Bringing the heat

Hydrogen's role in decarbonising Australian industrial process heat

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AUSTRALIAN HYDROGEN COUNCIL

AUSTRALIAN ALLIANCE FOR ENERGY PRODUCTIVITY

ABOUT THIS REPORT

AUTHORSHIP OF THIS REPORT

This report was produced by the Australian Alliance for Energy Productivity (A2EP) for the Australian Hydrogen Council (AHC) as a deliverable of the A2EP proposal Hydrogen for Industrial Process Heating Market Status Study for Australian Industry.

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DISCLAIMER

ABOUT A2EP

A2EP is an independent, not-for-profit coalition of business and research leaders helping Australian businesses pursue a cleaner and more successful future by producing more with less energy.

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Executive summary

Industrial process heat is an essential part of adding value to critical minerals and for producing products needed in a decarbonised world. High value jobs are created in the manufacture of aluminium for lightweight vehicles, for processing nickel and lithium for batteries, and in making the bricks, cement and glass for building materials.

The Australian industrial sector consumes more than 900 PJ annually for process heating, or more than 20% of total primary energy demand. Fossil fuels currently supply 87% of this demand (794 PJ). This means that industrial process heat is one of the biggest sources of emissions in Australia.

While electrically driven heating technologies are readily available to decarbonise low-temperature heating (<250 °C), a major roll-out of bioenergy and hydrogen supply and technologies will be needed to meet medium-to-high temperature process heat needs (>250 °C).

The intent of this research was to understand the current state of play for how users of industrial process heating are thinking about their decarbonisation options, with a particular focus on hydrogen. We undertook a review of the literature, and undertook more than 40 interviews with experts from:

- Academic and industry research bodies
- Suppliers of equipment, such as burners, boilers, kilns, furnaces, and ovens and associated instrumentation
- Manufacturers of alumina, aluminium, cement, bricks, glass, pulp and paper, food, beverages, and metals.

This wide cohort of energy users represented more than 400 PJ of process heating demand in Australia.

Industry sentiment and hydrogen readiness

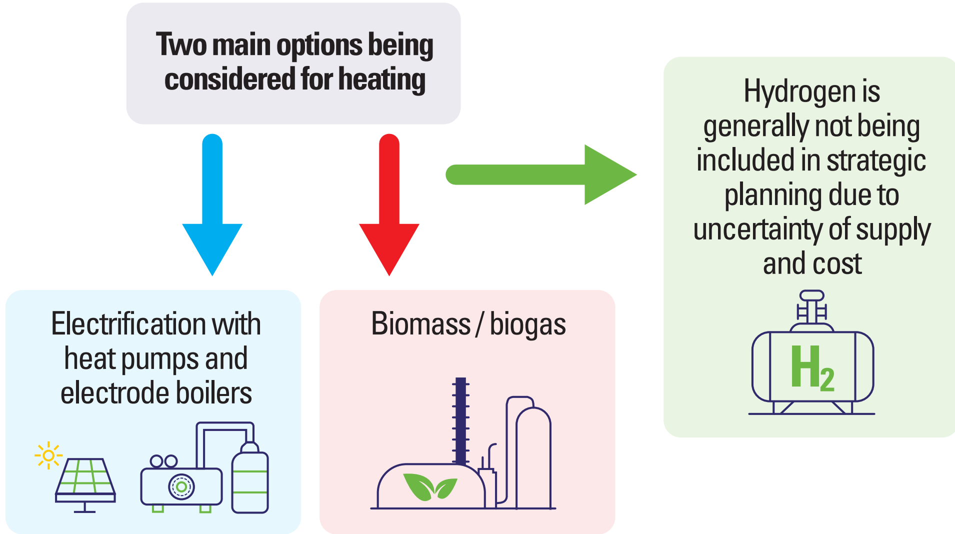
We sought interviewees' perceptions of risk and opportunity in their future decarbonisation choices. We found a consensus view that the electrification technologies should be applicable and are readily available for temperatures below 250 °C. However, several sectors expressed concern over the availability of renewable electricity to supply the required needs.

Interviewees were positive that bioenergies, such as biogas, can replace existing fuels such as natural gas more readily since they have a similar nature and shared combustion characteristics. Heating equipment for biogas requires little modifications when switching from natural gas. However, biogas has limited production prospects given it is largely dependent on waste from other parts of the economy.

Hydrogen, whilst being a higher cost per gigajoule when compared to direct electrification or bioenergy, is considered to be an essential part of decarbonising Australia's industry where electrification and bioenergy are either not technically feasible or available in sufficient quantities. While using hydrogen requires more technical modification in the heating equipment to replace natural gas or biomethane in a process plant, there are still clear benefits from its use.

As a result, there is a high potential demand from industry for heating that suits hydrogen's strengths, that is, the delivery of high temperatures. This demand is up to 240 PJ (excluding steel, chemicals and the hydrocarbon supply chain).

However, it is still very early and several industries are yet to investigate alternatives to fossil fuel heating options.



Among the high-temperature process heat applications, alumina refining, brick manufacturing and cement production show significant opportunities for adopting hydrogen as an alternative fuel. Retrofit costs for hydrogen are more expensive than biogas but may be lower when compared with electrification.

While not mentioned by stakeholders to a great degree, other renewable fuel options such as green ammonia and green methanol could part of a future energy mix. They will likely have an even higher cost per gigajoule when compared to hydrogen due to the additional processing required, however, other features such as ease of transportability may support their development.

Equipment availability

Equipment to support higher uptake of bioenergy and hydrogen is available but currently bespoke and expensive.

1. Existing burners can typically fire hydrogen-natural gas blends for up to 20% hydrogen concentration. When the hydrogen concentration approaches 50%, significant modifications are required to enable the burner to fire the fuel safely. The burner needs to be replaced with a specially designed one for higher hydrogen concentration and for pure hydrogen fuel.
2. Heating equipment for using hydrogen as an alternative fuel is at high commercial-readiness levels. Bespoke hydrogen burners can be sourced from reputable suppliers, however, this is at a capital cost that is five to six times higher than conventional natural gas burners with the same heating capacity. The cost of these burners is expected to decline as production ramps up in the next decades but is likely to never fall to the costs of conventional natural gas burners.
3. Hydrogen-fuelled boilers and kilns are available in the existing market. The most common approach in the industry is to adopt hydrogen-ready heating systems and run them initially on natural gas. Once hydrogen supply volume and price evolve to a commercial level, the heating system can switch to fire hydrogen mainly by replacing its burners.

Considerations in adopting hydrogen

As noted above, study participants tended to see hydrogen as further down the priority list for their business. Some of these views reflect an entirely rational understanding that it will always be cheaper to use less energy, or move to easier or cheaper alternatives if they are available. In other cases, the deprioritising of hydrogen reflected the current lack of clarity on hydrogen policy, regulation, cost and availability. With hydrogen industry development still in a nascent stage, end users are understandably cautious.

Even for the sectors more likely to need hydrogen as replacement fuel, the high cost and long life of industrial processes – such as alumina refineries, cement kilns, brick kilns and large boiler rooms – require a cautious approach given that investments within this decade can determine carbon footprint of those applications for decades to come.

On the regulatory front, study participants noted that blending hydrogen into natural gas is an option, but they have concerns about the impact of any inconsistent gas ratios on burner performance. The current lack of regulations relating to burning pure hydrogen fuel also reflect risk.

Hydrogen also has different heating characteristics to natural gas, so more hydrogen is required to have the same heat outcome and a change to equipment to manage matters such as flame speed.

Recommendations

In addition to more general support for hydrogen industry development to establish scale and reduce prices, A2EP recommends the following steps to further unlock the potential of decarbonising process heating:

Policy

- **Clarify a well-defined strategy and schedule for the deployment of hydrogen**
  This will build confidence in manufacturers, ensuring a viable market for hydrogen-ready equipment. Likewise, end users will feel more secure in their purchase of hydrogen-ready equipment and their access to hydrogen when it is needed.
- **Consider measures to protect local end users from uncertain international hydrogen prices** in order to assist them to de-risk the transition to hydrogen-based process heating.
- **Target government support packages for early adopters**
  Support should ideally be through tax and/or targeted market mechanisms.
- **Promote the production of hydrogen-capable equipment among manufacturers**
  It is also essential to create incentives for end users to adopt hydrogen as an alternative to natural gas if hydrogen is going to be a core part of the national decarbonisation plan.

Regulatory

- **Develop a clear set of regulations for the use of hydrogen as a fuel in industrial plants**
  It should be noted that the effectiveness of any changes to regulation would be dependent on the implementation date as some manufacturers might not be able to meet deadlines to only supply hydrogen-ready equipment as they are still only in the early stages of product development.
- **Address regulations to require boiler equipment to be hydrogen-ready**
  Work is needed to determine how this regulation might work in practice. At the least this should establish a precise and unambiguous definition of 'hydrogen-ready' for boilers and burners. This definition will eliminate any uncertainty for end users who purchase the equipment, ensuring that they understand precisely what steps are required to enable the equipment to burn hydrogen with full efficacy.
- **Clarify the NOx emissions thresholds that would be necessary to comply with Medium Combustion Plant regulations when using hydrogen as a fuel source**
  Replacing carbon dioxide emissions with high NOx emissions would not be an acceptable solution to the issue of pollution.

