Mechanical Vapour Recompression (MVR) for Low Carbon Alumina Refining

MVR Evaporation Feasibility Study

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Prepared by: Ray Chatfield
Alcoa of Australia Limited

Project Webpage: Alcoa Alumina Story

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1 Acknowledgements and Disclaimers

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2 Executive Summary

The alumina refining sector is currently a significant fossil fuel energy user and Green House Gas (GHG) emitter, with around 70 per cent of GHG emissions coming from fossil fuel-driven process heating in the Bayer refining circuit. Displacing the fossil fuels used for this process heating with a renewable energy source would reduce the Australian **alumina industry emissions by approximately 10 Mt CO_2-e per annum.**

Decarbonisation is a critical focus area for the alumina and aluminium industries. There is growing expectation from society that industry demonstrate how it will significantly reduce its greenhouse gas footprint, and in parallel the demand for low-carbon footprint alumina and aluminium products is expected to grow. The operators of Australian alumina refineries have announced 2050 net zero carbon ambitions along with substantive interim goals. Achieving these goals requires decarbonisation of the Australian alumina industry.

This Mechanical Vapour Recompression (MVR) Evaporation Feasibility Study investigates the feasibility of applying MVR technology at Alcoa's Wagerup Alumina Refinery, using the technology to drive a 65 tph single stage Falling Film Evaporator (FFE). MVR has the potential to displace fossil fuel use for steam generation in the Bayer alumina production process. A successful small-scale demonstration of MVR technology (two compressors in series) is necessary before progressing to larger-scale implementation of MVR in refinery process heating applications. If this demonstration project is successful, MVR could then be tested for the purpose of producing process heat (thirteen to seventeen compressors in series). If MVR can be applied to generate process heat, significant decarbonisation of the alumina industry becomes possible.

Alumina refineries require evaporation capacity to maximise efficiency and maintain process stability. Evaporation capacity is typically provided by multi-stage flash evaporation trains that use steam for heating, where the steam is generated by fossil fuel combustion. This installation will generate additional evaporation by recompressing exhaust water vapour from a previously installed FFE with electrically powered MVR and using the recompressed steam to heat the evaporator. When the electricity is generated from renewables this increased evaporation capacity comes with no additional GHG emissions.

The findings of this Feasibility Study are that implementation of MVR combined with a 65 tph FFE appears technically and commercially feasible and if successful will provide an operational benefit to the refinery whilst simultaneously demonstrating the technology. Key lessons learnt from this Feasibility Study are listed below.

- Ensure that refinery tie ins are robust.
- Ensure the current refinery power delivery system is capable of handling the additional duty.
- Select a simple and robust MVR design (two low-speed compressors in series) and developing specifications, including material of construction, running speed, start-up philosophy.
- Select MVR equipment based on the specifications and on Alcoa's purchasing processes, this includes obtaining performance guarantees.
- Conduct process modelling to ensure the unit will provide the required evaporation performance.

- Consider the addition of an inlet chamber to mitigate the expected heater tube vibration.
- Evaluate and select mist elimination options to allow clean vapour feed to the MVR units from the FFE vapour separator.
- Evaluate and select noise abatement measures both at the source and remote from source to meet existing refinery requirements.

The Key Performance Indicators (KPIs) for the MVR-FFE evaporation system relative to a conventional evaporator were determined in this Feasibility Study, and clearly show the economic advantages of the MVR-FFE system over conventional evaporation, including lower capital and operating costs. Sensitivity analysis indicates that the MVR evaporator outperformance is robust against variations in power, gas, and carbon prices.

A risk assessment determined three major project risks:

- Unsuccessful project outcome.
- Delivery of equipment or services delayed, or construction delayed by the supplier.
- Scope growth of modification of existing FFE or FFE unable to be retrofitted.

In each case risks were readily mitigated, as has been addressed in more detail in this Study.

Key messages

- Decarbonisation is a critical focus area for the alumina and aluminium industries.
- MVR driven by renewable generated electricity could significantly decarbonise the alumina industry in Australia and world-wide.
- A successful small-scale demonstration of MVR technology is necessary before larger-scale implementation of MVR in alumina refineries can be considered.
- Installing additional evaporator capacity on a single evaporator in an alumina refinery is a relatively low cost, low risk technology demonstration. Additional evaporator capacity is otherwise generated through steam generated by fossil fuel combustion.
- Installing additional evaporator capacity at Alcoa’s Wagerup Alumina Refinery using MVR to drive a 65 tph single stage FFE appears technically and commercially feasible.
- The proposed installation is suitable to demonstrate the applicability of MVR as a decarbonisation enabler in alumina production and should proceed.
- Project execution risks and the appropriate mitigations of these have been identified.
- Potentially major technical issues relating to vapour cleanliness and noise abatement have been considered and can be resolved.
- Capital costs are competitive with conventional evaporation options, operating costs are lower than conventional evaporation and sensitivity analysis indicates that MVR evaporator performance is robust against changes in power, gas, and carbon prices.

3 Introduction

Alumina refining is an intermediate step in the production of aluminium. Bauxite is processed in alumina refineries to produce aluminium oxide, called alumina. Alumina is then smelted using the Hall- Héroult process which uses electrolysis to remove the oxygen to produce pure elemental aluminium.

The alumina refining sector is currently a significant fossil fuel energy user and therefore Green House Gas (GHG) emitter. It is categorised as 'difficult to abate' along with many other heavy industries.

In 2020, the Australian six alumina refineries generated 2.7 per cent of the national GHG emissions and were the largest industrial consumers of energy for process heat[1]. Around 70 per cent of GHG emissions from alumina refineries come from using energy for process heating in the Bayer refining circuit.

Figure 1 Alcoa's Wagerup alumina refinery, Western Australia

Completely displacing fossil-fuelled Bayer process heating with a renewable energy source would reduce **alumina industry emissions by approximately 10 Mt CO_2-e per annum.**

The Mechanical Vapour Recompression (MVR) for Low Carbon Alumina Refining project (the Project) provides a pathway to substantially reduce GHG emissions from alumina refining by using renewable power to drive MVR, displacing fossil fuel-derived energy and steam.

Renewably powered MVR is regarded as the most viable means of providing low emission Bayer process heating due to:

- its zero-carbon potential using renewable power from the grid
- the reliability of the external power grid, removing need for back-up power infrastructure
- the viable economics for new facilities and retrofit options
- the reduced water use due to the removal of the boiler feed water and the recovery of waste vapour.

MVR has the potential to leverage Australia's renewable energy sources to sustain and grow the alumina industry in a carbon-constrained world. However, MVR technology is not currently used in alumina refineries other than one small facility in China[2]. Significant investment in

MVR is required to decarbonise alumina refining, and confidence in the technology is required before that investment can take place.

The Wagerup MVR Evaporation Project has three objectives:

1. Provide the operating experience with MVR necessary to progress decarbonisation with this technology.
2. Demonstrate a low capital, low operating cost, modular form of evaporation relative to conventional evaporators.
3. Provide additional process evaporation resulting in reduced caustic consumption and increased alumina production without increasing GHG emissions. This Project will demonstrate zero carbon emission evaporation.

3.1 Project Drivers

3.1.1 Alcoa and Sustainability

Alcoa's commitment to sustainability drives it to minimise negative impacts and maximise value across its global operations to contribute to a better society.

'Advance sustainably' is a strategic priority for our company. We believe we can accelerate value creation by meeting society's increasing expectations for sustainable solutions, which will benefit our company, our stakeholders, and communities around the world.

Our sustainability strategy supports our strategic priorities through three pillars:

- Sustain our operations, preserve our license to operate and grow our assets, creating sustainable value for the communities where we operate.
- Enhance the value of our products through differentiation to improve our profitability.
- Reduce risk, minimise negative environmental impacts, and improve our health and safety performance.

Our ambition is to achieve net-zero GHG emissions globally by 2050. This builds on our existing reduction targets of 30 per cent by 2025 and 50 per cent by 2030 from 2015 baselines. We aim to achieve this by:

- Increasing the use of renewable energy.
- Growing our low carbon portfolio.
- Bringing breakthrough innovations to the market.

Alcoa's sustainability performance is evidenced through achievements and recognition, including that we are:

- The world's lowest carbon intensity alumina producer. In 2020, we introduced the industry's first low carbon, smelter-grade alumina. EcoSource™ alumina is produced with no more than 0.6 metric tons of carbon dioxide equivalents (CO_2-e) per metric ton of alumina, which is half the industry average of 1.2 metric tons of CO_2-e.

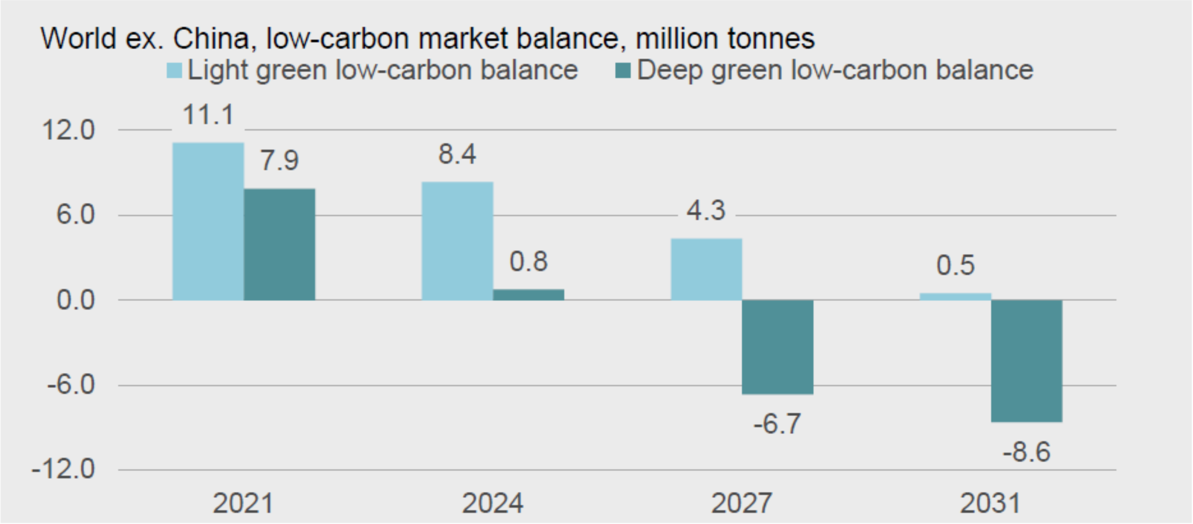
- Partnering with Rio Tinto on ELYSIS, a project to commercialise Alcoa-developed technology to make aluminium that eliminates all direct GHGs from the traditional smelting process.
- Included in the Dow Jones Sustainability Indices.
- Included on Human Rights Campaign Foundation's Corporate Equality Index.
- Aluminium Stewardship Initiative (ASI) certified across the value chain.
- A member of the International Council of Mining and Metals.

3.1.2 Emerging Low Carbon Drivers

The green and sustainable aluminium market is growing exponentially, particularly in Europe. The number of companies committing to the **Science Based Targets initiative** (SBTi) is growing rapidly, driving increased demand for low carbon aluminium [28,29,30].

The European market has driven most of the change to date due to the significant price of EU Carbon Permits and the proposed Carbon Border Adjustment Mechanism[3]. G7 commitments to achieve net zero commitments by 2050[4] and similar initiatives[5] are likely to substantially increase the market for low carbon aluminium.

CRU Group have forecast increasing demand for low carbon aluminium in key sectors with supply and demand to be balanced, or for a supply deficit to exist, by 2031 as shown in Figure 2.



DATA: CRU; Note: Light green scenario assumes 50%, and dark green scenario assumes 80% low carbon Al demand from key sectors by 2031. Key sectors are transport, construction and packaging end uses data. Low carbon Al defined as <4t CO2e /t Al for Scope 1 and 2 emissions.

Figure 2 Low carbon aluminium remains in surplus globally, but this is changing quickly – Source CRU[25]

Alumina from the Australian market is predominantly sold to China and the Middle East, regions that have also announced decarbonisation goals[6,7].

The operators of each Australian alumina refinery have announced 2050 net zero carbon initiatives along with substantive interim goals.[8,9,10,11] Achievement of these goals will require decarbonisation of the Australian alumina industry.

3.2 Rationale for this MVR Project

The purpose of this Project is to prove MVR can reliably operate within an alumina refinery. It is an important milestone in the development of a low carbon pathway for alumina refining.

Wagerup alumina refinery is an ideal location to demonstrate the technology. The refinery has a mothballed FFE which can be recommissioned and integrated with MVR at low cost. It will evaporate process liquor and provide benefits to the refinery and can be configured to operate over a range of conditions and capacities. This will enable MVR to be evaluated in the steady state, variable and upset conditions necessary to demonstrate reliable operation within an alumina refinery.

Two compressors will be used that will double the waste vapour pressure from 80 to 160 kPaA. This is the first step in developing a process which would ultimately require a large number of MVR compressors in series.

