A Roadmap for Decarbonising Australian Alumina Refining

In collaboration with the Australian Renewable Energy Agency, and in consultation with participants Alcoa, Rio Tinto and South32

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Glossary

Acronym	Full name
ARENA	Australian Renewable Energy Agency
CCUS	Carbon Capture, Utilisation and Storage
CRI	Commercial Readiness Index
CST	Concentrated Solar Thermal
DDS	Deloitte Decarbonisation Solutions
DEMM	Deloitte Electricity Market Model
GJ	Gigajoule
GL	Gigalitre
GWh	Gigawatt hours
IAI	International Aluminium Institute
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
KC	Kalina Cycle
kPa	Kilopascal
kW	Kilowatt
$MtCO_2$-e	Megatonnes of CO_2 equivalent
MVR	Mechanical Vapour Recompression
MW	Megawatt
NEM	National Electricity Market
ORC	Organic Rankine Cycle
PCAF	Partnership for Carbon Accounting Financials
PJ	Petajoule
SWIS	South West Interconnected System
tCO_2-e	Tonnes of CO_2 equivalent
TRL	Technology Readiness Level
UAE	United Arab Emirates
WEM	Wholesale Electricity Market

Limitations of our work

General use restriction
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Market dynamics
At the time of writing, the Australian energy market experienced significant disruptions resulting in increased price volatility and policy changes. This disruption may likely influence implementation timing of the Roadmap. For example, in June 2022, the WA Government's announcement to close state-owned coal generators by 2029 represents changing dynamics that have the potential to impact alumina refining operations in WA.[1] Additionally, Australia's updated Paris Agreement commitment to reduce emissions by 43 per cent by 2030 may lead to greater and more urgent climate action by industry.[2] New market mechanisms relating to capacity or load reduction should be closely monitored as they could impact the economics for the technologies and options discussed in this Roadmap report.

The Safeguard Mechanism requires Australia's largest greenhouse gas emitters to keep their net emissions below an emissions limit ('a baseline'). The Safeguard Mechanism builds on the National Greenhouse and Energy Reporting (NGER) scheme's reporting and record keeping requirements. The Clean Energy Regulator (CER) is responsible for administering the NGER scheme and the Safeguard Mechanism.

The Safeguard Mechanism applies to facilities emitting more than 100,000 tonnes of carbon dioxide equivalent per year, covering facilities in the electricity, mining, oil and gas, manufacturing, transport and waste management industries. Each facility is assigned a baseline and the operator of the facility must ensure the facility's net emissions do not exceed their baseline.

At the time of publishing the report, the Australian Government is consulting with industry and the community on options to reform the Safeguard Mechanism. Reforms to the Safeguard Mechanism may impact onsite and ecosystem decarbonisation initiatives described in the Roadmap.

More detailed modelling and analysis is required to assess the relationship between energy markets and decarbonising the alumina refining industry.

Industry supported roadmap
This report presents a collective view of the participating organisations. Participants have generally agreed with the model inputs and the direction of the report. The collective view presented by this report however does not indicate individual agreement with every finding or recommendation by the participating organisations.

The participating organisations agree on the importance of limiting global warming to 1.5°C, and the importance of reaching zero emissions alumina by 2050. The organisations recognise that actions to support this broad vision should be pursued with urgency.

The alignment on climate action between the major Australian alumina refiners should indicate to Australian decision makers that it is possible to meet rising alumina demand while reducing industry emissions to net zero by 2050. It should also provide confidence that the actions required in this decade to decarbonise are identified, should be pursued without delay and undertaken collaboratively.

Unless otherwise stated, the report is based on publicly available information. Participating organisations have not provided commercially sensitive information for technologies under development. While the report assumptions have been tested with Participants, there are risks and uncertainties in relation to cost, technology performance, and rate of technology implementation. Actual results may differ from those indicated by these predicted assumptions.

Focus of report

The contents of this report focus on Australian alumina refining specifically. On a global scale, Australian alumina refining has already low emissions intensity. The technologies and initiatives discussed in this report are designed specifically for an Australian context, to eliminate emissions from an industry that is already advanced within a global context.

Acknowledgement

ARENA and Deloitte acknowledge and pay respect to the past, present and future Traditional Custodians and Elders of this nation and acknowledge their continuing connection to land, waters and community.

Deloitte would like to acknowledge the positive engagement with ARENA and the Participants, namely Alcoa of Australia Limited (Alcoa), Rio Tinto Aluminium Limited (Rio Tinto) and South32 Limited (South32).

Deloitte has developed the Roadmap for ARENA and in consultation with Alcoa, Rio Tinto and South32 (together, the Participants). The Roadmap represents a shared understanding between participating organisations of potential pathways to decarbonise Australia's alumina refining industry. Participants have provided input during the development of the Roadmap through a series of workshops and interviews. It should not be interpreted that the Participants endorse each and every finding, nor does this report represent a commitment to deliver these outcomes.

The Participants recognise the need for meaningful action and collaborate with public and private sector stakeholders to accelerate the transition of the sector. Unless otherwise stated, the Roadmap is informed by publicly available information and assumptions have been validated through consultation with the Participants. The Key Decarbonisation Technologies explored in the Roadmap are at varying degrees of technology and commercial maturity and there are material risks and uncertainties regarding the development and implementation of technologies, which may impact the findings of the Roadmap.

ARENA and Deloitte thank the Participants for their enthusiasm and willingness to collaborate on the development of the Roadmap.

This report titled 'A Roadmap for Decarbonising Australian Alumina Refining' received funding from the Australian Renewable Energy Agency (ARENA).

Executive summary

The alumina industry plays an integral role in the Australian economy but it is also one of Australia's 'hard-to-abate' industries

As an industry, alumina refining plays an integral role in the Australian economy with a $7.5 billion contribution to Australia's exports expected in 2022.[3] Australia is the world's largest exporter of alumina, and is also a significant producer of the raw material bauxite.[4] However, the refining segment of the aluminium value chain contributes a significant portion of Australia's carbon emissions due to the high energy intensity of the alumina refining process. In 2020, alumina refining in Australia consumed 221 PJ of energy and emitted 14.9 million tonnes of CO_2 equivalent.[5]

Alumina refining is a 'hard-to-abate' industry of the Australian economy. This is because there are limited mature abatement pathways to facilitate deep decarbonisation. The nature and scale of alumina production in Australia creates several barriers to decarbonisation, such as:

- The reliance on natural gas or coal as the primary source of energy for process heating requirements in refineries
- The capital-intensive nature and complexity to undertake trials and demonstrations of emerging low emissions technologies
- The size of renewable energy capacity required to power low emission technologies

Significant investment is required to develop and implement innovative transformational technologies that enable refineries to be powered by renewable energy, thereby reducing the emissions intensity of alumina production. Changing consumer preferences, market mechanisms and regulatory frameworks, which favour low-carbon products, all pose key risks to Australia's competitiveness as a global leader in alumina refining.

Whilst there is a high cost to decarbonise, inaction on climate change will come at a greater cost to the broader Australian economy. Deloitte Access Economics estimates inaction on climate change could result in $3.4 trillion in economic losses over the next 50 years across the whole of the domestic economy.[6]

Australia holds a competitive advantage in low-carbon alumina production

All Australian alumina refiners[i] recognise the need to reduce their emissions, and are making substantial headway to address Australia's climate challenge. Australia is fortunate to hold an abundance of renewable energy resources such as wind and solar, which are already decarbonising the electricity network. Enabling refineries to utilise renewable energy to power refinery operations will reduce the emissions intensity of Australian alumina production. This creates an opportunity for Australia to be a global leader in low-carbon alumina production. New technologies need to be developed and commercialised to enable greater renewable energy utilisation.

Decarbonising alumina operations can also unlock wider Australian energy ecosystem opportunities, for example as an off-taker to support the development of renewable energy zones.

The purpose and process of the decarbonisation Roadmap and report

The Australian Renewable Energy Agency (ARENA) engaged Deloitte to assist with developing 'A Roadmap for Decarbonising Australian Alumina Refining' (the 'Roadmap') and prepare a report that sets out abatement pathways to net zero alumina refining in Australia. ARENA and Deloitte organised a series of workshops with all Australian alumina refiners to inform the roadmap development. The purpose of the Roadmap and report is to:

- Describe the challenges and opportunities
- Share knowledge about Key Decarbonisation Technologies
- Articulate necessary ecosystem changes to influence success

[i] Including Alcoa, Rio Tinto and South32.

- Identify initiatives the industry and government can pursue
- Map potential decarbonisation pathways to net zero

Key findings

At the core of the Roadmap are four key themes for decarbonisation, which were identified during the Roadmap development (refer to Figure i). It is imperative that each of these themes is carefully considered during future design and planning of decarbonisation initiatives. This will optimise future investment outcomes for the alumina refining industry in the transition to net zero. Four key decarbonisation technologies (the 'Key Decarbonisation Technologies') were identified during the Roadmap development activities. These are Mechanical Vapour Recompression (MVR), electric boilers, electric calcination and hydrogen calcination.

The development and commercialisation of these technologies will be integral to decarbonising alumina refining. These technologies reduce emissions by enabling the use of renewable energy or by maximising process heat recovery for two key steps in the alumina refining process: the Bayer process and the calcination process. When powered with renewable energy, some combinations of Key Decarbonisation Technologies can potentially eliminate up to 98 per cent of alumina refining emissions. Alternative solutions such as carbon offsets may be required to abate residual emissions and reach net zero.

The Roadmap (refer to Figure ii) shows the potential timing of development and deployment for the Key Decarbonisation Technologies.

The Roadmap also highlights the criticality of broader ecosystem initiatives, such as large-scale renewable energy deployment, regardless of which abatement pathways are pursued by industry. For example, firmed energy supply is integral to support decarbonisation, either through grid-based firming, on-site thermal energy storage or green hydrogen storage. In addition, the firmed energy and storage requirements for alumina refining could also provide broader ecosystem benefits, such as by enhancing load flexibility in the National Electricity Market (NEM) and Wholesale Electricity Market (WEM).

It should be noted that the Roadmap seeks to focus on step-change impacts on emission reduction from shifts to the Key Decarbonisation Technologies, rather than decreases that may be gained from other options such as fuel switching from coal to gas, mud washing, or other energy efficiency initiatives. This report seeks to highlight the potential of what are currently, early stage renewable energy technologies in alumina refining and how these can assist in driving real carbon abatement within the industry. If these other options are considered, this could result in short term reductions in carbon emissions. However, these in isolation, are not enough to meet net zero targets.

Figure i: Four key themes to decarbonise identified during Roadmap development activities

Transformational change

Key Decarbonisation Technologies require fundamental changes to mass-energy balances of refining processes.

Distinct pathways

There is no 'one-size-fits all' solution - the optimal choice of decarbonisation technologies varies between refineries.

Renewable generation and storage

Significant investment is required to power low emissions technologies with firm heat and renewable power.

Market and regulatory mechanisms

Evolving consumer preferences and regulatory mechanisms could facilitate promotion of decarbonisation.

Source: Deloitte, using Participants' input.

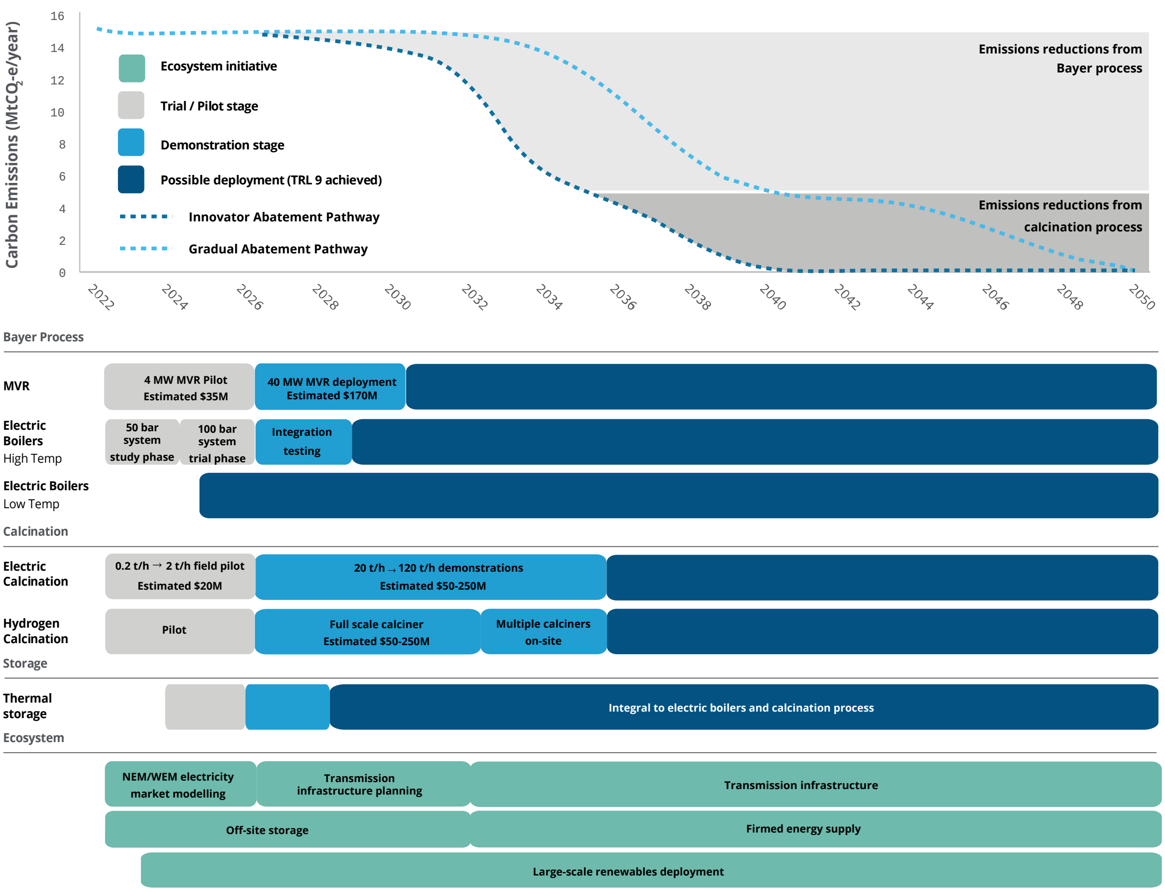
The Roadmap provides two potential abatement pathways to decarbonise alumina refining. These include:

1. An '**Innovator Abatement Pathway**', where technologies are deployed quickly by refiners once they have reached technology maturity (i.e. Technology Readiness Level 9). This pathway assumes that technical or commercial barriers for investment are materially reduced.

2. A '**Gradual Abatement Pathway**', where technologies are deployed over a longer timeframe to more fully account for potential barriers that would impact the pace of technology deployment by different refiners. The Gradual Abatement Pathway still enables the alumina industry to achieve net zero emissions by 2050.

These pathways both assume the technologies develop successfully and are powered by renewable energy. Any delays in technology progression or access to renewable energy would delay the timeline to reach net zero. Therefore, there is a strong timing imperative to act now.

Figure ii: Roadmap until 2050 with staging for key on-site and off-site ecosystem initiatives to achieve an 'Innovator Abatement Pathway'



Note: Refer to Appendix B for abatement pathway assumptions.
Source: Deloitte, using Participants' input.

A call to action

The Roadmap and report are intended to be seen as a call to action for industry and governments. The Roadmap provides a set of findings to inform future policy and investment decisions to transition the industry to a net zero future. It highlights the immediate need for targeted pilot projects to accelerate technology development and detailed modelling to support energy market enablement and system design.

Substantial ecosystem initiatives are also required to support the industry's transition to net zero. At full-scale implementation across the Australian alumina refining industry, Key Decarbonisation Technologies would require 3 to 5 GW[ii] of firmed new renewable electricity supply.[7] This demand could accelerate the development of renewable energy capacity in the WEM and NEM.

A concerted and collaborative effort by both industry and government stakeholders is needed to accelerate the development and implementation of Key Decarbonisation Technologies to achieve net zero by 2050, in line with climate targets of governments and industry.

[ii] 3-5 GW of new electricity is a range based on participant discussion and is dependent on the uptake of different Key Decarbonisation Technologies. The potential renewable capacity required to meet this demand is likely 3 to 5 times this amount. Detailed market modelling is required to establish a reliable estimate for electrical demand in the NEM/WEM.

1. Introduction

1.1 Overview

The alumina refining industry plays an integral role in the Australian economy. However, it is an emissions intensive industry. In 2020, emissions from the six alumina refineries amounted to nearly three per cent of Australia's total emissions.[8]

With an abundance of renewable energy resources and as a leading producer and exporter of alumina globally, Australia has a promising opportunity to establish a competitive advantage in the production of low-carbon alumina. This opportunity can be pursued by developing innovative and sustainable refining technologies.

Despite several decarbonisation challenges, all major producers[iii] of alumina in Australia recognise the importance of reducing their emissions to safeguard the long-term competitiveness of their alumina refineries in the global market.

1.2 Purpose and process

1.2.1 A Roadmap to decarbonise alumina refining

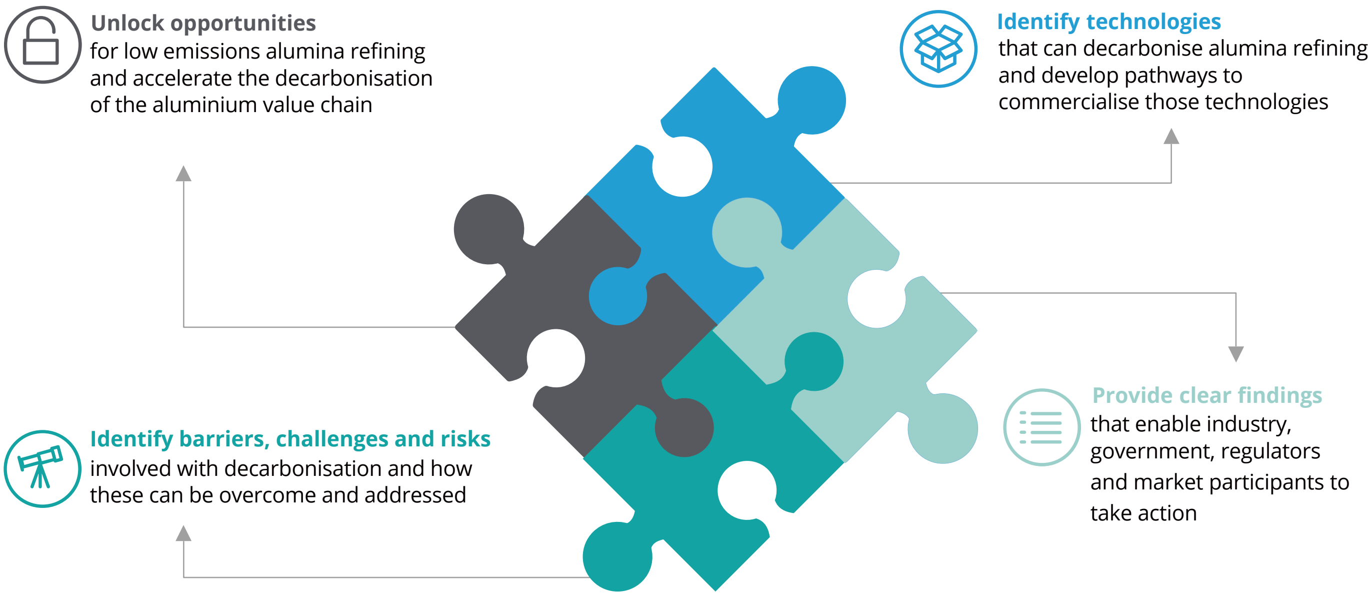
In December 2021, ARENA engaged Deloitte to assist with the development of a roadmap and prepare a report, which identifies the potential pathways to transition to net zero alumina refining in Australia. This document is intended to be a public knowledge sharing document to inform industry decarbonisation initiatives and ecosystem needs to support these initiatives.