Industry knowledge and capacity building

- **Communicate the potential locations of hydrogen sources to industry more directly**
  These include the hydrogen hubs and industry hubs with hydrogen supply infrastructure. Hydrogen generation hubs can be developed near large industrial plants that are expected to be the early adopters, particularly because larger energy users, such as cement manufacturers, are unlikely to relocate. Smaller users may decide to follow and move their production plants to those hubs and would benefit from tax incentives to encourage relocation of production facilities.
- **Prioritise industrial heating in workforce and skills development initiatives**
  The industry will need a trained workforce to enable the commissioning, maintenance and operation of hydrogen-fuelled heating plants. This training may require the involvement of the education centres such as vocational training providers and universities.
- **Communicate with industry about the capability of the national electricity market and the electricity grid to allow for the vast electrification of industrial heat applications**
  It is currently unclear to the end users whether the grid will have the capacity for electrifying most of their heat applications. (It should be noted that a lack of grid capacity would make hydrogen investment more attractive.)
- **Fund targeted research to address the technical and engineering issues related to the reduced heating performance of hydrogen-fuelled burners**
  The current focus of the Australian Renewable Energy Agency (ARENA) is the production of hydrogen via the Hydrogen Headstart and Hydrogen Research and Development Fund, while the Heavy Industry Low-carbon Transition Cooperative Research Centre (HILT CRC) is supporting the use of hydrogen for large energy users. Further research is needed to support understanding of technical issues for a broader set of uses to enable a wider uptake.

1 Introduction

Australian industry consumes 913 PJ of primary energy for industrial heating purposes, of which 87% (794 PJ) (Lovegrove et al, 2019) is currently supplied by fossil fuels, emitting 42 million tonnes of carbon dioxide equivalent annually (Lord, 2018).

If Australia is to meet its net zero emissions commitment by 2050, this 794 PJ will need to be decarbonised (Bouckaert et al., 2021).

This is a major task, with much process heating in the 'hard-to-abate' category for emissions reduction because of a need for high temperatures (higher than 250 °C) that are not suitable for electrification. Industrial process heat represents 8% (DCCEEW, 2022-1) of total Australian emissions but 24% of hard-to-abate emissions.

Processes can also require expensive and long-lived equipment that needs to be planned for in advance and requires clarity on the full costs of investment.

Currently, there is insufficient information about process heat decarbonisation options, including equipment availability and long-term cost. A changing policy environment, a lack of market signals and mixed messages from different parties have contributed to confusion and uncertainty in the minds of industrial energy users who need to be make decisions now if they are to meet future decarbonisation objectives and have only limited investment cycles to 2030.

What is a 'high temperature' in process heating?

Any industrial thermal processes requiring heat at above 250 °C is considered 'high temperature' in this report. The required thermal energy input to such processes cannot be supplied by existing heat pump or waste heat technologies and often requires combustion or direct use of electricity.

This study has sought to establish some common ground on the issues, so that future policy (particularly hydrogen policy) can be best targeted to where it is needed. We reviewed the literature and asked energy users and equipment suppliers on the perceived and actual barriers and opportunities for process heat decarbonisation, particularly for very high temperatures. See **Appendix A** for the literature reviewed and **Appendix B** for the list of participating organisations.

The research themes explored were as follows:

1. Identification of renewable fuels that are best suited to the different types and temperatures of process heat required across Australian industry.
2. Current intentions of major energy consumers for decarbonising their industrial heating demand.
3. Considerations of clean and renewable hydrogen as a fuel source (including why/why not).
4. Whether equipment is readily available to utilise hydrogen for industrial heating and the current and likely future cost premium to current technologies.
5. How government policy and regulation can reduce barriers to adoption of hydrogen as an industrial heating fuel source.

The current report was developed through the following steps.

Literature review
Reviewed more than 15 scientific publications on renewable heating in industry.

Initial consultation with industry experts
Consulted more than six research and development experts in the field of alternative fuels for industrial process heat.

Interviews with technology providers
Interviewed 13 manufacturers and suppliers of industrial heating systems to identify the current state of the supply chain that is required to enable the transition.

Interviews with major end users of process heat
Interviewed a further 23 organisations representative of more than 70% of the fossil fuels energy used in Australia for process heating (excluding steel, chemicals and oil and gas).

Figure 1: Steps in the development of this report

There are some important exclusions from this study, as follows:

- The study addresses existing industry in Australia, so does not allow for potential upside of increased local manufacturing due to lower energy input costs from Australia's future abundant renewable energy. Related to this, major 'green' manufacturing expansions for iron, battery minerals or alumina have not been considered.
- Other applications for hydrogen, such as power generation and mobility, are excluded from the scope of this work because they are already being extensively investigated. Similarly, applications where hydrogen could be used for green steel or green iron for process heating [around 94 PJ in energy value (Lovegrove et al., 2019)] or as a reductant are excluded from this study as they are being investigated by other initiatives, such as the HILT CRC.
- Applications that use hydrogen as participating feedstock in the chemical process, such as ammonia production [42 PJ is for heating (Lovegrove et al., 2019)] are also excluded as extensive research has been completed and pilot projects are already underway.
- Process heating for extracting and processing of oil and gas products [151 PJ (Lovegrove et al., 2019)] has been excluded, given traditional oil and gas can be expected to have less relevance in future decades.

2 Industrial process heating needs

Process heating transforms materials into higher value products, creating higher skilled jobs and boosting gross domestic product (GDP). As an example, Australia's largest process heat using sector, the alumina industry, uses natural gas and coal to transform bauxite ore into alumina. When compared to simply exporting bauxite ore, this increases the value per tonne by around 13 times (AAC, 2023), creating additional value of more than $6 billion annually, on-going skilled jobs for 8,000 people and additional profits and taxes.

> **What is industrial process heat?**
>
> Industrial process heat is defined as thermal energy used directly in the preparation or treatment of materials to produce manufactured goods.
>
> It can be sourced from combusting fuels such as natural gas, from electric heating devices such as resistive elements, or from renewable sources such as solar thermal collectors.

According to the Australian Energy Statistics published by Department of Climate Change, Energy, the Environment and Water (DCCEEW, 2022-1), in 2020-21 the mining and manufacturing sectors accounted for 42% of the total final energy consumption, 51% of which was in the form of fuel for process heat.

The cost of consumed energy to industry is around $8 billion annually using an average price of $10/GJ (Lovegrove et al., 2019).

2.1 The different uses of process heat

Based on the required application temperature, industrial heat can be grouped in to two main categories:

- Low temperature heating (below 250 °C)
- High temperature heating (above 250 °C) . This category has fewer heating options and relies on either some electric technologies or combustion.

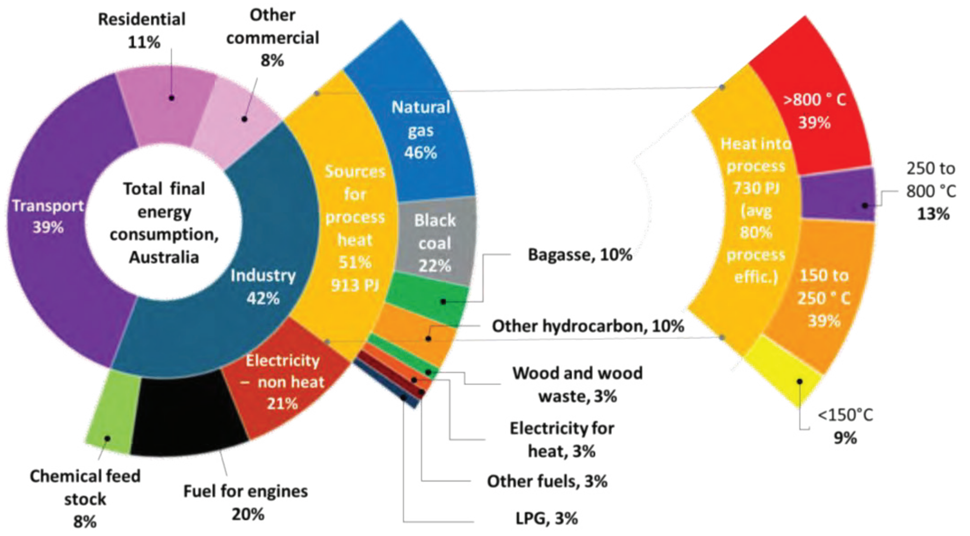


Figure 2: Breakdown of energy consumption type by Australian emissions percentage. Source: Regenerated data reported from ARENA. PJ amounts from Lovegrove et al. (2019).

Figure 2 provides a breakdown of final heat usage from final energy consumption, using data from 2016-17. The shape to the right shows the same yellow process heat but by temperature. We can see that 49% of process heat is produced at medium-to-high temperature ranges (that is, more than 250 °C).

As shown in Table 1, the range of temperatures used in industrial process heating varies by sector and application. The largest industrial heat consumer is for the production of alumina and non-ferrous metals, with a total heat demand of 171 PJ split equally into above and below 250 °C. The second largest industrial heat consumer is the food and beverage sector coming in at 115.2 PJ annually, although most of this is below 250 °C. We have excluded iron and steel (94 PJ) and oil and gas extraction (86.4 PJ) for this table given that these uses of industrial heat are unlikely to be a focus for decarbonisation.

