MECHANICAL VAPOUR RECOMPRESSION (MVR) FOR LOW CARBON ALUMINA REFINING

MVR TECHNICAL AND COMMERCIAL FEASIBILITY STUDIES

A SUMMARY REPORT

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Australian Government
Australian Renewable Energy Agency

ARENA

DISCLAIMER

This report was commissioned by the Australian Renewable Energy Agency (ARENA). The report was prepared by Pure Font Communications and summarises key findings of the MVR Evaporation Feasibility Study and the MVR Retrofit and Commercialisation Report, which were originally prepared by Alcoa of Australia Limited (Alcoa) pursuant to the project deliverables required under the Alcoa Mechanical Vapour Recompression (MVR) for Low Carbon Alumina Refining project funding agreement.

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GLOSSARY

CapEx	Capital Expenditure
CO_2-e	Carbon Dioxide Equivalent
EI&C	Electrical, Instrumentation and Control
EPCM	Engineering, Procurement and Construction Management Cost
FFE	Falling Film Evaporator
GHG	Greenhouse Gas
GW	Gigawatt
KPI	Key Performance Indicator
Ml	Megalitre
Mt CO_2-e	Metric tons of carbon dioxide equivalent
MVR	Mechanical Vapour Recompression
MW	Megawatt
OPEX	Operating Expenses
p.a.	per annum
tph	tons per hour
tpy	tons per year
SBTi	Science Based Targets initiative
VOC	Volatile Organic Compound

EXECUTIVE SUMMARY

Australia is one of the world's largest exporters of alumina, and a key player in the global alumina refining industry, contributing to 15 per cent of the industry's capacity. The country is also the world's largest producer of bauxite ore – the naturally occurring ore that is responsible for producing alumina when refined.

However, alumina refining is highly energy and emissions intensive as it relies heavily on generating steam from fossil fuels to provide the necessary process heat. Around 70 per cent of greenhouse gas (GHG) emissions in alumina refining come from producing steam for heating in the Bayer process – the industrial process in which bauxite ore is refined to produce alumina. In 2021, alumina refining accounted for 14.6 million tonnes of carbon dioxide emissions in Australia,[1] representing almost a quarter of the country's direct manufacturing emissions. It is estimated that displacing fossil-fuelled steam production with a renewable energy source would reduce alumina industry GHG emissions by approximately 10 Mt CO_2-e per annum (p.a.).

In May 2021, ARENA announced $11.3 million in funding to alumina producer Alcoa of Australia Limited (Alcoa) in support of their "**Mechanical Vapour Recompression (MVR) for Low Carbon Alumina Refining**" project, which aims to demonstrate and provide confidence in a low emission technology that has the potential to significantly reduce carbon footprint in the alumina refining industry.

Aligned with ARENA's investment priority of helping industries to reduce their emissions, the project is the first of its type in Australia and involves Alcoa studying the feasibility of using renewable energy-powered MVR to generate steam in the alumina refining process. By replacing fossil fuel boilers (typically used in refineries), MVR offers a pathway to decarbonise Australia's largest industrial process heat demand, while improving efficiency and reducing costs in the alumina refining process. Central to the MVR technology is its ability to enable waste vapour, that would otherwise be exhausted to the atmosphere, to be compressed and recycled.

The Project has two delivery stages:

- **Stage 1:** Alcoa will complete desktop studies and analysis to investigate the technical and commercial feasibility of integrating MVR, powered by renewable energy, in the Australian alumina refining process. Alcoa will also consider the commercialisation pathway of retrofit opportunities at brownfield alumina refineries.
- **Stage 2**: Alcoa will design, procure, execute, deploy, integrate, commission and operate a full-scale 4 MW module of MVR at its Wagerup Alumina Refinery in Western Australia, located about 120 kilometres south of Perth. The MVR module will be integrated with the alumina refinery's evaporation process, and will be powered by renewable electricity.

Alcoa has completed Stage 1 and has committed to proceeding with Stage 2. This Summary Report presents the key results from Stage 1 of the Project, as reported in Alcoa's Study Reports – the MVR Evaporation Feasibility Study and MVR Retrofit and Commercialisation Report. Additionally, this report discusses the implications of Stage 1 and provides a brief synopsis of the next steps planned for Stage 2.

1 Australian Aluminium Council, Sustainability Data 2000 to 2021

AT A GLANCE: SUMMARY OF KEY FINDINGS IN STAGE 1

MVR TECHNICAL FEASIBILITY

The Technical Study has shown that MVR technology is an important enabler for decarbonising alumina refining. MVR has a lower capital and operating cost than conventional evaporation, as well as zero carbon when powered by renewables.

Key Findings:

- MVR, when used in conjunction with a falling film evaporator (FFE), has a **total capital saving of $25M** (32 per cent) and a **Net Present Cost advantage of $47M** (42 per cent) over conventional evaporation in greenfield or expansion scenarios, making it potentially robust in relation to gas, power, and carbon pricing variations.
- MVR+FFE technology yields **zero carbon emissions** when powered by renewable energy.
- There is **no water consumption** for MVR+FFE, compared to 100 Ml (Megalitre) p.a. for conventional evaporators.
- MVR+FFE will not increase boundary noise at the refinery compared to the same evaporation that could be achieved using conventional evaporators.
- Overall, MVR+FFE has **lower operating costs** than conventional evaporation.
- While MVR+FFE uses significant amounts of electricity (3.3 MW, compared to 0.1 MW for a conventional evaporator), **the net energy cost** for MVR+FFE ($1.7M p.a.) **is about half of that for a conventional evaporato**r ($3.3 M p.a.) due to the elimination of fossil fuel consumption.

MVR COMMERCIAL VIABILITY

The Commercial Study has shown that MVR technology has a strong business case with a potential to be implemented at existing and new Australian alumina refineries. MVR is likely the lowest cost method to provide low/zero carbon process heat to partially decarbonise Australia's alumina industry which has, to date, been categorised as 'difficult-to-abate' along with other heavy industries.

Key Findings:

- An overall **investment of approximately $4.5B** would be required to implement MVR across Australia's six alumina refineries, together with provision of **approximately 1.2 GW of firmed renewable power**.
- MVR technology in alumina refining can become more commercially competitive with the establishment of **carbon markets** that incentivise emissions reduction.
- In **growth scenarios**, MVR technology has similar capital cost to conventional technology but with lower operating cost. In retrofit scenarios, MVR economics will largely depend upon the availability and price of firm renewable power and carbon.
- At Alcoa's low-temperature Wagerup refinery, the estimated capital cost of MVR is **$220 per annual tonne of alumina production.** For a high-temperature refinery, Alcoa estimates that the cost would be **$260 per annual tonne** (approximately 18 per cent more than a low-temperature refinery, on a per tonne of alumina basis).

1. INTRODUCTION

1.1 ALUMINA INDUSTRY IN AUSTRALIA

Alumina is the core ingredient for producing aluminium and is refined from the naturally occurring bauxite ore (see **Figure 1**).

