-Etsu Magnetic Materials Vietnam Co., Ltd plant in Hai Phong Province, Vietnam.[225] RE magnet-related research is undertaken at the Magnetic Materials Research Center in Fukui, Japan.[226]

[218] Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals, 10(10).

[219] Zhang Z, Jia Q and Liao W (2015) Chapter 277 - Progress in the Separation Processes for Rare Earth Resources. In Handbook on the Physics and Chemistry of Rare Earths, Volume 48. (Eds. J-C Bünzli, VK Pecharsky) 287 – 376; Fort D (2002) Purification of the Rare Earth Metals. In Purification Process and Characterization of Ultra High Purity Metals. (Eds. Y Waseda, M Isshiki) 145 - 177. Springer Series in Materials Processing. Springer, Berlin; Krishnamurthy N, Gupta CK (2015) Extractive Metallurgy of Rare Earths. CRC Press. 490 – 503.

[220] Fort D (2002) Purification of the Rare Earth Metals. Purification Process and Characterization of Ultra High Purity Metals: Application of Basic Science to Metallurgical Processing, 145–177.

[221] Fujian Changting Golden Dragon Rare-Earth Co., Ltd (GDRE) Who We Are? <http://www.rare-earth-metal.com/aboutus.html>

[222] Less Common Metals Ltd (2023) Cast Products. <https://lesscommonmetals.com/cast-products/>

[223] Less Common Metals Ltd (2023) Raw Materials. <https://lesscommonmetals.com/raw-materials/>

[224] Shin-Etsu Chemical Co., Ltd (2007) Shin-Etsu Rare Earth Magnets: Sintering Process. <https://www.shinetsu-rare-earth-magnet.jp/e/masspro/index.html>

[225] Shin-Etsu Chemical Co., Ltd Plants. <https://www.shinetsu.co.jp/en/company/plant/>; Shin-Etsu Chemical Co., Ltd (2014) Shin-Etsu Chemical to construct a rare earth magnet manufacturing plant in Hai Phong Province in Vietnam. <https://www.shinetsu.co.jp/en/news/news-release/shin-etsu-chemical-to-construct-a-rare-earth-magnet-manufacturing-plant-in-hai-phong-province-in-vietnam/>.

[226] Shin-Etsu Chemical Co., Ltd Research Centers. <https://www.shinetsu.co.jp/en/company/labo/> .

- The Ziron Tech (South Korea) metallisation process acquired by Australian Strategic Materials (Australia), as originally reported, purifies the final metal product through vacuum arc remelting.[227] See Section 3.3.1 for more information on ASM and Ziron Tech.

Patents related to the purification of RE metals represented 4.9% of global filings in our analysis of activity over the 2007 – 2022 period. This area saw a peak of activity in 2011, followed by quick decline. However, there has been a trend of relative growth in yearly filings post-2017. 52.6% of patents related to RE metal purification were filed by China, 30.5% by Japan, and 8.4% by the USA. Australia accounted for close to 1% of global activity. Australian organisations with related patents include Coogee Titanium.

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

**Table 11: Global RD&D focus areas for rare earth metal purification.**

| RD&D FOCUS AREAS | |
|---|---|
| **Rare earth metal purification** | • Developing strategies that prevent or mitigate equipment-derived contamination of RE metals during metallisation and purification, particularly in large-scale melting processes.[228]<br>• Assessing purification pathways that are compatible with large-scale production and which combine distinct purification technologies, to remove a wider range of impurities than would be possible individually.[229]<br>• Optimising the operational parameters of purification processes to enhance impurity removal while minimising the length of the process or the number of cycles required to achieve adequate purity.[230] |

### 3.3.4 Implications for Australia

The production of rare earth metals is key step to integrating Australia's RE separation activities with downstream magnet manufacture, and therefore represents a significant opportunity to diversify global supply chains and capture market share.

Metallisation of light and heavy rare earths at commercial scales remain globally limited outside of increasingly consolidated Chinese companies. With the global trend towards secure and resilient supply chains, this creates an opportunity for alternative sources that can provide highly pure RE metals to current and emerging magnet producers across Japan, South Korea, Europe and the US.

Light and heavy RE elements are used in the high-performance magnets used in EVs and wind turbines, highlighting the importance of a dual capability. The value of neodymium, praseodymium, dysprosium, and terbium oxides used to produce neodymium-iron-boron magnets was estimated at US$3.8 billion in

[227] Yoo BU, Lee YJ, Ri V, Lee SH, Nersisyan H, Kim HY, Lee JH, Earner N, MacDonald A (2018) Minimising oxygen contamination through a liquid copper-aided group IV metal production process. Scientific Reports 8(1), 17391.

[228] Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals, 10(10); McNulty T, Hazen N and Park S (2022) Processing the ores of rare-earth elements. MRS Bulletin 47(3), 258–266.

[229] Liu H, Zhang Y, Luan Y, Yu H, Li D (2020) Research Progress in Preparation and Purification of Rare Earth Metals. Metals, 10(10).

[230] Yu C, Pan B, Wang Z, Chen D, Zhang X, Yang W, Zhang D, Lu W (2022) Research of High-Purity Lanthanum Prepared by Zone Refining. Materials 15(13), 4603.