Table 1: Range of temperatures used in industrial process heating by sector and application in Australia.

Sector	Heat applications	Temperature range	Heating demand (PJ)	Heating equipment	Current main fuel or primary energy source
Alumina	• Digestion (Bayer) • Calcination of aluminium hydroxide	<250 °C >900 °C	153 68	• Boilers • Burners in calcination reactors	• Natural gas • Coal
Agriculture and food processing - Food and Beverage	• Drying • Frying • Baking • Pasteurisation • Rendering • Cooking • Space heating • Cleaning/washing	150 °C to 250 °C	98	• Boilers • Heat pumps • Electric heater • Microwave • Ovens	• Natural gas • Biomass • Biogas • Electricity
		>250 °C	17		
Cement	• Pre-heating	<250 °C	5	• Rotary kilns	• Natural gas • Coal • Refuse-derived fuel
	• Limestone calcination • Clinker production	900 °C to 950 °C 1,450 °C	30		
Other (textiles, mining, construction)	• Dyeing • Drying • Curing	<250 °C	15	• Boilers • Ovens	• Natural gas • Electricity
		>250 °C	10		
Pulp and paper	• Separating, processing and transporting fibre and water • Drying	120 °C to 150 °C	6	• Boilers	• Natural gas • Biomass • Biogas • Electricity
		>250 °C	14		
Brick	• Brick firing	1,100 °C	15	• Kilns	• Natural gas
Glass	• Melting raw materials	1,500 °C to 1,700 °C	7	• Burners in furnaces	• Natural gas
Aluminium smelting anode baking	• Baking of carbon anodes	1,050 °C to 1,200 °C	3	• Burners in ovens	• Natural gas
Other metal fabrication	• Pre-heating • Heating	>250 °C >900 °C	<3	• Induction heaters • Infrared heaters • Furnaces • Ovens • Resistance heaters	• Natural gas • Electricity
Aluminium forming	• Heating aluminium billets	375 °C to 590 °C	1	• Burners in ovens	• Natural gas • Electricity

2.2 The key future technologies to deliver process heat

Industrial processes often require heat across a wide range of temperatures and heating power. These applications span from food processing at temperatures below 100 °C to metal forming, smelting, and chemical processing at temperatures well above 1000 °C (see Lovegrove et al., 2019 for further detail).

As can be seen from Table 1, fuel combustion (usually natural gas) using a burner has been the primary source of industrial heat to date. A burner combusts the fuel and generates heat in the form of a sustained flame. The heat from the flame can be directly received by the target material in kilns, furnaces, and ovens. A burner can also be a part of a boiler system where the flame transfers heat to water and generates either hot water or steam. The generated steam is then directed to the point of use via steam reticulation lines and delivers the heat to the target material.

Developments in recent years have supported lower temperature heating needs being met by electrical technologies, such as heat pumps (Leak, 2022). Proven and available solar thermal, heat pump and electrode boiler technologies can economically deliver lower temperatures (<250 °C). This is almost half of Australia's industrial heat requirements.

The other half – the medium-to-high temperature needs – cannot be readily served by using electricity and most people agree that fuel combustion or catalytic conversion of hydrogen to release heat remains a required solution. This then leads to investigations of how to use a decarbonised fuel, such as clean hydrogen.

Table 2 shows the electrification and combustion options at a higher level or technology and commercial readiness.

Table 2: Alternative heating technologies for industrial process heat.

Technology	Maximum temperature	Efficiency	Application	Typical limitations
Electrical heating technologies, using renewable electricity				Needing low-cost renewable electricity to be economical with fossil fuels
Heat pumps	120 °C (current technologies)	200% to 600%	• Various low temperature applications, e.g. in food and beverage or pulp and paper industry	• High installed capital cost per kilowatt • Ratio of electricity to gas price limits adoption
Mechanical vapour recompression (MVR)	250 °C	>300%	• Waste heat recovery and upgrade for evaporation systems	• High installed capital cost per kilowatt • Typically limited to evaporation systems (e.g., wastewater, sugar)
Electrode steam boilers	250 °C	50% to 90%	• Various low-to-medium temperature application	• High installed capital cost per kilowatt • Ratio of electricity to gas price limits adoption and reduces carbon emissions only if electricity supply is largely renewable (>80%)
Resistance heaters	2,000 °C	~100%	• Heating of various target materials that can accept contact such as in electric boilers and furnaces	• Limited applicability - reduces carbon emissions only if electricity supply is largely renewable (>80%)
Alternative fuels				
Hydrogen	~2,000 °C	80% to 90%	• Replacing natural gas and coal in some applications	• Cost and availability
Biomass	Up to 1,000 °C	60% to 90%	• Steam generation	• Distance between source and user needing to be less than approximately 50 km to be economical (shorter for less dense fuels, such as bagasse)
Biogas/biomethane	~2,000 °C	80% to 90%	• Replacing natural gas and coal in some applications	• Availability of sufficient and predictable feedstock to give scale to production

It should be noted that several heating technologies have been excluded from this study due to their poor techno-economic feasibility or applicability to the researched applications. For example, electric arc, induction, radio frequency, infrared and microwave applications have seen minimal global adoption within the applications researched for this project. Typical adoption barriers include very high installed capital cost per kilowatt of heating capacity, limited heat output or limited applicability. Until technology development or breakthroughs are achieved, they remain niche heating options.

Similarly, concentrating solar thermal technologies (such as parabolic troughs, dish concentrators and central tower receivers) can replace existing steam process heat but have had very limited industrial implementations mainly due to the high installed capital cost per kilowatt of heating. Solar thermal (flat plate collectors and evacuated tube collectors) technology is suitable for solar hot water and low temperature steam but similarly are unlikely to be considered as a technology solution due to their limited applicability. Geothermal heating has not been considered given it is generally only able to provide low temperature heating (<100 °C) within Australia. The geothermal option was also excluded from this analysis as it is geographically constrained and often unavailable to the end users. However, it can be used for low temperature applications in certain circumstances (not covered in this report).

Electrification

On average, the share of electricity for producing industrial low-to-medium temperature heat is currently 15% in the G20 countries and 10% in Australia (Bloomberg NEF and WBCSD, 2021). Electrification has significant potential to scale for industrial processes well beyond this and the associated emissions will reduce as the grid continues to decarbonise.

When possible, electric heat pumps are a good choice, as the thermal output is usually two to six times more than their electric input, meaning efficiency at 200% to 600%. Alternatively, electric resistance heaters are lossless as they can convert all of their electricity input into heat.

In contrast, hydrogen wastes a portion of the input energy during its production from renewable electricity. Electrolysis efficiency is generally around 70% (although newer technologies can improve this (Hysata, 2022)[1] and further losses then occur to compress and transport it in different forms. Burning hydrogen also results in energy loss, with burner efficiency at around 90%.

Overall, this means that when converting electricity to hydrogen and then heat, at least 45% of the initial input energy is lost. If the same electricity was to be used for heating with resistance heaters or heat pumps, the total wastage of the input electricity would have been less than 10% which would only be due to transmission lines, based on transmission losses reported by the Australian Energy Market Operator in 2022 (AEMO, 2022).

However, energy efficiency and performance is not the whole picture. When considering decarbonisation options for process heat there are a range of matters to address, including the integration of new heating technology into the existing processes. For example, for some applications a flame is required, such as in cement rotary kilns. No electric heating technology can deliver the required heating for this process.

Combustion technologies

Even with current technology options, the need to combust fuel remains. For some industrial processes the required temperatures are beyond the reach of most proven renewable heating technologies, such as conventional solar thermal systems, electrode boilers and electric heat pumps (Edelenbosch et al., 2022). The hard-to-abate industry sectors generally involve processes with temperatures above 250 °C, which make up 53% or 474 PJ of annual industrial heating demand.

In other cases, replacing the heat source with electrical options can interfere with the process itself. Some end users may be willing to adopt hydrogen combustion to minimise the impacts on their thermal processes, even if this means bearing the extra cost of hydrogen fuel. These sectors are also hard to abate because the need to look beyond electrical technologies itself brings its own complications, as will be discussed in this report.

Hydrogen and bioenergy are considered particularly important for sectors that are more difficult to electrify. Bioenergy is a renewable form of heat, electricity and combustible fuel that is generated from the conversion of organic matter (biomass). Converting biomass to bioenergy comes with a significant loss of about 50% to 60% of the inherent energy in the biomass (He,Y. et al., 2020). The resulting benefits, such as transportability or suitability for burners, need to justify such losses. Bioenergy that is currently available includes biomass waste that can be directly burned, biogas that is produced through anaerobic digestion of biomass, and biomethane[2] that has high methane content. Both biomass and biogas can reach deliverable temperatures of around 500 °C, and biomethane has a range to around 1,000 °C.

Biofuels are in nature similar to conventional fossil fuels. This means they can be more easily integrated into existing applications. Bioenergy products can also offer cost-competitiveness when the source of biomass is in the vicinity of the bioenergy plants. The limitation for biofuels is where there is not a clear local supply, or where demand exceeds supply. Table 3 summarises the types of bioenergy and their pros and cons.

1. Hysata has claimed 98% electrolyser efficiency in news dated 16/3/2022.
2. Bio methane is produced from biogas by removing impurities such as carbon dioxide, hydrogen sulphide, and moisture.