The Roadmap and report were developed in consultation with Australian alumina refiners and consider the technical, commercial and market implications for emerging low emissions refining technologies. The Roadmap was informed by a series of workshops and interviews with key stakeholders, and it identifies potential opportunities for industry, government, regulators, and energy market participants to collaborate and coordinate investment to support low emissions alumina refining.

1.2.2 Workshop series

ARENA convened a working group with the three major stakeholders in Australia's alumina refining industry, Alcoa, Rio Tinto and South32. Through a series of collaborative workshops, the group established consensus on the most prospective technological pathways to decarbonise alumina refining in Australia, as well as key barriers that must be overcome to decarbonise. The key findings from each workshop are contained in Appendix A. The workshop series focused on four main areas identified in Figure 1.1.

Figure 1.1: Key focus areas of the workshop series



Source: Deloitte and ARENA for workshops.

[iii] Alcoa, Rio Tinto and South32.

2. Background

2.1 Overview

The alumina refining industry is a large contributor to Australia's national carbon budget due to the following factors:

1. A significant amount of energy is required to refine alumina and the industry is the largest consumer of process heat in Australia[9]
2. Existing alumina refining processes rely heavily on fossil fuels for process heating with a lack of low emissions alternatives

2.2 The refiners - facilities and locations in Australia

There are currently six active alumina refineries in Australia (refer to Figure 2.1). Four of the six Australian refineries are in Western Australia, and they are connected to the South-West Interconnected System (SWIS). The remaining two refineries are in Queensland and are connected to the National Electricity Market (NEM).[10] The Gove alumina refinery in the Northern Territory is no longer operational.[11]

The operating characteristics of individual Australian refineries differ due to the type of energy supply, the type of bauxite ore, differences in the refinery process design (i.e. low versus high temperature digestion) and whether electricity is generated on-site.

The four refineries in Western Australia process alumina using low temperature digestion, while the two refineries in Queensland use higher temperature digestion. The temperature of digestion is determined by the type of bauxite that is refined in each region and it is a key consideration when determining which abatement pathways should be pursued by different refineries.

Proximity to renewable energy zones or hydrogen hubs can facilitate access to affordable, reliable and large-scale renewable capacity.[12] For example, the Queensland Alumina Limited and Yarwun refineries are located in the identified Renewable Energy Zone of Fitzroy and near the proposed Gladstone Hydrogen Hub.[13] Similarly, the Kwinana refinery in Western Australia is near the proposed Kwinana Hydrogen Hub.

Figure 2.1: Key alumina refining locations in Australia with majority shareholder details, 2022

Note: Mt in this figure refers to alumina.

Source: Deloitte, Alcoa, Participant input, Renewable Energy Zones and hydrogen hubs announced under the Clean Hydrogen Industrial Hubs Program – Hub Implementation Grants. Only proximate Renewable Energy Zones and hydrogen hub locations are shown.[14]

2.3 Rationale for alumina refining focus

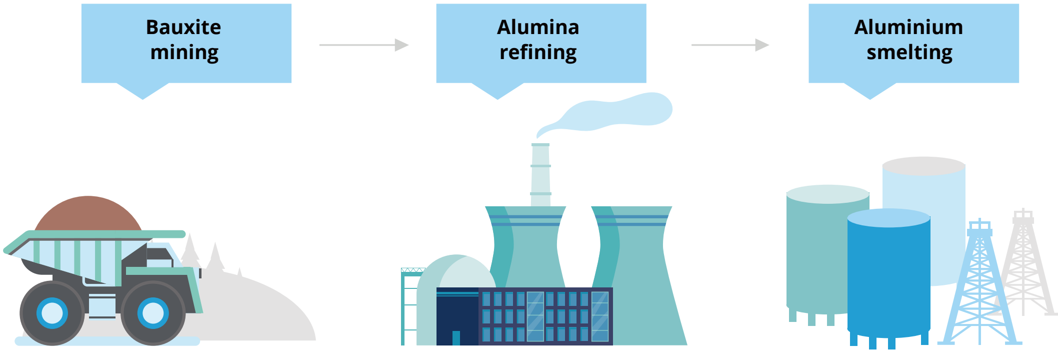
2.3.1 Australian manufacturing sector

The manufacturing sector makes up 20 per cent of final energy use in Australia,[15] with several key heavy industries accounting for approximately 66 per cent of the manufacturing sector's energy consumption.[16] These heavy industries include production of alumina, aluminium, iron, steel, chemicals, and cement. The manufacturing sector is also one of Australia's highest emitting sectors and accounts for 17 per cent of total national emissions. To deliver Australia's long-term emissions reduction commitments of net zero by 2050, Australian manufacturing industries, including the alumina refining industry, must improve energy efficiency and accelerate the uptake of renewable and clean energy to decarbonise energy systems and processes.

2.3.2 Primary aluminium value chain

The primary aluminium production value chain is made up of three stages (refer to Figure 2.2) with the focus of this Roadmap and report on Alumina refining. The secondary aluminium production value chain includes casting, semi-fabrication, manufacturing and recycling.[17]

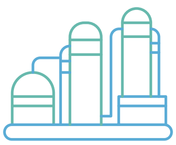
Figure 2.2: Primary aluminium value chain



Source: Deloitte, using Australian Aluminium Council.[18]

2.3.2.2 Bauxite mining

While Australia is a large producer of bauxite ore (102 Mt in 2020), emissions from this segment of the aluminium value chain represent only one per cent of Australia's overall primary aluminium value chain emissions (approximately 0.4 $MtCO_2$-e in 2020)[19]. Therefore, the emissions abatement potential is small in comparison to other segments of the value chain. Furthermore, there are already several prospective pathways to reduce emissions from bauxite mining such as the adoption of behind-the-meter renewable energy generation or through the adoption of electric and hydrogen fuel cell vehicles for mine-site fleets.

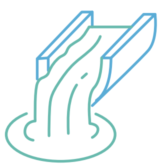


2.3.2.3 Alumina refining

Alumina refining is energy intensive with Australian refineries using on average 10.5 GJ of energy per tonne of alumina.[20] Alumina refining currently relies on fossil fuels to produce on-site heat and electricity. In 2020, emissions from the six alumina refineries were approximately 14.9 $MtCO_2$-e (refer to Figure 2.3). This equates to 42 per cent of Australia's total primary aluminium value chain emissions[21] and 15 per cent[iv] of Australia's manufacturing emissions.[22] In a national context, this equates to approximately three per cent of Australia's total annual emissions.[23]

Compared to bauxite mining and aluminium smelting, the abatement pathway for alumina refining in Australia is less clear. Alumina refining is a 'hard-to-abate' industry because traditional refining processes rely on the combustion of fossil fuels for process heat and there is a lack of low emissions alternatives that are technically mature and commercially feasible. Targeted intervention and transformational change are therefore needed to reduce emissions for the alumina refining industry.

The Roadmap provides a pathway to reduce emissions in the alumina refining industry and supports Australia and its major industry stakeholders to meet net zero by 2050 commitments.

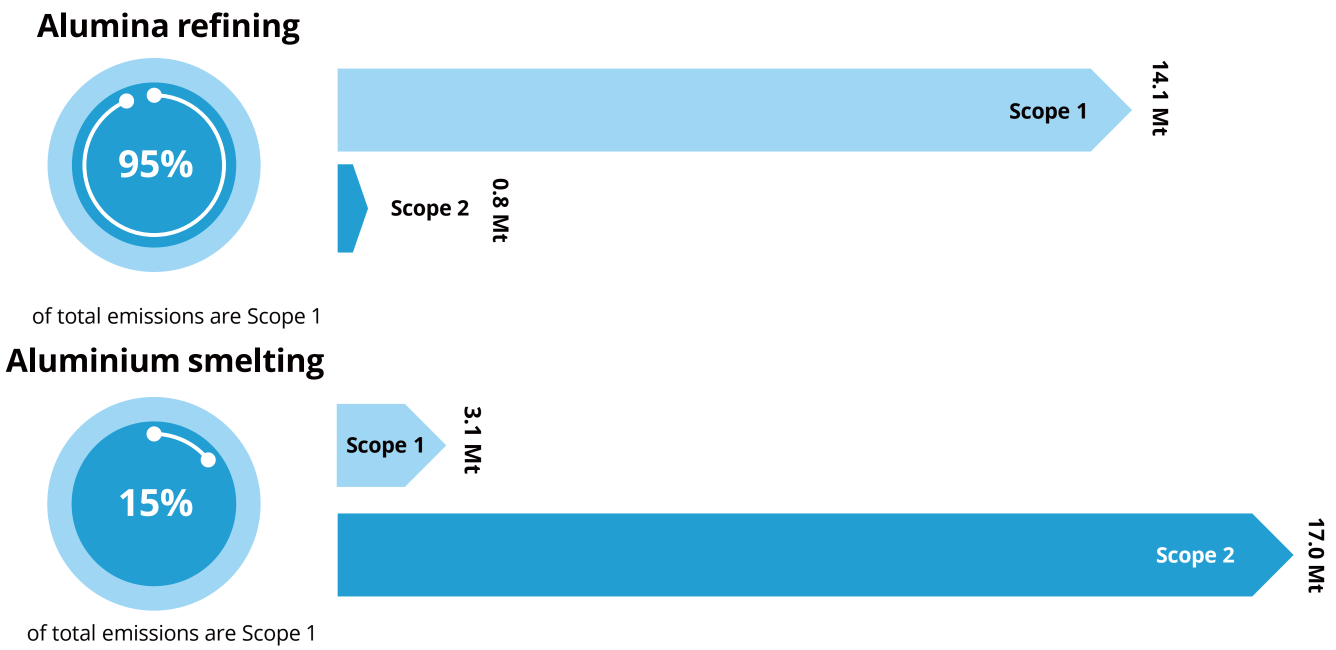


2.3.2.4 Aluminium smelting

Aluminium smelting is the most energy and emissions intensive segment of the primary aluminium value chain. In 2020, Australian aluminium smelting consumed 51.9 GJ of energy per tonne of aluminium produced, releasing 20.1 $MtCO_2$-e (approximately 57 per cent of total aluminium value chain emissions).[24] However, the majority of energy consumed by smelters is supplied from grid electricity and scope 2 emissions represent approximately 85 per cent of emissions for smelting operations (refer to Figure 2.3). Scope 2 emissions are expected to decrease as Australia's electricity grid decarbonises with increasing renewable energy penetration.

[iv] In 2019, which is the most recent data available at the time of writing.

Figure 2.3: Refining and smelting emissions in Australia, 2020



Source: Australian Aluminium Council.[25]

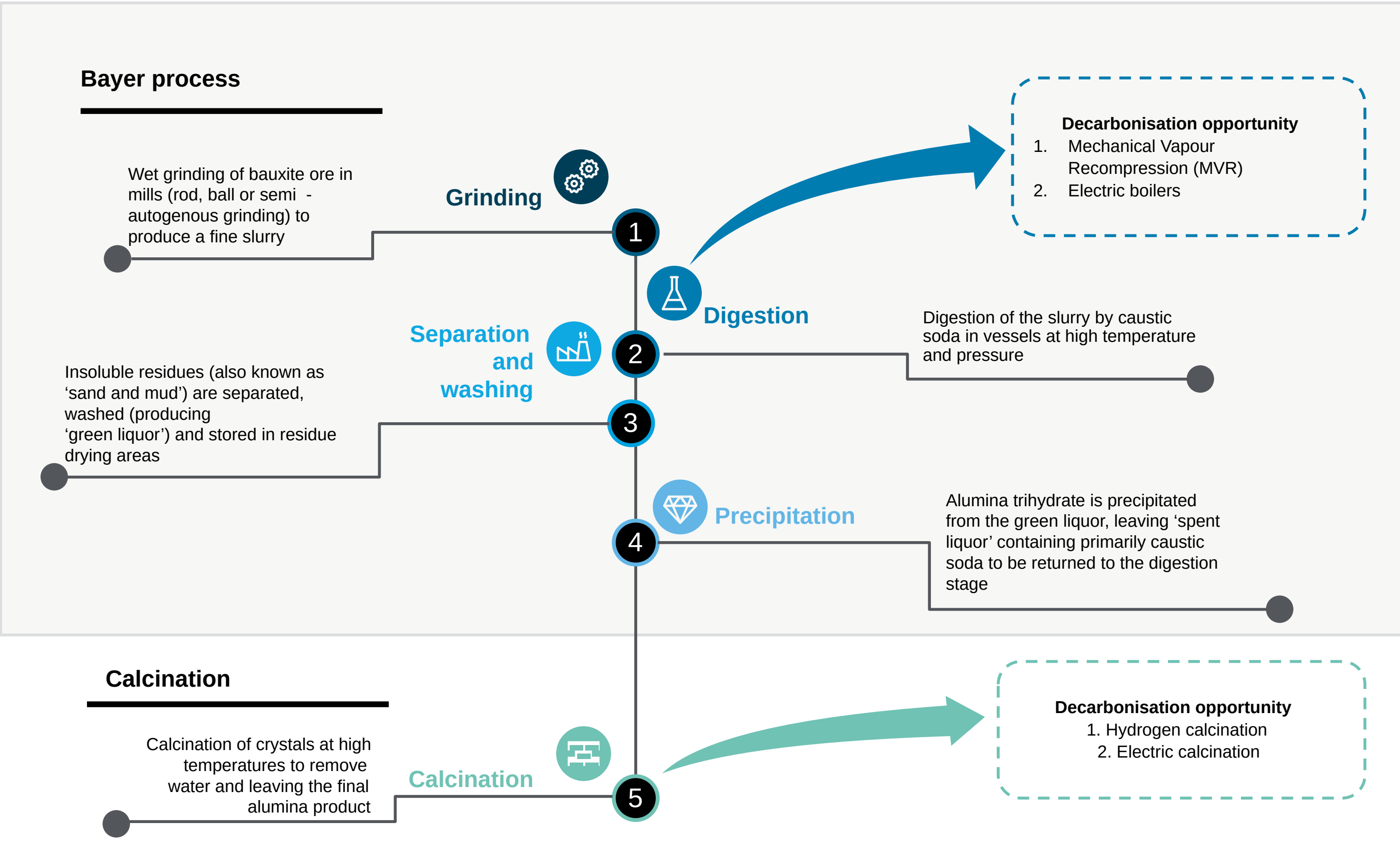
2.4 Alumina production

The alumina refining process is illustrated in Figure 2.4 and includes two main processes: the Bayer process and the calcination process.

The purpose of the Bayer process is to extract alumina hydrates from bauxite, separate the leach liquor from the bauxite residue and re-precipitate as refined tri-hydrate (gibbsite). The Bayer process includes the first four steps in Figure 2.4. The digestion process is energy intensive and utilises steam to heat a caustic soda and bauxite slurry and dissolve the alumina hydrates within the bauxite.[26]

The final step is the calcination process, where the combustion of fossil fuels generates the high temperatures (around 1,000°C) necessary to remove chemically bound water from the alumina tri-hydrate crystal to produce the final alumina product.[27]

Figure 2.4: Overview of the alumina refining steps



Source: Deloitte, using Mission Possible Partnership,[28] and SolarPACES.[29]

2.5 Market trends

Australia is the largest exporter of alumina globally (45 per cent of market share).[30] The major Australian alumina export markets are the United Arab Emirates (16 per cent of Australian trade flows), Bahrain (13 per cent) and China (13 per cent).[31] This report identifies four key global market trends that can materially impact the competitiveness of Australian alumina exports.

2.5.1 Net zero by 2050

In recent years, there has been significant momentum from governments and industry to commit to emissions reduction targets that aim to limit emissions to a 1.5°C or below 2°C climate aligned scenario. In Australia, both state and federal governments have committed to net zero by 2050, with some jurisdictions committing to earlier net zero targets and interim emissions reduction targets.[32] In addition, all major alumina refiners in Australia, including Alcoa, Rio Tinto and South32, have also announced net zero ambitions or commitments for their organisations.[33] Emissions reduction targets by industry and government demonstrate a commitment by all parties to take action to address climate change. The alignment with global momentum to establish emissions reduction targets, means that Australian alumina refiners will be able to maintain their international competitiveness as leading exporters of alumina.

2.5.2 Capital intensity and financed emissions

Capital intensity is the proportion of investment in fixed assets (such as machinery and equipment) to support business operations relative to other variable factors of production such as labour.

Capital intensity in the alumina refining industry has increased over the past five years and this trend is projected to continue over the next five years.[34] In 2016, for every dollar spent on wages, approximately $0.27 was invested in plant capital and equipment. In 2021-22, this increased to approximately $0.36.[35] This increase stems from investments in process automation and infrastructure to improve operational efficiency and expand production capacity. This rise in capital intensity requires financing to improve or expand operations. As a result, decarbonisation targets set by financial institutions and lenders can have an influence on the ability of the alumina refining industry to access capital.

The Partnership for Carbon Accounting Financials (PCAF) was established in 2015 and has led to heightened focus from financial institutions on financed emissions. Financial institutions manage risk and identify opportunities in part by measuring the carbon emissions they finance. As banks and investors look towards net zero for their lending portfolios, this could impact the cost of capital in emissions intensive industries. A total of 317 financial institutions have committed to measuring and disclosing greenhouse gas emissions associated with their portfolio of loans and investments.[36] Global banks such as Citi have included absolute emissions reduction across their portfolio.[37] The cost of capital may rise in industries where limited action is taken to reduce emissions and minimise climate impacts.

Investment trends: Aluminium Climate-Aligned Finance Working Group position statement

The Aluminium Climate-Aligned Finance Working Group was formed in 2022 between the top three lenders to the aluminium sector (Citi, ING and Société Générale) and the Rocky Mountain Institute's Centre for Climate-Aligned Finance.