2022.[231] A deliberate expansion downstream will require RD&D and established capabilities in both electrochemical and metallothermic reduction methods, to allow production of both light and heavy rare earth metals.

This section discusses the opportunities for domestic RD&D and for international engagement in the production of RE metals (summarised in Figure 10). 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 10: Actions for Australian RD&D and international engagement in the production of rare earth metals.**

| 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** | | • **Metallothermic reduction (HREE)** *(develop outside of China)* | • **Molten salt electrolysis (LREE)** | • **Molten salt electrolysis (LREE)**<br>• **Purification** |
| **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; HREE, heavy rare earth elements; LREE, light rare earth elements.

Electrochemical reduction, namely molten salt electrolysis and its related variants, remains the prevalent commercial process to produce light rare earth metals, including magnet-relevant neodymium and praseodymium. Electrochemical reduction methods are mature globally for various metals, but their application to rare earth metallisation remains concentrated in China. As a result, practical know-how and experience with the techniques at commercial scale is likely limited internationally. Therefore, any attempt to expand activities in the magnet supply chain beyond REO separation is likely to require both an expansion of industrial know-how in this technology and RD&D to address its prevailing challenges.

The international experience gap, the large proportion of patent filings over the last 15 years, and the drawbacks faced by current industry practices in China indicate electrochemical reduction of REs has room for innovation despite its maturity. There is an opportunity for Australia to pilot and demonstrate its technology onshore to produce RE metals. Current Australian capabilities in this area include a number of patents as well as commercial activity offshore (e.g., ASM's Korean Metals Plant).

However, RD&D will be required to ensure sustainable and safe domestic operations. This includes improving energy efficiency, developing continuous and automated processes, reducing greenhouse gas emissions ($CO_2$ and PFCs), and avoiding or managing the generation of hazardous byproducts (e.g., chlorine and hydrogen fluoride gas). RD&D opportunities include alternative and inert anodes as well as novel liquid systems for the electrolysis.

An alternative pathway would be to engage with RE metal producers (e.g. producers in Korea and Japan) to deploy overseas technologies onshore and establish commercial electrochemical reduction locally. In this

[231] Adamas Intelligence (2023) The Skyrocketing Value of Rare Earths Powering the Energy Transition. <https://www.adamasintel.com/value-of-rare-earths-used-in-energy-transition/>

case domestic RD&D can play a supporting role. For example, through economic and technical assessment of the technology in the Australian context, by supporting testing and piloting projects, and via process optimisation.

Metallothermic reduction and its variants can be applied to all REEs but are particularly relevant for heavy rare earths (e.g. dysprosium and terbium) and REs that are not easily metallised using molten salt processes. Metallothermic reduction is mature globally as a technique but is heavily concentrated in China and will require an expansion of industry know-how and RD&D to overcome technical barriers to commercial deployment. These represent strong drivers for innovation despite modest patent trends to date.

Areas requiring RD&D include the exploration of alternative reductants and strategies for continuous processing, to overcome low throughput and reductant supply limitations. There is an opportunity for Australia to modify existing technologies for RE applications and grow its capabilities and IP in this area. This could position Australia as an alternative technology partner and supplier of RE metals and reduce global reliance on Chinese companies. Australia holds a small number of patents in titanium and scandium with aspects that could be leveraged to produce RE metals, and has cross-cutting capabilities in metallothermic reduction, which can be translated for rare earth applications. Meanwhile, novel RE metal reduction pathways (e.g., gas-based processes) should strive for greater throughput, efficiency, and sustainability with regards to conventional metallothermic reduction, as well as compatibility with both magnet recycling and direct alloy production.

Purification is an important final step in RE metal production, as highly pure RE metals and alloys are required to produce magnets suitable for EV motors and wind turbines. While RE separation delivers highly pure REOs, the RE metal production process reintroduces impurities requiring additional purification.

Australia will require a comprehensive suite of purification techniques in order to produce highly pure light rare earth and heavy rare earth products. Different techniques are suited to different rare earth metals. Furthermore, a combination of multiple techniques is typically used to remove all types of impurities present in a RE metal.

Purification methods are commercially mature having been implemented at commercial scale for REs outside Australia. Despite low patent activity relative to other areas, purification has seen patent growth since 2017, potentially reflecting a growing interest in high purity materials that incorporate REs.

There is an opportunity for Australia to utilise existing technology and apply it to rare earth purification. Equipment for melting and vapour-based techniques are available off the shelf from overseas equipment manufacturers, but no domestic operations currently perform RE metal purification at pilot or commercial scale. Australia also has small number of patents in purification reflecting domestic capability to support onshore development.

RD&D will play a role in supporting the establishment of commercial operations. For example, RD&D projects will be required to optimise the purification processes to meet specified metal or alloy product characteristics. This includes mitigating the reintroduction of impurities derived from the equipment, minimising the number of cycles needed to remove impurities to an adequate level, and developing cost-effective pathways that integrate different purification methods in a series.

The deployment of a commercial operation in Australia will require strong engagement with overseas equipment providers to build domestic facilities, and engagement with off-takers (e.g. EV motor manufacturers) to de-risk projects and to meet upstream magnet producer requirements.

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