Decarbonisation of the Bayer Process – A Technical Assessment of Enabling Technologies and Process Economics

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https://doi.org/10.71659/icsoba2024-aa001

Abstract

This paper reviews the scale and nature of the decarbonisation challenge faced by the alumina refining industry globally and provides a technical assessment of potential retrofit pathways to reduce carbon emissions associated with the Bayer process. Three aspects of this challenge are considered. Firstly, the energy footprint of the industry is considered both from a global perspective, as well as detailed mapping of the energy flow through the Bayer process to highlight key areas of energy consumption and waste. Secondly, emerging and established technologies are investigated that have the potential to support decarbonisation through process electrification, low-grade energy recovery, and the reduction/elimination of cooling water requirements. Methods are proposed for the recovery and reuse of each low-grade energy loss from the process. A refinery-wide retrofit case study is then detailed, which applies a selection of these methods to eliminate the requirement for boiler generated steam during normal operation. The resulting Bayer energy footprint, CO_2 abatement achieved, economics, practical considerations, and challenges are discussed. Lastly, technologies are reviewed that have the potential to eliminate the residual fossil fuel requirement including green calcination, electrified steam generation, and on-site thermal energy storage.

Keywords: Decarbonisation, Electrification, Thermal energy storage, MVR, Heat pumps.

1. Introduction

Since the Paris Agreement on climate change came into effect on November 4, 2016, governments and industries around the world are committing to reducing their emissions and setting net zero targets. While these targets demonstrate commitment towards decarbonisation, the required engineering and technological solutions necessary to achieve these targets represent an immense challenge for the entire alumina industry. Further, there is a general lack of technically mature or commercially viable solutions and, as such, alumina refining is designated as a ‘hard-to-abate’ industry.

This paper aims to provide a comprehensive technical overview of the scale and nature of the challenge, the various approaches that show promise in enabling step reductions in Bayer energy consumption, and the technologies that may enable full transition to renewable energy sources.

With an initial objective to reduce net energy input into the process, a detailed mapping of energy flow through the Bayer flowsheet is presented, and the sources of significant energy losses are identified. Technology configurations are then proposed for the recovery of each of these low-grade energy sources into usable steam for process heating. For each technology configuration, a conceptual flowsheet is presented and major design constraints, engineering challenges, and practical considerations are discussed. Indicative capital costs are presented per application, and a refinery-wide retrofit approach is then proposed such that the need for continual boiler generated steam is eliminated. Methods for non-fossil fuelled steam generation are considered, along with

potential alternatives. Finally, initiatives focused on the development of green calcination technologies are discussed.

2. Industry Overview

In 2021 the global alumina refining industry produced 130 million tonnes of metallurgical (smelter) grade alumina, consuming approximately 1 300 petajoules (1 PJ = 10^{15} J) as direct process energy input (Figure 1) at an average specific energy of ~10 gigajoules per tonne alumina produced [8, 10].

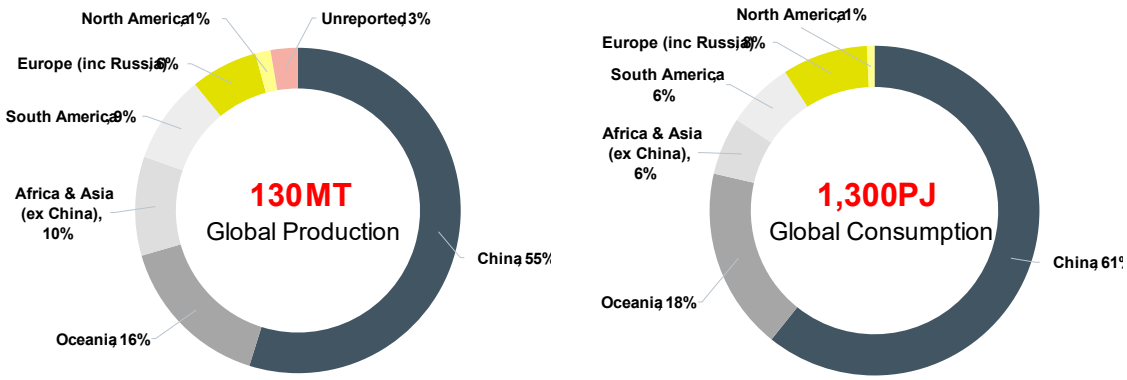


Figure 1. Global alumina production and energy consumption [8, 10].

To put the alumina industry's global energy requirement into context, if supplied as 100 % electrical energy it would exceed the total electrical generation capacity of most developed countries, placing it between Iran (11th largest at 1 288 PJ) and France (10th largest at 1 970 PJ) [5]. Hence, as illustrated in Figure 2, the energy footprint of the alumina refining industry is comparable to that of the total electrical generation capacity of a large country, albeit distributed globally.

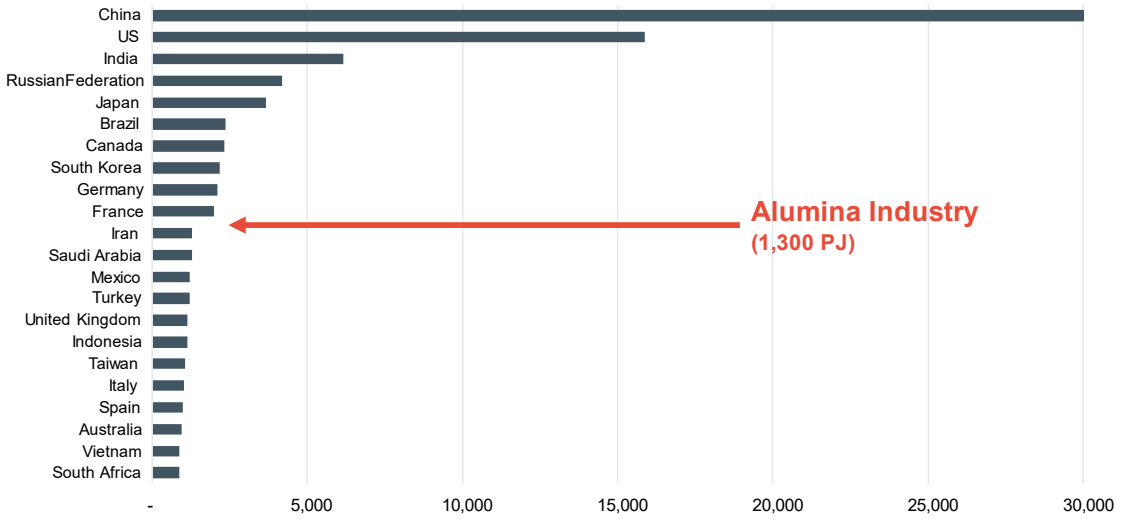


Figure 2. Electricity generation by country [5].

Over the past two decades global metallurgical alumina production has increased nearly 250 %, increasing the global energy footprint significantly. However, within this timeframe the average specific refining energy, and hence specific carbon emission, has reduced by approximately 30 % [1]. This has been achieved, in part, through efficiency improvements resulting in highly optimised core flowsheets. While further step-reductions in specific energy consumption are thus

expected to be complex or costly, they are necessary to enable decarbonisation through fuel switching away from fossil fuels.

The placement of alumina refineries is typically dictated by logistical considerations such as the location of the bauxite reserves. As such, there is a reliance upon fossil fuels to power the refineries with renewable energy making up a negligible proportion of the global alumina refining energy consumption. A breakdown of the energy supply mix for the alumina refining industry is shown in Figure 3, where it is noted that coal is the primary energy source.

