The Element of Possibility™

Mechanical Vapour Recompression for Low Carbon Alumina Refining

MVR Retrofit and Commercialisation Report

November 2022

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Alcoa of Australia Limited

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1 Acknowledgements and Disclaimers

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The cost estimates used in this report are AACE[15] class 5 equivalent and information extrapolated from these have lower accuracy. Process Key Performance Indicators (KPIs) should also be considered equivalent to that required for a class 5 estimate. Consequently, any outcomes derived from the comparison of two costs or scenarios can have a substantial inaccuracy range.

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 CO2-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.

Alcoa of Australia (Alcoa) is conducting a Mechanical Vapour Recompression (MVR) evaporation project that will define the feasibility of installing additional evaporator capacity at its Wagerup Alumina Refinery using MVR technology to drive a 65 tph single stage Falling Film Evaporator (FFE).

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 demonstration installation will generate additional evaporation by recompressing exhaust water vapour from an existing FFE with electrically powered MVR and use the recompressed steam to heat the evaporator. When the electricity for the MVR is generated from renewables, this additional evaporation capacity does not contribute any GHG emissions.

More generally, MVR has the potential to displace fossil fuel use for process heat throughout the Bayer process to produce alumina. To enable this, a successful small-scale demonstration of MVR technology (in this current evaporation demonstration, using two compressors in series) is necessary before larger-scale implementation of MVR for refinery process heating applications can be considered. The MVR evaporation demonstration, aimed for completion in 2025 will provide the required technical information to proceed to a large-scale trial using MVR to produce process heat from waste energy. Successful demonstration of this means significant decarbonisation of the alumina industry becomes possible as long as renewable energy is available.

This MVR Retrofit and Commercialisation Report outlines a potential path to commercialisation for MVR application in the alumina industry. The commercialisation pathway was developed by performing a detailed case study on Alcoa's Wagerup alumina refinery, the site of the first MVR demonstration, and then extrapolating the findings from this to other Australian refineries.

MVR has the potential to be applied in new (greenfield) refinery builds, existing (brownfield) refinery expansions and to retrofit existing refineries, removing fossil-fuel powered process heating. Each application uses similar principles; low grade wastewater vapour from the refinery's digestion, precipitation, evaporation, and calcination processes is compressed to produce steam to be used as process heat. However, there are some practical limitations on retrofit designs due to the need to use, repurpose and tie in the existing infrastructure, and there is some technical uncertainty around MVR application in high temperature alumina production.

For new installations, both brownfield expansions and greenfield, where MVR displaces conventional fossil-fuelled technology, both the design and operating cost of MVR is lower than that for conventional technology. MVR is already economic, as the capital cost of MVR is offset by boiler capital cost savings.

For a low-temperature refinery such as Wagerup, the estimated capital cost of MVR is approximately $220 per annual tonne of alumina production for a first off installation. For a high-temperature refinery the estimated cost is approximately $260 per annual tonne.

For existing fossil-fuelled facilities, the economics of retrofitting are more challenging in the short term, due to the complexity of integration with existing equipment and the sunk cost of the existing process heat generating systems, which become largely redundant. However, in the medium to long term retrofits are likely to become commercially competitive once carbon markets are fully established and trading at the true long-term cost of carbon abatement.

Australia has approximately 7.4 Mtpa high-temperature and 13.8 Mtpa low-temperature alumina production capacity. To achieve the approximately 10 Mt CO_2-e per annum potential reduction, and considering learning rate for large scale implementation, an overall investment of approximately $4.5B would be required to implement MVR, together with provision of 1.2 GW of firmed renewable power.

Although MVR is a proven technology in other industries, particularly on single-stage evaporators, the technology has not been proven to the extent required to power an alumina refinery. The compression ratios required (60:1 for low-temperature alumina refineries and higher for high-temperature alumina refineries) have not yet been demonstrated to enable short-term commercialisation. Therefore, additional demonstrations following the MVR evaporation demonstration are still required.

Commercialisation requires a full-sized demonstration of the MVR precipitation compressor train system described in this report. This would capture waste energy as vapour and deliver compressed vapour as live steam to the refinery, demonstrating the technology can achieve the required compression ratio and reliability. Successful execution of the proposed full-sized demonstration will provide technical and commercial certainty with respect to large-scale MVR implementation.

A full-sized demonstration project is a significant investment and carries an elevated level of technical uncertainty relative to other projects of its size. Government support or co-investment may be required.

3 Introduction

Alumina refining is an intermediatory 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 oxides to produce pure elemental aluminium.

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

In 2020, GHG emissions from Australia's six alumina refineries represented 2.7 per cent of the national total, and these are 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.

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.

Figure 1 Alcoa's Wagerup alumina refinery, Western Australia

Alcoa currently considers renewably powered MVR as the most viable means of providing renewable Bayer process heating due to:

- its zero-carbon potential using renewable power from the grid
- 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 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. Significant investment in MVR is required to decarbonise alumina refining, and confidence in the technology is required before that investment can take place.

As a first step in proving MVR technology in alumina refining, Alcoa is undertaking a demonstration of MVR for evaporation at the Wagerup refinery. The Wagerup MVR Evaporation Project has three objectives:

1. Provide the operating experience with MVR necessary to progress decarbonisation.
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.

This report reviews MVR technology in detail, using the information gained from the MVR Evaporation Feasibility Study at Alcoa's Wagerup Refinery as a base case for its installation and operation more generally. The use of MVR is then considered beyond evaporation circuits into other refinery processes where process heat is required, such as precipitation, calcination, and digestion, in both low-temperature and high-temperature refineries.

Extrapolating from the Wagerup MVR Project, indicative costings to use MVR to decarbonise the Bayer process in retrofit, brownfield expansion and greenfield scenarios are determined. This identifies the feasibility of using renewably powered MVR to provide Bayer process heating across Australia's alumina refining sector.

4 Rationale for MVR in Alumina Production

4.1 Alcoa and Sustainability

Globally, Alcoa's parent company, Alcoa Corporation (NYSE:AA) and its subsidiaries including Alcoa 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.

Our 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 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.

4.2 Business As Usual Australian Alumina Production

Australia is the world's second largest producer of alumina and the world's largest exporter of alumina. It is Australia's highest earning manufacturing export[4].

Alumina Refining:	2020	2019
Australian metallurgical alumina production Mt	21.1	20.5
Alumina exports volume Mt	17.8	17.1
Alumina exports value $m	6,301	8,251
Employment - Direct Employees	5466	5440
Employment - Contractors	2892	2920
Total GHG emissions from Australia's alumina refineries Mt	14.9	14.3
Emissions intensity for alumina production (emissions / tonne) t CO2-e per tonne	0.71	0.70
Total Direct Emissions (equiv. kt CO2)	14,122	13,500
Total Indirect Emissions (equiv. kt CO2)	799	790
Water consumption ML^	114,142	105,600
Water consumption per tonne of alumina production kl^	5.40	5.16
% of fresh water	37	38
% of grey/other water	63	62

Table 1 Australian alumina refining general statistics[3]

The six alumina refineries operating in Australia (see Table 2) produce mostly smelter grade alumina for the domestic and export markets.

	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, Queensland	2004
QAL	RTA	Gladstone, Queensland	1967
Worsley	South32	SW Western Australia	1984

Table 2 Australia's alumina refineries

GHG emissions from Australia's six alumina refineries in 2020 totalled 14.9 Mt at an emissions intensity of 0.706 t CO_2-e / t alumina[3]. At the future energy prices used in this report, the industry's annual energy spend is approximately $1.5B per year.

Alumina Refining Energy Consumption	2020	2019
Gas Gj	149,667,679	143,220,731
Diesel Gj	795,535	952,000
Fuel Oil Gj	175,356	188,000
Purchased Electricity Gj	3,913,712	3,772,000
Other (eg. coal) Gj	66,791,002	63,000,000
Total Gj	221,343,283	211,133,000
Energy consumption per tonne		
Gas Gj/tonne	7.08	6.99
Diesel Gj/tonne	0.04	0.05
Fuel Oil Gj/tonne	0.01	0.01
Purchased Electricity Gj/tonne	0.19	0.18
Other (eg. coal) Gj/tonne	3.16	3.08
Total Gj/tonne	10.47	10.31

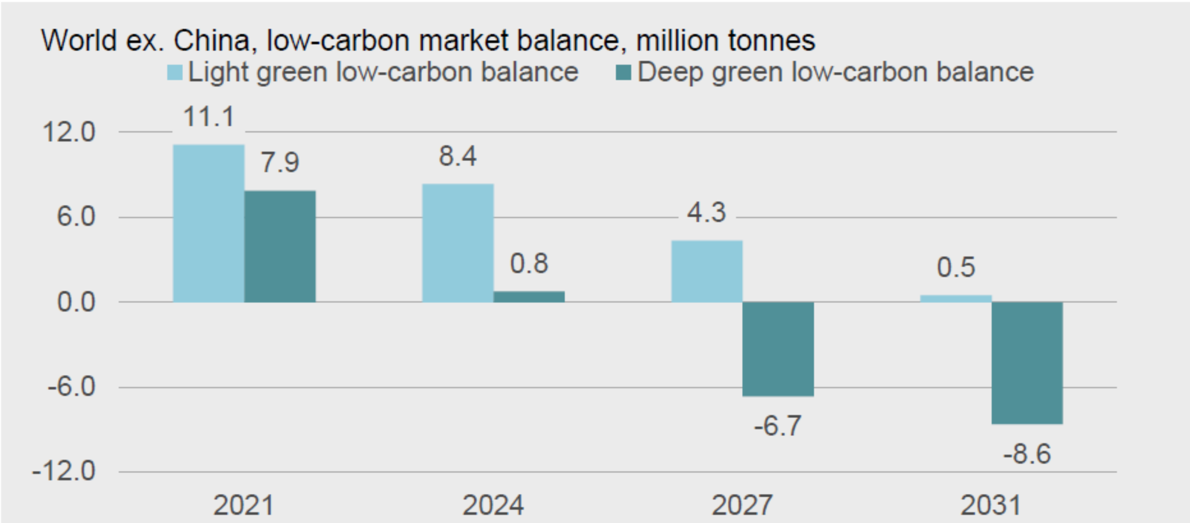
Table 3 Australian alumina refinery energy consumption[3]

4.3 Emerging Low Carbon Drivers

The green and sustainable aluminium market is growing, particularly into Europe. The number of companies committing to the **Science Based Targets initiative** (SBTi) is growing rapidly, driving increased demand for low carbon aluminium [20,21,22].

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[27]. G7 commitments to achieve net zero commitments by 2050[28] and similar initiatives[29] are likely to substantially increase the market for low carbon aluminium.

CRU have forecast increasing demand for low carbon aluminium in key sectors with supply or 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[18]

Alumina from the Australian market is predominantly sold to China and the Middle East, regions that have also announced decarbonisation goals[30,31].

The operators of each Australian alumina refinery have announced 2050 net zero carbon initiatives along with substantive interim goals[32,33,34,35]. Achievement of these goals will require decarbonisation of the Australian alumina industry.

4.4 Australian Alumina Refining Carbon Emissions

Alumina production has two distinct steps. The first step uses the Bayer process to extract alumina from bauxite and the second step removes chemically combined water from the alumina tri-hydrate crystal to produce alumina.

The Bayer process requires caustic solutions to be heated to approximately150–270°C, depending on bauxite type, consuming significant amounts of energy. This is responsible for 70 per cent of alumina refinery GHG emissions, or approximately 10 Mtpa CO_2-e in Australia.

The carbon intensity of the Bayer circuit varies significantly from refinery to refinery.

The second step in alumina production is heating alumina tri-hydrate crystals to about 950°C to remove chemically combined water. To the best of our knowledge, all alumina calciners in Australia burn natural gas. A typical calciner requires 3.25 GJ gas energy to calcine one tonne of alumina (Table 4).

The Clean Energy Regulator publishes Safeguard Facility Data which can be used to estimate emissions due to Bayer process heat and calciner emissions.

From this source, we can estimate the emissions due to the combustion of fossil fuel to raise steam and process heat. The resulting Bayer circuit carbon intensities range from 0.28 to 0.64 tonne CO_2-e per tonne alumina.

The lowest carbon intensity alumina refinery is Pinjarra, which has a large, third-party owned, embedded gas turbine cogeneration system. Next is Wagerup at 0.34 tonne CO_2-e per tonne alumina, with a stand-alone gas fired facility. Wagerup has a small gas turbine cogeneration system to satisfy internal power demands. Coal-fired facilities feature at the higher end of carbon intensity.

This analysis is a best estimate. There are several data inconsistencies, for example some facilities such as Kwinana produce a mixture of products, but only Smelter Grade Alumina (SGA) is recorded by the Australian Aluminium Council (AAC). Some facilities include mining emissions, which are typically very small, in their Safeguard data. Export power is also captured in Safeguard data. Safeguard reports only scope 1 emissions whereas AAC reports scope 1 and 2 emissions.

Refinery	SGA Production for period	Total Scope 1 Emissions[5]	Estimated Calciner Emissions	Estimated Miscellaneous	Estimated Boilers Emissions	Estimated Boilers Intensity	Powerhouse System
	M tonnes	M tonnes CO_2-e	M tonnes CO_2-e	M tonnes CO_2-e	M tonnes CO_2-e	t CO_2-e / t alumina	
Wagerup	2.9	1.47	0.48	0.03	0.97	0.34	Gas Boilers + Gas Turbine
Pinjarra	4.7	1.51	0.79	0.03	0.69	0.28	Gas Boilers + Gas Turbine
Kwinana	1.7	1.27	0.29	0.03	0.96	0.56	Gas Boilers
Yarwun	3.4[8]	2.12	0.57	0.04	1.51	0.44	Gas Turbine
QAL	4.0[6]	3.14	0.66	0.06	2.42	0.61	Coal Boilers
Worsley	4.5[7]	3.72	0.75	0.07	2.89	0.64	Coal Boilers
Total	**21.2**	**13.2**	**3.5**	**0.3**	**9.4**	**0.48**	

Table 4 Australian alumina refinery CO_2-e emissions for year 2019-2020

Upstream coal mining and gas production fugitive emissions also add approximately 3 percent [9].

With these considerations, the total CO_2-e emissions from combusting fossil fuels to provide Bayer process heat at Australian alumina refineries is estimated at 10.4M tonnes per year.

Harnessing Australia's abundant renewable energy, in part through using MVR, provides Australia the opportunity to grow the industry as demand for low carbon alumina grows.

4.5 Risks of Inaction

The direct risks of climate change through GHG emission are well documented and will not be further discussed. However, water use is an additional consideration. Water scarcity is a significant issue for alumina refineries at many locations, particularly in Western Australia. MVR significantly reduces water consumption associated with alumina refinery processes.

Inter-government co-operation and investor-led actions led to rapid evolution of the carbon market over the last year. Consumers are starting to demand and pay premiums for low carbon aluminium, particularly in high value products in the smartphone and auto industries. Companies are promoting their position by adopting Science Based Targets (https://sciencebasedtargets.org/). Financial market participants use Task Force on Climate Related Financial Disclosures (TCFD) to assess industry climate-related risks.

Risks of inaction will include lost opportunity in the low carbon aluminium market but will primarily be the financial risk of producing a high carbon aluminium product in an increasingly carbon-constrained market. European carbon prices would already represent a significant fraction of the price of alumina at the present Australian alumina carbon intensity, representing a significant risk and opportunity. If low carbon aluminium premiums increase to the point where they truly represent the European carbon price at the low carbon aluminium intensity difference to regular aluminium, then there will be sufficient premium to ship low carbon alumina from Australia to green energy smelters servicing Europe.

If Australia develops a carbon market similar to the EU and as proposed in other developed countries, there could be an immediate benefit to low carbon alumina producers.

In addition, the operators of each Australian alumina refinery have announced 2050 net zero carbon initiatives along with substantive interim goals. These reflect a recognition of a decarbonisation component of the social licence to operate in the community.

The alumina industry is well positioned to grow in Australia if we act and lead the industry. Failure to do so could see investment elsewhere and lost opportunity.

4.6 Alternative Technologies Considered

Alternative technologies considered included:

Direct Electric Heating

Electric boilers require three times the power relative to MVR to generate the equivalent pressure steam used in Alcoa’s Western Australian refineries, thus has a much higher overall cost for firm thermal energy. The three times capital investment in renewable power generation and transmission infrastructure to provide firm steam generation is significant.

Direct electric heated boilers operate at some refineries where there is occasionally excess hydro power at very low cost available. They are used for opportunistic steam generation and require duplicate base load infrastructure.

An electric boiler operating in this scenario is unlikely to operate for more than 20 per cent of the time.

Hydrogen (green)

Green hydrogen has very high operational costs and long lead time to implement at scale. It consumes four times the power of MVR to deliver the same quantity of steam to the refinery and would not provide any water savings.

Although hydrogen consumes four times more power than MVR for the same outcome, hydrogen uses intermittent power which has a significantly lower renewables generation build ratio. Considering intermittency, the required renewables build for hydrogen is still higher than for MVR, and there is a need for capital investment in the electrolysers and significant hydrogen storage to overcome production seasonality.

Solar Thermal

Alcoa is a participant in the ARENA funded project Integrating Concentrating Solar Thermal Energy[25] led by the University of Adelaide. The project aims evaluate the potential for energy produced from concentrating solar thermal (CST) technologies to be integrated into the Bayer alumina refining process.

Alcoa's view is that whilst solar thermal is competitive from an all-up dollar per tonne CO_2-e abated point of view, it has a number of limitations:

- It must be intricately linked to the alumina refinery. The only offtake is the refinery and therefore it has to be financed by the refinery at a high hurdle rate. By contrast, renewable power sources on a power grid are independent of the refinery, are low risk, and can be financed and operated by third parties.
- It has low penetration. Even with substantial thermal storage, solar thermal can only deliver around 40 per cent of process heat requirements. It requires duplicate infrastructure to provide continuous process heat.

Solar thermal may have potential to provide thermal energy during peak power cost periods.

Geothermal

Geothermal is technically possible but is extremely limited, expensive, and carries high technology risk. It is not considered a viable form of process heat.

Energy from Waste

Energy from waste has potential where an energy from waste facility is co-located. For example, Alcoa's Kwinana refinery could conceptually use power from the ARENA-funded Kwinana Waste to Energy Project[26] this would not be applicable to other locations. It is therefore unsuitable as an industry-wide solution.

Energy from waste might be better used for hard to abate emissions than for generating electricity.

Biomass as Fuel

The quantities of biomass required to provide energy to an alumina refinery are neither economic, nor sustainable.

5 Process Heat in the Alumina 'Bayer' Circuit

Two bauxite types are processed in Australia to make alumina. Western Australian bauxite (with a gibbsitic mineral structure) can be processed in a caustic solution at 140–170°C to extract alumina, referred to as low temperature digestion. Queensland and Northern Territory bauxites contain boehmite and require '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).

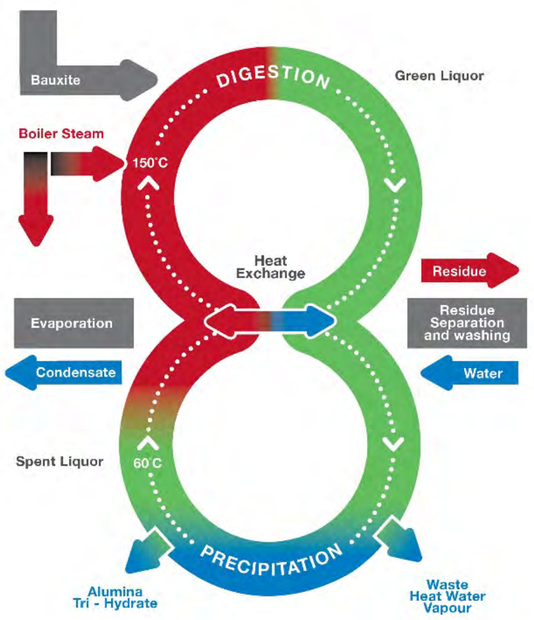


Figure 3 Bayer process flow

Evaporation also plays a key part in maintaining the refinery's water balance, as the liquor circuit has a defined volume. Any inputs from residue wash water and other sources need to be removed by evaporation.

There is no significant chemical energy change in producing alumina tri-hydrate from bauxite. All energy consumption occurs through driving the heat exchange (55 per cent) and evaporation (45 per cent) processes.

All heat inputs from steam are balanced by waste heat, generally in the form of low-pressure water vapour.

5.1 Sub Process: Evaporation

Alumina refineries use evaporation technologies designed around the combustion of fossil fuels. A typical multi-stage flash evaporation train is shown in Figure 4. Cold liquor at around 60°C enters a series of pressurised heat exchangers where it is heated to around 140°C using flash vapour 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 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.

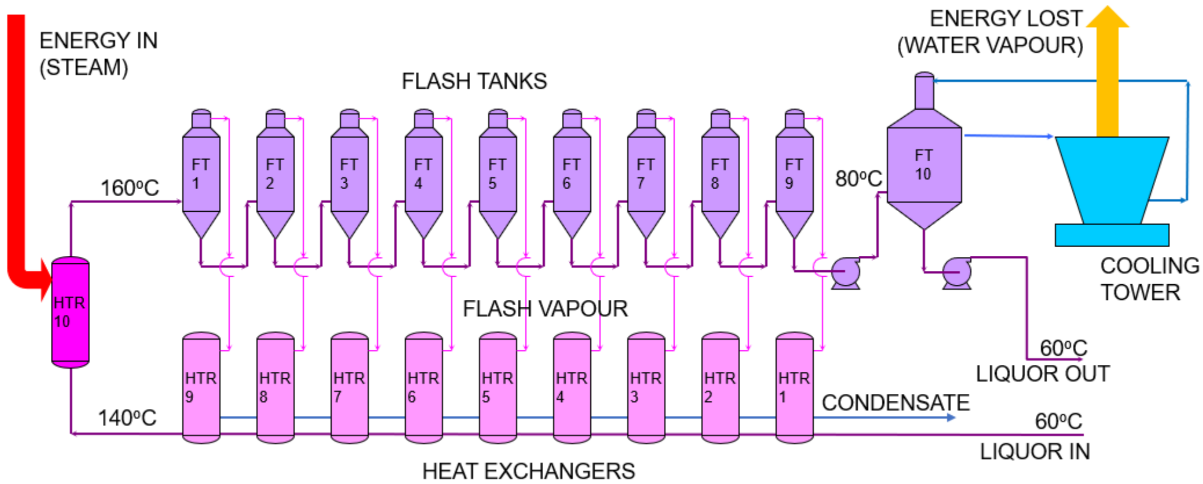


Figure 4 A conventional multi-stage flash evaporation train

5.2 Sub Process: Digestion

The digestion process is similar to the evaporation process except that bauxite is mixed with the hot liquor often after it exits the final heater, and this slurry is held in vessels for an appropriate time to allow the alumina-carrying components to dissolve out of the bauxite. The hot slurry is then flashed down to atmospheric pressure and the bauxite residues are removed. The flashing process causes additional evaporation, which helps with the refinery's overall water balance.

