Renewable energy options for industrial process heat

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pitt&sherry

Institute for Sustainable Futures

beyond ZERO emissions

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ITP

ITP Thermal Pty Ltd, is a part of the ITP Energised Group (ITP), which was formed in 1981 and is a specialist renewable energy, energy efficiency and carbon markets engineering and consulting group of companies. It has member companies and offices in the UK, Australia, India and China and has completed projects throughout the world.

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RENEWABLE ENERGY OPTIONS FOR INDUSTRIAL PROCESS HEAT

Study commissioned by the Australian Renewable Energy Agency (ARENA) to determine the potential opportunity for integrating renewable energy into industrial process heat applications in Australia. This report documents the analysis undertaken by ITP in conjunction with Pitt&Sherry, the Institute for Sustainable Futures, Sustainability Advice Team and Beyond Zero Emissions. It highlights technology options for renewable process heat applications across Australian industries and provides indicative cost estimates for renewable energy compared with fossil energy.

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EXECUTIVE SUMMARY

Key findings

- ***Australian industry accounts for 44% of the nation's end use energy and 52% of that is process heat, with an indicative value of $8 billion per year.***
- ***At present, heat is predominantly provided by gas combustion with coal the second biggest source.***
- ***There are more than 1,500 industrial sites using process heat, with the majority using less than 0.1PJ/year , however the bulk of the heat use is in a smaller number of large sites using more than 5PJ/year, such as alumina refineries and iron and steel production.***
- ***There are renewable options for all current industrial uses of process heat.***
- ***Renewable energy approaches to process heat using bioenergy, geothermal, renewable electricity, renewable hydrogen and solar thermal all have roles to play.***
- ***Process re-design, combined heat and power, and location of greenfields developments to benefit from available renewable resources, offer potential for overall least cost solutions.***
- ***Short term opportunities for renewable substitution of fossil fired heat that are already economic are estimated at 56PJ/year, equal to 12% of total industrial gas use for heat.***
- ***The level of industrial experience with renewable heat remains low and barriers include a low appetite for risk and short payback time expectations by industry.***
- ***Restructuring of ammonia and iron and steel production around the use of Renewable hydrogen could be central to achieving deep reductions in fossil fuel use in the long term.***

Introduction

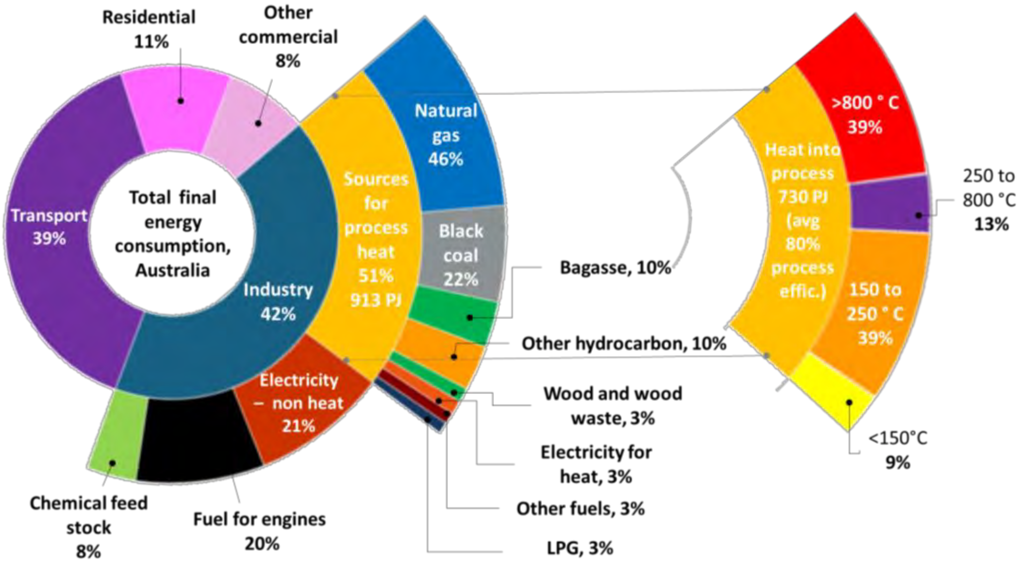
Australia, along with many other countries has accepted the goal of working to reduce greenhouse gas emissions to limit global warming to less than 2^{o}C. This implies a reduction in emissions to close to net zero by around 2050.

In Australia and many other countries, to date, much of the attention has been focussed on electricity production. However, end use energy in Australia is 30% in the form of heat, compared to 20% as electricity. Much of that heat use is by industry, where the uses are varied, complex and critical to continued operation.

This report was commissioned by the Australian Renewable Energy Agency (ARENA). Consistent with ARENA's goal to increase the supply and improve the competitiveness of renewable energy in Australia, this study examines the potential opportunity for using renewable energy in industrial process heat applications to reduce greenhouse gas emissions and to increase energy productivity.

Industrial process heat use in Australia

The following diagram provides a progressive breakdown of industrial process heat in the context of total final energy use in Australia.

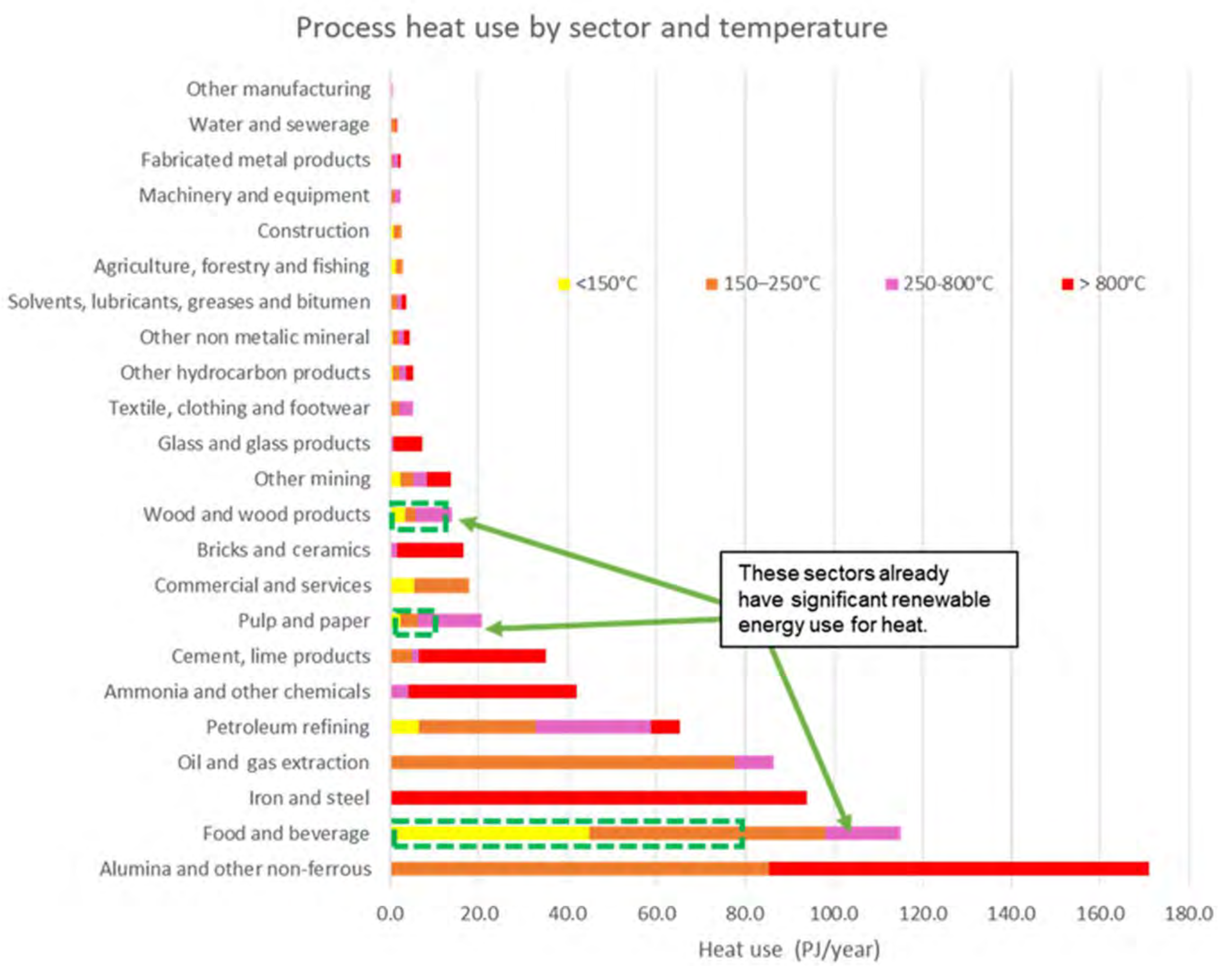


Based on interpretation of Australian Energy Statistics (AES) data from 2016-17, industry[1] is responsible for 42% of total final energy consumption. Of that, 51% is fuel used for process heat. The dominant existing fuel for heat is gas, with black coal the second largest. The actual heat used is less than the fuel consumed and can be categorised by temperature and ranges from less than 150°C to over 800°C.

At an indicative price of $10/GJ the annual cost to industry for process heat supply is around $8 billion. Clearly this justifies consideration of new energy options that could lower cost as well as improve environmental outcomes.

Analysing the quantities of heat used by industry sector and also by the specific temperature of use for each sector gives the following view:

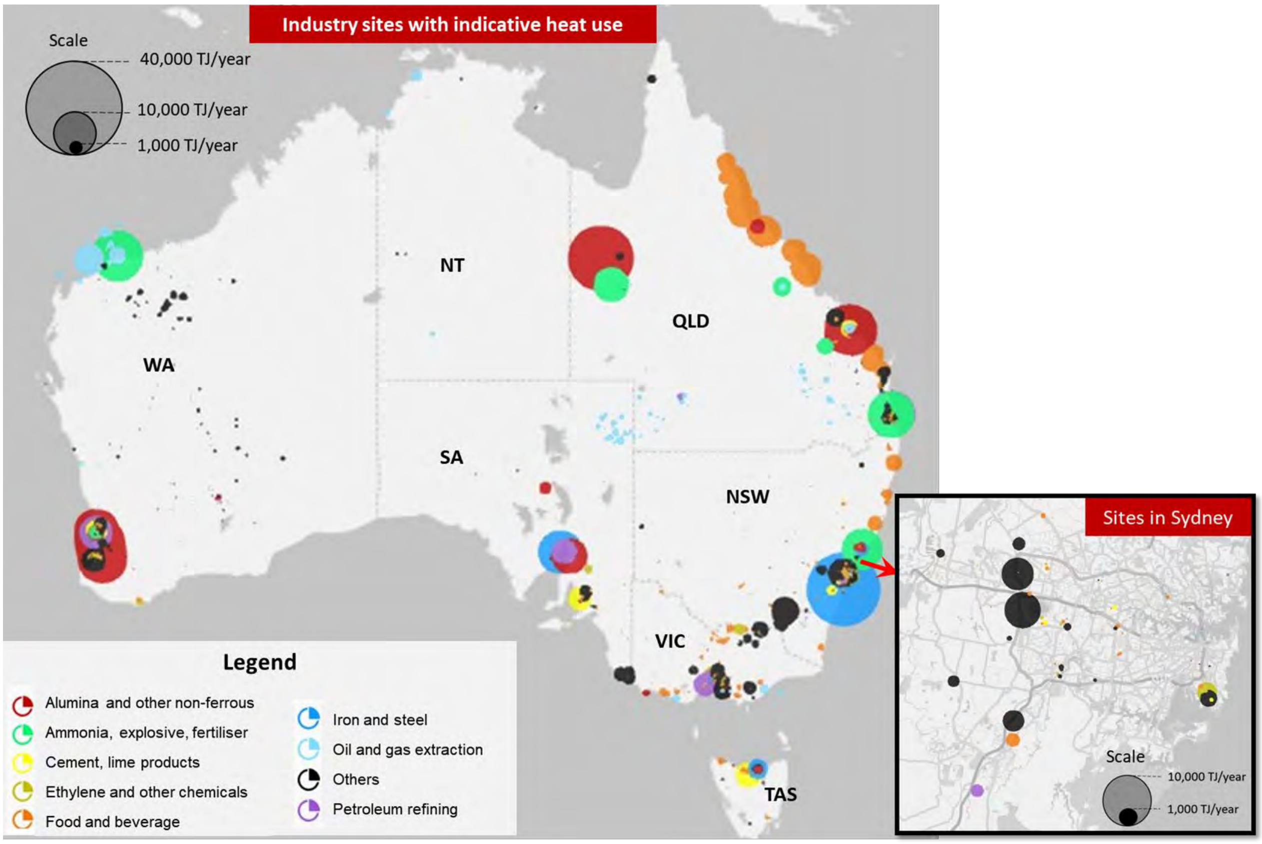
[1] In this study, industrial process heat use includes all heat use that is not transport, power generation, residential or the heating of commercial buildings.



It is apparent that some sectors are very large users of process heat. The top three are Alumina and other non-ferrous minerals, Food and beverage, and Iron and steel. Food and beverage however drops to number six if the heat provided by the combustion of fossil fuel only is considered, as there is already a large use of sugar cane waste (bagasse) at sugar refineries. The Pulp and paper and Wood products sectors also use significant amounts of biomass.

Location

The distribution of key industries and their heat use is illustrated in the map over the page. It shows varied concentrations of manufacturing activity around the populated city and coastal regions, plus activity that is associated with production of key industry inputs in regional areas. Each of the capital cities has within it a range of smaller manufacturing sites, as shown below for Sydney.



The location of specific industry facilities and the level of energy use by them is a key input to assessing the potential for renewable energy to be used for process heat, because the latter is based on available resources, land use cost and restrictions, and the economics of specific applications and supply options. Where electrification processes or fuel switching to renewable hydrogen is favoured, geographical location is less critical.

Cost of energy from fossil fuels

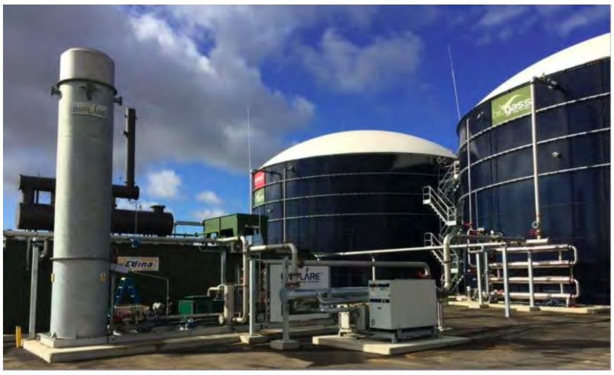
Overall energy costs include transmission, distribution, and connection servicing/retailing costs as appropriate, in addition to the wholesale cost of the energy. Contractual arrangements are complex and deal with each aspect separately so that the marginal cost of an additional unit of energy can be much lower than the overall total average cost of energy supply. Very large energy users typically pay something close to the wholesale price of the energy, whatever the type. Small users pay up to two to three times higher than wholesale.

Following the expansion of the LNG export industry, gas prices are now closely linked to international market prices. At present this means around \$8 - \$10/GJ for large users, while small users can be paying over \$20/GJ. Questions remain about the ability of large users to secure reliable long-term contracts for supply. LPG is more expensive than natural gas but is used when sites are too far from the gas network to be economically connected. Coal is the cheapest fossil fuel at around \$3 - \$5/GJ for a large consumer, depending on transport distance. Electricity is around $100 a megawatt hour (MWh) for large consumers and over $200/MWh for small. If converted directly to heat (e.g. in a resistor), this corresponds to $28/GJ and $56/GJ respectively. In some cases, however, using electricity can result in major reductions in the amount of energy needed (e.g. via heat pumps).

Renewable energy technologies

The relevant renewable energy technologies that can directly substitute for fossil fuels for industrial process heat are discussed below:

Bioenergy



Bioenergy systems involve either anaerobic digestion of wet waste materials or combustion or gasification of dry biomass solids. Bioenergy systems are the largest source of existing renewable process heat and are increasingly adopted where a low or zero cost biomass resource is available. In such cases they are often already cost competitive with gas or other fossil fuel sources. The long-term limiting factor on bioenergy adoption is the size of the biomass resource, however there is scope for much more uptake. Meeting up to around 30% of total national heat demand is technically possible.

Geothermal

The technically feasible geothermal solution in Australia is to exploit the heat in hot sedimentary aquifers, which can be up to 95ºC. The great artesian basin, which covers much of inland Queensland and NSW, is the best known of these. Although the present location of many industrial heat users around the high population coastal regions rules this out as an option, it could be very cost effective for those suitably located with a heat demand at those temperatures. Whilst there are some working examples in Australia, this appears to be an under-exploited opportunity in the areas where it is available.

Renewable electricity

Electric-driven heating options include heat pumps, electromagnetic heating, resistance heating and electric arc systems. These become renewable sources of heat if the electricity is produced renewably. Heat pumps are notable for delivering considerably more heat than the electricity consumed, particularly for small lifts in temperature. They extract heat from the environment or other sources like waste energy streams. Heat from the environment can be considered renewable irrespective of the electricity source for the heat pump. In some cases, electromagnetic heating can offer in some cases better optimised and hence more efficient delivery of heat to redesigned processes. It is possible to develop electric-driven options for all process heat applications if processes are suitably redesigned. It is also possible in some instances to replace process heat applications entirely using electrically-driven options, for example high pressure sterilisation. For large industry in particular, electrification of processes would be subject to network capacity in the supply area and/or onsite generation opportunities.

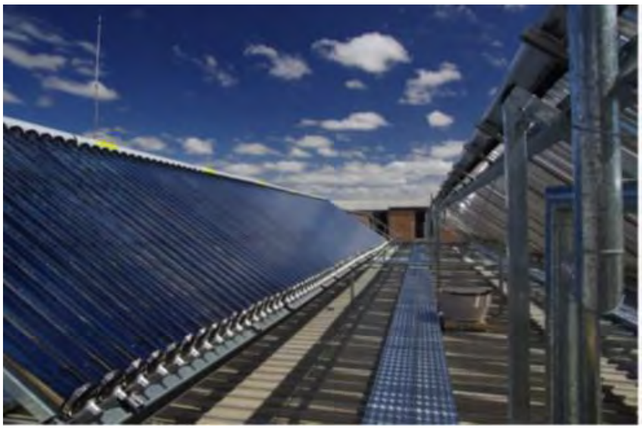
Renewable hydrogen

With natural gas being the biggest current source of process heat, hydrogen could in principal provide a substitute fuel with the minimum process change. Hydrogen is already made and used at scale from the steam reforming of natural gas. Renewable hydrogen could come from renewable electric-driven electrolysis of water or gasification and conversion of biomass. Other approaches, such as solar thermal water splitting, are in the development phase. While renewable hydrogen is currently much more expensive than natural gas, large cost reductions are predicted within the next decade. Blending can be done as an interim step to lower emissions with little or no change to equipment. Hydrogen can be stored and transported, thus negating the need for on-site renewables, and can also be used to power very high temperature processes that cannot be electrified.