Process evaporation was selected because is the simplest MVR application in alumina refining.

3.2.1 Economic Drivers

The economic drivers for MVR over conventional evaporation process are:

- Carbon: future investment in a carbon intensive process is a significant financial risk. A more holistic view of carbon impacts on alumina refining is in the report *MVR Retrofit and Commercialisation Report*[12].
- Operating Cost: The emergence of low-cost renewable power means MVR is now the lowest operating cost form of process evaporation.
- Modularity: MVR evaporator designs are modular and conveniently sized. New conventional evaporation units require much larger capacity to be economic. The significant capital, operating and ancillary costs associated with an additional conventional evaporator train are a barrier to incremental installations to optimise evaporation capacity. Modular MVR evaporation is ideal for incremental evaporation capacity installation.

3.2.2 Prior MVR Installations

MVR is an established technology but has never been deployed at a large scale in an alumina refinery. A small 30 tph MVR + FFE was installed in 2003 in China and there is also a very small installation in a Japanese facility that was once an alumina refinery. However very little information is available on the operation of these units.

GEA (France) was the technology provider for the 30 tph facility. GEA is also contracted as the technology provider for this project. GEA presented a paper *Mechanical Vapour Recompression applied to Alumina Spent Liquor Evaporation Plants*[13] in 2019. Its energy consumption can be back calculated to approximately 45 kWh/t evaporation, similar to this project.

GEA's Compacryst® salt crystalliser has 125 tph evaporation capacity in a single unit. It uses three MVR compressors in series consuming 5.5 MW total compressor power. It was used to displace an existing crystallisation system that used steam produced by cogeneration with natural gas, thus reducing overall CO_2-e emissions.

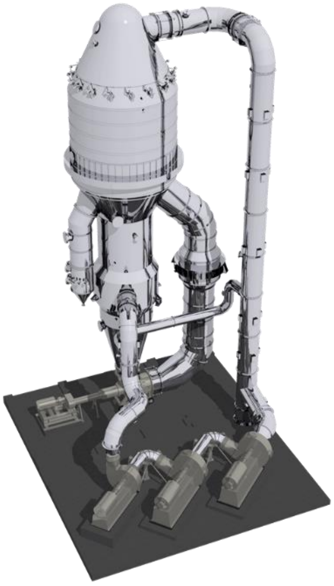


Figure 3 GEA's Compacryst® Crystalliser

A large and comparable MVR-driven process is used in a Turkish soda production facility commissioned in 2008. Its evaporation capacity is over three times that of Alcoa's Wagerup alumina refinery. The facility was so successful that an even larger MVR-driven soda extraction facility was built nearby in 2017.

Figure 4 A soda production facility in Turkey. Large falling film and forced circulation evaporators can be seen between the two buildings

Alcoa has visited this facility and numerous MVR evaporation facilities around the world to gain confidence in the technology.

3.3 Decarbonisation Strategy

MVR technology provides the potential to completely decarbonise the alumina refining Bayer circuit.

Alumina refineries require process heat, which is conventionally produced by combusting fuel to make high-pressure steam, emitting CO_2 in the process. In a future decarbonised state, MVR (driven by renewable power) is instead used to recompress very low-pressure process vapour back to high-pressure steam to heat the refinery. This is described in more detail in the *MVR Retrofit and Commercialisation Report*[12], which describes the feasibility of using MVR in place of traditional fossil fuel-fired systems in potential future expansion projects, retrofit opportunities at existing alumina refineries or new greenfield projects.

3.3.1 Demonstrating MVR Evaporation Feasibility

The first stage of the decarbonisation strategy is to demonstrate MVR operation in alumina refining on a smaller scale, in a duty common for MVR.

Alcoa's Wagerup alumina refinery has a Falling Film Evaporator (FFE) suitable for such a trial. It will use two x 2 MW capacity MVR compressors. Two-stage compressors are quite common in other industries. The compressors in this demonstration project will consume 3.2 MW of power which is about 0.3 per cent of the requirement to completely retrofit MVR to Australia's alumina refineries.

Conventional evaporator technology is considered as the baseline for commercial comparison and feasibility assessment.

Successfully demonstrating MVR evaporation feasibility comprises technical success (reliability and efficiency of the equipment) as well as meeting the evaporation requirements for the refinery, as described in Section 4.4.

4 Project Outline

Alcoa of Australia has three refineries in Western Australia, located at Kwinana, Pinjarra, and Wagerup. This Study outlines the feasibility of installing an MVR-driven evaporator at Alcoa's Wagerup alumina refinery.

4.1 Process Heat in the Alumina "Bayer" Circuit

Two bauxite types are processed in Australia to make alumina. Western Australian bauxite can be treated with caustic soda at around 140°C to 170°C to extract alumina, referred to as low temperature digestion. Queensland and the Northern Territory bauxite requires high temperature digestion at around 250°C to achieve good alumina recovery.

In both cases the Bayer liquor, a recirculating solution of caustic soda, dissolved aluminium, and water, is heated to the required temperature using steam. The hot Bayer liquor extracts the alumina-bearing components from bauxite (digestion), residual solids are removed (residue separation and washing), and the liquor is then cooled to precipitate alumina tri-hydrate crystals (precipitation). These are collected and calcined to form alumina.

The remaining 'spent' liquor is then reheated and some water is removed by evaporation to increase the caustic concentration again before it is recirculated back to digestion (evaporation).

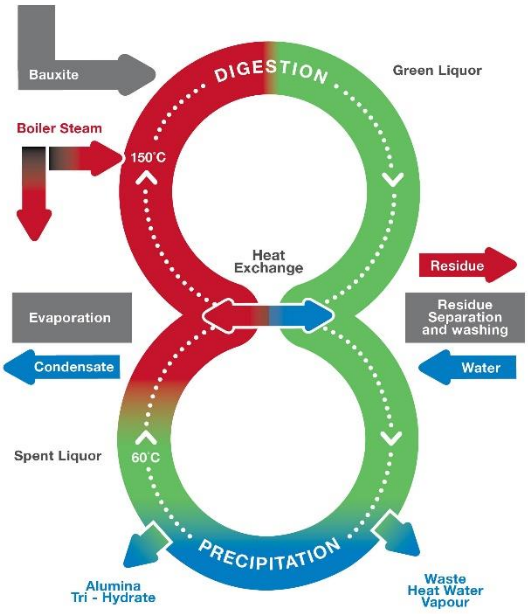


Figure 5 Bayer Process Flow

4.2 Evaporation Process

There are two primary methods used to evaporate spent liquor in the Bayer process:

- multi-stage flash trains
- multi effect single-stage evaporators, including falling film, rising film, forced circulation and natural circulation evaporators.

Multi-stage flash trains and multi effect single-stage evaporators make full use of the refinery steam temperature, typically around 170°C condensing temperature (in low temperature refineries), to provide efficient evaporation.

Evaporation methods are outlined in more detail in *Mechanical Vapour Recompression applied to Alumina Spent Liquor Evaporation Plants*[13].

4.2.1 Multi-stage Flash Evaporation

Alumina refineries use evaporation technologies designed around fossil fuels. A typical multi-stage flash evaporation train is shown in Figure 6. Cold liquor at around 60°C enters a series of pressurised heat exchangers where it is heated to around 140°C before being further heated to around 160°C using an external steam source. The hot liquor then passes through a series of flash tanks. The flash tank depressurises the liquor causing it to cool and 'flash off' water vapour (steam). The water vapour is recirculated to the heater where it is condensed, providing heat to the cold spent liquor. The outgoing spent liquor exits the last flash tank at about 80°C. It no longer has sufficient temperature to heat the incoming spent liquor, so it is flashed in a final 'barometric' flash tank down to about its original 60°C. The barometric flash vapour is condensed using cooling water.

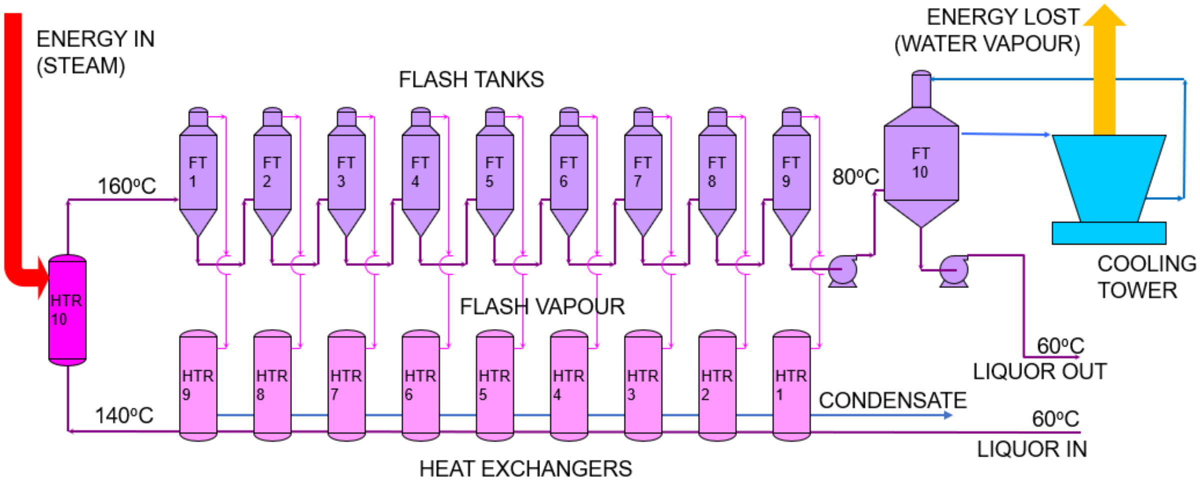


Figure 6 A conventional multi-stage flash evaporation train

About 20 per cent of the liquor is evaporated in the process. For every tonne of water evaporated, 0.25 tonnes of external steam is required. This is sourced from a fossil-fuelled boiler.

A modern multi-stage flash 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, require about 60 tph of steam, a significant cooling water system, and about 60 tph fresh water to make up for cooling water losses.

Figure 7 A conventional multi-stage flash evaporation train at Wagerup
Flash tanks are clearly visible in the silhouette. Heat exchangers are underneath the flash tanks

4.2.2 MVR with Single-Stage Evaporation

MVR provides the motive force to drive evaporation, similar to how boiler steam drives conventional evaporation. MVR is best suited to a single-stage evaporator configuration, such as the single-stage FFE used in this project.

The design has a single heat exchanger, an integrated vapour separator, no external steam supply, and no cooling water circuit. Vapour from the vapour separator is compressed by the MVR compressor causing the vapour's condensing temperature to increase by about 20^{O}C. This provides sufficient thermal driving force to heat the liquor falling through the heat exchanger tubes, causing the liquor to evaporate and create more vapour to be compressed. Condensed vapour from the heat exchanger is removed from the system as condensate and concentrated product liquor leaves the vapour separator.

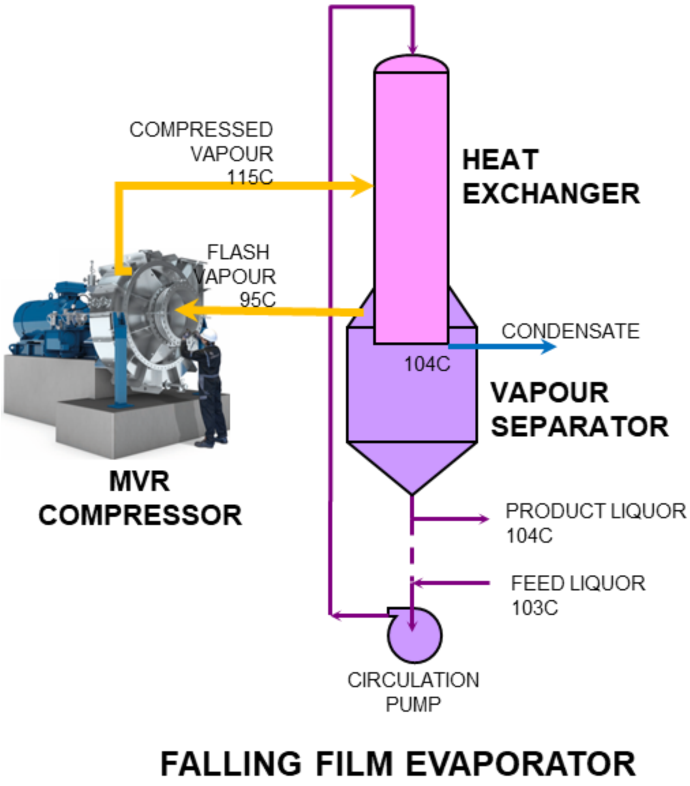


Figure 8 MVR coupled with an FFE

A detailed description of an MVR driven falling film evaporator is available at this website.