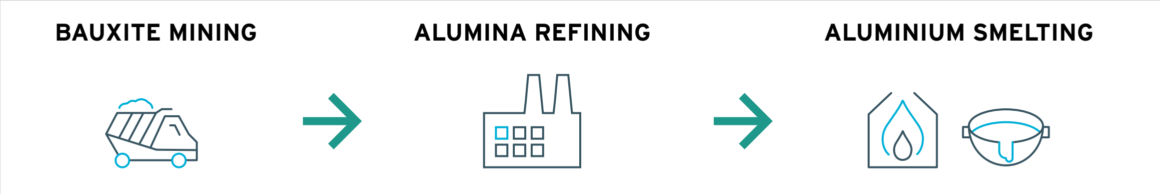


Figure 1. Primary aluminium value chain

Australia is one of the world's largest exporters of alumina, and **contributes to 15 per cent of the global alumina refining capacity**. It is also the world's largest producer of bauxite ore.

Alumina refining is a highly energy and emissions intensive process that utilises high-pressure steam generated from fossil fuels to provide the heat for extracting alumina from bauxite ore.

Australia processes two bauxite types to make alumina. Western Australian bauxite ore can be treated with caustic soda at around 140°C to 170°C in order to extract alumina (low-temperature digestion). Queensland and the Northern Territory bauxite ore requires high-temperature digestion at around 250°C in order to obtain alumina. Refineries that operate at higher temperatures may require different low emissions technologies to decarbonise the alumina refining process.

Around **70 per cent of GHG emissions in alumina refining come from steam production** used to heat **the Bayer process**. The remaining 30 per cent of emissions are then produced during the high-temperature calcination process, which removes chemically bound water to produce anhydrous aluminium oxide (alumina) that can be smelted into aluminium.

In 2021, alumina refining accounted for 14.6 million tonnes of carbon dioxide emissions in Australia,[2] amounting to almost a quarter of the country's direct manufacturing emissions. Direct emissions, known as 'Scope 1', are directly emitted from sources that are controlled or owned by an organization (for instance, emissions associated with fuel combustion in boilers, furnaces, and vehicles).[3] Alcoa has estimated that displacing fossil-fuelled steam production with a renewable energy source would reduce alumina industry GHG emissions by approximately 10 Mt CO_2-e p.a.

Low emissions steel and aluminium have been flagged as priorities in the Australian Government's first Low Emissions Technology Statement (2020) to help reduce emissions and stimulate economic activity. Innovation in metals refining such as using MVR technology can improve the competitiveness and decrease the emissions intensity of Australia's aluminium production.

With the green and sustainable aluminium market growing exponentially in recent years, particularly in Europe, MVR has the potential to be a strong player in leveraging Australia's renewable energy sources and contributing to this market in a carbon-constrained world.

2 Australian Aluminium Council, Sustainability Data 2000 to 2021

3 EPA Center for Corporate Climate Leadership, Scope 1 and Scope 2 Inventory Guidance

1.2 THE ROLE OF MVR IN ALUMINA REFINING[4]

Alumina produces aluminium when smelted, making it a crucial component in the primary aluminium value chain. When alumina is derived from bauxite ore, two major energy-intensive processes are involved.

As shown in **Figure 2**, initially, alumina hydrate is extracted from bauxite ore in the **Bayer process.** A key step of this process is the **digestion** of bauxite ore in a sodium hydroxide solution, which depending on bauxite type, requires steam at **around 200°C to 300˚C**, and consumes about two-thirds of the thermal energy input to the alumina refining process. The remaining one-third is required in the second process, the **calcination** of alumina hydrate crystals to produce alumina. The calcination takes place at temperatures **above 800°C** and heat is usually provided directly to the reactor by the combustion of fossil fuels.

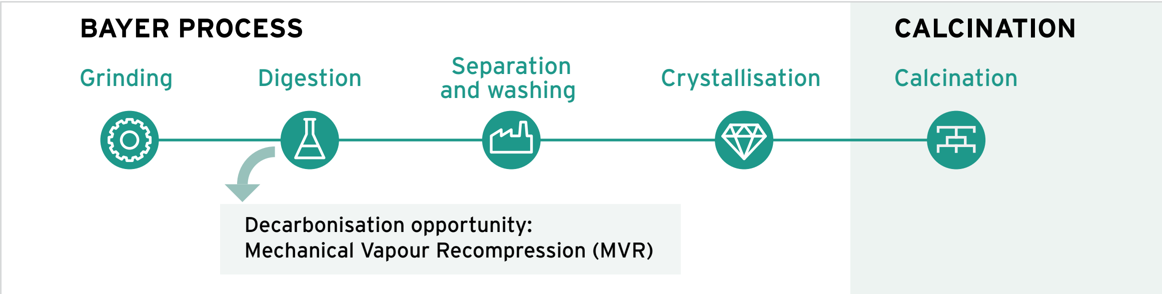


Figure 2. Overview of the alumina production steps

Traditionally, steam is supplied to the digestion process from gas-fired boilers or as discharge from the steam turbine of a combined cycle electrical power plant. By displacing fossil fuel boilers, **renewable energy-driven MVR provides the opportunity to decarbonise steam generation within the Bayer process.** In addition, although modern alumina refineries are highly optimised to re-use waste heat wherever practical, ultimately around 85 per cent of the energy input to the refinery leaves as low-grade heat, unable to be re-used with the current technology. MVR powered by renewable energy represents an attractive and sustainable means of upgrading and reusing the low-temperature waste vapour from the digestion step.

In short, MVR powered by renewable energy offers a potential pathway to decarbonise Australia's largest industrial process heat demand, as well as a way to improve efficiency and reduce costs in the alumina refining process. In addition, with the exponential growth of the green aluminium market in recent years, particularly in Europe, MVR has the potential to be a strong contributor towards leveraging Australia's renewable energy sources and contributing to this market in a carbon-constrained world.

1.3 ABOUT THE PROJECT

In May 2021, ARENA announced $11.3 million in funding to Alcoa to support their low carbon alumina refining MVR project (referred in this report as "the Project"). The Project aims at demonstrating and providing confidence in a low emission technology with the potential to reduce fossil fuels consumption and improve energy efficiency in the intensive alumina refining industry. By displacing fossil fuel derived thermal energy, the Project aligns with ARENA's investment priority of helping the Australian industry to reduce its emissions.

In the **first Stage** of the Project, Alcoa has evaluated the technical and commercial feasibility of integrating an MVR evaporator powered by renewable energy in an Australian alumina refinery and has investigated a commercialisation pathway of retrofit opportunities at existing alumina refineries.

Following the completion of Stage 1, Alcoa has committed to proceeding with the **second Stage** of the Project, involving the design, procurement, execution, deployment, integration, commissioning, and operation of a full-scale 4 MW module of MVR at its Wagerup Alumina Refinery in Western Australia.