Hydrogen could also be produced through biomass gasification if there was a sufficient resource available. It would need major investment in post processing and purification of the gas to be acceptable. In the medium term it could be a cost-effective way to introduce renewable hydrogen, however, it is hard to see the volumes required being available in Australia for the large hydrogen demand expected in the medium to long term.

Solar thermal

Commercially solar thermal technologies are available for all temperatures. Low temperature non-concentrating systems are cheaper, while higher temperatures require more complex and expensive concentrating systems. The low temperature systems already appear to be cost effective relative to existing fuels. Australia’s excellent solar resources make solar thermal an attractive option for many locations, subject to the availability of sufficient land area at suitable cost.



Whilst there are a few pilot installations, there appears to be considerable scope for wider adoption of solar thermal process heat.

Process optimisation

Industrial energy users are concerned by the increased cost of gas in recent years. This contributes to an interest in renewable energy options. Very few renewable options however can offer a return to very low historical costs, rather they offer a way to achieve a cap on costs with greater certainty and better environmental outcomes. Thus, careful consideration of available energy efficiency measures should always be the first step.

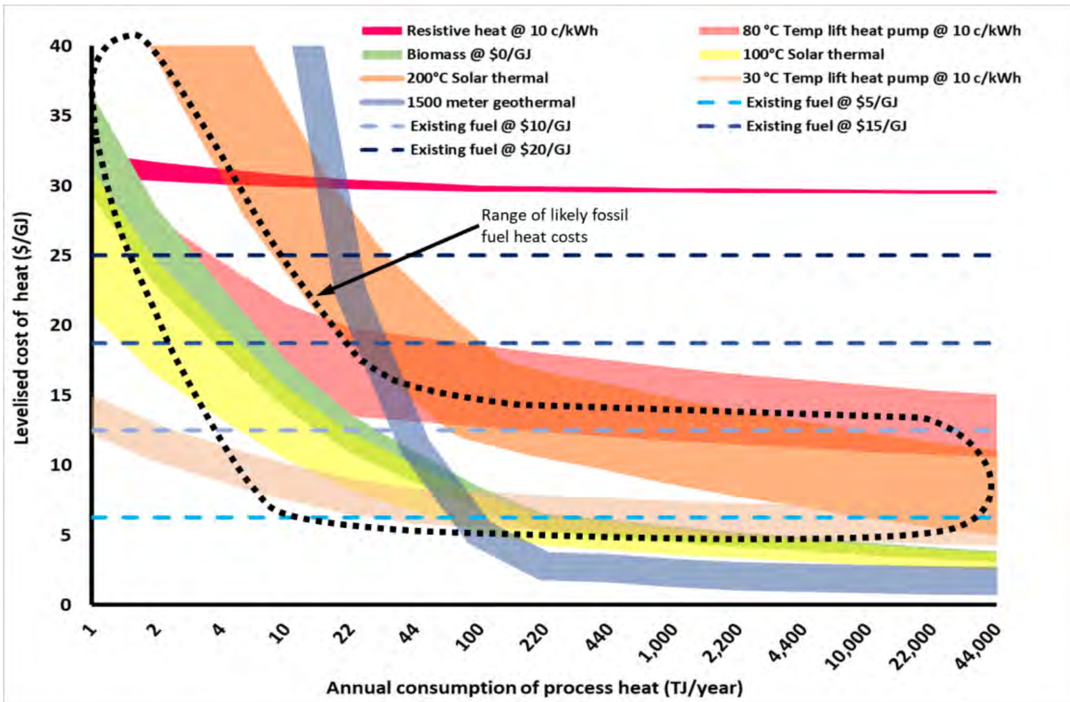
While avoidance of technical risk will tend to favour direct substitution of renewable for fossil heat sources, long-term strategic approaches suggest a more holistic approach that includes process redesign and optimisation. Key approaches include:

- Cascading input energy through stages of use to maximise value. Combined heat and power (CHP)[2] systems are a classic example of this.
- Delivery of energy directly to the point of use at closer to the minimum required temperature. This reduces what can be high thermal losses from large heat transfer fluid distribution networks and also benefits from the reduced cost of lower temperature sources. Electrical technologies offer advantages with this.
- Redesign of processes, to substitute mechanical or other approaches in the place of basic heating, or to simply improve the energy efficiency of heat use to reduce the investment requirements for the renewable energy equipment. Use of UV radiation for sterilisation instead of heat is a key example.
- Adjusting times of operation or processes to match the availability of renewable resources. This could involve operating heat-using steps in batches to match resources availability, with the stockpiling of intermediate products, or the introduction of thermal storage technologies to bridge the timing issues.
- Consideration of location of new greenfields developments to co-locate with favourable renewable resources.

Economics

Notwithstanding the potential for reducing energy use through process optimisation, it is valuable to examine the current economics of direct substitution of heat with renewables. The following graph compares the “levelised cost of heat” (LCOH)[3] from a selection of representative scenarios for various renewable options.

[2] Combined heat and power systems are also often referred to as cogeneration systems.
[3] A levelised cost of heat, amortises the investment cost across lifetime energy production whilst also allowing for the variable costs of operation such as fuel.



This is plotted against the annual consumption of process heat[4], on a logarithmic scale. LCOH amortises the capital investment across lifetime energy production, plus allows for any input costs. The capital cost contribution to LCOH is very size dependant, with strong economies of scale apparent in the reduction in LCOH as size of the system increases. The 'existing fuel' lines are flat since the plant is assumed to be fully depreciated and only the contribution from the marginal cost of fuel is covered. Also shown is an indicative outline of the range of process heat costs from fossil-fired systems. This also shows a strong size dependence. This is because large users pay much less for their energy than smaller ones do. In the case of gas, large users are connected directly to the transmission system and pay close to the wholesale price, smaller 'mass market' users are connected to the distribution system and pay much more.

This representative analysis indicates that there are renewable process heat options with an LCOH close to or below the existing cost of heat, in many cases, across all sizes of system.

Technology-specific observations that can be made from this include:

- Biomass options look currently competitive across all sizes as long as the feedstock is zero or low cost (such as a waste stream).
- Heat pumps with low temperature lift and low cost of electricity are competitive across all sizes.

[4] To place this in context a large Alumina plant uses around 30,000 to 40,000TJ/year, whereas a modest sized factory in the food sector might use 20TJ/year

- Low-temperature solar thermal is competitive across all sizes if the solar resource is good, subject to land or roof area availability. Higher temperature concentrator systems are more likely to be competitive in larger systems.
- Although not shown here, CHP systems using biomass or solar thermal inputs are favoured for larger systems compared to heat only systems, as long as electricity has a value of around 10c/kwh or more.
- For low temperatures, geothermal heat can be attractive. However, to justify the minimum fixed costs of a single pair of wells, annual heat use needs to be greater than around 20TJ/year.
- Final end use efficiencies vary widely across industries and can have a significant impact on the actual cost of useful heat delivery. For example, after allowing for distribution and other losses, some steam applications may have an end use efficiency of 50% or less.

Improving process efficiency should be one of the first steps when considering future supply options, especially when moving from those where economics depend on volume of fuel use to those where economics depend more on initial capital cost.

Future trends will be to a reduction in costs for renewable solutions as the technologies are further deployed. Fossil fuel costs are subject to globally-driven cost fluctuations.

Observations for key sectors

Alumina and other non-ferrous minerals

Australia's six alumina refineries are responsible for a large share of process heat use. Other important contributors to heat use in this sector are copper, nickel and zinc refineries. Heat use is split between digestion processes below 200°C and calcining processes above 800°C. The large scale of plants and their location tends to preclude significant bioenergy contributions. The low temperature heat is amenable to solar thermal solutions or renewable electric-driven mechanical vapour (steam) recompression, and these appear close to economic compared to current gas costs. The higher temperature processes could be addressed with renewable hydrogen as a replacement fuel or other approaches, but require process modification and improvement in the cost benefit position. There is scope for new green field refineries and other plants, located to maximise benefit from renewable resources. Australia could position itself for growing global demand for zero emissions aluminium, copper and other non-ferrous metals.

Food and beverage

The food and beverage sector is notable for the existing large use of biomass in the form of sugar cane waste in sugar refineries. However, there is still 37 PJ of heat in other subsectors provided by fossil sources, predominantly gas and limited quantities of coal and LPG. All the renewable approaches should be considered in this sector, with many applications already economic or close to economic. Lower temperature processes like washing and sterilising have the most options. Bioenergy is particularly good for sites that generate their own waste. There are many opportunities for process redesign. Ultimately use of renewable gas (hydrogen or methane) can ensure all processes could be converted.

Abattoirs, dairy processing, fruit and vegetable processing, breweries and various other sub-sectors, all of which use only hot water and low pressure steam, which, together with the non-metropolitan location of many plants and the availability of biowaste in many cases, makes them attractive targets for early adoption of renewables.

Some sugar mills have been modernised/rebuilt to become much more efficient, meaning that they are able to export a significant proportion of the electricity they generate. Doing this at all sugar mills is an untapped potential source of more dispatchable renewable electricity and heat. Such sites could also adapt hybrid approaches with other renewable and process design options to maximise the overall value produced.

Ammonia and other chemicals

Production of ammonia is a very large user of natural gas; polyethylene is the second largest user in the sector. In the case of ammonia, steam reforming of methane is the major use of process heat as well as the source of hydrogen feedstock for ammonia[5].

There is considerable interest in the feasibility of using renewable hydrogen as an alternative feedstock for ammonia production, and some feasibility studies are currently underway. This is not economically competitive in the short term, but it represents the easiest major strategic industrial transformation and is linked to the idea of future renewable energy exports. There could be particular advantages in the context of a greenfield development dedicated to emissions free ammonia. In such a context, the capital investment in steam reforming can be avoided, helping to offset other costs.

In the medium term, various groups around the world have demonstrated pilot-scale solar-thermal driven steam reforming of methane, including the CSIRO at Newcastle. This has the potential to replace a major proportion of identified process heat if methane continues to be used as a feedstock. This is an encouraging future prospect worthy of continued effort, which is not too far from being economically viable at current cost of natural gas.

Iron and steel

The Iron and steel sector is notable as the major user of coal as its source of process energy[6] in blast furnaces. The coal (by means of coke) is needed to heat the material and also remove oxygen from the iron ore. Some renewable energy substitution within existing facilities is possible.

[5] In this study we exclude the reactant feedstock from our definition of process heat.
[6] In the case of Iron and steel we treat all the coal as providing process heat. Although much of it is needed to remove the oxygen from the iron oxide ores, it does not in itself become part of the product in the way that natural gas does in ammonia production.

Whilst Brazil has demonstrated that biochar can be substituted for coke, it would require a huge amount of biomass to convert steel making, which would be very challenging in Australia. Globally there are commercially mature advanced iron production methods based on direct reduction using gas mixtures produced from natural gas. These are then followed by electric arc furnaces for the final stages of steel making. These can be the basis of future systems that use renewable hydrogen but require the construction of completely new facilities. Whilst not yet cost effective, if the world moves to emissions free iron and steel, Australia has both the iron ore and renewable energy resources to be a competitive provider in that context. Previous efforts to establish significant sized pilot systems in Australia could be re-visited.

Cement and lime

Cement kilns work at very high temperatures. They are able to very effectively utilise a wide range of bioenergy waste materials. In Australia they are already doing so, indicating that they are cost competitive with gas and even coal. There is scope to further expand their use economically. In the context of efforts to reduce GHG emissions however, there is the bigger issue of the CO_2 inherently produced from the reduction of limestone. To address this, the world will need to move to alternative cement materials or apply carbon capture and storage.

Pulp and paper

This sector is a large user of steam and hot water, with the five Australian mills that produce pulp from timber being the biggest sites. The sector is already a significant user of renewable energy through use of its own biomass waste products, currently providing around 50% of the sector's overall needs. There is scope to increase this and to further supplement it with solar thermal and electrically-driven processes. Focus on increasing use of these biofuels for higher value dispatchable electricity generation from CHP could increase the value returned.

Oil and gas

The major use of process heat in this sector is for the regeneration of scrubbing systems that remove CO_2 from gas. Whilst a big use of heat, it is actually only a very small fraction of the energy streams being processed. It is also largely provided by waste heat from gas turbine-driven compressors and other sources. However, if such drives are converted to electricity, then not only could that electricity be provided renewably, the waste heat could also be addressed with renewable options, considering the modest temperature required.

The bigger long-term issue for this sector is how it will evolve in a world moving to reduce GHG emissions. It may metamorphose into or be overtaken by a renewable / zero emissions electric or hydrogen based approach for transport.

Other sectors

There are many diverse operations in other smaller sectors. Ceramics and glass, textiles, agriculture and activities such as laundries in the commercial and services category are key examples. Heat is used across all temperature ranges and all renewable energy options should be considered on a site-by-site basis.

Examples include:

- Microwave heating can be retrofitted to gas-fired brick kilns. Experience in the UK indicates a 50% reduction in energy use and a 60% reduction in firing time is possible.
- The main uses of natural gas and LPG in agriculture are for glasshouse heating and for heating poultry sheds. Although relatively small in terms of total energy, bioenergy-based heating is increasingly being adopted. These would also appear to be highly prospective applications of solar thermal energy.

Motivations and challenges

There are demonstrated and available renewable energy technologies for every application of process heat. However, not all are sufficiently proven in a commercial sense to make the risk of change acceptable, as subtle technical differences can be important in many applications. These risks are not just to the provision of process heat itself, but can affect aspects of product quality, continuity of supply, and business competitiveness. This is especially so with process substitution. Not all are sufficiently economic to be a choice that will maintain competitiveness and make business sustainable. Not all fit with the level of skills available in a particular industry or region. Not all can be employed at the scale necessary for any given application. As a result, the level of industry experience remains low and so uptake represents a challenge. In seeking to advance the uptake of renewable heat in industry, it is important to understand the drivers and barriers that industry faces.

In addition, whilst positive internal rates of return are apparent for many renewable energy solutions, companies typically require simple payback times of just a few years for their energy investments. In contrast to these difficulties, however, it is clear that industry in the main understands that its future may depend on these new ideas, is actively scanning for viable new ideas, and is investing in the assessment of potential new ideas. When issues become an existential threat, actions can be taken with higher technical risk and with longer-term payback.

The biggest driver for increased uptake is likely to be the visible presence of relevant working examples and this may need assistance for initial pilot systems.

Opportunities

The level of opportunity by sector is estimated as:

Sector	Total fossil heat use in PJ/year	Opportunity potential (ST - 0 to 5 yrs potential; MT - 5 to 10 yrs potential; LT- 10 to 20+ yrs)		Key process	Bioenergy	Geothermal	Heat pump	Other electric	Solar thermal	Hydrogen	Comments
Alumina and other non-ferrous	169	ST	9	Alumina digestion, calcination			✓		✓		Low temperature portion is accessible in medium term if barriers overcome. High temperature processes need R&D and global demand for zero emissions product
		MT	67				✓		✓		
		LT	93				✓		✓	✓	
Iron and steel	94	ST	0	Iron ore reduction, steel production							Needs global demand for zero emissions products, will require major investment in new plants
		MT	5		✓						
		LT	89					✓		✓	
Oil and gas extraction	87	ST	4	CO2 scrubbing regeneration, steam							If drives are electrified, low temperature heat can be addressed by other techs. In LT, linked to future of transport fuels
		MT	18				✓		✓		
		LT	65							✓	
Petroleum refining	65	ST	3	Distillation, hydrogen use							Some MT opportunities at medium temperatures. LT linked to future of transport fuels
		MT	13		✓		✓	✓	✓		
		LT	49							✓	
Ammonia and other chemicals	42	ST		Steam reforming of methane, steam							Needs global demand for zero emissions products, could be first segment to adopt renewable hydrogen as energy input.
		MT	8						✓		
		LT	34							✓	
Food and beverage	37	ST	7	Hot water, frying, steam, baking	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	19		✓	✓	✓	✓	✓		
		LT	11		✓	✓	✓	✓	✓	✓	
Cement, lime products	34	ST	10	Calcining, roasting	✓						Strong existing use of bio waste can grow. Long term future of the sector unknown
		MT	16		✓						
		LT	8							✓	
Commercial and services	18	ST	9	Steam	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	9		✓	✓	✓	✓	✓		
		LT			✓	✓	✓	✓	✓	✓	
Bricks and ceramics	16	ST	3	Kiln heating	✓						Well suited to bioenergy if resource is available. Some electrification potential also
		MT	8		✓						
		LT	5		✓					✓	
Pulp and paper	14	ST	2	Hot water, process steam	✓						Strong use of bioenergy already, Progress may be limited by biomass supply, leverage other RE technologies for lower temperature processes
		MT	6.3			✓	✓	✓	✓		
		LT	6			✓	✓	✓	✓		
Other mining	14	ST	3	-	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	4		✓	✓	✓	✓	✓		
		LT	7		✓	✓	✓	✓	✓	✓	
Glass and glass products	7	ST	0	Glass melting							Progressive switch to electric resistance heating plus bioenergy
		MT	3		✓			✓			
		LT	4					✓		✓	
Other sectors	31	ST	6	-	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	9		✓	✓	✓	✓	✓		
		LT	16		✓	✓	✓	✓	✓	✓	
Total	**628**	**ST**	56								
		MT	185.3								
		LT	387								

The short-term (ST) opportunities are those using existing technology that are immediately economic, medium-term (MT) opportunities would be aided by measures to spur industry uptake and long-term (LT) represents a vision for an emissions free industry, with major structural change required, and a role for R&D, policy and funding to create the value chain that will make this happen.

The total short-term opportunity, estimated at 56PJ/year, corresponds to around 12% of industrial gas use for heat, which is significant in light of tight supply concerns.