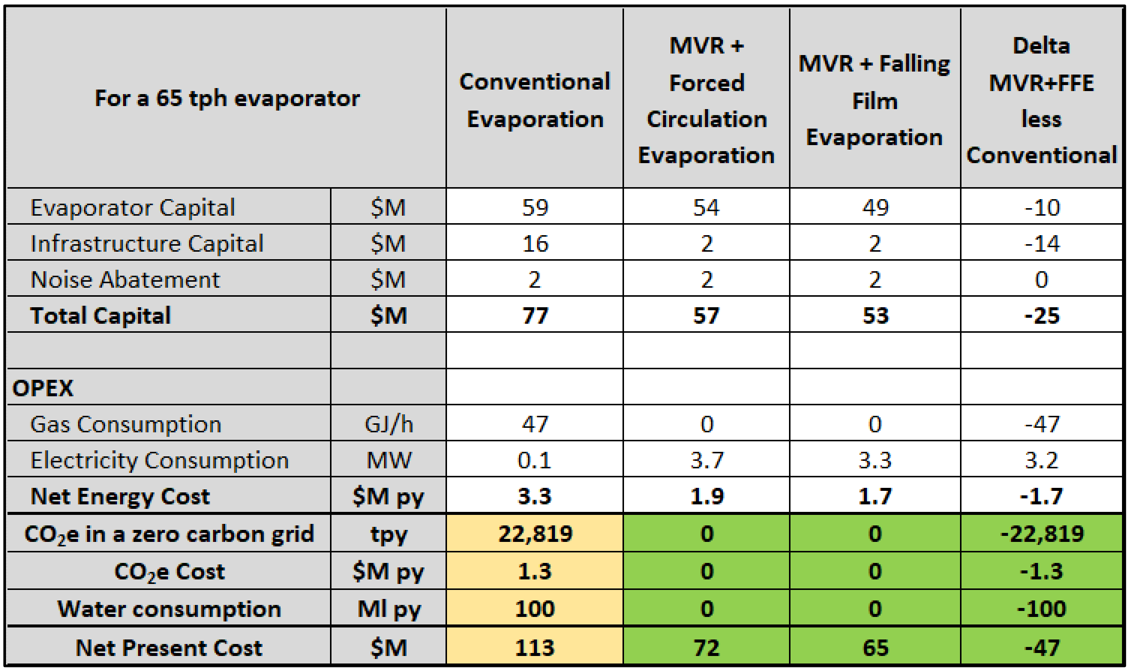
This design enables a modular design of about 20 per cent the capacity of a conventional multi-stage flash evaporator. This enables small increments of evaporation to be added to the process with minimal capital investment. It uses significant amounts of electricity, but if powered by renewable electricity has a zero-carbon footprint. Overall, it consumes about 33 per cent of the energy of a conventional evaporator.

4.2.3 KPI Comparison Summary

Key Performance Indicators (KPIs) for conventional evaporation and MVR with two types of single-stage evaporation are outlined in Table 1. The two forms, MVR + FFE and MVR + forced circulation evaporators (forced circulation evaporator operation is explained at this website), provide superior net energy cost than conventional evaporators. The KPIs are financial, that is capital (CAPEX) and operating cost (OPEX), and non-financial, carbon emissions and water consumption.

Conventional evaporation uses high-pressure boiler steam to generate power through steam turbines and uses turbine exhaust steam in the refinery. Costs from this Combined Heat and Power (CHP) system are charged to ‘power’ and to ‘steam.’ The power charge is the equivalent of the purchase price from the applicable power grid. The steam charge is the balance to net off the total powerhouse cost. As a result, higher power pricing results in lower costs being attributed to steam.

Renewable power has substantially disrupted the economics of self-generation and it is now frequently beneficial to bypass the steam turbines and purchase power. This reduced energy cost ‘chargeable to power’ has increased the energy cost ‘chargeable to refinery steam,’ making evaporation processes that rely on boiler steam more expensive. As a result, MVR based evaporation using renewably generated power is potentially superior to conventional evaporation.



For a 65 tph evaporator		**Conventional Evaporation**	**MVR + Forced Circulation Evaporation**	**MVR + Falling Film Evaporation**	**Delta MVR+FFE less Conventional**
Evaporator Capital	$M	59	54	49	-10
Infrastructure Capital	$M	16	2	2	-14
Noise Abatement	$M	2	2	2	0
Total Capital	**$M**	**77**	**57**	**53**	**-25**
OPEX					
Gas Consumption	GJ/h	47	0	0	-47
Electricity Consumption	MW	0.1	3.7	3.3	3.2
Net Energy Cost	**$M py**	**3.3**	**1.9**	**1.7**	**-1.7**
CO_2e in a zero carbon grid	**tpy**	**22,819**	**0**	**0**	**-22,819**
CO_2e Cost	**$M py**	**1.3**	**0**	**0**	**-1.3**
Water consumption	**Ml py**	**100**	**0**	**0**	**-100**
Net Present Cost	**$M**	**113**	**72**	**65**	**-47**

Table 1 Evaporation Technology KPIs - including forced circulation

In addition, MVR technology does not require cooling water.

Capital cost assumptions in this comparison

- Conventional evaporator costs are based on Alcoa proprietary information.
- MVR + FFE costs are estimated using Alcoa proprietary information.

- Forced circulation evaporator costs are derived from the MVR + FFE case on the basis of same heat exchanger area and flash tank size, but larger compressors to provide the higher thermal driving force for a forced circulation evaporator.

Capital cost reductions provide the majority of the MVR benefit. A conventional evaporator requires larger capacity (240 tph) than MVR to achieve economies of scale. The comparable MVR evaporator capacity is 65 tph, which is a convenient increment size for additional evaporation capacity. The 65 tph conventional evaporator capital cost estimate is based on a 240 tph evaporator using the relationship Cost = C x $(\text{Capacity})^N$ where N = 0.85. This is a compromise between two alternatives where N = 0.7 for a situation where only 65 tph evaporation is required, and N = 1.0 if the full 240 tph is required and would be fulfilled by 4 x 65 tph MVR evaporators. A value of N = 0.7 would indicate significant economy of scale, whereas a value of 1.0 indicates no economy of scale.

Overall estimate accuracies could be considered AACE class 5, or approximately –30 per cent / +50 per cent. Estimate costs are escalated to 2021.

Financial assumptions

Financial assumptions including energy costs and the cost of capital are outlined in Section 4.3. Net Present Cost (NPC) is calculated over 25 years.

Noise Control

Boundary noise is an important regulatory, environmental and community factor for alumina refineries. MVR compressors are noisy and special attention has been placed on noise attenuation. Similar noise abatement considerations would arise for new conventional evaporator installations.

Load variability

Conventional evaporators operate in steady-state equilibrium. Process changes need to be made slowly to avoid suboptimal performance, in particular with regard to condensed steam (condensate) quality.

The MVR + FFE evaporator will operate at constant pressure, and operating load can be varied while still maintaining optimal performance. This allows the MVR + FFE unit to realise cost benefits by operating at higher load during periods of lower power pricing, such as through participation in an essential system services market.

4.2.4 Maintenance

Maintenance costs are expected to be lower for the MVR + FFE evaporator than for a conventional evaporator, however differences are relatively small (approximately $150,000 per year) and have not been costed in detail.

Heater Tube Fouling

Heater tube cleaning and maintenance is a significant consideration in alumina refining due to heater fouling and caustic corrosion. Heating fouling is commonly caused by the deposition of sodalite from the Bayer liquor. Deposition rates are strongly temperature dependent, with fouling rates being much higher at higher temperature.

Conventional evaporators require a large temperature operating range to be efficient and are often impacted by sodalite scale. The scale is detrimental to heat transfer and also causes accelerated corrosion from the acid wash required to remove it. There is a significant maintenance effort to manage heater cleanliness and heater tube integrity.

Conversely, MVR evaporators do not require large temperature variations. Temperature variations (deltas) are generally less than 10°C, and in FFEs may be as low as 1°C. Therefore, it is possible to select an operating temperature optimised for steam generation and fouling rate. The demonstration project will operate between 83 and 102°C and will require infrequent (biannual) cleaning.

This minimal maintenance requirement could be assumed for all types of MVR + single-stage evaporator combinations.

Powerhouse, Cooling Water and MVR Systems

The *MVR Retrofit and Commercialisation Report*[12] determined that the capital infrastructure required to power a conventional refinery and MVR refinery are equivalent.

However, conventional evaporation ancillary systems, including the powerhouse, steam distribution systems and cooling water systems, require extensive maintenance. Sustaining maintenance is typically estimated to be a small percentage of the capital cost for greenfield refineries.

Specific MVR maintenance requirements should be minimal. Key components, such as shaft seals, compressors, bearings, and impellers, should be long-lived and therefore incur minimal additional maintenance cost or downtime.

4.2.5 Cost Sensitivity Analysis

MVR use in this Project provides a capital advantage of $25M and a Net Present Cost (NPC) advantage of $47M over conventional evaporation (Section 4.2.3).

The sensitivity of the estimate was evaluated against potential variations in gas, power, and carbon pricing (Figure 9). Each factor has a strong influence on Project economics. Despite this the benefits are robust with respect to all factors. Carbon price has the greatest influence with higher carbon pricing causing a higher relative benefit for MVR. Carbon pricing is likely to increase over time, therefore it is likely MVR economics will improve relative to conventional technology in the medium to long term.

Note that the sensitivity estimates have an elevated level of uncertainty, approximately the same as an AACE class 5 estimate.

Assumptions:

- Sensitivities are relative to the NPC provided in Section 4.2.3 and cost assumptions in Section 4.3, including carbon.
- Power cost range was assumed to be proportional to the gas cost range, being -50 to +65 per cent of base value in the South-West Interconnected System (SWIS) Whole of System Plan (WOSP, 2020)[15]. The power cost range is arbitrary but provides relative indication of sensitivities.

- Annual costs are converted to net present cost by multiplying by 7.8. This factor is derived by determining the Net Present Value (NPV) of the series zero for the first year, followed by one for the next 25 years at 12 per cent discount rate, representing a project where the weighted average of capital expenditure is in the first year and no income, followed by 25 years of return.

Figure 9 Cost sensitivities for MVR+FFE vs Conventional Evaporation

4.3 Financial Assumptions

Financial assumptions outlined below are from public data or are typical for industry.

A 12 per cent discount rate was used, representing an all-in cost including financial risk due to investing in a commodity-based industry and being subject to commodity price volatility.

Gas and power pricing are taken from the SWIS WOSP, 2020[15]. As large-scale MVR deployment is not expected in the short term, forecast average pricing from 2031 to 2040 was used, based on potential investment decisions around 2030.

4.3.1 Natural Gas

The natural gas price is $7.91 /GJ delivered to the South-West of WA, using the Base price averaged over the focus period.

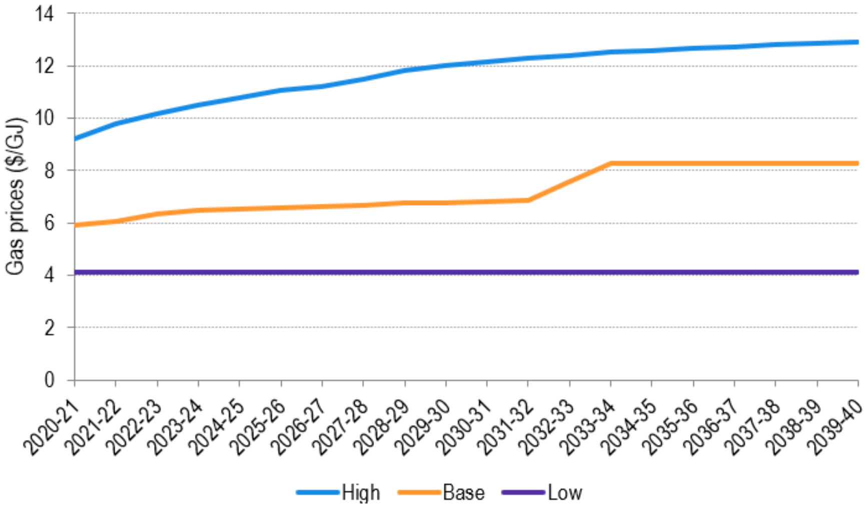
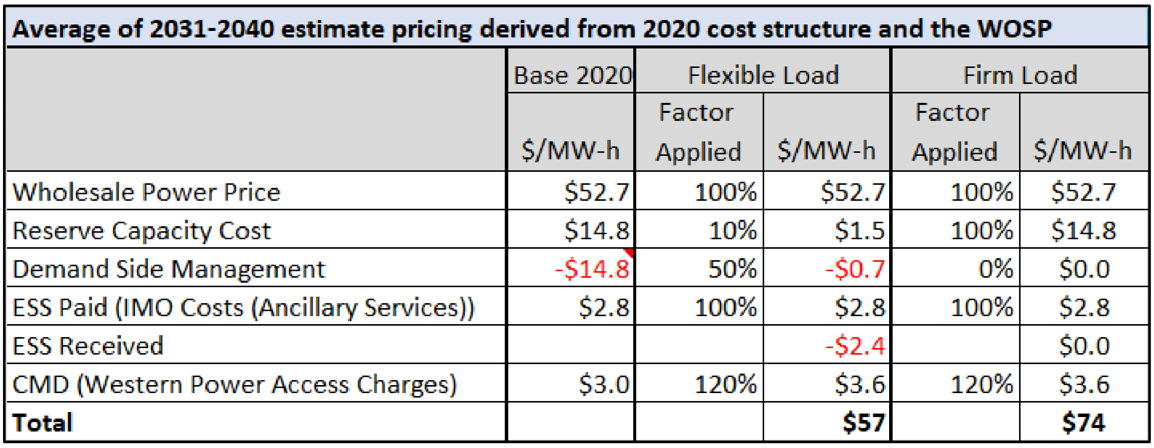


Figure 10 Natural gas prices for SW WA. Source SWIS WOSP

4.3.2 Power

Power price was determined based on a combination of inputs. One project objective is to show that MVR can realise a lower power cost by adapting to the market. The headline delivered power price was $74/MW-h, based on the SWIS WOSP Double-Bubble scenario, adjusted to match 2021 forecast to actual. The Double-Bubble scenario was chosen as it is the closest approximation to a scenario with substantial industrial electrification and trending to zero carbon by 2050. Power prices were estimated or derived from the WOSP and are represented as the Base case.