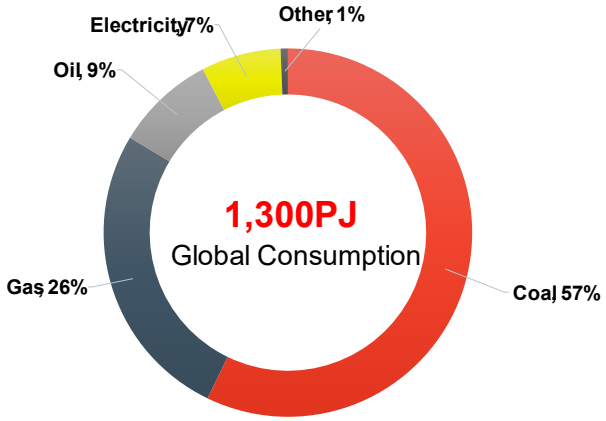


Figure 3. Global alumina refining energy supply mix [10].

3. Bayer Process Energy Mapping

Figure 4 illustrates the industry average specific energy usage (GJ/t alumina), broken down into the necessary energy input forms.

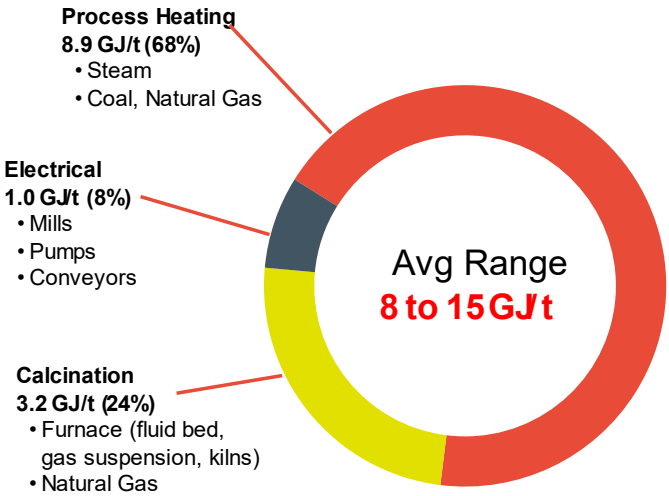


Figure 4. Specific energy requirement and form, global average [9].

A breakdown of the energy pathways through a typical alumina refinery are outlined as follows:

- **Process Heating** of key refinery facilities including digestion, pre-desilication, and liquor evaporation. Heat is supplied primarily via steam raised from coal or natural gas fired boilers. Low temperature digestion notionally operates at 150 °C via indirect heating with live steam, and most of this energy is recovered and retained within the digestion facility via recuperative liquor heating. A portion of this energy is consumed via the endothermic

gibbsite dissolution reaction, and the digestion product slurry leaves the facility at its atmospheric boiling point (~108 °C). Ultimately, this energy input for process heating exits the process to the environment via cooling utilities. Inevitably, a portion of this energy is also lost to the environment via heat loss and/or atmospheric vapour venting.

- **Calcination** of alumina hydrate, to form product alumina, typically takes place at ~1 100 °C via direct firing using natural gas. Modern calciner technologies are capable of recuperating large portions of energy via counter-current solid-gas contacting. While the resulting exhaust gases are relatively cool (< 200 °C), significant energy is lost to the environment due to the large (~50 %) water vapour component of the exhaust. Other minor energy outflows occur via environmental heat loss and alumina product cooling.

- **Electrical Energy** input into the process is, historically, limited to use in electrical drives such as mills, conveyors, agitators, and pumps.

3.1 Bayer Process Decarbonisation

A key enabler for industry decarbonisation is process electrification. As highlighted by Figure 4, this presents a significant challenge for the alumina industry. Not only must the industry transition energy sources away from fossil fuel, but it must also undergo a significant technology transition. That is, significant technology development and retrofit is required to enable electrification of conventional process heating and calcination methods.

Figure 5 details the energy flow through the Bayer process for a typical Gibbsitic low temperature flowsheet operating with a first-quartile level of energy efficiency. High temperature boehmitic/diasporic flowsheets encounter additional challenges due to more arduous heating requirements and are not considered within this paper.

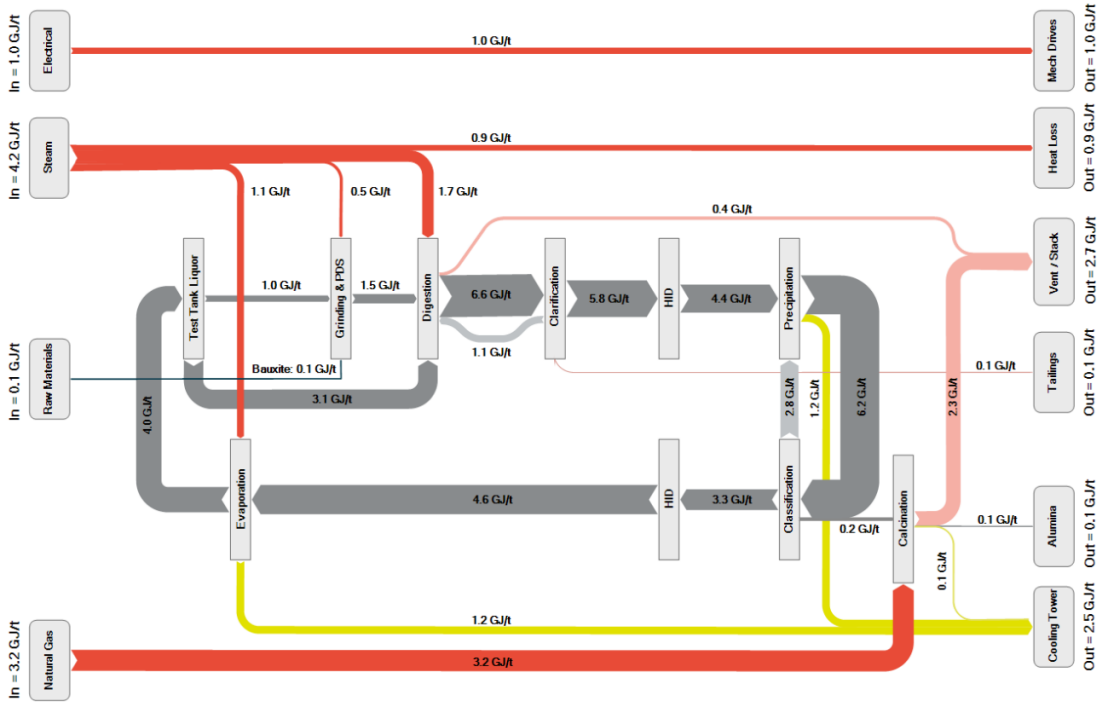


Figure 5. Bayer process energy map [1]. Note: imbalances due to omission of minor streams, steam input energy excludes boiler losses (approximately an additional 20 % of the stated steam input energy).

The right-hand side of Figure 5 highlights the significant extent of energy lost to the environment. More than 50 % of the energy added to the process is lost through low-grade vapour venting or evaporation in cooling towers or ponds. As such, even a refinery with industry-leading energy efficiency through careful thermal design will still suffer from significant energy wastage to the environment. To address the decarbonisation challenge and reduce the input energy required, it is thus vital that energy losses to the environment are minimised through recovery and reuse.

4. Recovery of Low-Grade Waste Energy

The initial objective of this paper is to eliminate energy losses through the recovery and reuse of the waste energy sources highlighted in Figure 5. In turn, this will reduce the scale of electrified steam generation and green energy requirement, hence reducing the total cost of decarbonisation. The remaining (reduced) fossil fuelled process energy requirement may then be substituted with electrified methods.