There are examples around the world where renewable heat uptake has been boosted through capital subsidies and loans, renewable energy targets, technology demonstration, tax incentives and planning codes.

Conclusion

Renewable process heat represents a major opportunity for Australia. So far most renewable energy deployment has been in the electricity sector, but electricity is currently only around 20% of national end use energy, although this is expected to grow with increased electrification of transport, space heating and industrial processes. There are renewable options for all current industrial uses of process heat. Renewable energy approaches to process heat using bioenergy, geothermal, renewable electricity, renewable hydrogen and solar thermal all have roles to play.

There are a range of options for use of renewable energy that are apparently economic when compared with heat produced at current fuel prices, and could certainly be economic if appropriately supported to recognise the environmental benefits and reduce the risks of early uptake. However, there is no simple answer and there are no silver bullets that will solve all problems.

The level of industrial experience with renewable heat remains low and barriers include a low appetite for risk and short payback time expectations by industry.

Opportunities range from near-term approaches that are already economic compared to current fossil fuel prices and simply require encouragement to overcome decision making lag, to long-term visionary approaches that involve restructuring key industries. In the visionary area, restructuring of ammonia and iron and steel production around the use of renewable hydrogen could be central. Ultimately it needs action in a global context, however, Australia has the natural advantages of both raw material and renewable energy resources to be very competitive in these industries in a low emissions world.

1. INTRODUCTION

Australia along with many other countries has accepted the goal of working to reduce greenhouse gas emissions to limit global warming to less than 2°C. This implies a reduction in emissions to close to net zero by around 2050. The transition to renewable energy technologies has developed significant momentum in Australia and globally. The transition is by its nature disruptive, there are huge challenges for energy users, large and small, trying to chart to future uncertainties of changing policy environments, changing fossil fuel costs and emerging renewable energy technologies.

This report has been commissioned by the Australian Renewable Energy Agency (ARENA). Consistent with ARENA's goal to increase the supply and improve the competitiveness of renewable energy in Australia, this report seeks to examine the potential opportunity for using renewable energy in industrial process heat applications to reduce greenhouse gas emissions and to increase energy productivity.

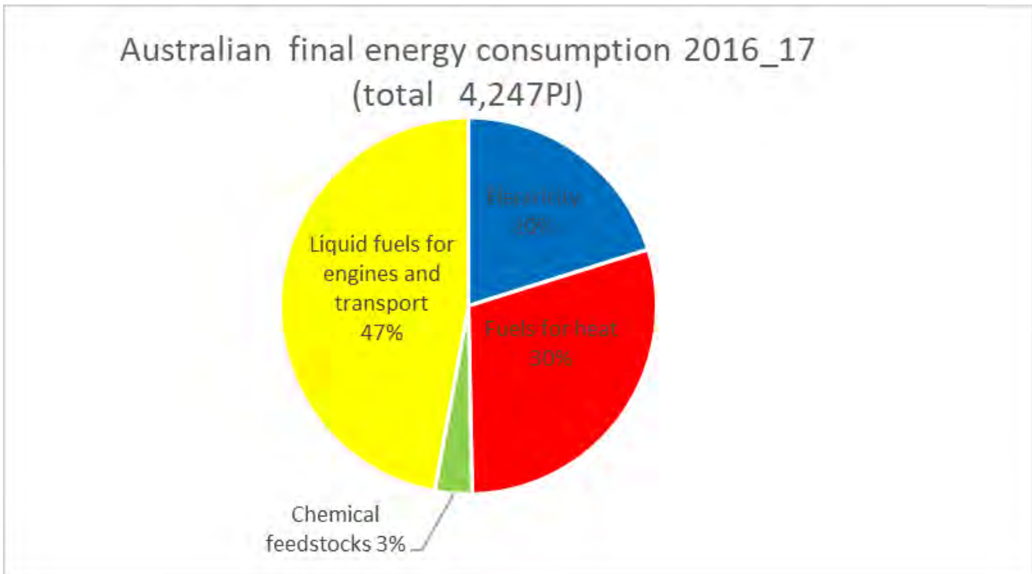


Figure 1: Final energy consumption in Australia 2016-17. Based on Australian Energy Statistics data.

In Australia and many other countries much of the attention to date has been focussed on electricity production. However, as shown in Figure 1, final energy consumption in Australia is 30% in the form of fuels for heat, compared to 20% as electricity[7]. Much of that heat use is by industry, where the uses are varied, complex and critical to continued operation. Although electrification of transport and of building heating and cooling is expected to increase the overall

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[7] This allocation has been determined by examining the AES data by fuel type and sector and estimating the allocation to end use energy type in each case. Note that a small fraction of the electricity is also used for heating, both for domestic and commercial buildings and industry, in subsequent analysis in this report the heat produced by electricity is identified.

energy share supplied by electricity, the provision of industrial process heat in a CO_2 constrained world will likely have a wider range of solutions.

While globally heat accounts for half of total end use energy demand, only 10% of that is currently supplied by renewables (IEA, 2019).Current uptake rates of 2.6% growth per year lag the target of 4% per year required under the UN Sustainable Development Scenario for 2030 to meet the Paris target of less than 2°C temperature increase, as shown in Figure 2.

Figure 2: Renewable heat targets for 2030. Reproduced from IEA 2019.

1.1. Recent studies

As a result of the importance of renewable energy to mitigate climate change, a large and growing body of literature is publicly available covering all major renewable energy technologies applicable to Australia and their application to industrial process heat. Here we provide a brief summary of several recently-published studies. More details can be found in 0.

Our previous report *Renewable Energy Options for Industrial Gas Users* provided an overview of the range of renewable energy options and illustrated the economic viability of renewable energy compared with natural gas use as a function of gas costs and showed real-world case studies of renewable energy integration in various industries (Lovegrove et al., 2015a, 2015b).

The International Energy Agency has recently published a number of pertinent resources, including the *Renewable Energy for Industry* study (Philibert, 2017). In addition to the well-known renewable energy options, bioenergy and solar thermal, the study points out opportunities for electrification to replace heat-driven industrial processes, including electrical heating and mechanical steam recompression. The report further shows pathways to introduce renewable energy in high-temperature processes, including iron and cement production and into hydrogen-rich chemical products and energy carriers (e.g. ammonia, methanol).

The *Technology Briefs* on *Solar Heat for Industrial Processes* and *Biomass for Heat and Power*, published jointly by the IEA and IRENA, provide overviews of the technologies, their status, costs and benefits, as well as barriers and enablers for their uptake (IEA-ETSAP / IRENA, 2015b, 2015a).

In the US, the Department of Energy hosts a range of useful resources that are publicly available. A recent series of Bandwidth Studies provides a systematic and comparable analysis of the typical energy use and energy saving potential in 16 energy-intensive industrial sectors (Energetics Inc., 2017).

The UK Department of Energy and Climate Change and the Department for Business, Innovation and Skills commissioned a series of *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050* across eight sectors with the highest heat use and GHG emissions. The reports explain the specific features of each industry, how the processes work and what fuels they currently use. Evidence is synthesised to produce a series of potential pathways for emissions reduction (WSP Parsons Brinckerhoff, 2015).

A recent study published by the UK government considers the technical and economic potential of switching to alternative fuels (biomass and waste, hydrogen, electricity) in the UK industrial sector by 2030 and 2040 (Lyons et al., 2018). It found that the largest opportunities for fuel switching are reduction processes (i.e. blast furnaces), other high-temperature direct heating processes (e.g. furnaces and kilns for cement and other non-metallic mineral production) and indirect steam heating applications. From the point of view of process integration, hydrogen was found to be the most widely applicable of the fuels considered, due to its relative similarity to natural gas, followed by biomass and waste and electricity last. With cost effectiveness considered, biomass and waste energy supply are found to be the most competitive.

In Australia, the Australian Alliance for Energy Productivity has published a guide for businesses about replacing steam with electricity technologies to boost energy productivity (Jutsen et al., 2018) and the Beyond Zero Emissions' *Zero Carbon Industry Plan – Electrifying Industry* focuses on electrically heating industrial processes through a range of heating processes (Lord, 2018).

Overall these various investigations identify that renewable energy technology solutions do exist for all industrial process heat applications. Some can be applied in a straightforward manner whereas others require fundamental restructuring of the industrial process itself. In this study we build on these ideas and analyse them for the Australian context.

1.2. Approach and report structure

This report begins by examining the amount and nature of the use of process heat by industry in Australia in Chapter 2.

The key renewable energy technology options that offer potential solutions to industrial users are introduced briefly in Chapter 3, with further detailed technical and economic information for each provided in dedicated Appendices.

The key renewable energy technologies are (in alphabetical order):

- bioenergy
- geothermal
- renewable electric heating
- renewable hydrogen
- solar thermal.

System optimisations are also considered, such as use of combined heat and power (CHP) approaches, energy storage technologies and process redesign to replace or reduce heating requirements in some key areas.

Chapters 4 to 11 address specific industrial sectors in order of the amount of process heat they use. The key industrial sectors covered in this study are (in order of volume of heat use):

- alumina and other non-ferrous minerals
- food and beverage
- ammonia and other chemicals
- iron and steel
- cement and lime products
- oil gas and petroleum
- pulp and paper
- others.

Each industry is analysed by considering:

- the nature of the industry, basic processes, location and size of plants, industry trends, and potential for process changes;
- what process heat energy is being used at what temperature ranges, to undertake what processes and
- which specific renewable energy technologies / options could be used based on process heat temperature, end use application and economics.

Following this, the motivations, challenges and barriers to adoption are considered in Chapter 12, building on information collected from industry stakeholder interviews and other sources. Industry opportunities are outlined in Chapter 13 and recommendations in Chapter 14. The approach to interviewing stakeholders is described in Appendix H. The authors gratefully acknowledge the time and assistance offered by our interviewees.

2. INDUSTRIAL PROCESS HEAT USE IN AUSTRALIA

In this chapter the energy sources used by the key Australian industry sectors are reviewed.

The majority of process heat used by industry is currently supplied by the combustion of fuels. The fossil fuels used to supply process heat for use by industry in Australia are: natural gas, LPG and coal, including, in some specialist applications, coke and coal by-products. Biomass fuels have a significant existing role for particular niche applications.

The most comprehensive source of energy use data for Australia is the Australian Energy Statistics (AES), accompanied by the annual Australian Energy Update report (Ball et al., 2018), which is compiled by the Department of the Environment and Energy (previously by the Bureau of Resource and Energy Economics). The data from these sources, combined with other published material and the sector knowledge of the authors, have been used to deduce the nature of industrial process heat use in Australia. More detail on the background and method for this is provided in Appendix B.

2.1. Sectors using heat

The overall national final consumption of fuels for heat is estimated at 1279 PJ/year as indicated in Figure 1. This then provides heat estimated at 1023 PJ/year to end users. It can be allocated to sectors as shown in Figure 3. This has been derived from AES statistics by estimation of the share of each fuel for each sector that is used for heat purposes together with an estimated average efficiency of conversion.

Within this allocation it is apparent that residential use for hot water and space heating is very substantial. It is however outside the scope of the present study. Heating and cooling of commercial buildings is also outside the scope of this study. A large share of the ‘commercial and services’ sector falls into that category. Removing these two shares gives the breakdown in Figure 4, the overall industrial use of process heat by sector.

The Food and beverage, Pulp and paper and Wood products sectors are notable for having large shares of renewable energy use already. When the data is analysed to show fossil fuel use only the result is as shown in Figure 5.

The sector names used here are adapted from the headings used within AES, changed to be more descriptive of activity. The AES sectors largely follow the categorisation of industry given by ANZSIC (Australian and New Zealand Standard Industrial Classification), which has a hierarchy of Divisions, Subdivisions and Groups. Some of the headings capture whole divisions whereas some are actually at the Group level, if an individual Group is particularly significant in energy use terms (e.g. iron and steel). The majority of the sectors listed are Subdivisions or Groups of the overall Division of Manufacturing.

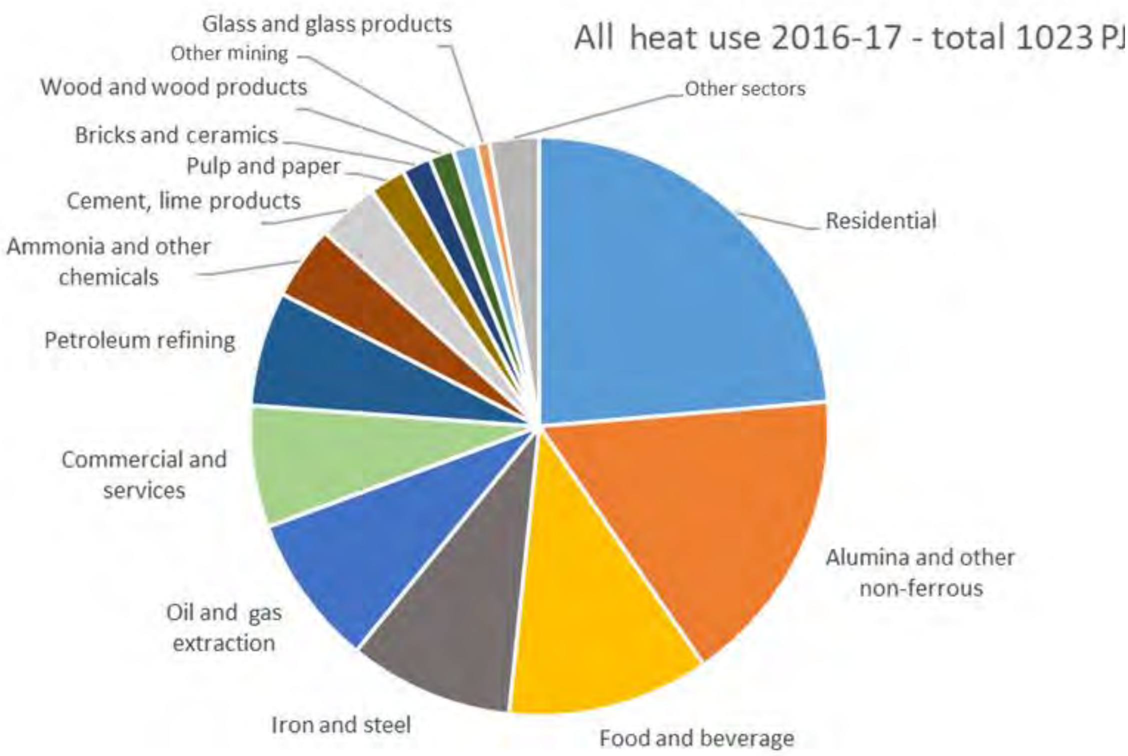


Figure 3: All heat use in Australia 2016-17. Based on Australian Energy Statistics data.

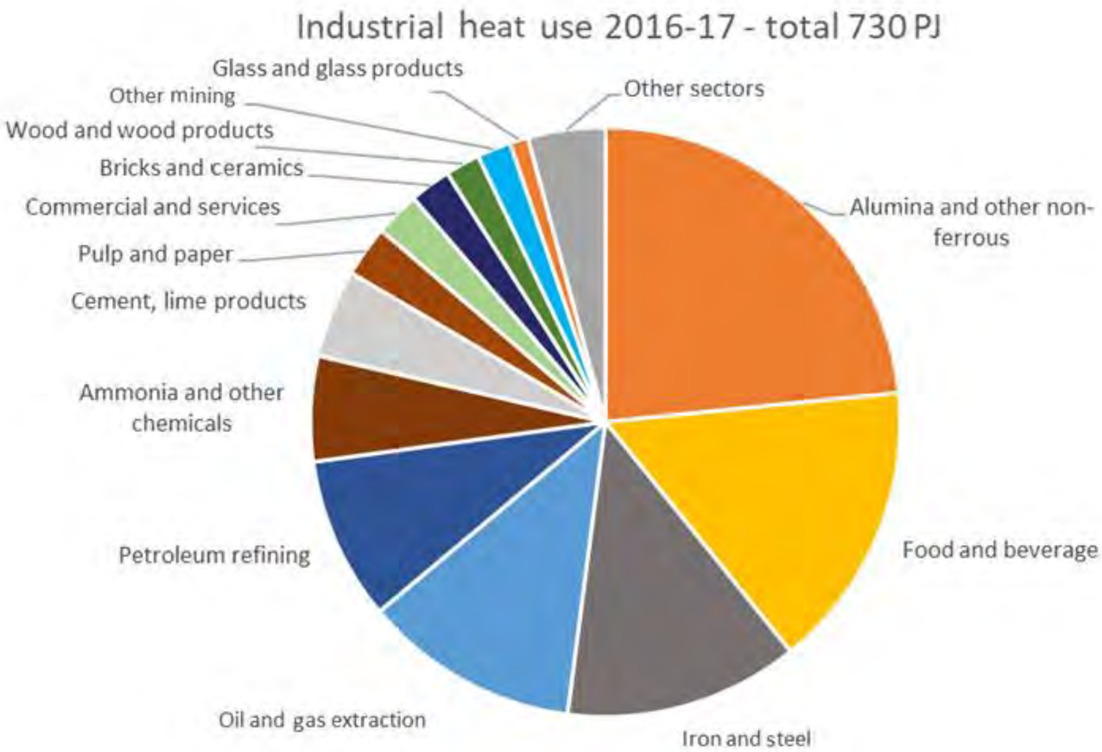


Figure 4: Industrial heat use in Australia 2016-17. Based on Australian Energy Statistics data.