Average of 2031-2040 estimate pricing derived from 2020 cost structure and the WOSP					
	Base 2020	Flexible Load		Firm Load	
	$/MW-h	Factor Applied	$/MW-h	Factor Applied	$/MW-h
Wholesale Power Price	$52.7	100%	$52.7	100%	$52.7
Reserve Capacity Cost	$14.8	10%	$1.5	100%	$14.8
Demand Side Management	-$14.8	50%	-$0.7	0%	$0.0
ESS Paid (IMO Costs (Ancillary Services))	$2.8	100%	$2.8	100%	$2.8
ESS Received			-$2.4		$0.0
CMD (Western Power Access Charges)	$3.0	120%	$3.6	120%	$3.6
Total			**$57**		**$74**

Table 2 SWIS power price structure

The anticipated MVR all in power cost is $57/MW-h, 22 per cent lower than the headline power price.

- **Wholesale Power Price** as determined by the market.

- **Reserve Capacity** cost is a capacity charge applicable to the SWIS. It is an annual charge based on the median of the three highest half-hour metering intervals on the four highest load days of the summer period. The implied cost of power for the six hours total recording period is over $20,000 per MW-h, far higher than economic for continued MVR evaporator operation. Alcoa actively minimises import power during these periods. MVR evaporation will be stopped during these periods and a 90 per cent avoidance success rate is assumed. An objective of this project is to demonstrate that the MVR evaporator can be readily stopped and started as required to avoid these charges.

  The National Electricity Market (NEM) is in the process of developing a capacity market to apply in its post-2025 reform work. The exact nature of the future NEM Capacity Market is unknown; however, a reasonable assumption would be that the introduction of one would target generator and load behaviour modification during periods where there are extreme power prices when the network is under strain – similar in concept to the SWIS process. These high price periods can often be predicted and avoided; thus, we would expect a similar net financial outcome in the NEM as in the SWIS.

- **Demand Side Management (DSM)** is when the facility is paid to reduce load to support the grid. The price per MW is similar to what a generator is paid to provide power capacity to the grid. Under the SWIS rules, the amount paid in DSM cannot exceed the amount paid for Reserve Capacity. As DSM can be called by the network operator at any time, it was assumed only 50 per cent of the potential saving would be realised.

- **Essential System Services (ESS)** cover short-term load variation capability to keep the grid stable. All grid users pay for ESS; however, Alcoa anticipates providing ESS load rejection services by reducing MVR power on demand. An objective of this project is to demonstrate that the MVR could provide ESS by simulating ESS events. ESS services and benefits are discussed further in Section 5.4.

- **Contracted Maximum Demand (CMD)** is the maximum MW limit allowed under the transmission contract in the SWIS without being subject to an excess network usage charge. A 120 per cent factor was used to cover peak load periods.

4.3.3 Renewable Power

Analysis of the SWIS WOSP shows that the lowest cost solution for incremental new load is 100 per cent renewable power. This assumes the absence of a price on carbon or policy settings that discourage investment in fossil fuelled power generation. Therefore, we can suggest:

- incremental load for industrial electrification is 100 per cent renewable, and
- Large-Scale Generation Certificates (LGCs) are not required to promote renewables and any equivalent pricing mechanism is already built into the WOSP.

Alcoa modelling indicates significant growth in battery storage post 2030, which would enable firmed power to approach 100 per cent renewables. The ability for MVR to flex load and participate in ESS strengthens the argument to assume 100 per cent renewables.

It is assumed that possible future Power Purchase Agreements (PPAs) will be competitive with grid pricing.

4.3.4 Carbon Price

The price of carbon used was the Australian Carbon Credit Unit (ACCU) value of \$55/t CO_2-e, 17 January 2022.

4.4 Success Criteria

Success criteria can be split into two categories:

- MVR Process and Equipment. This is important for the future uptake of MVR in alumina refining.
- FFE Performance. This is important for the economics of this project and potential future use.

MVR Process and Equipment Objectives:

- MVR technical success: demonstrate the technology in an alumina refinery such that MVR can be further developed to decarbonise other process heat duties.
- MVR reliability: necessary to develop reliability models for large scale deployment.
- MVR Efficiency: measured as isentropic efficiency as manifested by power consumption.
- Provision of grid services (ESS).
- Noise abatement such that large scale MVR implementation can be realised within regulatory requirements.

Evaporation Objectives:

- Meet the evaporation rate required to deliver project economics.
- Provide good condensate quality.
- Economic energy operation measured in MVR and ancillary power per tonne of evaporation.

Key KPIs, success criteria and expected performance are listed in Table 3. The data is an aggregate of Alcoa experience with evaporation process equipment, process design and vendor data.

KPI	Criteria	Expected
Evaporation Rate	56 tph year average	60 tph when online
Evaporator condensate quality	<150uS	120 uS
MVR power per tonne evaporation	<48 kW-h/t	46 kW-h/t
MVR vibration monitoring	Can detect carry-over	Detects carry-over
MVR maintenance	<$250,000 per year	$150,000 per year
MVR reliability	>98% availability	>99% availability
Noise generated	<85 dBA local	83 dBA local
Ability to modulate MVR load for grid services	>0.6 MW/min	2 MW/min

Table 3 Operational KPIs

4.5 Pathway to Commercialisation

Potential commercial implementation of MVR is discussed in the separate *MVR Retrofit and Commercialisation Report*[12].

This Project is an important precursor to the potential large-scale implementation of MVR. Future implementations of MVR will require 40 to 100 compressors depending on refinery size and compressor type. Operational data from this project could be used to optimise future designs.

This demonstration project will compress vapour to twice its original pressure to provide process heat to the FFE. Provision of full process heat for a low temperature alumina refinery will require a compression ratio of 60 times requiring compressor trains with many (13 to 17) low-speed compressors in series. A refinery will require several compressor trains to deliver the required steam capacity.

Reliable operation with low-speed compressors will provide confidence to use high-speed compressors in future designs. One high-speed compressor provides compression almost equivalent to two low-speed compressors with lower implementation cost. The proposed future compressor train design will consist of a mix of low-speed and high-speed compressors[12]. Results from this demonstration will determine the mix of compressors used in the next development stage.

The main cost drivers of full implementation are:

- Compressor price including local power distribution.
- Site power supply and distribution infrastructure.
- Capturing low pressure vapour to supply the compressors.
- Noise abatement.

Compressors

The proposed future compressor train design will consist of a mix of low-speed and high-speed compressors[12]. This trial will provide data to inform compressor selection.

Higher than expected wear or other speed-related reliability issues during the trial would reduce the attractiveness of high-speed compressors and encourage low-speed compressor use, which would increase costs and spatial requirements.

The first stage low-speed and first stage high-speed compressors in a retrofit train are pushing the boundaries of compressor capacity. A subsequent full train trial as outlined in Section 11.1.1 will provide further confidence in MVR operation and provide useful application data to MVR manufacturers.

Site Supply and Distribution

Power supply and distribution are well known technologies. The trials will not contribute to better understanding these aspects.

Vapour Capture

This demonstration will provide confidence that clean vapour can be supplied to the compressors. The flash tanks that will provide vapour to the compressors in future scenarios are highly loaded, in terms of volume flow of vapour for the vessel size. The demonstration FFE vapour separator is also highly loaded but will have increased the mist elimination capability to suit.

Noise Abatement

The project (and likely future MVR installations) must achieve no boundary noise impact. Noise abatement treatments will be applied in a manner consistent with those required for a full MVR installation. The demonstration will identify if the treatments are adequate, and the outcomes will impact the overall capital cost.

5 Project Design and Execution Plan

5.1 Technology Selection

Alcoa reviewed many technologies to provide renewable process heat and determined that MVR is the most suitable.

5.1.1 Range of Technologies Considered

A range of technologies were considered and excluded for different reasons, as summarised below:

- Green hydrogen – which consumes four times the power of MVR to deliver the same quantity of steam to the refiner.
- Solar thermal – while competitive from an all-up dollar per tonne CO_2-e abated point of view, must be intricately linked to the alumina refinery and can only deliver around 40 per cent of process heat requirements.
- Geothermal – expensive with high technology risk.
- Energy from Waste – only has potential where an energy from waste facility is co-located.
- Biomass as Fuel – not economic or sustainable.
- Direct electric heating – more expensive than MVR and only used when excess hydro power at low cost is available.

These technologies are discussed in more detail in the *MVR Retrofit and Commercialisation Report*[12].

5.1.2 Selected Technology – Mechanical Vapour Recompression

MVR has zero carbon potential when driven by renewable power.

Renewable power that could come from a grid, such as the SWIS, has the added advantages of reliability and potential 100 per cent penetration. Back-up infrastructure would not be required, and power loads can be modulated to assist with grid stability and reduce operating costs.

In addition, water consumption is substantially reduced as low-grade heated water vapour is captured for re-use.

5.2 Technology Design

The design selected for the trial employs an unused FFE. It provides the opportunity to demonstrate the technical feasibility and potential economic benefit while being used in the refinery.

The FFE was designed by GEA, who were contracted to assist in adapting the evaporator to MVR operation. The evaporator has 2,500 m² of heat exchanger tubes and was originally designed to operate at 85 tph peak evaporation, 860 kPaA inlet steam pressure and 480 kPaA separator pressure. The new design condition is 76 tph peak, 126 kPaA inlet steam pressure and 63 kPa separator pressure.

Two low-speed compressors in series will be used to drive the FFE.