1.4 ABOUT THIS SUMMARY REPORT

This **Summary Report** presents the key results from **Stage 1** of the Project, as reported in Alcoa's Study Reports – the MVR Evaporation Feasibility Study (referred in this report as "**Technical Study**") and MVR Retrofit and Commercialisation Report (referred in this report as "**Commercial Study**"). These key results will be presented in Chapter 2 (MVR Technical Feasibility) and Chapter 3 (MVR Commercial Viability). Additionally, the implications of Stage 1 will be discussed in Chapter 4. In conclusion, Chapter 5 will provide a brief synopsis of the next steps planned through Stage 2.

4 Renewable Energy Options For Industrial Process Heat (November 2019)

2. MVR TECHNICAL FEASIBILITY

2.1 TECHNICAL STUDY OBJECTIVES

Alcoa of Australia has three refineries in Western Australia, located at Kwinana, Pinjarra, and Wagerup. The Technical Study had the specific objective to investigate the technical feasibility of installing additional evaporator[5] capacity at Alcoa's Wagerup Alumina Refinery using MVR technology. The feasibility assessment considered the use of conventional evaporation technology as the baseline for the purpose of commercial comparison.

2.2 RATIONALE FOR MVR

MVR technology powered by renewable energy provides the opportunity to almost fully decarbonise the Bayer process in alumina refining by removing its current heavy reliance on fossil fuels. In particular, alumina refineries require process heat, and Alcoa has identified that renewable-powered MVR is well-placed to provide this heat as it:

- has a **zero-carbon** potential when supported by renewable power
- has a potential economic viability for to enable **retrofitting in existing facilities**
- **reduces water usage** by eliminating boiler feed water and recycling waste water vapour.

Prior to selecting MVR, Alcoa had reviewed alternative technologies, but they were deemed unsuitable for this application due to the reasons stated below:[6]

- Green hydrogen: Operationally very expensive with a long lead time for implementation at scale, green hydrogen is also estimated to consume approximately four times the power of MVR to deliver the same quantity of steam and does not offer any water savings
- Solar thermal: Technology using solar thermal can only deliver around 40 per cent of process heat requirements and requires duplicate infrastructure to supply continuous process heat.
- Geothermal: Technology using geothermal has extremely limited feasibility, is expensive, and carries high technology risk.
- Energy from waste: This approach is only suitable where an energy from waste facility is co-located, making it unsuitable as an industry-wide solution
- Biomass as fuel: The quantities of biomass required to supply energy to an alumina refinery were not considered to be economic or sustainable
- Direct electric heating: Boilers that are direct electric-heated are used for opportunistic steam generation and need duplicate base load infrastructure. In these circumstances, it is unlikely that an electric boiler would operate for more than 20 per cent of the time. In contrast, MVR uses 33 per cent of the power needed for an electric boiler to generate the equivalent pressure steam in Alcoa's WA refineries and is therefore cheaper to operate.

Although MVR is an established technology in industrial processes involving evaporation and distillation, it has never been deployed at a large scale in an alumina refinery. A small 30 tons per hour (tph) MVR + FFE was installed in 2003 in China, and a very small installation exists in a Japanese facility that was once an alumina refinery. However, information about how they operate is scarce.

In terms of a large and comparable MVR-driven process, Alcoa considered a Turkish chemical production facility that was commissioned in 2008. The facility has an evaporation capacity that is more than three times that of Alcoa's Wagerup alumina refinery and has been so successful that a larger MVR-driven soda extraction facility was built close to the original facility in 2017. Alcoa has visited the Turkish facility and many other MVR evaporation facilities around the world to gain confidence in the technology.

5 Evaporation is an ancillary process in alumina refining, that also produces waste vapour and can be used with MVR to provide process steam. It is anticipated that evaporation provides the least cost and least risk pathway to explore the use of MVR in an alumina refinery before progressing on to the digestion process.

6 The analysis of alternative technologies has been conducted by Alcoa and does not necessarily represent the views of ARENA or the Australian Government. Neither ARENA or the Australian Government accept responsibility for any information or advice contained herein.

2.3 INTEGRATING MVR TECHNOLOGY IN ALUMINA REFINERIES

2.3.1 DECARBONISATION STRATEGY

In a conventional alumina refinery, fuel is burnt in a boiler and high-pressure steam is created through the evaporation of boiler feedwater, emitting CO_2 in the process. The high-pressure steam may pass through a turbine to generate power for pumps, motors, and ancillaries. Medium-pressure steam is extracted to provide process heat to the refinery. The wastewater vapour from process heating is released into the atmosphere at low temperature rather than recycled, thus leading to substantial water loss. **Figure 3** below shows how process heat is obtained from fossil fuels in a conventional refinery.

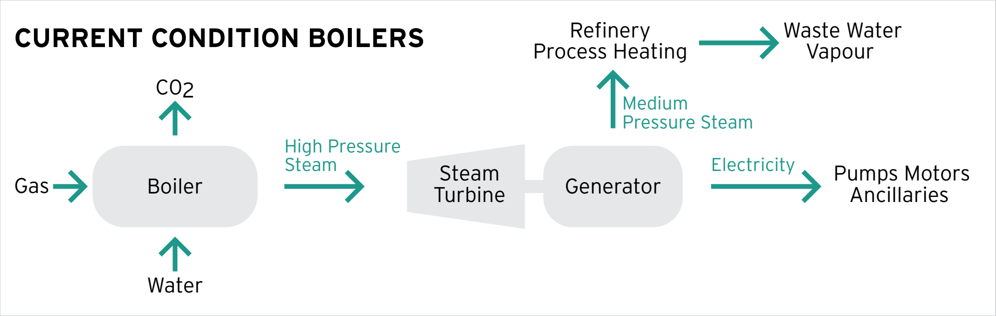


Figure 3: Current Condition - Process Heat from Fossil Fuels

Alcoa's MVR project explores a pathway to enable alumina refining to substantially reduce emissions through the use of renewable power driving mechanical vapour recompressors, thereby displacing fossil fuel derived thermal energy. In particular, it has focused on how process heating, currently fully dependent on steam derived from fossil fuels, could be decarbonised.

If MVR proves to be technically feasible, renewable power would drive MVR in future to provide process heat to alumina refineries. Waste process vapour will be captured and recompressed to medium-pressure steam to heat the refinery. Renewable power will also be used to drive the refinery's pumps and motors. **Figure 4** below shows how process heat will be obtained from MVR and renewable power.