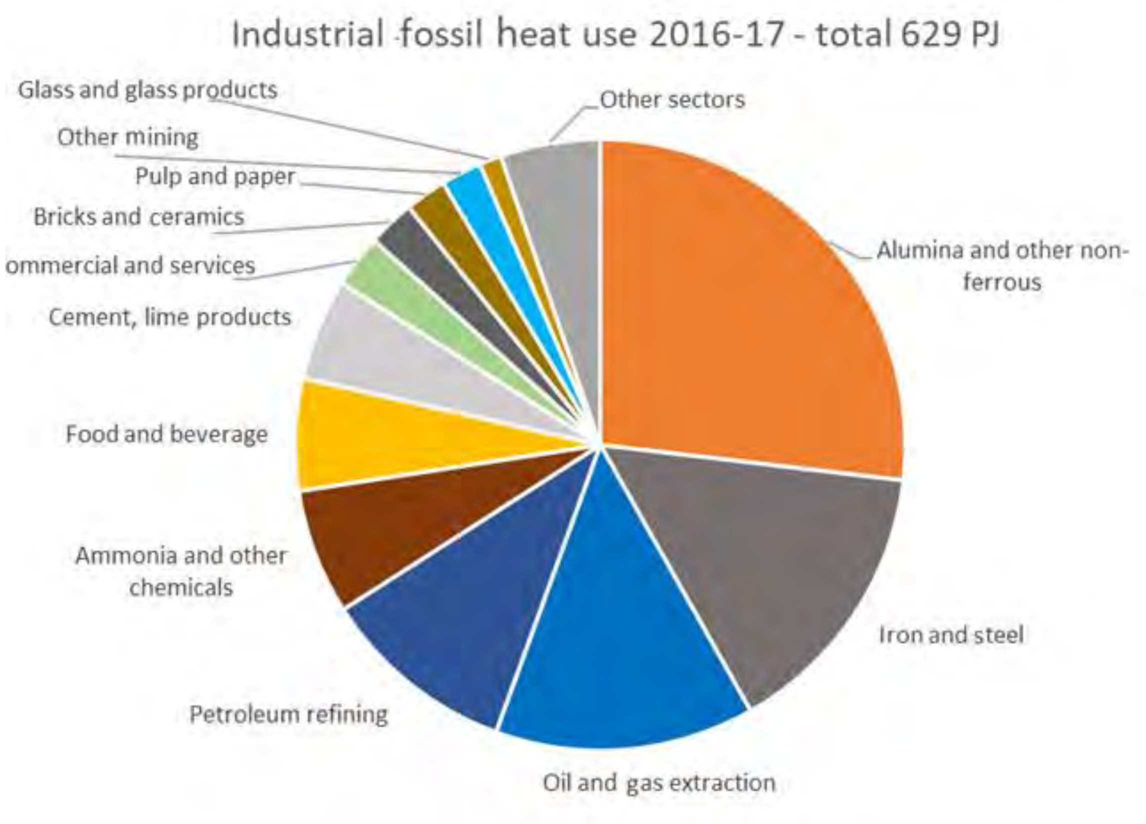


Figure 5: Industrial heat use from fossil fuels in Australia 2016-17. Based on Australian Energy Statistics data.

Every company has separate and confidential contracts for its fuel supply and these will cover transmission, distribution, delivery, connection and other costs in addition to wholesale fuel costs. Thus, estimating the overall annual cost for supply of this heat is a challenging task. Nonetheless, if an indicative price of $10/GJ is used (being slightly higher than the average spot wholesale price of gas over the last two years), then the annual cost to industry for process heat supply is around $8 billion. Clearly this justifies consideration of new energy options that could lower cost as well as improve environmental outcomes.

In considering renewable energy substitution, it is of significant importance to understand the temperature of use of the process heat. The energy uses from Figure 4 have been further allocated to temperature ranges, as shown in Figure 6 and Table 1.

This allocation by temperature has been estimated based on knowledge of the nature of the processes in each sector. It is indicative rather than a precise quantification. The temperature is of the heat transfer medium that delivers heat to the process. This in many cases is higher than the minimum temperature needed for the process itself. For example, if steam is produced in a gas-fired boiler and distributed in a factory for a cooking process, then the temperature indicated is that of the steam, not the higher combustion temperature of the gas flame, nor the lower temperature of the product being cooked.

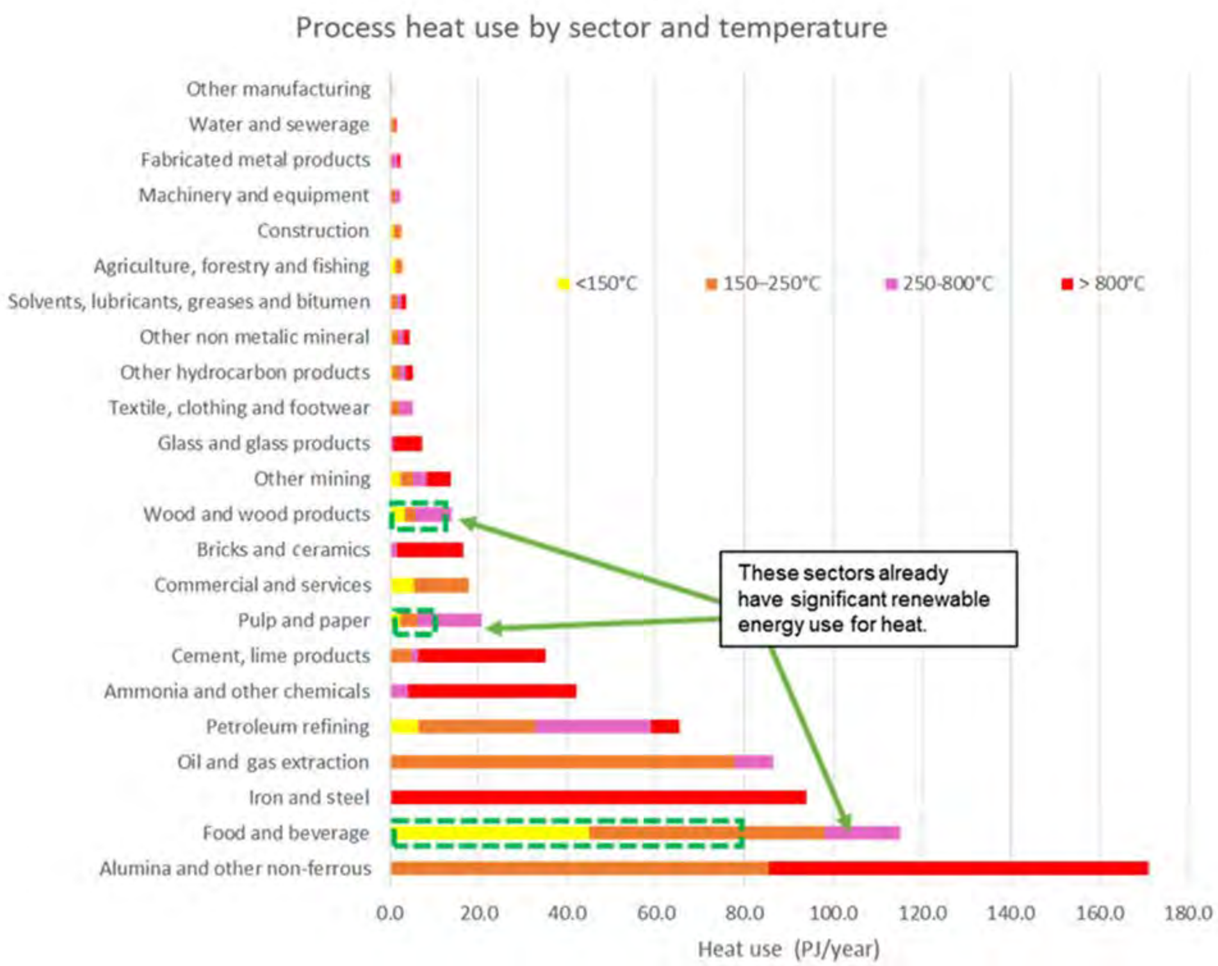


Figure 6: Industrial heat use in Australia 2016-17, by sector and temperature of use.

Temperature is an important variable in assessing the options for renewable energy. In simple terms, the lower the temperature of use, the more direct use of renewable energy options are technically capable of providing it and the more cost effective it is likely to be.

Applications with a fundamental process temperature significantly lower than the heat transfer fluid (e.g. many processes in the food and beverage sector) may have the potential for process redesign to lower the temperature of or eliminate the heat transfer fluid.

Table 1. Sector versus heat use per year in each temperature range.

Sector	PJ/year <150°C	PJ/year 150–250°C	PJ/year 250-800°C	PJ/year > 800°C
Alumina and other non-ferrous	0.0	85.5	0.0	85.5
Food and beverage	45.0	53.1	17.2	0.0
Iron and steel	0.0	0.0	0.0	93.9
Oil and gas extraction	0.0	77.8	8.6	0.0
Petroleum refining	6.5	26.1	26.1	6.5
Ammonia and other chemicals	0.0	0.0	4.2	38.0
Cement, lime products	0.0	5.0	1.6	28.5
Pulp and paper	2.5	3.7	14.4	0.0
Commercial and services	5.4	12.6	0.0	0.0
Bricks and ceramics	0.0	0.0	1.7	14.9
Wood and wood products	3.3	2.2	8.4	0.0
Other mining	2.3	3.0	3.0	5.3
Glass and glass products	0.0	0.0	0.7	6.6
Textile, clothing and footwear	0.3	1.8	3.2	0.0
Other hydrocarbon products	0.5	1.5	1.5	1.5
Other non metallic mineral	0.4	1.3	1.3	1.3
Solvents, lubricants, greases and bitumen	0.4	1.1	1.1	1.1
Agriculture, forestry and fishing	1.3	1.7	0.0	0.0
Construction	0.8	1.9	0.0	0.0
Machinery and equipment	0.1	0.9	1.5	0.0
Fabricated metal products	0.0	0.5	1.4	0.4
Water and sewerage	0.4	0.9	0.0	0.1
Other manufacturing	0.0	0.3	0.3	0.0

2.2. Fuel use for process heat

The shares of industrial process heat provided by the fuels currently used to provide it are shown in Figure 7. The estimated 730 PJ/year of industrial heat use requires the consumption of approximately 913 PJ of primary energy.

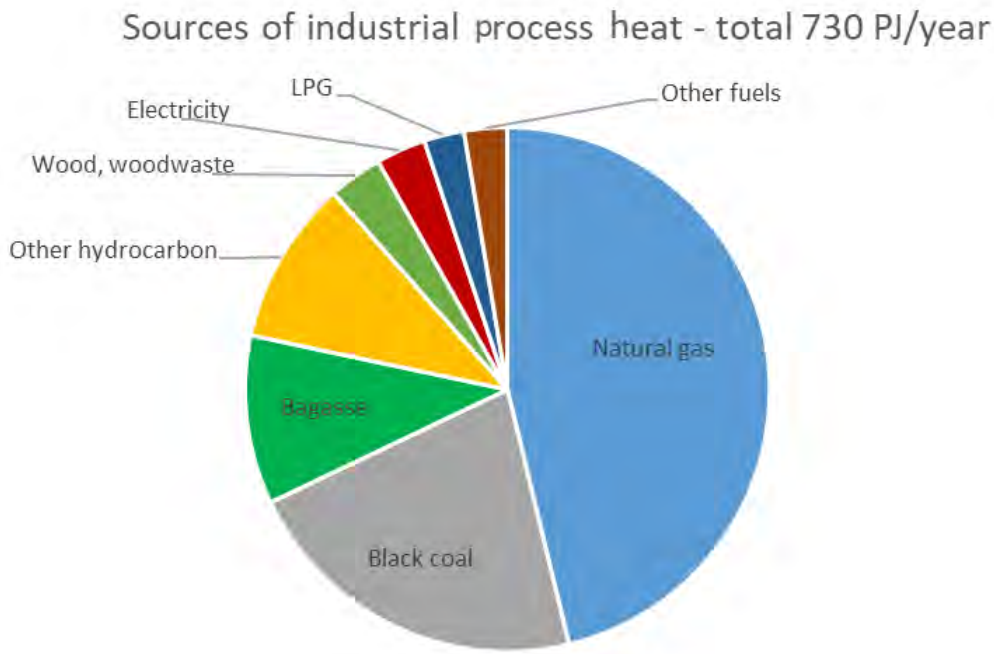


Figure 7: Fuel sources contributions for industrial heat use in Australia 2016-17.

Some fuels are closely linked to industry sectors. For example, the Iron and steel sector gets most of its heat from coal, coke and derived coal by-products, and is responsible for most of the consumption of those fuels. Bagasse, the solid waste from sugar cane, is both produced and used almost exclusively in sugar mills. The Oil and gas and Petroleum sectors obtain process heat from their own hydrocarbons and are responsible for the bulk of the other hydrocarbon consumption. Similarly, wood waste is produced and used by the Pulp and paper and Wood product sectors.

Natural gas is by far the largest existing source for industrial heat. It is used across all sectors.

Electricity is already a significant source of heat. Whilst the existing electricity fuel mix means that this is largely a non-renewable and high GHG source of heat, it does offer the potential for an automatic shift to renewables as the generation mix shifts to higher renewable shares, or through onsite generation or individual power purchase contracts between users and generators.

It is notable that, via the contributions of bagasse and wood waste and the growing renewable share of electricity, the existing share of industrial heat that is renewable is already around 15%.

2.3. Locations and intensity of process heat use by industry

The location of specific industry facilities and the level of energy use by them is a key input to assessing the potential for renewable energy to be used for process heat, since it is based on available resources, land use restrictions and the economics of specific applications, which in turn are linked to levels of energy demand.

Precise data for this is not readily available. However, the National Pollution Inventory (NPI) has exact locations of industry facilities, along with their industry sector. Whilst actual levels of energy use are not provided, the levels of combustion-related pollutants, together with the overall heat use that can be identified for a sector, have been used to deduce an indicative distribution as shown in Figure 8.

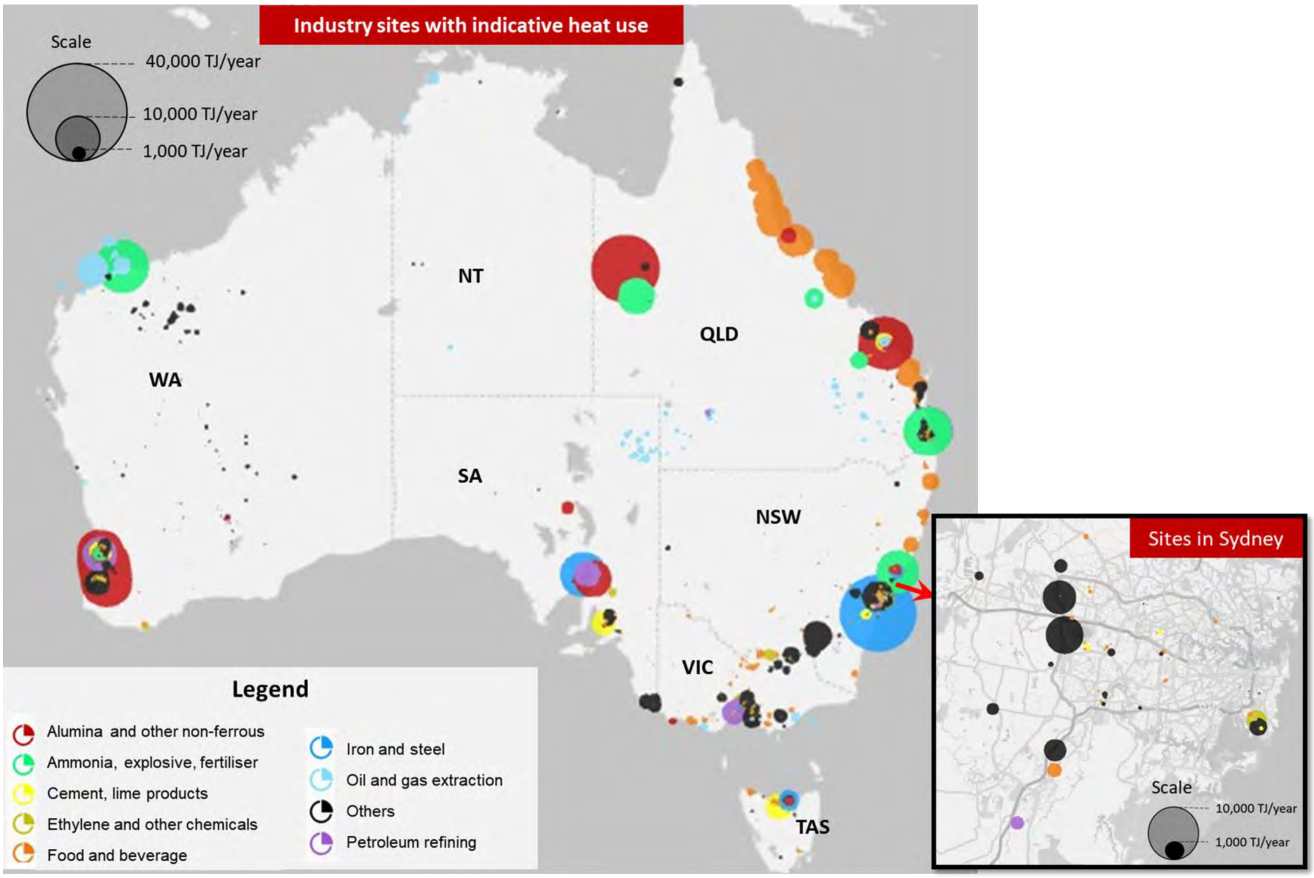


Figure 8: Locations and intensity of industrial heat use in Australia 2016-17.

The NPI data covers 1572 separate sites. It is apparent that there is a huge range in the quantity of energy use per site. Table 2 quantifies this distribution. There are a great number of sites where annual heat use is less than 0.1PJ/year, corresponding to an average use at 80% capacity factor of less than 5 MW_{th}. Food and beverage, Commercial and services and Other mining are notable in this regard. The distributions then tail off to the larger categories of energy use, with just a small number in the over 5 PJ/year (greater than 200 MW_{th}) use range. Many smaller sites are not visible at the scale of Figure 8. Some industry sectors are dominated by a relatively small number of large users (e.g. Alumina, Ammonia and Iron and steel) whereas others have a large number of smaller sites.

The distribution shows varied concentrations of manufacturing activity around the populated city and coastal regions, plus activity that is associated with points of production of key industry inputs in regional areas. Each of the capital cities has within it a range of smaller manufacturing sites, as shown for the example of Sydney in Figure 8.