The Bayer circuit described in Figure 5 is a 'Low Temperature' digestion circuit as the digestion temperature is in the range 150–180°C and the process uses gibbsitic bauxite

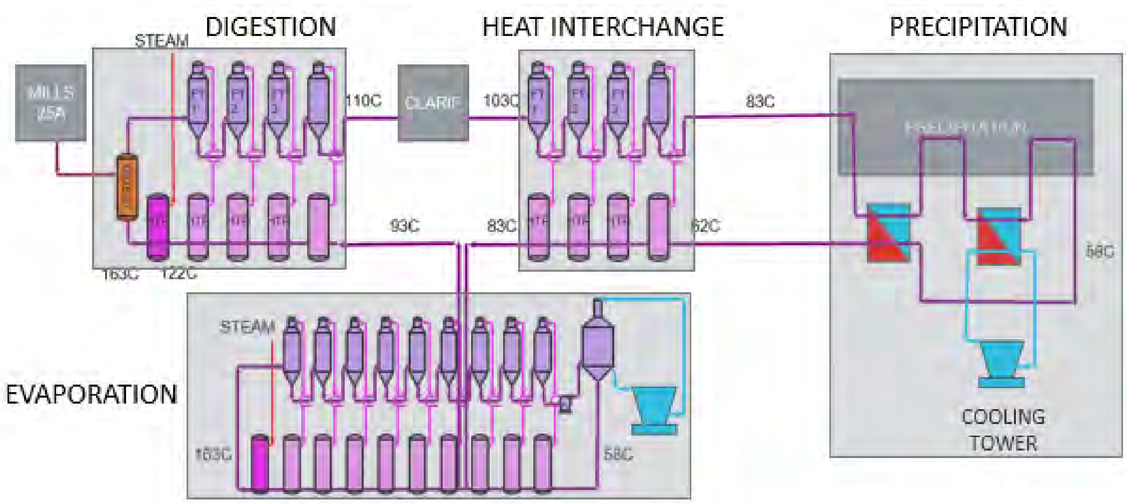


Figure 5 Conventional low-temperature digestion

Some refineries process boehmitic bauxite, which requires digestion temperatures of 250°C and above. These are considered 'High Temperature' digestion circuits. In a high temperature digestion refinery, Bayer slurry liquor is flashed from 250°C or higher to around 70°C. This temperature decrease far exceeds that of a low temperature digestion facility, so there is more flash evaporation. However, high temperature digestion generally requires heating steam to be directly injected into the digesters rather than into heat exchangers alone to achieve the required temperature, so more process evaporation is eventually required. It is common for high temperature digestion facilities to have additional evaporation, where the steam to drive the additional evaporation is sourced from mid-way down the digestion flash train.

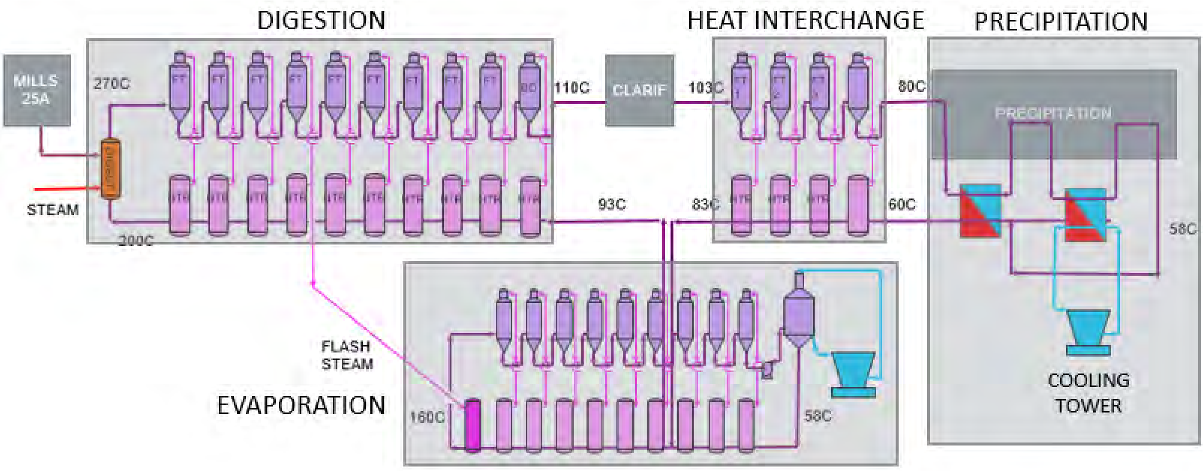


Figure 6 Conventional high-temperature digestion

High temperature digesters operate at very high pressure, typically over 5 MPa. This requires a steam pressure about eight times higher than that of a low temperature digestion system, which typically operates around 600 kPa.

5.3 Sub Process: Powerhouse

Steam to heat the process comes from boilers which are fossil-fuel fired. Low temperature digestion alumina refineries generally have boilers operating at high pressure and the steam is depressurised in a turbogenerator to make power before it continues on to provide process heat. High temperature digestion refineries generally do not have a turbogenerator because the digestion process requires high pressure live steam.

Some alumina refineries have a co-located gas turbine generator which provides export power to the grid. Waste heat from the gas turbine is captured to make live steam for the refinery. Alcoa's Pinjarra refinery has about half its steam sourced from the waste heat of a gas turbine.

6 Mechanical Vapour Recompression Overview

MVR technology provides the potential to almost decarbonise the alumina refining Bayer circuit completely, as detailed in Alcoa's MVR Evaporation Feasibility Study[23].

Alumina refineries require process heat. In a conventional refinery, fuel is burnt in a boiler to make high pressure steam, emitting CO_2 in the process. The high-pressure steam passes through a turbine to generate power, and medium-pressure steam is extracted to provide process heat to the refinery.

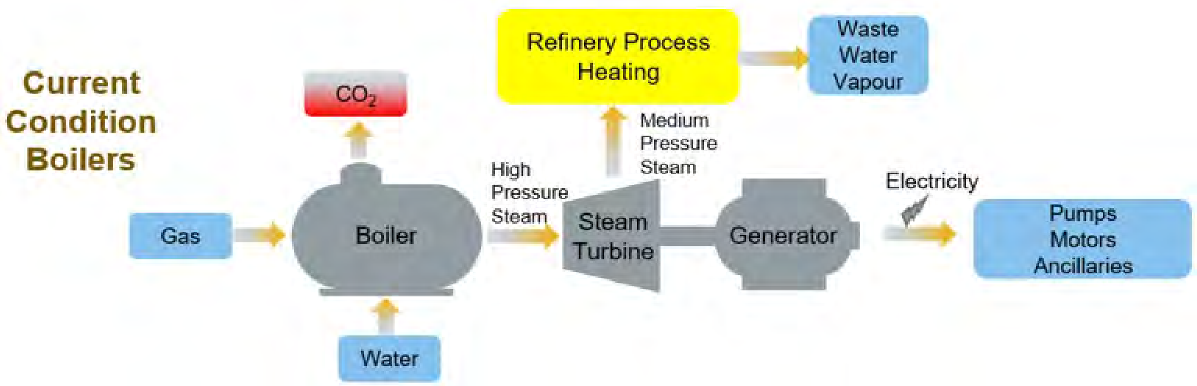


Figure 7 Current condition - process heat from fossil fuels

In a future state, renewable power drives MVR to provide process heat to the refinery. Waste process vapour is captured and recompressed to medium-pressure steam to heat the refinery. Renewable power is also used to drive the refinery's pumps and motors. In a zero-carbon grid there are zero carbon emissions.

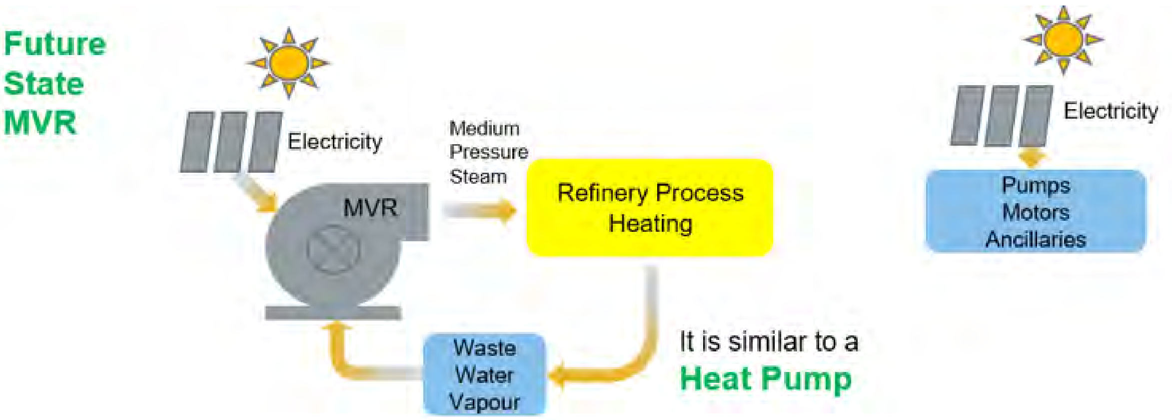


Figure 8 Future state - process heat from renewable power and MVR

To achieve this future condition, very low-pressure wastewater vapour must be taken from the previous conventional evaporator example and compressed to high-pressure steam (60x its original pressure) to displace the external steam presently supplied by fossil fuel-fired boilers.

This process is very efficient as the heat in the waste vapour is recovered. MVR requires about one third the power of an electric boiler to achieve the same outcome.

However, a refinery that self-generates power from boiler steam will no longer be able to do so, as there is no boiler steam. The refinery will need to import all power for the existing process as well as to drive MVR.

7 MVR Refinery Study

7.1 Project Design Overview and Key Assumptions

The study scope is to evaluate MVR implementation at existing Australian alumina refineries and future alumina refineries. The study methodology is based on doing a deep-dive study using Alcoa's Wagerup alumina refinery as the basis, and then extrapolating the findings to other alumina refineries.

The study assumes that Wagerup is indicative of all Australian refineries, although noting that Wagerup is a low-temperature digestion refinery, and results will not be directly transferrable to high-temperature refineries. In addition, some synergies available with site equipment at Wagerup may not be available at other facilities.

The study investigates three scenarios

1. Retrofitting MVR to an existing facility, both low and high temperature.
2. Brownfield expansion using MVR, i.e., small- or large-scale production growth within an existing facility.
3. Greenfield growth using MVR, i.e., large-scale growth requiring new infrastructure.

Further detail of these scenarios is discussed in Section 9.5.

The Wagerup study provides the building blocks to enable financial analysis of the various scenarios.

7.2 MVR Retrofit Overview – Low-Temperature Digestion, Wagerup Alumina Refinery

Retrofitting an existing facility has financial, technical, and spatial challenges.

Significant investment in steam generation infrastructure was made when the Wagerup refinery was originally built, as is the case with most alumina refineries. MVR installation will also require significant investment, making most of the original infrastructure redundant. However, there are still benefits to an existing refinery:

1. The existing boiler infrastructure can be used as backup supply, thus reducing MVR investment requirements. Back-up fuel will be 0.5 per cent of present consumption.
2. Existing facilities are often steam-limited when a boiler is out for maintenance. The addition of MVR can overcome that limitation.
3. Existing power generation infrastructure can be used for peaking capability. This has not been included in the project economics.
4. Refinery cooling water circuits are often stretched during summer. MVR alleviates that issue as it reduces waste heat rejection.
5. Water is saved, reducing alternative water management investment needs.

The flowsheet to retrofit MVR into an existing facility is different to that for a new facility. The cost of retrofitting is heavily impacted by complexity and process tie-ins, so the design is deliberately simple to minimise construction cost and misses some opportunities to obtain optimum efficiency. A greenfield flowsheet is discussed in Section 9.5.

The Wagerup retrofit steam supply configuration is outlined in Figure 9.

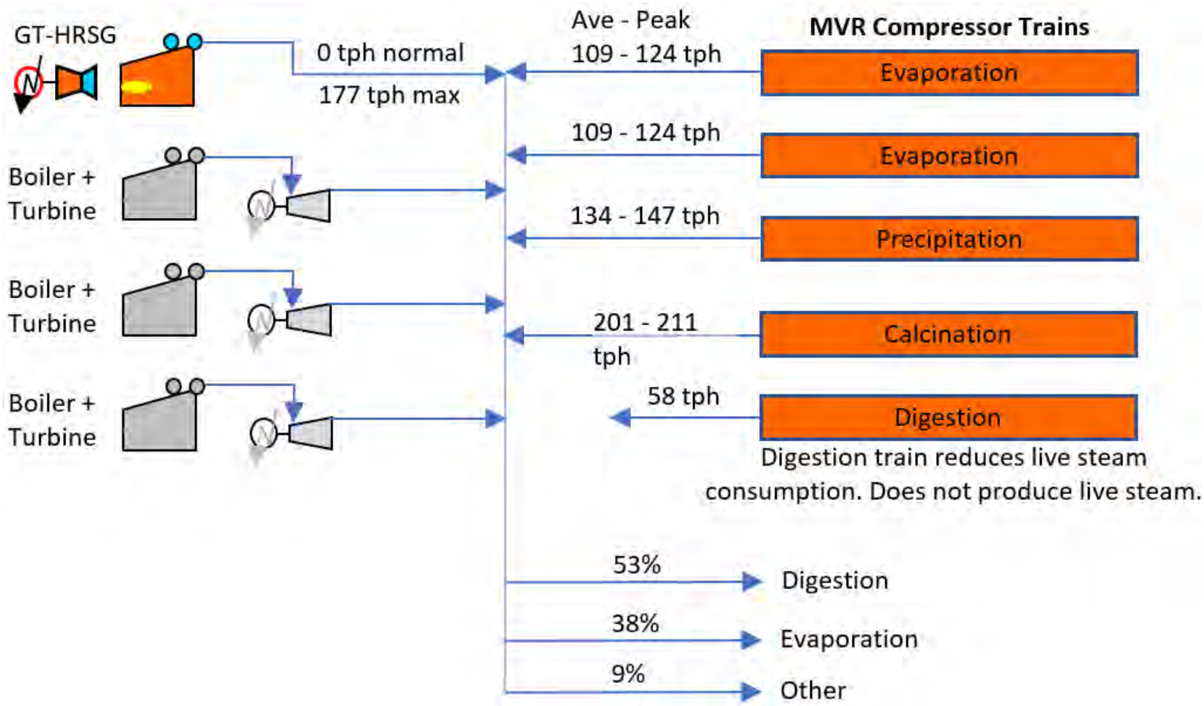


Figure 9 MVR live steam production elements

Four trains of MVR compressors deliver steam directly to the existing refinery steam distribution system. There is an additional 'digestion' train which impacts steam consumption but does not deliver steam directly to the steam distribution system. The sum of all compressor train outputs exceeds refinery steam requirements by 8 per cent, so the existing gas turbine is normally off-line. If a compressor train is off-line for maintenance, the gas turbine is fired up to provide make-up steam to the refinery. This compares favourably to the existing system, where the refinery is significantly short of steam if a boiler is out for maintenance. The three existing boilers are put into long-term hibernation to preserve their integrity.

The four main compressor trains conveniently provide logical capacities that suit the sparing philosophy, but they stretch the maximum capacity of compressors available on the market. It would not be possible to combine the two smaller evaporation trains into one large train.

7.2.1 Load Flexibility

Load flexibility is important to manage power costs and the existing gas turbine + heat recovery steam generator (GT-HRSG) is an important asset to enable this. In the immediate future this is gas-fired, but in the long term it could be green hydrogen fired. The GT-HRSG will be used to support the grid during peak load periods and provide back up steam to the refinery.

At a minimum, the GT-HRSG is used to avoid capacity charges, thus it will operate during extreme high grid demands, about 18 hours per year. This will enable 35 MW of power generation plus 177 tph steam production, enabling 40 MW MVR load reduction. Process evaporation will also be minimised along with other short term process actions, enabling a further 56 MW load reduction. The total potential load reduction is 131 MW, being 62 per cent of the 213 MW refinery total base power load using MVR. This data is used to calculate the average power cost to the refinery.

7.2.2 Operations and Maintenance Philosophy

The system is designed to provide very high steam availability to the refinery. Should any one compressor train be out of circuit, the gas turbine (GT-HRSG) is used to make up steam. It takes approximately 30 minutes for the GT-HRSG to achieve full capacity, so if there is an unplanned compressor train outage there will be a brief period when the refinery will be steam-limited.

The main compressor trains have 10 compressors in series. There are 46 compressors in total, without installed spares. Having this many compressors in series increases the likelihood of a compressor being out of circuit and could adversely impact overall availability. However, there is sufficient installed capacity within the system to cope with a single compressor failure whilst still providing the average refinery steam requirements, although not peak requirements.

An unplanned outage would result in the failed compressor stopping. Vapour/steam would continue to pass through the compressor until there is a convenient time to stop the complete compressor train to enable a fast repair or install a bypass to enable a longer period for maintenance.

Planned maintenance would see a complete compressor train taken out of circuit and the total train maintained at one time. Shaft seals require maintenance approximately once every two years, depending on vapour quality. Bearings may need replacement every 10 years. Hence planned maintenance is modelled at six days every two years per train.

7.2.3 Modelling

Alcoa’s full refinery Mass and Energy Balance (MEB) model was used to model the complex interactions that occur when making process changes. Multiple options were considered, and the proposed system was chosen because of its minimal complexity and ability to achieve economies of scale in the compressor trains.

Condensate waste heat recovery was the most complex impact in the MEB model, as energy is being recovered through individual heat recovery flash stages.

Precipitation vapour is sourced from cooling water circuits within the MEB model.

Calcination used a simplistic model, where there is a known amount of energy recovered to the scrubbing water. Scrubbing water flow was modelled as a fixed flow of known temperature and the water is flashed within the MEB model to create vapour to the compressors.

Modelling was done at normal operating peak flow, that is, the expected normal flow when the refinery is at full production rate. This is important when considering equipment sizing and understanding the true variability within the refinery.

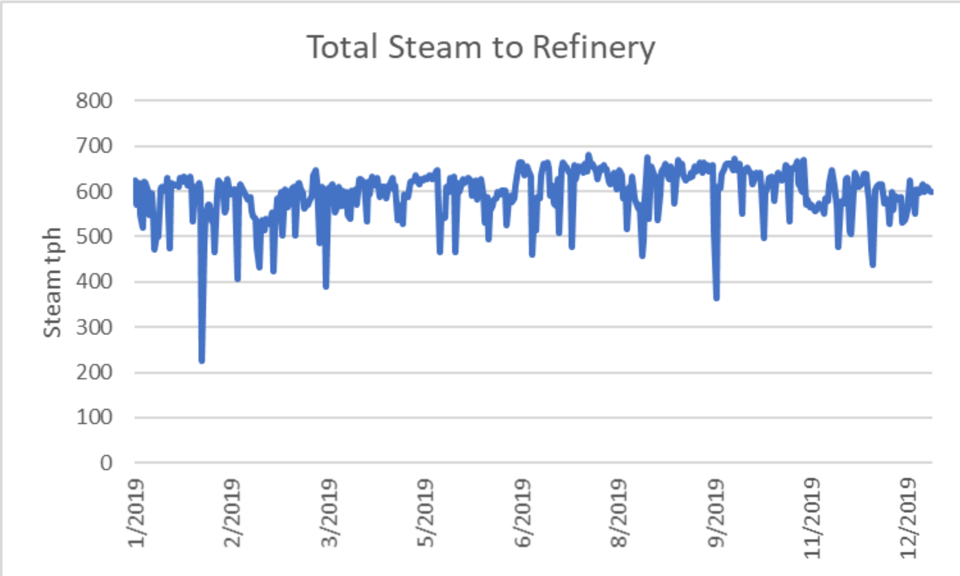


Figure 10 Variability in measured refinery live steam requirement

7.3 MVR Retrofit Detail – Low-Temperature Digestion Refinery

The overall project scope can be broken down into the following areas:

- evaporation
- precipitation
- calcination
- digestion
- power system
- miscellaneous scope.

The detailed scope considers using a mixture of low and high-speed centrifugal compressors; however, it does not preclude using other compressor types.

7.3.1 MVR Vapour Sources

MVR requires a waste vapour source to be captured and compressed to create a useable high-pressure steam, typically called 'live steam' in the industry.

In the digestion circuit, there is no significant chemical energy change in the production of alumina tri-hydrate, so all heat inputs from steam are balanced by waste heat, generally in the form of low-pressure water vapour.

The simplest example of this is a typical evaporator train. Waste vapour in the last flash tank is presently condensed and energy is lost via a cooling tower.

With MVR, the waste vapour is captured and compressed to live steam pressure.