Table 3: Bioenergy options for process heat.

Bioenergy options	Advantages	Barriers
Biomass	• Plentiful	• Dispersed – Typically not located where high temperature heating processes are located • Quality of fuel is variable • Supply of fuel may be seasonal • Maximum viable transport distance is ~20km • Low social understanding of benefits
Biogas	• Can be incorporated into existing heating equipment	• Approximately maximum production potential 350PJ/year • Low social understanding of benefits • Supply is limited and underdeveloped
Partially upgraded biogas	• Can be easily incorporated into existing heating equipment	• Same as for biogas but comes with a higher cost $1-2/GJ
Biomethane	• Compatible with existing heating equipment	• Same as for biogas but with substantially higher cost of production

In contrast, the precursor ingredients of hydrogen are abundant and relatively low-cost. It can be produced with renewable, non-fossil energy at large scale via the electrolysis of water. Renewable electricity can be sourced directly from solar and wind farms, and also from the electricity network, enabling the ubiquitous generation of hydrogen wherever water is readily available. But, unlike biogas, hydrogen requires more equipment and process modifications at the application side to enable safe and efficient fuel substitution whilst maintaining existing production levels.

There are also energy efficiency benefits from using hydrogen. The chemical properties of the flue gases from fossil fuel combustion mixtures make heat recovery from flue gases expensive and inefficient. In some cases, 30% of the entire plant energy consumption can be lost via these flue gases. However, hydrogen combustion – especially with pure oxygen – leads to clean flue gases that are mainly water vapour, so providing a far higher quality of heat compared to flue gases from fossil fuel combustion. As a result, local pollution and particulate matters in the plant can be avoided and the potential for heat recovery is much higher. The higher quality heat allows far greater process plant integration to utilise what was previously just 'waste heat'.

The exhaust can be used for other processes and applications such as low-temperature heating and even drying. Cascading hydrogen-fuelled heating systems with this application can help to improve the economics of the entire production process. Furthermore, the water vapour from hydrogen combustion can be upgraded to a higher temperature by mechanical vapour recompression to further improve the plant energy productivity.

At present, green hydrogen is not produced at scale due to a number of constraints, such as lack of end-use demand, lack of distribution infrastructure and poor economic competitiveness against existing fuels and renewable electricity.

3 Industry perspectives

More than 40 interviews were undertaken for this study, conducted in three phases:

- Phase 1 was conducted with six people, from two universities, CSIRO and the Future Fuels CRC. The purpose of this initial phase was to establish the overall state of knowledge and key issues identified related to progress with alternative fuels for industrial process heating.
- Phase 2 interviews were with suppliers of equipment and technology, where the study team met with 13 people across 13 organisations to understand types of technology and their commercial readiness. These organisations were generally chosen based on their existing activities in process heating, producing furnaces, burners, boilers, kilns and instrumentation. A new market entrant was also included (Star Scientific) given its innovative approach to using hydrogen for heat without requiring combustion.
- For Phase 3 the study team interviewed process heat end users across alumina, cement, bricks, metal forming, beverage and dairy, meat processing, pulp and paper industries and other metals processing. There were 26 people across 23 organisations interviewed in this phase.

See **Appendix B** for the detail of the organisations interviewed. Data collection in the three phases enabled the identification of the key areas to be discussed with the stakeholders. The first phase revealed the technical challenges that hydrogen-based heating systems may face. Those areas were highlighted in the discussions with heating system suppliers in Phase 2. These two phases allowed for a picture of available technologies which fed into the discussions with the end users in Phase 3.

Overall, we found the role of hydrogen for process heat applications to be uncertain with end users and consequently the heating systems suppliers.

The driving factors for this uncertainty included the lack of supply chain/infrastructure for at-scale hydrogen supply, the high/uncertain cost of hydrogen, and a perceived lack of economic advantage over electrification technologies. Discussions with industrial heat users showed that they perceive the case for electrification to be a strong and, in many cases, the preferred option for decarbonising process heat applications. The main reason for that is due to the inherent conversion inefficiencies and transport losses of hydrogen (including the energy required for its compression), heat from green hydrogen suffers from a higher heating cost.

3.1 Perceived market challenges to hydrogen uptake

With hydrogen industry development still in a nascent stage, end users are understandably cautious. Even for the sectors more likely to need hydrogen as replacement fuel, the high cost and long life of industrial processes – such as alumina refineries, cement kilns, brick kilns and large boiler rooms – require a cautious approach given that investments within this decade can determine carbon footprint of those applications for decades to come.

The issues raised by interviewees and some proposed policy responses are shown in Table 4.

Table 4: Perceived market issues with hydrogen as raised by participants through this study.

Issue	Description	Policy recommendation
Timeline for the availability of hydrogen	• End users are concerned that hydrogen is still 10-15 years away as the supply chain and support systems are not in place. Meanwhile, they have pressure to decarbonise now and need to make long term, strategic decisions that may lock in fuels with more certainty on price and availability. • There are also questions about whether a natural gas-hydrogen blend will be a realistic option, or the transition will be towards pure hydrogen, skipping this interim stage.	• Clarify a well-defined strategy and schedule for the deployment of hydrogen. This will build confidence in manufacturers, ensuring a viable market for hydrogen-ready equipment. Likewise, end-users will feel more secure in their purchase of hydrogen-ready equipment and their access to hydrogen when it is needed.
Future price protection	• Some study participants raised a concern that they may lose access to affordable hydrogen if the future hydrogen economy is open to the global market.	• Consider measures to protect local end users from uncertain international hydrogen prices in order to assist them to de-risk the transition to hydrogen-based process heating.

Table 4: Perceived market issues with hydrogen as raised by participants through this study. (continued)

Issue	Description	Policy recommendation
Cost	• The general perception is that hydrogen is a hazardous fuel with safety issues related to its leakage and explosion. As a result, the entire heating plant may need significant upgrades to be intrinsically safe. This means that that even in the case of hydrogen leakage, the risk of explosion must be eliminated. The cost of such upgrades will increase capital expenditure required for retrofit projects and new developments. • Hydrogen equipment is very expensive compared with incumbent technology – see **Section 3.3**.	• Target government support packages for early adopters, ideally through tax and/or targeted market mechanisms. • Promote the production of hydrogen-capable equipment among manufacturers. It is also essential to create incentives for end-users to adopt hydrogen as an alternative to natural gas if hydrogen is going to be a core part of the national decarbonisation plan.
Lack of applicable regulations	• There is a perception among the end users that regulations today will not allow the burning of pure hydrogen since they would need approval from regulators, which is perceived as a prohibitively difficult process. • In some states, any fuel blend with more than 50% hydrogen is not considered a hydrocarbon fuel and the required regulations are lacking. Some states, such as Western Australia (WA), have already resolved this issue with new regulations, and the other states are catching up. In late 2022, Australia's energy ministers agreed to amendments to the National Gas Law and Regulations to bring hydrogen blends, biomethane and other renewable gases under the national gas regulatory framework (DEECCW, 2022-2).	• Develop a clear set of regulations for the use of hydrogen as a fuel in industrial plants. Note that the effectiveness of any changes to regulation would be dependent on the implementation date as some manufacturers might not be able to meet deadlines to only supply hydrogen-ready equipment as some manufacturers are still in the early stages of product development. • Address regulations to require boiler equipment to be hydrogen-ready and how this regulation might work in practice. At the least this should establish a precise and unambiguous definition of 'hydrogen-ready' for boilers and burners. This definition will eliminate any uncertainty for end-users who purchase the equipment, ensuring that they understand precisely what steps are required to enable the equipment to burn hydrogen with full efficacy. • Clarify the NOx emissions thresholds that would be necessary to comply with Medium Combustion Plant regulations when using hydrogen as a fuel source. Replacing carbon dioxide emissions with high NOx emissions would not be an acceptable solution to the issue of pollution.
Distance from hydrogen production	• The cost of relocating the factory to a location in the vicinity of hydrogen resources is not perceived as a viable option due to the significant and uncertain cost (see Figure 3 that shows an example cement factory). Hence, the vicinity to hydrogen supply points remains a concern.	• Communicate the potential locations of hydrogen sources to industry more directly. These include the hydrogen hubs and industry hubs with hydrogen supply infrastructure. Hydrogen generation hubs can be developed near large industrial plants and precincts that are expected to be the early adopters, particularly because larger energy users, such as cement manufacturers, are unlikely to relocate. Smaller users may decide to follow and move their production plants to those hubs and would benefit from tax incentives to encourage relocation of production facilities.
Skills gaps	• Installation and operation of hydrogen heating plants requires Type B gas advanced qualifications for trades people, which need two years of training. This skill shortage indicates a current presence of a capability gap. It should be noted there is already a large shortage of trades people for standard gas systems, let alone with Type B gas advanced qualifications.	• Prioritise industrial heating in workforce and skills development initiatives. The industry will need a trained workforce to enable the commissioning, maintenance, and operation of hydrogen-fuelled heating plants. This training may require the involvement of the education centres such as vocational training providers and universities.