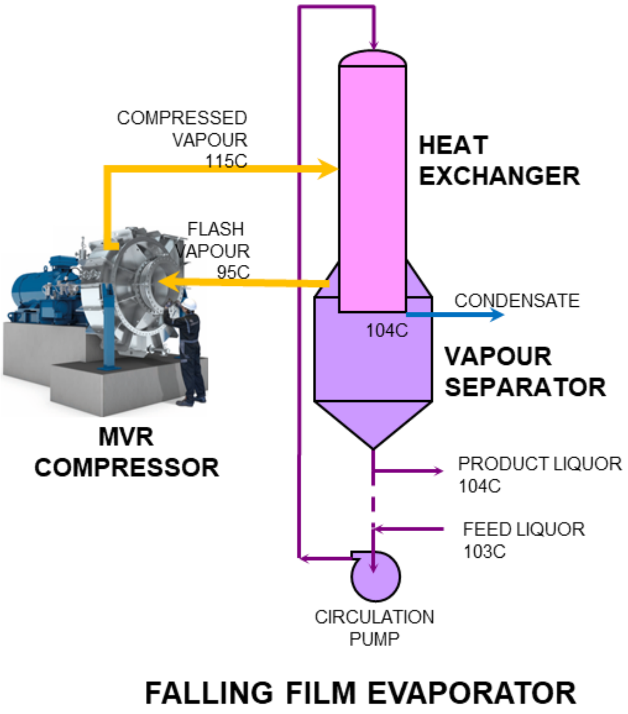


Figure 11 MVR coupled with an FFE

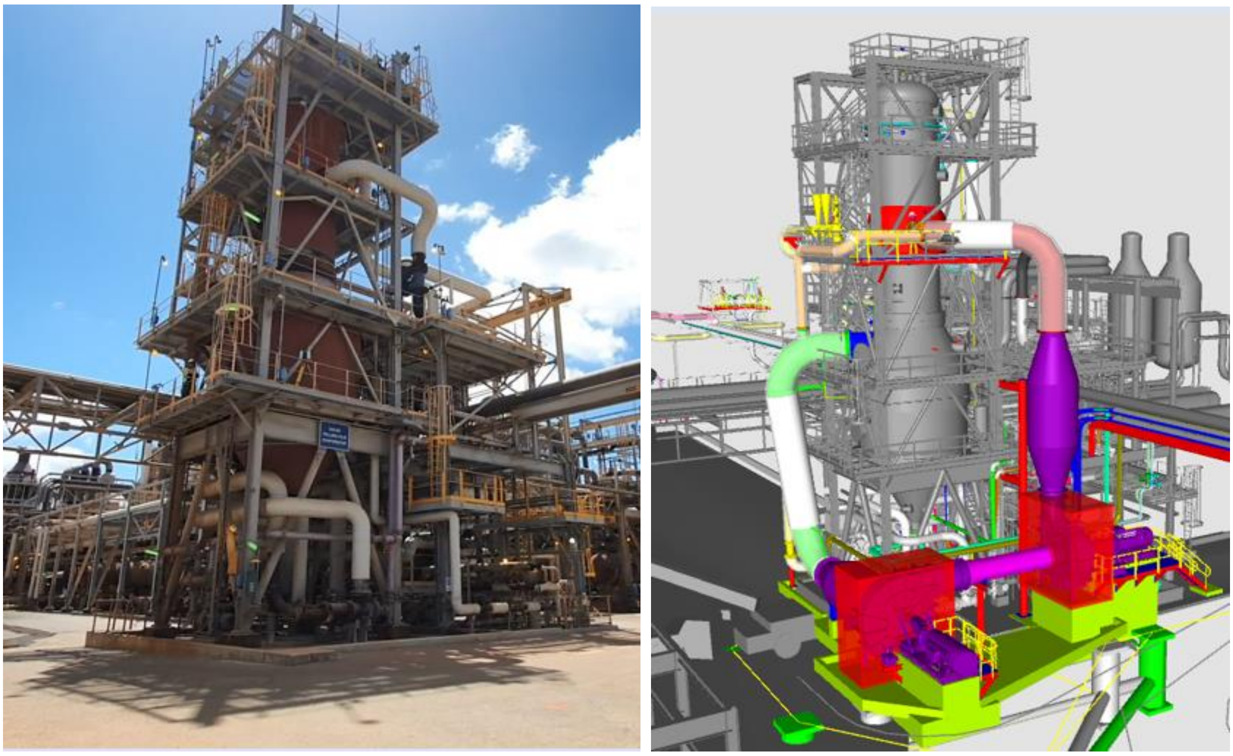


Figure 12 (L) The existing FFE at Wagerup (R) MVR added to the existing FFE

5.2.1 Process Requirements

The evaporator will remove water from Bayer liquor. The liquor will pass through the evaporator causing water to boil and the vapour to pass into the vapour separator. The liquor will then be pumped to the refinery with a small portion recirculating to the evaporator inlet.

Vapour captured in the vapour separator will be cleaned by mist eliminators before passing to the compressors. The compressors will increase the vapour pressure approximately two-fold, resulting in the vapour condensing temperature increasing by 19°C (delta T). This provides the driving force for the heat exchanger to transfer heat to the liquor. The liquor will have a boiling point elevation of 9°C (over pure water) due to the dissolved salts in solution. As a result, it needs to be 9°C hotter than the surrounding vapour before it will boil. Thus, of the 19°C increase in condensing temperature, only 10°C remains to drive evaporation. Accordingly, a small increase in compressor delta T will almost proportionally double the evaporation rate. The increase in evaporation rate is valuable in this scenario where the investment in the FFE is already sunk and the only way to achieve additional evaporation is through more compressor power. In a scenario where both the FFE and MVR system are being designed, there will be an optimum trade-off between additional heat exchange area and compressor power.

5.2.2 Compressors

The compressors selected are low-speed compressors and will operate at around 3,300 rpm, producing around 9.5°C delta T each. They will be direct driven by a high-speed motor and variable speed drive. A single high-speed compressor, operating at around 8,000 rpm, could have almost produced the same total delta T, at slightly higher efficiency and slightly lower cost. Low-speed compressors were chosen because of their proven operation and maintenance performance.

A full cost benefit analysis of high-speed vs low-speed compressors was not conducted for this demonstration; however, a generic analysis is in the *MVR Retrofit and Commercialisation Report*[12], Section 8.6

The compressor and evaporator system curve is shown in Section 6.1.3 of this report.

The compressors were tendered between recognised low-speed compressor suppliers.

5.2.3 Vapour System

Pressure losses in the vapour system reduce system performance, so ductwork was slightly oversized to minimise losses.

5.2.4 Liquor System

The system required relatively complex tie-ins to process pipework. In addition to liquor, services included a contained over-pressure protection system, acid, caustic, and hot water wash capability, condensate, and non-condensable gas systems.

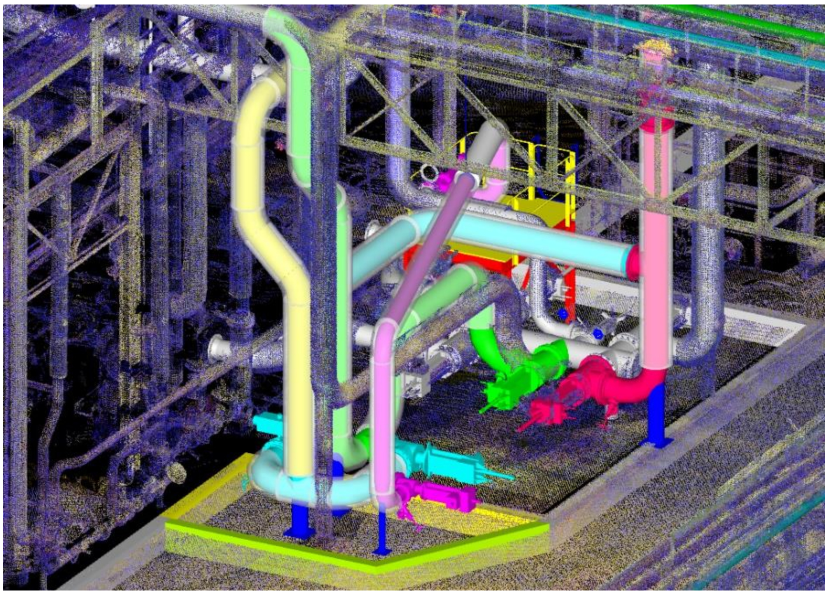


Figure 13 Liquor Feed and discharge system connection at existing process end

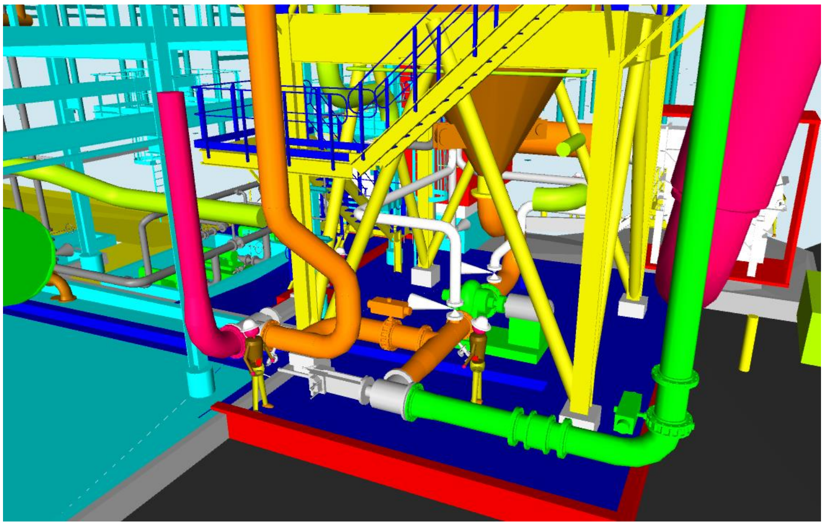


Figure 14 Liquor Feed and discharge system connection at FFE end

5.2.5 Power System

The MVR + FFE system adds significant load to the refinery's power system. The refinery can deliver the required load 95 per cent of the time. The evaporator will be turned off as required. A new 22 kV power distribution feeder approximately 1 km long will connect the powerhouse to the MVR substation. The MVR evaporator will have a dedicated 5 MVA, 22/6.6 kV transformer. The compressor motors will be 6.6 kV and all other drives will be low voltage.

There are no power quality issues such as voltage, frequency, or reliability in the system. Fault level criteria are considered in the design. The compressors are driven via 2 MW electronic variable speed drives enabling soft starts, thus not imposing on the refinery power network despite their size and inertia.

Figure 15 MVR power supply system and route

5.3 Renewable Energy Supply

Renewable power is key to achieving a low carbon alumina refinery.

The Wagerup refinery is ideally located for future electrification with significant power generation grid infrastructure in close proximity. Alcoa expects that future renewable power should be readily available through this infrastructure.

5.3.1 Behind-the-Meter vs Grid Renewables

Power has many cost components as outlined in Section 4.3.2.

Electron charges: There is no benefit from behind-the-meter renewables other than reduced losses due to grid inefficiency in delivering the power. However, it is often the case that the best location for renewable power generation is not co-located with the customer facility.

Figure 16 A large scale solar PV farm

Generation Capacity charges (WA): Peak grid generation power load coincides with the rooftop solar PV power contribution ceasing. Therefore, solar power provides little contribution to reduction in capacity charges. Wind power does generate during peak periods from a probabilistic point of view and will provide capacity credits. Capacity charges to the refinery per MW are about 60 per cent higher than capacity payments received by the generator, so wind power is likely to be viable behind-the-meter for good wind resource locations.

Contract Maximum Demand (CMD) transmission charges: A consumer may use power to agreed transmission contract limits (in MW) defined as the CMD. If a consumer exceeds that limit, charges are applied for the MW amount consumed over that limit, applied over all trading periods in that month. As renewable power supply is intermittent it will be necessary to contract for the maximum demand irrespective of whether the renewable power is behind-the-meter or otherwise.

5.3.2 Ownership vs Power Purchase Agreements

Power generation is generally not a mining company’s core business, and it is less likely to execute a renewables project as effectively, and PPA providers can often accept a lower return on investment than mining companies. A grid-connected renewable system has lower commercial risk than a standalone renewable power system, as the grid-connected system has customer diversity.

Co-located renewable generation and mining facilities are common. The renewable facilities are typically owned and managed by a specialist renewable power provider through a PPA with the mining company.

5.3.3 Large Scale Generation Certificates (LGCs)

LGC purchasing is a recognised form of proof of renewable power. Procurement and surrendering of LGCs provides a financial incentive for third parties to build more renewable power. As renewable power is now lower cost than conventional power, the market for LGCs is expected to decline with the end 2021 spot price being around $40 compared to around $23 forward price in 2026. (https://www.demandmanager.com.au/certificate-prices/ /).

A good discussion on LGCs and price drivers can be found at https://www.ecogeneration.com.au/the-rocky-road-for-lgcs-to-2030-and-beyond/

5.4 Grid Ancillary Services

Power load modulation capability is important to manage power costs, particularly in a high renewables grid. South Australia's 2019/20 average power price vs peak avoidance shows that cutting power just nine hours per year can save eight per cent of annual power costs.

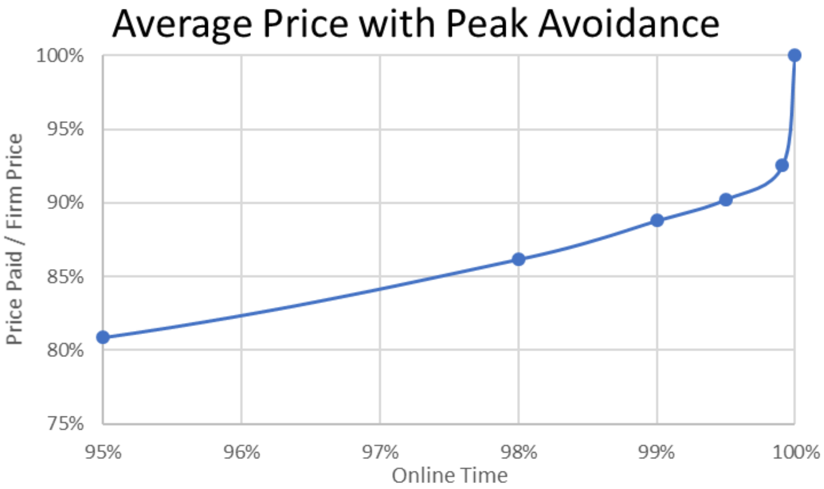


Figure 17 South Australia's 2019/20 average power price vs peak avoidance

In addition to saving operation costs by peak avoidance there are many other opportunities to provide grid ancillary services such as spinning reserve and raise and lower contingency Frequency Control Ancillary Services (FCAS).

The energy market is undergoing transition in response to the demands placed on it by renewables and there are plans for tariff reform to incentivise flexibility[20].