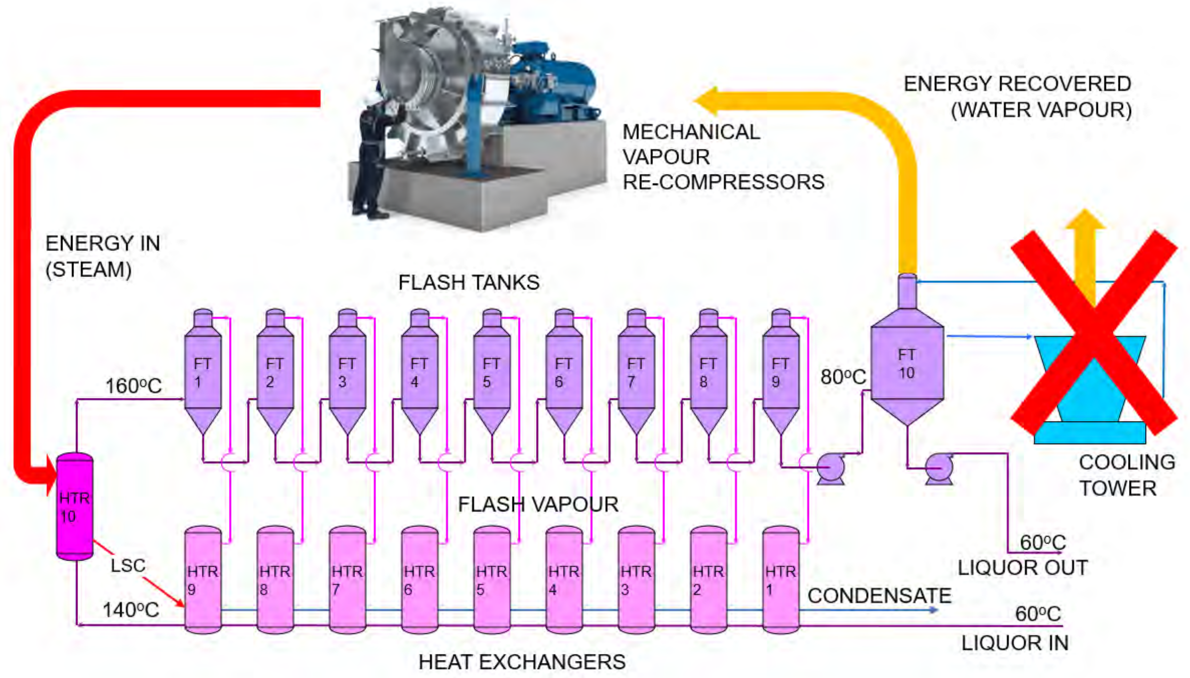


Figure 11 MVR retrofit to conventional evaporation energy flow

Another key factor in the energy flow is hot condensate (LSC) from heater (HTR) 10. Hot condensate presently goes to the boilers where its energy is recovered, however with MVR the boilers are not used. Instead, the hot condensate goes to HTR9 where it provides energy to the liquor being heated. Its energy is additive with the energy from flash tank (FT) 1 vapour. It continues down the heater train to HTR1 providing energy to the liquor as it cools. Condensate heat recovery in this and the Digestion process in the refinery reduces the overall refinery steam consumption by 5 per cent.

Other vapour sources are calcination stack gases which are about 50 per cent moisture, precipitation cooling circuits, digestion blow off vapour and condensate waste heat.

Overall, there is approximately 25 per cent excess waste vapour available in the refinery that could be collected and used with MVR. The system is optimised to use the highest-pressure available waste vapour to minimise power loads. The system design pressure is 880 kPaA, matching the existing live steam system.

Each compressor train can be flexed or shut down. For the conventional evaporator scenario, excess energy is flexed through the existing cooling tower. The process system partially or fully reverts to its present operation; thus, the overall system is highly flexible to the refinery steam needs.

Vapour sources are given in Table 9, Section 8.2.

7.3.2 Evaporation

The evaporation system collects waste vapour from existing liquor flash systems and a new condensate waste heat recovery system. The cold end heat recovery section of the evaporator is shown in Figure 12. The entire evaporator is shown in Figure 11.

Most of the waste low pressure vapour to be compressed comes from Flash Tank (FT) 10 and goes to compressor stage 1. The vapour will typically be about 14 kPa absolute, 52.5°C. About 10 per cent of the total vapour to compressor 1 is from new Condensate Flash Tank (CFT) 2. It combines with the flow from FT10 and is also at 14kPa absolute.

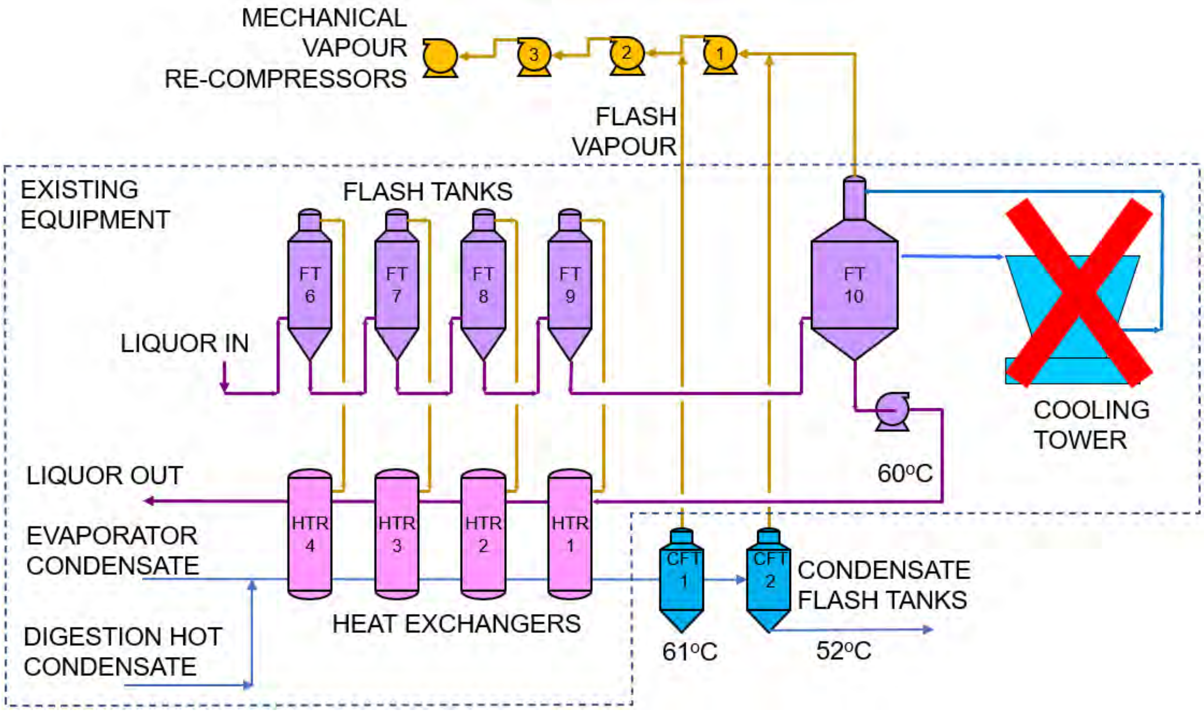


Figure 12 Evaporation waste heat recovery

Vapour to compressor 1 is very low pressure and density and requires the largest centrifugal compressor available on the market to cater for the volumetric flow rate.

The second stage compressor takes vapour from the stage 1 compressor and the new first stage condensate flash tank CFT1. This extra complexity has three benefits:

1. It reduces the capacity requirement of compressor stage 1.
2. Compressor stages 1 and 2 have about the same inlet volume flow rate, so the same compressor design can be used – reducing sparing requirements.
3. It is more efficient as CFT1 vapour is at a higher pressure than CFT2 so less compression is required.

After compressor stage 2 the vapour is further compressed through multiple stages until it reaches live steam pressure and is re-used in the refinery.

Hot condensate heat recovery is described in Section 7.3.1. In addition to evaporator condensate, there is hot condensate from the digestion system. Digestion flash condensate at about 100°C is combined with evaporation hot end flash condensate, then flashed down through the evaporator cold end heaters, then flashed down through the two new condensate flash stages providing vapour to the evaporator compressors. The cold end condensate flash systems are upgraded to accept the significantly higher condensate flow through the system.

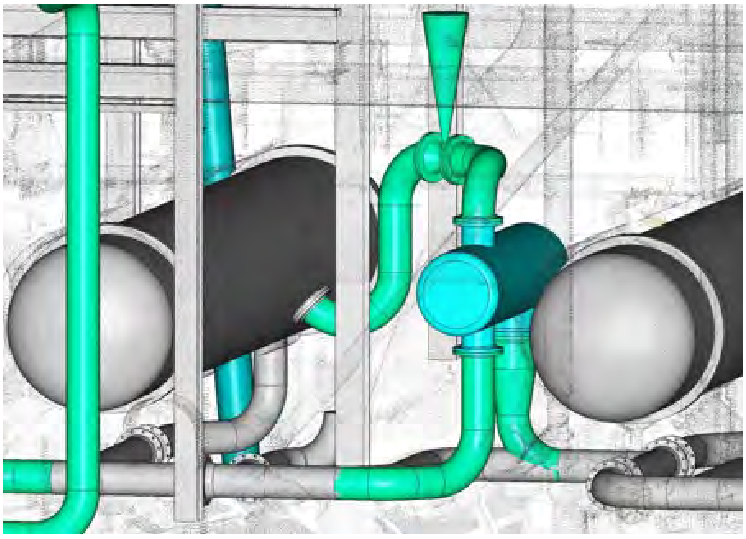


Figure 13 Horizontal condensate flash tanks are used to upgrade the condensate flash system

The existing cooling water and barometric condensing systems, symbolised by the cooling tower, remain for optional use. The evaporation system has the ability to rapidly revert to its present operation should the compressor train(s) be out of service.

If there is a need to reduce live steam production from the evaporator flash trains, it is possible to use the cooling tower to condense some of FT10 vapour, or to restrict condensate flash vapour evolving from the two new condensate flash tanks. The first four compressors in the stage are variable-speed driven so they can be controlled to optimise the system.

Wagerup has three cold end evaporator flash trains, two large and one small. Condensate heat recovery is only implemented on the two large trains.

Total live steam from the three-evaporator cold end compressor trains at Wagerup is 246 tph, which is too much for a single train. The design is optimised to two trains of 123 tph each fed with vapour from one large train and half the small train. Normal power consumption is 25 MW per train.

7.3.3 Precipitation

Energy is added to the liquor circuit in digestion to dissolve gibbsite and energy is removed from the liquor circuit in precipitation to extract gibbsite. Cooling water from a cooling tower is circulated to indirect liquor heat exchangers and the energy is lost to atmosphere from the cooling towers.

Two options were considered to recover precipitation waste energy:

1. Flash the precipitation liquor in flash tanks then compress the vapour.

2. Flash the precipitation cooling water in flash tanks then compress the vapour.

Flashing precipitation liquor has the advantage of producing a high-pressure vapour, requiring less compression to get it to live steam pressure. However, it has complexities of flashing a slurry, which is prone to deposit scale on equipment. It requires the cooling water system to be maintained as a back-up, or redundancy built into the MVR and flash system.

Flashing precipitation cooling water enables a relatively simple and reliable design but requires more MVR power. The existing slurry cooling system is upgraded by doubling the number of heaters in circuit which enables a reasonable approach temperature of 10°C, a higher cooling water exit temperature and the ability to operate with a higher cooling water inlet temperature.

Two cooling water flash tanks are inserted between the slurry heat exchangers and cooling tower. Cooling water from the heat exchangers are flash cooled in flash tanks. Vapour is extracted from the flash tanks to the compressor train. The flash train exit temperature is such that very little additional cooling is required in the cooling tower before the cooling water is circulated back to the heat exchangers.

Similar to evaporation, the last flash stage vapour goes to the first stage compressor and the first stage flash vapour goes to the second compression stage. The capacity of the compressor train is limited by the second stage volume flow which is at the limit of the largest available centrifugal compressor. Two compressors in series were considered for this duty to maximise capacity, however the capacity with just one compressor is suitable for normal operation. Its 134 tph normal operation and 147 tph peak capability fits into the overall sparing philosophy. Normal power consumption is 32 MW.

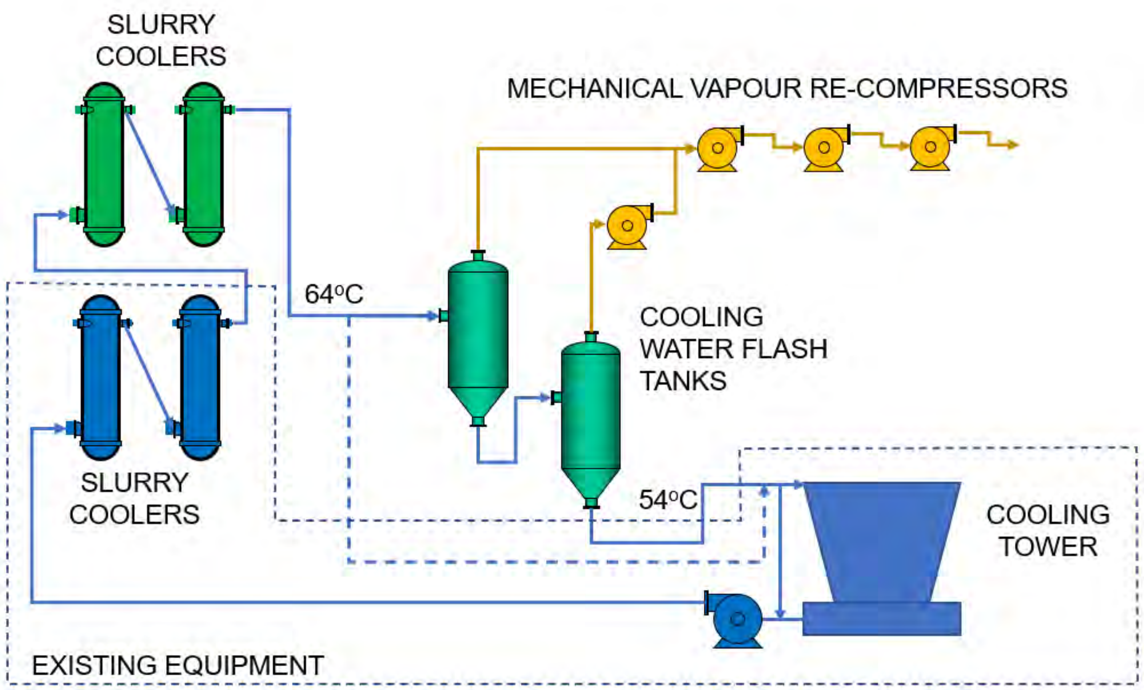


Figure 14 Precipitation waste heat recovery

The first five compressors are variable-speed drive enabling good flow flexibility, followed by five fixed-speed compressors. To reduce steam produced by this system, compressor speeds are reduced, causing the flash tank pressures to increase. The cooling water exiting flash tank

2 becomes warmer, putting more cooling load on the cooling tower. The flash tank 1 to flash tank 2 temperature drop is governed by the first compressor delta T, which is 7.5°C at maximum speed.

When operating at full capacity, all variable speed compressors are operating at maximum speed. As the final compressor discharge pressure is set by the plant live steam pressure, the stage 1 compressor inlet pressure drops to about 13.5 kPa and cooling water exit last flash tank drops to 51.5°C, capturing more waste heat.

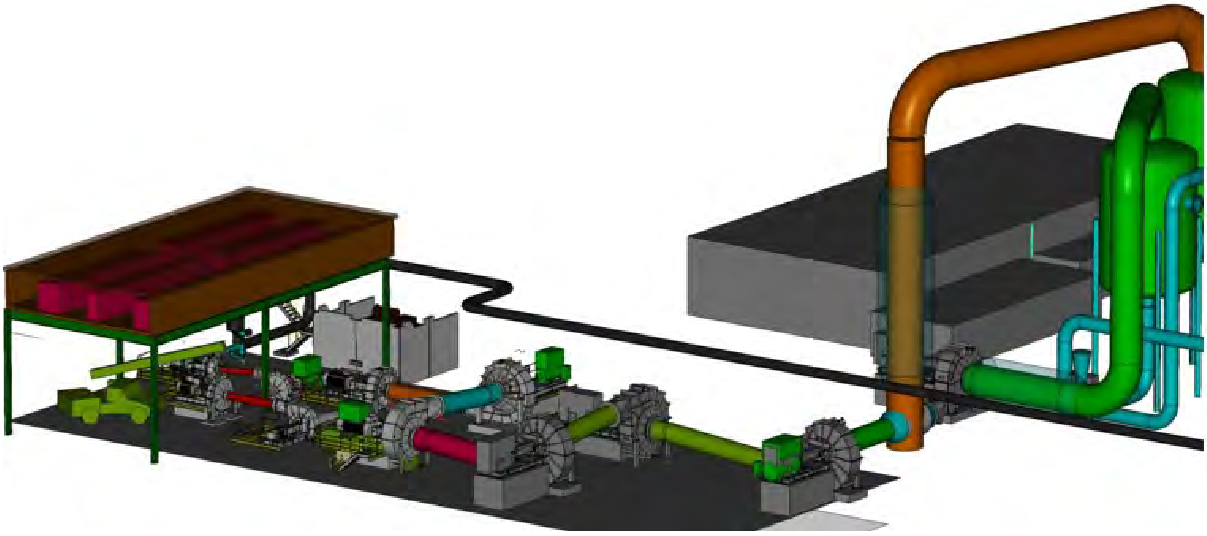


Figure 15 Precipitation flash tank and compressor layout

7.3.4 Calcination

The calcination process heats alumina tri-hydrate crystals to high temperature, releasing chemically combined water, producing alumina. The water is lost to atmosphere as vapour via the stack, along with other combustion products. Overall, about 0.7 tonnes of water vapour per tonne alumina is lost.

A proposed process to capture this energy and water vapour is to direct the stack gases to a scrubber[8]. Cooling water passes counter-current to stack gases and gains heat and mass as it condenses water vapour from the gases. The warm water then progresses to three flash tanks in series where the water is cooled, then recycled back to the scrubber.

Vapour from the three flash tanks is collected and compressed in a similar fashion to the precipitation design.

Wagerup has four calciners and the total waste energy collected significantly exceeds requirements. Heat is recovered from only three calciners to reduce capital costs. It also keeps the system within the limits of the largest available compressor. Its 201 tph normal operation and 211 tph peak capability fits into the overall sparing philosophy. Normal power consumption is 40 MW.

In Figure 16, only one of the three calciners is shown for simplicity. Recirculation water from the other two calciners combines and splits before and after the single train of flash tanks.

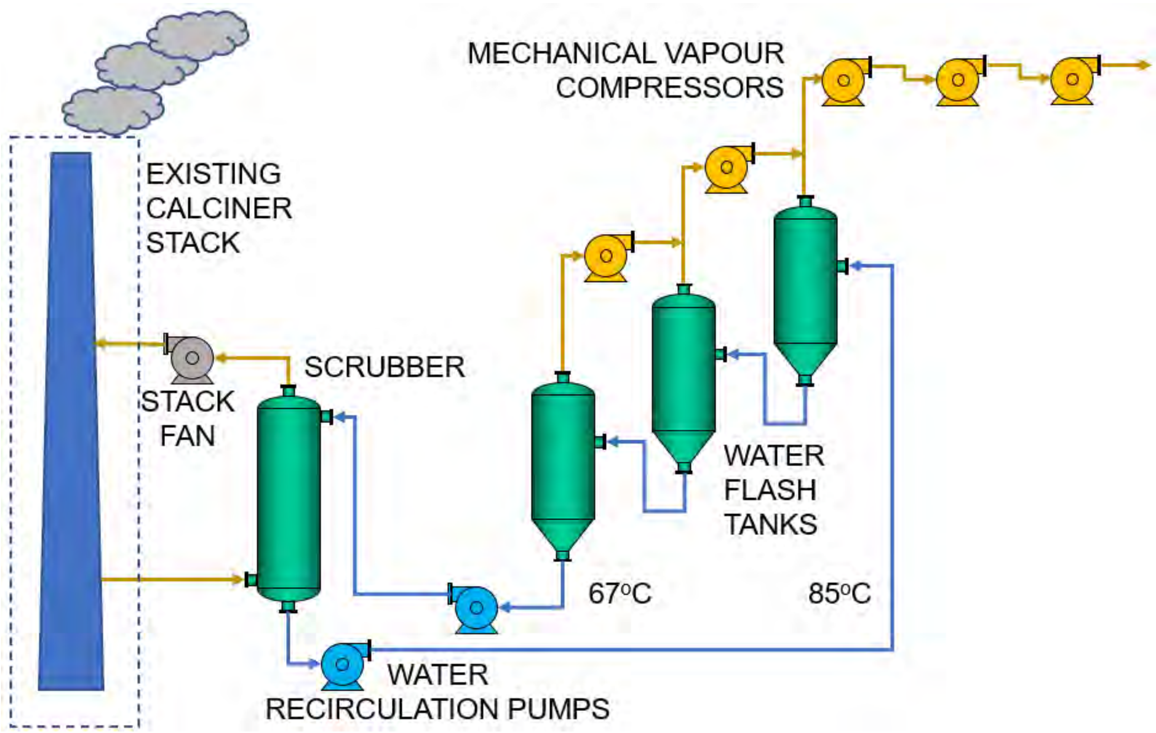


Figure 16 Calciner stack waste heat recovery

A point of concern with the calciner concept is stack gas buoyancy and its impact on boundary emissions. A previous study used continuous stack gas heating to provide buoyancy, which significantly negated energy benefits. In this MVR study stack gas heating is not included. The reasons supporting this decision are:

- The stack gas will be predominantly cleaned of volatile organic compounds (VOCs) by the water scrubber.
- Stack gas buoyancy can be an issue under certain atmospheric conditions that can be forecast. If necessary, alternative actions can be taken during these periods.
- Unconfirmed dispersion modelling indicates stack velocity is more important than temperature.

As a counter measure, a risk allowance item is included in the capital estimate for larger stack fans that can bleed in air to increase the calciner stack velocity.