Table 4: Perceived market issues with hydrogen as raised by participants through this study. (continued)

Issue	Description	Policy recommendation
Concern about grid capability	• It is currently unclear to the end users whether the grid will have the capacity for electrifying most of their heat applications. It should be noted that a lack of grid capacity would make hydrogen investment more attractive.	• Communicate with industry about the capability of the national electricity market and the electricity grid to allow for the vast electrification of industrial heat applications.
R&D support	• There are a range of technical issues (see **Section 3.2**) that have been identified and while solutions need to be industry driven, policy can support the necessary research and development.	• Fund targeted research to address the technical and engineering issues related to the reduced heating performance of hydrogen-fuelled burners. Further studies and knowledge sharing from organisations such as ARENA are also needed to encourage wider uptake of alternative fuels beyond very large energy users.

Figure 3: ADBRI cement factory in Adelaide, South Australia (Courtesy: Adelaide Brighton Cement Ltd).

3.2 Perceived technical challenges with using hydrogen in process heating

Replacing existing fuels with hydrogen requires certain considerations. In general, biogas requires little modification to the heating plant because its chemical composition (and hence combustion properties) are similar to natural gas. In contrast, hydrogen is more challenging to adopt. The main considerations for hydrogen heating systems are listed below in Table 5. Modifications are suggested here, noting that these need to be led by industry.

Table 5: Perceived technical issues with hydrogen as raised by participants in this study.

Issue	Description	Required modification
High flame speed of hydrogen	• Due to its different physical and chemical properties, the flame speed of hydrogen is five to six[3] times faster than typical hydrocarbon fuels. In premixed fuel and oxidiser (i.e., hydrogen and air/oxygen), the flame can propagate upstream of the fuel line if the fuel injection orifice and its back pressure are not optimised for hydrogen.	• The fuel supply line, its pressure and the nozzle should be modified to increase the velocity of fuel to ensure that the flame is safely maintained outside of fuel lines and prevent it from travelling back into the fuel pipes. The required components for this purpose have already been produced and are ready to use. Burner manufacturers have confirmed that they have access to off-the-shelf products and can deliver bespoke solutions.
Hydrogen leakage	• The small molecules of hydrogen can penetrate through tiny pores and leak from the pipes, fittings and joints if they have not been designed to suit hydrogen. Potential end users perceive this as a safety risk, as the accumulation of unburned hydrogen in the plant room (especially in confined areas) can lead to fire and explosion. It is a higher risk due to its wider flammability range and lower ignition energy compared to natural gas/LPG. A mixture of hydrogen with air can be ignited even in the presence of static electricity or a spark in electrical switches (Kotchourko and Jordan, 2022).	• Fuel distribution, including pipework, needs to be upgraded and special fittings and valves are required to eliminate leakage (Kotchourko and Jordan, 2022). Burner component suppliers have confirmed that such fittings are currently available. Hydrogen detection sensors are also available and needed to maintain the safety of plant rooms. Some potential end users believe that to switch to hydrogen, their plant rooms need to be upgraded to be 'intrinsically safe', which is considered to be costly. Intrinsically safe means that all their electrical circuits and any potential ignition points should be fully isolated from the surrounding atmosphere to ensure that hydrogen air mixture will not be exposed to a source of ignition in the case of any leakage. The minimum safety considerations are provided in SA ISO/TR 15916:2015.
Pipe embrittlement	• Pipe embrittlement is the result of chemical and physical reactions when some conventional metals are in contact with hydrogen. It degrades the mechanical properties of the pipeline and may lead to mechanical failure and hydrogen leakage. This effect can reduce the lifetime of the pipes. If not addressed and prevented, hydrogen embrittlement can lead to catastrophic consequences especially in pressurised vessels and pipes (refer to SA ISO/TR 15916:2021). The focus of this document is on pipes that are used within process plants. However, lessons learned from related work at large scale gas transport pipelines, such as the recent Parmelia project conducted by APA Group, are likely to extend the knowledge in this area.	• Burner manufacturers consider that there is a need for upgrading fuel distribution lines, including the pipework to eliminate pipe embrittlement. Proper selection of materials is the key solution. The behaviour of various materials in the presence of hydrogen has been studied extensively in other industries such as oil and gas. A detailed guide for material selection has been provided in Annex C of Australian Standard document SA ISO/TR 15916:2021. Pipes and fittings using suitable materials are commercially available for hydrogen applications.

3. Hutny, W. P., & Lee, G. K. (1991). Improved radiative heat transfer from hydrogen flames. *International journal of hydrogen energy*, 16(1), 47-53.

Table 5: Perceived technical issues with hydrogen as raised by participants in this study. (continued)

Issue	Description	Required modification
Low volumetric heating density of hydrogen	• Due to its chemical and physical properties, hydrogen has a high gravimetric energy density (J/kg) but low volumetric (J/m^3) energy density. This means that while 142 MJ of heat can be produced from burning a kilogram of hydrogen (which is ~2.5 times higher than natural gas), burning 1 m^3 of hydrogen will only produce one-third of the heating energy that is attainable from natural gas is produced. This affects the performance of burners.	• When replacing natural gas with hydrogen in a burner system, burner manufacturers consider two options: 1. hydrogen should usually be pressurised, and/or 2. the fuel pipes and the burner should be larger to deliver the same heating power to match the requirements of the process.
Hydrogen level fluctuations in gas blends	• When using a blend of hydrogen and natural gas, the concentration of hydrogen can vary in the main gas pipelines. Pockets of low or high hydrogen concentration can lead to changing flame speed and affect a burner's performance.	• Burner manufacturers confirmed that when using a blend of hydrogen and natural gas, the hydrogen concentration must be monitored with appropriate sensors. The burner should be able to respond to variations in the hydrogen concentration by changing the oxidiser amount and tweaking the nozzle velocity. The required sensors and controls for this purpose are commercially available.
Poor heat transfer from hydrogen flame to the heat	• Unlike hydrocarbon flames that have high luminosity with high radiative heat transfer rate, a hydrogen flame has poor radiation characteristics. High radiation from the flame is required to facilitate the heat transfer from combustion products to the target surface, such as the heat exchangers of boilers. Our discussions with boiler manufacturers showed that they are concerned that the low radiative power from hydrogen flame hampers its heating power in a boiler.	• Boiler manufacturers address this issue by increasing the size of the heat exchanger of the boiler by 20% to 30%, relative to a natural gas boiler, to compensate for the lower heat transfer from the hydrogen flame. The overall cost of the boiler increases 10% to 20%. • In the longer term, thermal oxidisers are being developed. These systems react hydrogen and oxygen on a non-participating catalyst to generate heat. The catalyst is usually placed on the heat exchanger surface. As the chemical reaction takes place directly on the surface, there is no need for radiative and convective heat transfer. Heat can be directly received from the reaction by the heat exchanger, eliminating the drawbacks of combusting hydrogen. At the time of writing this report, thermal oxidisers were at technology readiness levels of five to six and their industrial applicability was yet to be realised.
Flame invisibility	• Due to its physical and chemical properties, hydrogen combustion creates a colourless flame that is primarily invisible, requiring specially engineered sensors for flame detection. There is a risk of hydrogen leakage and uncontrolled combustion if unburned fuel remains undetected.	• Burner manufacturers confirmed that flame detection and characterisation are needed to ensure that the flame is burning under optimal conditions. The main approach is to use flame detectors that are infrared or ultraviolet sensors. These detectors are commercially available. The second approach is to introduce additives such as particles to the flame to increase its luminosity and making it more visible. Research and development is still ongoing to confirm suitability of the additives.
Higher NOx generated from combusting hydrogen	• Compared to other hydrocarbon fuels, hydrogen has a higher flame temperature, leading to higher NOx levels.	• Burner manufacturers consider burning hydrogen with oxygen rather than air to alleviate this issue, because nitrogen is no longer in the mix. According to A2EP discussions with burner manufacturers, in the case of burning with air, flue gas treatment may be required where the common methods of flue gas recirculation or other means to reduce NOx levels are insufficient.

Table 5: Perceived technical issues with hydrogen as raised by participants in this study. (continued)

Issue	Description	Required modification
Unburned hydrogen	• Unburned hydrogen can accumulate in confined spaces and lead to fire, explosions or detonation. Under buoyancy effects it rises in the air which is an advantage in open spaces as it helps to prevent hydrogen from accumulation. Hydrogen has a wide flammability range and low ignition energy, meaning that its mixture with air can be ignited by static electricity or electrical sparks (Kotchourko and Jordan, 2022).	• Boiler manufacturers use induced draft fans to ensure that hydrogen is not accumulated in the plant. They also consider installing hydrogen detection sensors. Plant upgrades to intrinsically safe states may be required. There is an uncertainty among the potential end users of hydrogen about the necessity of such costly upgrades.
Corrosion	• Hydrogen combustion produces high-purity water that, in contact with high-temperature NOx molecules, can produce acidic components leading to corrosion.	• Similar to boiler designers avoiding sulphuric acid when burning natural gas, care needs to be taken to ensure that water does not form anywhere in the equipment.
Safety	• Due to its inherent properties, hydrogen has a flammability range of 4% to 77% in an air/hydrogen mixture, which is much wider than the flammability range of natural gas (at 4% to 17%).	• According to the interviews with burner manufacturers, such a wide flammability range leads to necessary modifications to the burners and also more stringent safety measures.