Table 2. Numbers of sites and heat use by sector

	Number of sites in range							
Sites in range (PJ/year)	< 0.1	0.1 to 0.5	0.5 to 1	1 to 5	5 to 45	Total number of sites	Main Fuel	Total heat use PJ/yr
Average power at 80% CUF, (MW_{th})	(< $5MW_t$)	(5 to 20)	(21 to 40)	(40 to 200)	(200 to 1,800)			
Alumina and other non-ferrous	17	5	3	4	8	37	Natural gas	171
Food and beverage	244	52	1	16	7	320	Bagasse / gas	115.2
Iron and steel	6	2	0	2	2	12	Coal	94
Oil and gas extraction	24	34	13	24	3	98	Natural gas	86.4
Petroleum refining	3	2	0	2	3	10	Hydrocarbons	65.3
Ammonia and other chemicals	68	7	3	7	5	90	Natural gas	42.2
Cement, lime products	30	8	1	3	1	43	Black coal	35.2
Pulp and paper	21	15	2	5	1	44	Natural gas	20.6
Commercial and services	105	3	0	0	0	108	Natural gas	18.0
Bricks and ceramics	14	9	4	5	1	33	Natural gas	16.6
Wood and wood products	22	12	4	6	0	44	Wood waste	14.0
Other mining	335	34	5	0	0	374	Natural gas	13.6
Glass and glass products	2	6	0	3	0	11	Natural gas	7.3
Other sectors	337	4	2	4	1	348	Natural gas	31
Total	1,228	193	38	81	32	1,572		730

Although the smaller energy use sites dominate in total numbers of site, it is important to note that the shares of total heat use are dominated by the larger sites. This is shown further in Table 3 and Table 4. Table 3 shows the total heat use in each size range for each sector. From this it is apparent that the large heat use in the large alumina refineries is the largest category of all, with Iron and steel second. Food and beverage also figures prominently for large plants, as a consequence of the inclusion of sugar refineries in that category.

Table 4 presents the data in terms of the average heat use per site in each size range. In this presentation Iron and steel dominates with Alumina second. This shows that a fractional reduction in heat use from just a single plant in those categories has the greatest potential impact.

Table 3. Total heat use within ranges of use per site by sector

	Total heat use per category of plant usage (PJ/year)					Total heat use PJ/yr
Sites in range (PJ/year)	**< 0.1PJ**	**0.1 to 0.5**	**0.5 to 1**	**1 to 5**	**5 to 45**	
Alumina and other non-ferrous	0.5	1.3	2.4	6.8	160	171
Food and beverage	7.1	10.3	1.0	50.5	46.3	115.2
Iron and steel	0.6	0.9	0.0	9.7	83	94
Oil and gas extraction	1.4	8.3	9.0	39.1	28.6	86.4
Petroleum refining	0.3	1.0	0.0	9.8	54.2	65.3
Ammonia and other chemicals	1.1	1.4	3.0	14.3	22.4	42.2
Cement, lime products	2.8	4.0	1.0	13.0	14.5	35.2
Pulp and paper	1.2	2.4	1.3	8.9	6.8	20.6
Commercial and services	10.0	8.0	0.0	0.0	0	18.0
Bricks and ceramics	0.5	1.7	3.1	5.9	5.4	16.6
Wood and wood products	0.7	3.2	3.0	7.1	0	14.0
Other mining	4.4	6.2	3.1	0.0	0.0	13.6
Glass and glass products	0.1	1.6	0.0	5.6	0	7.3
Other sectors	3.5	1.8	1.8	18.1	5.9	31
Total	34.1	51.9	28.5	189.0	427.1	730

Table 4. Average heat use per site within ranges of use per site by sector

	Average heat use per plant (PJ/year/business)					Total heat use PJ/yr
Sites in range (PJ/year)	**< 0.1PJ**	**0.1 to 0.5**	**0.5 to 1**	**1 to 5**	**5 to 45**	
Alumina and other non-ferrous	0.03	0.3	0.8	1.7	20.0	171
Food and beverage	0.03	0.2	1.0	3.2	6.6	115.2
Iron and steel	0.09	0.4	-	4.85	41.5	94
Oil and gas extraction	0.06	0.2	0.7	1.6	9.5	86.4
Petroleum refining	0.09	0.49	-	4.9	18	65.3
Ammonia and other chemicals	0.02	0.2	1.0	2.0	4.5	42.2
Cement, lime products	0.09	0.5	1.0	4.3	14.5	35.2
Pulp and paper	0.06	0.2	0.6	1.8	6.8	20.6
Commercial and services	0.10	2.7	-	-	-	18
Bricks and ceramics	0.03	0.2	0.8	1.2	5.4	16.6
Wood and wood products	0.03	0.3	0.7	1.2	-	14
Other mining	0.01	0.2	0.6	-	-	13.6
Glass and glass products	0.06	0.3	-	1.9	-	7.3
Other sectors	0.01	0.4	0.9	4.5	5.9	31
Total	0.1	0.5	0.8	2.8	13.3	730

2.4. Cost of fossil fuels for process heat

The cost competitiveness of renewable energy for industrial process heat is dependent on the present and future cost and availability of the fossil fuels currently used, as well as the opportunities for improving system or process efficiency. It is important to note that the price for a fuel paid by a user is very much dependant on the volume and the location of use. Overall energy costs include transmission, distribution, and connection servicing/retailing costs as appropriate, in addition to the wholesale cost of the energy. Contractual arrangements are complex and deal with each aspect separately so that the marginal cost of an additional unit of energy can be much lower than the overall total average cost of energy supply.

Very large energy users typically pay something close to the wholesale price of the energy, whatever the type. Small users pay close to full domestic retail costs, which can be three to four times higher than wholesale.

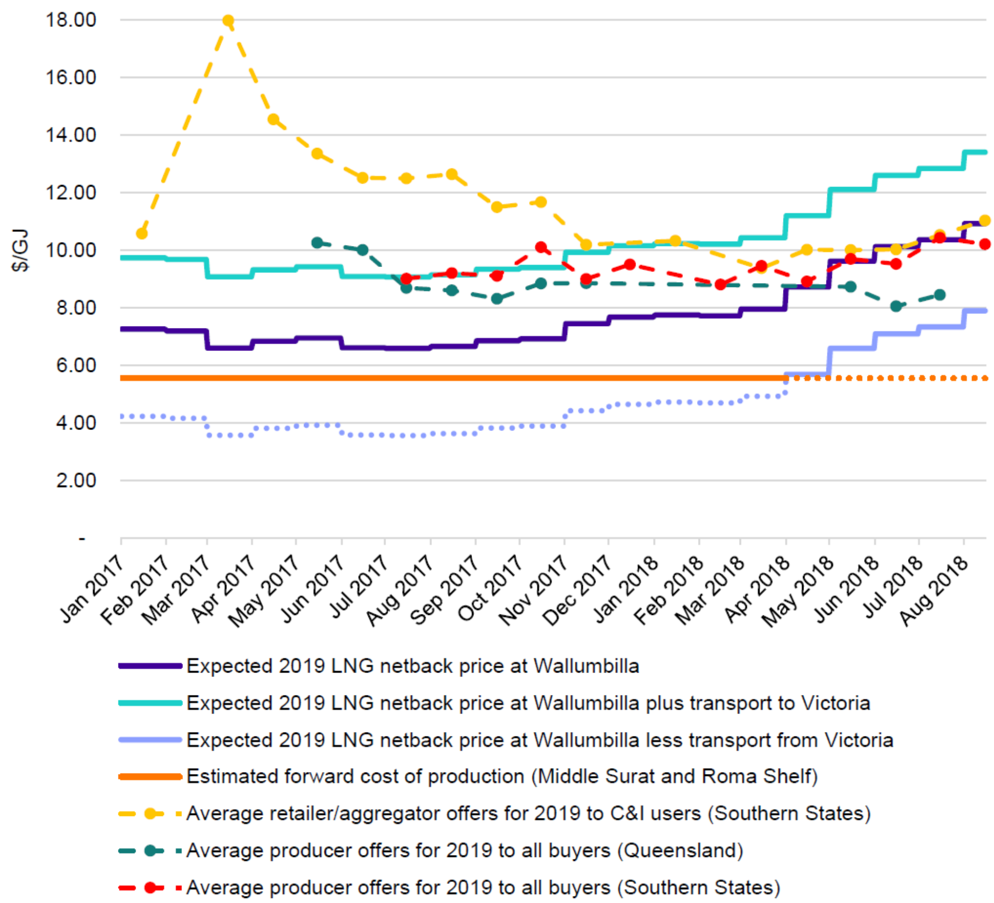


Figure 9: Monthly average gas prices offered for 2019 supply against expectations of 2019 LNG netback prices. Reproduced from (ACCC, 2018).

As noted above, gas is the dominant fuel for industrial process heat at present. The price and availability of gas has been the subject of considerable attention in recent years, particularly in eastern Australia. Large increases in cost and tightening of availability have been directly caused by the start of LNG exports from three new LNG plants, located at Gladstone in QLD. Pipelines supplying gas to these plants are connected to the wider eastern Australia pipeline network, which connects gas fields in QLD, SA and VIC with gas markets in south east QLD, NSW, VIC and SA. Because of these connections, wholesale gas prices across the whole of eastern Australia have moved to opportunity cost levels, i.e. to the export netback price in Gladstone, plus pipeline transport costs to Gladstone (see Figure 9).

Events since then have been investigated by the Australian Competition and Consumer Commission (ACCC). In its fifth interim report from the inquiry into gas supply arrangements in eastern Australia, the ACCC suggests that it expects average wholesale prices to be slightly lower in 2019 than in 2018 (ACCC, 2018). If the expectation that domestic prices have 'converged' with export parity prices is confirmed, domestic prices will remain exposed to the variability of both global crude oil prices and the US$/A$ exchange rate, since most LNG export contract prices are linked to crude oil prices. That said, in the absence of drastic government intervention in domestic gas markets, there is no prospect that prices can or will revert to anywhere near their pre-2016 level. Overall, base price levels in all LNG export contracts are set by prevailing price levels in the main export markets, i.e. Japan and China. These are now, and are always likely to be, well above the former level of Australian domestic prices.

The gas industry classifies customers into three groups: electricity generators, other large industrial consumers connected at the transmission level, and 'mass market' or distribution network-connected customers. This classification is, however, not applied with complete consistency across the country. In some market regions, i.e. some States, many very large consumers are connected at the distribution network level. In others, particularly QLD, most are connected at the transmission level. Each group has a different pricing and market structure, tends to exist in very different business size groupings, and is exposed differently to national and international forces. Within the distribution-connected customers, there is also considerable variation. The cost of gas for example is considerably higher in the case of small facilities with <0.12 PJ/year. Facilities with consumption higher than 0.12 PJ/year are classified as major consumers and have a gas price advantage. Overall wholesale gas prices are in the region of $8 - $10/GJ and this is close to the price paid by large industrial users. Small users can be paying over $20/GJ.

For LPG, domestic market wholesale prices are explicitly linked to the Saudi Aramco wholesale price, which is set monthly, ex Ras Tanura (a major oil refinery and export port location on the Persian Gulf coast), in US dollars. Hence the Australian price varies daily depending on the US/Australia exchange rate, as well as monthly depending on the Saudi Aramco price. The Saudi Aramco LPG price is, in turn, strongly affected by, but not firmly linked to, the crude oil price. The retail price also includes transport from the point of production/supply in Australia to the consumer's location, and, like all other energy sources, depends on the volume consumed. In general, however, LPG is considerably more expensive than natural gas, notwithstanding the large recent increase in natural gas prices. It is thus used almost exclusively by sites which are too far from the gas network for cost-effective connection.

Figure 10: Saudi Aramco propane / butane average price in 2004 to 2019. Data from (Western Australia Department of Mines Industry Regulation and Safety, 2019).

Figure 10 shows the large historical fluctuations in the price of LPG. The current price of around 40c/l corresponds to an energy cost of $15/GJ. Users, however, will be paying two to three times as much as this depending on their circumstances.

Coal is used by far fewer facilities than either natural gas or LPG, and most users require large volumes. Most industrial facilities that use coal are located relatively close to the mine from which they are supplied, and typically are a large and long-term customer. In some cases, such as the cement works at Berrima in NSW, the mine is wholly owned by the consumer. These relationships mean that the cost of coal to industrial consumers is not greatly affected by changes in the internationally-traded price of either coking or thermal coal (as relevant). Acil Tasman's 2012 fuel price estimates for the Australian Energy Technology Assessment suggest that mine gate prices are in the range $2 to $3/GJ. If truck transport is required, transport up to 200 km could add a further $1 to $2/GJ. This makes coal the cheapest existing fuel for process heat other than zero cost waste materials.

For all the fossil fuel sources used for process heat, there are heat losses associated with its combustion and transfer to the process. A good quality boiler for example will be around 80% efficient. Where a large network of steam is involved or other heat transfer fluid distribution to small points of use in a large plant, overall efficiencies at use can be much lower. Thus, the cost of delivered heat is higher than the fuel cost in inverse proportion to the energy efficiency of the means of supplying it.

Table 5 shows the recent history of average wholesale electricity prices in the National Electricity Market (NEM). The very largest users, directly connected to the electricity transmission system may be paying close to the average wholesale price for the total cost of supply. Again, depending on size and location, smaller industrial sites will be paying up to two to three times this price. Contractual arrangements however are complex and include fixed connection charges, peak demand charges and other factors. The average wholesale prices indicated are also the average of short peak price events combined with extended periods at a considerably lower price.

Table 5: Recent history of weighted average wholesale electricity prices (AER, 2019).

Financial year	QLD $/MWh	NSW $/MWh	VIC $/MWh	SA $/MWh	TAS $/MWh
2015-16	64	54	50	67	97
2016-17	103	88	70	123	76
2017-18	75	85	99	109	88
2018-19 (YTD)	83	89	92	97	62

To place these prices in context, Table 6 shows the direct conversion between the typical electricity price units of c/kWh or $/MWh and the $/GJ unit that is typically used for gas and other fuels and is used to compare heat costs throughout this report.

Table 6: Conversion between typical electricity price units and costs per GJ.

c/kwh	$/MWh	$/GJ
5	50	13.9
10	100	27.8
15	150	41.7
20	200	55.6
25	250	69.4
30	300	83.3
35	350	97.2

In these simple energy terms, electricity is typically several times more expensive, even than gas. Its potential economic attractiveness for process heat use is dependant on its ability to considerably increase the overall energy efficiency (with heat pumps for example) in certain applications.

3. RENEWABLE ENERGY TECHNOLOGIES FOR PROCESS HEAT

This chapter provides an introduction and overview of technologies for renewable process heat generation. Additional information for each technology can be found in the respective Appendices dedicated to each.

The key renewable energy technologies covered are[8]:

- bioenergy
- geothermal
- renewable electric heating
- renewable hydrogen
- solar thermal.

The reliable operation of renewable energy systems depends on the accurate prediction of the long-term availability of local renewable energy resources over the expected lifetime of the system. Therefore, information on the local availability of renewable energy resources is crucial for the selection, design and assessment of on-site technological solutions for process heat generation. Future use of renewable energy-based hydrogen in gas streams may reduce local constraints in the electrical system while electrification of industrial processes offers on-site generation or grid supply, with the cost and feasibility of the latter depending on local grid capacity.

For Australia, the Australian Renewable Energy Mapping Infrastructure (AREMI) provides an online mapping tool to display renewable energy resource data, along with other important resource data such as existing electricity infrastructure, oil and gas distribution infrastructure, mine areas, export infrastructure, topography, land restrictions etc., for the conceptualisation of renewable energy systems.

3.1. Bioenergy

The most commonly used technology options to produce process heat from biomass and waste feedstocks are:

- anaerobic digestion
- combustion
- gasification.

[8] The ordering here is alphabetical and is not to imply any order of importance or priority.

Each of these technologies can be used for process heat production, for electricity production, or for both by utilising CHP.

Anaerobic digestion involves introducing wet biomass or putrescible waste into digestor vessels from which air is excluded. Bacterial action converts the hydrocarbons into a mixture of methane and CO_2 (biogas), which can then be combusted in the same manner as natural gas. Figure 11 shows an example of a system at the RichGrow site at Jandakot WA. The system takes between 35,000 and 50,000 t/year of organic waste, which is converted to biogas and used to run a gas engine with heat recovery, producing 2 MW_e of electricity and up to 2.2 MW_{th} of heat. The gas could equally be used purely for heat production.

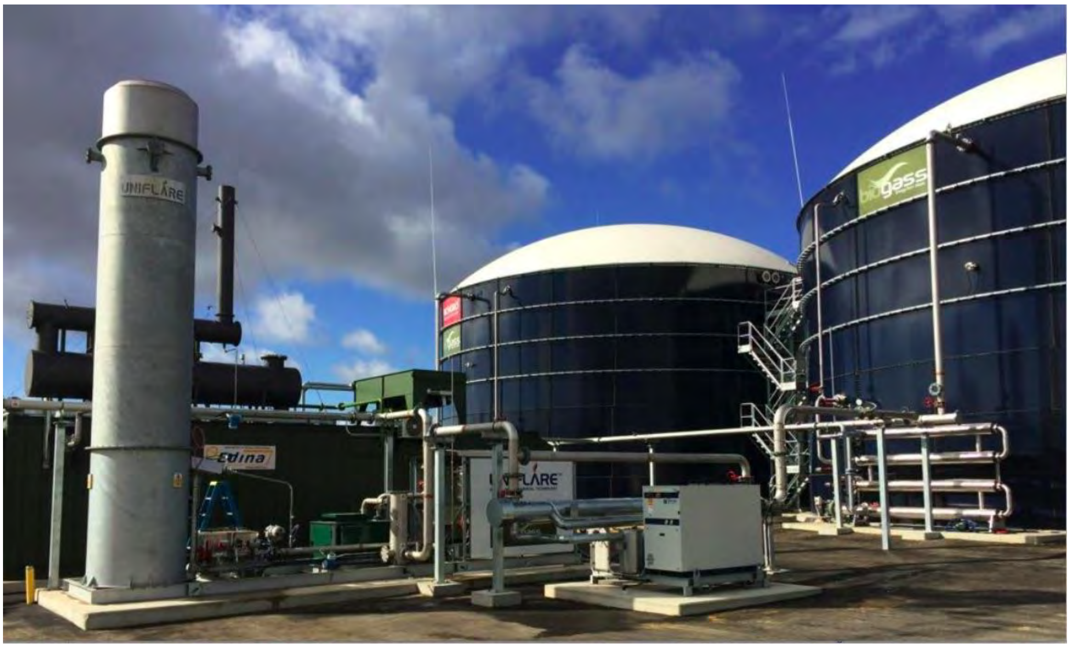


Figure 11: Integrated waste to biogas system. (image K Lovegrove).