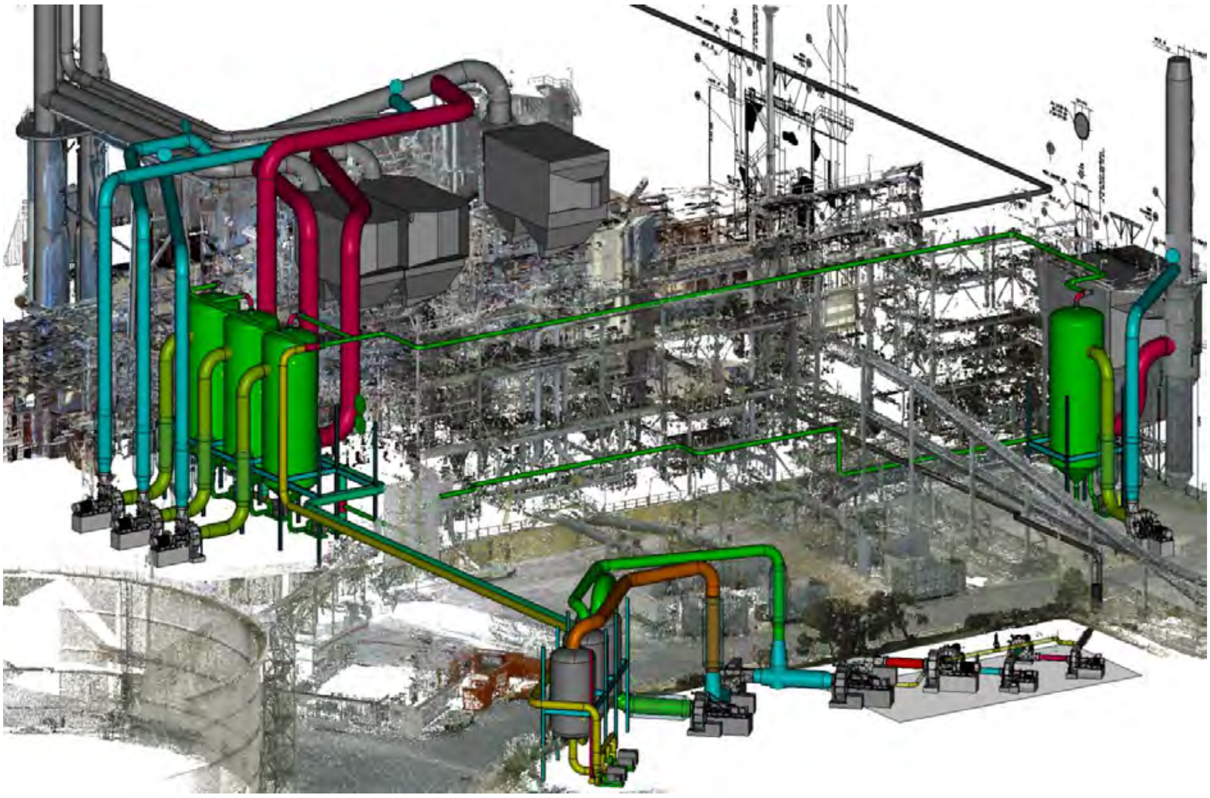


Figure 17 Calciner compressor train system - 4 calciners shown

7.3.5 Digestion

Use of MVR in digestion is quite different to the other process areas.

The existing digestion heat recovery system includes blow off (BO) tanks which operate at just above atmospheric pressure, and excess energy is lost to vapour condensers.

As in evaporation, live steam condensate for the final live steam (LS) heater no longer returns to the powerhouse but is flashed down the heater train to recover its energy to the liquor stream. The combination of energy recovered from live steam condensate and the condensate waste heat recovery circuit in evaporation causes additional excess blow off vapour. The existing blow off heater (HTR 1) has very little heat pick-up under the new scenario so it is taken out of circuit, providing additional BO vapour to the MVR compressors.

Blow off vapour has small quantities of mud in the vapour which must be removed before compressing. It is collected from the two digestion units, cleaned in a scrubber, then compressed through six low-speed compressor stages. All stages are variable-speed driven and the system can achieve full capacity with one compressor bypassed.

The compressed vapour then goes to an existing heater (HTR 4) prior to the live steam heater. HTR 4 was previously out of circuit, but as the blow off heater is now out of circuit the total number of heaters in circuit, and thus liquor pressure drop, remains the same.

For simplicity, only one of Wagerup's digestion trains is shown in Figure 18. Vapour is collected from both trains and combined before the scrubber, then directed to the compressors, then distributed to HTR 4 of both units.

The installed spare heater (HTR SPARE) is required to enable heater washing without shutting down digestion. When any one of four heaters in a unit are required offline for cleaning, the MVR heater (HTR 4) reverts to normal operation and all compressor output goes to the other unit's MVR heater and only 80 per cent of excess BO vapour is used. This is expected to occur 20 per cent of the time.

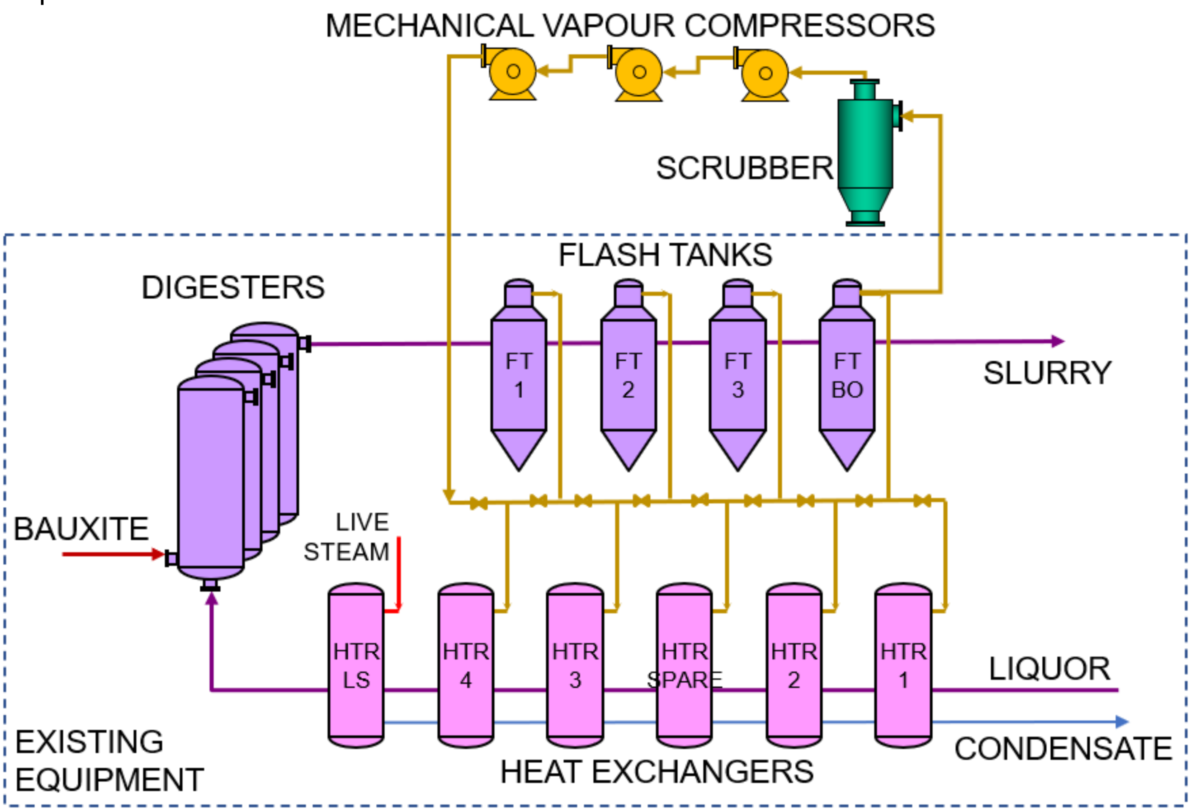


Figure 18 Digestion waste heat recovery

This configuration was chosen as it provides improved overall performance. The feed temperature to the live steam heater is approximately 15°C hotter than previously. This reduces the load on the live steam heater which enables a lower live steam header pressure. Live steam to digestion comes from the other MVR compressor trains in the refinery. The reduced live steam pressure enables all compressor trains in the refinery to operate at a lower pressure and thus lower power consumption. The ability and benefits of operating a lower live steam header pressure have not been factored into the economics.

There is a simple alternative design whereby excess blow vapour is compressed to live steam pressure and fed directly to the live steam heaters, along with live steam from the other MVR compressor trains in the refinery. It does not require the change in heater configurations. This requires two additional compressors and consumes more power. Normal power consumption is 12 MW.

7.3.6 Power Infrastructure and Delivery

Presently, all the refinery's power requirements are generated on site using three steam turbines and one gas turbine. In addition, there is a 25 MW tie to the 132 kV grid which is used to export and import power as required. With MVR, these fossil-fuelled generation facilities are normally shut down, thus it is necessary to import power to drive existing refinery equipment as well as MVR. 213 MW of imported power is required for normal operations, approximately 1,700 GW-h per year.

The total load is beyond the capability of the existing 132 kW system. Fortunately, there is a 330 kV twin circuit system that connects into the main South-West Interconnected System (SWIS) grid at the refinery boundary that has enough capacity. It is owned by others and access by negotiation is assumed.

The 330 kV system feeds into three 100 MVA 330/22 kV transformers, one of which is redundant. The existing refinery power requirements are satisfied by two 22 kV feeders to the existing 110 K substation. Existing power generation equipment and the 25 MW Western Power tie remain connected via 110 K; however, the 25 MW tie is normally isolated.

New substations are built for each of the MVR compressor trains, one 22/11 kV transformer per train with no built-in redundancy. Transformer sizes are rationalised and one of each transformer is kept in stores as a spare.

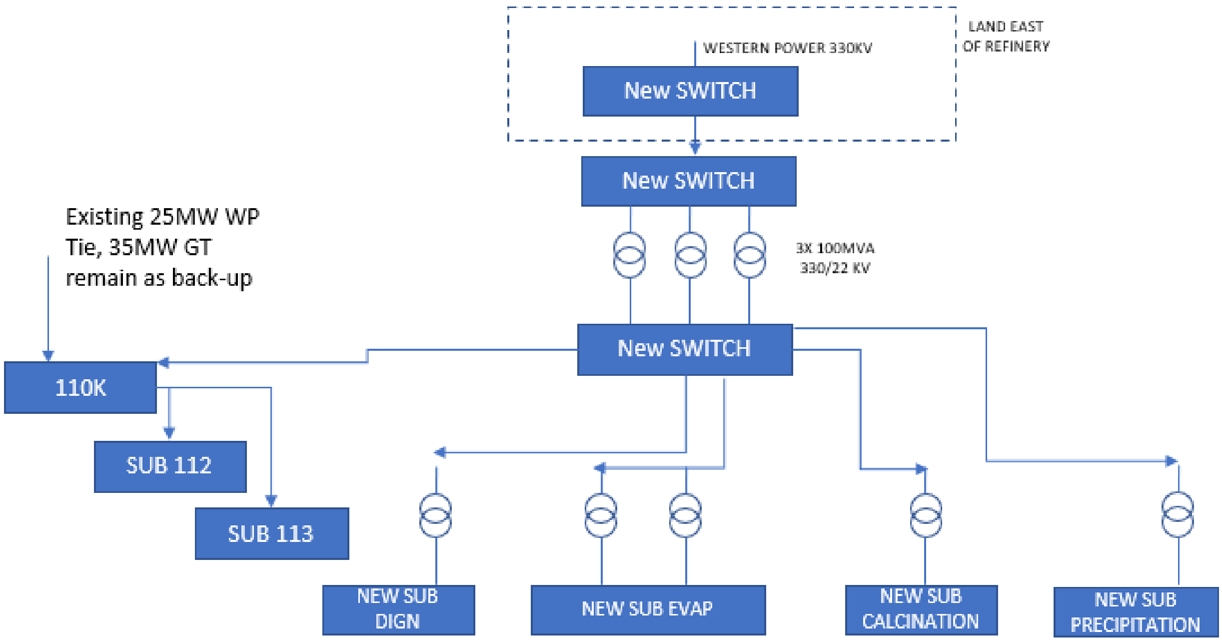


Figure 19 Power distribution system

	MW
Digestion MVR	12
Calcination MVR	39
Precipitation MVR	32
Evaporation MVR	51
Infrastructure Losses	5
Total MVR	139
Refinery - Sub110K	74
Total Refinery	213

Table 5 Substation loads

Existing power generation is used if an MVR train is out of circuit, or at times of high peak grid load when power prices are high. The preferred generation equipment is the existing GT-HRSG as it will generate about 35 MW of power whilst making 177 tph steam.

Switch room and substation locations were optimised to be near the power load centroid. Power supply to the main switch room is via a long underground 33 kV system.

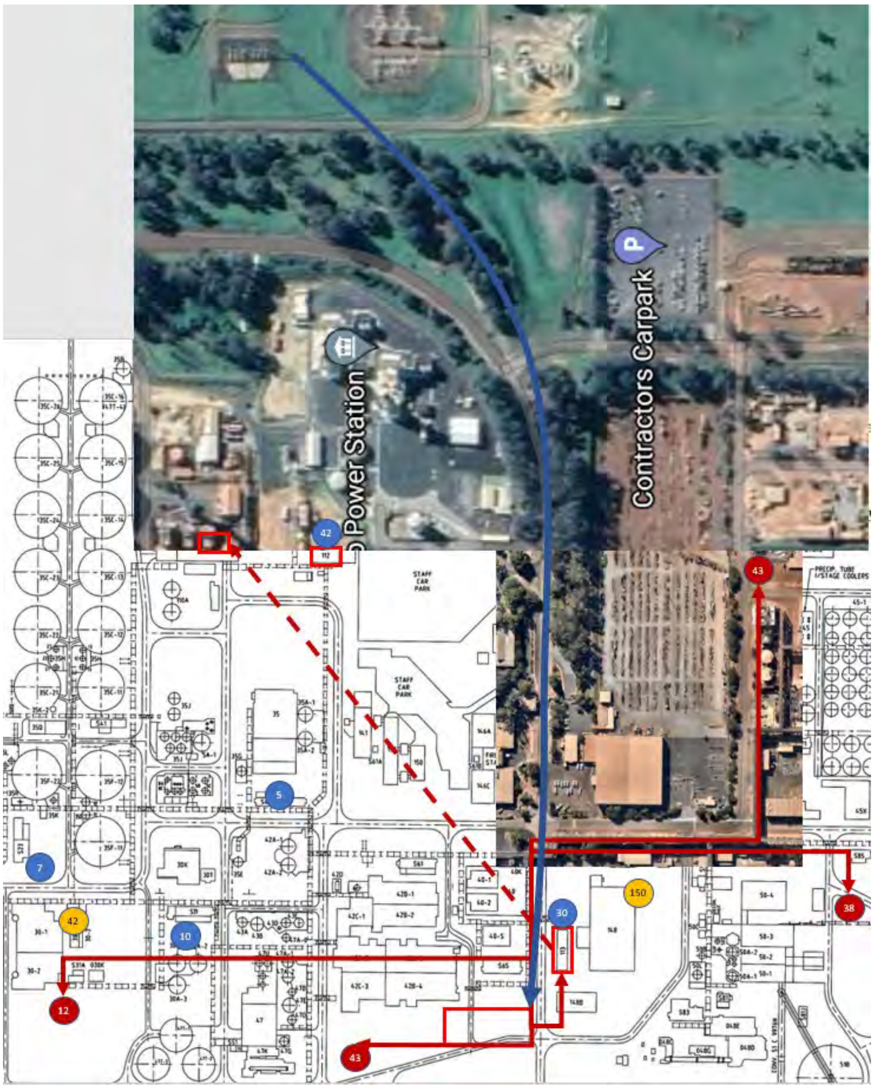


Figure 20 Power distribution system plan

7.3.7 Miscellaneous Scope

Presently, non-condensable gases from the process are combusted in the boilers to destroy VOCs. As the boilers will not be operating, a new regenerative thermal oxidiser is included in the scope to destroy VOCs.

7.4 Compressors

7.4.1 A Typical Compressor Train

A typical compressor train has around 10 compressors in series. The first stage compressor takes very low-pressure, low-density vapour causing the volume flow rates to be extremely high, beyond the capability of most compressors. The first four stages are generally low-speed compressors because of their volumetric flow capability. Once the vapour is compressed such that the volume flow is less than 120 m^3/s, high-speed compressors can be used that have almost twice the compression ratio of low-speed compressors.

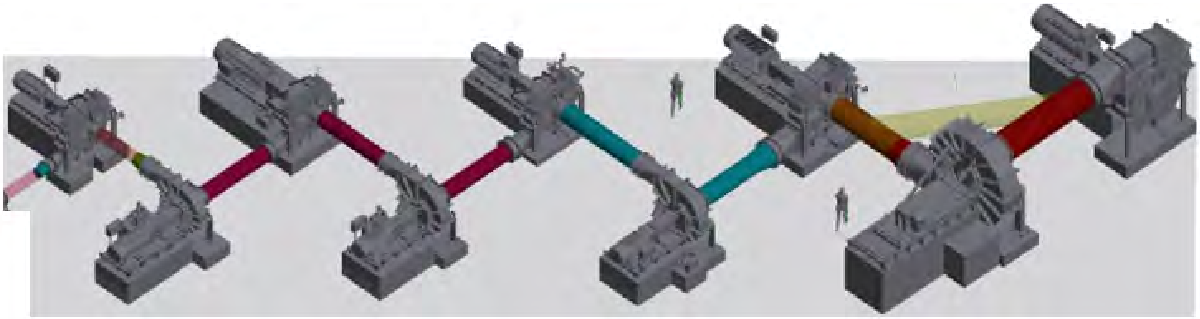


Figure 21 Typical low-speed compressor layout

Many compressors in series creates a reliability issue as the failure of any compressor causes the whole train to fail. The system is designed such that if any one compressor fails but can continue to have steam pass through it, then the train as a whole can continue to operate.

However, special attention is required to prevent compressor surge when a compressor is stopped. A normal compressor train would require a single anti-surge line from the last compressor discharge to the first compressor inlet. The anti-surge valve would open should the volumetric flow through the compressor drop below a critical point.

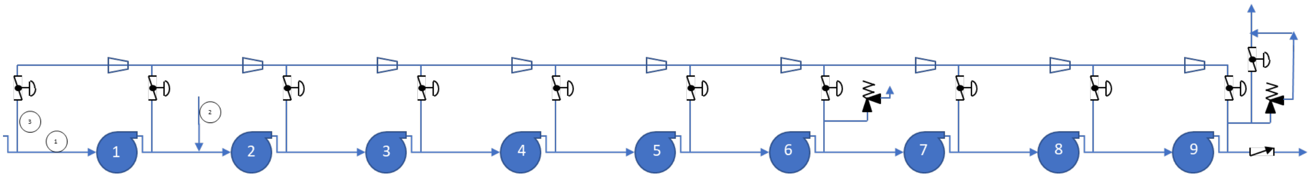


Figure 22 Compressor anti surge and pressure relief system

As this system is designed to have any one compressor out of circuit, the upstream compressors are generally oversized for the duty, causing them to operate near their surge point. In this case, the anti-surge valves around a problematic compressor would open to increase its volume flow to keep the compressor to the right of the surge point. As any compressor can be out of circuit, valving is required around each compressor.

7.4.2 Compressor Types

There are three styles of compressors available on the market.

1) Low speed centrifugal. These compressors typically operate around 3,000 rpm and are direct driven using a two-pole motor and electric variable-speed drive. They are proven, robust and make up most of the MVR market.

MVR duties often have liquid droplets in the gas stream. If the droplets hit the impeller at high speed the impeller will wear. The vapour is at, or very close to its condensing temperature at the first stage of the compressor train. Moisture will accumulate on the inlet ducting walls and hit the impeller leading edge at its highest velocity point. Low speed compressors generally have desuperheating water sprayed into the compressor inlet which helps keep the compressor clean from scale build-up.

They generally have a fabricated casing and impeller, enalbling large volumetric designs. Low speed compressors have a low compression ratio, about 60 per cent of a high speed compressor.

Quotations for low-speed compressors were recieved from Howden and Piller.

Figure 23 Howden's ExVel Turbo Fan *Low speed centrifugal compressor*

2) High speed centrifugal. These compressors generally operate above 7000 rpm and are gear driven. Impellers are generally machined into complex shapes from a solid billet of stainless steel enabling high compressor efficiency and high tip speed which enables a high compression ratio. Titanium impellers are an option, enabling higher compression ratios, at a capital cost premium. Larger compressors require fabricated impellers which limits the maximum allowable tip speed and thus compression ratio.

Figure 24 Howden's SF14 Turbo Compressor High speed centrifugal compressor

As they operate at high speed, they are susceptible to wear, thus the inlet vapour should be superheated to ensure water does not collect in the inlet ducting wall.

There are many high-speed compressor installations in NSW powerhouses on wastewater treatment duties. Soda production facilities in Turkey also use high speed compressors on combinations of falling film and forced circulation evaporators. Their total evaporation capacity is over three times that required to retrofit the Wagerup refinery.

Figure 25 A soda production facility in Turkey. Large falling film and forced circulation evaporators can be seen between the two buildings

Quotations for high-speed centrifugal compressors were received from Howden and CSSC-JZ.

3) High Speed Axial Flow. Axial flow compressors have high volumetric capacity and are compact. They were developed for air separation units.

   A quotation for this type of compressor was received from MAN Energy solutions. MAN has significant experience with this type of compressor and high speed centrifugal (or radial) compressors and are confident it will perform well in MVR duty.

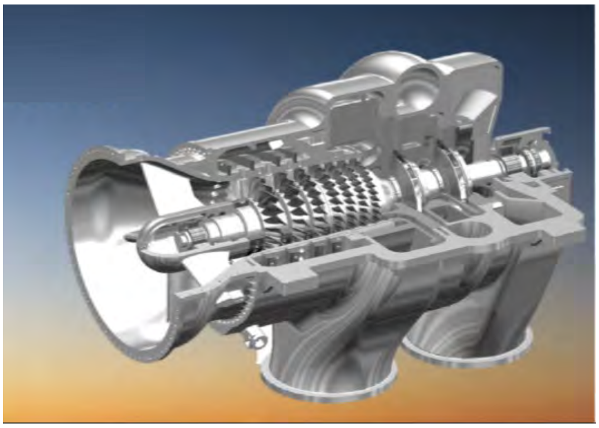


Figure 26 MAN's AIRMAX axial flow compressor with radial back end

The centrifugal compressors selected in this study are operating at their volumetric limit (today) whereas the axial flow compressor can easily achieve the volumetric requirements, and more, necessary for an MVR-powered alumina refinery.

MAN's quotation included a single large motor driving the stage 1 axial flow compressor on one side and an integral gear driven five stage compressor on the other side. It has the smallest footprint of all the compressor systems and the single large motor opens the possibility for a high voltage motor, negating the 22/11 kV transformer and associated switchgear. Starting such a large motor in the refinery system requires a soft start or variable speed drive.

7.4.3 Compressor Selection

The all-up cost of purchasing the necessary compressors for the duty was within 20 per cent for all three compressor types. Considering the similar costs, the following compressor selection should not be considered definitive. Compressor selection was made to enable an indicative capital and operating cost estimate. Spatial requirements might drive a different selection, particularly for the axial flow compressor option. Up to 17 compressors in series were required for the low-speed compressor only option, having a significant footprint.

Compressors selected were those proven and common in MVR duty, using high-speed compressors as a preference due to their efficiency and fewer quantity required, and low-speed compressors where high-speed compressors did not have the capacity.