This Working Group will create a framework that defines how lenders can support the decarbonisation of the aluminium value chain. Participating financial institutions will disclose the degree to which the emissions associated with their aluminium portfolio are in line with climate targets to limit global warming to 1.5°C.[38]

2.5.3 Market demand for low-carbon products

Consumer demand is evolving globally, with increasing preference for low-carbon products from end-users and aluminium producers.[39] This trend is driven by end-users who are seeking to reduce emissions throughout their supply chain (i.e. scope 3 emissions[v]) and reduce the embodied carbon of their products. As a leading exporter of alumina[vi], the Australian alumina refining industry must align with changing domestic and global consumer preferences to maintain its international competitiveness in the future.[40]

European and North American markets in particular are experiencing significant customer demand for low-carbon alumina and aluminium products, including in the automobile and mobile phone industries. Consumer based demand has also led to collaborative initiatives like the smelting industry's ELYSIS technology development.[41]

[v] Scope 3 emissions are defined as indirect emissions that occur in the value chain of the reporting company, including both upstream and downstream emissions.

[vi] Australia is the second largest producer and the largest exporter of alumina globally with approximately 15 per cent of total global production.[32]

Case Study: Elysis low-carbon aluminium smelting

In 2018, Rio Tinto and Alcoa Corporation established a joint venture called ELYSIS™ to commercialise an innovative technology that eliminates all scope 1 emissions in aluminium smelting.

Apple is a technology and investment partner of the ELYSIS™ joint venture. After using the first batch of aluminium with no direct emissions in the smelting process for MacBook Pros, Apple has committed to using the next batch for the company's new iPhones.

Apple's involvement has helped to raise the profile of low-carbon aluminium. Collaboration between producers and end-users and a focus on emissions throughout the entire supply chain demonstrates the growing market demand for products with low embodied carbon.

Increasing demand, specifically for low-carbon products, may indicate that a customer segment would be willing to pay a higher price for products with lower embodied carbon, which is a form of 'green premium'. For example, the international London Metals Exchange is moving towards a material passport (LMEpassport), which establishes a market specifically for sustainably produced aluminium considering both carbon and recycled content.[42]

Green premiums create an incentive for alumina refiners to reduce the emissions intensity of operations. Given Australia's competitive advantage in producing low-carbon alumina, growth in a green premium could also lead to increased international competitiveness with customers in Europe, Brazil, and Canada.

Green premiums for low-carbon alumina are emerging. However, current premiums are not currently sufficient to support the adoption of low emissions technologies in the near-term in the absence of other support mechanisms.

2.5.4 Emerging regulatory frameworks for emissions reduction

The global alumina refining industry is highly competitive and the three producers in Australia compete in the global market with alumina suppliers from over 15 countries. Since commodity markets are primarily driven by prices rather than other differentiating factors, emerging regulatory frameworks that penalise emissions intensive industries can materially impact international competitiveness.[43]

The Safeguard Mechanism requires Australia's largest greenhouse gas emitters (including Alcoa, Rio Tinto, and South32) to keep their net emissions below an emissions baseline. The Safeguard Mechanism applies to facilities emitting more than 100,000 tonnes of carbon dioxide equivalent per year, covering facilities in the electricity, mining, oil and gas, manufacturing, transport and waste management industries. Each facility is assigned a baseline and the operator of the facility must ensure the facility's emissions do not exceed their baseline.

Under the Safeguard Mechanisms reforms, the Australian Government proposes to:

- Gradually reduce baselines to help Australia reach net zero emissions by 2050
- Introduce credits for facilities that emit less than their baseline
- Provide tailored treatment to emissions-intensive, trade-exposed facilities so businesses are not disadvantaged compared to international competitors and emissions do not increase overseas

Reforms to the Safeguard Mechanism may impact on-site and ecosystem decarbonisation initiatives described in the Roadmap.

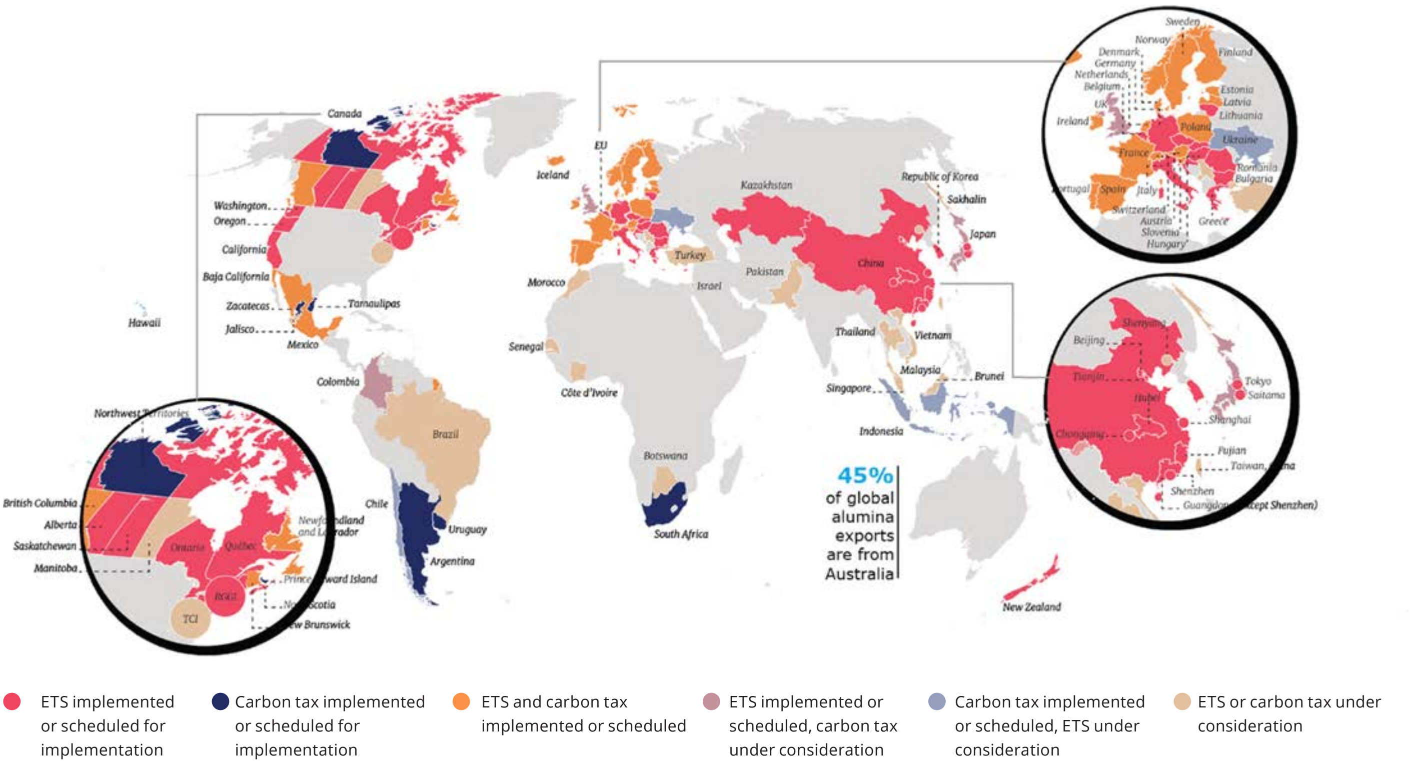
In various international jurisdictions, emerging regulations, or policies such as a carbon border adjustment mechanism or an emissions trading scheme are being implemented or introduced to incentivise emissions reduction. Carbon border adjustment mechanisms[44] are currently being introduced by the EU and are under consideration by the USA, the UK, Canada, and Japan.[45] Implementing these policy tools could lead to increased taxation and greater financial risk for emissions intensive industries such as alumina refining. The current global status of carbon pricing and taxes is shown in Figure 2.5.

2.5.5 Risks of accelerated technology development and early adoption

Trials and demonstrations of emerging low emissions technologies are capital intensive and complex. There is a higher risk of cost overruns and delays to schedule. There are also risks associated with being an early adopter of low emissions technologies at commercial scale due to uncertainty in future energy price trajectories and uncertainty regarding the treatment of emissions under emerging market and regulatory frameworks.

In the near-term, traditional fossil fuel technologies are expected to be the lowest cost option for producing alumina. In the absence of incentives or regulation, Australian alumina refineries may therefore choose to gradually develop and implement low emissions technologies to mitigate risks of early adoption and maintain international competitiveness in the short term. Key Australian alumina importers in the Middle East also have net zero targets, namely the United Arab Emirates (2050), Bahrain and Saudi Arabia (2060).[46] Unlike Europe, imports in these countries are not currently supported by any carbon pricing mechanisms. As approximately 42 per cent of Australian alumina is exported to the Middle East and China, the absence of strong carbon policy in these regions may limit incentives for Australian alumina refineries to accelerate the development and implementation low emissions technologies for that segment of the market.[47]

Figure 2.5: Current global carbon pricing and Australia's major alumina importers



Source: IBISWorld[48] and The World Bank.[49]

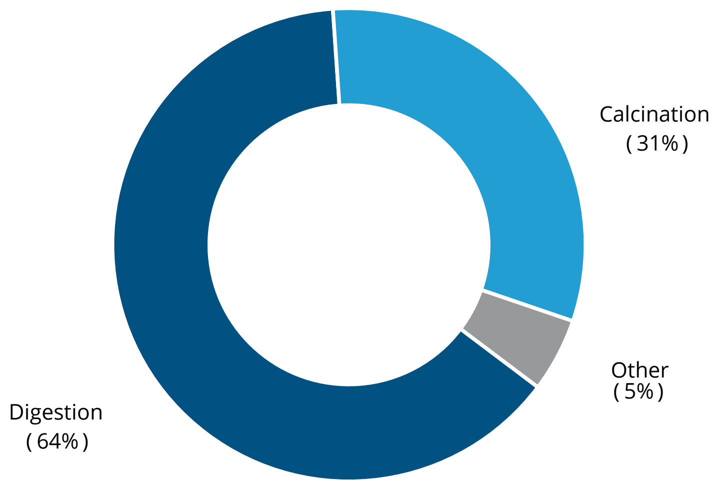
3. Energy consumption and emissions profile

3.1 Energy consumption in current alumina refineries

Alumina refining is an energy intensive process and currently consumes on average 10.5 GJ per tonne of alumina produced in Australia.[50] This energy is largely derived from on-site combustion of gas and coal for process heating and electricity generation (refer to Section 2.2).[51]

Digestion and calcination represent 95 per cent of energy consumption in the alumina refining process (refer to Chart 3.1). Innovative low emissions technologies are required to fundamentally transform the alumina refining process and eliminate the consumption of fossil fuels on-site.[52]

Chart 3.1: Breakdown of energy consumption in Australian alumina refineries by process agnostic of source



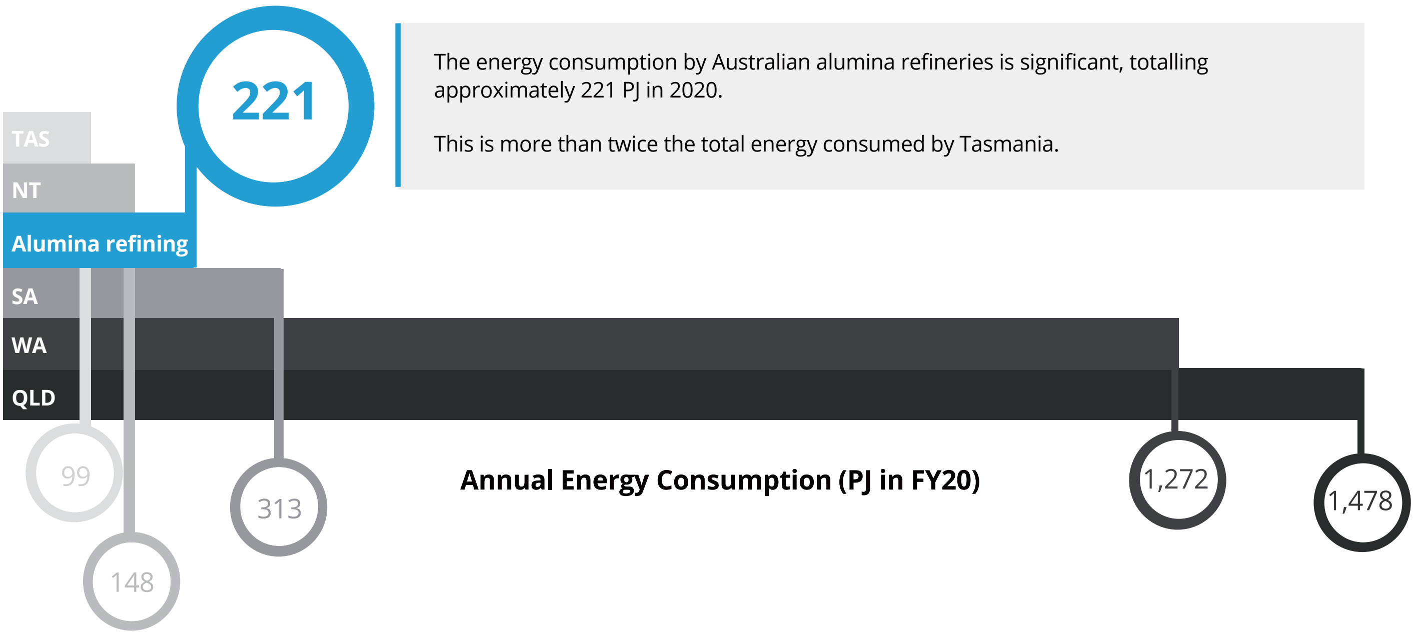
Source: Participants and Australian Aluminium Council.[53]

3.1.1 Energy consumption by Australian alumina refineries

Energy consumption by Australian alumina refineries is significant, totalling approximately 221 PJ in 2020 (or approximately 61,000 GWh).[54] This is more than twice the total energy consumed by Tasmania[vii] (refer to Chart 3.2).[55] As a result of the industry's high energy consumption, transitioning the energy system of the alumina refining industry is similar in scale to transitioning a small Australian state. This presents both a significant challenge and an opportunity.

New low emissions technologies offer the potential for an energy transition from fossil fuels by utilising renewable energy in the form of renewable electricity and green hydrogen. These technologies also have the potential to improve process efficiency and reduce overall energy demand, thereby reducing refinery emissions. These Key Decarbonisation Technologies are explored further in Section 4.

Chart 3.2: Annual energy consumption by Australia's alumina refining industry compared to select Australian states and territories, 2020



Source: Department of Industry, Science, Energy and Resources.[56]

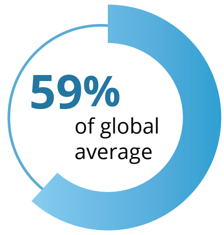
The energy consumption of Australian alumina refining is relatively high compared to similar industries, such as cement (50 PJ) and iron and steel (114 PJ) in 2019.[57] The average annual energy consumption by a typical Australian household is 125 GJ, meaning the annual energy consumption by alumina refining equates to approximately 1.7 million households.[58]

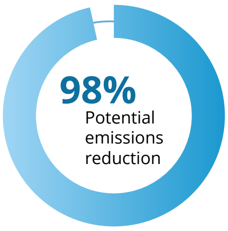
A significant portion of the energy consumed in alumina refining is currently lost to the atmosphere as waste heat. Some of the Key Decarbonisation Technologies discussed in Section 4 are circular by design as they enable refineries to capture waste heat for reuse in the refining process. This improves the energy and water efficiency of the alumina refining process, which reduces the overall energy and water consumption of refineries. As a result, the total energy intensity of a low temperature refinery that has implemented low emissions technologies could be up to 50 per cent lower than refineries with traditional fossil fuel technologies.[59] This is shown in Figure 3.1.

[vii] State and Territory energy consumption includes coal, oil, gas, and renewable energy.

3.1.2 Australian alumina refining emissions intensity

The average emissions intensity of Australian alumina refining is 0.71 tCO_2-e per tonne, which is approximately 59 per cent of the global average (1.21 tCO_2-e per tonne). This difference in emissions intensity is largely due to a heavy reliance on coal in overseas jurisdictions while natural gas is used to produce alumina at most Australian refineries.[61] Coal is 1.8 to 2.1 times the emissions intensity of natural gas (depending on type of coal used).[62] In 2020, Australian alumina refineries consumed approximately 150 PJ of natural gas and 67 PJ of coal.[63] Other minor sources of energy for the industry include diesel, fuel oil and purchased electricity. Some refineries also generate electricity on-site using gas turbine and heat recovery steam generators or back-pressure steam turbines to partially meet their electricity needs.





Australia's alumina refining emissions could be significantly reduced in the future by integrating several of the Key Decarbonisation Technologies that are currently under development (refer to Section 4). These technologies can be powered by 100 per cent renewable energy, and therefore offer a pathway to reduce on-site alumina refining emissions[viii] by up to 98 per cent.[64]

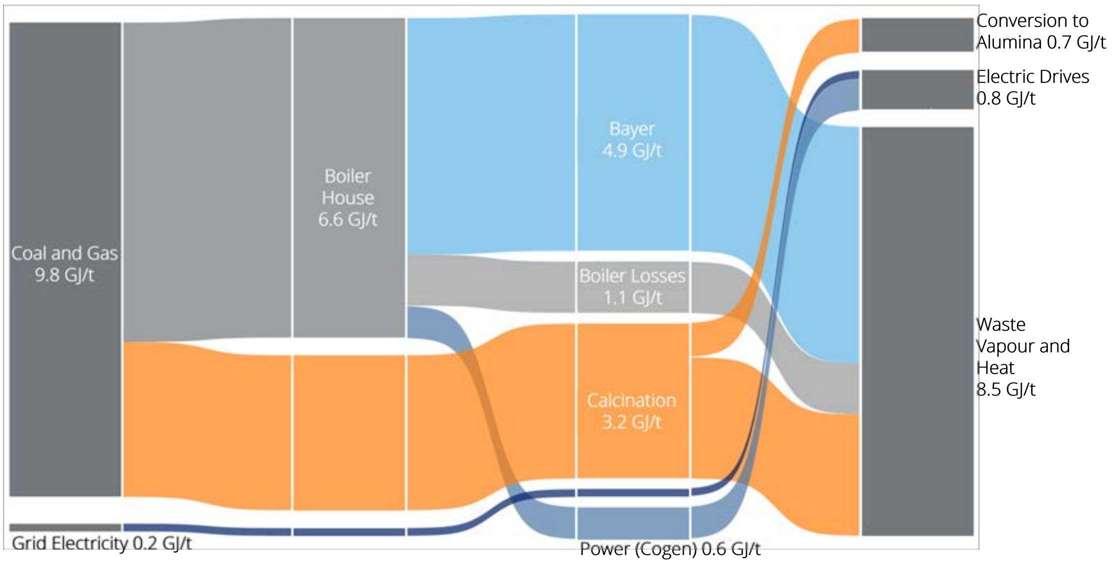
[viii] Up to 98 per cent emissions reduction is possible for low temperature refineries implementing MVR and electric calcination. Actual emissions reductions will depend on refinery type and technologies implemented.