3.3 Equipment status for hydrogen use in industry

The use of hydrogen in industry in not new. It is already used across various industries as a chemical feedstock or in chemical processes. However, hydrogen use for process heating is not widespread and has immature supply chains.

We have found that burners for hydrogen blends and pure hydrogen are available from reputable suppliers, as are all the necessary instruments for the efficient and safe operation of hydrogen burners, such as pressure and UV sensors. However, these burners are currently custom-designed. No off-the-shelf product was identified during this study. As shown in Table 6, the lead time for a burner (usually sourced from international suppliers) can be two to four times longer than natural gas burners. The capital cost of a hydrogen burner is four to eight times higher than the cost of natural gas burners and some of the required sensors for hydrogen applications need to be gold-plated and higher material grades, resulting in 50% to 70% extra costs.

Table 6: Example prices and lead time for hydrogen burners and instruments (not including valves and fittings).

	Example CAPEX		Indicative lead time	
	Natural gas	**Hydrogen**	**Natural gas**	**Hydrogen**
Burner	$30,000	$180,000[4]	Three months	6-12 months
Instruments (flow, level, pressure, temperature sensors)	$2,000-$3,000	$3,500-$4,000	Off-the-shelf	7-8 weeks

4. The cost estimated in Arup Group Limited (2022) shows a more conservative cost increase of 50-60% for hydrogen burners from the baseline natural gas burners. This can be due to the difference in the size of the equipment. It is expected that for larger systems the cost difference between a natural gas burner and a hydrogen burner will be smaller.

For boilers, an estimation provided by the UK Government (Arup Group Limited, 2022) claims a conservative upfront cost of a hydrogen boiler to be ~20% higher than that of a natural gas boiler with the same thermal output. Australian boiler and burner manufacturers confirm that hydrogen-based systems, including both burners and boilers, are presently custom-designed. As the system size increases, the design costs account for a smaller percentage of the total cost. Should the market for hydrogen-based heating grow, mass production of burners and boilers will result in a reduced upfront cost of these equipment.

The fittings and valves for hydrogen applications are 10% to 50% more expensive than natural gas ones for the same dimensions. However, to deliver the same calorific value with hydrogen, larger and/or high pressure components may be required, increasing the component costs further. The key seems to be in designing flexibility into equipment given current uncertainty. Burner operation life is usually in the range of 10 to 15 years, whereas boilers last for well over 20 years. In the case of installing a new boiler system suitable for hydrogen, the consensus is to make the boiler hydrogen-ready but use a conventional fuel burner until hydrogen fuel is accessible. These boiler systems can switch to run on hydrogen by modifying or replacing their burners.

Heating technology suppliers have advised us that they are receiving enquiries about the availability of burners and boilers that can operate over a range of hydrogen concentrations in gas blends. The pull from the market side is driven by the fact that natural gas suppliers have already expressed their intention to consider adding hydrogen to the existing gas networks. This potential change in the primary fuel supplied to the end users has forced them to consider retrofitting or modifying their burners to respond to the potential upcoming changes.

Some end users have expressed their intention for full decarbonisation via hydrogen-based process heating. Some large plants are considering their own hydrogen generation plants allowing them to switch to pure hydrogen, skipping the interim transitional period of using hydrogen/natural gas blends. This is the second driving force to develop pure hydrogen burners and boilers among the suppliers.

For a hydrogen/natural gas blend with hydrogen concentrations of less than 20%, existing burner technologies can be retrofitted and modified without a significant need for further R&D. These modifications are mainly limited to upgrading valves, fuel flow control and ongoing measurement/monitoring of the fuel blend. Suppliers perceive these modifications as not difficult and already feasible. At higher concentrations of up to 50%, significant modifications such as valves, control units and gold-plated sensors and seals are required. At concentrations higher than 50%, the burner needs to be redesigned.

3.4 Industry readiness summary

The industrial sectors selected for this study included building material manufacturers, metal forming, beverage and dairy, meat processing, pulp and paper and alumina. The list of entities that were included in each category has been provided in **Appendix A**.

Stakeholders were asked to share their future decarbonisation plans for process heat. Following their initial response, subsequent discussions focused on their preference for any specific technological options, including hydrogen, bioenergy, electrification or various combinations thereof. In cases where hydrogen was not considered as a viable decarbonisation pathway, additional inquiries were made to comprehensively understand the underlying reasons for this exclusion.

Table 7 shows the outcomes of the discussions with stakeholders about their current thinking for process heating decarbonisation. It is a modified version of Table 1, with the same left-side columns. The total process heating energy demand from the sectors interviewed is 426 PJ.

A red decarbonisation option indicates that the respondent considered it unlikely for their business, orange indicates technical barriers need to be overcome, likely requiring R&D, and green indicates a possible or likely solution. The detail of the sector considerations is provided in **Section 4**.

Table 7: Total heat consumption and opportunity for alternative heating options. Notes: The baseline heat demand for each application was sourced from Lovegrove et al. (2019).

Sector	Heat applications	Temperature range	Heating demand (PJ)	Hydrogen	Bio-energy	Electri-fication	Comments
Alumina	• Digestion (Bayer)	<250 °C	153	Unlikely	Unlikely	R&D	Most efforts are towards electrification using MVR or electrode boiler technology
	• Calcination of aluminium hydroxide	>800 °C	68	Possible	Unlikely	Possible	Both electrification and hydrogen being piloted with results expected by 2026
Agriculture and food processing - Food and Beverage	• Drying • Frying • Baking • Pasteurisation • Rendering • Cooking • Space heating • Cleaning/washing	150 °C to 250 °C	98	Unlikely	Possible	Possible	Hydrogen unlikely given viability of electrification
		>250 °C	17	Unlikely	Possible	Possible	Hydrogen unlikely given viability of electrification
Cement	• Pre-heating	<250 °C	5	Unlikely	Possible	Unlikely	
	• Limestone calcination • Clinker production	900 °C to 950°C 1450 °C	30	R&D	Possible	Unlikely	Low appetite for hydrogen – requires R&D for converting kiln to hydrogen.
Other (textiles, mining, construction)	• Dyeing • Drying • Curing	<250 °C	15				Not investigated but low temperature heating likely to be electrified
		>250 °C	10				Not investigated
Pulp and paper	• Separating, processing and transporting fibre and water • Drying	120 °C to 150 °C	6	Unlikely	Possible	Possible	Hydrogen not likely given availability of biomass and viability of electrification
		>250 °C	14				
Bricks and ceramics	• Brick firing	1,100 °C	15	Possible	Possible	Possible	All three pathways are possible and under investigation
Glass	• Melting raw materials	1500 °C to 1700 °C	7	R&D	Possible	Possible	Further research required for hydrogen uptake
Aluminium smelting anode baking	• Baking of carbon anodes	1050 °C to 1200 °C	3	R&D	R&D	Unlikely	Likely switch to inert anodes not needing process heating
Aluminium forming	• Heating aluminium billets	375 °C to 590 °C	1	R&D	Possible	Unlikely	Low appetite for hydrogen – not an immediate pathway

Unlikely: Respondent considered it unlikely for their business
R&D: Respondent indicated technical barriers need to be overcome, likely requiring R&D
Possible: Respondent indicated it a possible or likely solution

The sectors interviewed accounted for 410 PJ of heating energy demand. They have not yet committed to a specific path for decarbonising. Nevertheless, several users have expressed a preference for a specific pathway and are actively investing in research and development to validate its feasibility.

Among these sectors, the alumina and brick industries have shown a serious inclination towards hydrogen as a potential solution. In the case of alumina calcination processes, almost half of the energy usage is under investigation for electrification, while one-third is being considered for hydrogen adoption. It should be noted that brick manufacturing processes are exploring all three routes to decarbonise heat. These two applications account for a total energy demand potential of 38 PJ from alumina and brick. Manufacturers of these products consider hydrogen a potentially viable fuel (9% of the total energy demand investigated) with another 15 PJ within the alumina industry still undecided.

Despite bioenergy typically carrying lower technical transition risks, large-scale users are not giving it much consideration due to challenges related to securing substantial volumes within Australia's current policy framework and feedstock availability.

Four industries (cement, aluminium smelting, aluminium forming and glass production) have the potential to utilise hydrogen if technical and financial obstacles can be overcome, amounting to an additional 54 PJ of energy demand.

Out of all the pathways considered, electrification is receiving the most significant attention, with a potential for 216 PJ of the 410 PJ investigated. It should be noted that the 216 PJ of electrification heating demand does not directly correspond to 216 PJ of electrical demand, as the likely coefficient of performance (COP) is expected to be greater than one when employing heat pump and mechanical vapour recompression (MVR) technologies. This estimate also excludes the possibility of electrifying current bioenergy users for low-temperature heating, which would consequently free up bioenergy sources like bagasse for high temperature processes.

All participants in this study agreed (either explicitly or implicitly) that when considering organisational and sectoral decarbonisation initiatives for process heating, in almost all situations it is best to start with improving energy efficiency – that is, reducing energy consumption and/or improving performance for existing use.

After this, electrification (with clean energy) is the next logical step, particularly for lower process heating needs. Alternative fuels are the next step for remaining industrial process heating requirements.

For those organisations that consider they need to look beyond electrification to biofuels and hydrogen, the concerns raised relate to access to alternative fuels and cost.