Combustion systems use dry biomass material in fixed bed or fluidised bed combustion boilers to produce process steam. Pulverised biomass is automatically fed to a combustion chamber that is surrounded by walls constructed of steam pipes. These pipes are connected to a 'water drum' pressure vessel at the bottom and 'steam drum' pressure vessel at the top as they are in coal or gas-fired boilers. Figure 12 shows an 8 MW_{th} biomass boiler using grape marc installed by Australian Tartaric Products for its facility at Colignan, Victoria. The boiler provides steam for process heat and for a 600 kW_e Organic Rankine Cycle generator. The largest use of biomass combustion in Australia at present is in the sugar industry, where the majority of sugar mills burn waste bagasse.

Gasification systems are an alternative use of dry biomass and are similar to combustion boilers, however only limited amounts of air are added and the unit is sealed and lined with refractory insulation. The heat from partial combustion converts the balance of the material into a mix of volatile gases that can then be collected for subsequent use as a fuel.

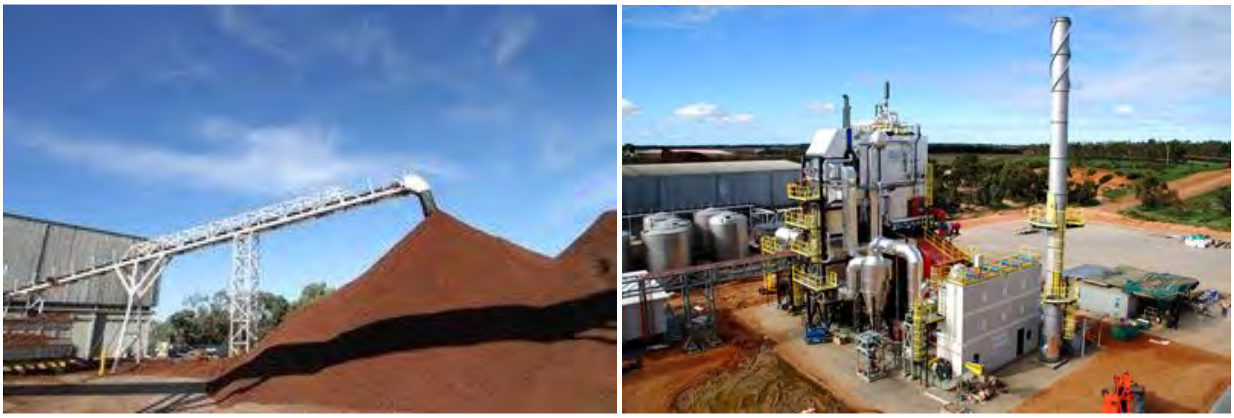


Figure 12: Automatic feed handling and 8 MW_{th} boiler using grape marc. (Reproduced from Australian Tartaric Products.)

Appendix C includes more detailed information on bioenergy technologies and their costs, an estimation of the potential of bioenergy for the near term, and assessment of biomass resources in Australia.

Depending on the biomass feedstock, the plant capacity, and the conversion technology, cycle efficiencies for current bioenergy plants generating electricity vary from 15–35% (Stucley et al., 2012a). However, cycle efficiencies for process heat are higher, and range from around 80% up to 90%.

The capacities of bioenergy plants range from small industrial heating systems with capacities in the tens of kW, to the world's largest plant, the Alkolmens Kraft CHP plant at the UPM-Kymmene Pietarsaari paper mill in Finland, which has an electrical output of 240 MW_e, with about 160 MW_{th} thermal capacity (100 MW_{th} process steam, and 60 MW_{th} district heating) (Pöyry, 2019). However, the comparatively low calorific value of biomass compared to black coal or natural gas leads to relatively high transport costs. Plants larger than 100 MW_{th} are generally only found when co-located with processing facilities, which themselves create the feedstock, such as sawmills, paper or sugar production. In such situations, CHP is common, with much of the electricity used on site, which tends to increase the economic viability of the bioenergy plant.

In some cases the biomass is densified to increase its calorific value, by drying and compression into pellets or briquettes. This can assist with transport, handling and storage, as well as the biomass' suitability for existing feed handling systems (such as those set up for pulverised coal). However, such densification comes at a significant cost and it is not always an ideal solution for biomass use.

Existing bioenergy plants in the different industry sectors are summarised in the respective sections below.

Bioenergy is already providing heat and electricity in many industry sectors in Australia. Bagasse accounts for the greatest share of bioenergy plant (approximately 64% of electrical capacity), followed by landfill gas generators (23%) and the pulp and paper sector (10%). The use of bioenergy CHP in waste water treatment and heat applications in the forest products industry is also well established. There are currently 222 operating bioenergy plants, with electricity generation accounting for 92 per cent of the energy outputs (KPMG, 2018).

Bioenergy has the potential to provide a significant proportion of Australia's energy supply. Geoscience Australia report long-term potential of up to 73 TWh electrical, 30% of current consumption (Geoscience Australia, 2014). The 2008 Bioenergy Roadmap (CEC, 2008) did not discuss heat from bioenergy, but identified approximately the same long-term potential for electricity, with 11 TWh near term potential (by 2020)[9]. This would equate to approximately 97 PJ thermal energy[10], with long-term potential approximately seven times greater. Figure 13 shows each feedstock's contribution to the identified potential at 2020, with a more detailed breakdown given in Appendix C.

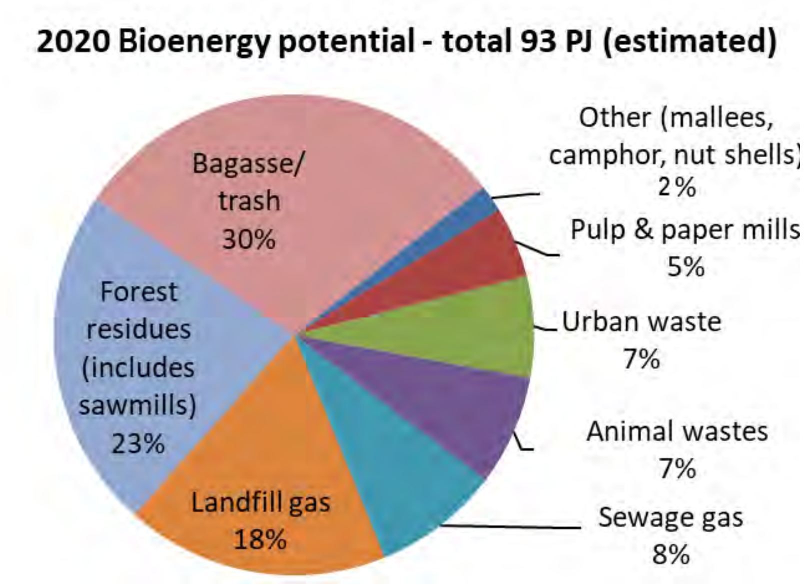


Figure 13: Bioenergy heat potential in 2020, all sources.

The availability of biomass feedstocks is a critical factor for new bioenergy projects. Feedstocks are very varied, and the specific feedstock will affect the overall cycle efficiency as well as the type of technology used. Feedstocks can be solid or liquid, and include wood, bark, bagasse,

[9] Geoscience Australia and the Bioenergy Roadmap were focussed on electricity production, hence their original data is presented in TWh; if the same resource were used exclusively for heat, the energy content would be considerably higher as the conversion efficiency is greater. Bioenergy can be used to produce electricity, or heat, or (most efficiently) both, with the specific mix usually determined by demand on site.

[10] Assuming that electrical output was based on 40% overall conversion efficiency.

agricultural crops (e.g. straw and rice husk), energy crops (e.g. mallee), and waste products (e.g. wood or paper waste, black liquor, sewage sludge, manure). Feedstock availability contributes to four key barriers to bioenergy project development, namely quality assurance for feedstocks, long-term supply contracts, logistics for collection and transport, and competing land/water demand for non-energy purposes (IEA Bioenergy, 2015). The low density of biomass feedstock often limits the distance to which it can be economically transported and thus the size of many bioenergy projects.

There are therefore some important questions that have a strong influence on cost effectiveness of bioenergy projects, including:

- Does the feedstock require collection or does it arise at a processing plant? For example, stubble left after a crop or in forest residues requires collection, while abattoir or paper mill wastes arise at a single point. As collection and transport costs are a limiting factor for many bioenergy feedstocks, this will strongly influence cost effectiveness.
- Is the feedstock a waste that would incur disposal costs if not used for bioenergy? This may result in a low, zero or even negative cost for the fuel, while for some feedstocks (such as energy crops) the fuel cost will have to cover all the production costs.
- What technology is suitable? The main division is between liquid and solid feedstocks, with the former suitable for anaerobic digestion, while the latter is suitable for combustion or gasification/combustion.

Projects where the bioenergy fuel can be used at, or very close to, the point of production, and where the fuel cost is zero or negative will be the most cost competitive. This is particularly so in those situations where the fuel would incur disposal costs if not used for bioenergy. Thus animal processing, food production and pulp and paper mill wastes are likely contenders for fossil fuel substitution as the bioenergy resource arises on site and requires disposal, and the sectors have a significant thermal demand. The Clean Energy Finance Corporation (CEFC) considers that the Australian bioenergy market, including waste to energy (W2E), is underdeveloped, with an overall investment opportunity of between $3.5-$5 billion to 2020, and suggest that feedstock arising from intensive livestock and food processing industries offers a large investment opportunity (CEFC, 2015).

A more recent development has been the use of anaerobic digestion CHP in piggeries, where there has been significant growth, with 18 of the 20 plants in operation established since 2012. Food and beverage also have a significant number of plants in operation. All of these applications involve companies primarily using their own wastes. However, brick companies and horticulture are starting to use bioenergy for process heat applications, mostly fuelled by forest or sawmill residues.

3.2. Geothermal

Geothermal energy systems rely on drilled wells to access heat sources of various types and temperatures within the earth's crust. The two most important advantages of geothermal solutions are that the footprint at ground level is very small and, once developed, wells can produce heat 24 hours per day on demand. Typically, a pair of injection and extraction bore holes are drilled for continuous water flow in and out of the reservoir. The extractable heat rate depends on the permeability/ porosity and thickness of the reservoir.

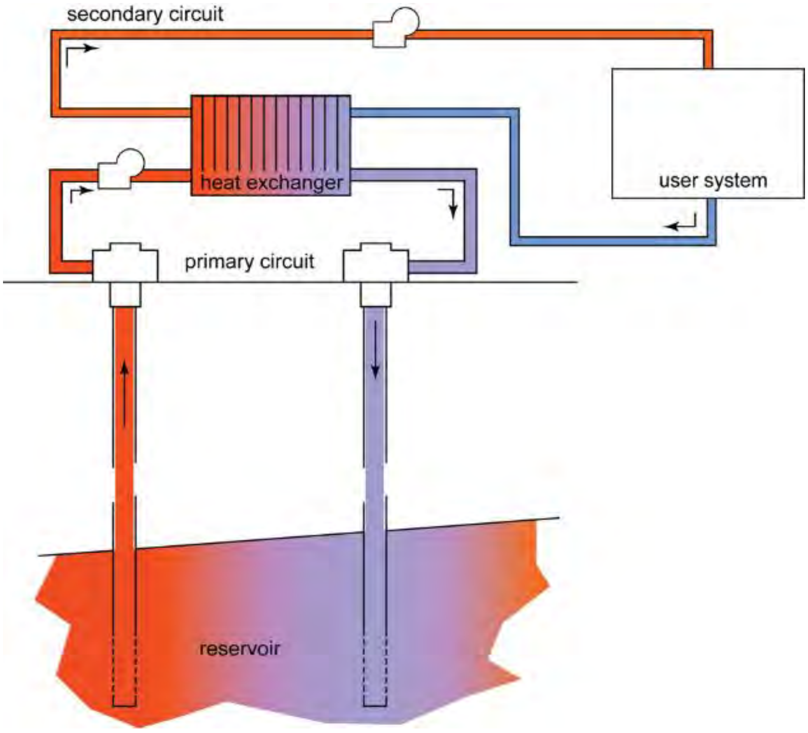


Figure 14: Typical geothermal 'doublet'. (Reproduced from (Pujol & Bolton, 2015)*).*

There is a distinction between engineered geothermal systems (EGS) and hot sedimentary aquifer (HSA) systems. EGS involves drilling to maximum achievable depths into rock that is identified as high temperature, fracturing it and introducing water into circulation. This is an approach that received a lot of attention some years ago but remains in an R&D phase. HSA on the other hand is more straight forward and involves drilling boreholes to lesser depths to intersect known sedimentary aquifers. The Great Artesian Basin is the best known such aquifer. In Australia, water temperatures up to 95°C can be expected.

Project economics vary with the achievable water flow rate through the reservoir, which depends on its permeability. As this is often unknown at project start, hydrogeology experts are required to conduct an assessment of the resource potential.

Geothermal heat generation costs (excluding heat exchangers and process integration) have been estimated at between around 3.75 and 6.66 $\$/GJ_{th}$, depending on the achievable flow rate, and hence are competitive with gas prices.

This can be an attractive option for suitably sited industries with a low-temperature process heat requirement. For example, a meat processing plant, owned by the Midfield Group in Victoria, uses 42ºC groundwater from an 800m deep bore. It is boosted to 82ºC with heat recovered from a gas engine CHP system, and then used in sterilisation.

More details on geothermal technology, including technical approaches, resources, global status and trends, technology selection guidance, costs and opportunities are provided in appendix **C.3.2**.

3.3. Renewable electric heating

Electricity is a versatile form of energy that can be used through a number of techniques for process heat applications.

In the context of this study, the electricity can be provided to a user by the grid, or if the roof and land area are available for photovoltaics, could be generated on site. The general mix of grid electricity will be increasingly renewable over time, or a user could contract with a renewable generator for a direct offtake agreement. Wind and solar PV electricity have become increasingly cheaper, to the extent that offtake agreements for large systems in high resource areas are now considerably cheaper than average wholesale electricity prices. Industrial heat users however will still need to consider distribution, transmission and connection costs. They will also need to consider the costs of backing up variable generation from wind and solar PV.

Electric-driven heating methods include:

- heat pumps / vapour recompression
- electromagnetic heating (induction, dielectric, infrared, ultraviolet)
- resistance (ohmic) heating
- electric arc heating.

Heat pumps make the heat that is contained in the surroundings (e.g. ground, air) or other source (such as a lower temperature waste heat stream) useful, by elevating its temperature through a mechanical compression process. This allows the heat to be supplied to a process at a desired operating temperature. The heat supplied is a mixture of the source heat and the electricity consumed to drive the heat pump. The amount of heat supplied is thus greater than the amount of electricity consumed. This is expressed in the Coefficient of Performance (COP), which reflects the ratio of heat made available to the electric energy input to the heat pump process. Heat pumps are particularly useful for reusing heat currently wasted by many industrial processes.

Low-temperature lift heat pumps are already economically attractive if used at high capacity, and particularly when providing simultaneous heat and cooling duty.

The heat pump process often involves an electrically-driven compressor. The larger the temperature increase is, the more electric energy is required. For temperature uplifts below around 50°C, the COP of heat pumps is typically larger than three, indicating that a heat pump provides more thermal energy (heat) than is required as input energy for the pumping process in the form of electric energy. Hence, a heat pump makes more efficient use of electric energy for process heat applications than direct electric heating. The application of current heat pumps is limited to temperatures of around 160°C, with systems capable of 200°C expected by 2030 (IEA, 2014).

A notable variation on the heat pump for industrial processes using steam is mechanical vapour recompression (illustrated in Figure 15). If a low-temperature waste steam is available, it can be recompressed back to initial process temperature and pressure by an electrically-driven turbine. In this way, the large amount of latent heat embodied in the steam is preserved and converted to a high temperature through a smaller input of work.

Figure 15: Mechanical vapour recompression turbine. (Reproduced from TLT-Turbo).

Electromagnetic heating technologies transfer energy using electromagnetic waves to heat the target without direct contact and do not require a heat transfer medium. This can result in higher system efficiencies. They can be categorised according to the wavelength/frequency of the electromagnetic waves used. The main categories are induction, dielectric (radio or microwave) and infrared heating. The principle of energy transfer differs somewhat across the different electromagnetic heating technologies, but they all transfer heat to the bulk of a heated object. Ultraviolet light is primarily used for photo-chemical (non-thermal) processes such as curing of coatings.

The simplest and oldest electricity-based method of heating is resistance heating. This involves generating heat by passing an electric current through a resistive heating element. There are two types of electrical resistance heating:

- direct resistance, where the resistive heating element is also the target material
- indirect resistance heating, where the resistive heating element transfers its heat to the target material via radiation and convection. (Electric ovens and boilers work this way).

Resistance heating is useful because of its simplicity. It converts electricity to heat at essentially 100% efficiency although this is a considerably less efficient use of electricity than a heat pump. Other advantages include greater controllability, lower maintenance and absence of emissions from combustion. Resistance heating is used for both low and high-temperature applications in various sectors including food, textiles, printing, chemicals, glass and plastics. It is also used for some processes that require higher temperatures than achievable with natural gas, such as carbon fibre production.

Many types of industrial oven, furnace and kiln can be powered either by a fuel or electricity (just as a domestic oven can be gas or electric). This is indirect resistance heating.

An electric arc furnace is a century-old technology that uses electricity to melt metal. Their most common use is to melt steel for recycling, and these furnaces produce about one quarter of world steel output. Electric arc furnaces are also used to convert direct-reduced iron into steel. This is a key example of direct resistance heating.

Each electric heating method has its benefits and limitations. A more detailed description of electric heating technologies and their typical applications can be found in Appendix E.

3.4. Renewable hydrogen

Hydrogen is a combustible gaseous fuel that can be produced using renewable energy and could substitute for natural gas in almost every application that gas is used. Substitution would require suitable modification to burner settings and controls.

There has been considerable recent Australian and international interest in hydrogen. Key reports include a CSIRO Australian ‘National Hydrogen Roadmap’ (Bruce et al., 2018), the COAG Energy Council report ’Hydrogen for Australia’s future’ (Hydrogen Strategy Group, 2018) and an ARENA-commissioned study of opportunities for Australia from hydrogen exports (ACIL Allen Consulting, 2018). The interest in hydrogen exports is linked to plans by Japan in particular to move to zero emissions hydrogen imports as a major source of primary energy in the coming decades. ACIL Allen have estimated the potential market for global Australian hydrogen exports in 2040 to be between 74.6 and 382 PJ per year with a value of $A2.6 billion to 13.4 billion per year, and the largest export markets being Japan, Republic of Korea and China. If this market does begin to develop, it will both drive and require major cost reductions for hydrogen production. This in turn will make renewable hydrogen an increasingly viable option domestic for process heat along with transport and dispatchable electricity generation.