The Key Decarbonisation Technologies can be used in combination to optimise energy efficiency and reduce emissions in the alumina refining process. The expected energy intensity for low emissions refineries is largely reduced by reusing recovered waste heat (refer to Figure 3.1). Alumina refining has the largest demand for process heat by industry in Australia, and enhanced heat recovery could reduce energy intensity in refineries by up to 50 per cent relative to traditional fossil fuel technology.[65]

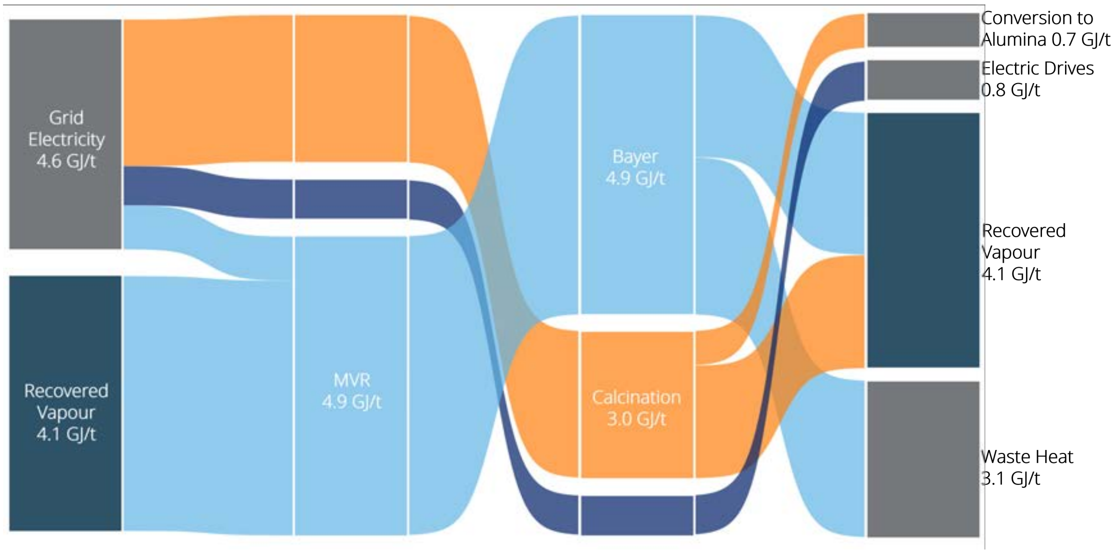
Figure 3.1 demonstrates the potential improvement in energy efficiency that would result if future low temperature refineries implement MVR (refer to Section 4.2) in combination with electric calcination (refer to Section 4.5 and Section 4.6). In this scenario, future low emissions refineries are expected to reduce primary energy required from 9.8 GJ/t to 4.6 GJ/t. This efficiency gain significantly reduces the amount of renewable energy required to power the process compared to existing technologies.

Figure 3.1: Sankey Diagrams highlighting the difference in energy flows between current alumina refineries and a hypothetical low emissions alumina refinery

Current alumina refineries:



Future alumina refineries:



Source: Deloitte, using Participants' input.[67]

With deployment of these key technologies, approximately 3.1 GJ/t of energy is still lost in the form of waste heat and vapour. This highlights that even with these technologies implemented, there may still be opportunity for future technologies to reduce energy intensity.

3.1.3 Forecast alumina refining emissions and climate aligned scenarios

Under a 'do-nothing' scenario, alumina refining emissions are projected to remain relatively stable to 2050 (refer to Chart 3.3).

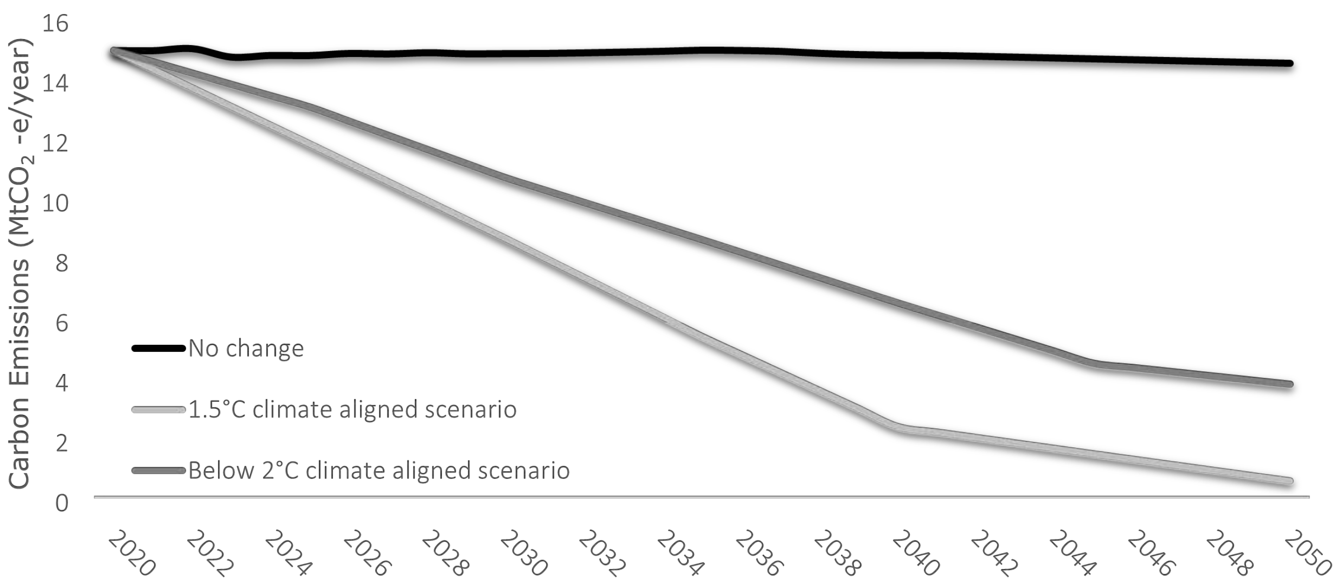
Limited emissions reduction is expected through grid decarbonisation because existing alumina refining processes rely heavily on on-site fossil fuel combustion to generate electricity and process heat. Only a small portion of today's alumina refining emissions are attributed to imported electricity. Decarbonisation efforts must therefore target existing on-site process heating requirements as this will not be benefit from grid decarbonisation. The 'Innovator' and 'Gradual' abatement pathways are different to the climate aligned scenarios shown in Chart 3.3 and are discussed further in Section 7.1.

Climate scenario modelling approach

The International Aluminium Institute (IAI) recently modelled a 1.5˚C scenario to guide efforts to meet global climate goals for the aluminium value chain, including alumina refining (refer to Section 2.3.2). The scenario is the most ambitious global value chain decarbonisation approach and is based on the International Energy Agency's (IEA) Net Zero by 2050 scenario, in combination with the IAI's material flow analysis and future demand scenarios.[68] However, a global, value chain modelling approach was not considered appropriate in forming a view on decarbonising the Australian alumina refining industry, because global energy systems vary significantly by region.[69]

For the Roadmap, Deloitte therefore adopted the Network for Greening the Financial System (NGFS) Global Change Analysis Model (GCAM) as an input to the Deloitte Decarbonisation Solutions™ (DDS™) tool to model climate aligned scenarios specific to the Australian alumina industry, including a 1.5˚C and below 2˚C scenario. For more details on the climate-aligned scenarios, justification of the modelling methodology and a comparison to the IAI findings, please refer to Appendix B.

Chart 3.3: Projected emissions for the Australian alumina industry under a 'do-nothing' scenario, and using 1.5˚C and below 2˚C climate aligned scenarios as modelled using DDS™



Note: Refer to Appendix B for climate aligned scenario assumptions.
Source: DDS™ using climate model NGFS GCAM5.3, data collected from Participant feedback,[70] IBISWorld.[71]

4. Potential decarbonisation technologies

4.1 Key Decarbonisation Technologies

The Key Decarbonisation Technologies identified in this report are MVR, electric boilers, hydrogen calcination and electric calcination. Electric steam generation (including MVR and electric boilers) addresses emissions from steam production for the Bayer process and is considered a near-term opportunity (viable by 2030), while electric calcination and hydrogen calcination are considered medium-term opportunities (viable beyond 2030) as shown in Figure 4.1.

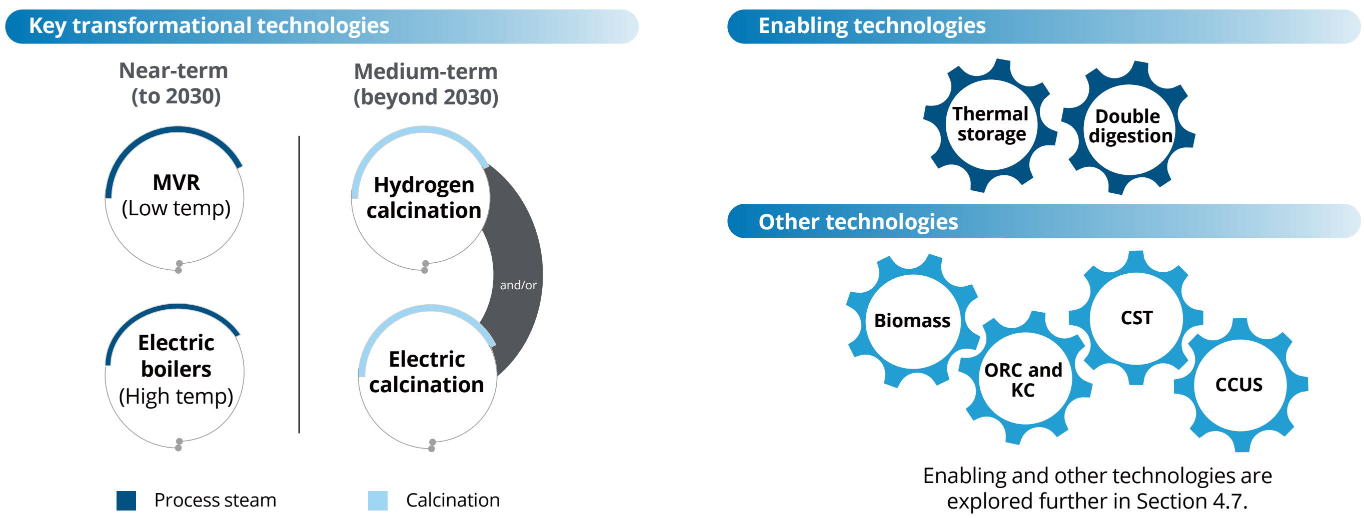
Several enabling and other technologies shown in Figure 4.1 also have the potential to support emissions reduction (refer to Section 4.6). The enabling technologies covered in this report are double digestion and thermal storage. Other technologies covered include biomass, concentrated solar thermal (CST), carbon capture and storage and organic rankine and kalina cycles. The other technologies are expected to be less feasible or offer lower abatement potential than the Key Decarbonisation Technologies.[72]

Due to differences between individual refineries, there is no one-size-fits-all solution. Each refinery may require different technologies and different combinations of technologies to significantly reduce emissions. Therefore, all Key Decarbonisation Technology options should be pursued by industry. The preferred combination of Key Decarbonisation Technologies at each refinery will depend on several key factors, including:

- Required digestion temperature to process the bauxite[viii]
- Current power contract arrangements and pricing
- Future power pricing
- Remaining refinery and resource life
- Ease of retrofitting
- Proximity to renewable energy zones and hydrogen hubs (refer to Figure 2.1)

While previous emissions reduction initiatives have focused on incremental improvements in energy efficiency with traditional fossil fuel technologies, the Key Decarbonisation Technologies shown in Figure 4.1 enable refineries to utilise renewable energy and potentially offer a step change in overall energy efficiency by capturing and reusing waste heat.

Figure 4.1: High-level overview of the Key Decarbonisation Technologies, enabling and other technologies



Source: Deloitte, using Participants' input.[73]

[viii] Depending on the specific chemical composition of bauxite, different processing temperatures and conditions are required.

Despite their potential for abatement, there are several barriers impeding the uptake of all four Key Decarbonisation Technologies at Australian alumina refineries. These barriers include lack of access to low-cost renewable power at very large-scale and high availability for MVR, electric boilers and electric calcination. In addition, renewable hydrogen is currently not cost-competitive or readily available in large volumes to support hydrogen calcination. These technologies are also at varying levels of technology readiness and require further demonstrations to inform the techno-economic feasibility to identify the infrastructure required to support uptake. The barriers and opportunities of implementing low emissions technologies are explored further in Section 5.

The combination of MVR (refer to Section 4.2) with electric calcination (refer to Section 4.5) or hydrogen calcination (refer to Section 4.4) could reduce a refinery's carbon emissions by up to approximately 98 per cent, as well as reducing water consumption.[74]

Thermal storage is particularly important as an enabling technology. Thermal storage provides refineries with greater flexibility to reduce grid electricity imports during periods of high electricity pricing or a lack of renewable generation capacity. This ensures reliable power supply to refineries to sustain operations and improves the overall business case of low emissions technologies by mitigating uncertainty of long-term power prices and volatility.

Additionally, the Roadmap does not consider fuel switching from coal to gas, mud washing, or other energy efficiency initiatives that may deliver near-term emissions reduction at select refineries.

Table 4.1 summarises the parameters of the Key Decarbonisation Technologies, including MVR, electric boilers, hydrogen calcination and electric calcination. These considerations are explored further in subsequent sections.

Table 4.1: Key Decarbonisation Technologies

Key Decarbonisation Technologies	MVR	Electric boilers	Hydrogen calcination	Electric calcination
Technology readiness level in alumina refining	7-8 (low temperature) 4-5 (high temperature)	9 (low temperature) 4-5 (high temperature)	6	4
Potential impact on sector emissions				
Capital cost[ix]	$$	$$	$$	$$$
Key benefits	• High energy and cost savings • Widely applicable to various sites	• Commercially available for low temperature applications • Mature technology with high technology readiness level for low temperature conditions • Near-term solution for reducing refining emissions	• Combustion of H_2 in pure oxygen produces pure steam exhaust which can be captured and utilised in the refinery to improve efficiency • Lower capital cost and on-site work under a retrofit scenario (excluding hydrogen production) • Compatible with MVR, allowing steam to be captured and recycled in the process	• Compatible with MVR, allowing steam to be captured and recycled in the process • Potentially lowest cost calcination technology for new greenfield refineries
Constraints	• Requires large-scale access to renewable power[x] • Significant on-site electricity infrastructure costs • Not currently technical proven for alumina refining • May not be suitable for high temperature refining or may need to be coupled with other technologies such as electric boilers • Firm electricity required through battery storage, or otherwise	• Requires very large-scale access to renewable power • Significant on-site electricity infrastructure costs • Not yet proven at the high pressures required for high temperature facilities • Higher operating costs than fossil fuel fired boilers • Firm thermal energy required via thermal storage or otherwise	• Requires very large-scale access to renewable power to create hydrogen • Requires extensive external infrastructure and market development to establish a hydrogen supply chain • Renewable hydrogen is currently not cost-competitive or readily available at large volumes • Firm thermal energy required via hydrogen storage or otherwise	• Requires very large-scale access to renewable power • Significant on-site electricity infrastructure costs • High capital intensity for individual refinery • Firm thermal energy required via thermal storage or otherwise

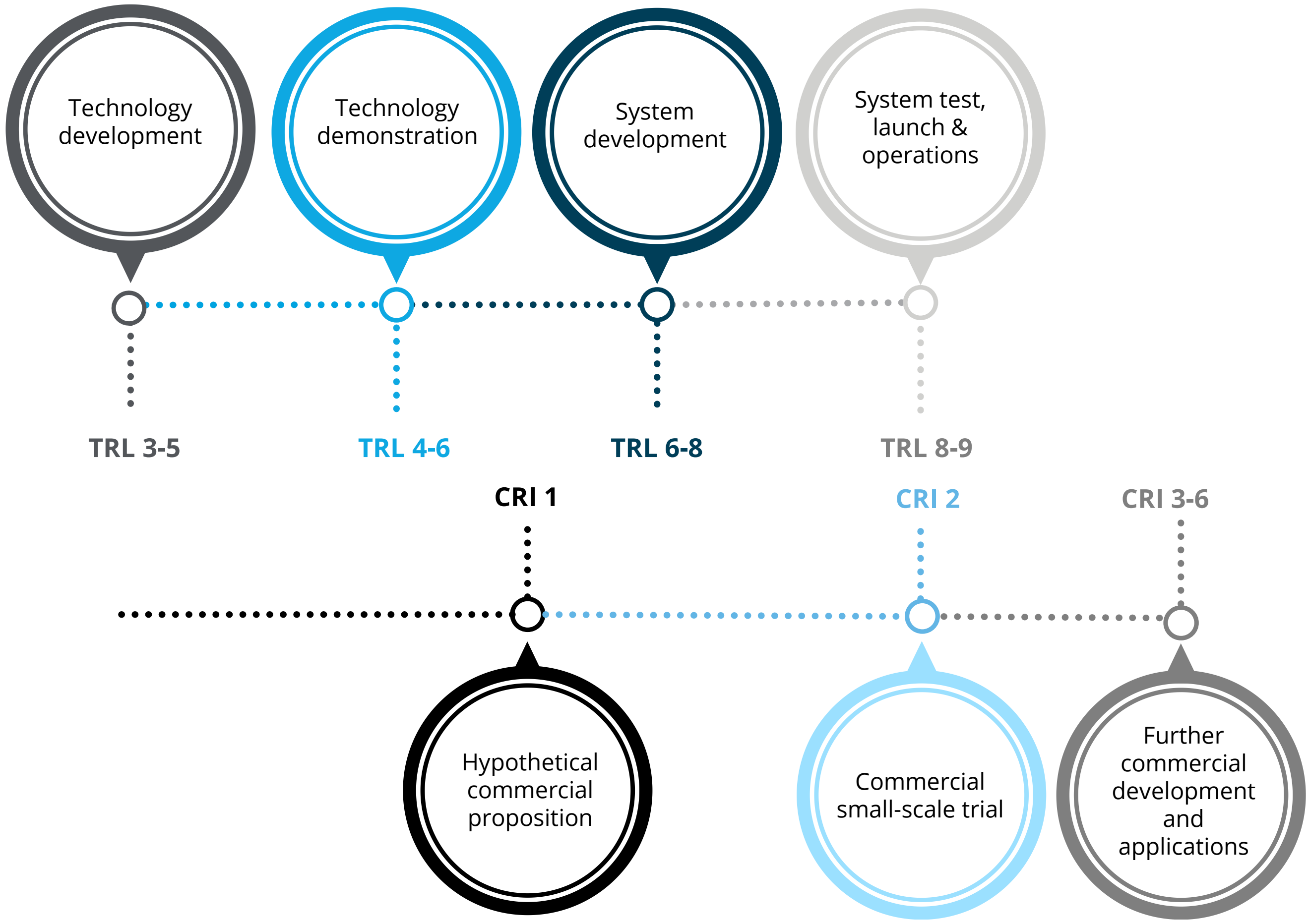
Source: Participant input, Mission Possible Partnership,[75] Thermal Kinetics,[76] Alcoa[77] and Hydrogen Council.[78]

[ix] $$ indicates CAPEX spending for a greenfield facility of up to approximately $700M, while $$$ indicates CAPEX greater than $700M

[x] MVR requires approximately one third the electric power of electric boilers.[79]

The Technology Readiness Level (TRL) framework outlined in Figure 4.2 is used to assess the maturity of technologies at different stages of development. The abatement pathways assume that the Key Decarbonisation Technologies must achieve TRL 9 before they can be implemented at refineries at full scale.