Howden offers both low-speed and high-speed compressors proven in MVR duty.

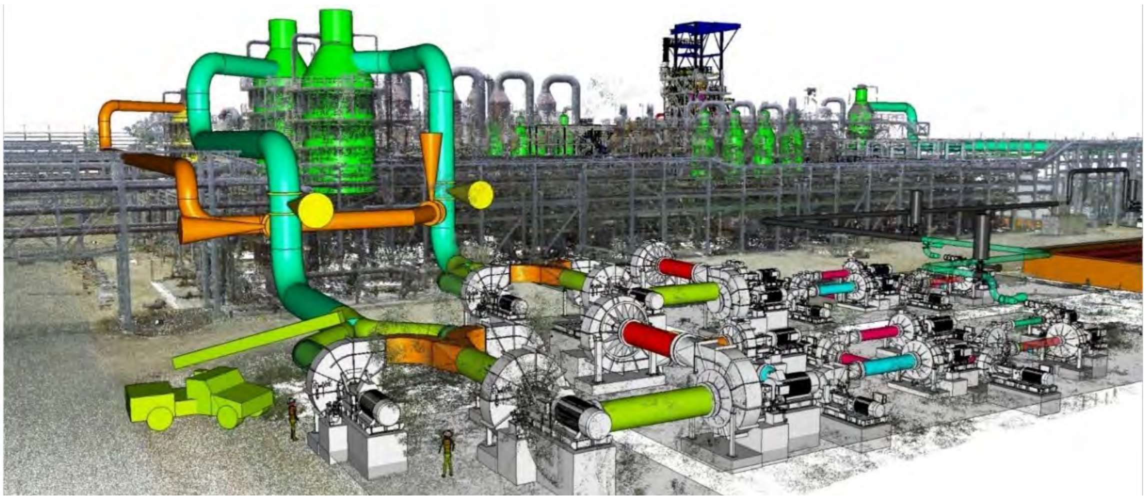


Figure 27 Evaporator compressor layout with 13 low speed compressors per train

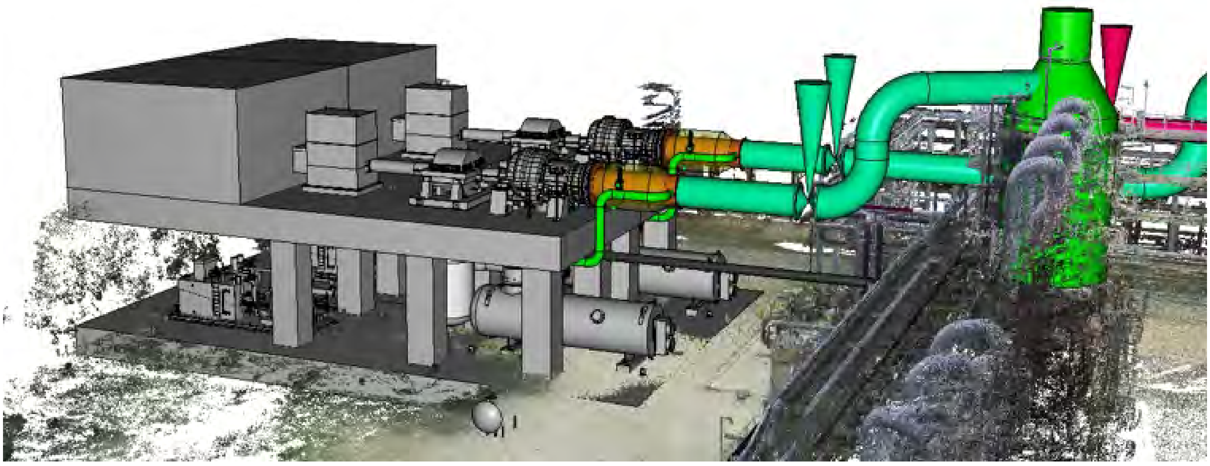


Figure 28 Evaporation compressor layout with one axial flow low pressure duty and one multistage high-pressure duty driven by one motor

7.5 Reliability and Availability

The MVR-powered alumina refinery in this study will require 46 compressors in five compressor trains. Although the compressors are highly reliable, the cumulative effect of this many compressors on reliability can be significant. Philosophies used to improve overall system availability are detailed below.

7.5.1 Individual Compressor Failure

Within a compressor train, should any one compressor fail then that compressor can be stopped, and the compressor train continues to operate. An example of this might be a motor, bearing or gland failure. The compressor train must always achieve the target exit pressure of 880 kPaA, however it is acceptable for its capacity to reduce. The compressor is not bypassed using valving. It could be bypassed if the system is shut down and temporary ducting installed.

The evaporator compressor trains have excess capacity in the low-speed, variable-speed driven compressors. They can pick up additional load using their variable-speed drives and maintain target last stage flash tank pressure, which is important for downstream processes. The precipitation and calcination trains allow an increase in first compressor inlet pressure and thus reduction in capacity should a compressor be out of circuit.

The requirement to allow continued operation with one compressor out of circuit makes compressor selection difficult, in particular the high-speed compressors as they need to operate over a significant volume range. The criterion causes an additional 3 per cent power consumption and 5 per cent increase in capital cost.

Unplanned compressor outage data was not available. Planned outage requirements are twice per year for shaft glands and once every five years for major overhaul. It is arguable that the criterion to be able to operate with one compressor stopped is not justified. A full refinery demonstration will help determine if this criterion is justified.

7.5.2 Excess Capacity

Overall, the MVR system has 8 per cent excess capacity over normal operating requirements. This provides significant capacity to absorb the above scenario of an individual compressor failure or long-term degradation of compressor performance.

7.5.3 Right Sizing

Compressor train capacities were selected considering the existing four steam boiler sources as back up steam sources, economies of scale for the compressor trains and maximum compressor volumetric capability. Any one compressor train can be out of circuit and the refinery will not be short of steam with the smallest boiler available used as back-up.

The smallest trains are the evaporator trains at 124 tph live steam each, coincidently governed by process conditions and the maximum available compressor size. Early design proposals had three smaller MVR trains, but these were abandoned in favour of two larger trains for better economies of scale.

The precipitation train normal operating rate of 134 tph and peak operating rate of 147 tph leaves behind about 80 tph heat recovery capacity, deemed surplus to requirements. It would have also exceeded the capacity of the largest available compressor. Two smaller trains were considered but the idea was abandoned, and one larger train was adopted to allow better economies of scale.

The calcination train has 201 tph normal operating capacity, more than the size of the back-up GT-HRSG. The calcination train has the lowest power consumption per tonne of live steam produced, so normally operates near its maximum capacity. Excess capacity is built into the precipitation and evaporation trains to enable normal refinery operation, with the GT-HRSG, with the calcination train out of circuit. If the largest of the three calciners is out of circuit, then the system has sufficient capacity without the GT-HRSG.

7.5.4 Boiler Back-up

The HRSG component of the GT-HRSG is maintained hot to enable rapid start-up should it be required. This is achieved by maintaining the steam drum at live steam pressure and using a small amount of blowdown to ensure flow into the bottom drum. Losses from this system are estimated at 0.5 per cent of the HRSG capacity, or 1 tph live steam sourced from the MVR system, 0.2 per cent of MVR power consumption.

Rapid starting is only required to cover unplanned compressor outages. A full-sized train demonstration will help determine the need for this additional loss.

Boiler back online requirement is estimated at 2 per cent of the time, combusting 0.5 per cent of present-day fossil fuel requirements.

7.5.5 Grid Reliability

The refinery is presently able to operate completely islanded from the grid. With MVR, the refinery will be completely dependent on the grid.

The refinery is located within the backbone of the SWIS 330 kV system, between significant coal-fired generation facilities at Collie and the major consumer at Perth. Alinta has 380 MW[11] peaking facilities co-located at the Wagerup refinery and 285 MW[11] cogeneration facilities co-located at the Pinjarra refinery 30 km to the north. No network augmentation is required to deliver power to Wagerup once the power is in the grid.

The 330 kV system is very stable. Discussions with Western Power indicated short transient outages (that the system should be able to ride through) could be expected once per year and there had not been any significant outages or shortfalls since the Varanus island incident which impact gas supplies to the south-west of WA.

The proposed MVR system design would ideally include a battery for black start capability. The battery is not included in the capital estimate, as battery storage is already commercially viable and is being considered in the SWIS. Colocation with the refinery would offer synergies.

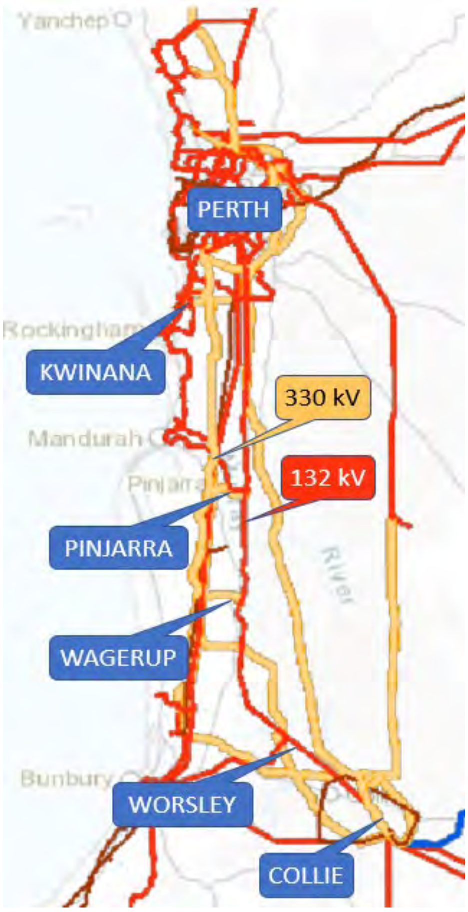


Figure 29 SWIS grid

7.6 Train Design and Control

Steam flow to refinery requirements can vary significantly. In Figure 30 showing one year's operation, the minimum flow is about one third of the peak flow.

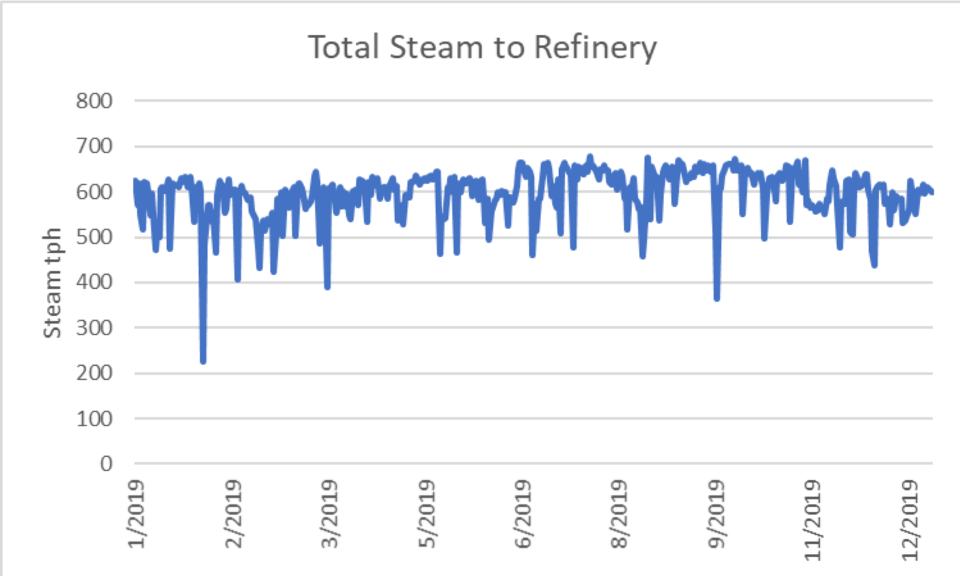


Figure 30 Variability in refinery live steam requirement (repeat of Figure 10)

Compressors in comparison work in a relatively narrow volume flow band. In the typical compressor curve shown in Figure 31, operation to the left of the curve is not permitted as the compressor can become unstable and cause itself serious damage. Optimum operation is about 40 per cent higher volume flow relative to the surge point, and at about 60 per cent the compressor pressure rises, and efficiencies drop dramatically. As described earlier, the criterion enabling one compressor to be out of circuit also constrains the compressor normal operating range.

Small variations in live steam production are achieved using the variable-speed driven low-speed compressors. Inlet guide vanes (IGVs) are also proposed for the high-speed compressors; however, it is likely that they will not be necessary as there is already significant control range.

Larger capacity variations are achieved using the anti-surge system described in Section 7.6.1. If the required flow is less than that allowed due to surge limits, bypass valves open to enable flow to recirculate through the compressor.

To achieve the full turndown required, individual compressor trains are taken offline.

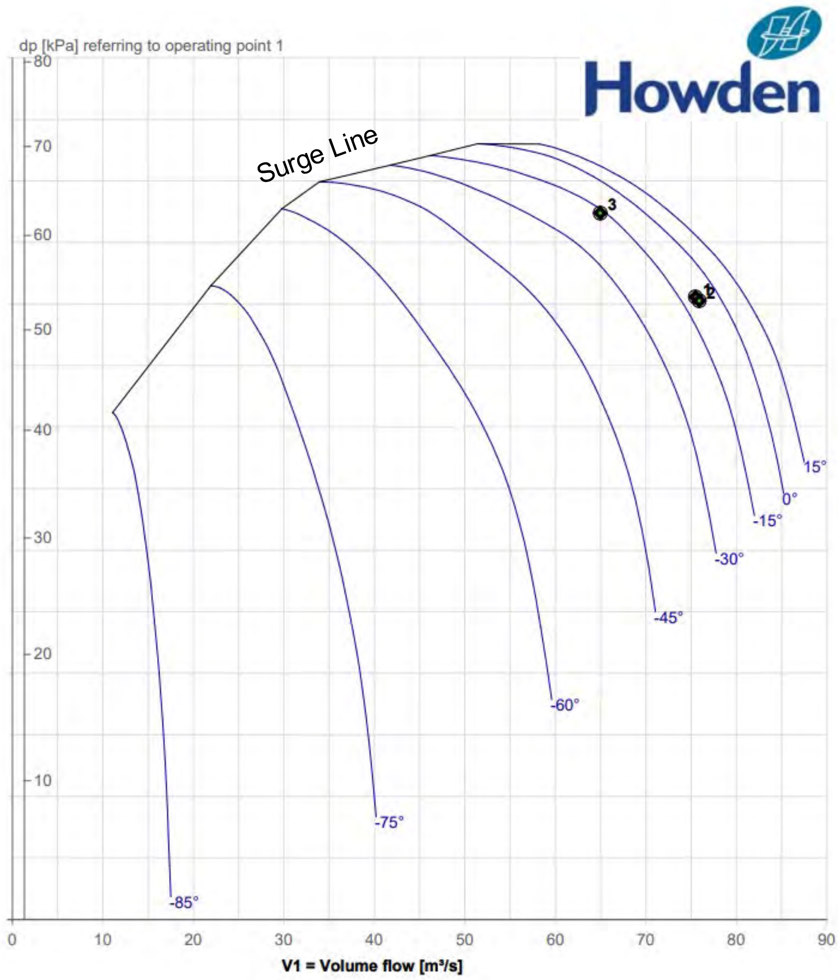


Figure 31 High speed compressor performance curve - Courtesy Howden

7.6.1 Anti-Surge System

As compressors cannot operate below a critical flow, it is common to recirculate compressor discharge back to the compressor inlet to allow operation with a low inlet flow. Figure 32 shows the anti-surge system. If a particular compressor is near its surge point, then its discharge and suction control valve is opened to allow flow recirculation. Surge can happen quickly and cause significant damage. Anti-surge control is generally via a Programmable Logic Controller (PLC) which has a response time much faster than the refinery Distributed Control System (DCS).

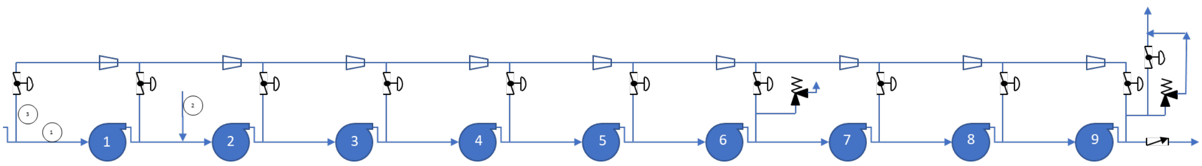


Figure 32 Compressor anti-surge system - repeated

7.6.2 Start-up

Anti-surge is particularly important for start-up when there is no net flow until the system achieves full capability. At start-up, the anti-surge valves on at least compressor 8 and 9 (in Figure 32) discharges are open, as well as compressor 1 suction anti-surge valve and compressor 9 discharge valve to atmosphere. Compressor 1 to 4 are started using their variable speed drives and ramp up until they achieve their maximum speed. Desuperheating water is added at compressor 1 to keep the steam within design limits. Excess vapour is vented to atmosphere.

Compressors 5 to 9 have large direct online (DOL) motors, up to 6 MW. Power voltage droop due to DOL starting is minimised by next starting the last compressor, compressor 9. It has the lowest volumetric capacity and is designed for 500 kPaA inlet pressure. At start-up it will be less than 100 kPaA, so low inlet density and thus low power draw.

Compressor 1 to 4 variable-speed drives will have an over-ride control to enable them to participate in the grid essential system services (ESS) market. This is a fast-acting control that can also respond to voltage droop. Compressors 1 to 4 will be drawing about 6 MW of power when stage 9 is started, so could theoretically substantially cover power droop within the substation, and the whole refinery if other trains are operating. The ability for the variable-speed drives to participate in the ESS market and to compensate for voltage droop will be tested in the Wagerup MVR+FFE project.

With five compressors operating and the atmospheric dump valve open there will be sufficient vapour from the flash vessels to ensure the compressors are not surging. Anti-surge valves will automatically close.

Stages 8,7,6 and 5 are then sequentially started and the atmospheric dump valve will automatically close when the system is capable of discharging into the live steam header.

7.7 Compressor Operating Points

Howden's range of compressors were selected to provide a basis of design. Howden have a range of both low-speed and high-speed compressors and have been helpful in sizing and optimising for the challenging duty.

A particular challenge is the desire to be able to continue operation with one compressor out of circuit. The most challenging scenario is the last compressor out of circuit. The upstream compressor's normal operating point has a volume flow 45 per cent higher than the last stage. If the last stage it out of circuit, then it needs to operate at a significantly different point with sufficient safety margin from its surge point. The criterion causes the compressor to operate at about 3 per cent lower efficiency than optimum. The lower efficiency results in additional heating to the vapour, which is then desuperheated with water, creating more steam. The net result is a 2 per cent increase in power consumption. Larger motors also need to be selected for the later stages due to the significant change in duty. This criterion needs to be challenged and its need proven or otherwise in a full train demonstration.

The compressor curve in Figure 33 is typical for the high-speed compressors. Operating point 1 is normal operation, point 2 is maximum flow, point 3 is when the upstream compressor is out of circuit.

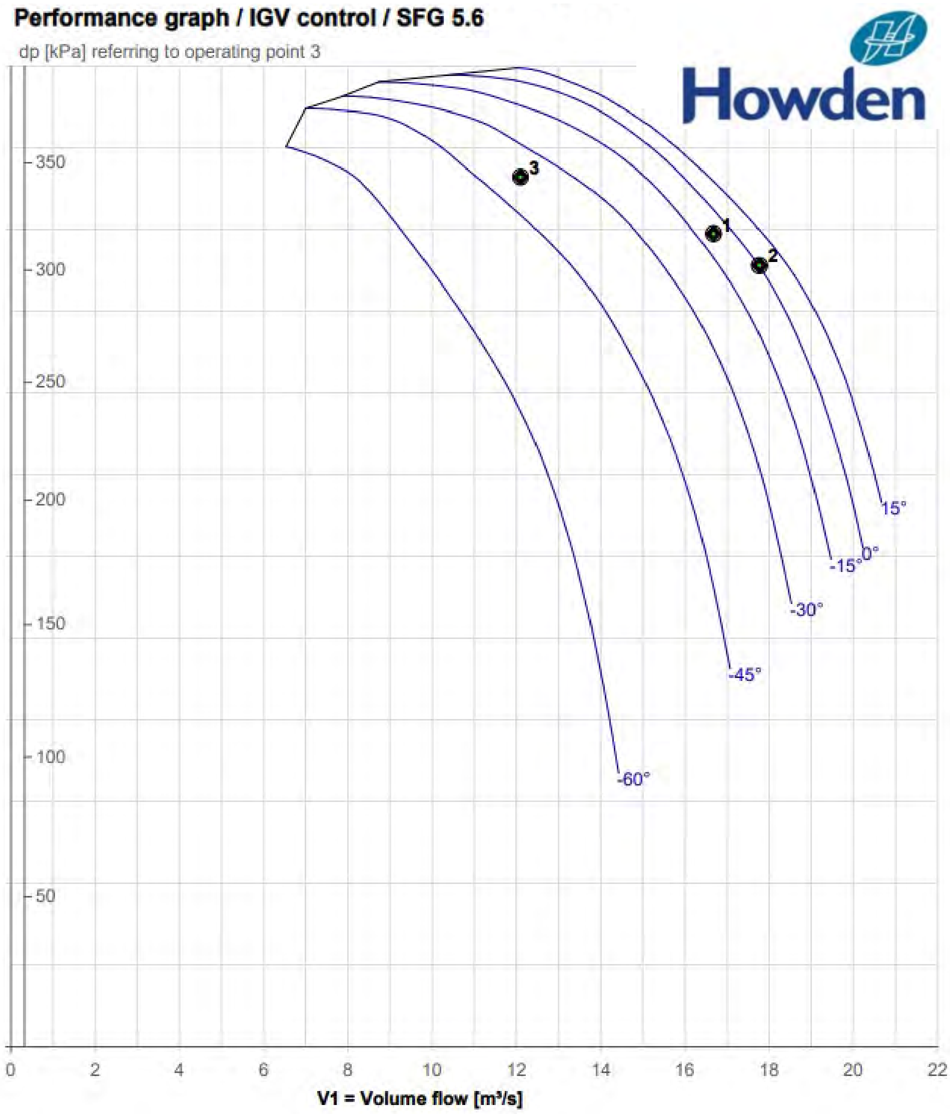


Figure 33 Second last compressor stage performance curve. Courtesy Howden

Gas: Vapor Standard density (1013 mbar, 0°C, dry): 0.8041 kg/m³
Composition: H2O: 100% (Vol/Mol-%)

		1	2	3	
		St. 9 Evap. Normal OP	St. 9 Evap. Max OP	St. 9 Evap. Stage 10 out	
Gas		Vapor	Vapor	Vapor	
Ambient pressure	kPa	101.205			
Site level	m	10			
Conditions at Battery Limits					
Mass flow (humid)	kg/h	101800	112300	119900	
Relative humidity	%	0	0	0	
Inlet temperature	°C	140	141.3	158.7	
Inlet pressure	kPa	313.4	325.2	524.8	
Pressure rise	kPa	206.8	204	362	
Outlet pressure, abs.	kPa	520.2	529.2	886.8	
Operating Data Compressor					
Control type		IGV	IGV	IGV	
Actual volume flow	m³/h	60036	63976	43564	
Mass flow (humid)	kg/h	101800	112300	119900	
Inlet density	kg/m³	1.6956	1.7553	2.7523	
Inlet pressure	kPa	313.4	325.2	524.8	
Inlet pressure losses, abs.	kPa	0	0	0	
Pressure rise	kPa	206.8	204	362	
Outlet temperature	°C	[redacted]			
Outlet pressure, abs.	kPa	520.2	529.2	886.8	
Isentropic efficiency	%	[redacted]			
Isentropic head	kJ/kg	99.467	95.572	106.385	
Compressor speed	1/min	15420	15420	15420	
Driver speed	1/min	1485	1485	1485	
Power					
Power on coupling	kW	[redacted]			
Rated driver power	kW				

Table 6 Second last compressor stage performance data. Courtesy Howden

A typical set of data points for the precipitation compressor train is given in Table 7.