4.1 Enabling Technologies

Heat pumps are devices that can move heat energy from a low temperature source to a high temperature sink. This technology encompasses closed cycle refrigerant based systems, or open-cycle mechanical vapour recompression (MVR). Numerous forms of heat pump technology are already well established and proven in other industries with Technology Readiness Levels (TRL) often at an 8 or 9 (note: per the U.S. Department of Energy, a TRL of 8 or 9 implies that an actual system has been demonstrated and/or operated over the full range of expected conditions). For the alumina refining industry however, there are multiple integration challenges that must be overcome. For example, for an open cycle MVR application these challenges may include variability in tie-in process conditions, contamination/fouling, arduous heat sink requirements, demands of high operating factors, and the sheer scale of application.

In the context of heat recovery, heat pumps may be applied to act as the cold utility in place of cooling towers or evaporative ponds etc. (Section 4.1.1) or boost low-grade vapour sources to a usable saturation temperature (Section 4.1.2). Thus, heat pumps enable capture and conversion of previously unusable low-grade energy sources into an energy state that can offset energy supply into the process.

Heat pumps require an energy input, often in the form of mechanical/shaft work via electric drives. The ratio of usable product energy to the electrical energy input (Coefficient of Performance, COP) is largely dependent on, and inverse to, the extent of temperature rise required. As an example, for a typical heat pump system with a COP of 3.0 implies that for each unit of electrical energy input to the heat pump, 3 units of usable energy are produced. This may be contrasted against electric boilers that have a COP of approximately 1.0, meaning that three times more electrical energy input is required to produce the same output energy compared to the heat pump solution.

4.1.1 Closed-Cycle High Temperature Heat Pumps

Closed-cycle high temperature heat pumps are electrically driven heat pumps that can deliver temperatures of over 100 °C using a refrigerant or working fluid in a single, multi, or cascade cycle configuration.

Fundamental to assessing the suitability of a closed-cycle high temperature heat pump is the selection of the working fluid appropriate for the application. A variety of working fluids are available, with selection dependent on the temperature range of the heat source and heat sink. For an application seeking to replace a cooling tower or evaporative pond, the heat source will operate

(typically) between 30 to 60 °C. Within this temperature range, commercially available closed-cycle high temperature heat pumps of suitable scale (> 40 MW heating capacity) and TRL 8–9 typically use CO_2, ammonia, or synthetic refrigerants as the working fluid [4]. However, these systems currently have a typical maximum heating temperature of 110–120 °C, while viable heat sinks within the Bayer process require temperatures up to and including live steam conditions (165 to 175 °C or higher).

As this technology is rapidly advancing, hydrocarbon-based refrigerant systems are emerging at scale, and promise to provide a wider working temperature range, with capability to deliver to higher hot-end temperatures.

Figure 6 summarises the working temperature range of various natural, hydrocarbon, and HydroFluoroOlefin (HFO) based working fluids against the required operating temperature range of the applications considered within this paper (shaded in grey). Compatible working fluids are indicated in red.

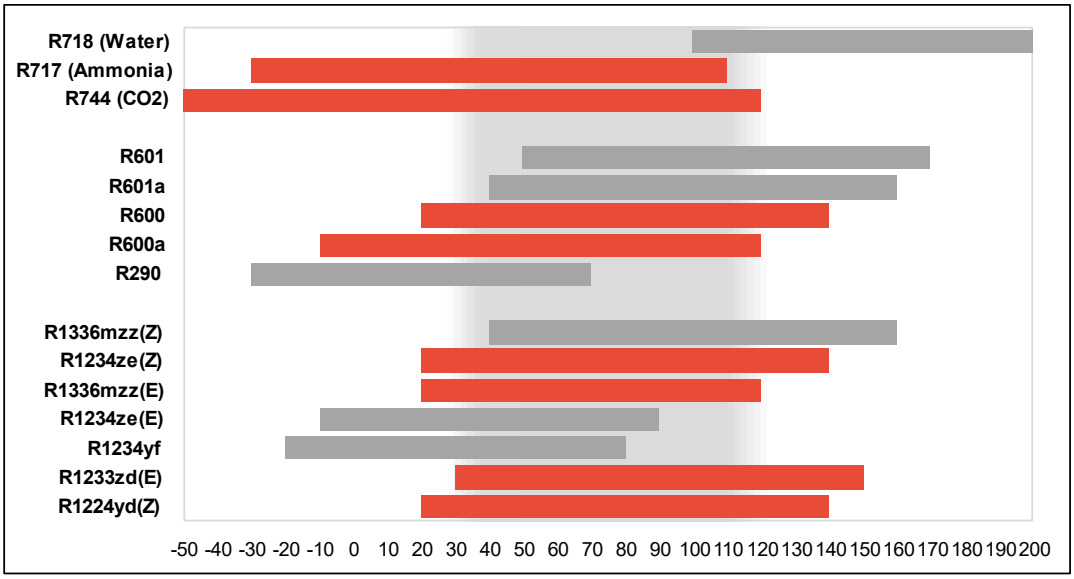


Figure 6. Temperature applications for different closed cycle working fluids [4].

4.1.2 Mechanical Vapour Recompression

Mechanical vapour recompression (MVR) utilises fans or compressors to boost the saturation conditions of vapour (steam) for reuse. Multiple fans or compression stages may be used in series to boost steam conditions as required. Figure 7 provides an example energy balance around an MVR system. Here, 1 MW of waste blow-off tank vapour at atmospheric conditions is compressed via 7 or 8 MVR stages to generate 800 kPa (abs) saturated steam. Approximately 0.2MW electrical energy is required, with ~80% of this converted into steam enthalpy. Desuperheating (via water/condensate sprays) is necessary between MVR stages and provides a minor energy addition to the system. The resulting steam is produced at a COP of ~6, implying that this method utilising low-grade waste vapour produces usable 800 kPa (abs) steam at $1/6^{th}$ the energy of an electric boiler.

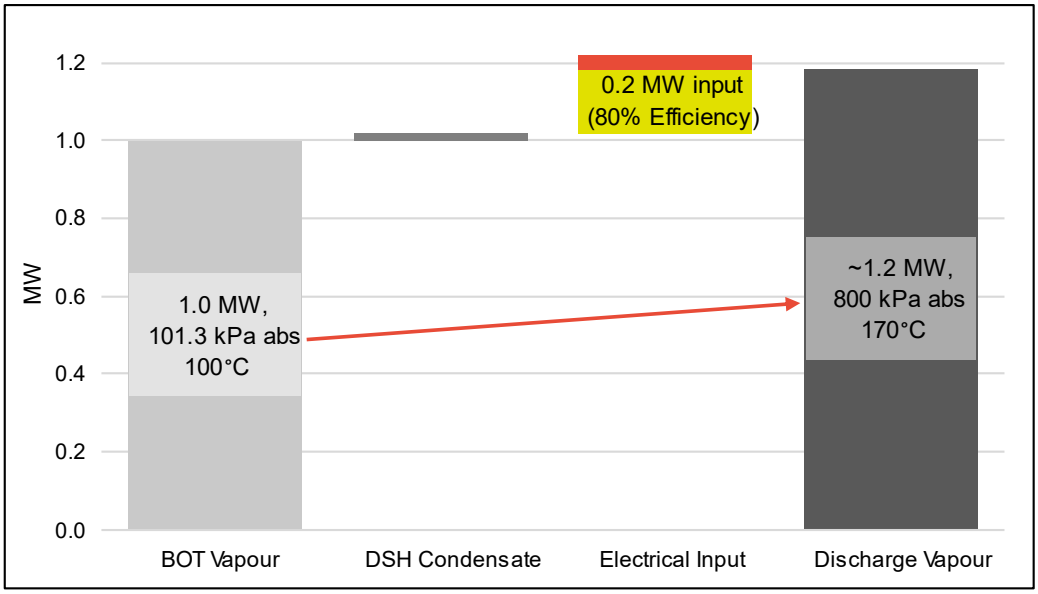


Figure 7. MVR energy balance, 1 MW blow-off feed to 800 kPa (abs) steam.