Hydrogen is already used at large scale as a feedstock in petroleum refining and chemicals production such as ammonia. The bulk of this hydrogen is currently produced by the steam reforming of methane from natural gas. A fraction of the natural gas feed is burnt to heat high temperature catalytic reactors fed with methane and steam to produce mixtures of hydrogen and carbon monoxide. Further reactions between steam and carbon monoxide (so called water gas shift reactions) produce more hydrogen and carbon dioxide.

Hydrogen can also be produced renewably. Hydrogen produced through electrolysis is well established and large electrolysis systems are commercially available. If the electricity that drives electrolysis is renewable, then the hydrogen produced will be renewable also. There are other less well-known approaches, including the gasification of biomass or the reforming of methane from landfill gas or digestor gas.

In the R&D area, CSIRO and others have worked for many years on solar thermal-driven steam reforming of methane. If the methane is sourced from natural gas, the resulting hydrogen will be a fossil renewable hybrid. If it were applied to bio-sourced methane, it would be fully renewable. This is the most technically advanced example of a concentrating solar fuel (Hinkley et al., 2016). There are a range of processes at early R&D stage that can directly split water to hydrogen using the input of solar thermal energy. There are also photocatalytic and biological approaches in the early R&D phase.

Hydrogen is not currently cost competitive with natural gas as a fuel source in Australia. The CSIRO hydrogen roadmap (Bruce et al., 2018), assesses the present cost of renewable hydrogen at approximately $5.50/kg. This corresponds to $38.8/GJ, considerably higher than wholesale natural gas at around $10/GJ. However, this is projected to fall to around half that cost by 2025 (Figure 16). Given the required strategic investments in infrastructure are made over the coming years, the predicted cost decline of renewable hydrogen is likely to make renewable hydrogen a cost-effective substitute for current fossil fuels in several applications, in particular transport and remote area power generation.

On the other hand, where hydrogen is used as a feedstock, such as in ammonia production, renewable hydrogen will reach cost competitiveness sooner compared to steam methane reforming, as the cost and inefficiency of the reforming step can be eliminated (Philibert, 2017).

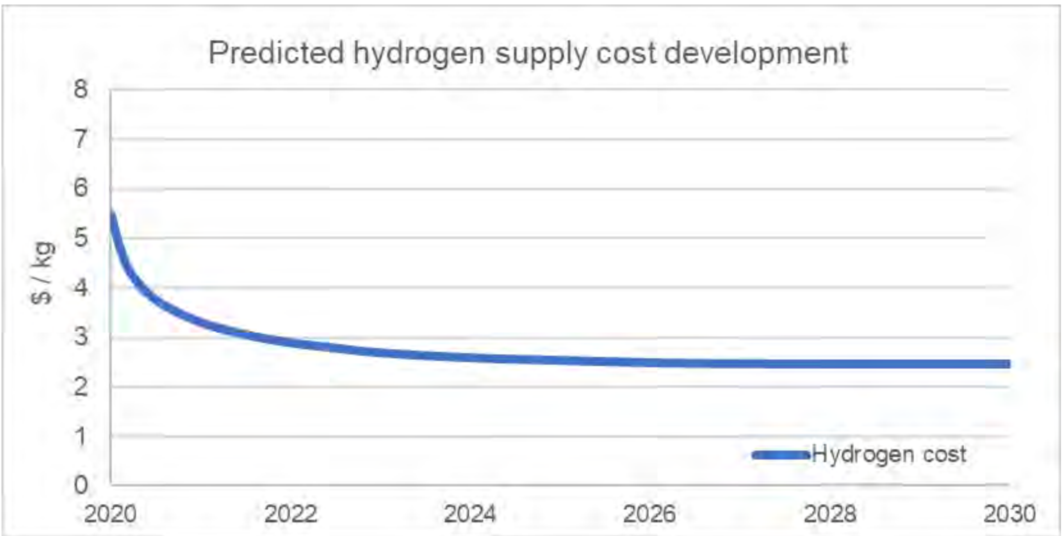


Figure 16: Predicted hydrogen supply cost development. (Data from (Bruce et al., 2018)*).*

Hydrogen has a higher heating value of 141.7MJ/kg, several times higher than fossil fuels such as methane, diesel and coal. However, its low density requires pure hydrogen to be stored either at high pressure or as a liquid at extremely low temperatures. Alternatively, hydrogen can be stored chemically. Options include ammonia (NH_3), methanol (CH_3OH), metal hydrides, methylcyclohexane (MCH) or adsorption in metal organic frameworks.

Zero emissions ammonia can be made by combining renewable hydrogen with nitrogen from a standard air separation unit. Carbon neutral methanol could be produced with renewable hydrogen and CO_2 captured from the atmosphere, with an extra energy cost for atmospheric CO_2 capture compared to air separation in the production of renewable ammonia (Philibert, 2017).

A key enabler for use of hydrogen is adapting the existing gas network to accept increasing percentages of hydrogen. Levels of around 15% can already be managed and investigation of steps needed for up to 100% are underway.

3.5. Solar thermal

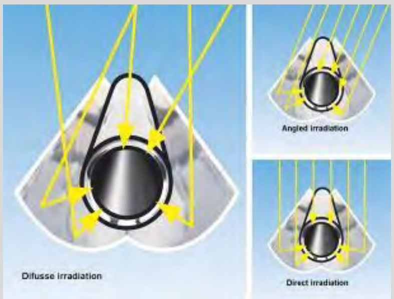
Solar thermal technologies collect solar radiation and directly convert it to heat, which in turn can be used directly, stored or used to produce fuels or electricity. Their efficiency is limited by heat losses from the hot collector surfaces that increase with temperature and with the area of the hot absorbing surface. Solar concentrators are used to reduce the hot surface area.

Solar thermal technology solutions must be optimised for the temperature range needed. Various approaches are used to reduce thermal losses and so improve efficiencies and these increase the complexity and cost of the system. Low-temperature heat (e.g. for pool heating) can be provided by black, uninsulated rubber or PVC tubes laid flush on a rooftop. At the other extreme, temperatures of over 1000°C are possible with point focus concentrators such as heliostat tower systems or paraboloidal dishes. The range of collector technology options available and heat transfer fluids (HTF) that can be used is summarised in Table 7.

Overall, Australia is among the countries with the highest solar irradiation in the world. Higher irradiation directly translates to higher yield and hence lower cost of solar energy. Irradiation tends to increase inland from the coast due to the decreasing occurrence of clouds and humidity in the atmosphere. Most locations that are 100 to 200 km away from the coast receive very high solar irradiation; in Western Australia even the coastal regions receive very high irradiation.

Table 7: Solar thermal technologies & key characteristics.

Collector Type		Note
Unglazed flat plate 20 – 40°C		Unglazed collectors are suitable for temperatures of around 40°C and are often used for swimming pool heating. For this application, they are typically fabricated from rubber or PVC tubing. HTF: water, air
Glazed flat plate 30 - 85°C		Flat plate glazed collectors are the dominant technology in the Australian domestic solar hot water market. They consist of a metal sheet with passages for fluid flow, mounted in an insulated case with a glass cover sheet. They can be connected in large arrays for industrial processes. HTF: water, air, glycol

Evacuated tube 50 - 150°C		Evacuated tube collectors are the competing solar technology for domestic and commercial solar hot water. An evacuated space between two concentric tubes minimises heat loss and allows the inner surface to reach higher temperatures and exchange heat to a fluid. A series of individual tubes are mounted together in panels. HTF: water, glycol
Evacuated tube plus non-tracking mirror. 50 – 200°C		Addition of a curved mirror behind an evacuated tube collector can boost the energy absorbed allowing higher temperatures and more efficient operation. HTF: water, glycol
Parabolic trough 100 - 450°C		The focal properties of the parabola are utilised in trough concentrator systems. The tubular receiver is fixed to the focal line of the array of mirrors, which track the sun along one axis throughout the day. Trough systems can heat a heat transfer fluid such as synthetic oil, or generate steam for process heat or power generation. HTF: water, steam, synthetic oil (molten salt)
Linear Fresnel 100- 450°C		A Linear Fresnel system is an analogue of a trough concentrator and provides heat over the same temperature range. Long semi-flat mirror strips laid out in parallel rows are each tracked independently so as to focus direct beam radiation on a linear focus that is fixed on a non-moving tower. HTF: water/steam, synthetic oil (molten salt)

Heliostats and tower 300 - 2000°C		For higher temperatures still, the heliostat field plus tower arrangement is available. Many Individual mirrors on double-axis tracking devices are all simultaneously moved to reflect sunlight to a single receiver on a tower, which can reach temperatures of typically around 600°C but in principle several thousand degrees can be obtained. HTF: water/steam, molten salt (particles, sodium)
Dish 300 – 2000°C		A mirrored paraboloidal dish system can also offer these high temperatures and with higher efficiency, but they are not as commercially mature. HTF: water/steam, chemical process

Additional factors, besides irradiation, that significantly influence the cost of solar thermal energy are final temperature and system size. An approximately linear increase of costs with temperature has been estimated based on data points across different collector technologies along with a dependence on system size, as shown in Figure 17.

Globally, the total installed capacity of solar thermal energy for direct use as heat was 472 GW_{th} in 2017, similar to those of solar photovoltaics and wind electric capacity. Much of the installed solar thermal heat capacity is currently used for domestic water heating in China and Europe using evacuated tube collectors, while 280 MW_{th} has been installed for industrial process heat. Recent large-scale projects in Oman for enhanced oil recovery and Denmark for district heating will add several hundred megawatts of industrial process heat capacity, using parabolic trough technology. In Australia, the Sundrop Farms CHP system in Port Augusta, SA is currently the largest operational solar thermal system with 36.6 MW_{th} of capacity. The higher temperature solar thermal systems, particularly towers, are most often used for electricity production. Full scale systems have not yet been built in Australia, although several have been examined[11]. Internationally, approximately 5 GW_e of solar thermal electrical generation is in operation. The thermal energy collection capacity of these plants is around 30 GW_{th}.

[11] The Aurora solar thermal power project for Port Augusta was proposed as a 135MW_e / 600MW_{th} system with 8 hours of full load storage. The project developer, SolarReserve have however pulled out and it remains to be seen if another party will take over the project as proposed.

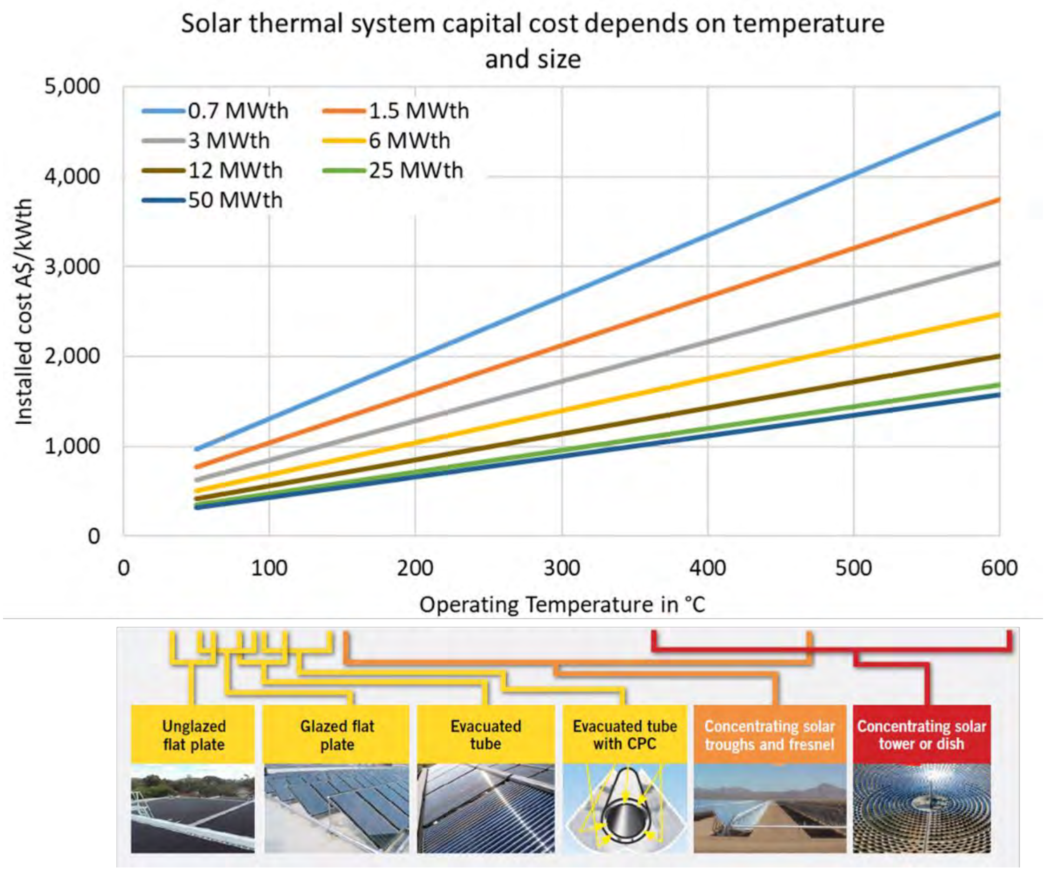


Figure 17: Solar thermal specific cost versus temperature, for a range of system capacities, in A$ 2019.

Appendix F includes a more detailed description of the main solar thermal technology types, global status and trends in solar thermal energy, solar resources, technology selection criteria, design guidance, a list of suppliers and cost charts.

3.6. System optimisation

The many industrial heat uses that involve the circulation of heated water, or steam or other heat transfer fluid to points of use, are open to a direct substitution of a renewable heat source for the existing fossil-fuelled source. However, the processes that industry uses and the approaches for providing heat were typically developed in earlier days of low - gas and coal energy sources. Thus, energy consumption had a lower priority than ease of process control and maintenance of product quality. The use of fossil fuels also meant that the primary supply of heat could be at a much higher temperature than actually needed for the process, with little penalty.

In a world of increasing primary energy costs, and with renewable energy options notable in having a cost-sensitivity to temperature, a range of approaches to system optimisation should be considered in addition to direct substitution of a renewable energy source for a fossil one.

Key approaches can be categorised as:

- Cascading input energy through stages of use to maximise value. Combined heat and power (CHP)[12] systems are a classic example of this.
- Delivery of energy directly to the point of use at closer to the minimum required temperature. This reduces what can be high thermal losses from large heat transfer fluid distribution networks and also benefits from the lower cost of lower temperature sources.
- Redesign of processes, to substitute mechanical or other approaches in the place of basic heating, or to simply improve the energy efficiency of heat use to reduce the investment requirements for the renewable energy equipment.
- Adjusting times of operation or processes to match the availability of renewable resources. This could involve operating heat using steps in batches to match resources availability, with the stockpiling of intermediate products, or the introduction of thermal storage technologies to bridge the timing issues.
- Consideration of location of new greenfields developments to co-locate with favourable renewable resources.

This section provides some introductory background to the key optimisation technology building blocks of combined heat and power, thermal energy storage and alternative process technologies.

3.6.1. Combined heat and power

Where a heat source is available at a higher temperature than the temperature of process heat required, a thermodynamically optimal system can first generate electricity by lowering the temperature, before providing the process heat. This approach is readily applied to steam produced by bioenergy or solar thermal. High temperature and pressure steam is introduced to a

[12] Combined heat and power systems are also often referred to as cogeneration systems.

single-stage turbine that partially expands it to the desired temperature while at the same time generating electricity. The steam exits the turbine at the temperature and pressure required by the process heat application.

Alternatively, where a gaseous fuel is used (i.e. natural gas, biogas or hydrogen), use of a gas fired reciprocating engine or turbine to generate electricity can be followed by heat recovery at temperatures up to around 500ºC from the exhaust gases.

As shown in Figure 18, a 1.5 MW_e/36 MW_{th} combined heat and power concentrating solar power system is in operation at Sundrop Farms in Port Augusta, SA. Sundrop Farms utilises large, advanced greenhouses to allow for year-round tomato yields of around 15,000 tonnes per year. Greenhouse inputs are fertilisers, freshwater, heating/cooling, and electricity. The solar plant contributes heat, power and freshwater to the greenhouses. Seawater is extracted for evaporative cooling and for desalination. Solar field contractor Aalborg CSP estimates that the system produces 20,000 MWh_{th} of heat, 1,700 MWh_e of electricity, and 250,000 kl of freshwater annually.

Figure 18: Sundrop Farms greenhouses and concentrating solar power plant (image Aalborg CSP).

Organic Rankine Cycle (ORC) electricity generation systems are a relatively recent innovation in CHP. The main difference to a steam-based system is the use of an alternative working fluid, particularly suited for efficient power generation using low to medium-temperature heat and small system sizes (in the range of approximately 300 kW_e to 3.5 MW_e), as well as good part-load behaviour and high process heat temperatures. On the other hand, ORC CHP units have significantly higher costs than steam CHP units.

A novel approach to CHP is the use of concentrating solar photovoltaics, which require water cooling to maintain the cells at an acceptable temperature. This cooling water can then provide a heat stream, at up to 80ºC. Melbourne-based company RayGen has developed a concentrated

PV CHP system based on a solar tower concentrating system and a cavity receiver containing the CPV cells.

The production of biogas from biodegradable materials is well established and there are several operating plants in Australia. The biogas (and natural gas) can be used in an engine/micro gas-turbine to generate power and heat that can be supplied to the machinery and process respectively. Typically, microturbines have a fuel-to-electrical-power efficiency of between 30 to 40%, and the balance is transferred to heat in the flue gas exhaust and engine cooling water. The exhaust from the engine has a very high temperature in the range of 450 to 480 °C. This exhaust heat can be utilised to heat HTF oil or steam for heat supply to the industrial process. Such CHPs have very high overall efficiencies in the order of 75 to 90%. The cost economics are good, and the paybacks are usually less than four years in most cases.