Stage / Scenario	P in	Pout	Superheat	Condensing Delta T	Inlet Vapour Density	Flash Steam	Desuperheat water	Inlet Mass Flow	Inlet Volume Flow	Speed as % of Max.	Pressure Rise Ratio	Motor Power
	kPa	kPa	°C	°C	kg/m3	tph	tph	tph	m3/s			MW
Precipitation												
Normal Flow												
1 Howden ExVel Low Speed	13.6	19.5		7.3	0.09	64.1	1.4	64.1	195.0	100%	0.43	1.3
2 Howden ExVel Low Speed	19.3	26.4	2.0	6.7	0.13	39.9	2.5	105.4	232.6	100%	0.37	2.0
3 Howden ExVel Low Speed	26.2	34.2	2.0	6.0	0.17		2.0	107.9	178.8	87%	0.30	1.7
4 Howden ExVel Low Speed	34.0	42.1	2.0	5.0	0.21		1.6	110.0	142.7	77%	0.24	1.4
6 Howden SF Series High Speed	42.0	72.3	20.0	13.6	0.25		5.9	109.9	123.5	100%	0.72	4.1
7 Howden SF Series High Speed	71.7	125.7	5.0	15.3	0.43		4.4	115.8	75.5	100%	0.75	4.1
8 Howden SF Series High Speed	124.6	209.8	5.0	15.6	0.72		4.2	120.2	46.7	100%	0.68	4.0
9 Howden SF Series High Speed	208.1	331.3	5.0	15.2	1.16		4.1	124.4	29.9	100%	0.59	3.9
10 Howden SF Series High Speed	328.8	507.8	5.0	15.5	1.77		4.5	128.6	20.1	100%	0.54	4.2
11 Howden SF Series High Speed	504.2	888.4	5.0	22.3	2.65		1.4	133.0	13.9	100%	0.76	5.4
System Exit / Total	880.7		40.0					134.4				32.0

Table 7 Precipitation compressor train normal operating points

7.8 Noise

Compressors are noisy, and special consideration to noise abatement may be required

For the Wagerup cases noise impacts were evaluated and noise abatement measures determined. The solution mix included noise offset projects.

A key finding was that most noise would come from ducting and pipework. Noise from the compressor enters the pipework and travels unabated through the pipework, radiating its sound energy to the atmosphere. To resolve this, silencers are included in ductwork before the first compressor and after the last compressor to attenuate noise at its source and prevent it radiating out from pipework. There will be about 130 MW of MVR compressors generating noise. Presently we have 62 MW of steam turbines generating a similar noise in live steam pipework which would not be present with MVR.

The overall noise solution included:

1. Train inlet and exit silencers.
2. Normal thermal insulation on duct and pipework.
3. Silencers on interconnecting ductwork between compressors within a train.
4. Noise-attenuating hoods over the compressors themselves.
5. Low noise, air-cooled motors.
6. Curtailment of steam turbines as the only required noise offset.

The Wagerup MVR+FFE demonstration project will test all of these items except the noise offset. Duct silencing is not normally done for MVR, however there are instances where fan noise is attenuated on exhaust stacks.

7.9 Water

Water consumption and conservation is a significant concern for Alcoa's alumina refineries, particularly in a drying climate.

MVR captures wastewater vapour and re-uses it in the process. During normal operation at Wagerup, wastewater vapour captured would be 486 tph. The alumina refinery is a net consumer of water and as such requires water storage systems. A sizeable portion of stored water is lost to evaporation. As MVR reduces the refinery's dependence on water, an amount of storage evaporation loss reduction can also be assumed.

The estimated water saving is 600 tph, or 5.2 GL per annum.

8 Extrapolating Wagerup MVR KPIs to Other Australian Refineries

8.1 KPIs

A refinery's power generation system can have a significant impact on KPIs.

Generally, low-temperature refineries generate power for internal use by decompressing steam. High-temperature refineries do not generate power by decompressing steam because they need high pressure steam for digestion.

When MVR displaces boilers, low-temperature refineries can no longer generate their own power, thus need to import additional power to drive MVR as well as to replace their existing generation. However, a high-temperature refinery only needs to import additional power for MVR.

High-temperature digestion alumina refineries need to compress waste vapour to a higher pressure to make digestion steam compared to low temperature alumina refineries. Consequently, high temperature alumina refineries consume more MVR power than low temperature refineries.

The net outcome is that the carbon abatement per MW of incremental renewable power consumed due to MVR implementation is similar for high and low temperature refineries. However, high-temperature refineries will require renewable energy to replace their existing imported power which is independent of MVR and the KPIs in Table 8,

It has been assumed that all low-temperature refineries have a steam/power balance similar to Wagerup, and all high-temperature refineries do not self-generate power. This makes a significant difference to import power requirements due to the implementation of MVR.

KPI Comparison	Hi Temp	Lo Temp	
MW-h per GJ displaced	0.111	0.099	MW-h / GJ gas
Carbon Displaced	0.284	0.342	t CO2e / t alumina
Carbon Displaced	0.500	0.520	t CO2e / MW-h consumed

Table 8 Process KPI comparison for High and Low temperature gas-fired refineries assuming high-temperature refineries do not self-generate power, and low-temperature refineries do self-generate power

Coal-fired alumina refineries can expect higher carbon abatement because of their higher emission base. Coal-fired boilers are generally around 93 per cent efficient on a lower heating value basis, and gas-fired boilers are generally around 84 per cent on a higher heating value basis. We can expect higher emissions from a coal-fired facility relative to an equivalent gas-fired facility.

It might not be practical to retrofit MVR to all facilities, due to the space required to install MVR compressors. For the purposes of this report, all facilities are included in the all-up cost extrapolation with no special cost additions. This is consistent with looking at the big picture of what alumina refining might look like 20 years from now. There are many uncertainties, including growth potential.

8.2 MVR KPI Detail – High-Temperature Refineries

The high temperature digestion energy flow sheet is fundamentally different to a low temperature digestion flow sheet. The high digestion temperature above 250°C is significantly above the maximum temperature that can be achieved in a shell and tube heater; thus, the final stage of heating is by contact steam. The gap between last shell and tube exit temperature and digestion temperature governs the whole refinery energy balance. Steam to drive the evaporation process is exported from digestion and there is generally an excess amount of energy in digestion blow off which is exhausted to atmosphere.

Unlike a low-temperature digestion refinery, the only significant heat sink is digestion.

Figure 6 shows a typical high-temperature digestion flow sheet from an energy perspective. Waste heat sources are similar to a low-temperature digestion refinery, i.e., evaporation barometric flash tanks, precipitation cooling circuits, and calcination.

Thus, a high-temperature digestion system can be considered as the same as a low-temperature system, except the final steam pressure needs to be about 6,900 kPaA, 285°C condensing temperature.

Alcoa's affiliate Alumina Española S.A. has a high-temperature digestion alumina refinery in San Ciprian, Spain that operates digestion at approximately 250°C. Process data from this refinery is used to represent a generic high-temperature alumina refinery in Australia. A significant difference however is that it uses a live steam pressure of 5,100 kPa, 265°C condensing temperature. Similar to a low-temperature facility, there is an energy balance impact as boiler feed water is no longer heated from process waste energy. This results in additional excess blow off vapour and excess vapour energy within the digestion flash train. As this vapour is at a higher pressure, it requires less power to be compressed to live steam pressure.

	Low Temp		High Temp	
	Mass Flow	Condensing Temperature	Mass Flow	Condensing Temperature
	Ratio	°C	Ratio	°C
Evaporation	34%	54		
Preciptation	20%	56	27%	56
Digestion BO	12%	102	21%	99
Digestion FT3			13%	143
Calcination	33%	73	39%	73
Total Inputs	**100%**	**48**	**100%**	**83**
Live Steam	**126%**	**174**	**141%**	**265**
Average Delta T		**126**		**182**

Table 9 Vapour sources

A summary of vapour sources for the two refinery types is given in Table 9. Vapour sources are optimised to achieve the required live steam, hence there is no vapour sourced from evaporation for the high-temperature refinery even though there is a small amount available.

Live steam ratio is the ratio of live steam to source vapour, the difference being desuperheating water used to cool the vapour between compression stages.

Average Delta T is the average condensing temperature rise from source to live steam. High Temperature is 54 per cent higher.

As a result of the higher compressor Delta T requirement, High Temperature requires 34 per cent more power per tonne of live steam produced. Some high-temperature refineries operate at a higher temperature of around 270°C. They require more steam input; however, this is balanced by more blow off vapour reducing the net impact on the overall Delta T, and thus power consumption.

Some low-temperature refineries operate with split live steam systems delivering two different live steam pressures to the refinery, typically high pressure to digestion and low pressure to evaporation. This is done to optimise power generation for the powerhouse steam turbines whilst achieving the required digestion temperature. Again, the net impact of the split system on MVR power consumption is minimal because the weighted average Delta T for the high- and low-pressure live steam is similar to that of a refinery without a split system.

Wagerup and San Ciprian alumina refineries use approximately the same live steam per tonne of alumina, thus these KPIs can be extrapolated from per tonne of live steam to per tonne of alumina.

MVR compressors for the higher steam pressure required in high temperature refineries are not proven. Compressors have previously operated at the required discharge pressure but not temperature, and at the required temperature but not pressure. The duty is technically feasible, but the technology will need to be developed. It is likely the compressors will need to be derated, thus requiring more than an additional four (theoretical and not derated) high speed compressor stages on each train. These final compressor stages are physically quite small as the steam has a very low volumetric flow rate at their high operating pressure.

For this study, it was assumed that additional compressor capital cost is proportional to power consumed.

		Low Temp with Cogen	Hi Temp without Cogen	Hi Temp with Cogen
Motor Switchroom Power	kW-h/t steam	217	294	294
Motor Switchroom Power	kW-h/t alumina	398	546	546
Infrastructure losses 4%	kW-h/t alumina	16	22	22
Lost Generation	kW-h/t alumina	231	0	231
New Import Power	kW-h/t alumina	645	568	798

Table 10 Power KPIs

Cogeneration (Cogen)

Older high-temperature digestion refineries generally do not produce power through steam turbines; thus, the power consumption impact of MVR is purely MVR power consumed. Wagerup would lose 230 kW-h per tonne generation capability with MVR implemented, increasing its low-temperature incremental imported power requirement.

More recent high-temperature refineries self-generate power using a GT-HRSG combination. This type of refinery would lose self-generating capability when MVR is implemented, but the GT-HRSG is valuable if it is used a small percentage of the time to avoid peak power charges and to firm the grid, similar to the Wagerup example.

Natural gas energy saved would be 6.6 GJ/t alumina for low temperature and 5.1 GJ/t alumina for high temperature, both for gas-fired boilers. The high energy usage for low temperature is primarily due to self-power generation.

8.3 Carbon Abated

MVR, powered by renewables, enables zero carbon process heat for the Bayer circuit. Refinery emissions are provided in Section 4.2.

If the technology was applied to all Australian alumina refineries, the total scope 1 and 2 carbon abated per the Safeguard Facility Data would be 9.4 Mtpa.

Any reduction in fossil fuel consumption could also reduce third-party upstream fossil fuel emissions. For natural gas this is approximately 0.0041 t/GJ[9], or 8 per cent. Coal upstream emissions are 0.003 t/GJ[9], or 3 percent.

Including upstream emissions, the potential total carbon abatement using MVR in Australia's operating refineries is 10.4 Mtpa CO_2-e. This compares well with potential abatement of 11 Mtpa reported by the Australian Aluminium Council[16].

9 Capital Estimate

The capital estimate for the Wagerup full MVR installation is equivalent to AACE Class 5.

The scope of work is summarised in Section 7.3. 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.

9.1 Estimate Inputs

Process Flow Diagrams (PFDs) were developed similar to those shown in Section 7.3 using Alcoa's in-house mass and energy balance models.

Piping and Instrumentation Diagrams (P&IDs) were marked up to show significant equipment and pipework.

The retrofit design was modelled in 3D in conjunction with existing refinery models and 3D point clouds.

Bills of materials for major pipework, ductwork, civil works, and structure steel were developed from the 3D model. The estimator was asked to make provisions for minor bills of materials.

Budget estimates were received from compressor vendors, however at the time of writing final budget pricing was not available. Pricing used is based on earlier budget pricing. The compressors and associated motors make up 35 per cent of total direct costs.

Power system single line diagrams and material take offs were produced.

9.2 Estimate Methodology

Alcoa developed an estimating package and obtained two estimates of AACE Class 5, 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.

A project risk review was conducted, and risk costs derived from the review were added.

Escalation was set at 1.25 per cent, representing the cost escalation that could be expected between project full authorisation and mid-commitment, six months. This needs to be considered in the economic analysis.

9.3 Estimate Breakdown

The approximate total installed cost of a complete retrofit at Wagerup alumina refinery, as of December 2021, is $622 M.

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

Table 11 MVR retrofit capital cost for low temperature refinery example Wagerup

Total cost distributions are as expected considering the repetitive nature of the compressor trains, large average motor size (around 3.5 MW) and a few process tie ins.

Figure 34 Total cost centres

Direct costs distributions similarly are as would be expected for a project consisting predominantly of compressors, large duct work and significant power.

The Mechanical Equipment – Other category includes flash tanks, heat exchangers, silencers, and miscellaneous equipment.

Approximately two-thirds of direct costs are for compressors or associated with compressor power provision.

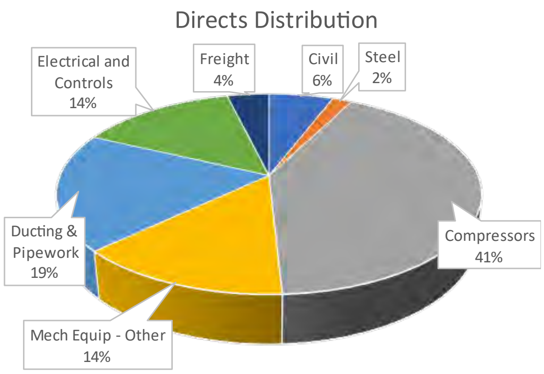


Figure 35 Directs distribution

Direct cost centres are consistent with compressor power consumption, except for the proposed digestion implementation which has smaller motors than other centres.

Costs include power distribution from the main switch house to the substations.

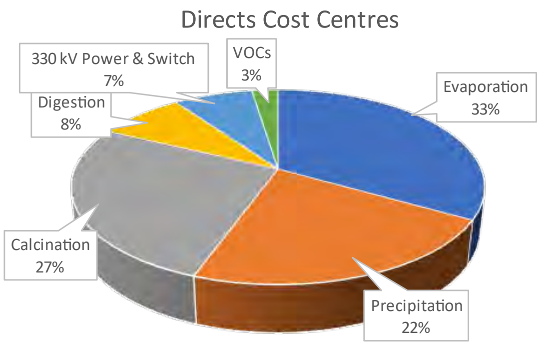


Figure 36 Directs cost centres

9.4 Extrapolating Capital Cost to Other Facilities

Ideally, the capital cost for each refinery could be estimated based on actual steam consumption, however this data is not publicly available. For the purposes of this report, we can categorise refineries as being high-temperature or low-temperature digestion.

Per Figure 35, approximately 67 per cent of capital can be directly related to the compressors, including electrical and control, freight, civil works and steel. Total compressor cost is approximately proportional to power consumed. As per Table 10

Table 10, a high-temperature refinery consumes 36 per cent more MVR power per tonne of alumina due to its higher operating pressure.

Low-temperature refineries will need to re-power their main switchboard from the new power source as their existing generation equipment will be idled. This cost of $30M is not applicable to high-temperature refineries.

Considering these points, on a per tonne of alumina basis, the capital cost for a high-temperature refinery can be expected to cost approximately 18 per cent more than a low-temperature refinery. Therefore, the capital cost for conversion of the Wagerup refinery ($220 per annual tonne of alumina) converts to $260 per annual tonne for a high-temperature refinery.

MVR implementation can be implemented in stages consisting of at least one compressor train and supporting infrastructure. The minimum implementation of one compressor stage will be in the order of $200M, thus the implementation rate can be adjusted to suit market forces.

Australia currently produces 7.4 Mtpa high-temperature and 13.8 Mtpa low-temperature alumina production. Thus, the total cost to implement MVR in Australia is approximately $4.5B, excluding capital reductions from learning.

9.4.1 Capital Reduction from Learning

Ruben (2015)[24] reports a 1.4 per cent learning rate for hydroelectricity, which is a mature technology, through to 12 per cent for onshore wind power. MVR is a mature technology, however its application in alumina refineries is not. The low-pressure compressor sizes required in the refinery are at the limits of available low speed compressors and are not available in high-speed centrifugal compressors. This is a similar scenario to wind turbines where the unit size is continuing to grow. A 5 per cent learning rate based on the Wagerup scenario is assumed.

> Applying a 5 per cent learning rate would reduce the total cost to implement MVR in Australia to approximately $4.5B

Capital cost reduction due to learning is not considered in the economic analysis.

9.5 Brownfield and Greenfield Growth Capital Cost

Brownfield and Greenfield growth scenario capital costs are significantly different to retrofit scenarios with respect to utilising existing infrastructure and avoiding spend on new infrastructure and equipment.

	Retrofit	Brownfield	Greenfield
Applies to	Existing alumina refineries assuming no increase in production capacity	Existing alumina refineries with small (creep) and large (new production train) increases in capacity	New alumina refineries
MVR Sparing	No spare compressor train	No spare compressor train	Spare compressor train required
Boilers and cooling water circuits	Used as back-up to MVR trains and to avoid peak power charges (generally less than 1% of time)	Used as back-up to MVR trains and to avoid peak power charges (generally less than 1% of time)	None. Pays 'firm power price'
Boilers and cooling water circuits investment	Sunk	Not required	Not required
Gas infrastructure	Sunk	Sunk	Not required
Power Infrastructure	Full power infrastructure	Full power infrastructure	Full power infrastructure

Table 12 Capital use in Retrofit, Brownfield, and Greenfield Scenarios

The Wagerup retrofit study provides a good baseline capital estimate from which capital avoidance can be subtracted based on the appropriate scenario.

9.5.1 Process Design

A retrofit or brownfield expansion can use existing boilers as back-up for when a compressor train is offline. This does not apply to a greenfield expansion, and it is necessary to take extra steps to achieve full steam redundancy when a compressor train is offline.

Table 13 shows two options.

		7 Trains		6 Trains	
		Maximum	Normal	Maximum	Normal
Evaporation 1	tph	123	89	123	104
Evaporation 2	tph	123	89	123	104
Precipitation 1	tph	107	77	147	124
Precipitation 2	tph	107	77		
Calcination 1	tph	126	110	126	110
Calcination 2	tph	126	110	126	110
Digestion	tph	58	58	58	58
Total	**tph**	**772**	**611**	**705**	**611**
Required	**tph**	**611**	**611**	**611**	**611**
Excess		**26%**	**0%**	**15%**	**0%**
N-1 Excess		**6%**		**-9%**	

Table 13 Greenfield live steam supply options

The '7 Trains' option maximises capability from precipitation and calcination and splits those trains into two smaller trains such that whenever a train is out of circuit there is excess capability.

The '6 Trains' option maximises capability from calcination and splits those trains into two smaller trains. If a large train is out of circuit, there is a process heat shortfall of 9 per cent. This is similar to present operations where a boiler out of circuit will cause a shortfall. A small electric boiler of 35 tph capability might be justified to satisfy full requirements for all scenarios except Precipitation 1 train out of circuit.

The ‘7 Trains’ scenario has been used for greenfield capital estimates and the previous retrofit scenario is used for brownfield retrofits.

Evaporator designs in existing alumina refineries were an economic solution based around fossil-fuelled boilers providing live steam to drive the process. With low-cost renewable power, the most economical solution now is to use MVR with single-stage evaporation processes, such as falling film (FFE) and forced circulation evaporators. The Wagerup demonstration MVR+FFE project should consume 6 per cent less power per tonne of evaporation relative to a conventional evaporator. Falling film evaporators however have their limits. They are not good in situations where the liquor is likely to deposit scale. They are useful in pre-concentrating the liquor prior to final evaporation. Up to two-thirds of evaporation could be achieved using FFEs, and the remainder in forced circulation or conventional evaporators which use more power. In a growth scenario, a refinery optimised with MVR+FFE evaporation could use up to 2 per cent less power than a conventional refinery retrofitted with MVR.

9.5.2 Brownfield Growth Capital

The most significant difference between Retrofit and Brownfield Growth scenarios is that new boilers, power generation equipment and cooling circuits are not required for the growth scenario, saving significant capital.

In growth scenarios it is possible to achieve greater synergies, such as precipitation cooling being right sized initially rather than reworking existing equipment. There are also construction economies of scale. Field establishment costs for MVR become less significant. There is no need to repower the existing main switch room as this would be upgraded regardless of MVR. Some risk related items are not applicable in a growth scenario. Overall, a 20 per cent lower cost relative to a retrofit is expected.