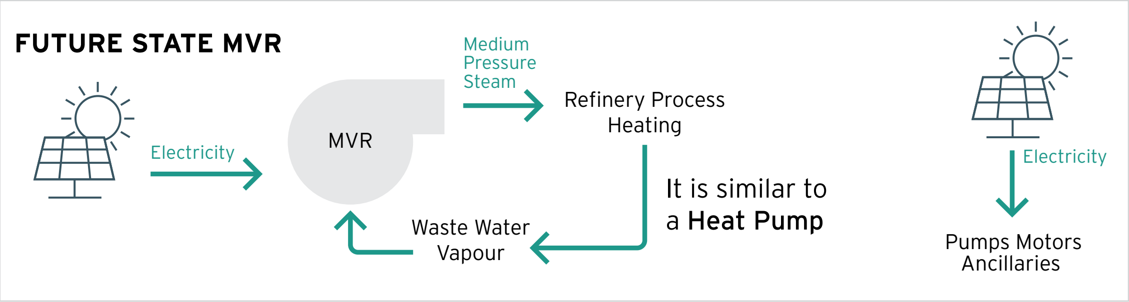


Figure 4: Future State - Process Heat from Renewable Power and MVR

2.3.2 THE BAYER PROCESS

Alumina refineries utilise the Bayer process to **release alumina** from bauxite ore in a caustic soda solution ('Bayer liquor'). Bayer liquor is **heated** to the required temperature using steam. **Bauxite ore** is then added and the majority of the alumina-bearing components subsequently dissolve in the liquor.

The liquor is subsequently cooled and residual (undissolved) solids removed from the liquor.

Further cooling takes place to reach 60°C for precipitating alumina hydrate crystals. The crystals are separated from the liquor and calcined to form alumina. The remaining 'spent' liquor is reheated and returned to digestion.

However, some amount of water is **evaporated** from the spent liquor before returning to digestion, to balance fresh water introduced to 'wash' the bauxite residue and to improve process efficiency and alumina recovery. This plays a crucial part in maintaining the refinery's water balance.

2.3.3 EVAPORATION TECHNOLOGY

Traditionally, alumina refineries use evaporation technologies based on fossil fuels for their steam production. There are two principal methods used to evaporate spent liquor in the Bayer process:

- Multi-stage flash trains
- Single-stage evaporators, including falling film, rising film, forced circulation and natural circulation evaporators.

Multi-stage trains use process steam in the first stage to evaporate a portion of the spent liquor creating a waste vapour stream. Heat from the waste vapour is then recovered using heat exchangers and used to evaporate further liquor in the second and subsequent stages until no more heat can be economically recovered. The remaining heat in the evaporated waste vapour stream is then discharged to atmosphere.

In a typical multi-stage flash evaporation train, about 20 per cent of the liquor is evaporated in the process. A modern multi-stage evaporator has about 12 heaters and 12 flash tanks. To achieve reasonable economies of scale, a typical evaporator train will provide about 240 tph evaporation, will require about 60 tph of steam, a significant cooling water system.

On the other hand, single-stage evaporators consist of a single heat exchanger with no heat recovery. The Technical Study assessed retrofitting an existing moth-balled single stage evaporator with an MVR. This approach provided the simplest, least cost and lowest technical risk way to test the feasibility of MVR in an alumina refining environment.

For the purpose of this study, a single-stage FFE with a capacity of 65 tph was used. The FFE will remove water from the spent Bayer liquor through evaporation when the liquor passes through it, and vapour would pass into the lower separator. Vapour captured in the lower separator will be cleaned by mist eliminators before passing to the MVR compressors. The compressors, powered by renewable electricity, will in turn generate steam from this vapour for refinery process heat. This study found that a single-stage evaporator with MVR would only consume about one-third (33 per cent) of the energy of a conventional multi-stage evaporator.

It is envisaged that retrofitting MVR to an existing refinery will require multiple MVR compressors operating in series to provide steam to a multi-stage evaporator. However, for refinery capacity expansion, the single stage FFE and MVR arrangement enables a modular design of about 20 per cent the capacity of a conventional multi-stage flash evaporator. This allows small increments of evaporation to be added to the process with minimal capital investment.

2.3.4 RISK MANAGEMENT

As part of the risk assessment procedure, Alcoa identified the following top risks and their corresponding mitigation efforts in advancing this Technical Study:

- **Unsuccessful project outcome**, with mitigations including engaging the original FFE supplier as a technical adviser to confirm design feasibility
- **Delay in delivery of equipment, services, or construction**, with mitigations including early engagement with the construction companies, and early issue of the formal tender for long-lead equipment
- **Unanticipated growth in scope of existing FFE modification, or FFE unable to be retrofitted**, with a full assessment of FFE condition introduced in November 2021, for completion early in the study's execution phase.

However, none of the project risks were material to the studies conducted in Stage 1.

2.3.5 KPI COMPARISON SUMMARY

In the Technical Study, conventional evaporator technology was considered as the baseline for commercial comparison and feasibility assessment.

The **Key Performance Indicators (KPI)** for MVR+FFE installation, relative to a conventional evaporator, are outlined in Table 1 below.[7] The KPIs are financial, that is capital (CAPEX) and operating cost (OPEX), and non-financial, carbon emissions and water consumption.

FOR A 65 TPH EVAPORATOR		CONVENTIONAL EVAPORATION	MVR + FALLING FILM EVAPORATION	DELTA MVR+FFE LESS CONVENTIONAL
CAPEX				
Evaporator Capital	$M	59	49	-10
Infrastructure Capital	$M	16	2	-14
Noise Abatement	$	2	2	0
Total Capital	**$M**	**77**	**53**	**-25**
OPEX				
Gas Consumption	GJ/h	47	0	-47
Electricity Consumption	MW	0.1	3.3	3.2
Net Energy Cost	**$M py**	**3.3**	**1.7**	**-1.7**
CO_2e Cost	**$M py**	**1.3**	**0**	**-1.3**
NON-FINANCIAL				
CO_2e in a zero carbon grid	tpy	22,819	0	-22,819
Water consumption	Ml py	100	0	-100
NET PRESENT COST	**$M**	**113**	**65**	**-47**

Table 1: Key KPIs for Conventional and MVR + FFE

As shown in **Table 1**, the KPIs that the Technical Study relied on are primarily financial, that is capital expenditure (CAPEX) and operating expenses (OPEX). Non-financial parameters include carbon emissions and water consumption.

Based on a preliminary analysis of the KPIs, the Technical Study identified several key benefits of installing MVR+FFE. Among other things:

- MVR+FFE has a **total capital saving of $25M** (32 per cent) and a **Net Present Cost advantage of $47M** (42 per cent) over conventional evaporation in greenfield or expansion scenarios, making it potentially robust in relation to gas, power, and carbon pricing variations. Capital cost reductions provide the majority of the MVR benefit. A conventional evaporator would require larger comparable capacity (240 tph) than MVR to achieve economies of scale
- MVR+FFE technology yields **zero carbon emissions**, in contrast to 22,819 tpy (tons per year) for a conventional evaporator when powered by renewable energy
- MVR technology **does not require cooling water**. Hence, there is no water consumption for MVR+FFE, compared to 100 Ml p.a. for conventional evaporators
- Similar to conventional evaporators, MVR+FFE will support **noise abatement** by including noise control deterrents; and therefore, will not increase noise levels relative to conventional evaporation. Noise is a significant issue for many industrial facilities, and is an important regulatory, environmental and community consideration for alumina refineries.
- Overall, MVR+FFE has **lower operating costs** than conventional evaporation. Renewable power has substantially disrupted the economics of self-power generation, with evaporation processes that rely on boiler steam being more expensive. As a result, MVR-based evaporation using renewable- power is potentially superior to conventional evaporation

7 Underlying assumptions are included in Alcoa's MVR Retrofit and Commercialisation Report.

- MVR+FFE uses significant amounts of electricity (3.3 MW, compared to 0.1 MW for a conventional evaporator), but when powered by renewable electricity, it has a **zero-carbon footprint**. Moreover, the **net energy cost** for MVR+FFE ($1.7M p.a.) is about half of that for a conventional evaporator ($3.3M p.a.) due to the elimination of fossil fuel consumption.