Dependant on the application and duty, either low-speed fans (Section 4.1.2.1), high-speed compressors (Section 4.1.2.2), or a combination of both may be utilised.

4.1.2.1 Low Speed MVR Fans

Low speed MVR is a mature technology that is very well established across multiple industries as a stand-alone configuration, or as part of a unit operation such as an evaporator or crystalliser. It is well suited to lower grade vapour sources, particularly where large volumetric flow rates are required, and may be applied from vacuum conditions, up to ~1 000 kPa or beyond depending on vendor capability.

As a general guide, each low-speed MVR fan stage is capable of a maximum lift of ~10 °C in saturation temperature, or up to a 1.5 compression ratio. Reference installations exist with up to 10 stages operating in series; however, overall system efficiencies and COPs drop as stage numbers increase.

Practical constraints exist when applying MVR to vacuum vapour systems as volumetric flows and vapour duct sizing may become impractically large. In addition, a large number of MVR stages may be required simply to boost the vapour from vacuum to positive pressure. Brown-fields applications may also encounter real estate constraints that prohibit co-location nearby the vapour source.

4.1.2.2 High-Speed Compressors

High-speed compressors are well established in gas compression applications within the oil and gas industry. Each compression unit may comprise a single compression stage, or a series of compression stages driven off a common shaft and drive. Each high-speed compression stage is capable of a 20–25 °C lift in saturation temperature or a compression ratio of 2–3, approximately twice that of low-speed MVR fans. In addition, pressures exceeding 3 000 kPa may be achievable.

High speed compressors are typically more capital intensive than low-speed MVR fans and are less suited to large volumetric flow or vacuum applications. They are also less forgiving of feed

vapour droplets or contamination. However, they enable far higher discharge pressures while comprising a smaller footprint than an equivalent multi-stage low speed fan installation.

4.2 Application to the Bayer Process

Based on the energy balance presented in Figure 5, low-grade energy recovery technology configurations have been considered for the study that combine closed-cycle heat pumps (where needed) with multi-stage low-speed MVR fans. All recovered waste energy is assumed to be upgraded to saturated 800 kPa (abs) steam. There may be lower-grade energy sinks within the Bayer process, such as pre-desilication or wash water heating; however, these opportunities need to be identified and assessed on a case-by-case basis.

Closed-cycle heat pumps have been modelled based on reference COPs for installations with similar temperature lift duties [4]. CO_2 or ammonia-based systems have been assumed, capped at a maximum delivery temperature of 110 °C. Multi-stage MVR systems have been configured based on reference Hatch and vendor data, ensuring system duties and capacities are within equipment physical and practical limitations.

Multiple system configurations were considered for each low-grade energy recovery application. The systems adopted below provide technically feasible solutions that minimise intrusive process alterations and provide flexibility in the location and layout of key equipment. Non-intrusive tie-in locations have been selected to avoid impact to the process or the need for replacement of existing process equipment. For example, direct substitution of cooling towers with heat pumps rather than reconfiguration of the process cooling tie-in and equipment to allow for a more effective overall system design.

4.2.1 Digestion Blow-off Vapour Recovery

Some refineries vent excess digestion energy to the atmosphere via a digestion blow-off tank in the form of atmospheric flash vapour at a slight superheat. This presents an opportunity for energy recovery as the digestion blow-off vapour can be captured, cleaned, and recompressed to a usable pressure/saturation temperature.

The generation of blow-off tank vapour is dependent on refinery design and energy balance. Typically, the blow-off tank is operated at atmospheric pressure, with the quantity of liberated vapour being dependent on the capacity and condition of the recuperative digestion liquor heating system and the liquor to digestion (LTD) temperature. For a green-field alumina refinery, the elimination of blow-off tank vapour generation should be prioritised through sound thermal design. However, for a brown-field retrofit application, where the refinery produces excess blow-off tank vapour, the recompression method considered below is an effective means of energy recovery. Recompression and thus recovery of this low-grade vapour may be accomplished via MVR (low speed fans or high-speed compressors).

The proposed energy recovery system is a multi-stage low-speed MVR application to produce 800 kPa (abs) steam. A vapour cleaning method will be required to remove contamination and prevent damage to the MVR equipment.

A schematic of the proposed system is shown in Figure 8, with the relevant KPIs shown in Table 1.

Table 1. Digestion blow-off vapour recovery KPI's.

Parameter	Unit	Value
Inlet Pressure	kPa (abs)	101.3
Regen Steam Pressure	kPa (abs)	800
Regen Steam Energy	GJ/t	0.5
Total Electrical Input	GJ/t	0.1
MVR Stages	-	7
MVR Overall Efficiency	%	~80
System COP	-	6.3

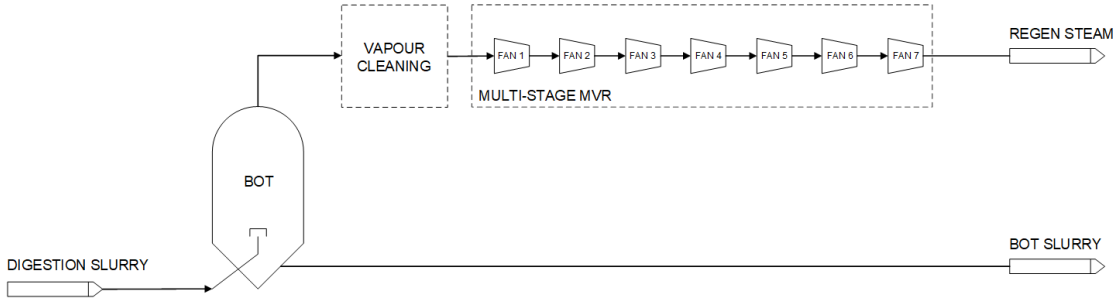


Figure 8. Blow-off energy recovery through MVR.

It should be noted that a level of vapour contamination is to be expected during normal and upset conditions due to entrainment of caustic liquor droplets and/or slurry particulates. This contamination leads to fouling of vapour ducting and any downstream equipment and must be addressed in order to reliably recover and reuse this vapour source. Hence, technology selection must consider feed vapour quality limits, the presence of non-condensable gases, final steam pressure requirements, turndown, and system efficiency to name a few.

4.2.2 Evaporation Barometric Cooling

Conventional multi-effect flash evaporators utilise a barometric or surface condenser at the cold end of the flash train to condense the low-grade vapour from the barometric flash tank. The quantity of vapour liberated is dependent upon the cold-end (barometric) evaporative temperature, which is typically in the range of 60 to 70 °C. Cooling water, as the heat sink, is controlled through the condenser to achieve the required low-end temperature. The low-grade energy is then ultimately rejected to the environment.