Figure 4.2: TRL framework[xi]



Source: ARENA.[79]

[xi] TRL means 'Technology Readiness Level' and CRI means 'Commercial Readiness Index'.

4.2 Mechanical Vapour Recompression

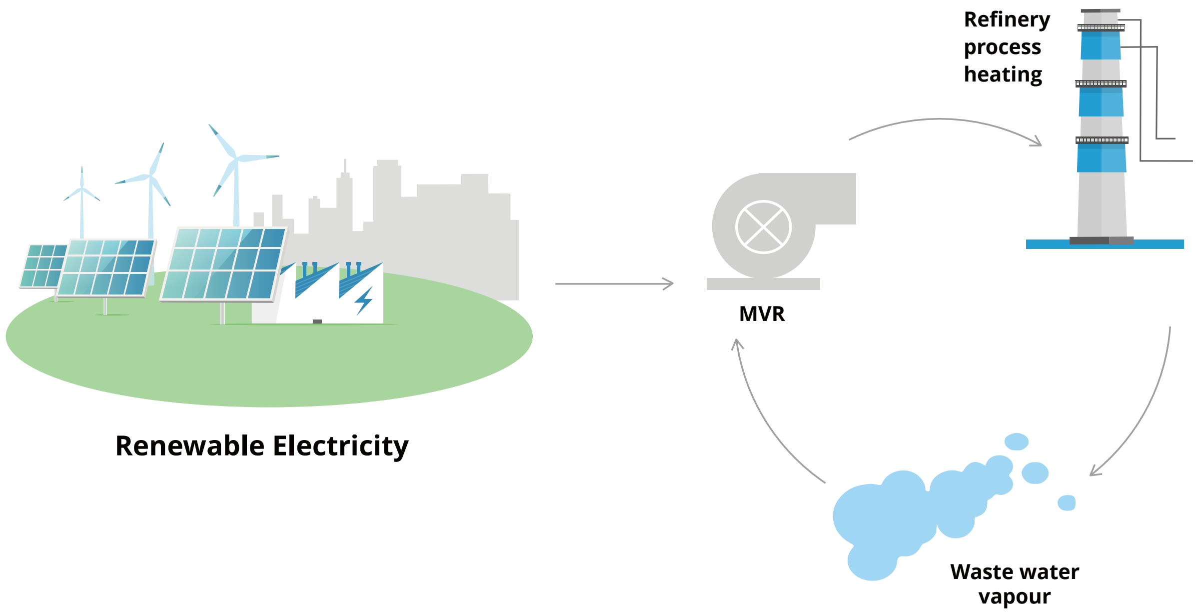
4.2.1 Description

Process heating is required in the Bayer process of an alumina refinery.[80] Currently, fossil fuel fired boilers produce steam to meet this process heat demand. Refineries with high temperature digestion operate with a steam pressure of approximately 5,000 kPa to 10,000 kPa, 325°C to 400°C, while low temperature digestion systems typically operate with steam pressure at approximately 600 to 800 kPa, 175°C to 230°C.[82]

In contrast to fossil fuel boilers, the MVR process captures waste water vapour at relatively low temperature and pressure and recompresses this through a series of turbo fans and compressors to the temperature and pressure required for the Bayer process. This process recovers waste heat that is otherwise lost to the atmosphere. MVR also reduces or eliminates steam demand supplied by fossil fuel fired boilers (refer to Figure 4.3) and reduces water losses in the Bayer process. The expected water savings with MVR are significant with estimated reductions of approximately 5.2 GL/year if adopted by all Australian refineries.[83]

Further, MVR powered with renewable electricity provides a pathway for zero emissions heat in the Bayer process.[84]

Figure 4.3: Process diagram of MVR powered by renewable electricity



Note: Electricity in this diagram refers to electricity from renewable sources such as solar.

Source: Alcoa.[85]

The compressors used in MVR are a highly efficient means of providing heat because they capture the energy in the waste vapour system. A relatively small amount of energy is needed to recompress waste vapour to the required temperature and pressure. MVR requires approximately one-third of the power of that required for an electric boiler.[86]

Significant investment in MVR is required to realise its full abatement potential in alumina refining. The technology must also be technically proven before that investment can take place. The techno-economic feasibility of MVR technology is currently being investigated by Alcoa through pilot scale demonstrations in alumina refining at its Wagerup Alumina Refinery.[87]

Case Study: Mechanical Vapour Recompression for low-carbon alumina refining

In May 2021, ARENA announced $11.3 million in funding to Alcoa to demonstrate MVR technology at its Wagerup Alumina Refinery. MVR has the potential to electrify the production of steam in the Bayer process using renewable energy. This $35 million project is a first-of-a-kind demonstration of MVR in alumina refining in Australia.

Alcoa's main objective for the project is to demonstrate the technical and commercial feasibility of using MVR powered by renewable energy to produce process heat. Stage 1 of the project involves desktop studies to investigate the feasibility of integrating MVR at the refinery. For Stage 2 of the project, Alcoa will deliver a 4 MW MVR module, powered using renewable energy at the Wagerup Alumina Refinery. The project will be commissioned in 2023.

The project will generate significant technical, commercial, and regulatory learnings for decarbonising the alumina refining sector. The knowledge sharing outputs will enable alumina refiners to evaluate the feasibility of MVR for their refineries to reduce emissions and improve international competitiveness.

4.2.2 Emissions reduction and abatement potential

As highlighted in Section 4.2.1, MVR can be powered by renewable energy, providing a pathway to decarbonise the generation of process steam for the digestion process. In addition, the recovery of waste energy means the MVR process is substantially more efficient than a traditional boiler and the renewable energy required is far less than the fossil fuel energy being displaced.

Displacing the combustion of fossil fuels with renewable electricity for process heating and steam generation in the Bayer process could reduce refining emissions by up to 70 per cent.[88] If implemented across all Australian alumina refining, this could reduce alumina refining emissions by approximately 10 $MtCO_2$-e per annum.[89]

To realise the full abatement potential of MVR, alumina refineries will require increased accessibility to renewable energy at large-scale and high availability.

4.2.3 Implementation in refineries

MVR is a highly energy efficient technology, which can deliver deep reductions in energy intensity for low temperature refineries and potentially for high temperature refineries. However, replacing steam provided by fossil fuel boilers with MVR in alumina refineries would increase the demand from the electricity grid in two ways:

1. To power the MVR equipment
2. To replace the electricity previously provided by on-site cogeneration[xii]

MVR could be retrofitted to existing refineries, or in new greenfield installations. Retrofitting existing refineries is a more likely option in Australia in the near-term due to the sunk capital investment in existing refineries and the high capital costs of greenfield development. A key barrier to MVR implementation is proving the technology at scale in an alumina refinery.

Once it is technically proven, MVR is expected to be economically attractive where boiler replacement is required at a refinery, or for a greenfield development. This is due to operating cost savings, which offset the capital cost of MVR installation compared to fossil fuel boilers.[90]

The industry currently expects that MVR technology will be the preferred technology for decarbonising the Bayer process at low temperature alumina refineries in Australia (refer to Section 7.1). The use of MVR in high temperature refineries requires further investigation and analysis. Electric boilers may be used instead of, or in support of, MVR in some refineries.

[xii] Co-generation units use steam produced by a boiler at high pressures to generate electricity through a steam turbine. The low-pressure discharge steam is then used for process heating. This is an efficient way to produce both electricity and heat. This electricity produced can then power other aspects of the refinery such as pumps, motors, and other ancillaries.

4.3 Electric boilers

4.3.1 Description

Electric boilers can be used to generate primary steam needed in the alumina refining process. This technology can be used for both low and high temperature refineries in place of coal or gas fired boilers. Although electric steam generation technology operating at the pressure required for high temperature refining (approximately 50 Bar) has not yet been commercially proven, it is considered the most prospective decarbonisation technology to generate steam for high temperature refineries.[91]

Electric boilers have higher operating costs than current fossil fuel fired boilers. Since electric boilers are a relatively mature technology, there is lower potential for further cost reductions through innovation. Access to low-cost renewable electricity or other financial support mechanisms, for example may be required to make this technology economically viable.[92]

4.3.2 Emissions reduction and abatement potential

Steam generation is responsible for up to 70 per cent of the carbon emissions of an alumina refinery. Where electric boilers powered by renewable energy replace conventional fossil fuel fired boilers to produce steam, the avoidance of fossil fuels would substantially reduce or eliminate refining emissions in the Bayer process.

Electric boilers can also be used as a stand-alone option for generating process heat where MVR is not feasible. Alternatively, electric boilers may be used in conjunction with technologies like MVR, where MVR is unable to provide steam at the required high temperatures and pressures. This approach will be particularly relevant for high temperature refineries.

4.3.3 Implementation in existing refineries

Electric boilers are currently being implemented in some overseas jurisdictions, specifically Brazil and Ireland, where low-cost electricity is available.[93] Electric boilers at low temperature are a mature technology that offers a near-term solution for reducing refining emissions. However, there are significant operating costs and capital costs associated with the electricity supply infrastructure and potential site-based constraints on implementation. For example, there may be insufficient on-site area for additional equipment and electrical supply infrastructure.

4.4 Hydrogen calcination

4.4.1 Description

Replacing natural gas with renewable hydrogen could eliminate emissions from the calcination process, which represents up to 30 per cent of alumina refining emissions. Combusting hydrogen directly with oxygen (known as oxy-firing) releases pure steam as a combustion product. Additional steam is also generated as a result of the calcination process by removing chemically bound water from the alumina trihydrate. This steam stream is potentially suitable for use in the refinery. MVR can be used to capture and recycle this steam in the Bayer process, thereby improving energy efficiency, reducing steam production and reducing water consumption.[94]

In contrast, current calciners combust natural gas in air, discharging an exhaust flue gas-stream consisting of nitrogen, carbon dioxide and water vapour (steam). The steam in the current technology arrangement cannot be economically separated from other flue gases and therefore, cannot be readily reused in refineries.

Replacement of natural gas with hydrogen would require very low-cost hydrogen to be cost-competitive on a GJ for GJ basis. However, the potential to capture the pure steam stream from oxy-firing hydrogen calcination and reuse it in the Bayer process improves the economics of hydrogen calcination.

Another advantage of hydrogen calcination is that a buffer of hydrogen fuel can be stored on-site or off-site as a form of energy storage. This avoids the need for electrical or thermal storage.

Using hydrogen instead of natural gas is currently not economically feasible, nor is hydrogen currently available at the scale required. For renewable hydrogen to be cost competitive, large external infrastructure development is required to bring down the cost of hydrogen production and provide this at the required scale. The industry will likely look to use hydrogen at scale if the production cost of hydrogen trends below $2 per kilogram.[95]

The techno-economic feasibility of hydrogen calcination technology is currently being investigated by Rio Tinto through laboratory testing at its Bundoora research facility.

Case Study: Investigating hydrogen calcination in alumina refining

In August 2021, Rio Tinto and Sumitomo Corporation announced a partnership to study the construction of a hydrogen pilot plant at Rio Tinto's Yarwun Alumina Refinery in Gladstone and explore the potential use of hydrogen at the refinery.

The two global companies have signed a letter of intent that focuses on Yarwun as the location for a Gladstone hydrogen plant that Sumitomo has been studying. If the project proceeds, the pilot plant could also produce hydrogen for the Gladstone Hydrogen Ecosystem announced in 2021.

The partnership complements a $1.2 million technical feasibility study into using hydrogen to replace natural gas in the calcination process at the Yarwun Alumina Refinery. The study received $0.58 million funding from ARENA.[96] The study aims to:

- Investigate the technical feasibility of replacing natural gas with hydrogen as part of the calcination of gibbsite in alumina refining
- Investigate the technical and safety implications for retrofitting hydrogen burner in its existing calciners.

4.4.2 Emission reduction and abatement potential

Alumina calciners in Australia are powered by natural gas with energy intensity of 3 GJ/tonne of alumina produced.[97] Calcination at Australian alumina refineries produces approximately 3.5 $MtCO_2$-e per annum.[98] If this energy was provided from renewable sources, emissions from the calcination process could be significantly reduced or eliminated.

Calcination emissions could potentially be reduced to zero if the process is fuelled entirely by renewable hydrogen. If hydrogen calcination was implemented across Australian alumina refining, this could eliminate the existing 3.5 $MtCO_2$-e per annum from the calcination process.[99] Further, steam released by oxy-fired hydrogen calcination can be reused in the Bayer process, leading to further emissions reduction. When combined with electric steam generation, hydrogen calcination could reduce a refinery's emissions by up to approximately 98 per cent. Further, the combination of these technologies could also reduce water consumption.[100]

4.4.3 Implementation in existing refineries

Hydrogen calcination technology requires less infrastructure changes on-site than electric calcination, reducing the capital intensity of implementation.[101] Hydrogen calcination could subsequently have a lower capital cost for alumina refineries than electric calcination assuming that hydrogen production would be undertaken off-site by third parties. However, the cost of renewable hydrogen means that operating costs are expected to be higher than electric calcination.[102]

Due to losses occurring in the conversion from renewable energy to hydrogen, electric calcination is more energy efficient than hydrogen calcination. However, the proximity of some alumina refineries to proposed large-scale hydrogen production projects in Australia could potentially improve the cost competitiveness of hydrogen calcination. Hydrogen projects or hubs enable hydrogen suppliers and consumers to share key infrastructure between ecosystem partners, which significantly reduces costs for individual organisations. Figure 2.1 shows the location of refineries relative to planned hydrogen hubs announced under the Clean Hydrogen Industrial Hubs Program – Hubs implementation Grants.

Both hydrogen and electric calcination are prospective decarbonisation technologies and application may be site-dependent, reiterating that there is no one-size-fits-all solution.

4.5 Electric calcination

4.5.1 Description

Electric calcination aims to replace the combustion of fossil fuel sources with electric heating. Similar to hydrogen calcination, electric calcination produces pure steam that can be captured and recycled in the Bayer process, which reduces the need for other boiler or MVR generated steam.[103]

Electric calcination is expected to require thermal storage to ensure continuous supply of thermal energy to the calciners.

Thermal storage provides refineries with additional flexibility to reduce grid electricity imports during peak pricing events, thereby improving the economics of electric calcination. This additional load flexibility also allows refineries to participate in demand management, providing additional benefits to the broader energy network.

Electric calcination is at an early stage of development with low technology readiness level (TRL 4). It is capital intensive and requires low-cost, large-scale, firm renewable electricity to be viable.[104]

The techno-economic feasibility of electric calcination technology is currently being investigated by Alcoa through a pilot scale demonstration at its Pinjarra Alumina Refinery.

Case Study: Demonstration of electric calcination in alumina refining

In April 2022, Alcoa announced that it will demonstrate electric calcination technology at its Pinjarra Alumina Refinery, with $8.6 million funding support from ARENA and $1.7 million from the WA Clean Energy Fund. This project is a first-of-a-kind demonstration of electric calcination in Australia.

Alcoa's main objective for the project is to demonstrate the technical and commercial feasibility of using electric calcination technology powered by renewable energy. Stage 1 will investigate the techno-economic feasibility of integrating electric calcination powered by renewable energy and consider the commercialisation pathway under retrofit and growth scenarios. Stage 1 includes design and construction of a 140 kW field pilot with the capacity to calcine 200 kg per hour of alumina at Alcoa's Pinjarra Alumina Refinery. Stage 2 involves the detailed design, procurement, construction, operation, and performance testing of a 1,400 kW field pilot with the capacity to calcine approximately 2,000 kg per hour of alumina at the Pinjarra Alumina Refinery.[105]

The project aims to:

1. Improve understanding of the techno-economic feasibility of electric calcination powered by renewable energy as a low emissions technology under growth and retrofit scenarios in Australia
2. Improve understanding of the economic benefits that renewably powered electric calcination can achieve through increased load flexibility and the provision of Western Australian South-West Interconnected System Essential System Services
3. Demonstrate techno-economic performance of electric calcination powered by renewable energy at pilot scale within an operational alumina refinery to de-risk technology development

4.5.2 Emissions reduction and abatement potential

As previously highlighted in Section 4.5.1, electric calcination has the potential to eliminate some or all emissions from the calcination process by replacing fossil fuels with renewable energy. If implemented at all Australian refineries, this could cut Australian emissions by approximately 3.5 $MtCO_2$-e per annum.[106] This technology can also partially meet a refinery's need for process steam in the Bayer process, supporting further emissions reduction.

When combined with MVR (refer to Section 4.2), electric calcination could reduce a refinery's carbon emissions by up to 98 per cent, energy intensity by approximately 50 per cent as well as reducing water consumption.[107]

4.5.3 Implementation in existing refineries

Currently, there are high costs associated with retrofitting electric calcination to existing refineries.[108] Retrofits can involve upgrades to electricity supply infrastructure with likely existing technical constraints on implementation.

4.6 Electric calcination or hydrogen calcination

Electric calcination is more capital intensive than hydrogen calcination because, unlike hydrogen calcination, it cannot easily be retrofitted. However, electric calciners have lower relative renewable energy demand due to the relatively higher efficiency of using renewable electricity to produce heat in comparison to producing hydrogen for hydrogen calcination.

Hydrogen calciners have higher operating costs when compared to electric calciners due to the high cost of hydrogen supply.[109] However, hydrogen calciners may have a stronger business case where the facility is in close proximity to a hydrogen hub such that infrastructure can be shared with nearby industries.

Both technologies offer the same emissions reduction potential through the elimination of fossil fuels in the calcination process. Ultimately, the decision to install electric or hydrogen calcination will be highly site-specific.