Essential System Services (ESS)

The SWIS WOSP[15] estimates ESS serves will cost $144 M per year in 2035 and will require 330 MW of frequency regulation, or $0.43M per MW. Some of these services could be fulfilled by MVR.

This demonstration project is too small to realise ESS benefits, however there is significant potential for large MVR installations in alumina refineries.

FCAS using the MVR compressor's significant inertia is technically possible but would limit evaporator capacity and may not be economic. Frequency control events are generally short lived over transient events whilst generation is adjusted to suit demand, or demand adjusted to suit supply. If the provision of FCAS resulted in just 10 per cent loss of evaporation capability, then it becomes an economic trade-off. The full cost of ESS provision has not been determined at this stage of the study.

> *Compressors consume 3.2 MW, ESS is $0.43M per MW if fully committed = $1.4M py revenue. If 10 per cent of project process revenue is lost whilst providing ESS, ESS income will exceed lost process revenue.*

This demonstration project will test the MVR evaporator capabilities to participate in these markets by simulating the Australian Energy Market Operator (AEMO) inputs for ESS.

Discussions with the AEMO suggest ancillary service provision may be economic. Significant ESS rule changes will apply from October 2023. We anticipate a reduction in Reserve Capacity Price due to the ability to participate in Demand Side Management.

Contingency Reserve (previously referred to as Spinning Reserve in the SWIS) participation by load rejection appears practical. It will be tested by either substantially slowing the compressors to reduce their power consumption, or tripping. Substantial speed reduction is preferable as it makes restart easier. We anticipate the MVR + FFE system will be robust and not suffer operational issues either way. Load rejection events are generally short lived, and the ESS benefits received should outweigh evaporator performance losses. Conventional evaporators are not robust to this type of interruption.

Load rejection performance will be tested by a manual signal to the compressor variable speed drive. The response will be recorded within the variable speed drive Programmable Logic Controller (PLC).

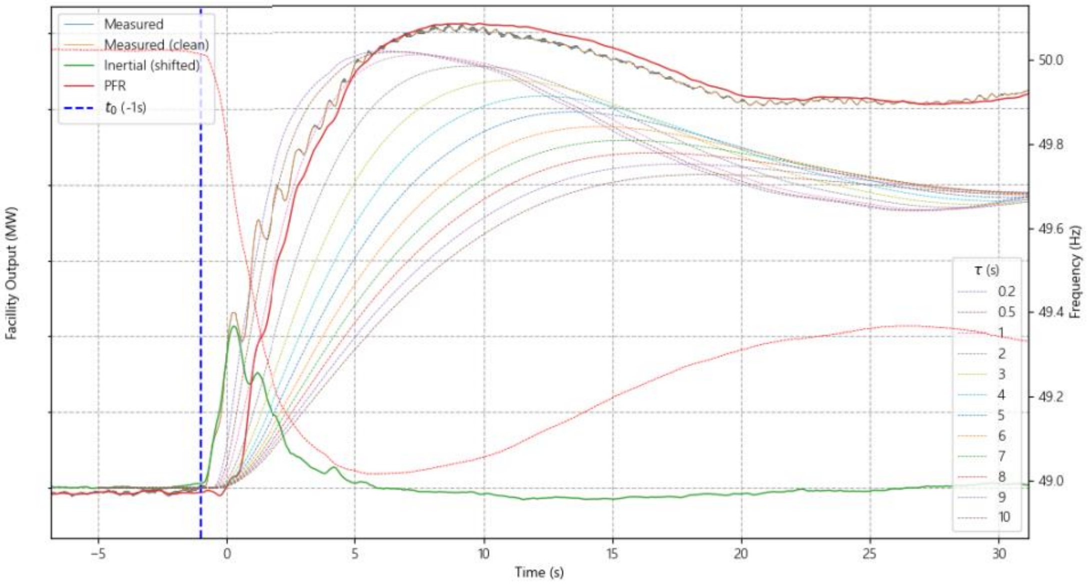


Figure 18 AEMO WEM ESS Accreditation - contingency reserve response quality and Speed Factor [21]

The maximum allowable ramp rate of five minutes should be well within the capability of the system.

The high inertia of the MVR compressors and lag in the evaporator process will allow Raise Contingency Service participation for short-term events of up to 15 seconds. The ability to participate in this market will be tested by the same data for load rejection.

Further information on ESS is available below.

https://aemo.com.au/-/media/Files/Electricity/WEM/Participant_Information/Guides-and-Useful-Information/Guidelines/Participation-Guideline-for-Energy-Storage-Systems-in-the-WEM.pdf

https://aemo.com.au/-/media/files/electricity/wem/security_and_reliability/2021/renewable-energy-integration--swis-update.pdf?la=en

5.5 Project Impact, Measurement and Verification

Project impact will be measured against the conventional evaporation alternative for the same evaporation capacity increase. Conventional and MVR + FFE KPIs are provided in Section 4.2.3. The expected carbon saving is 0.042 t CO_2-e /t evaporation, or 21,000 tpa CO_2-e. This considers 93 per cent expected evaporator utilisation and 100 per cent renewable power.

For conventional evaporation performance, long term averages of the existing process will be used, from two of the four evaporator trains that have minimal net liquor enthalpy change. For MVR, actual data will be used. Results will be corrected to consider net changes in liquor product enthalpy.

The data required for this analysis and collection method is in Table 4. Metered data will be automatically collected by the refinery process control historian.

Data	Units	Source
External Data		
Fuel carbon intensity	tCO_2-e/GJ	External data
Conventional		
Steam consumption	tph	Flow meter
Steam inlet enthalpy	kJ/kg	Calculated
Steam condensate exit enthalpy	kJ/kg	Calculated
Average boiler efficiency	%	Calculated
Power consumption - Pumps	MW	Meter
Evaporation condensate	tph	Flow Meter
Liquor inlet temperature	°C	Temperature indicator
Liquor exit temperature	°C	Temperature indicator
Liquor flow	kL/h	Flow meter
Change in liquor enthalpy	kJ/kg	Calculated
Carbon intensity	tCO_2-e/t Evap	Calculated
Energy intensity	GJ/t Evap	Calculated
MVR + FFE		
Power consumption - Compressors	MW	Meter
Power consumption - Pumps	MW	Meter
Evaporation condensate	tph	Flow Meter
Liquor inlet temperature	°C	Temperature indicator
Liquor exit temperature	°C	Temperature indicator
Liquor flow	kL/h	Flow meter
Change in liquor enthalpy	kJ/kg	Calculated
Carbon intensity	tCO_2-e/t Evap	Calculated
Energy intensity	kW-h/t Evap	Calculated

Table 4 Data capture for KPI analysis

6 Project Operations and Maintenance

6.1.1 Operational Requirements

FFEs are relatively common in the industry. We anticipate that the MVR + FFE heater tube fouling rate will be relatively slow, requiring washing once every six months. This compares favourably to conventional evaporators which suffer from fouling at their maximum operating temperature, requiring some heaters to be washed much more frequently.

The FFE will be brought online by first passing liquor through the system, then starting the compressors. There will be a short period of time when steam is not condensing within the FFE due to the presence of air, which will be purged as part of the start-up procedure.

Once operational, we do not anticipate any onsite operator intervention until the system is taken offline for washing.

All process monitoring and control functions will be via the Distributed Control System (DCS) and will be controlled from a control room.

The existing operations team will operate the equipment.

6.1.2 Maintenance Requirements

The compressors do not pose any unusual challenges. Alcoa already operates large air blowers in calcination that operate at similar speeds.

The overall equipment maintenance strategy is shown in Table 5.

Package	**Item**	**Maintenance Frequency**
Compressor Package	Oil sampling	Once every 3 months
	Oil Filter	Once every 1 year
	Shaft carbon seal	Once every 3 years
	Impeller, bearings	Once every 10 years
	Impeller balancing	
	Motors	Until indicated by the conditional monitoring panel.
Falling Film Evaporator	Acid Wash	Once every 6 months
	Re-tube	Once every 25 years
	Woven Mist Eliminator	Once every 5 years
	Chevron mist eliminator	Once every 25 years
	Mist eliminator spray nozzles – top chamber	Inspection once every year

Table 5 MVR + FFE Maintenance plan

6.1.3 Power Load Management

The refinery will occasionally be power load limited as previously described. It is assumed the MVR + FFE will be shut down during these periods, however it is anticipated the evaporator can continue to operate during load restricted periods due to its wide operating range.

The system curves for the MVR compressors and evaporator are given in Figure 19. The compressor head is reported in terms of delta T °C, representing the change in steam condensing temperature as it is compressed. The higher the delta T, the greater the heat transfer driving force and thus evaporation rate. The evaporation rate, or steam load, is the horizontal axis.

The compressors are variable-speed driven. The curve shows speeds between 90 and 100 per cent, however depending on the scenario it should be possible to operate down to about 82 per cent.

Transcribing the system curve data to the power curve (lower graph) it can be seen that the system could operate between 3.2 MW and 1.2 MW when the system is clean whilst operating clear of the surge line. When the system is dirty the range is 2.6 MW to 1.7 MW. The system will have an anti-surge bypass, so it is possible to extend the range of operation, however below 70 per cent speed there is not sufficient delta T to drive the evaporator. At 50 per cent speed, power consumption will be just 0.4 MW and all flow will be via the bypass valve.

The evaporator should be able to readily flex load 0.4 MW to 3.2 MW without having to shut down the system.

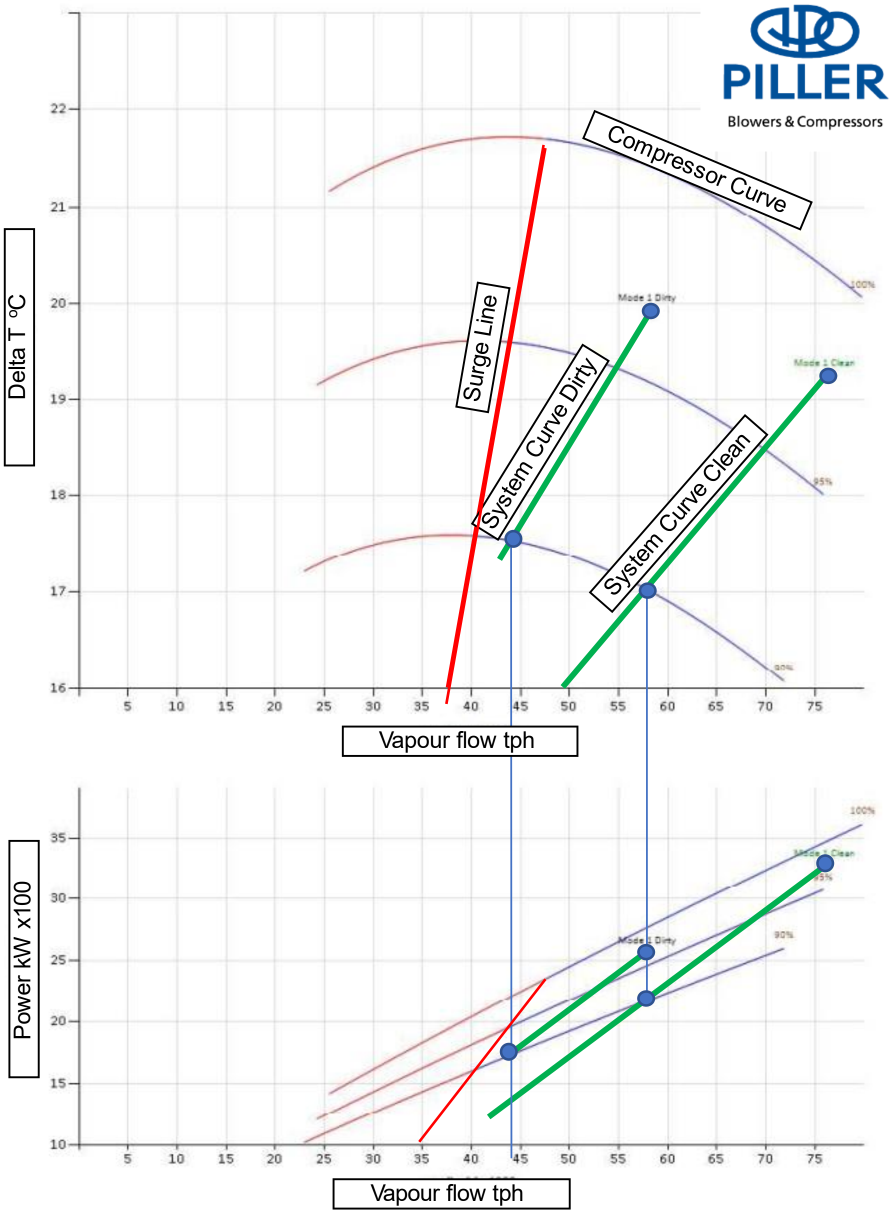


Figure 19 Evaporator system curve overlayed on compressor system curve to show range of operation

The ability to flex load is important for two reasons.