The brownfield growth capital estimate is shown in Table 14, with changes from the base capital estimate highlighted in orange.

Direct Costs - Disipline	AU$M
Earthworks	1
Civil	17
Steel	5
Mech Equip - Comp	126
Mech Equip - Aux	42
Ducting	14
Pipework >400DN	18
Pipework <400DN	25
EI&C	43
Insulation	8
Overseas Freight	7
Freight	4
Special Items	
ALCOA 330/22kV Switchyard	
330 kV Power Hookup	1
VOC Destruction	8
Brownfield Scope Reduction and Synergies	-32
Direct Costs Total	**287**
Indirect Costs	
Field Establishment Costs	
EPCM	23
Owners Costs	11
Contingency & Growth	105
Indirect Costs - Total	**139**
Total Costs	**426**
Adders	
Risk review scope	16
Weight considering check estimate	48
Escalation 1.25% total	6
Grand Total	**496**

Table 14 MVR brownfield capital cost for low temperature refinery example

In a greenfield facility similar to Wagerup, boiler and cooling water requirements make up about 14 per cent of total refinery capital, excluding power generation. For boiler and cooling water systems equivalent to MVR capability the capital cost is $695M. An equivalent brownfield facility has existing built-in redundancy and would require only three boilers costing approximately $520M. Note that the MVR estimate, and the above boiler and cooling water estimates are AACE Class 5 equivalent, thus the delta capital saving carries significant uncertainty.

Given the uncertainty in the estimates, the costs for MVR ($496M) and conventional ($520M) are comparable, that is MVR does not significantly add to or reduce the capital cost of a brownfield expansion.

9.5.3 Greenfield Growth Capital

Greenfield capital for MVR will be greater than brownfield due to the need for redundancy as outlined in Section 9.5.1.

Factored estimating methods are used to determine the additional cost. The factored estimate uses cost = constant x (capacity)$^{\wedge N}$ where N = 0.7 for volumetric flow capacity and N = 0.95 for repetitive designs. Per the 7-train option in Table 13, evaporation and digestion trains are the same as the Retrofit case, but precipitation and calcination trains are smaller than Retrofit, and there are twice as many. The resulting all up capital cost increase is $120M, taking the total MVR solution to $615M.

The 7-train option in Table 13 would be approximately $65M lower cost than a 6-train system but would expose the refinery to significant production losses if a compressor train is out of circuit. It could potentially be an option if the system proves to be highly reliable.

Greenfield MVR costs are equivalent to or potentially lower than conventional greenfield boiler and cooling system costs within the uncertainty of this analysis.

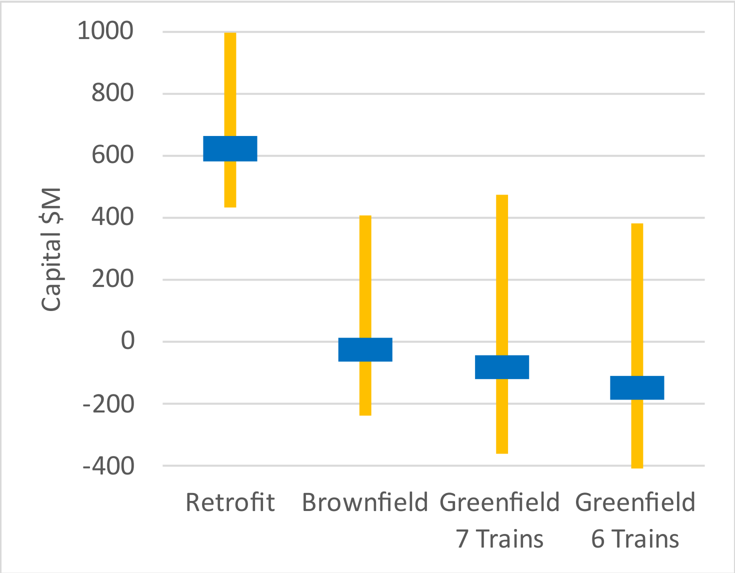


Figure 37 Capital investment considering infrastructure savings. Range shows the considerable errors possible when subtracting one value from another

Brownfield and Greenfield capital costs using MVR to generate steam are anticipated to be equivalent to or lower than capital costs for conventional fossil fuel firing.

However, considering the accuracy of the analysis they are considered equal.

10 Economics of MVR

10.1 Economic Assumptions

10.1.1 Energy Price Dynamics

Economics of MVR are strongly driven by gas verses electric power energy costs. As we are examining the cost differential between the two it is especially important to have a common and consistent basis for energy costs.

This study uses the first version of the South-West Interconnected System (SWIS) Whole of System Plan (WOSP) to provide a consistent basis for competing energy prices. The first version of the WOSP was published in August 2020. Importantly, it does not include any potential carbon price or emission reduction target. The outcomes are based purely on the lowest cost mix to deliver reliable power to the system. The exception to this is rooftop solar which has government subsidies.

Energy costs for this study focus on the period 2021 to 2040.

10.1.1.1 *Gas Price*

Gas prices are provided in the WOSP[12] as shown below. $7.91/GJ is the average delivered price to the SW of WA for the focus period.

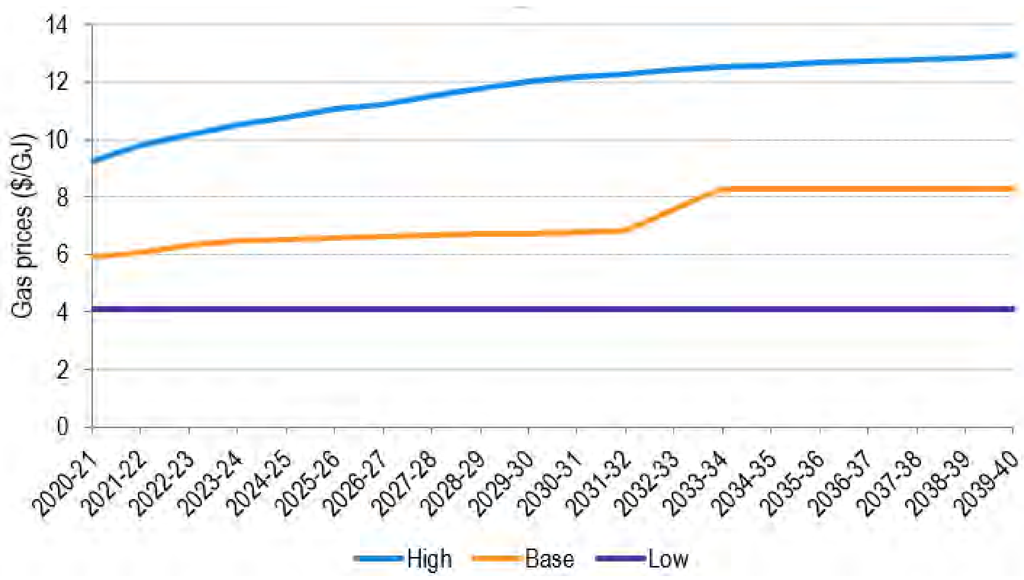


Figure 38 SWIS WOSP gas price assumption

10.1.1.2 ***Coal Price***

The delivered price of coal is assumed $2.7 per GJ based on Figure 39, sourced from the Australian Energy Market Operator (AEMO)[17]. Coal-fired boilers have significantly higher maintenance costs compared to gas boilers. An additional $1.4 per GJ is added to the cost of coal to reflect the additional maintenance OPEX of coal-fired boilers.

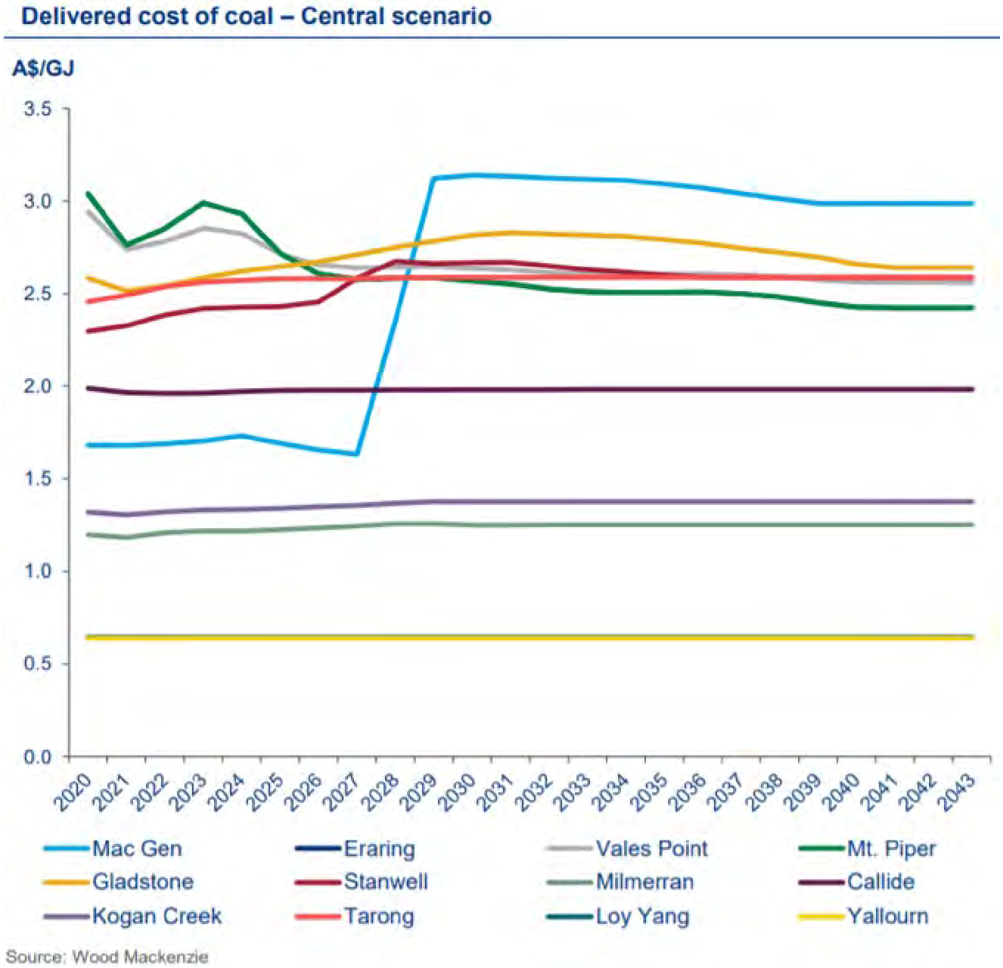


Figure 39 Delivered coal price assumption

10.1.1.3 *Power Price*

The cost of providing power is reported in the SWIS WOSP[12].

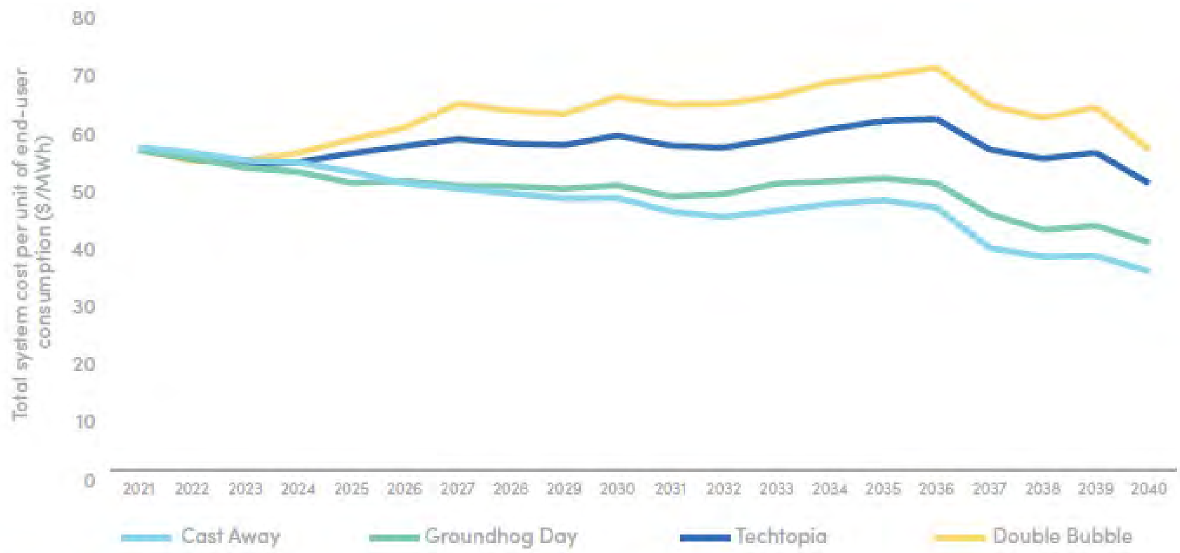


Figure 4.42: All scenarios – total annual system cost per MWh end-user demand

Figure 40 SWIS WOSP power price forecasts

The Double-Bubble scenario was chosen for this study as it represented a significant load increase on the grid as would be expected with large scale electrification.

The Double Bubble and Techtopia scenarios have the same cost of generation technology inputs, the only difference is the load. On this basis the characteristics of the incremental load can be determined by subtracting one from the other. This analysis showed that 95 per cent of incremental load is satisfied by renewable power.

Alcoa's analysis of future power pricing based on the SWIS WOSP and load flexibilities are outlined below.

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 15 SWIS power price structure

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

- **Reserve Capacity** cost is a capacity charge that is applied in 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) realises the equivalent of reserve capacity costs in their wholesale electricity price, resulting in extreme power prices when the network is under strain. These high price periods can be predicted and avoided; thus, we would expect a similar net financial outcome in the NEM as in the SWIS.

- **Demand Side Management** is a credit for provision of mid-term load reduction on demand, typically for a few hours per event. In the SWIS, the credit cannot exceed reserve capacity charges thus demand side benefits are small.

- **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 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.

- **Contracted Maximum Demand (CMD)** is the network maximum demand charge. A 120 per cent factor was used to cover peak loads.

The Wagerup retrofit design uses the existing GT-HRSG as a back-up for when an MVR train is out of circuit. It also provides support when there is a shortage of power, signalled by high power pricing. This realises an additional $1.1/MW-h lower cost. A greenfield refinery will not have that back-up thus will not realise this benefit.

In addition to the GT-HRSG providing power and steam support, the evaporation process can be flexed for short periods of time to substantially avoid capacity charges.

A composite power price of $62.4/MW is determined using a 63 per cent flexible and 37 per cent firm price mix.

10.1.1.4 *Behind-the-Meter vs Grid Renewables*

The power required to drive MVR is significant, potentially beyond what can be generated locally by renewables. It is plausible that some renewables generation could be connected behind the meter.

Wholesale Power Price: There may be benefits from behind-the-meter renewables. However, it is often the case that the most cost-effective location for renewables is not co-located with the customer facility.

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 greater capacity. 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.

Grid Capacity charges (CMD): Grid capacity charges are based on a contracted peak power consumption for the 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.

10.1.1.5 *Large Scale Generation Certificates (LGCs)*

The SWIS WOSP is based on no external subsidies with the exception of rooftop solar photovoltaics. The WOSP should represent the long-term cost of power inclusive of LGCs, if they exist in future. The estimated power cost used in this report is based on the SWIS WOSP. For the purposes of this report, LGCs, if they exist, are included in the estimated future power price.

10.1.2 Maintenance

MVR will attract maintenance costs but will be offset by substantially reduced boiler and generation equipment maintenance costs. The analysis assumes that day to day MVR maintenance costs are completely offset by boiler, generation equipment, cooling water systems maintenance savings.

It is typical to assume 2 per cent of capital costs for long term maintenance. This project assumes 1 per cent of capital in consideration of the offsets.

10.1.3 Financial Analysis Assumptions

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

OPEX and cost of carbon are presented as pre-tax costs. Consistent with this, depreciation is not applied to investments.

To determine the cost of carbon abated, the project Net Present Value (NPV) is converted to annual payments using the same discount rate and project life. Annual payments are then added to operating costs.

10.2 Sensitivities

Figure 41 represents OPEX price sensitivity for Wagerup refinery, which has a powerhouse consisting of three high pressure boilers and steam turbines to generate power, along with a small gas turbine plus low-pressure waste heat boiler to generate additional steam and power.

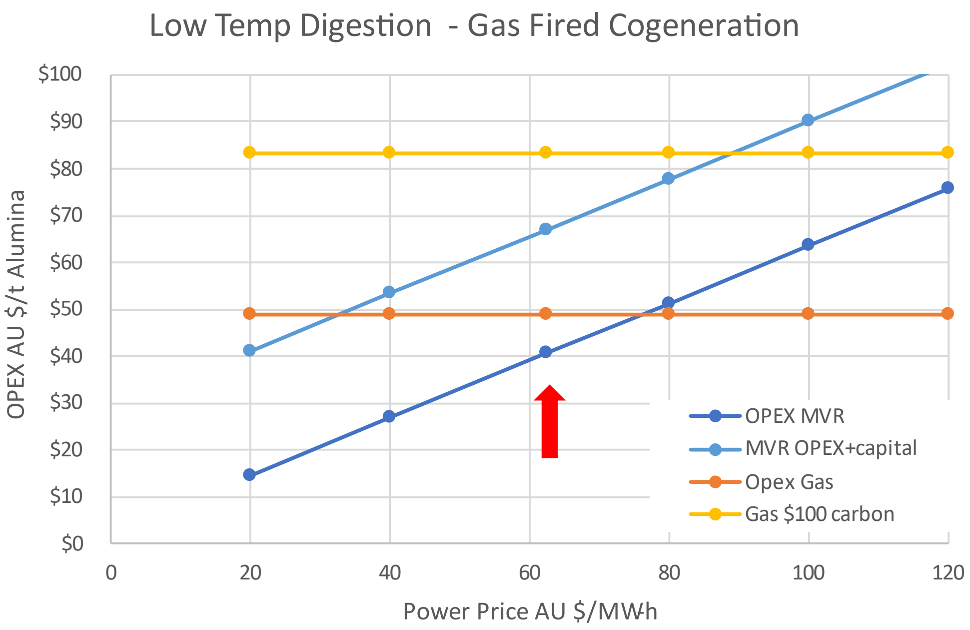


Figure 41 OPEX sensitivities for a low-temperature gas fired refinery

OPEX MVR represents operating costs using MVR to produce refinery steam. As the existing boilers and gas turbines would no longer be operating, it primarily represents the cost of power to drive MVR equipment and power to drive the refinery that was previously provided by the powerhouse.

MVR OPEX + CAPEX represents the Retrofit scenario which includes the significant cost of servicing the capital requirement. Greenfield and growth expansions carry no additional capital cost thus are represented by line 'OPEX MVR.'

OPEX Gas represents the present refinery energy operating cost at forecast prices and Gas $100 carbon represents the impact of a $100 /t$CO_2$-e cost.

MVR operating cost is about equal to gas operating costs. If carbon is included at AU$100/t CO_2-e the gap is $30/t alumina operating cost.

Figure 42 represents OPEX price sensitivity for a high temperature digestion refinery with gas turbine cogeneration sufficient to satisfy internal power demands. Most facilities built before 1990 did not have gas turbines to generate power. All required power was imported from the grid. Since the 1990s some high and low temperature digestion facilities have added gas turbines with high pressure steam heat recovery systems to improve overall energy efficiency.

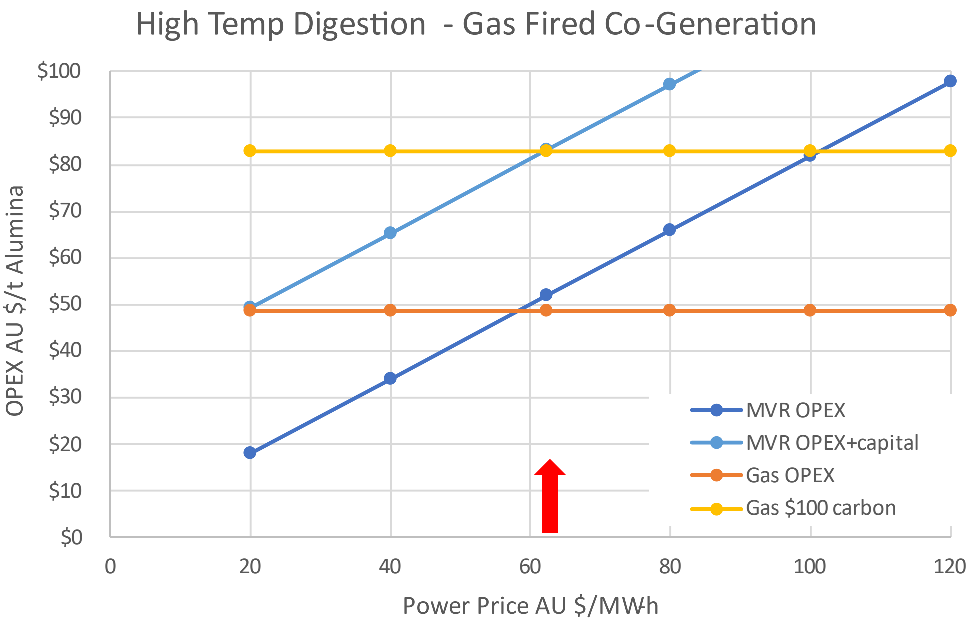


Figure 42 OPEX sensitivities for a high-temperature gas fired refinery

High-temperature digestion MVR economics are similar to that of low-temperature facilities in that it is not economic without a price on carbon. Capital costs and operating costs are higher per tonne of alumina produced.

10.3 Cost of Carbon Abated

The cost of carbon abated is very competitive to other technologies. This applies to both retrofit and growth scenarios. For growth scenarios it is zero cost as MVR OPEX is lower than fossil fuelled boilers at forecast pricing. The cost of carbon abated is sensitive to three significant factors as depicted in Figure 43.

Refinery cogeneration is the most significant sensitivity. Most low-temperature alumina refineries co-generate. Modern high-temperature alumina refineries can operate with GT-HRSG cogeneration, however, most do not. The reason cogeneration is the most significant sensitivity is that self-generation by combusting fossil fuels is halted, requiring significant additional import power. This analysis assumes a zero-carbon grid, thus there is no scope 2 import power carbon in the base case scenario and no carbon reduction claimed due to loss of self-generation capability.

High-temperature vs low-temperature digestion flow sheets cost of carbon abated is not so significant, compared to that of cogeneration.