4.7 Enabling and other technologies/ processes

Other decarbonisation technologies have also been identified to reduce emissions from alumina refining and/or improve the economic viability. These are summarised below.

4.7.1 Thermal Storage

A thermal storage system can store and supply heat energy to the alumina refining process. This may be more cost effective than alternatives such as batteries. The integration of thermal storage is critical to enable the uptake of the Key Decarbonisation Technologies.

Batteries, pumped hydro and other electricity storage technologies can be used to firm electricity supply from variable renewable energy sources such as wind and solar. Similarly, thermal storage can be deployed on-site at alumina refineries to ensure continuous supply of thermal energy to refineries.[110] Thermal energy storage can also improve the economics of Key Decarbonisation Technologies by enabling refineries to take advantage of low-cost renewable energy during certain periods and use energy from thermal storage when grid energy pricing is high.

4.7.2 Electrical Storage

For electrical storage requirements, Australian refineries would require both long- and short-term storage options to maintain their current refinery operations. Long-term grid-based electrical storage would store energy over 1-2 months to cover periods of electricity scarcity (due to the seasonal transition between wet and dry seasons in QLD and the "shoulder" seasons of Spring and Autumn in WA).[111] The short-term storage would be less than 8 hours to facilitate alumina production during periods of no wind and solar.[112] Potential longer-term storage for alumina refining will require gigawatt-scale storage capacity and as a result will likely be developed off-site.[113] The use of both electrical and thermal storage can support the supply of firm variable renewable energy to alumina refining processes.

4.7.3 Double Digestion

Double digestion technology could act as an enabler of MVR adoption in high temperature plants. This process involves two distinct digestion steps at different temperatures (high and low), which can result in more energy efficient plant operations. In particular, this technology allows for processing of boehmitic bauxite with less energy than the current single stage high temperature processes used for this particular type of bauxite.[114]

In high temperature refineries, this could allow the low temperature digestion to occur using MVR and the high temperature digestion to occur using electric boilers. Double digestion in high temperature refineries could simultaneously provide a substantial reduction in total energy requirement and also enable use of MVR technology, thereby delivering deep cuts to emissions.

4.7.4 Concentrated Solar Thermal

Concentrated Solar Thermal (CST) can concentrate sunlight producing high temperatures. This heat can be captured and used to produce steam, or it can be stored overnight with thermal storage.[115] This means that steam can still be generated when the sun is not shining.[116] Some applications under investigation currently include provision of steam for digestion, solar reforming of natural gas and directly in solar calcining.[117] There is also an ARENA funded study being delivered by the University of Adelaide, which is investigating the integration of CST into the Bayer process.[118] Steam can be produced directly up to 500°C for 80 bar, while power tower technology can produce 1000°C suitable for calcination. Limitations with CST are that it requires very good solar energy resources, adequate land area adjacent to the refinery and has relatively high capital costs.[119]

4.7.5 Biomass

Cogeneration facilities can be co-fired with biomass instead of coal. However, due to the lack of availability of large volumes of sustainably sourced biomass at a commercially competitive price point and in close proximity to the point of consumption, the feasibility of biomass in alumina refinery applications is low.[120]

4.7.6 Organic Rankine Cycle and Kalina Cycle

The Organic Rankine Cycle and Kalina cycle are technologies to generate electricity from low grade waste heat sources. The Organic Rankine Cycle uses organic working fluids with low boiling points to recover heat from lower temperature heat sources. The Kalina cycle uses an ammonia-water mixture as the working fluid for this process.[121]

These cycles have been demonstrated since the 1990's for waste heat recovery.[122] However they do not directly displace the consumption of fossil fuels for process heating and therefore rely on other Key Decarbonisation Technologies to achieve meaningful emissions reduction. Furthermore, the efficiency of the refining process should be optimised using the Key Decarbonisation Technologies first to minimise waste heat, before considering the application of these waste heat to energy technologies.

4.7.7 Carbon Capture, Utilisation and Storage

Carbon Capture, Utilisation and Storage (CCUS) technologies capture direct CO_2 emissions to use as an input for another industrial process or to be stored permanently underground. However, the current high cost attributed to this technology makes it cost prohibitive for industry deployment.[123] Therefore, technologies which reduce emissions through the uptake of renewable energy, or improved efficiency are expected to be more economic than CCUS technologies. In addition, the technical feasibility varies depending on the regional geography and the specific technology used to enable CCUS.

4.7.8 Other process improvement

Emissions reductions can be achieved by switching to less emission intensive fuels. For example, bituminous coal is approximately 1.8 - 2.1 times more emissions intensive than natural gas.[124] Therefore, refineries that switch from coal to natural gas will reduce their emissions.

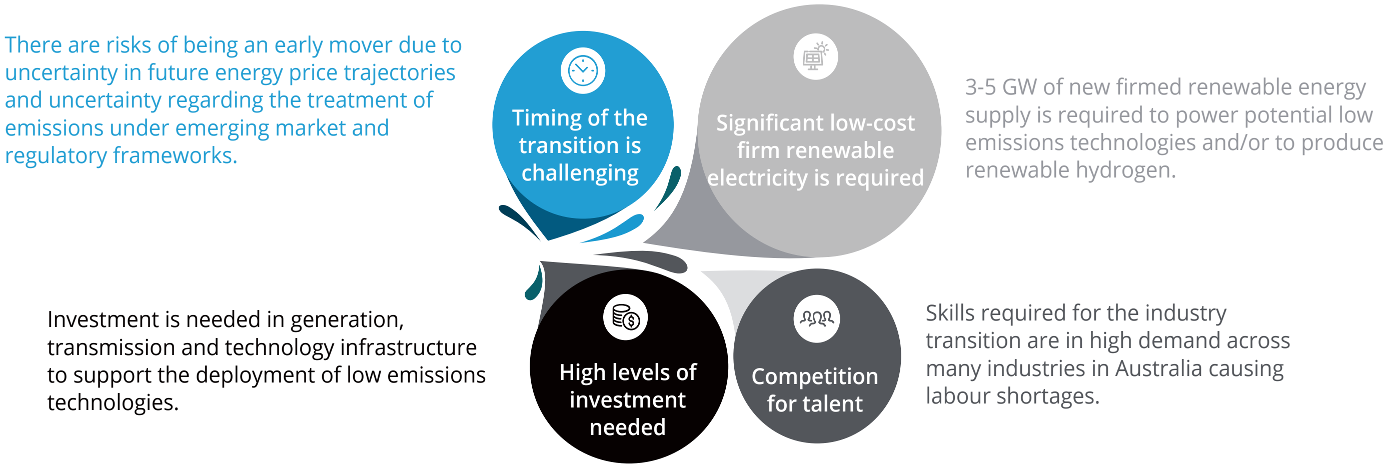
As the scope of this report focuses on emerging technologies that provide a pathway to achieve net zero emissions, opportunities for fuel switching from coal to natural gas and other process improvements have not been explored in detail.

5. Barriers and opportunities to decarbonisation

5.1 Key barriers to achieving the future state

During the workshops, a range of barriers and opportunities for decarbonisation were identified and discussed. Four key barriers were consistently raised throughout the workshop series (refer to Figure 5.1).

Figure 5.1: Key barriers raised in workshops[xiii]

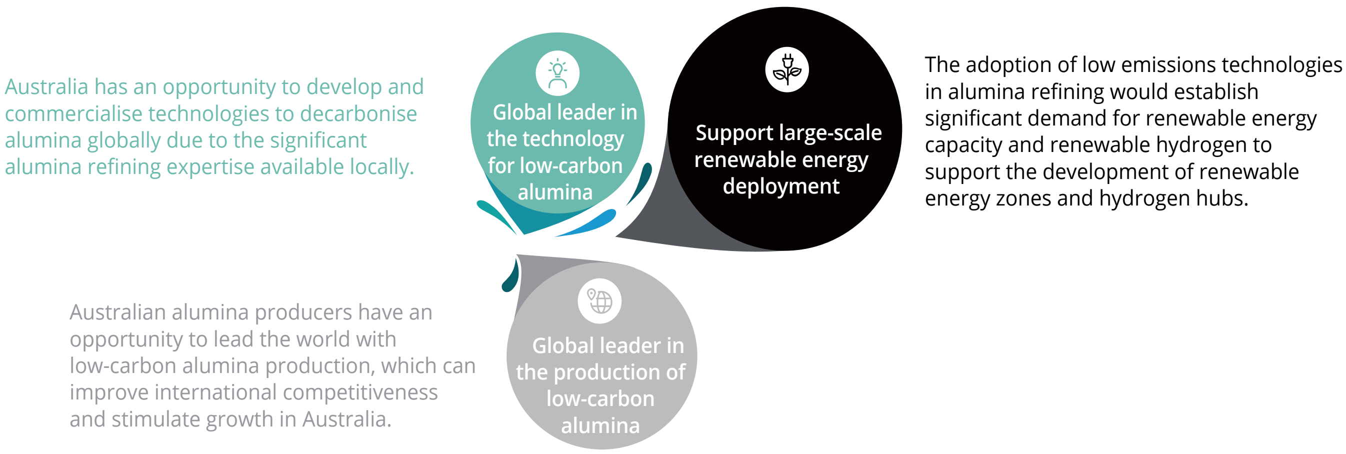


Source: Deloitte, using Participants' input.[125]

5.2 Key opportunities in achieving the future state

Three key opportunities were also identified throughout the workshop series (refer to Figure 5.2).

Figure 5.2: Key opportunities raised in workshops



Source: Deloitte, using Participants' input.[126]

[xiii] 3-5 GW of new electricity is a range based on participant discussion. Refer to Executive Summary for further detail.

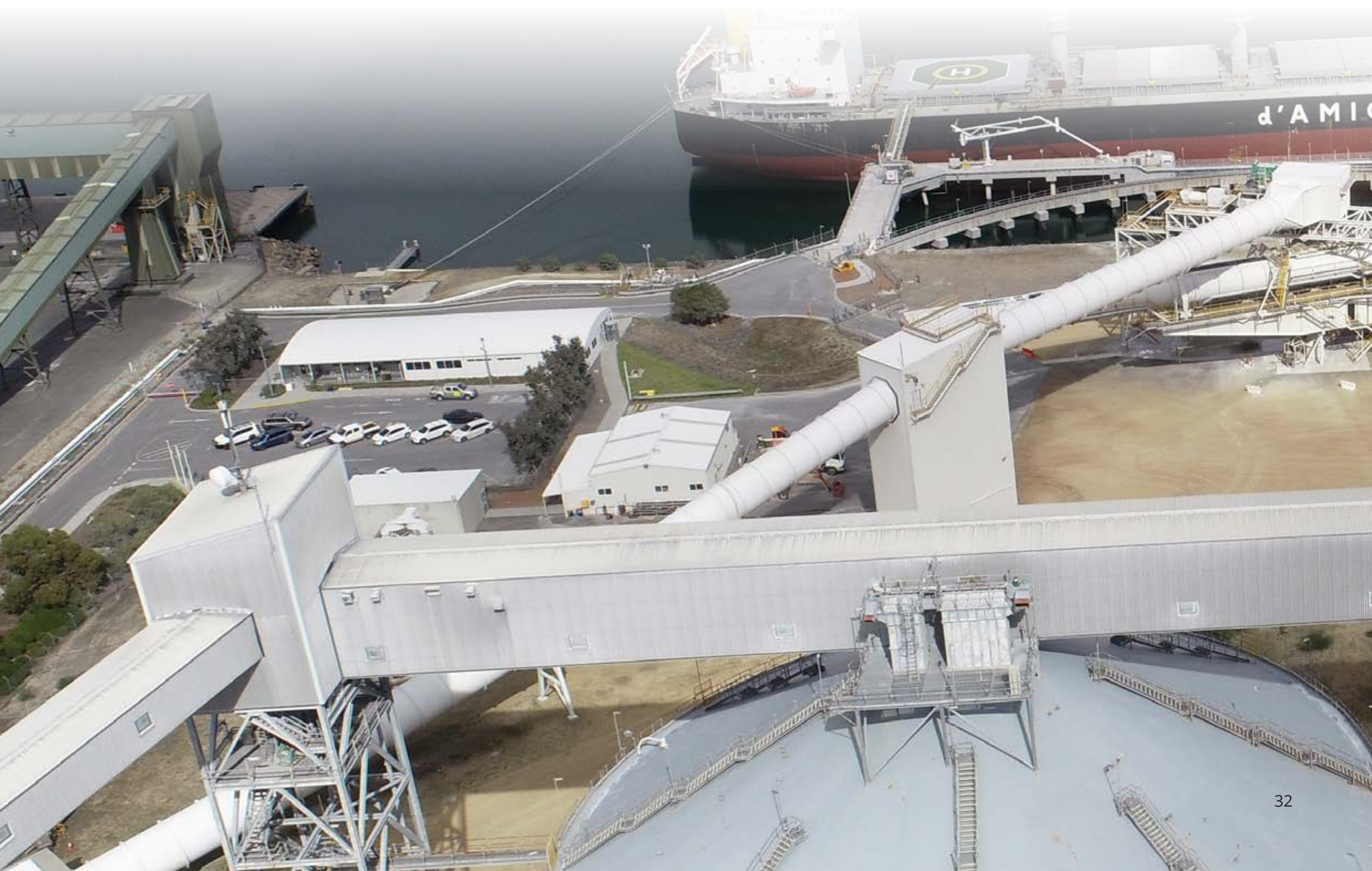
5.3 Collaboration to achieve these opportunities and overcome barriers

During the early stages of technology development, most alumina industry refiners are expected to independently advance technologies by relying on their own internal capabilities. As technologies become more mature, coordinated action or joint ventures by inter-industry and intra-industry stakeholders may be beneficial to share risks and development costs.

Collaboration with adjacent industries that are also investigating large-scale electrification can support the development of large-scale renewable energy generation and renewable hydrogen production capacity. Participants identified that alumina refining industry collaboration on electricity market modelling for different scenarios could be valuable to inform planning decisions and ensure coordinated investment in shared infrastructure.

The unique configuration of individual refineries means that there is no one-size-fits-all solution and this can impact opportunities for collaboration. However, collaboration can assist in overcoming the barriers highlighted in Section 5.1 by increasing government engagement and facilitating the deployment of shared infrastructure. Collaboration through knowledge sharing also helps to avoid duplicating studies and demonstration projects, thereby reducing investment during early stages of technology advancement.

Australian alumina refining stakeholders have the potential to benefit from collaboration by improving the international competitiveness of Australian alumina exports and stimulating growth in the Australian alumina industry.



6. Ecosystem implications and benefits

6.1 Overview

The Roadmap (refer to Figure 7.1) has implications extending beyond the alumina refining industry. Low emissions technologies can support large-scale renewable energy deployment as foundation customers or major offtakers and offer greater load flexibility to support the stability of the energy system, thereby providing wider ecosystem benefits. However, the Key Decarbonisation Technologies will also require firmed energy supply through grid-based electricity storage, on-site thermal energy storage and hydrogen storage (refer to Figure 6.1).

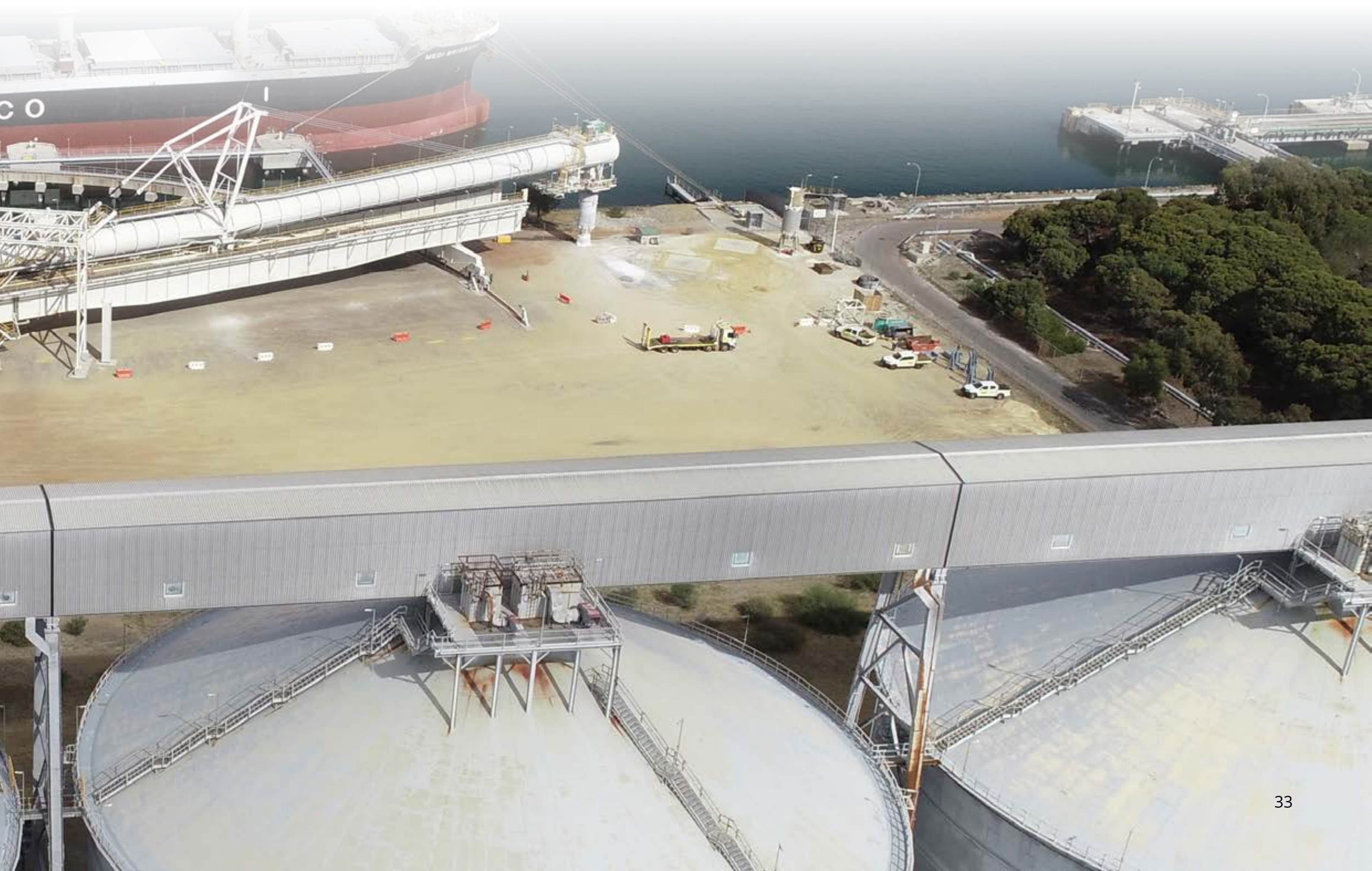
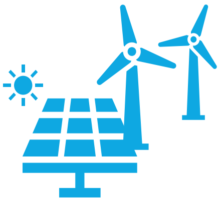


Figure 6.1: Implications for supporting ecosystem infrastructure

Implications for supporting infrastructure

Theme 1: Large-scale renewables implementation



Increased demand for renewable energy

- Alumina refiners are currently large users of coal and gas, however the adoption of low emissions technologies enables refineries to utilise renewable electricity and hydrogen in the future. This is expected to **result in 3-5 GW** of new firm electricity demand.
- A recent example driving demand for large-scale renewables includes Rio Tinto's formal request for proposals to supply renewable energy to their Gladstone assets (the Yarwun refinery, QAL refinery and Boyne smelter). These assets require approximately 4 GW of solar and wind capacity with firming.
- The alumina industry could act as anchor customers for new large-scale renewable energy projects, which can help to address the future renewable capacity requirements in our electricity systems.