The application of heat pumps to recover this low-grade energy from the cooling water is evaluated. In this configuration, closed-cycle heat pumps replace the duty of the cooling tower or evaporative pond, effectively acting as a cold utility. Process condensate may be used as a heat sink for the recovered (and upgraded) energy delivered by the heat pump to produce vapour before recompression to the required pressure via low-speed MVR. This configuration is shown in Figure 9. A centralised heat pump system may be implemented that combines multiple cooling duties, thus alleviating space constraints adjacent to the evaporation unit. The evaluated flowsheet utilises a closed-loop heat pump and 7 low-speed MVR fans to recover and produce steam at 800 kPa (abs). A schematic of this configuration is shown in Figure 9, with the relevant KPIs shown in Table 2.

Table 2. Evaporation energy recovery KPIs.

Parameter	Unit	Value
Regen Steam Pressure	kPa (abs)	800
Regen Steam Energy	GJ/t	2.4
Total Electrical Input	GJ/t	1.0
Heat Pump Overall Efficiency	%	~95
MVR Stages	-	7
MVR Overall Efficiency	%	~80
System COP	-	2.5

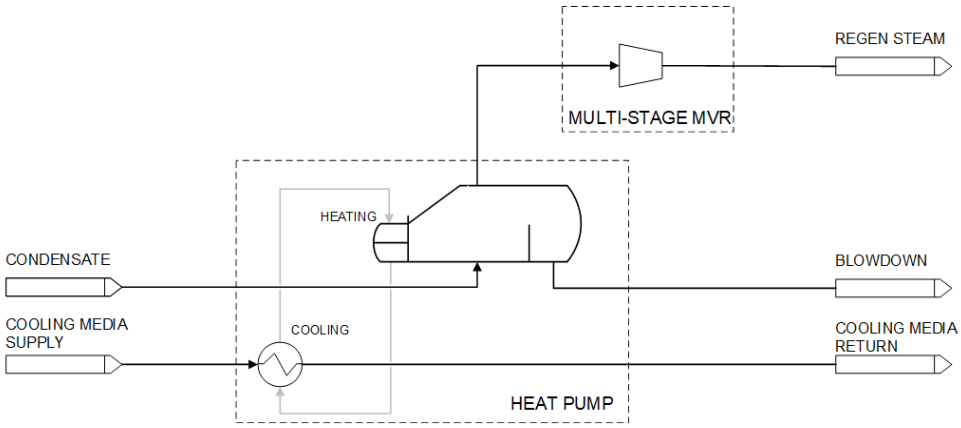


Figure 9. Evaporation energy recovery through heat pump and MVR.

Unlike digestion blow-off vapour, the low-grade vapour out of the evaporation barometric flash tank is under vacuum conditions due to its low temperature. The direct application of MVR to recover this low-grade vapour may only be viable with significant reconfiguration of the evaporation unit. In addition, there may be space constraints with regards to co-locating the large ducting and multi-stage MVR system required.

In a green-field alumina refinery, consideration should be given to replacing the conventional multi-effect evaporator with falling film or forced-circulation MVR evaporators, as these technologies are largely electrically driven and produce minimal waste energy.

4.2.3 Precipitation Inter-Stage Cooling

A significant portion of energy leaves the Bayer circuit in precipitation through inter-stage cooling. As the liquor is cooled and the exothermic precipitation process occurs, the hydrate slurry temperature is controlled to maintain the supersaturation profile across the precipitation train. The cooling media is typically cooling water, which is returned to cooling towers or evaporative ponds where the majority of this energy is lost to the environment.

System configurations have been explored utilising a heat pump and low-speed MVR to recover this energy from the cooling media to produce 800 kPa (abs) steam. This configuration is similar to that shown in Figure 9, with either a centralised or distributed heat pump installation adopted. The relevant KPIs for the precipitation inter-stage cooling recovery are shown in Table 3.

Table 3. Precipitation energy recovery KPIs.

Parameter	Unit	Value
Regen Steam Pressure	kPa (abs)	800
Regen Steam Energy	GJ/t	2.6
Total Electrical Input	GJ/t	1.0
Heat Pump Overall Efficiency	%	~95
MVR Stages	-	7
MVR Overall Efficiency	%	~80
System COP	-	2.5

Due to the large residence time and sensitivity of the precipitation circuit, it is crucial to ensure that the temperature profile across the circuit remains relatively constant. Disruption to this temperature profile has the potential to cause alumina quality issues and/or upset the generation of fine and coarse seed. Therefore, consideration into both the planned and unplanned downtime of the heat pump and MVR system must be made to ensure that these risks are controlled.

4.2.4 Calcination Alumina Product Cooling

Calcination is the single most energy intensive process unit operation within a typical alumina refinery. As such, there is opportunity to recover significant quantities of low-grade energy via the flue gas and alumina product cooler.

The alumina product cooler reduces the product temperature by ~200 °C, to 75 °C via the use of cooling water. A modern calciner may use a fluid bed cooler, with cooling water used as the cooling medium and energy rejected to the environment via cooling towers or evaporative ponds. However, this low-grade energy source is relatively small compared to the other sources available, and recovery may only be viable if included as part of a multi-service centralised heat pump system.
A vacuum flash / MVR system was assessed and deemed not suitable due to the required vacuum conditions. Flash cooling at deep vacuum has practical limitations when coupled with MVR and cannot be overcome without increasing the alumina product temperature target.

The proposed configuration is as per Figure 9, and the application KPIs are shown in Table 4. It is proposed that this application forms part of a centralised heat pump system that may be implemented across a combination of cooling water services.

Table 4. Alumina product energy recovery KPIs.

Parameter	Unit	Value
Regen Steam Pressure	kPa (abs)	800
Regen Steam Energy	GJ/t	0.25
Total Electrical Input	GJ/t	0.1
Heat Pump Overall Efficiency	%	~95
MVR Stages	-	7
MVR Overall Efficiency	%	~80
System COP	-	2.9

4.2.5 Calcination Stack Gas Energy Recovery

Stack gases from a modern calciner represent a large portion of low-grade energy loss vented to the atmosphere (~2.3 GJ/t). For a natural gas fired calciner, the stack gas consists of ~50 % water vapour, with the remainder being air and combustion byproducts. Approximately 70 % of the stack gas energy is associated with the latent heat of water vapour at ~1.6 GJ/t.

Multiple approaches have been investigated or implemented to recover this lost energy [12]; however, only a few of these have been capable of recovering both the sensible heat of the stack gas as well as the latent heat of water vaporisation. This is because the partial pressure of water vapour within this stack gas is ~50 kPa (abs), with a corresponding saturation temperature of approximately 80 °C. Hence, recovery techniques either require low temperature heat sinks or application of a heat pump to boost the recovered energy to a usable temperature.

This study assessed multiple alternative applications utilising both closed-cycle heat pumps and MVR, along with various methods of tie-in to the stack gas source capable of recovering between 60 % and 80 % of the total stack gas energy; however, the greater the energy recovery the lower the COP and the higher the technical risk.

The proposed configuration utilises a direct contact spray tower to cool and condense the stack gas, followed by a vacuum flash system and compression of the resultant low-pressure flash vapour to 800 kPa (abs) via MVR.

Technical risks exist, such as the management of sulphur/acid condensation and alumina fines associated with calciner stack gas. In addition, the buoyancy and resultant dispersion of the cooled stack gas must be addressed within the design. The selected configuration also presents risk and complexity in the operation of a vacuum flash system down to ~30 kPa (abs), coupled with the significant compression ratio required to reach 800 kPa (abs) resultant steam pressure. Compression ratios of this magnitude push the limit of what has been commercially deployed and proven. The proposed schematic is shown in Figure 10, with the application KPIs shown in Table 5.

Table 5. Calcination stack gas energy recovery KPIs.