2.4 CONCLUSION

This Technical Study shows that MVR technology powered by renewables can provide additional process evaporation for the alumina refinery. The technology has lower capital and operating cost, as well as zero carbon when powered by renewables. This study also indicates that MVR provides operational benefits at alumina refineries, and key risks can be managed adequately.

3. MVR COMMERCIAL VIABILITY

3.1 COMMERCIAL STUDY OBJECTIVES

In addition to the Technical Study, Alcoa also conducted a second study within Stage 1 of the project, namely, the Commercial Study. While the Technical Study (as discussed in Chapter 2) investigated the feasibility of integrating the MVR technology in the alumina refining process, specifically, for driving a 65 tph single-stage FFE, the scope of the Commercial Study was much broader.

The Commercial Study aimed to **evaluate the commercial feasibility of implementing MVR at existing** (brownfield) **and new** (greenfield) **Australian alumina refineries** through two scenarios:

- A complete MVR retrofit into an existing facility, both in low-temperature and high-temperature digestion refineries.
- A new facility or unit expansion using MVR.

The study conducted a deep-dive analysis using Alcoa's Wagerup alumina refinery as the basis, and then extrapolated its findings to other alumina refineries.

This study also provided a development pathway needed to prove the MVR technology to the level required before a significant investment can take place in Australian alumina refineries.

3.2 THE ROAD TO A GREEN AND SUSTAINABLE ALUMINIUM MARKET

The alumina refining sector is currently a significant fossil fuel energy user and GHG emitter. Along with many other heavy industries, the sector is identified as 'difficult-to-abate'. Given Australia's vast renewable energy resources and proximity to high-quality bauxite ore, it is well-positioned to reduce the carbon footprint from its alumina industry and play a key role in the global low carbon aluminium market.

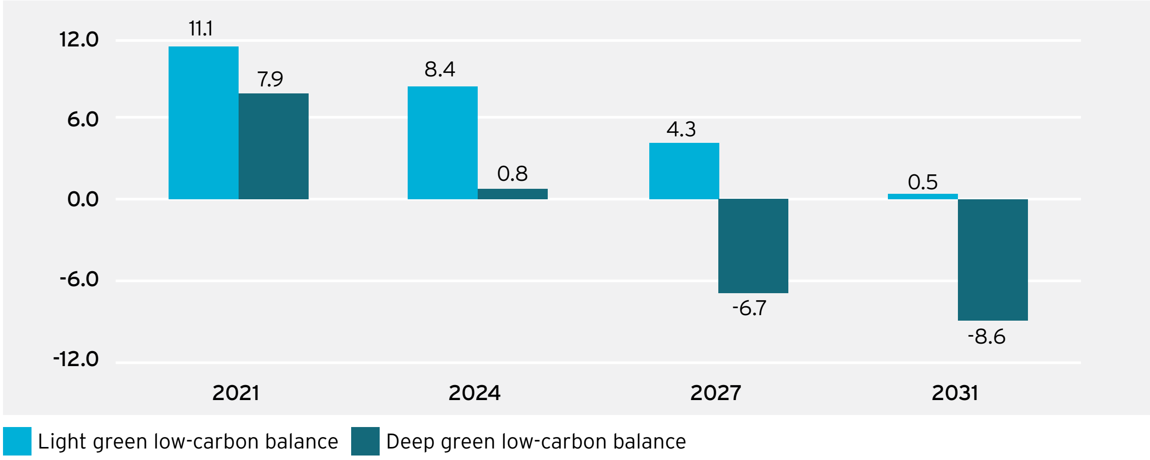
3.2.1 EMERGING LOW CARBON DRIVERS

The green and sustainable aluminium market is growing, particularly in Europe. To date, the European market has driven most of the change in the aluminium market due to its significant price of EU Carbon Permits and the proposed Carbon Border Adjustment Mechanism. Recent G7 leaders' commitment to maintain the 1.5 degrees Celsius global warming threshold[8] is likely to significantly increase the demand for low carbon aluminium. Consumers are also starting to demand and pay premiums for low carbon aluminium, particularly in high-value products in the smartphone and auto industries.

Globally, the number of companies committing to the **Science Based Targets initiative** (SBTi) is growing rapidly, driving increased demand for low carbon aluminium. Furthermore, while the global supply of low carbon aluminium is currently in excess, its demand is expected to increase quickly. According to CRU forecast illustrated in Figure 5, by 2031, supply and demand will be almost completely balanced assuming 50 per cent low carbon aluminium uptake in key sectors. Prior to this, an 80 per cent uptake in key sectors is forecasted to lead to a supply deficit by 2027. It is anticipated that a deficit in low carbon aluminium products under a high demand scenario, might lead to higher prices and incentives for low carbon products.

8 G7 Climate, Energy and Environment Ministers' Communiqué (May 2022)

World ex. China, low-carbon market balance, million tonnes



DATA CRU, Note Light green scenario assumes 50%, and dark green scenario assumes 80% tow carbon Al demand from key sectors by 2031. Key sectors are transport, construction and packaging end uses data. Low carbon Al defined as <4t CO_2e /t Al for Scope 1 and 2 emissions.

Figure 5: Low carbon aluminium market balance – Source CRU International Limited[9]

3.2.2 AUSTRALIA'S ALUMINA REFINERIES

Australia is one of the world's largest exporters of alumina, contributing to 15 per cent of the global alumina refining capacity; as well as one the world's largest producers of bauxite ore.

The six alumina refineries operating in Australia (see **Table** 2 below) produce mostly smelter grade alumina for the domestic and export markets. Alcoa owns and manages three of these six refineries.

REFINERY	OWNER/MANAGER	LOCATION	STARTED
Wagerup	Alcoa	SW Western Australia	1984
Pinjarra	Alcoa	SW Western Australia	1972
Kwinana	Alcoa	SW Western Australia	1963
Yarwun	Rio Tinto Aluminium (RTA)	Gladstone, QLD Queensland	2004
QAL	RTA	Gladstone, QLD Queensland	1967
Worsley	South32	SW Western Australia	1984

Table 2: Australia's alumina refineries

These six alumina refineries are the largest industrial consumers of energy for process heat in Australia and were responsible for 14.6 million tonnes of carbon dioxide emissions in the country in 2021.[10] At the future energy prices used by Alcoa in this study, the alumina industry's annual energy spend is expected to be approximately $1.5B per year. Harnessing renewable energy through MVR provides Australia the opportunity to substantially grow the alumina industry as demand for low carbon alumina increases.