1. It enables the refinery to readily operate near system limitations. For example, if an event caused the refinery to be operating near its maximum import limit, an auto-control scheme would allow the system to rapidly flex to ensure the import limit is not reached, yet also provide maximum evaporation.
2. It aids the ability to provide grid ESS by being able to rapidly respond to signals from the market operator.

Load flex demonstration is a project deliverable; however, automation of load flexibility is not.

7 Environmental, Health and Safety

The project will follow the existing Alcoa Large Projects WAO Health and Safety Management Plan and all applicable laws.

A Hazard and Operability Analysis for the project showed no major findings, and the project will not pose any environmental risk.

The system will have an over-pressure protection safety valve, mainly to protect the compressor casings which have a lower pressure rating than other equipment in the system.

MVR impellers operating at high speed have significant kinetic energy. The compressors will be purchased from reputable compressor suppliers. Impellers will be subject to non-destructive testing and an overspeed testing prior to installation.

7.1.1 Noise

Special attention was paid to noise abatement as it could pose a significant issue for large scale implementation. Alcoa has two noise criteria for the project:

- Less than 83 dBA at 1 m from equipment.
- No increase in refinery boundary noise.

Local noise abatement was directly addressed for the FFE + MVR project, with external abatement projects added to achieve the more stringent boundary noise requirement.

Noise control actions are:

- Compressor inlet, transfer, and outlet duct silencers: Noise entering ductwork is subsequently emitted from duct and vessel walls. Noise control can be achieved through abatement at the source or using noise-abating cladding. In this case the best solution was to abate at the source. This solution is not common in MVR installations. Silencers and ductwork are shown in Figure 20.
- Compressor enclosures: Enclosures covering the combined compressor and motor system or over only the compressor were considered. Enclosures over the combined compressor and motor would introduce motor cooling issues, limit maintenance access, and take up substantial space. Minimal sized enclosures over the individual compressors were selected, targeting 40 dBA reduction.
- Motors: Low-noise air cooled motors were selected. Water-cooled motors were considered but rejected due to the additional complexity of a water chiller to achieve maximum allowable cooling water inlet conditions during summer.
- Offset Projects: Two small noise offset projects will be implemented to achieve zero net increase in boundary noise.

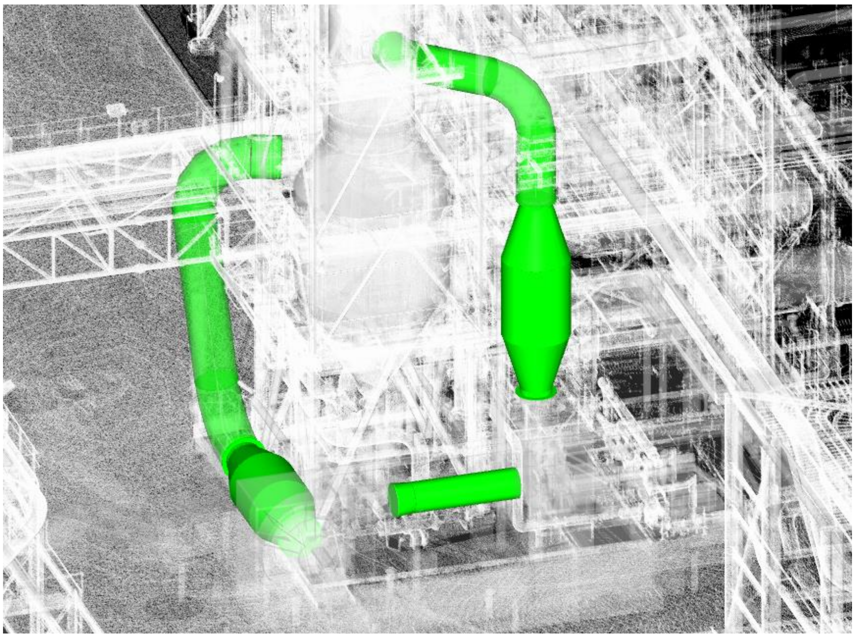


Figure 20 MVR vapour ductwork including compressor inlet and discharge silencers

8 Project Execution Assumptions and Risk

8.1 Project Assumptions

8.1.1 Schedule

No allowance has been made for uncontrollable disruptions, such as COVID 19 impacts. However, the overall schedule has three months contingency.

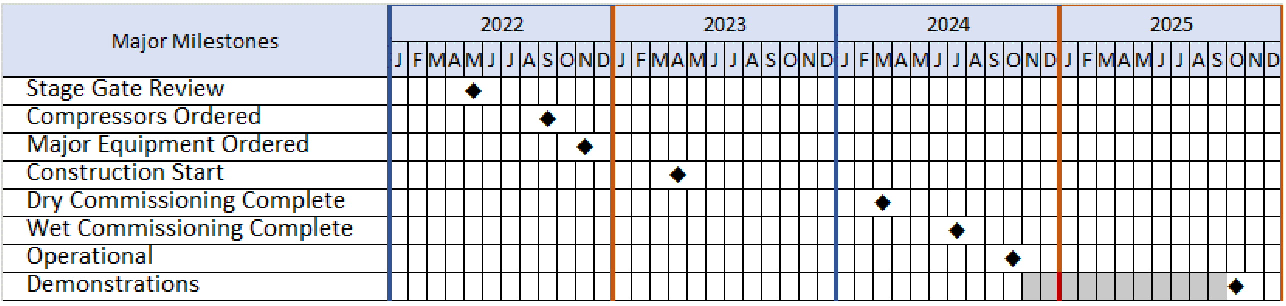


Figure 21 Wagerup MVR + FFE demonstration project schedule

8.1.2 Existing Falling Film Evaporator

The project assumes that the FFE is in good condition. There are some known issues, and these will be managed as per Alcoa’s standard practices for equipment management.

8.2 Specific Technical Risks

8.2.1 Carry-over

The project aims to demonstrate very high flash tank vapour loading whilst maintaining clean vapour supply to the compressors. The FFE vapour separator is designed for a much lower flash tank loading than required (about 50 per cent). However, such duty is within Alcoa experience and maximum recommendation operating parameters for FFEs[22]. The technical risk will be keeping the mist elimination system clean at high separator loading. Factors in its favour are:

- The liquor is relatively stable under operating conditions thus is not expected to foul the mist eliminators.
- Mist eliminators can be washed with every heat exchanger wash cycle.
- Mist eliminators are continuously sprayed with condensate to wash contaminants and desuperheat the vapour to the compressors.
- Compressors have a desuperheating spray which also washes the impellers.

8.2.2 Tube Vibration

Vapour entry velocity to the FFE was an area of concern. GEA’s experience indicated that high velocity vapour at the entry could cause tube vibration.

This was investigated using a combination of a TEMA (Tubular Exchanger Manufacturers Association, Inc. software) flow-induced vibration assessment, publicly available data,[23] and in-house Computational Fluid Dynamics (CFD) modelling. The modelling showed small regions of very high velocity near the vapour inlet that might cause tube vibration. Therefore, an inlet chamber was added to the heat exchanger to improve flow distribution into the tubes and eliminate the high velocity areas.

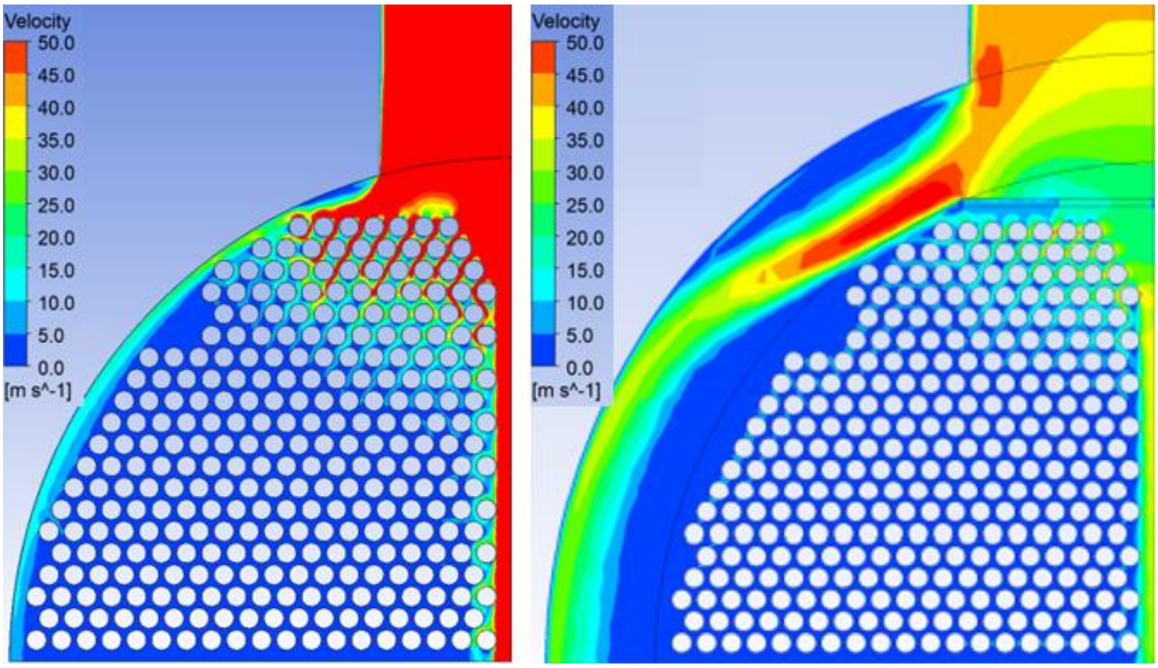


Figure 22 LHS: Original Vapour Feed, over 50m/s velocity through first few tubes of tube bundle. RHS: Vapour Feed Chamber, peak velocity through tubes reduced to avoid tube vibration

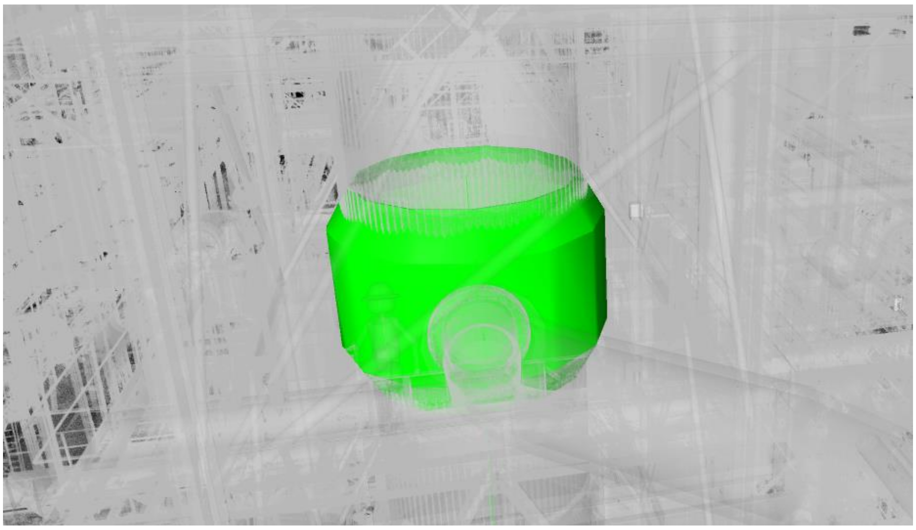


Figure 23 Vapour feed chamber (green) around evaporator heat exchanger (grey)

8.2.3 Compressor Performance and Reliability

Compressor performance and reliability is not considered a significant risk. Alcoa representatives have visited four facilities where MVR compressors are used and each of them reports very high reliability. Some of the compressors were 28 years old and still operating reliably.

Compressor reliability is closely related to compression vapor and shaft seal water cleanliness. This project will closely monitor these parameters. The shaft seal water will be condensate from the FFE.

The compressor type selected is a simple design using low-speed impellers directly driven by a two-pole motor. It will have protection systems built in to trip the compressor if excessive vibration is detected.

The compressors will be purchased from reputable vendors with significant operating experience.

8.3 Risk Management

A project risk assessment was conducted. The top threats and opportunities are listed in Table 6. Risk is ranked based on both severity and probability. A high-risk ranking does not necessarily indicate a high probability event.

The project risk assessment will be reviewed monthly upon formal commencement of execution phase and exceptions addressed.