4.1 Alumina

Alumina production consumed approximately 221 PJ of energy in 2020 (AAC, 2020), which is almost 21% of the total energy used by Australia's manufacturing sector. Alumina processing requires significant amount of heat at various temperatures for two main processes, digestion (Bayer process) at below 250 °C, and calcination at above 800 °C.

The digestion process contributes to 64% of the total heat requirement and is amenable to solar thermal technologies and electrification using heat pumps, MVR or electrode boilers. Calcination accounts for the remaining 31% of the required thermal energy and may be an area for alternatives fuels such as hydrogen (ARENA, 2022).

Switching to alternative fuels such as hydrogen or biogas does not cause any material compatibility issues with the process because the fuel is only for the purpose of heating and does not participate in the chemical process.

In work undertaken by Advisian for the Clean Energy Finance Corporation (Advisian, 2021), the opportunity identified for hydrogen as a heat source in this sector is the high-temperature calcination process. It has concluded arguably that the retrofit from natural gas to hydrogen for the calcination process is perceived as being straightforward. Combustion of hydrogen in pure oxygen for calcination produces pure water vapour that can be captured by mechanical vapour recompression to drive the low-temperature Bayer process.

As advised by interviewees, the challenges of adopting hydrogen as a heat source for this process include the following:

- Lack of experience with using hydrogen as fuel in the mining sector.
- Cost competition with electrification,[5] where the competition becomes more in favour of electricity when considering that the infrastructure in place for Bayer process can be used for the calcination processes, which avoids maintaining two different types of infrastructure (i.e., electricity and hydrogen).
- Orderly transition – the industry needs to understand the feasibility and viability of transitioning to 100% hydrogen. The competing option is to move along different ratios of natural gas to hydrogen or electricity to hydrogen. Long term operating cost is a major consideration.
- From an operating and resource availably point of view, the industry expects a form of hydrogen reservation policy to protect the domestic customers.

Overall, the appetite for adopting hydrogen in this sector is high. The heat demand that is convertible to hydrogen in this sector equates 190 PJ per annum in Australia. Mining companies have commenced pilots: Alcoa is looking at electrification of the Bayer and calcining process, Rio Tinto is investigating hydrogen for calcining and is undecided for the Bayer process, while South32 is still investigating. This gives an estimated current trajectory of hydrogen for alumina as between 21 to 35 PJ annually.

4.2 Agriculture and food processing

Agriculture and food processing involves various heating applications, such as drying, frying, baking, pasteurisation, rendering, cooking, space heating and cleaning/washing. According to Lovegrove, K. et al (2019), 17.2PJ of heat was used at a temperature of above 250 °C in this sector in 2016-2017. The remaining 98.1 PJ was almost uniformly distributed between temperature below 150 °C and the 150 °C to 250 °C range. This study addressed two key elements of this sector: food and beverage production and meat processing.

According to the subjects interviewed, the preferred decarbonisation pathway for food and beverage production is to start with improving energy efficiency, then look to electrify (mainly with heat pumps) and decarbonise electricity use through onsite PV and green power purchase agreements (PPAs). There appears to be little demand for hydrogen, mainly because of the low-temperature nature of the processes and the relative ease with which they can be electrified. However, the industry is concerned about the future capability of the grid for full electrification and may consider hydrogen as an alternative. We also note the strongly positive indications of innovators in this space in using hydrogen, such as Star Scientific.

5. Electrification would avoid needing to upgrade the facility to be a major hazardous facility.

The preferred pathways for decarbonisation in meat industry were similar. Once again, the preferred path as stated by study participants was to start with energy efficiency measures, such as detailed energy auditing, to provide granular data on energy flow in meat processing plants. The next steps is to electrify with heat pumps, microwaves, and resistance heater with decarbonised electricity (through on-site solar PV and green PPAs). Electrification with low and high-temperature heat pumps is considered to be most economical due to low process temperatures.

Overall, the food and beverage industry has a low appetite for hydrogen at this stage but has not ruled it out. The appetite for hydrogen adoption in the meat sector is negligible.

4.3 Cement

According to the Concrete Institute of Australia (VDZ, 2022), total national cement production was 9.69 Mt in 2021, of which 5.3 Mt is locally produced clinker and cement. Concrete as a downstream product of cement relies on two major pathways for decarbonisation: advanced concrete structure design with less concrete use[6] and decarbonising cement.

The process of cement manufacturing involves several steps:

- the input of limestone and other minerals
- grinding and preheating
- limestone calcination at 900 °C to 950 °C
- clinker production in a kiln at 1,450 °C
- cooling, blending and storing the cement.

Approximately 26% of the emissions released in the production of cement are fuel-based emissions, with most from heating the kiln (VDZ, 2022).

General industry views on decarbonising cement production are to start with decarbonising the electricity use and improving kiln energy efficiency, then moving to using waste materials such as refuse-derived fuel (sometimes called RDF) added to natural gas as a source of heat in rotary cement kilns. Energy efficiency and RDF have already been adopted by several cement manufacturers.

Although biofuels such as biogas can be technically compatible with rotary kilns, their lack of availability and geographical restriction has prevented wider use. According to Lovegrove et al. (2019), the use of waste-based bioenergy is a suitable and growing option for reducing emissions in the calcination process. Such options have already been adopted in several cement manufacturing facilities, proving that it is economical. However, the inherent CO_2 production from the reduction of limestone still requires management, such as via sequestration.

Potential opportunities for hydrogen in the process of cement manufacturing include in preheating the lime, heating the lime at 900 °C to 950 °C, and melting the material at 1,450 °C.

The challenges for switching to hydrogen in rotary kilns as noted by a member of the cement industry in this study include the following:

- Existing rotary kilns require a long flame that enters from one end of the kiln and is extended for tens of metres within it. A hydrogen burner with a capability to produce such a long flame with enough heating power has not been reported, meaning that there is a technology gap. It may not even be technically possible to develop such a burner with enough heating power for this application. If such issues cannot be resolved then a hydrogen retrofit solution cannot be possible, in which case a completely new production system will need to be developed.
- The radiative heat transfer from hydrogen flame should be improved (maybe through adding soot and other flame colouring particles).
- Hydrogen should be available at the location of cement plants. As identified by interviewees, relocating cement plants to locations near hydrogen resources is extremely lengthy, costly and complex.
- The price of hydrogen to cement manufacturers needs to be known and justifiable and this is not currently the case.
- 8% of cement consumed in Australia is imported, and 42% of the total clinker used in the cement industry in Australia is also sourced from overseas (Cement Industry Federation, 2020). In the case of further decarbonisation in local cement manufacturing, nation-wide measures should be in place to track and verify the carbon footprint of the imported cement. Otherwise, the local manufacturers may lose market competitiveness.
- Reservation approaches may be needed to ensure that local cement manufactures will have access to affordable hydrogen if the future hydrogen economy is open to the global market.
- The volumetric energy density of hydrogen should be increased significantly, such as by compressing it to higher pressures. However, even operating with pressurised hydrogen, a single burner may not be able to produce enough heating power.

Because of these perceived complexities and the fact that less than a third of the total emissions in cement production is related to heat, the appetite for hydrogen is low at the time of preparing this report.

6. Noting that cement accounts for only 12% of concrete on a mass basis.

4.4 Pulp and paper

The production of paper is an energy-intensive process. Energy is consumed mainly for two purposes: to separate, process and transport fibre and water using electricity, and to dry the paper with heat. The drying process accounts for 33% and 81% of energy required to produce virgin and recycled paper respectively. The required heat for this process is usually supplied via 120 °C to 150 °C steam (Lovegrove et al., 2019).

After improving energy efficiency and moving to electrify, the next best way to decarbonise pulp and paper production is considered to be replacing fossil fuels with biomass. As a result, this sector offers little competitive opportunities for hydrogen and the appetite for hydrogen is very low in this sector. Most of the thermal process take place at low temperatures suitable for electrification with emerging heat pumps. Additionally, paper manufacturing plants often have access to large biomass resources that can outcompete other alternative fuels.

Further, the Australian pulp and paper industry is a declining sector and is under cost and price pressure, which exacerbates any risk perception of moving to new (and relatively expensive) technology.

4.5 Bricks

Brick production requires heat at above 1100 °C in large kilns. These kilns currently fire natural gas. The high temperature required in these kilns limits the renewable options to either electrification or alternative fuels. Bioenergy, hydrogen, direct electric heating and microwave heating are the potential options for these applications.

Industry participants in this study stated that after improving energy efficiency and moving to electrify, the next best way to decarbonise brick manufacturing is to switch fuels in the kilns to biofuels, and possibly consider hydrogen as well.

The potential application for hydrogen in brick manufacturing is for the large kilns for curing bricks where products are heated in these kilns to 1100 °C. Recent modifications in kiln design and hydrogen burner technologies can enable 100% hydrogen-fuelled kilns in this sector. Kilns for 100% hydrogen fuel are available.

The challenges for adopting hydrogen as noted by members of the brick industry in this study include:

- Cost of hydrogen, where manufacturers are concerned that opening the future hydrogen supplies to international markets can raise its price for them.
- Australian standards and regulations lack clarity and inclusion for hydrogen. The manufacturers are concerned whether plants that burn 100% hydrogen need to be intrinsically safe. This can lead to high costs for the manufacturing plant.
- Uncertainty about whether hydrogen will be realised at scale.