Parameter	Unit	Value
Steam Product Pressure	kPa (abs)	800
Steam Product Energy	GJ/t	2.3
Total Electrical Input	GJ/t	0.5
MVR Stages	-	11
MVR Overall Efficiency	%	~80
System COP	-	4.3

Section 5.3 will outline ongoing development projects for electric and hydrogen calcination technologies. In both cases a near pure water vapour off gas will be produced. This will be highly advantageous to energy recovery as it may lend itself to direct vapour recompression into live steam. Alternatively, the near pure water vapour content will allow for steam condensation at higher temperatures. This may enable simpler and more efficient methods for energy recovery via indirect heat transfer such as reboilers (if required).

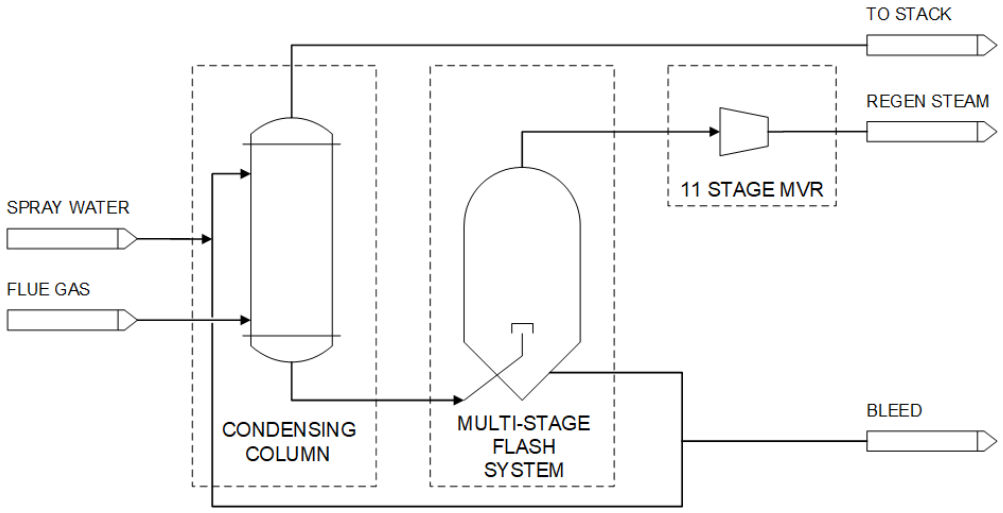


Figure 10. Flue gas energy recovery through MVR.

4.3 Application CAPEX Comparison

Economic analysis has been completed with a focus on capital cost (CAPEX) comparison only. Operating costs and NPV analyses have not been performed as they are highly variable and region specific due to the cost and availability of renewable energy supply and local carbon pricing.

Figure 11 provides indicative cost comparison of the low-grade energy recovery applications, showing the low-end recovery temperature and indicative CAPEX per $MW_{delivered}$ to recover each into 800 kPa (abs) steam. Bubble size represents the relative quantity (MW) of delivered energy, and bubble colour distinguishes technology pathways per low-grade source (closed-cycle heat pump + MVR indicated in yellow, and MVR-only indicated in grey). Note: “delivered energy” is the energy supplied back to the process as 800 kPa (abs) steam, and comprises recovered low-grade energy, electrical input to the system as shaft power, and any condensate supply used to generate steam.

Cost information has been compiled based on major equipment costs from a variety of public domain, vendor, and Hatch database sources, with lang factors applied to determine total indicative installed costs. These costs are for the core facilities only, with minimal or no sparing of major equipment. No provision has been included for power transmission infrastructure upgrades etc. A comparative cost for renewable energy installation has also been included, sourced from public domain publications for Australian energy supply costing [6].

Exchange rates of 0.65 USD/AUD and 1.10 USD/EUR were used for present-day currency conversions, and appropriate exchange rates were used for historical vendor pricing.

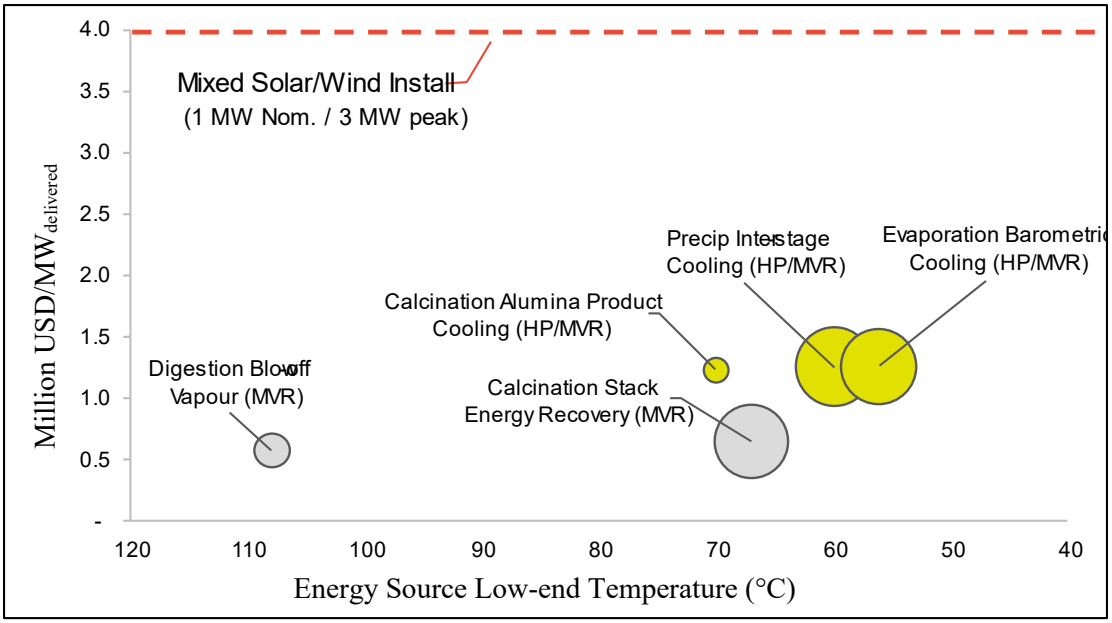


Figure 11. Indicative installed capital cost comparison of low-grade energy recovery.

Figure 11 illustrates the following key observations:

1. Based on these indicative costs, all low-grade energy sources appear recoverable at a much lower specific CAPEX than the installation of an equivalent renewable energy resource. Hence it is far more economical, albeit costly, to utilise waste energy sources rather than replace the lost energy.
2. Intuitively, the lower the temperature of the energy source, the more expensive it is to recover into a usable form. For non-vapour energy sources < 70 °C, a 2-stage heat pump system has been applied (closed-cycle, followed by open loop MVR). This results in a step-change in specific CAPEX, as seen with the cooling water applications.
3. While not shown in Figure 11, for the same given target conditions, COP generally decreases as the source temperature decreases. This implies that energy input (hence, OPEX) increases as source temperatures decrease.
4. Digestion blow-off vapour recovery provides the highest thermal performance, with a COP of 6.3. It is also the cheapest application in terms of CAPEX per $MW_{delivered}$. While it only provides a small portion of the overall refinery steam energy demand (~10 %), it is a relatively low CAPEX and low OPEX application that should be prioritised for refineries with excessive blow-off vapour.
5. Calcination stack energy recovery provides a significant proportion of the overall refinery steam energy demand while also being the second lowest option in terms of CAPEX per $MW_{delivered}$. It has the second-best thermal performance with a COP of 4.3, making it an attractive application.
6. While electric boilers have a relatively low direct CAPEX, they operate at a COP of ~1.0 meaning that they require 3 to 6 times the electrical energy input compared to that of the low-grade energy recovery options proposed above. This inherently results in a far higher OPEX due to the relative cost and consumption of electrical energy.