Event	Cause	Effect	Mitigation Action Plan
Unsuccessful project outcome	Implementation of MVR technology for the first time within Alcoa	Regret cost	a) GEA engaged as a technology adviser in Stage1 to confirm design feasibility. b) 12 weeks commissioning duration and 12 weeks ramp-up duration has been allowed for c) Unknown Unknown Risk to be accepted
Delivery of equipment or services delayed, or construction delayed by the supplier	a) Delay in issue of Scope of Work /Tender b) Terms and Conditions Agreement c) Supplier organisation d) Resources e) Performance f) Sub-contractors g) COVID 19 or another uncontrollable event	Delay in schedule and impact on cost	a) Early engagement with the construction companies including site walk b) Formal tender for long-lead equipment such as compressors, silencers, and variable speed drives (VSDs) issued early c) Escalation has been applied in the Total Installed Cost (TIC) estimate allowing retention of key resources Note: The impact of risks of pandemic such as COVID 19 is accepted. No specific allowance has been made to mitigate the risk. The early tender/contract award should reasonably mitigate this risk.
Scope growth of modification of existing FFE or FFE unable to be retrofitted	Unknown existing conditions or integrity issues	Impact on schedule and cost	a) Sample visual weld inspection and thickness testing found the FFE is in reasonably good condition b) Leak test done to check tube integrity. A very small number of the heater tubes leaked and will be plugged. There will be negligible impact on FFE performance. c) A third-party engineering specialist was engaged in the engineering study who confirmed the FFE can be modified d) The FFE will be re-rated, lowering the design pressure which further reduces the risk e) The suppliers and contractors were engaged, and site walked in FEL3. Budgetary quotes received. f) The full assessment of FFE condition initiated in November 2021 will be completed early in the execution phase.

Table 6 Project risk assessment

8.4 Cost and Feasibility Implications of Risk Mitigation

The Project is carrying 14 per cent capital contingency and 12 per cent schedule contingency to cover risk events. These amounts are within expectations and are acceptable to the project.

None of the project risks were material to the feasibility of the Project.

9 Project Cost

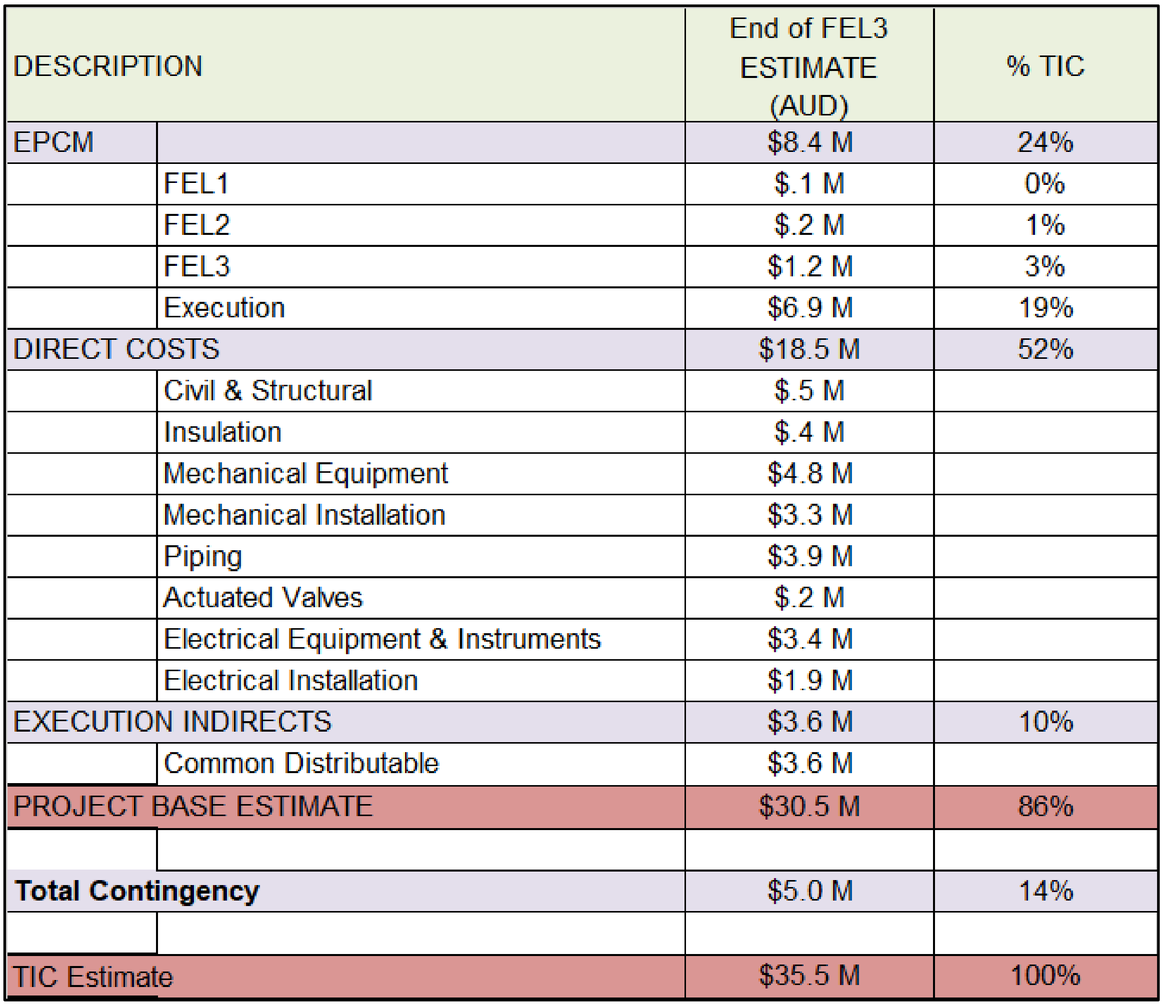
9.1 Capital Estimate

The project capital estimate is $35.5M as detailed in Table 7.

Alcoa contracted an engineering service provider to develop the project scope of work and complete the capital estimate to AACE class 3 accuracy.

The capital estimate is specific to the existing equipment available to this project, which uses an existing FFE, thus cannot be readily used to infer the cost of future MVR + FFE installations.

The compressor supply is just over 10 to 15 per cent of the total direct cost. Other significant costs include piping connections to the FFE, including integration of wash and over-pressure protection systems, and power supply infrastructure.



DESCRIPTION		End of FEL3 ESTIMATE (AUD)	% TIC
EPCM		$8.4 M	24%
	FEL1	$.1 M	0%
	FEL2	$.2 M	1%
	FEL3	$1.2 M	3%
	Execution	$6.9 M	19%
DIRECT COSTS		$18.5 M	52%
	Civil & Structural	$.5 M	
	Insulation	$.4 M	
	Mechanical Equipment	$4.8 M	
	Mechanical Installation	$3.3 M	
	Piping	$3.9 M	
	Actuated Valves	$.2 M	
	Electrical Equipment & Instruments	$3.4 M	
	Electrical Installation	$1.9 M	
EXECUTION INDIRECTS		$3.6 M	10%
	Common Distributable	$3.6 M	
PROJECT BASE ESTIMATE		$30.5 M	86%
Total Contingency		$5.0 M	14%
TIC Estimate		$35.5 M	100%

Table 7 Wagerup MVR + FFE project capital estimate

Engineering, Procurement and Construction Management Cost (EPCM) make up 24 per cent of the total project. Of this $1.5M is sunk costs of Front-End Loading (FEL) stages 1, 2 and 3. Execution EPCM costs are 19 per cent of the total project.

Construction and commissioning costs are $18.5M direct and $3.5M indirect. Commissioning costs are small and not readily separable from the estimate. Following commissioning, testing and operation will be conducted by Alcoa personnel. These costs are not included in the capital estimate.

No new insurances are required.

9.1.1 Capital Estimate Assumptions

Normal costs are assumed with no special escalation for COVID 19 or other special events including freight costs.

Exchange rates at the time were AUD:USD 0.73 and AUD:EUR 0.63.

The estimate is based on local sourcing for all items except the compressors which are priced in Euros. The estimate is therefore quite insensitive to exchange rates.

10 Feasibility Analysis

10.1 Feasibility

The primary objective of this Project is to prove the technical and commercial feasibility of using MVR to decarbonise alumina refining.

Technical feasibility

The installation appears highly likely to be technically feasible. MVR is a proven technology outside of alumina refining and can be readily integrated into refining operations. The probability of technical success has been maximised by:

- Ensuring that refinery tie ins are robust.
- Ensuring the current refinery power delivery system is capable of handling the additional duty.
- Selecting a simple and robust MVR design and developing specifications (in consultation with the FFE original equipment manufacturer, GEA) including material of construction, choice of running speed, start-up philosophy.
- MVR selection based on the specifications and Alcoa’s purchasing processes, including obtaining performance guarantees.
- Liaising with GEA regarding the general arrangement of the machines and vapour ducts with respect to the FFE.
- Addition of an inlet chamber to mitigate expected heater tube vibration.
- Evaluation and selection of mist elimination options to allow clean vapour feed to the MVR units from the FFE vapour separator.
- Simulation of mass and heat balances for various potential operating cases.
- Evaluation and selection of noise abatement measures both at and remote from source to meet requirements.

The system should achieve a 60 tph evaporation rate when in operation and have sufficient availability to achieve the 56 tph KPI year on year.

Commercial feasibility

The commercial feasibility of MVR is covered in the *MVR Retrofit and Commercialisation Report*[12.]

The project is considered commercially feasible primarily due to forecast increased alumina production and reduced sodium hydroxide consumption. Return on investment will therefore be heavily influenced by both alumina and sodium hydroxide price. This would be the case irrespective of whether the additional evaporation capacity was obtained through the MVR-FFE combination or conventional means.

ARENA’s funding support has been critical to progressing the project.

This project will be implemented under existing operating licences. The feasibility of participating in ancillary grid services is not known at this stage. This will be tested by observing MVR response to simulated ESS events.

10.2 Sensitivity Analysis

The project capital cost is relatively insensitive to exchange rates. The imported compressors are a small component of the overall project. Quotes received are in Australian currency.

The most significant financial benefit from this project is from an increase in alumina production intensity. Benefits are very sensitive to the alumina price. Alumina prices can be found at LME Alumina (Platts) | London Metal Exchange.

Sensitivities to power, gas, and carbon costs relative to conventional evaporation are described in Section 4.2.5.

11 Conclusions and Next Steps

- Decarbonisation is a critical focus area for the alumina and aluminium industries.
- MVR driven by renewable generated electricity has the capacity to significantly decarbonise the alumina industry in Australia and world-wide.
- A successful small-scale demonstration of MVR technology is necessary ahead of larger-scale implementation of MVR in alumina refineries to ensure adequate de-risking.
- Installing additional evaporator capacity on a single evaporator in an alumina refinery is a relatively low cost, low risk technology demonstration. Additional evaporator capacity is otherwise generated through steam generated by fossil fuel combustion.
- Installing additional evaporator capacity at Alcoa’s Wagerup Alumina Refinery using MVR to drive a 65 tph single stage Falling Film Evaporator (FFE) is considered both technically and commercially feasible. Project execution risks have been identified and mitigated.
- Potentially major technical issues relating to vapour cleanliness and noise abatement have been considered and mitigated in planning.
- Capital cost is competitive with conventional evaporation options, operating costs are lower than conventional evaporation and sensitivity analysis indicates that MVR evaporator outperformance is robust against variations in power, gas, and carbon prices.
- The project is suitable to demonstrate the applicability of MVR as a decarbonisation enabler in alumina production and should proceed.

11.1.1 Next Steps Following the MVR Evaporation Feasibility Trial

If the trial is successful, the next steps are to:

- Demonstrate MVR application in alumina refining at a larger scale by taking waste vapour and compressing to pressures suitable for refinery duty. If successful, consideration can be given to large-scale roll out of the technology in duties which cover 55 per cent of refinery live steam requirements.
- Apply MVR to vapour having particulate matter, such as may be found in the digestion part of a Bayer process circuit.
- Apply MVR to a high-temperature digestion alumina refinery.
- Apply MVR to vapour having combustion products such as may be found in the calcination part of an alumina refinery.

A full description of next steps is in the *MVR Retrofit and Commercialisation Report*[12]

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13 Glossary

AACE	Association for the Advancement of Cost Engineering
ACCU	Australian Carbon Credit Unit
AEMO	The Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
CFD	Computational Fluid Dynamics
CMD	Contracted Maximum Demand
CO_2-e	Carbon Dioxide Equivalent
DCS	Distributed Control System
DSM	Demand Side Management
EPCM	Engineering, Procurement and Construction Management Cost
ESS	Essential System Services
FCAS	Frequency Control Ancillary Services
FEL	Front End Loading
FFE	Falling Film Evaporator
GHG	Green House Gas
IRR	Internal Rate of Return
kPaA	KiloPascals (absolute pressure)
KPI	Key Performance Indicator
LGC	Large-Scale Generation Certificate
MVR	Mechanical Vapour Recompression
NEM	National Electricity Market
NPC	Net Present Cost
NPV	Net Present Value
OPEX	operating expense
PDRB	Alcoa Project Decision Review Board
PLC	Programmable Logic Controller
PPA	Power Purchase Agreement
SBTi	Science Based Targets initiative
SWIS	South-West Interconnected System

TEMA	Tubular Exchanger Manufacturers Association, Inc.
TIC	Total Installed Cost
tph	Tons Per Hour
VSD	Variable Speed Drives
WOSP	Whole of System Plan