3.2.3 POSITIONING AUSTRALIA IN GLOBAL LOW CARBON ALUMINIUM VALUE CHAIN

Globally, Australia has a potential competitive advantage over other countries for low carbon alumina refining because of its extensive renewable energy resources and access to high-quality bauxite ore.

Alumina from the Australian market is currently exported mainly to China and the Middle East. While low carbon aluminium producers already use renewable smelting power in Brazil, Canada, Iceland and Norway to produce aluminium, it is anticipated that green premiums for low carbon alumina need to substantially increase before it becomes economically viable for Australia to tap into these export markets. There is a possibility that when the supply and demand balance for low carbon aluminium changes around 2027 to 2031 (see **Figure 3** above), the premium may change sufficiently to overcome freight costs.

Additionally, if a carbon market develops in Australia, the economic case for MVR would improve.

9 CRU Dec 2021, Aluminium Long Term Market Outlook, as cited in the MVR Retrofit and Commercialisation Report.

10 Australian Aluminium Council, Sustainability Data 2000 to 2021

3.3 EVALUATING MVR IMPLEMENTATION AT AUSTRALIAN ALUMINA REFINERIES

As mentioned earlier in this chapter, this Commercial Study evaluated the commercial feasibility of implementing MVR at existing Australian alumina refineries (brownfield) and new alumina refineries (greenfield). The study methodology is based on a deep-dive study using Alcoa's Wagerup alumina refinery as the basis, and then extrapolating the findings for applicability to other alumina refineries.

The study also explored a development pathway in order to prove the MVR technology to the level required before a significant investment can take place in Australian alumina refineries.

It was assumed that Alcoa's Wagerup refinery was indicative of all Australian refineries except for the digestion temperature, as Wagerup is a low-temperature digestion refinery processing gibbsitic bauxite ore. The study also recognised the fact that synergies of Wagerup equipment may not be available at other facilities that utilise high-temperature digestion.

3.3.1 MVR RETROFIT CAPITAL ESTIMATE

The capital estimate for the Wagerup full MVR installation is equivalent to AACE Class 5. Alcoa obtained two estimates of AACE Class 5 from external consultants, dated December 2021. Alcoa reviewed the estimates and applied weightings to the two estimates to obtain final values after incorporating scope changes and compressor price updates.[11]

The estimated total MVR retrofit capital cost of the proposed scope at Wagerup alumina refinery (a low-temperature refinery) is AU$622M (see Table 3 below). The system displaces 611 tph of live steam to process for the Wagerup refinery operating at 2.88 Mtpa alumina. The total MVR power consumed is 134 MW at the compressor motors.

DIRECT COSTS - DISCIPLINE	
Earthworks	$ 1M
Civil	$ 17M
Steel	$ 5M
Mech Equip - Comp	$ 126M
Mech Equip - Aux	$ 42M
Ducting	$ 14M
Pipework >400DN	$ 18M
Pipework <400DN	$ 25M
EI&C	$ 43M
Insulation	$ 8M
Overseas Freight	$ 7M
Freight	$ 4M
Special Items	
ALCOA 330/22kV Switchyard	$ 15M
330 kV Power Hookup	$ 1M
VOC Destruction	$ 8M
Direct Costs Total	**$ 335M**
INDIRECT COSTS	
Field Establishment Costs	$ 23M
EPCM	$ 34M
Owners Costs	$ 11M
Contingency & Growth	$ 121M
Indirect Costs - Total	$ 189M
Total Costs - including scope revisions	**$ 524M**
ADDERS	
Alcoa Risk Review Scope	$ 31M
Weight considering check estimate	$ 59M
Escalation 1.25% total	**$ 8M**
Grand Total	**$ 622M**

Table 3: MVR retrofit capital cost for low-temperature refinery example in Wagerup.

11 Further information on estimate methodology and inputs is included in Alcoa's MVR Retrofit and Commercialisation Study.

The **total cost distributions** (see **Figure 6** below) are as expected, considering the repetitive nature of the compressor trains, large average motor size of around 3.5 MW and few process tie-ins.

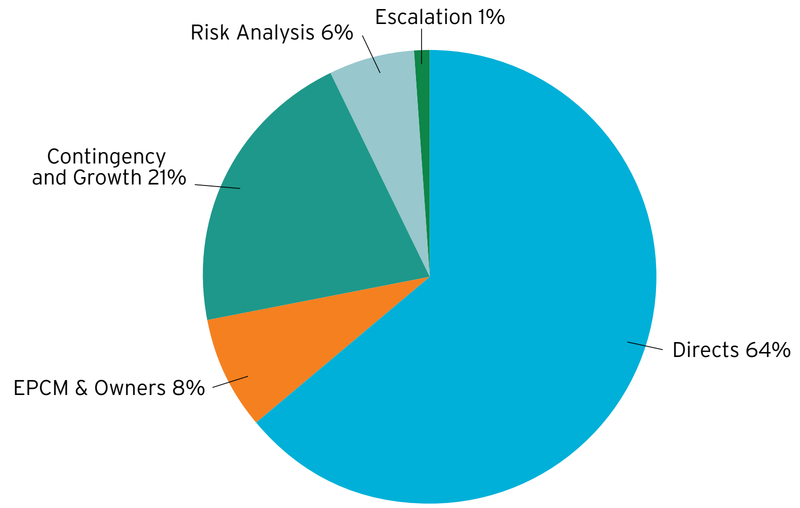


Figure 6: Total cost centres

Direct costs distribution (see **Figure 7** below) is also as expected for a project consisting mainly of compressors, large duct work and significant electric power supply. The portion called "Mech Equip – Other" includes flash tanks, heat exchangers, silencers and miscellaneous equipment. Approximately two-thirds of direct costs are associated with the compressors and related equipment, and with compressor power supply.