4.4 Refinery Retrofit Case Study

Implementation of all low-grade energy recovery opportunities discussed in Section 4.2 would provide over 180 % of the total steam demand of the refinery. Various combinations of the opportunities were considered and assessed against overall CAPEX, COP, complexity, and

technical risk. A target of 110 % steam demand was selected to provide slight design margin for process variability and catch-up.

Refinery-wide retrofit pathways sized for 110% steam demand ranged in cost between 130 and 180 USD per tonne/annum refinery capacity for this Gibbsitic low temperature flowsheet. These costs were in reasonable alignment with findings of a similar case study [11], which assessed application of MVR-only configurations to most of the low-grade energy sources considered within Section 4.2.

Based on the selection criteria mentioned above, the retrofit pathway selected for this case study includes the following three applications:

- Digestion blow-off vapour recovery,
- Calcination stack gas energy recovery, and
- Evaporation barometric cooling.

This pathway in its entirety would provide 125 % of the refinery steam energy demand at a COP of 3.4. Accordingly, only a portion of the evaporation barometric cooling (having the lowest COP) would be recovered to meet the target capacity of 110 % steam energy demand, resulting in an indicative retrofit pathway cost of 130 USD per tonne/annum refinery capacity.

Figure 12 illustrates the energy flow through the refinery with the above retrofit pathway implemented.

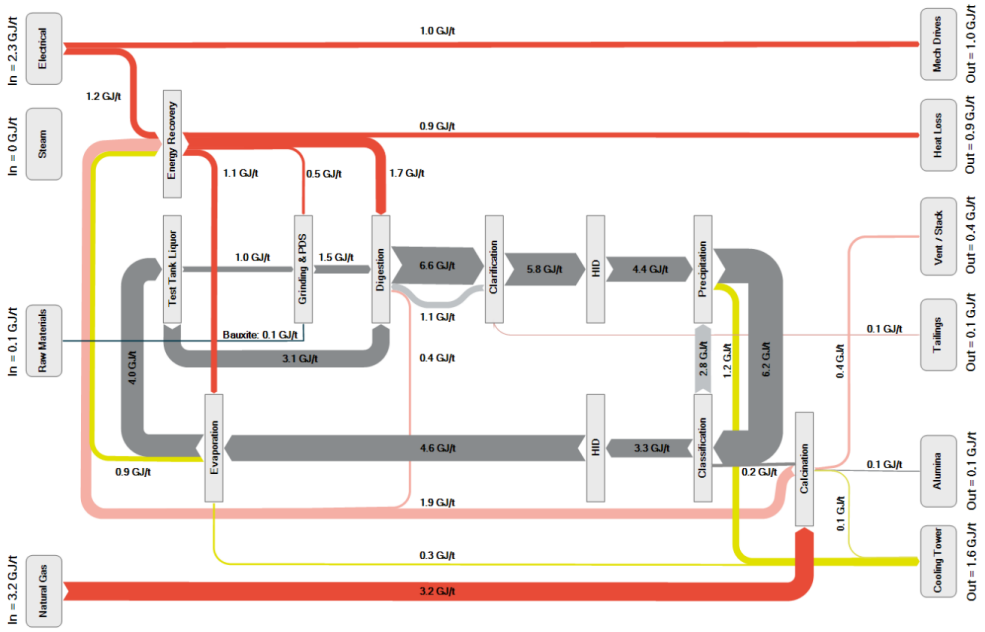


Figure 12. Bayer process energy map with low-grade energy recovery.
Note: Imbalances are due to omission of minor streams. Low grade energy recovery solutions require additional minor streams that are omitted from the diagram, including process condensate for desuperheating and steam generation.

The applicable low-grade energy outflows now report to the distributed "Energy Recovery" facilities for upgrading back into live steam. Note: each recovery option is treated individually, rather than an integrated system; there are opportunities to integrate the systems as a complete unit in order to reduce capital cost. In total, approximately 60 % of the recoverable Bayer waste energy has been captured and upgraded to usable live steam. An opportunity remains for the capture and reuse of the surplus 40% energy losses, potentially via thermal energy sales to offsite

customers, or electricity sales via alternative heat-to-power technologies such as the Organic Rankine Cycle.

This retrofit provides a potential annual carbon abatement of ~0.63 t CO_2-e per tonne/annum refinery capacity for a coal fired boiler, or ~0.30 t CO_2-e per tonne/annum refinery capacity for a natural gas / gas turbine fired boiler. This represents ~70 % of a typical Australian refinery's scope 1 emissions [11]. For the indicative retrofit capital cost of 130 USD per tonne/annum refinery capacity, this translates to an approximate abatement capital cost range of 210 to 420 USD per tonne CO_2-e abated annually. Note: this is based on the emissions intensity range provided for the fossil-fuel based boilers; it was assumed the additional electricity demanded to enable heat recovery would be supplied by net-zero renewables. This cost is for up-front conversion capital cost only and does not consider ongoing OPEX or electricity costs.

4.4.1 Practical Considerations

The low-grade energy recovery methods discussed in the preceding sections are yet to be widely implemented within the alumina industry. Hence, several practical considerations must be overcome both at an application level, and also a refinery wide level where a number of these technologies are adopted (per Figure 12). These practical considerations are assessed on a case-by-case basis; however, key considerations are discussed at a broad level below.

4.4.1.1 Start-up

In a retrofit refinery, where most or all steam is generated via waste heat, start-up of the refinery or units/trains may be problematic while there is insufficient waste heat being produced by the process. Alternative deployable steam generation systems (e.g., gas fired package boilers, heat recovery steam generators) would still be required for these needs. In this context, backup electric boilers may appear feasible; however, it must be considered that they operate with a COP of ~1.0 versus a COP greater than 3.0 for the low-grade energy recovery solutions. This implies that 3 times the electrical supply capacity would be required for an equivalent amount of steam generated via electric boilers during this start-up period – an impractical short-term load for which to size electrical supply infrastructure on, and likely not a tolerable expectation to place on the electricity utility provider. In this context, onsite thermal energy storage finds particular relevance (Section 5.1).

In the retrofit flowsheet presented in Section 4.4, 50 % of steam generation is provided via recovery of the calciner stack energy. It may be feasible to run the calciner independently of the refinery using stockpiled hydrate to produce steam for refinery start-up. In this case, the calciner would act as a pseudo gas fired boiler.

4.4.1.2 Reliability and Redundancy

The various heat pump technologies discussed within this paper have reference installations achieving very high availability and reliability. However, numerous integration challenges are foreseen when applying to the Bayer process that may impact reliability. In the retrofit flowsheet, there is heavy reliance on the use of the calciner as a means of steam production. Hence, a trip or outage of the calciner may result in flow-on refinery trips unless alternative rapidly deployable steam generation systems are available.

In addition, refinery production becomes more intimately linked with the reliability of the electrical supply infrastructure, including the generation and transmission infrastructure that is often under the control of a 3rd party grid operator. On-site firming of electrical supply thus becomes necessary, such as on-site thermal energy storage with steam generation (Section 5.1).

4.4.1.3 Integration and Interdependence

The retrofit flowsheet not only replaces the need for steam boilers, but also replaces the need for a portion of the existing cooling systems (cooling towers or evaporative ponds). As such, failure of one of these systems represents a loss in a portion of both the refinery's hot and cold utility. The Bayer process is already a tightly coupled recirculating flowsheet, with strong interdependencies between processing facilities, unit operations, and energy sources. Further coupling of utilities will increase operational complexity and may lead to reduced refinery utilisation and production. The requirement for equipment sparing and hot-standby steam boilers or backup cooling systems must be assessed on a case-by-case basis to enable short-duration decoupling.