Transmission infrastructure requirements

- Significant transmission infrastructure will be required to power alumina refineries with renewable energy in the future.
- Upgrades to existing infrastructure and development of new infrastructure may be needed in specific locations of the WEM and NEM.
- The potential energy requirements of future alumina refineries should be considered when planning network augmentation and transmission infrastructure investment.

Reduction in total energy demand

- The key technologies identified in this report could facilitate a step change in energy efficiency and materially reduce the total energy demand of alumina refineries (relative to traditional power generation).
- Due to the potential energy efficiency improvements, the expected future alumina refining industry demand for renewable energy could be less than the current demand from fossil-fuel sources. Overall, there will still be an increase in renewable energy demand.
- These gains in energy efficiency reduce the overall investment needed in additional energy generation and as a result, improve the business case for decarbonising the alumina refining industry.

Source: Deloitte, using Participants' input.[126]

[xiv] 3-5 GW of new electricity is a range based on participant discussion. Refer to Executive Summary for further detail.

Implications for supporting infrastructure

Theme 2: Future energy system stability

Increased demand for renewable energy

- Energy reliability is essential for alumina refining and many other industries. Alumina refineries overwhelmingly use energy in the form of heat. As a result, providing continuous and reliable heat from variable renewable energy sources is central to the challenge of decarbonisation.
- Energy storage can provide firming to overcome reliability challenges from variable renewable energy supply.
- Energy storage is likely to be a mix of grid-based electricity storage, on-site thermal energy storage and hydrogen storage. Many of these storage technologies are in early stages of development and the optimal mix is not yet known.

Flexible energy demand

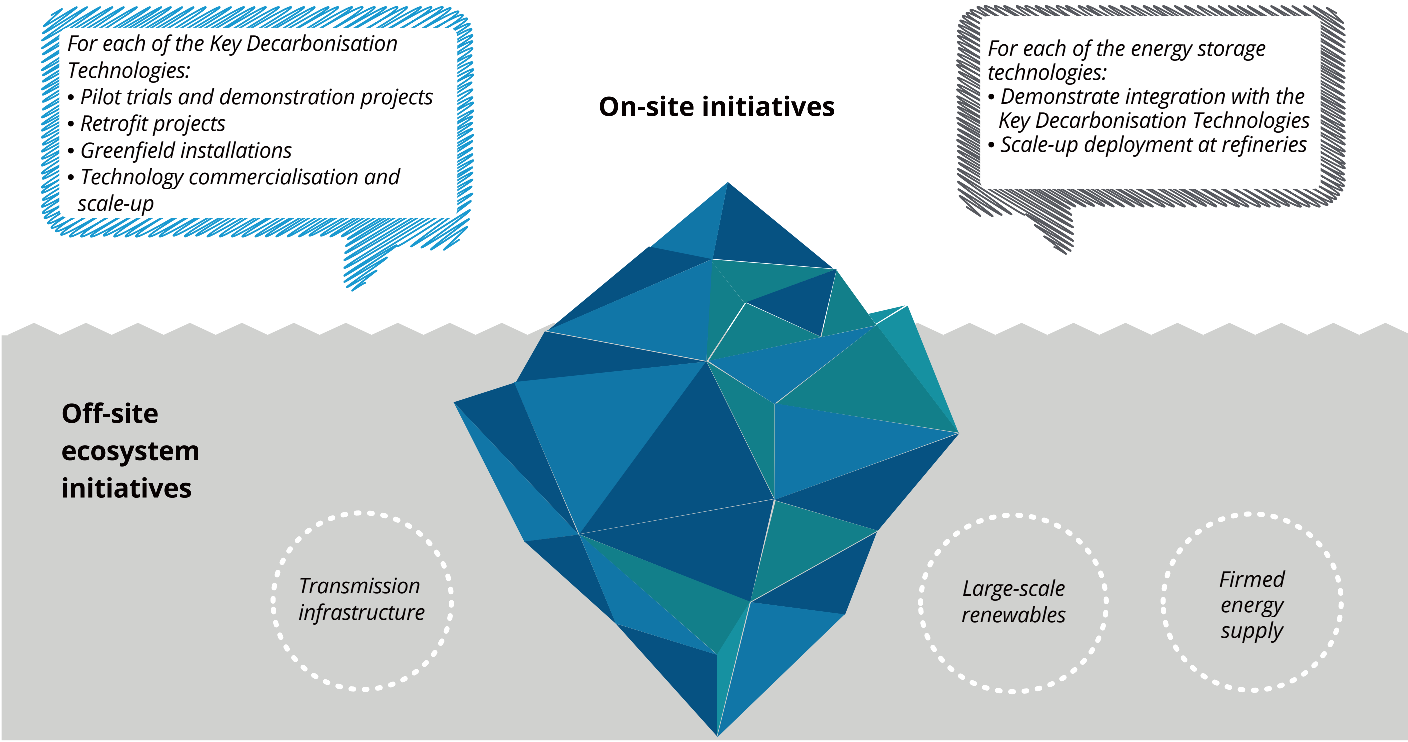
- Designing low-carbon alumina refineries to operate in a more flexible way will allow alumina refineries to support the transition of the electricity system to a higher share of variable renewable energy.
- While refineries need a firmed supply of heat energy, electrification technologies combined with on-site thermal energy storage would enable refineries to provide demand response and reduce the load on the grid during peak pricing events.
- Hydrogen production combined with storage can also provide a flexible load to the grid to utilise excess renewable energy supply.
- The ability to avoid peak pricing events and potentially support system security will improve the business case for the Key Decarbonisation Technologies.

Source: Deloitte, using Participants' input.[126]

6.2 On-site and off-site ecosystem initiatives

Decarbonisation will require both on-site initiatives and off-site ecosystem initiatives to be coordinated. Off-site ecosystem initiatives include higher levels of renewable energy generation within the NEM and WEM, along with supporting transmission and storage infrastructure. A list of on-site and off-site ecosystem initiatives are shown below in Figure 6.2.

Figure 6.2: On-site and off-site ecosystem initiatives



Source: Deloitte, using Participants' input.[126]

7. Alumina refining decarbonisation Roadmap

7.1 Overview

The Roadmap (refer to Figure 7.1) identifies opportunities for alumina refiners, government, regulators, and energy market participants to collaborate and coordinate investment for the development and implementation of low emissions alumina refining. The Roadmap outlines a high-level framework for decision points, investment, and timing, while focusing on initiatives to decarbonise alumina refining in Australia. Please refer to Figure 7.3 for details regarding the initiatives shown in Figure 7.1.

As the Key Decarbonisation Technologies are currently under development, the Roadmap provides two abatement pathways, namely:

- An 'Innovator Abatement Pathway', where technologies are deployed quickly (over 5 years) by refiners once they have reached technology maturity (i.e. TRL 9). This pathway assumes no technical or commercial barriers to investment.
- A 'Gradual Abatement Pathway', where technologies are deployed over a longer timeframe (over 10 years) once they have reached technology maturity (i.e. TRL 9) to reflect potential capital constraints, staged deployment and evolving regulatory frameworks. However, this pathway remains in line with targets to achieve net zero by 2050.

The abatement pathways shown in Figure 7.1 only consider the potential abatement that can be achieved through implementation of the Key Decarbonisation Technologies. Potential abatement from other process improvements discussed in Section 4.6 are excluded from this analysis. The pathways also assume Key Decarbonisation Technologies are successfully commercialised and are powered by 100 per cent renewable energy. The Roadmap has been modelled using a sigmoid function to simulate slow initial uptake of technologies, followed by acceleration over the medium-term once technologies are proven at scale. Slower decarbonisation is then assumed in the final stages of technology deployment to achieve 100 per cent implementation across the industry. Details of the underlying assumptions to model the abatement pathways are contained in Appendix B.

Technical complexity, poor access to large-scale renewable energy capacity or unfavourable economic conditions could delay technology deployment. Conversely, continual innovation, evolving consumer preferences and emerging regulatory frameworks could accelerate technology deployment. The drivers, which can slow or accelerate adoption of these Key Decarbonisation Technologies, are discussed in Section 7.2.2. The abatement pathways illustrate the significant challenges for the alumina industry to decarbonise operations.

The Key Decarbonisation Technologies have the potential to eliminate up to 98 per cent of emissions at alumina refineries. This corresponds to all emissions relating to the Bayer and calcination processes. Additional solutions such as carbon offsets may be required to abate residual emissions and reach net zero.

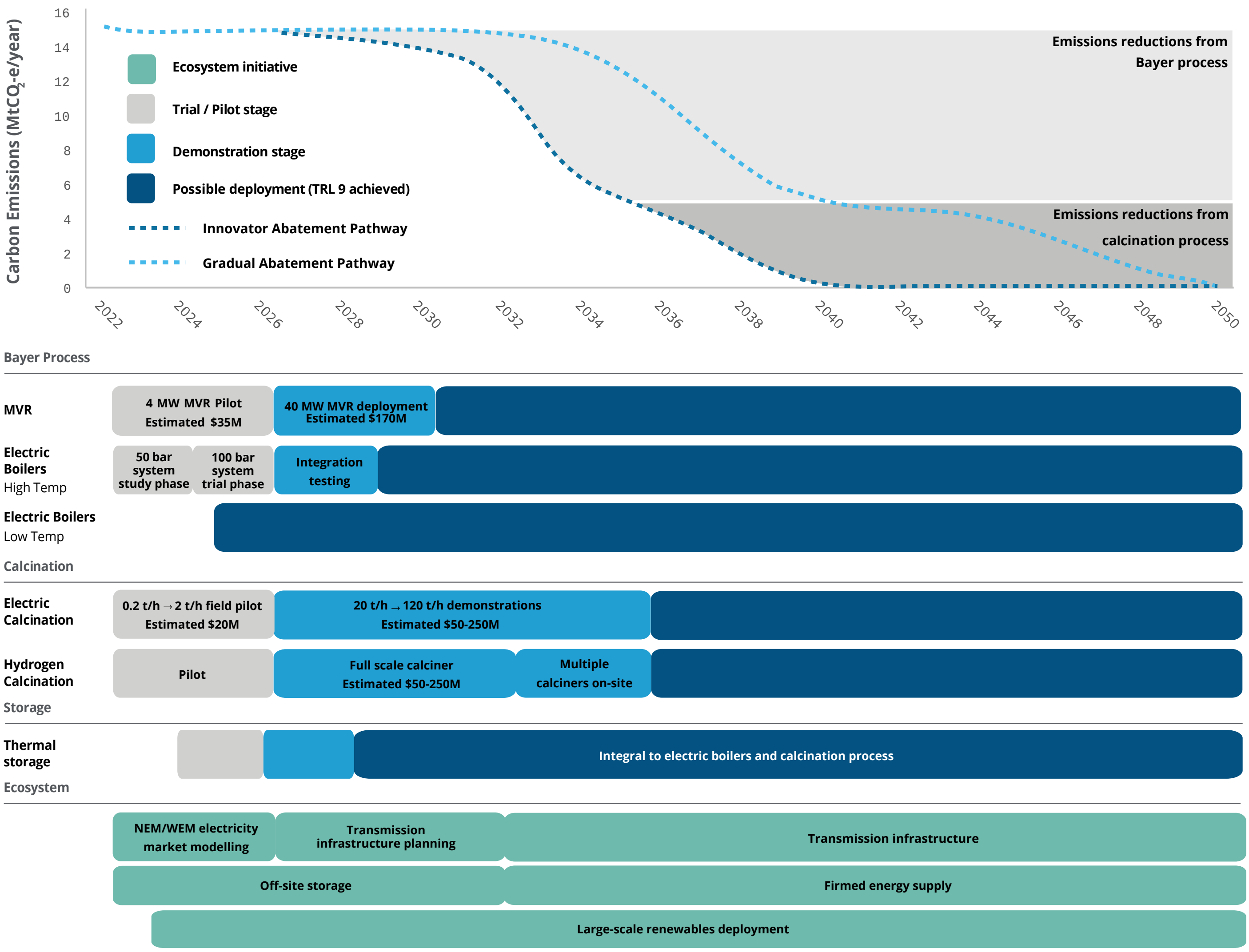
Future scope 2 emissions from grid sourced electricity may result in a different emissions profile than those modelled in Figure 7.1. Detailed modelling of refineries' grid electricity demand and scope 2 emissions is beyond the scope of the Roadmap. However, the workshops identified this modelling as a priority for further investigation.

The workshops identified approximate timelines for when the Key Decarbonisation Technologies are expected to become more mature and suitable for commercial-scale deployment (refer to Figure 7.1). The TRL framework (refer to Figure 4.3) is used to assess the maturity of technologies at different stages of development.

The abatement pathways assume that the Key Decarbonisation Technologies must achieve TRL 9 before they can be implemented at refineries at full scale. The timeframes of these steps are influenced by numerous factors and individual stages can sometimes be achieved concurrently.

With respect to the deployment of specific technologies, Bayer technologies (MVR and electric boilers) are expected to become viable by 2030, whereas hydrogen and electric calcination are assumed to be deployed from 2035 due to challenging economics, lower levels of technical maturity and the long development time frames of these technologies. Near-term initiatives include pilot trials and technology demonstrations, which aim to develop technologies to TRL 9. However, these deliver limited emissions abatement due to the sub-scale nature of those initiatives. Consequently, in both emission abatement pathways, limited reductions in emissions are seen until 2030, when the Key Decarbonisation Technologies are expected to be proven and viable.

Figure 7.1: Roadmap until 2050 with emissions abatement pathways and staging for key on-site and off-site ecosystem initiatives to achieve an 'Innovator Abatement Pathway'



Note: Refer to Appendix B for decarbonisation pathway assumptions.
Source: Deloitte, using Participants' input.[126]

7.2 Roadmap initiatives and implementation timeframe

The Roadmap timeframe focuses on three key time phases, namely:

1. Immediate initiatives to 2025
2. Near-term initiatives to 2030
3. Medium-term initiatives beyond 2030

Figure 7.2 shows the Roadmap for the development of Key Decarbonisation Technologies through a series of initiatives over these timeframes. The Roadmap addresses steps required to decarbonise the Bayer and calcination processes. It also explores the key ecosystem initiatives previously discussed in Section 6 in more details. These ecosystem initiatives can accelerate the uptake of low emissions technologies in the alumina refining sector. The timing of initiatives is based on the 'Innovator Abatement Pathway' shown in Figure 7.1.

Figure 7.2: Details of on-site and ecosystem initiatives required over the Roadmap timeframes to achieve the 'Innovator abatement pathway'

Bayer | Calcination | Ecosystem

Today to 2025

MVR
- MVR pilot trials undertaken at Australian refineries.
- Alcoa is currently trialling a 4 MW MVR compressor train at its Wagerup alumina refinery.

Electric boilers
- Feasibility studies (50 bar) and pilot trials (100 bar) begin at Australian refineries for high temperature and pressure applications.
- Low temperature electric boilers are technically mature and ready to deploy.

Electric calcination
- Pilot trials of electric calcination at Australian refineries (0.2 tonnes of alumina produced per hour (t/h) to 2 t/h field pilot).
- Alcoa is currently trialling electric calcination at its Pinjarra alumina refinery.

Hydrogen calcination
- Studies and pilot trials of hydrogen calcination at Australian refineries.
- Rio Tinto is currently investigating the feasibility of hydrogen calcination technology for its Gladstone refineries.

Ecosystem
- Increasing supply of low-cost, firm renewable energy and increasing scale of large-scale renewables projects.
- Ongoing research and modelling to understand the impact of alumina refining decarbonisation on the Australian energy market.

Storage and firming
- Ongoing development of medium and long duration storage technologies.
- Feasibility and integration testing is seen for thermal storage technologies at Australian refineries.

2026 to 2030

MVR
- 40 MW MVR completes demonstration stage testing and is technically proven in alumina refining to achieve TRL9.
- Increasing scale of MVR deployments at Australian refineries.

Electric boilers
- Integration into high temperature and pressure refineries.
- Electric boilers are proven at high temperature and high pressure to achieve TRL9. Increasing scale of electric boilers at Australian refineries.

Electric calcination
- Continued development of electric calcination, progressing towards TRL9.
- Increasing scale of electric calcination (20 tonnes of alumina produced per hour (t/h) to 120 t/h) deployments at Australian refineries.
- Electric calcination is demonstrated in combination with MVR to enable steam capture and recycling.

Hydrogen calcination
- Full-scale calciner retrofit and 100 per cent hydrogen fuelled calcination testing, progressing towards TRL 9.
- Multiple hydrogen calcination projects are demonstrated in combination with MVR to enable steam capture and recycling.

Ecosystem
- Increasing investment in transmission infrastructure accommodates greater renewable energy capacity.
- Increasing cost competitiveness of renewable hydrogen and growing market and supply chain maturity.
- Emergence of market and regulatory mechanisms which incentivise low-carbon alumina production.

Storage and firming
- On-site and off-site energy storage integrated at refineries to increase the security and reliability of energy supply.

Beyond 2030

MVR
- MVR is technically mature and economically viable.
- Increasing deployment of MVR at large-scale for suitable Australian refineries.

Electric boilers
- High temperature and high pressure electric boilers are deployed for steam generation at suitable Australian refineries.

Electric calcination
- Electric calcination reaches technical maturity and becomes economically viable in growth scenarios.
- Full-scale demonstration of electric calcination at Australian refineries.

Hydrogen calcination
- Hydrogen calcination is technically mature and economically viable in retrofit scenarios.
- Increasing deployment of hydrogen calcination at suitable Australian refineries.

Source: Deloitte, using Participants' input.[126]

7.2.1 Drivers to accelerate timing of initiatives

Several drivers will impact the timing of the industry's ability to move from the 'Gradual Abatement Pathway' to the 'Innovator Abatement Pathway' shown in Figure 7.1. These drivers include power pricing, policy mechanisms, financed emissions, ecosystem and consumer demand. Indicators for accelerating the timing of initiatives or alternatively slowing progress towards decarbonisation are shown in Figure 7.3.