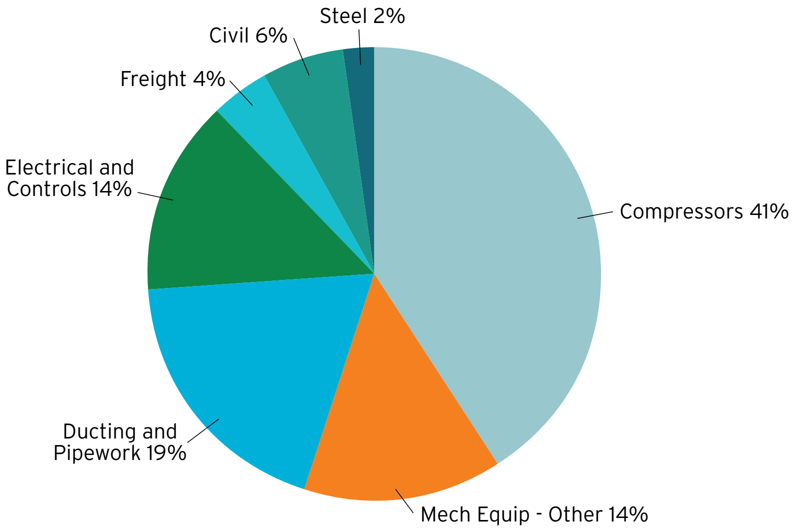


Figure 7: Direct costs distribution

Direct cost centres (see **Figure 8** below) are consistent with compressor power consumption, except for digestion which has smaller motors than other centres. **Figure 8** shows the breakdown of costs across a complete refinery, dominated by vapour recovery and MVR equipment at the 4 sources of waste vapour ("Digestion", "Calcination", "Evaporation" and "Precipitation"), as well as electric power supply and other ancillary equipment ("VOCs").

Cost centres include power distribution from the main switch house to the cost centre substation.

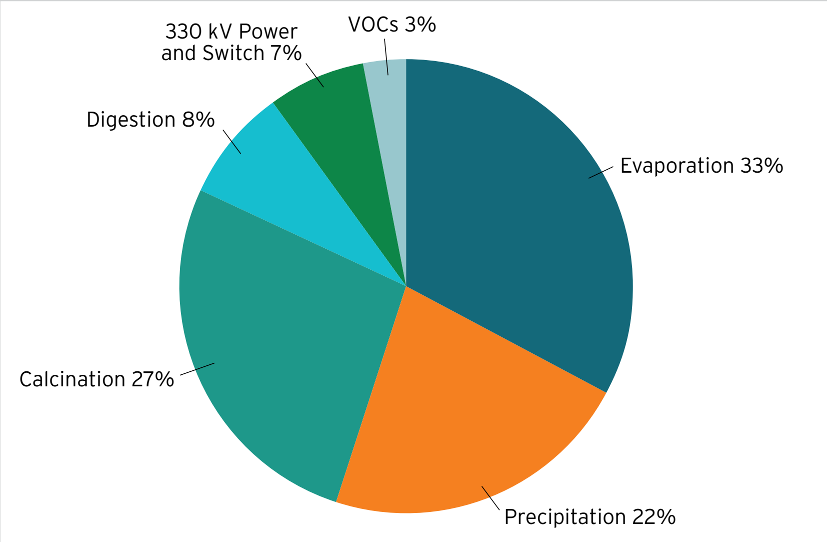


Figure 8: Direct cost centres

Retrofitting an existing facility has financial, technical and spatial challenges. MVR requires significant investment, making most of the original steam supply infrastructure redundant, and is dependent on the grid's capacity to accommodate further electricity supply.

However, there are still benefits to an MVR retrofit in an existing low-temperature refinery:

- The existing boiler infrastructure can be used as back-up supply, thus eliminating the investment needed for MVR redundancy.
- Existing facilities are often steam-limited when a boiler is out for maintenance. MVR provides additional steam capacity.
- Existing power generation infrastructure can be used independently for peaking capability rather than being tied to providing the required flow of process steam.
- Refinery cooling water circuits are often stretched during summer. MVR alleviates that issue as it reduces waste heat rejection.
- Water use is reduced, as MVR captures waste vapour and recycles it providing a particular benefit in a dry climate such as Australia.

3.3.2 EXTRAPOLATING CAPITAL COST TO OTHER FACILITIES

Based on the above capital evaluation, the Commercial Study estimated that a high-temperature refinery could be expected to cost approximately **18 per cent more** than a low-temperature refinery, on a per tonne of alumina basis.

At Alcoa's low-temperature Wagerup refinery, the estimated capital cost of MVR is **$220 per annual tonne of alumina production**, while for a high-temperature refinery, the estimated cost is **$260 per annual tonne**.

However, the study noted that retrofitting MVR at some facilities may be difficult due to spatial constraints and suggested that it may be preferable to look for alternative opportunities for older facilities.

The study also found that while a retrofit or brownfield expansion can use existing boilers as back-up for when a compressor train is off-line, a greenfield expansion does not have that opportunity, making it is necessary to take extra steps to achieve full steam capability when a compressor train is off-line. Overall, greenfield capital for MVR will be greater than brownfield due the need for redundancy.

3.3.3 KEY FINDINGS OF THE COMMERCIAL STUDY

MVR has a strong business case in a carbon-constrained world. When powered by renewable energy, MVR could be the lowest cost means of providing process heat to an alumina refinery.

The study found that:

- If the estimates are extrapolated to all alumina production across Australia's six alumina refineries, an overall **investment of approximately $4.5B** would be required to implement MVR, together with provision of **approximately 1.2 GW of firmed renewable power**
- MVR technology in alumina refining can become more c**ommercially competitive** with the establishment of **carbon markets** that incentivise emissions reduction, and
- in **growth scenarios**, MVR technology has **similar capital cost** to a conventional technology but with **lower operating cost**, and in retrofit scenarios, MVR economics will depend upon the availability and price of firm renewable power and carbon.

COMMERCIAL BENEFITS OF MVR

- Cost of abatement can be lower than other technologies.
- High technology readiness level – large-scale deployment could start in the medium term.
- Power consumption per tonne of steam could be substantially lower than electric boilers and hydrogen, therefore significantly less renewable power infrastructure investment required.
- Significant water savings.

The Commercial Study also identified issues that need to be addressed to implement MVR in alumina refineries. These include:

- Current industry knowledge gap in understanding the benefits of MVR for alumina refining
- Need for further testing to achieve proven reliable performance of MVR within an alumina refining setting. For example, Alcoa recommended an additional demonstration of a compressor train of 60:1 ratio (requiring many compressors in series) before substantial implementation
- Potentially high cost to develop MVR at its early stage as, among other things, renewable power cost is still high
- Large-scale renewable power supply – approximately 1.2 GW of firmed new renewable power would be required to drive MVR in Australian alumina refineries
- Current economic barriers. These could be resolved as the carbon and power markets evolve over time to provide incentives to invest in the development and implementation of low emissions refining technologies.

3.4 DEVELOPMENT PATHWAY FOR MVR TECHNOLOGY

This study also provided a development pathway needed to prove the MVR technology to the level required before a significant investment can take place in Australian alumina refineries. It has proposed a **fast-tracked** MVR technology development plan through overlapping the engineering and early execution processes to an acceptable extent that minimises financial risk. Approximately ten per cent of funding would be put at risk due to the potential need to re-engineer or abandon early work. This approach has the potential to significantly accelerate the development schedule. See **Figure 9** below.