Renewable Power Price is understandably a significant sensitivity.

Refinery fuel type is also very significant. Coal-fired steam has a low operating cost relative to MVR, so the net cost of abatement is higher on a per tonne basis, despite more carbon being abated for the same capital outlay.

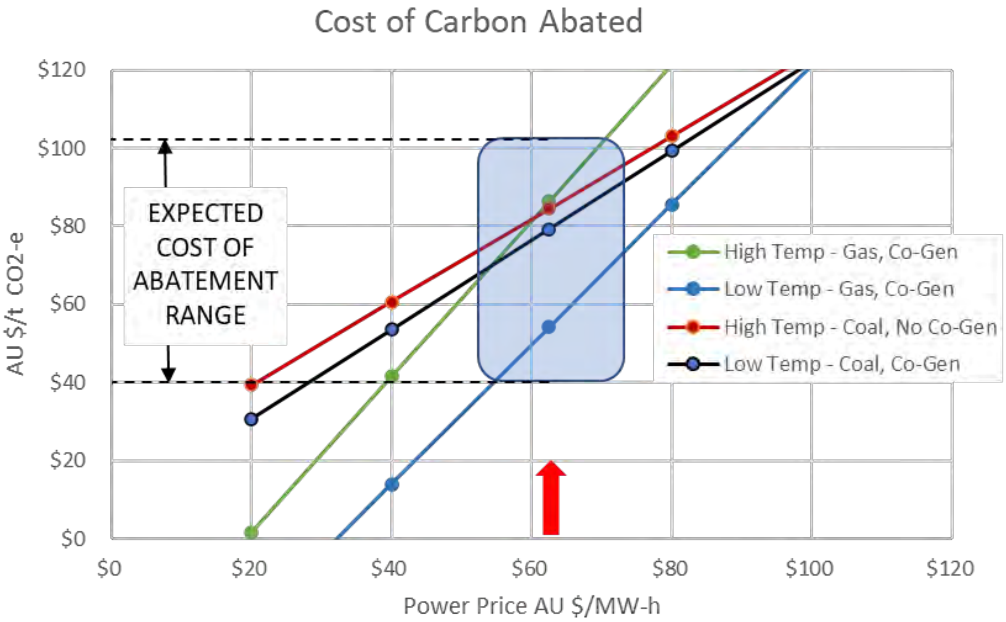


Figure 43 Cost of carbon abated using MVR

All up, the cost of abatement is expected to be in the range \$40 to \$100 per tonne of CO_2-e using the financial assumptions previously defined, with a strong sensitivity to power price.

10.4 Risks

A project risk review was conducted on the study outcomes in consideration that it might lead to a demonstration of the technology.

Considering the study targeted a AACE Class 5 estimate, there were no significant financial risks identified. The largest risk item contributed to only 2 per cent of the capital estimate.

The financial risk attributed understates the overall risk at its present technology readiness level because technology demonstrations are envisaged before full implementation.

Although there is confidence in MVR technology, prudence is required before implementing on a large scale. The most significant risks are:

- MVR reliability in an alumina refining environment.
- MVR reliability operating at high pressure beyond their normal duty.
- Operation and control with many compressors in series.
- MVR reliability in dirty vapours.
- Calcination waste heat recovery has many unproven aspects.

These risks will be mitigated by the proposed technology demonstration plan.

11 MVR Commercialisation Pathway to 2040

MVR has a strong business case in a carbon-constrained world. It is likely the lowest cost means of providing process heat to an alumina refinery.

In growth scenarios, MVR technology has comparable capital cost to conventional technology but with lower operating cost.

MVR retrofit economics will depend upon the availability and price of firm renewable power and carbon.

There are several barriers to MVR implementation, these are, in order of priority:

1. Understanding the benefits of MVR, which this report addresses. The key benefits of MVR are:
    a. Cost of abatement is within the realm of present carbon pricing.
    b. Technology readiness level (TRL) is high. Large scale deployment could start in the medium term.
    c. Power consumption per tonne of steam is substantially lower than electric boilers and hydrogen, thus significantly less investment is required in renewable power infrastructure and supply.
    d. Water savings are significant.
2. Proven reliable performance within an alumina refinery. This will be addressed in part by the Wagerup MVR+FFE demonstration facility that has a compression ratio of 2:1 (requiring two low speed compressors in series). Following the Wagerup demonstration, there will be a need for another demonstration of a compressor train of 60:1 ratio (requiring many compressors in series) before there can be substantial implementation.
3. The total cost to develop MVR to the point of commercialisation, excluding calcination, will be in the order of $220M. This is a significant investment and carries an elevated level of technical uncertainty relative to other projects of its size. Government support or co-investment may be required.
4. Large scale renewable power supply. Grids are becoming constrained and significant investment is required in both renewable energy and the grid. Approximatley1.2 GW of firmed new renewable power is required to power MVR in Australian alumina refineries.
5. Power cost is a significant risk. Power prices above AU$200/MW-h (as is the case in Europe today and recently seen during mid 2022 in the NEM), are three times the power cost used in this report would render MVR uneconomic.
6. Economic barriers today are significant. However, in the medium to long term retrofits are likely to become commercially competitive once carbon markets are fully established and trading at the true long-term cost of carbon abatement.

11.1 Proposed Commercialisation Pathway

11.1.1 Technology Development

A fast-tracked technology development plan could be achieved by overlapping engineering and early execution processes to an acceptable extent that minimises financial risk. This would place approximately 10 per cent of funding 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.

Duration risks are significant as the development process requires a change in typical project management methodology by accepting financial risk. To be successful, it requires high level support and sign-off from government and business. The investments required are significant and uncertainty will place the schedule at risk. Certainty on decarbonisation policies and pathways are critical.

Year 20XX		Total AUD	20	21	22	23	24	25	26	27	28	29	30	31	32
Low Speed MVR Evaporator (Wagerup)		$36										Engineering			
	Prove low speed MVR reliability											Construction			
	Determine flash vapour impact on compressors											1 Yr Operation			
Low Temperature Precipitation Retrofit Demonstration		$170													
	Prove high speed MVR reliability														
	Prove control of many compressors in series														
Digestion BO Retrofit Demonstration		$20													
	Prove low speed MVR on vapour with particulates														
High Temperature Digestion Compressor Development		$30													
	Develop high temperature digestion compressor														
Calcination Retrofit Demonstration															
	Prove calciner WHR system														

Table 16 MVR development pathway - fast tracked

11.1.1.1 ***Low-Speed MVR Evaporator***

This is the demonstration project at Wagerup, outlined in the MVR Evaporation Feasibility Study Report. It aims to provide confidence in low-speed MVR operation in the Bayer circuit. This is an important stepping stone before implementing MVR at large scale. It is intended to provide data on reliability, compressor performance in clean flash vapours and the ability to flex load to support grid ancillary services.

It will also demonstrate an MVR modular evaporator that could be used in future growth scenarios.

11.1.1.2 ***Low-Temperature Precipitation Retrofit***

The priority development requirement for both retrofit and greenfield or brownfield growth projects is the proof of operation of multistage compression. It is a key component of evaporation, precipitation, and precipitation MVR installations. Its proof of operation would allow immediate implementation in evaporation and precipitation duties, providing 55 per cent of refinery live steam requirements.

The vapour source from precipitation is clean and more amenable to MVR, thus a precipitation demonstration would have greatest probability of success.

A key study required as part of an MVR precipitation demonstration will be compressor selection. Section 7.4.2 outlines that there are three types of compressors and the net capital difference between the three is not significant. In particular the potential to use axial flow compressors should be examined. The technology would likely need to be tested in parallel with centrifugal compressors.

Some low-pressure duties push known centrifugal flow compressor capacity to their limits. These compressors are in either late development or very new to the market. The second stage normal operation duty in both evaporation and precipitation duties have the compressor operating beyond its good design point, resulting in relatively low efficiency. An MVR precipitation demonstration project would provide incentives to improve compressor performance at very high-volume flow rates.

11.1.1.3 ***Digestion Blow Off (BO) Retrofit***

Digestion duties are a lower priority in the short to medium term because benefits are only significant after the implementation of MVR evaporation. This is because MVR evaporation includes condensate waste heat recovery which changes the digestion energy balance, creating more blow off steam.

11.1.1.4 ***High-Temperature Digestion Compressor Development***

As previously outlined, high-temperature digestion compressors are technically feasible but outside previous proven duties. This stage envisages the development and demonstration of a final stage compressor, implemented at a high-temperature digestion refinery. Successful demonstration of high temperature operation would prove the entire concept.

11.1.1.5 ***Calcination Retrofit***

The lowest priority development requirement is vapour capture from calcination. Alcoa and Rio Tinto are considering separate calcination decarbonisation projects that provide near pure vapour that can be compressed using MVR. The schedule proposes calcination demonstration later in this decade.

11.1.2 Renewable Power Supply

Large scale renewable supply does not appear to have significant constraints other than supply and demand in the SWIS system. The first version of the SWIS WOSP double bubble scenario included network builds to enable increased demand supported by renewables. These costs are built into the modelled power price. Going forward, the future versions of the WOSP need review to specifically include the renewable power demands brought on by alumina refinery electrification. It can be assumed the same is required for the National Electricity Market (NEM).

This report outlines power requirements and thus supports the development of the plan. Further to this, regional facilities need to collaborate and provide a yearly demand profile to facilitate renewables and transmission planning.

Regional power price modelling needs to be made available to industry in detail to provide confidence in power price forecasts. Present WOSPs provide good information on inputs and outputs, but details around economic modelling are not readily available. Ideally, the WOSP models would be accessible by industry to run their own scenarios.

11.2 Potential Impacts in Australia

11.2.1 Environmental and Energy

Potential GHG reductions by retrofitting MVR to existing Australian refineries are outlined in Section 8.3.

If MVR development proceeds as outlined in Section 11.1.1, and is implemented at all Australian refineries, then it would be possible to achieve an emissions reduction profile approximating that of the IAI 1.5°C scenario[13]. This assumes that implementation is also fast tracked, that is, engineering begins in the same year of the demonstration first operation.

For high-temperature refineries, it is assumed that Digestion BO Retrofit is proven before full scale implementation.

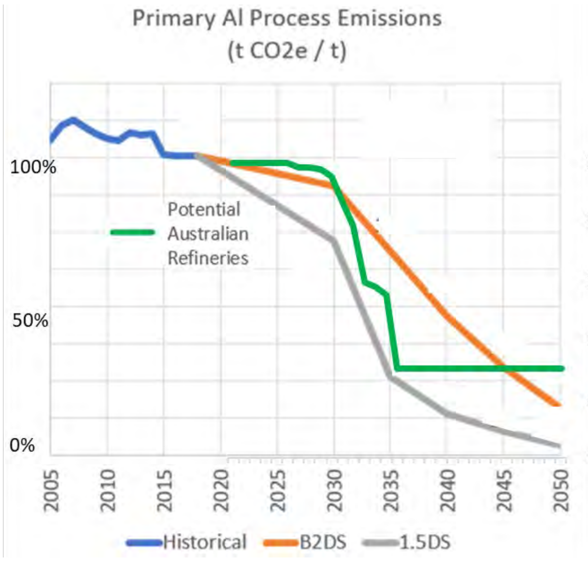


Figure 44 Potential refining carbon intensity overlaid on IAI's 1.5°C scenario

This assumes MVR is retrofitted to existing calciners and this is reflected in the following profiles.

Emissions remaining from 2035 onwards are predominantly from combustion in the calcination process.

The renewable power required, Australia wide, firmed to the assumptions used to determine the power price, is 1.2 GW.

For Western Australia, the requirement is 0.9 GW, approximately 37 per cent of the average SWIS load. It would require infrastructure build similar to that proposed in the SWIS WOSP double bubble scenario.

Water consumption and conservation is a significant concern for many alumina refineries. MVR recovers a significant amount of water that would have previously been lost to atmosphere. In Australia, approximately 25 GL per annum could be saved.

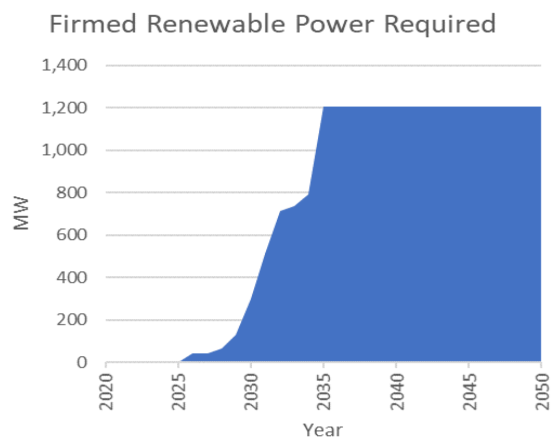


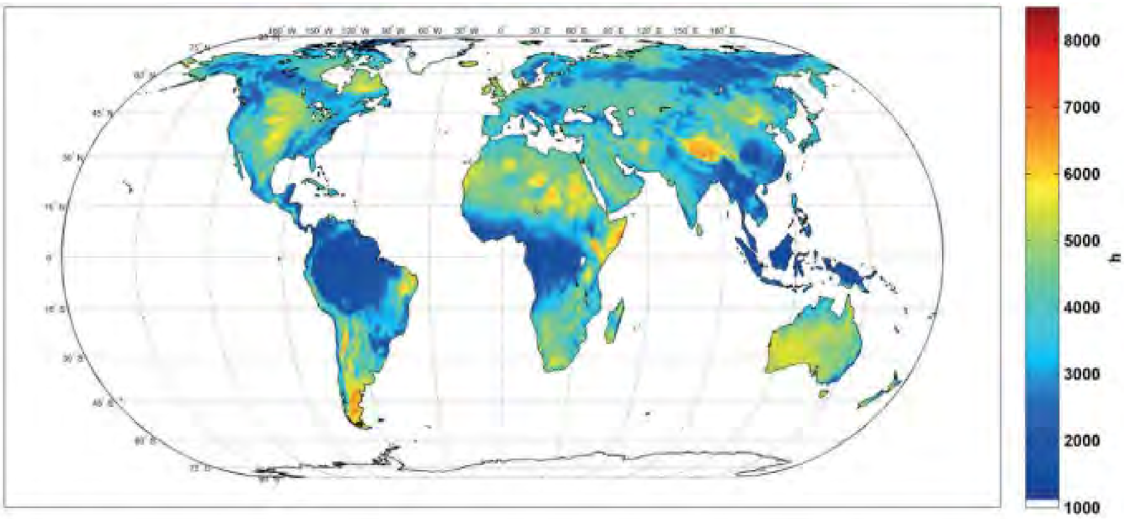
Figure 45 Firmed renewable power requirement

11.2.2 Australian Growth Outlook

Low-carbon alumina markets are outlined in Section 4.3. The low-carbon alumina supply and demand could be in deficit by up to 8.6 Mtpa by 2031, representing approximately one third of Australian alumina production. This represents a significant opportunity for Australia.

Australia's alumina industry went through a significant growth phase between 1960 and 2004 Growth was fuelled by good quality bauxite, low-cost energy and low sovereign risk. The last new refinery was commissioned in 2004[5] (Rio Tinto – Yarwun). While the Rio Tinto Gove refinery was closed in 2014[6], other operating facilities continue to increase production by about 1 per cent per annum using technology improvements and low-cost incremental debottlenecking.

MVR technology has the same capital cost as a conventional technology but has lower operating cost. Coupled with Australia's abundant renewable resources, particularly in Western Australia near bauxite deposits, we have an opportunity to develop a low-carbon aluminium industry. Synergies with initiatives such as the Asia Renewable Energy Hub and the hydrogen industry improve overall economics.



Disclaimer: The boundaries and names shown and the designations used on maps included in this publication do not imply official endorsement or acceptance by the IEA.

Source: Adapted and based on Fasihi, Bogdanov and Breyer (2016), "Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants".

Figure 46 Hybrid solar and wind full load hours adjusted by critical overlap in 2005. Source IEA 2017, Renewable Energy for Industry, Insights Series 2017, Figure 8, p29

Globally, Australia has a competitive advantage over all other countries for alumina refining using renewable energy because of its excellent renewable energy resources and close proximity to high quality bauxite.

Most alumina refinery growth in the last 15 years has occurred in China. China's advantage has been very low capital cost and low-cost coal, but the facilities need to import bauxite from which is expensive, resulting in high overall operating costs.

Long-Term (2030 to 2060)

China's pathway toward carbon neutrality is likely to accelerate beyond 2030; China has made no secret of its ambitions to shift increasing volumes of its electricity generating capacity to renewables, hydro-electric and nuclear power. That said, we see a growing likelihood that China will seek to relocate energy-intensive industries, such as aluminium smelting and, to a lesser extent, alumina refining, outside the country, presenting further opportunities for direct investment in the industry. We also see no slowdown in the rate of technological development and innovation in the industry, as it strives to achieve increasingly ambitious decarbonisation targets over the longer-term to 2060. Australia's aluminium industry is well-positioned to play a more significant role in the global aluminium industry of the future, based on its fundamental competitive advantages of

- *Abundant high-grade bauxite reserves*
- *Potential to generate vast quantities of electricity from renewable sources*
- *Low investment risk in a stable jurisdiction, and*
- *Close geographic proximity to the Chinese and other SE Asian markets.*

China's aluminium industry has begun its long journey to carbon neutrality. The Dual Carbon policy targets set by President Xi will drive substantial change throughout the industry over the decades ahead and ensure that the targets are met. Anticipating these changes could result in substantial benefits for other countries. We see Australia's aluminium industries as well-placed to become major beneficiaries of the change, should they take the opportunity to expand into the voids created by the rollout of China's domestic energy policies[14]

Source: CM Group, November 2021, Executive Report Prepared for the Australian Aluminium Council on Implications of China's Dual Carbon Policy on Australia's Aluminium Industry.

12 Next Steps for the Alumina Industry

12.1 Development

A fast-tracked development pathway is outlined in Section 11.1.1.

The proposed precipitation demonstration would test low-speed compressors operating at low pressure and the extremes of their volumetric capacity capability, high-speed compressors operating in the mid to high pressure ranges and control schemes necessary to operate many compressors in series. The demonstration might also choose to test an axial flow compressor in the low-pressure duty. An important outcome of the demonstration would be proof of MVR reliability. As identified in Section 7.5.1, approximately 5 per cent capital cost and 3 per cent operating cost could be saved if the criterion to be able to continue to operate with one compressor out of circuit could be relaxed.

The Digestion Blow Off (BO) demonstration would test the reliability of scrubbing systems to clean vapour before it can be compressed. This is especially important for high-temperature refineries which will source a sizeable portion of their vapour from the digestion blow off.

The Calcination retrofit demonstration is scheduled last in anticipation of alternative zero/low carbon calcination technologies which could significantly change calcination MVR requirements.

12.1.1 Next Stage Development Costs

Development costs for the next stage are significant. Approximately $170 M (AACE Class 5, December 2021) would be required to conduct a precipitation compressor train demonstration.

12.1.2 Development Partnerships

A full-sized demonstration project is a significant investment and carries an elevated level of technical uncertainty relative to other projects of its size. Government support or co-investment may be required. A good example of this is the ELYSIS carbon free smelting process developed under a partnership between Alcoa Corp., Rio Tinto, Apple and the Canadian and Quebec Governments.

In Australia, potential partners are Australian alumina producers, compressor vendors and Government.

13 Conclusions and Recommendations

MVR appears to be the lowest cost method to rapidly decarbonise the Bayer process in the alumina industry. Its inherent efficiency, by capturing waste heat and compressing it to a useful pressure, minimises the external infrastructure required to generate process heat from renewable resources. The compressor systems require about one third the renewable power of direct electrification using electric boilers, and about one quarter the renewable power of hydrogen.

For a low-temperature refinery, the capital cost of MVR is $220 per annual tonne of alumina production. For a high-temperature refinery the cost is $260 per annual tonne. To implement MVR across Australia's six alumina refineries (approximately 21 Mtpa alumina production capacity), an overall investment of approximately $4.5 B is required, together with provision of 1.2 GW of firmed renewable power. This would reduce alumina industry emissions by approximately 10 Mt CO_2-e per annum.

This cost of abatement is already within the realm of recent carbon pricing in the European market, and the Australian carbon and power markets are anticipated to evolve such that MVR is economic to retrofit in the medium term.

Although MVR is proven in other industries, particularly on single-stage evaporators, their utility has not yet been proven for alumina refinery duty. This requires a 60:1 compression ratio for low-temperature refineries, and much more for high-temperature refineries.

A fast-tracked technology development plan to prove MVR to the point of commercialisation in alumina refineries, excluding calcination, would cost in the order of $220 M to implement. If successful, it would enable adoption of MVR by Australian alumina refineries from 2030. This proposed development timeline approximately modelled on the 1.5°C decarbonisation scenario proposed by the International Aluminium Institute.

A full-sized demonstration project is a significant investment and carries an elevated level of technical uncertainty relative to other projects of its size. Government support or co-investment may be required.

14 Glossary

AACE	AACE International, the Association for the Advancement of Cost Engineering
AAC	Australian Aluminium Council
ACCU	Australian Carbon Credit Unit
AEMO	Australian Energy Market Operator
ARENA	Australian Renewable Energy Agency
ASI	Aluminium Stewardship Initiative
BO	Blow Off
CMD	Contracted Maximum Demand
CFT	Condensate Flash Tank
CO_2-e	Carbon Dioxide Equivalents
CRC	Cooperative Research Centres
DCS	Distributed Control System
Delta T	Change in vapour condensing temperature due to pressure change
DOL	Direct Online
ESS	Essential System Services
FFE	Falling Film Evaporation
FT	Flash Tank
GHG	Green House Gas
GT-HRSG	Gas Turbine + Heat Recovery Steam Generator
HTR	Heater
HTR SPARE	Spare Heater
IGV	Inlet Guide Vane
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LCAP	Low Carbon Aluminium
LGC	Large Scale Generation Certificate
LS	Live Steam
MEB	Mass and Energy Balance

MVR	Mechanical Vapour Recompression
NEM	National Electricity Market
NPV	Net Present Value
P&ID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
PFD	Process Flow Diagram
QAL	Queensland Alumina Limited
SBTi	Science Based Targets initiative
SGA	Smelter Grade Alumina
SWIS	South-West Interconnected System
TCFD	Task Force on Climate Related Financial Disclosures
TRL	Technology Readiness Level
VOC	Volatile Organic Compound
WOSP	Whole of System Plan

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