Figure 7.3: Key drivers for industry advancing the transition more quickly or more slowly

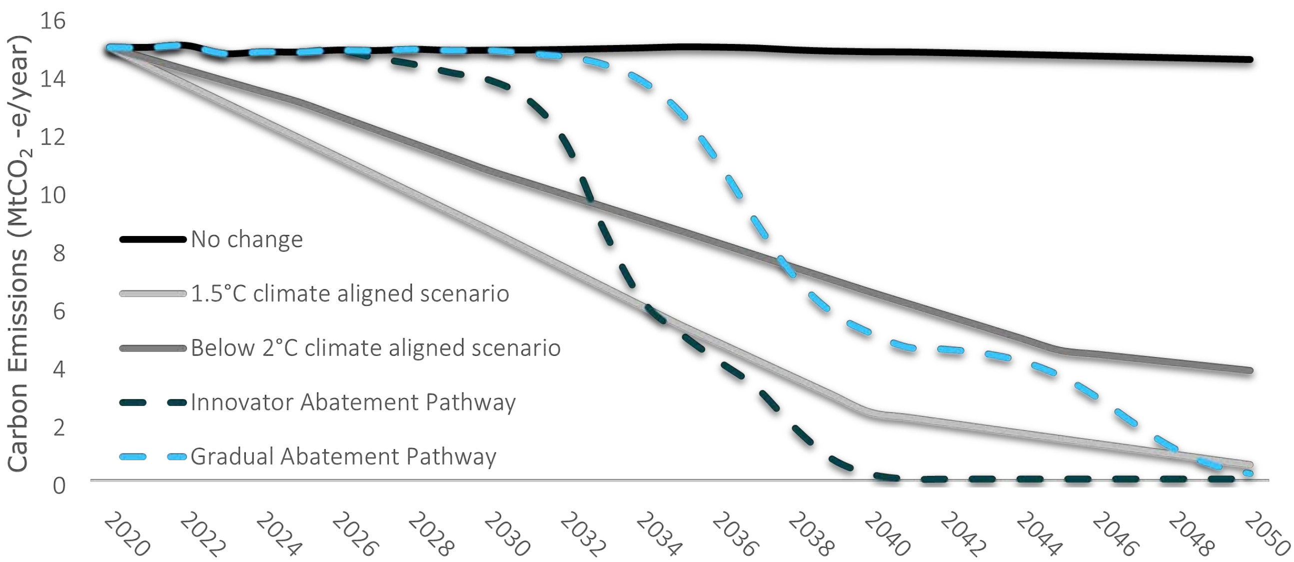
Innovator Pathway	Drivers	Gradual Pathway
• Large-scale renewable implementation occurs with investment from public and private sector. The supply chain for new renewable installations is mature and brings down costs.	**Power pricing**	• Increased volatility in wholesale power pricing leads to uncertain business cases for low emissions initiatives. • Insufficient energy storage and firming to support the uptake of renewable energy supply in the alumina refining industry.
• Carbon border adjustment mechanisms and other carbon price mechanisms increase across alumina export markets improving the business case for low-carbon alumina production. • Federal or State Government energy policy encourages accelerated growth in low emissions technologies. • Alumina refineries reflect the cost of carbon in future investment decisions.	**Policy and mechanisms**	• Carbon price mechanisms move slowly in Australian alumina export markets and have fractured impacts on trade flows. • Competitiveness of Australian alumina is not linked to carbon intensity.
• Financial institutions move quickly towards reducing the emissions intensity of their lending portfolio increasing pressure on high emitting business partners.	**Financed emissions**	• Key sectors for low-carbon aluminium products experience limited demand restricting the value proposition for decarbonisation. • Emissions intensity of financial organisations' portfolios receives limited attention.
• Investment in infrastructure to support manufacturing transition to renewable energy is strong. • Collaboration between industry and government to define ecosystem requirements. • Refineries are incentivised to provide demand flexibility to support higher levels of renewables on the grid.	**Ecosystem**	• Slow transmission and generation infrastructure investment and deployment results in delays for low emissions technology deployment. • High demand from other industries for new renewable energy capacity leads to alumina refining missing out on accelerated renewable asset options. • Individual industries 'go-it-alone' across manufacturing in Australia with limited collaboration and coordination of investment.
• Consumers' growing awareness and demand for low-carbon alumina facilitates growth of a green premium.	**Consumer demand**	• Limited awareness and demand for low-carbon alumina from consumers and along the value chain results in limited green premiums or incentives. Low-carbon alumina is not a large share of the overall alumina market.

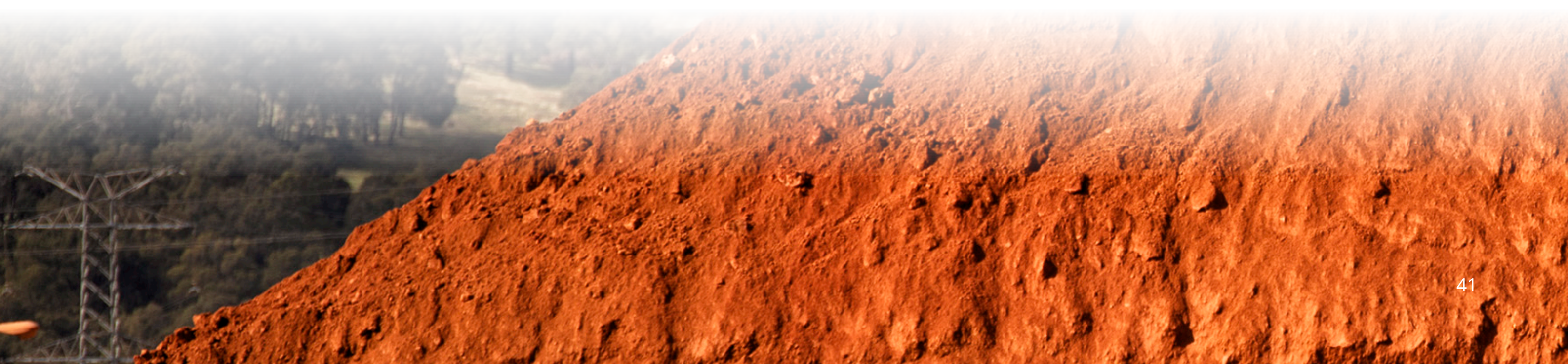
Source: Deloitte, using Participants' input.[126]

7.2.1.1 Alignment of abatement pathways with climate aligned scenarios

The 'Innovator Abatement Pathway' and 'Gradual Abatement Pathway' are shown with an overlay of the climate aligned scenarios in Figure 7.4. Although there is a delayed start in the immediate and near-term, the 'Innovator Abatement Pathway' moves closer to the 1.5˚C climate aligned scenario over the medium-term.

Figure 7.4: Alignment of abatement pathways with climate aligned scenarios.





8. Conclusion

Achieving significant emissions reductions by 2050 will require advances to low emissions technologies and innovation. This must also be combined with widespread adoption of best practices by industry, as well as focused co-investment from both the private and public sectors. Targeting 'hard-to-abate' industries like alumina refining will be critical to meet Australia's climate commitments, while maintaining domestic jobs and economic benefits. The Roadmap provides a framework to assess the potential technologies that could contribute to reduce emissions for the industry, and it is clear that collaboration from industry and government will be integral to the transition to net zero.

Four Key Decarbonisation Technologies have the potential to almost entirely eliminate alumina refining emissions in Australia. Some are considered near-term opportunities (MVR and electric boilers with initial deployment by 2030), whilst others are longer-term considerations (electric and hydrogen calcination with initial deployment by 2035). Yet, despite the material carbon reduction potential of the Key Decarbonisation Technologies, significant barriers to their application remain. The need for high volumes of low-cost firmed renewable energy and, by extension, renewable hydrogen, alongside uncertainties regarding carbon costs, are barriers to accurately projecting supply for low-carbon alumina.

The Key Decarbonisation Technologies are not yet commercially or technologically feasible. However, while the investment required to retrofit refineries with new decarbonisation technologies or replace existing infrastructure with new low emissions capacity to bring them into the realm of commerciality is large, there is also a material cost of inaction and not transitioning when the carbon impacts are considered.

This report seeks to highlight not only the potential carbon reduction technologies available to the alumina refining sector, but also the role of industry in supporting the broader implementation of renewable energy. Australian alumina refining decarbonisation will significantly increase demand for renewable energy, as well as reliable transmission infrastructure, energy storage and potentially renewable hydrogen. To meet this future demand, alumina refineries could act as anchor-customers, providing large-scale and stable demand for renewable energy, or supporting the development of renewable hydrogen projects in industrial regions such as Gladstone and Kwinana. Additionally, as the alumina refining industry is one of Australia's largest users of process heat, transitioning this load to the electricity sector (either through direct electrification or via green hydrogen usage) will require thermal and electrical energy on a scale not seen before. Thermal and electrical energy storage, as well as load flexibility, are all expected to play significant roles in the energy transition.

The Roadmap and report have been produced in consultation with Australian alumina refiners (i.e. Rio Tinto, Alcoa, South32) with all Participants acknowledging the need for action in order to reach net zero by 2050. Decarbonisation efforts in the near-term are limited by not only the pre-commercial nature of the technologies discussed, but also supply chain constraints and commercialisation processes for major projects. The abatement pathways presented in this report highlight how delays to technology development and deployment can impact industry and government targets of net zero by 2050. Therefore, now is the time to act.

In summary, while the Roadmap and report are intended to provide a framework for future policy and investment decisions within Australian alumina refining, it should also be seen as a call to action. A concerted effort from industry and governments is needed to commercialise decarbonisation technologies and transition a traditionally 'hard-to-abate' industry of the Australian economy into one that is at the forefront of the transition to net zero.

Appendix A - Workshop findings

Workshop 1

Workshop 1 focused on decarbonisation technologies for the Bayer process including MVR and other potential decarbonisation technologies to produce renewable steam and heat. This workshop provided an update on the current state of development of MVR and the feasibility of other low emissions technologies to reduce emissions and recover energy in the Bayer process.

The key findings of workshop 1 were as follows:

1. Electrifying steam generation is a feasible decarbonisation pathway using MVR and electric boilers with energy storage.
2. Key challenges for MVR and electric boilers include the high capital cost of deployment, uncertainties in future electricity prices and access to reliable renewable energy capacity.
3. Cost-effective energy storage (electrical and/or thermal) is essential for all solutions to mitigate the variability of renewable energy supply and projected wholesale electricity price volatility.
4. Increased load flexibility could also improve the business case for electrification by enabling alumina refineries to avoid high power price events.

Workshop 2

Workshop 2 focused on decarbonisation technologies for the calcination process including a deep dive on hydrogen calcination and electric calcination. The Participants looked at applications for these calcination technologies, the challenges and feasibility issues and the role that these technologies could play in the decarbonisation pathway. Workshop 2 also explored the transformation of the energy market that would be required to enable the uptake of low emissions technologies and the transition to net zero emissions alumina refining.

The key findings of workshop 2 were as follows:

1. Electric and hydrogen calcination can lead to improved energy efficiency, which improves the feasibility of decarbonisation initiatives.
2. Pathways to decarbonisation need to be further developed with specific timeframes and investment decisions that align with emissions reduction targets.
3. Collaboration with key stakeholders is required to plan and develop the significant supporting infrastructure (whether electricity or hydrogen) needed to support the uptake of low emissions technologies.
4. Different combinations of low emissions technologies will be required at different refineries due to site-specific considerations.

Workshop 3

Workshop 3 focused on additional decarbonisation technologies and potential decarbonisation scenarios. Participants focused on the technology readiness level, impact on sector emissions, and the benefits and constraints of each technology. The required steps for decarbonisation were also discussed.

The key findings of workshop 3 were as follows:

1. The technologies required to decarbonise the alumina refining industry already exist. The main barriers are access to large-scale firm renewable energy supply and the significant capital investment required to deploy low emissions technology.
2. Different refineries have contrasting operating characteristics and will require different combinations of technologies to decarbonise.
3. The challenges and opportunities of each low emissions technology were explored in detail (refer to Section 4 for more details).

Workshop 4

Workshop 4 focused on potential collaboration models towards decarbonisation. Participants focused on collaboration options to achieve strategic objectives on the path to decarbonisation. The workshop involved discussion on ways to overcome barriers that are preventing the transition towards low emissions refining.

The key findings of workshop 4 were as follows:

1. Potential ACCC restrictions, IP sharing and on-site pilot testing of technologies will be key barriers to collaboration between refiners.
2. Due to site-specific considerations, there is no one-size-fits-all solution and the optimal technology mix is likely to be different at each refinery. This limits opportunities to share investment and risk in the development of innovative technologies.
3. Implementing technologies at a specific refinery will benefit one party more than others which limits the ability to share benefits.
4. Knowledge sharing activities for early trials and demonstrations can avoid duplication of studies and reduce R&D investment.
5. Supply of firm renewable energy is critical for refineries and considered by Participants as the highest priority to enable industry decarbonisation. This represents a potential opportunity for refiners to collaborate to ensure coordinated planning and investment in supporting infrastructure.

Workshop 5

Workshop 5 focused on potential decarbonisation pathways and the investment required for net zero alumina production. The workshop looked at the type of initiatives and level of investment needed to commercialise and implement Key Decarbonisation Technologies. Timeframes and pathways to decarbonisation were developed.

The key findings of workshop 5 were as follows:

1. Multiple abatement pathways are available to achieve decarbonisation and the optimal mix of technologies will be different at each refinery.
2. The ongoing economics of Key Decarbonisation Technologies is a limiting factor in the pursuit of low emissions refining.
3. Management of energy consumption is key to future refinery operation and medium-term storage or flexible energy demand can improve the business case.
4. Broader ecosystem challenges associated with alumina decarbonisation will be substantial and will require careful navigation.

Appendix B - Modelling methodology and assumptions

Climate scenario modelling approach
To provide greater spatial resolution to an Australian manufacturing industry focus, the Network for Greening the Financial System (NGFS) Global Change Analysis Model (GCAM) was adopted. The DDS™ tool was used to model the decarbonisation trajectory in alignment with the 1.5˚C and below 2˚C climate scenarios for Australian alumina refining.

The NGFS GCAM model captures Australia's regional energy system and manufacturing industry, including for non-ferrous metals such as alumina.[127] The model has been used previously in multiple peer-reviewed scientific studies for climate change mitigation with emissions pathways analysis, energy system transition characteristics and quantification of investments required to transform the energy system.[128] In an effort to optimise future decarbonisation investment outcomes for an Australian alumina refining context, the NGFS GCAM model was adopted for this Roadmap.

For more details regarding the NGFS climate model, please refer to the NGFS (2020) technical documentation accessible: https://www.ngfs.net/sites/default/files/ngfs_climate_scenario_technical_documentation_final.pdf

Key assumptions for the climate aligned scenarios

The key assumptions to model the climate aligned scenarios for Australia's alumina refining emissions are as follow:

1. 1.5˚C and below 2˚C science-based targets were modelled using DDS™ assuming the NGFS GCAM v5.3 model.
2. A FY 2020 base year emissions of 14.9 Mt CO_2-e adopted based on Australian Aluminium Council (2021).[129]
3. Projected alumina emissions between FY 2020 and FY 2028 were based on calculated compound annual growth rate (CAGR) of alumina output published by IBISWorld.[130]
4. Projected alumina emissions post FY 2028 was based on average calculated CAGR for alumina output between FY 2022 and FY 2028 published by IBISWorld.[131]
5. The 'no change' scenario assumes stable production volumes while showing small overall emissions intensity reductions as grid decarbonisation increases with time (as determined by Deloitte Electricity Market Model (DEMM)).
6. The climate scenarios modelled leverage scientific information from leading bodies and methodologies including the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways, the International Institute for Applied Systems Analysis (IIASA) Shared Socio-Economic scenarios and the Science-Based Target (SBT) methodologies amongst others.
7. The scope of Deloitte's analysis focused on Australian alumina refining industry, based on scope 1 and 2 emissions. A high level analysis of the potential of the decarbonisation and the potential for renewable energy supply was also undertaken.

Key assumptions for the abatement pathways

Assumptions adopted to model abatement pathways decarbonisation are shown as below. Assumptions relevant to both abatement pathways are first shown, followed by specific pathway specific assumptions.

Overarching Assumptions:

1. All low emissions technologies are powered by 100 per cent renewable energy.
2. Up to 98 per cent of the emissions associated with alumina refining can be addressed by the Key Decarbonisation Technologies identified. The majority of emissions resulting from alumina refining are assumed to result from the digestion (65 per cent) and calcination (33 per cent) processes.
3. The uptake of technologies has been approximated by sigmoid functions to account for progressive technology deployment through the alumina industry and resulting carbon abatement.
4. The sigmoid function is used to simulate slow initial uptake of technologies, followed by accelerated adoption over the medium-term once technologies are proven at scale. Slower decarbonisation is then simulated in the final stages of technology deployment to achieve 100 per cent implementation across the industry.

Innovator Abatement Pathway

5. The adoption of low emissions technologies is conditional on the development of ecosystem initiatives, which are required to support the uptake of Key Decarbonisation Technologies.
6. Increased appetite from Participants to decarbonise operations encourages early deployment of technologies addressing Bayer emissions, leading to a reduction in industry emissions by up to 7 per cent from 2027 to 2030.
7. Electric boilers and/or MVR are expected to be technically mature (i.e. TRL 9) in both low and high temperature refineries by 2030 and are rapidly deployed across the industry over 5 years from 2030 to 2035 to decarbonise Bayer process emissions.
8. Electric calcination and hydrogen calcination achieve TRL 9 by 2035 and are rapidly deployed across the industry over 5 years from 2035 to 2040 to decarbonise calcination process emissions. Hydrogen calcination demonstration estimated cost excludes hydrogen production.

Gradual Abatement Pathway Assumptions:

9. Key Decarbonisation Technologies begin deployment as soon as TRL 9 is achieved, which is 2030 for digestion-based technologies and 2035 for calcination based technologies.

10. No substantial reductions in emissions are achieved until 2030 due to the small scale of pilot trials and demonstrations in the near-term.

11. Electric boilers and/or MVR are expected to be technically mature (i.e. TRL 9) in both low and high temperature refineries by 2030 and are deployed across the industry over 10 years from 2030 to 2040 to decarbonise Bayer process emissions.

12. Electric calcination and hydrogen calcination achieve TRL 9 by 2035 and are deployed across the industry over 10 years from 2035 to 2045 to decarbonise calcination process emissions. Hydrogen calcination demonstration estimated cost excludes hydrogen production.

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