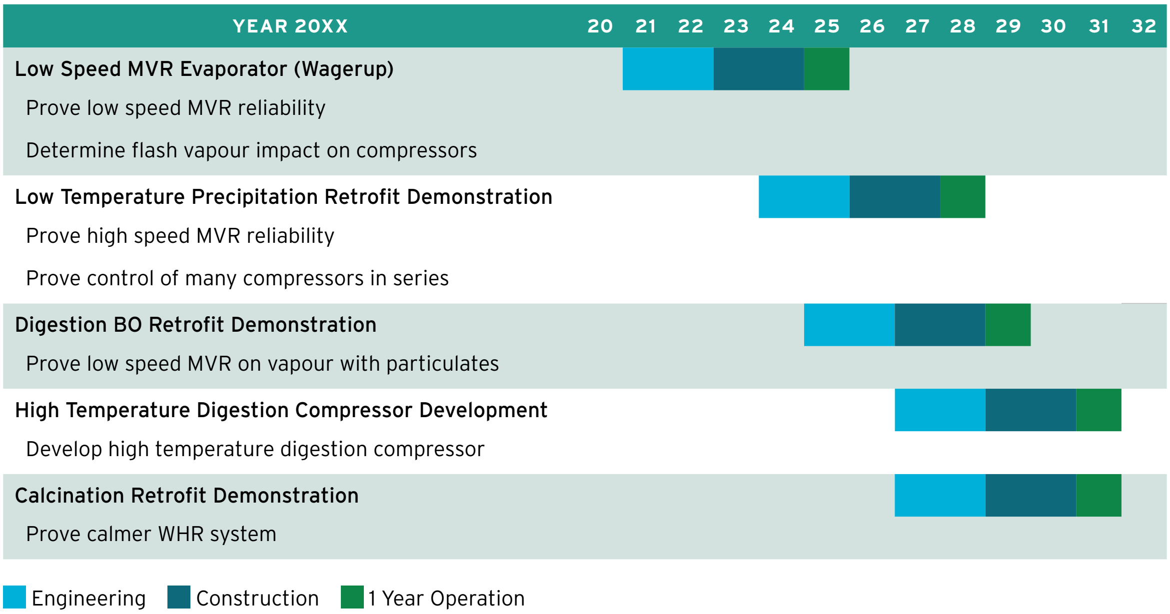


Figure 9: MVR development pathway – fast tracked

If MVR development proceeds as shown in **Figure 9** and is implemented at all Australian refineries, then it would be possible to achieve an emissions reduction profile close to that of the International Aluminium Institute's 1.5°C decarbonisation scenario[12]. A fast-tracked development pathway would enable adoption of MVR by Australian alumina refineries from 2030.

3.5 CONCLUSION

Overall, this Commercial Study shows that MVR has the potential to be applied in new (greenfield) refinery builds, existing (brownfield) refinery expansions, and could also be retrofitted in existing refineries. This study also indicates that MVR, powered by renewable energy, has a strong business case in a carbon-constrained world. The technology is likely the lowest cost method to decarbonise the Bayer process in the alumina industry, removing the need for fossil fuels during process heating.

12 International Aluminium Institute, 1.5 Degrees Scenario: A Model To Drive Emissions Reduction (October 2021)

4. CONCLUSION AND IMPLICATIONS

4.1 SUMMARY OF STAGE 1 FINDINGS

In conclusion, the Technical Study in Stage 1 of the Project has shown that MVR has a lower capital and operating cost than conventional evaporation, as well as a zero-carbon technology when powered by renewables. In terms of the technology's commercialisation pathway, the Commercial Study has shown that MVR technology has a strong financial case with the capacity to be introduced at existing and new Australian alumina refineries. MVR is likely the lowest cost method to provide low/zero carbon process heat to partially decarbonise Australia's alumina industry which has, to date, been categorised as 'difficult-to-abate' along with other heavy industries.

4.2 IMPLICATIONS

The implications discussed in this chapter are based on information extracted from either the MVR Evaporation Feasibility Study and the MVR Retrofit and Commercialisation Report prepared by Alcoa or other public resources, therefore they do not necessarily represent the views of Alcoa or of ARENA and the Australian Government.

4.2.1 MVR A KEY ENABLER FOR ACHIEVING GREEN GLOBAL ALUMINA INDUSTRY

On balance, the two studies have revealed that MVR can be technically and commercially feasible in alumina refineries, and that MVR is likely the lowest cost method to provide low/zero carbon process heat to partially decarbonise Australia's alumina industry which has, to date, been categorised as 'hard-to-abate'. The technology has a strong business case in a carbon-constrained world, with a potential to substantially reduce fossil fuel consumption in alumina operations and contribute to a green global aluminium value chain.

Given Australia's abundantly available renewable energy resources and proximity to high-quality bauxite ore, the country is well-positioned and has a competitive advantage to participate in the world's growing low carbon aluminium value chain.

As discussed in Chapter 3, alumina from the Australian market is currently exported mainly to China and the Middle East. The operators of each Australian alumina refinery have also announced 2050 net zero carbon initiatives along with substantive interim goals and the achievement of these goals will require decarbonisation of the Australian alumina industry.

With consumers already starting to demand and pay premiums for low carbon aluminium, particularly in high-value products in the smartphone and auto industries, this trend could support investment in the development and implementation of low emissions refining technologies and present a market opportunity to increase the competitiveness of Australia's low carbon alumina industry.

4.2.2 BRIDGING INDUSTRY KNOWLEDGE GAP AND ACCESSING RENEWABLES

The Commercial Study also identified issues that need to be addressed to achieve MVR commercialisation of alumina refineries. These include:

- The presence of industry knowledge gap in understanding the benefits of MVR
- Potentially high cost to develop MVR at its early stage as, among other things, renewable power cost is still high
- Large-scale renewable power supply – approximately 1.2 GW of firmed new renewable power would be required to drive MVR in Australian alumina refineries.

4.2.3 OTHER IMPLICATIONS

MVR provides a potentially viable pathway to eliminate the approximately 70 per cent of GHG emissions from alumina refineries. Currently, the alumina refining industry is the largest consumer of process heat in Australia, and it predominantly relies on fossil fuels.

Substantial investment is required in this decade to de-risk and customise the MVR technology for alumina refineries, following which deployment at scale could occur through the 2030s. As a global leader in alumina production and with excellent renewable energy resources, Australia is well-placed to lead this development and is well-positioned to benefit from the expected surge in demand for low carbon alumina and aluminium. (See section 4.2.1 above)

At the same time, substantial investment will also be required to provide firmed renewable energy at the scale required for this transition

Finally, to achieve this transition in the timeframe expected by global carbon commitments, coordinated action is required by the alumina industry, the energy supply industry, energy planning authorities, as well as governments at all levels.

5. NEXT STEPS

Based on the findings in Stage 1, Alcoa will proceed to Stage 2 of the ARENA-funded project — a full-sized demonstration of a 4 MW module of MVR at its Wagerup Alumina Refinery. The MVR module will be integrated with the refinery's evaporation process and will be powered by renewable electricity.

Further information is available at
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