4.4.1.4 Location

Some low-grade energy sources, such as calciners or cooling towers, are often located long distances from major energy sinks such as digestion. In addition, brownfield retrofit applications do not have the luxury that a greenfield refinery may have to provision space for heat recovery systems adjacent to the heat source. Multi-stage MVR systems take up a reasonable amount of space and must be within close proximity to the vapour source as it is impractical to duct low-grade vapour long distances. Large scale closed-cycle heat pumps also have a reasonable footprint; however, it is far simpler to pump warm water long distances. These constraints shape the overall system design, and lead to consideration of centralised systems for energy upgrading and steam generation rather than distributed systems.

5. Energy Substitution Technologies

As discussed in Section 2, nearly all energy consumed by the Bayer process globally is produced from fossil fuel sources. This is primarily used for process heating and product calcination. As long as fossil fuels remain integral to the energy mix used by the Bayer process, full decarbonisation is not possible. Hence, even though this is not the central focus of this paper, it is important to acknowledge that the integration of energy substitution technologies will also be critical to achieve a zero emissions Bayer process.

5.1 Electric Steam Generation and Thermal Energy Storage

Electric boilers offer a viable alternative to coal and gas fired steam boilers. However, the objective throughout this paper has been to minimise the residual need for boiler generated steam through the recovery and reuse of low-grade waste energy. This has been a primary objective for the following reasons:

1. Electric boilers operate at a COP of ~1.0. Compared to the retrofit case study considered within this paper, steam generated via electric boilers would require more than 3 times the electrical input.
2. This further extends into three times additional capital requirements for renewables generation, firming, and high voltage transmission infrastructure.
3. Within Australia, electricity costs per unit may be twice that of natural gas and four times that of coal. Firmed electrical supply attracts a further premium.
4. Electric boilers are currently lacking in steam delivery pressures required to provide a practical solution for many Bayer refineries, particularly boehmite/high temperature digestion facilities.
5. Electric boilers often require extremely clean condensate. For example, some electrode style boilers rely on a stable feed water conductivity in the order of 2 µs/cm or lower. This may necessitate additional capital in water treatment facilities.

Accordingly, electric steam generation may be considered economically viable for start-up or backup scenarios only. However, as these scenarios occur infrequently it is not practical to install provision for 100% electric steam generation for sustained operation. This is particularly the case for the electrical supply infrastructure and the flow-on implications for the grid operator.

On-site thermal energy storage (TES) provides a potential solution for this backup duty. TES technologies store thermal energy in solid state mediums such as refractory, concrete, or rock, liquid state mediums such as molten salt, or phase change mediums such as metals. The TES facilities may be gradually charged over an extended timeframe utilising any available headroom in electrical supply capacity, to provide sufficient steam generation for the duration of a restart. Several in-development TES technologies are approaching a TRL of 8 or 9, and some of these technologies integrate traditional heat recovery steam generators (HRSG) that alleviate many of the limitations associated with electric boilers discussed above.

5.2 Steam Substitutes

Several potential substitutes exist to replace steam as the main heat source for digestion and evaporation. Molten salt heating, such as that utilised for digestion heating at the Aluminium Oxid Stade refinery in Germany [7], allows high digestion temperatures to be reached using fuel oil, natural gas, or electricity as a fuel source. Modern variations of this are also under assessment, including the use of molten salt heated via concentrated solar thermal. However, there is a general lack of such systems in operation at the scale required for a modern alumina refinery.

5.3 Green Calcination

Alumina calciners are direct natural gas (or fuel oil) fired furnaces that consume approximately one third of the total Bayer process energy requirement, with a large non-recovered energy loss to the environment via stack gases. Alternative technologies to eliminate the use of fossil fuels as an energy source do not currently exist on an industrial scale. Initiatives are ongoing to develop both hydrogen and electric calcination methods. Both options eliminate the need to combust fossil fuels for calcination, and both promise to produce recoverable near-pure water vapor as vent gas, which will further enable energy recovery methods similar to those described in Section 4.2.5. However, both are at the developmental stage and thus have low TRL [1].

5.3.1 Hydrogen Calcination

Hydrogen calcination involves replacing natural gas with green hydrogen and is achieved by reacting hydrogen with 100 % oxygen, resulting in pure steam as the only combustion byproduct. This steam is recoverable and may potentially be reused economically through simplified variants of the configurations discussed in Section 4.2.5. Another benefit of hydrogen calcination is that any excess green hydrogen can act as energy storage for the refinery, reducing the need for grid-based firming, minimising the need for heavy investment in thermal energy storage or large-scale batteries. In addition, the technology may be retrofittable to existing calciner installations.

While these benefits may be attractive, there are fundamental concerns about the availability of green hydrogen at the scale and price necessary for hydrogen calcination to be economically viable [1]. In addition, hydrogen generation has associated energy losses in its production, and challenges associated with safe storage and handling.

From an industry application perspective, Rio Tinto is currently evaluating the techno-economic feasibility of hydrogen calcination by developing a pilot plant at their Yarwun refinery in Gladstone, Australia. The project is being delivered in two parallel work packages and once work

package 2 is completed, it is anticipated the calciner can be operated for 2 hours using 100 % hydrogen fuel [3].

5.3.2 Electric Calcination

Electric calcination involves substituting natural gas with electric heating that is renewably sourced. Like hydrogen calcination, electric calcination also promises to produce near-pure steam [2] that can be recovered and reused in the Bayer process via simplified variants of the configurations discussed in Section 4.2.5. However, less steam is comparatively produced as there is no combustion of hydrogen to produce additional water vapor.

Moreover, as electric calcination relies directly on intermittently available renewable electricity and is vulnerable to any upsets in the grid, energy storage is required for firming and ensuring continuous power supply [1]. This contrasts with hydrogen calcination where excess hydrogen may be produced and stored when excess renewable power is available.

6. Conclusion

The alumina industry is faced with the significant challenge of finding economical ways to decarbonise the 'hard-to-abate' Bayer process. There is a general lack of technically mature or commercially viable technologies that may enable such step reductions in carbon emissions through transition to renewable energy sources. Rather, the industry must look sideways to adopt low-grade energy recovery and electrification technologies from other industries, as well as pioneer the development of new technologies that enable electrification of fossil fuel driven unit operations such as electric or hydrogen fuelled calcination.

This paper presents a case study for a typical modern Gibbsitic low temperature flowsheet that has been fully retrofitted with low-grade energy recovery systems to eliminate the need for continual fossil fuel fired steam generation. At a capital cost ranging from 130 to 180 USD per tonne/annum refinery capacity for a brownfield retrofit, this represents a significant investment. However, such retrofits reduce electrical supply requirement for site steam generation by a factor of 3 compared to steam generation via conventional alternatives, such as electric boilers.

Significant modifications are required to the Bayer process to retrofit the proposed low-grade energy recovery systems. This introduces numerous technical challenges and practical considerations that must be overcome. However, through careful engineering, these challenges are surmountable. Ultimately, the pathway for decarbonising the alumina industry will only be resolved through the incremental adoption of low-grade energy recovery and electrification technologies, followed by the transition to fully electrified process heating.

7. Acknowledgement

The authors would like to thank Callan Gault, Global Director Bauxite & Alumina (Hatch) for his support and expert input throughout the development of this paper.

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