Due to the availability of 100% hydrogen kilns, the end users expressed interest in adopting hydrogen as the heat source, noting they are confident that the quality of the product is not affected by using hydrogen. This total heat load convertible to hydrogen in this sector is ~15 PJ annually.

4.6 Glass

Manufacturing glass and glass related products consume 7 PJ of primary energy for process heat (Lovegrove et al., 2019). The process requires heating materials in a furnace to 1500 °C to 1700 °C. Most of the current furnaces in this sector fire natural gas. Glass industry players tend to see options for decarbonising glass as starting with waste heat recovery.

The promising pathway for incorporating clean energy to glass production is to first electrify the process. The energy portion that cannot be provided by electric power can be switched to hydrogen in a hybrid furnace (Zier, 2021). The appetite for considering hydrogen as an alternative fuel in this sector is strong. The total heat load convertible in this sector is ~6.7 PJ annually.

Early trials for hydrogen-fuelled glass production have shown issues such as discolouration and brittleness. Further research and development is required to address these material compatibility issues.

4.7 Aluminium

Aluminium smelting is the most energy-intensive segment of aluminium supply chain, accounting for 57% of the total aluminium value chain emissions. This sector consumed 51.9 GJ of energy per tonne in 2020 (AAC, 2023) The smelting process is electrified which relies on the grid to decarbonise.

Approximately 5% of the energy consumed in aluminium smelting is used for process heat. The main requirement for process heating is baking of carbon anodes used in the electrolysis smelting pots. In preparation for smelting, the anodes are baked in ovens consuming 2.4 GJ of natural gas per tonne of produced aluminium giving a total of 3.4PJ of natural gas for the 1.6 Mt of aluminium produced annually in Australia. The industry is researching inert anode alternatives which do not require a baking process (thereby removing the need for natural gas) and which do not emit CO_2 as they are consumed in the smelting process. However, inert anodes are yet to be a commercial alternative and it is unknown when this will be possible. Hydrogen represents a possible alternative to natural gas for baking of the anodes.

The total heat load convertible in this sector is ~3.4 PJ/year.

Another segment in the aluminium industry is metal forming, such as aluminium extrusion. Aluminium forming requires large amount of heat at medium-to-high temperatures of up to 375 °C to 590 °C for aluminium extrusion processes. For other applications, such as powder coating, heat is required at less than 250 °C. The potential opportunity for hydrogen includes both the high-temperature extrusion and low-temperature powder coating processes, but after energy efficiency and electrification initiatives have been pursued. The usual issues of hydrogen availability and cost then need to be managed.

Overall, hydrogen is considered an option by industry participants as an option, but not one of the immediate pathways. The uncertainty over the capability of the grid for the full electrification of the industry is a positive force for considering hydrogen. There is currently a low appetite for it in this sector.

4.8 Other - metal fabrication, forging, mineral processing (non-ferrous and alumina), etc.

Fabricated metal products consume around 4 PJ of heat that is almost uniformly distributed across all temperature ranges from 250 °C to more than 800 °C. Electrification has been a common method of supplying process heat to these applications. Widely used heating methods include electric furnaces, induction heating, combustion-based ovens, natural gas burners and infrared heating.

An energy intensive mineral processor needs to address Scope 1 emissions in its process heating and reductant processes. Investigation into replacing existing reductants (coal and coke) with hydrogen and biochars is currently in progress. Natural gas flames for high temperature process heat currently use coil type burners to >900 °C. Biogas is seen as hard to secure. Sites are considering converting boilers due to proximity to neighbouring hydrogen production hub.

The options for decarbonisation pathways in this sector are in the following order:

1. Process integration/optimisation first to reduce energy use
2. Electrification and decarbonising the electricity use
3. Hydrogen.

There is a potential opportunity for hydrogen both as reductant and to fuel the high temperature processes, and this sector is currently interested in hydrogen as a potential solution. However, the usual challenges for switching to hydrogen apply, such as uncertainty about cost and local supply. Due to its potential suitability for this sector, hydrogen is considered an option, but is not one of the immediate pathways.

Appendix A - Literature reviewed for this study

Table 8: Literature investigating the use of hydrogen and biogas for industrial process heat.

Project/report name	Investigator	Status
Australian hydrogen market study, Sector analysis summary	Advisian Pty Ltd	Completed in 2021
Renewable energy options for Australian industrial gas users	ITPower Australia / ARENA	Completed in 2018
Renewable energy options for Industrial process heat	ITPower Australia / ARENA	Completed in 2019
Where are the most viable locations for bioenergy hubs across Australia?	University of Adelaide (ECMS)	Completed in 2022
Australia's massive opportunity for underground hydrogen storage	Commonwealth Scientific and Industrial Research Organisation	Completed in 2021
Modelling Future Fuel Options for Australia	University of Adelaide, Energy Network Australia, Victoria University	Completed in 2021
Advancing Hydrogen: Learning from 19 plans to advance hydrogen from across the globe	University of Adelaide	Completed in 2019
Lessons learned from major infrastructure upgrades	RMIT University	Completed in 2020
Regulatory mapping for future fuels	RMIT University; GPA Engineering, University of Sydney	Completed in 2020
National Hydrogen Roadmap	Commonwealth Scientific and Industrial Research Organisation	Completed in 2018
Hydrogen for Australia's Future	Commonwealth of Australia	Completed in 2018
IEA Bioenergy	International Energy Agency	Continuing
A Roadmap for Decarbonising Australian Alumina Refining	ARENA	Completed in 2022
Anaerobic Digestion for Electricity, Transport and Gas. An opportunity assessment for the RACE for 2030 CRC	Griffith University, University of Technology, Sydney, The Australian Alliance for Energy Productivity	Completed in 2023
Electrification and renewables to displace fossil fuel process heating. An opportunity assessment for the RACE for 2030 CRC	University of South Australia, Queensland University of Technology, RMIT University, University of Technology Sydney, The Australian Alliance for Energy Productivity	Completed in 2021
Australian hydrogen market study, Sector analysis summary	Advisian Pty Ltd	Completed in 2021

Appendix B - Research participants

This study was carried out in three phases between September and December 2022, with each set of conversations building on the previous phase.

In Phase 1 members of the study team met with representatives of academic and industry research bodies as shown in Table 9.

Table 9: Organisations interviewed in Phase 1 of this study.

Institute	Expertise
RMIT University	Combustion – hydrogen burners
RMIT University	Combustion – Internal combustion engines
CSIRO	Alternative fuels
Adelaide University	Alternative fuels
Adelaide University	Combustion – hydrogen burners
Future fuels CRC	Alternative fuels

Phase 2 was a series of interviews with suppliers of equipment, such as burners, boilers, kilns, furnaces, and ovens and associated instrumentation. These are shown in Table 10.

Table 10: Organisations interviewed in Phase 2 of this study.

Supplier	Type of technology	Commercial Readiness
Furnace Engineering	Furnaces/ovens	Considering hydrogen systems
FCT Combustion	Burners	Develops and delivers hydrogen burners for up to 100% hydrogen
Honeywell	Burners	Develops and delivers burners for up to 100% hydrogen
Bosch	Boilers	Ready to deliver hydrogen ready and hydrogen capable boilers
SAACKE	Burners	Ready to supply burners for up to 100% hydrogen

Table 10: Organisations interviewed in Phase 2 of this study. (continued)

Supplier	Type of technology	Commercial Readiness
DIREXA	Kilns	Ready to supply hydrogen-fuelled kilns to heavy industries
Star Scientific	Hydrogen oxidiser	TRL 5-6
O'Brien Energy	Boilers	Ready to supply boilers for up to 40% hydrogen
Simons Boilers	Boilers	Not ready to supply hydrogen boilers
East Coast Steam	Burners	Ready to supply burners for hydrogen blends
Windsor Energy	Boilers	Ready for biomass boilers but early stage for hydrogen boilers
Tomlinson Energy	Boilers	Developing their capabilities
Endress and Hauser	Instrumentation	Ready to deliver instruments and valves for hydrogen

Phase 3 was a series of interviews with manufacturers of alumina, aluminium, cement, bricks, glass, pulp and paper, food, beverages, and metals. Thes organisations are shown in Table 11.

Table 11: Organisations interviewed for Phase 3 of this study

Sector	Entity	Final products and services
Building materials	Boral	Cement
	Adbri	Cement
	MECLA	Cement
	CSR	Brick
	Brickworks	Brick
	Concrete Institute of Australia	Cement to concrete
Metal forming	Capral	Extruded aluminium
Other Metals Processing	Tronox	Titanium dioxide pigment

Table 11: Organisations interviewed for Phase 3 of this study. (continued)

Sector	Entity	Final products and services
Beverage and dairy	Coca-Cola Europacific Partners	Soft drink
	Lion	Brewery
	A2 Milk	Dairy
Meat processing	Australian Meat Processor Corporation	Meat products
	Australian Pork	Meat products
	Teys Australia	Meat products
Pulp and Paper	Visy	Various
	Opal	Various
	Borgs	Various
	Kimberly Clark	Various
	Norske Skog	Various
	Australian Forestry Products	Various
Alumina	Rio Tinto	Alumina
	South 32	Alumina
	Alcoa	Alumina

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