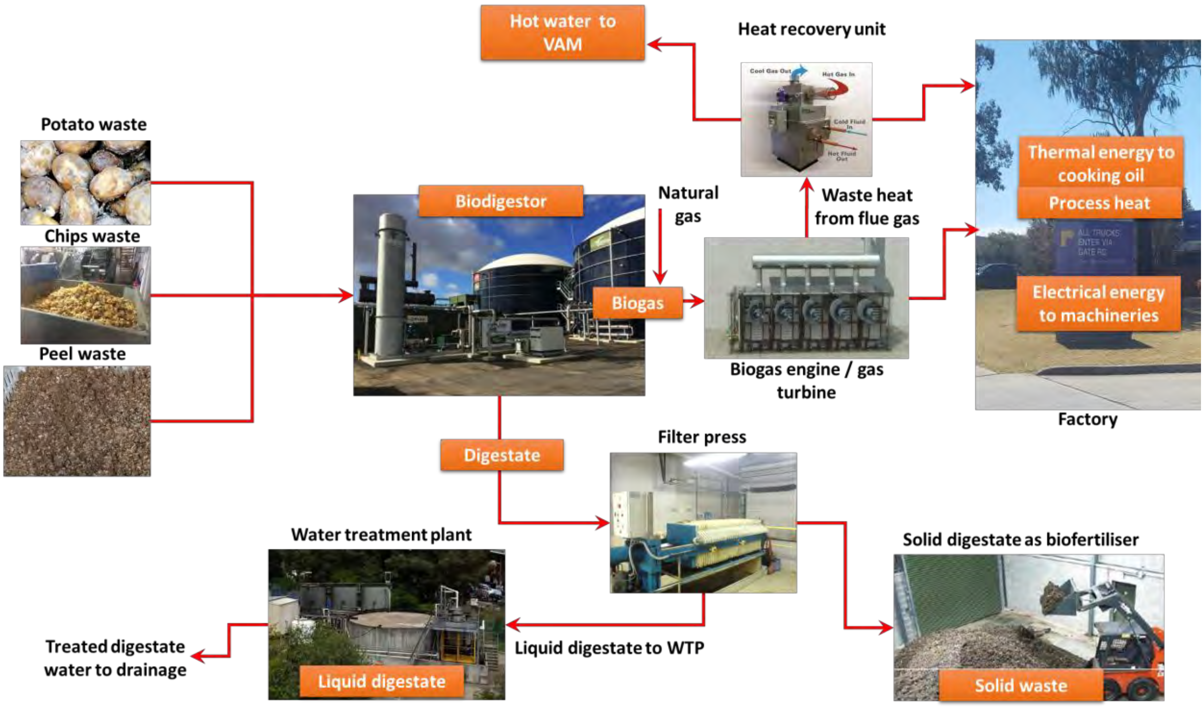


Figure 19: Example of an AD biogas based combined heat and power system[13].

3.6.2. Thermal energy storage

Thermal storage is used to provide a constant heat supply by compensating for variations in available energy input, e.g. bridging cloudy periods and supplying heat into the night for solar driven systems. In addition, thermal storage can be used with other variable heating technologies, e.g. heat pumps, to provide a buffer to generate and store heat during periods of low energy costs and use the stored heat during peak cost/demand times.

[13] Diagram ITP using adapted images from Snackbrand, Biogass Renewables, Capstone, Valorgas, Dry Coolers, K-pack Systems.

Whilst there are many approaches to thermal storage under development around the world, there are only a few that could be regarded as commercially available. Table 2 provides an overview of commercially available thermal energy storage technologies with their approximate usage temperature ranges and indicative costs. Unit costs have been estimated for a storage system size of 300 MWh (1080 GJ). For ease of comparison, a temperature difference of 100°C between hot and cold storage was assumed for thermal oil and molten salt storage systems. Storage costs scale down with increasing temperature difference. Depending on the process application of the stored energy, part or the full temperature range available with each fluid may be used. For water-based storage, typical operating temperature ranges are assumed.

Table 2: Overview of thermal energy storage technologies, including temperature ranges and approximate costs.

Technology	Operating temperature range	Indicative installed cost A$/kWh$_{th}$
Water	up to 180 °C	~0.05–15
Compressed water/steam	up to 285°C	~80–120
Mineral oil (e.g. Xceltherm 600)	up to 315°C	~10–20
Low-temperature synthetic oil (e.g. Therminol 55)	up to 290 °C	~50–160
Medium-temperature synthetic oil (e.g. Therminol 66)	up to 345 °C	
High-temperature synthetic oil (e.g. Therminol VP-1)	up to 400°C	
Molten salt	~220 to 565 °C	~60–120
Concrete	up to 600 °C	~5–20
Packed bed of rocks (Strasser & Selvam, 2014)	up to 800 °C	~30–50

Below 180°C, hot water storage tanks can be used, which is an inexpensive solution. Above ~100°C, tanks need to be pressurized to avoid water boiling. Higher pressure hot water / steam storage can be configured as a steam supply system where a pressure reduction valve causes water to boil to steam as it is drawn off.

Thermal oils can be used to store thermal energy from temperatures below ambient temperature up to around 400°C. The upper temperature limit is given by the chemical stability limit of the oil used, which varies across different oils. Generally, increasing temperature corresponds to increasing cost.

Slightly higher temperatures than with standard thermal oils, up to 425°C, may be used with new silicone fluids (Wacker, 2017).

Molten salts (e.g. Hitec HTS, Solar Salt, and others) have been successfully employed as a heat transfer/storage medium in industry (e.g. in heat treatment) and in CSP systems. Molten salts tend to be relatively inexpensive, abundant and exhibit favourable heat transfer properties.

The lower and upper temperature limits of molten salts are set by their freezing and degradation/corrosion limits, respectively, and the salt composition should be selected based on the temperature requirements of each application. Most commercial binary eutectic salt mixtures (sodium/potassium nitrate) have a freezing temperature between 130 and 230°C and upper temperature limit between 450 and 600°C. New molten salts that can be used at up to 700°C or more are currently being investigated (Jonemann, 2013).

Phase change materials to store thermal energy at high temperature are being developed but they are still in the research phase. The University of South Australia is a leader in this area. Some of the commercially available storage technologies with their suppliers are further discussed in Appendix G.

3.6.3. Process efficiency measures

Process substitution, like the various other technologies in this report, can be classified into those that are mature within themselves, where the chemistry, physics and engineering is well understood, and those that require work in the R&D phase. For the former, the barriers to uptake are in the commerciality of the options. The latter present, an investment in R&D that, for industry, is both risky and a separate business decision to normal activities.

Three key examples are introduced here, and others are discussed in the context of particular industry processes.

Dewatering

For industrial processes where the dried end product is required, advanced filtration and vacuum drying are applicable. Advanced filtration refers to the reapplication of a secondary, electrically-powered, physical extraction of water, or the improvement of dewatering in the initial separation phase. Vacuum drying is drying under reduced air pressure that reduces the total heat inputs required in the drying phase. Vacuum drying is a mature technology in a number of industries and is usually used in batch processes. There can be a high capital investment in the equipment for both of these options.

There are many examples where wet waste is dried by the application of heat from fuel combustion, and technically mature options for achieving results with much reduced heat use.

Sludge drying is a key activity in the wastewater sector but also in other industries depending on processes. Active drying using heating or hot air is used to either speed up the process or to reduce the footprint required on a site or both.

Mechanical vapour recompression (MVR) removes of water (and other solvents) from liquid streams and recovers of the heat of vaporisation. MVR can be used for reducing water content, sometimes for full drying, for recovery of solvents including water from waste streams, and the resultant concentration of contaminants in a smaller residual volume. MVR provides an extremely efficient method when the product stream to be concentrated, dried or separated is liquid. Where a vapour stream exists in an established process, MVR can be used to harvest that vapour as liquid and return the heat of vaporisation to the process. As a stand-alone drying method MVR can be set up to require no external heat input beyond a 'start up' heating input and provide very high coefficients of performance.

Sludges can be routinely dealt with by various forms of filtration / centrifugation / rapid sedimentation and can be effectively separated at that point for air drying. For difficult sludges, alternative methods include traditional dewatering and geotubes, advanced filtration and vacuum drying.

Traditional sludge dewatering by sludge drying beds is slow and involves allowing the sludge to settle in large outdoor tanks or ponds often with geofabric or sand and gravel bed separation from an underdrain system. The sludge containing solution flows into the pond and sludge builds up as clear water flows out the underdrain assisted by ambient air drying.

Sludge dewatering by geobags / geotubes involves putting sludge into large geofabric bags that sit on the ground and slowly lose moisture while the sludge is consolidated. The bag and the sludge when dry are generally disposed of together. This is a lower capital option than the creation of dedicated drying beds and a much lower operating cost option than mechanical drying or using heat.

Pasteurisation alternatives

Specific to food and beverages is the need to ensure the destruction of pathogens, which is traditionally achieved with pasteurisation. As an alternative to direct substitution of renewable heat to drive pasteurisation, there are new advanced techniques available that achieve the desired results. These include high-pressure processing, or radiative processes, in addition to the advanced filtration approaches mentioned above. This is discussed further in Chapter 5.

Drying

Drying in the timber industry and others such as prefabricated concrete panel production is usually forced drying using heat but traditionally a slower ambient drying process is used. Clearly in a world of increased fuel costs, greater use of ambient drying is warranted. It however requires inventories of material being locked up for longer periods, with a consequent greater space and working capital requirement.

The mere forcing of more ambient air through or past the product will not significantly decrease drying time due to both the restrictions on movement of water through the product (to get the inside moisture out to the surface where it can dry) and the heat requirement for the latent heat of evaporation, which is significant. Heat delivery techniques such as dielectric heating by microwave or radio frequency (RF) heating are able to overcome the heat distribution issue to some extent. For wood products such as particle board, medium density fibreboard (MDF) and plywood the potential for use of ambient air drying is low due to the need to contain the item during production. These products are dried during the production process, not after. Rapid drying is highly attractive in production economics and allows for the process to be entirely self-contained. Microwave drying / curing for particle board and fibreboard is established as viable. For the traditional sawn board timber industry however, these processes alter the final nature of the timber and the product is not market acceptable when a sawn board / sawn section product is required.

In the timber industry, traditionally, timber is left to air dry for ’one year per inch’ of thickness for hardwoods, differing for softwoods. There is no energy cost in ambient drying and the racking of timber and other costs are still similar, but there are significant inventory costs and significant space is taken up by timber that is air drying for 1-4 years[14].

For products with a less constrained structure such as brick firing, dielectric heating is able to provide the heat required for drying. This applies notably to all forms of reconstituted wood fibre (paper, cardboard, MDF) and to textiles. Similarly, for the thinnest sheet products (paper, textiles) drying can be electrified through the application of infra red radiation.

Catalytic enhancement

The attractiveness of catalysis to significantly reduce or even remove the external heat requirement for a number of different processes is high. A catalyst has the effect of speeding up a chemical reaction for a given temperature. Alternatively, it can allow a process temperature to be lowered by compensating for a reduction in reaction rate that would otherwise occur. Lowering the temperature can then reduce heat loss and make the supply of heat accessible to cheaper lower-temperature sources. In some cases, temperature can be lowered to ambient so that no external heating is needed. The IEA suggests that there is potential to reduce the energy intensity of products in the chemical industry by 20 to 40%by 2050 (IEA 2013 Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes).

[14] For hardwoods and softwoods at the end of the ambient drying process there is a need for steam curing (a process sometimes called reconditioning).While short in duration this is a higher-temperature steam process and an intense user of heat. This is not a drying process but steam can be replaced in some cases with alternative heating forms (even electric heating in some instances) and the injection of finely atomised (high pressure) water sprays.

3.7. Economic assessment

There are a range of options for use of renewable energy that are apparently economic when compared with heat produced at current fuel prices, and could certainly be economic if appropriately supported to recognise the environmental benefits. However, there is no simple answer and there are no single solutions that will solve all problems. Fuel substitution, improved system and process efficiency, changed processes, and increased electrification will all play a part.

To undertake a complete conversion of industrial process heat use to renewable energy, as required for an eventual near zero emission economy, is technically possible but will be considerably more expensive if done on a substitution basis. Rather, a conversion of industry in this manner requires major changes to the processes used to achieve a least cost result.

There is some tension between long-term and short-term planning. Some opportunities that are economically viable in the short term will only reduce fossil fuel use by a modest amount. It could be argued that this delays the necessary approach to full industry re-design in those cases. Nonetheless it would build industry confidence and momentum in the uptake of renewable solutions.

To understand the complexity of the situation, it needs to be considered that each industrial site will have a unique set of circumstances that includes:

- lifetime of existing assets
- capacity factor of heat use
- cost of existing fuel
- temperature of heat use
- times of use
- available renewable energy resources
- available land or roof area.

It is extremely difficult for companies to evaluate a long-term least cost process change in the absence of policy certainty. While some substitution of renewable energy for fossil fuel is, and may become cost competitive, certainty regarding long-term requirements for zero emissions is likely to both change and accelerate the required process changes, which can then be incorporated into normal equipment replacement cycles.

Some general economic analysis follows, which can help to illuminate the situation regarding short term investment decisions, but cannot address the longer-term process changes that either require or would be accelerated by policy settings that drive strong emissions reduction.

3.7.1. Direct substitution

The many cases of industrial heat use that involve the circulation of heated water or steam or other heat transfer fluid to points of use are open to a direct substitution of a renewable heat source for the existing fossil-fuelled source.

Industrial users will typically make an investment decision informed by the simple payback time or in the case of a major rebuild, an internal rate of return. However, both of these assessment methods are specific to the existing cost of fuel. Here we evaluate the levelised cost of heat[15] (LCOH) from the various renewable heat options. This amortises the capital investment as well as covering any input fuel cost (such as gas, coal, electricity or biomass) and operation and maintenance cost. The levelised cost of heat can then be compared with the cost of heat from existing fuel as appropriate to an individual circumstance.

For the comparisons presented here, the financial parameters used are:

Cost of equity: Nominal pre-tax return on equity: 10%

Debt share: 60%, Nominal pre-tax return on debt: 7.78%, term 10 years

Inflation: 2.5%

System life: 20 years

O&M: 2% of capital cost per year

Thus, if an LCOH determined on this basis is equal to the current marginal cost of delivered heat from a current fuel source, then this implies the renewable option would have a discounted payback period of 20 years and an internal rate of return of 10% on equity. If the LCOH of the renewable option is less than the current cost of heat, then the payback time will be less and the IRR higher.

The various technology appendices discuss the installed costs of the different renewable technologies. Costs shows an economy of scale as system capacity is increased. This behaviour has been assumed for all technologies. A power law dependence is a well accepted model. i.e.;

Installed cost is proportional to (system capacity in MW) ^x

Where x is an exponent that is less than one and is often equal to 0.7

[15] This is a levelised cost of energy evaluated for the case of energy as heat.

Fossil fuel-fired

A curve fit of capital cost with a power law dependence on size, with an exponent of 0.7 for less than 10 MW and an exponent of 0.9 for more than 10 MW, has been fitted to updated cost information as shown in Figure 20.

Figure 20: Gas boiler specific cost versus size.

Figure 21 shows the LCOH for a new build fossil-fired system or a fully depreciated existing system for a range of fuel prices with an assumed 80% conversion efficiency and 70% capacity factor. In the case of the fully depreciated system, it can be seen that the cost of heat is higher than the input fuel cost, reflecting the 80% conversion efficiency assumed. For a new build system, LCOHs are higher, allowing for the amortisation of the capital cost component. For small systems, the higher specific capital costs cause the upward trend in LCOH that reflects the upward trend in installed costs for small systems shown in Figure 20.

The graph in Figure 21 (and subsequent graphs in this section) uses a logarithmic scale on the horizontal axis for annual heat use. This allows the whole range of annual consumptions indicated in Table 2 to be examined with more attention to the many sites that fall below 100 TJ/year consumption.

Smaller industry customers see much higher fuel prices and hence cost of process heat compared to the large users. Figure 22 reproduces the results of Figure 21 and shows the indicative cost of heat from fossil-fired systems based on likely LPG, gas and coal prices as a function of annual consumption, for 2019. This trend should be considered as the basis for a comparison to the renewable options that follow.

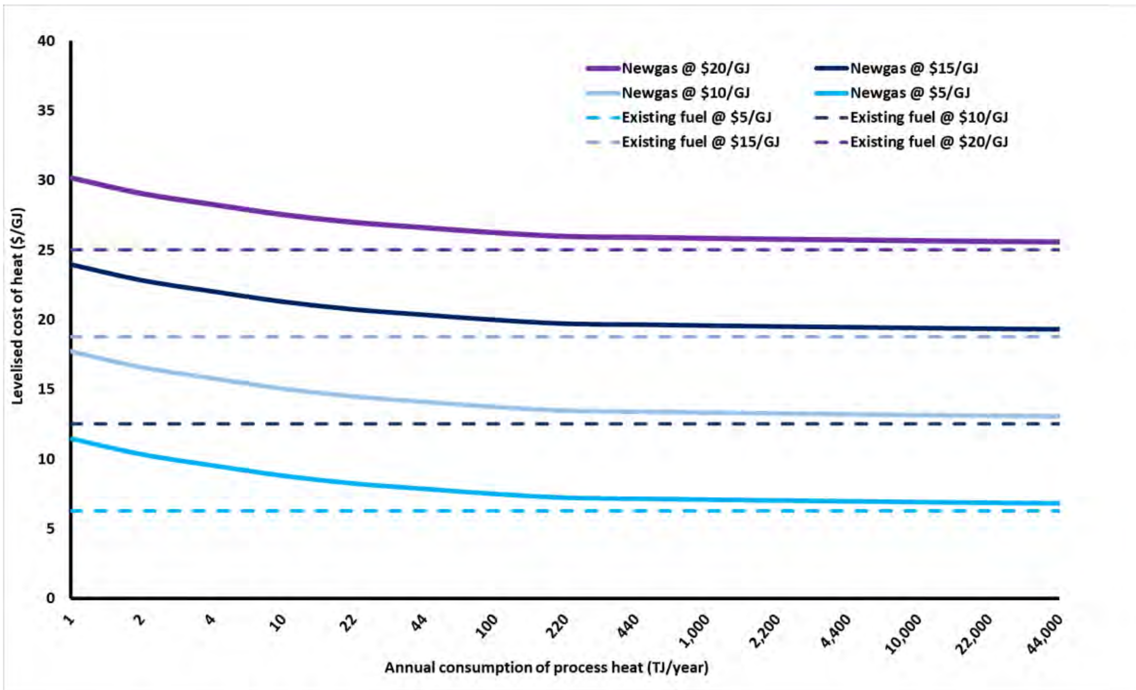


Figure 21: LCOH of natural gas fired process energy production considering either new build or already fully depreciated systems, for a range of gas prices.

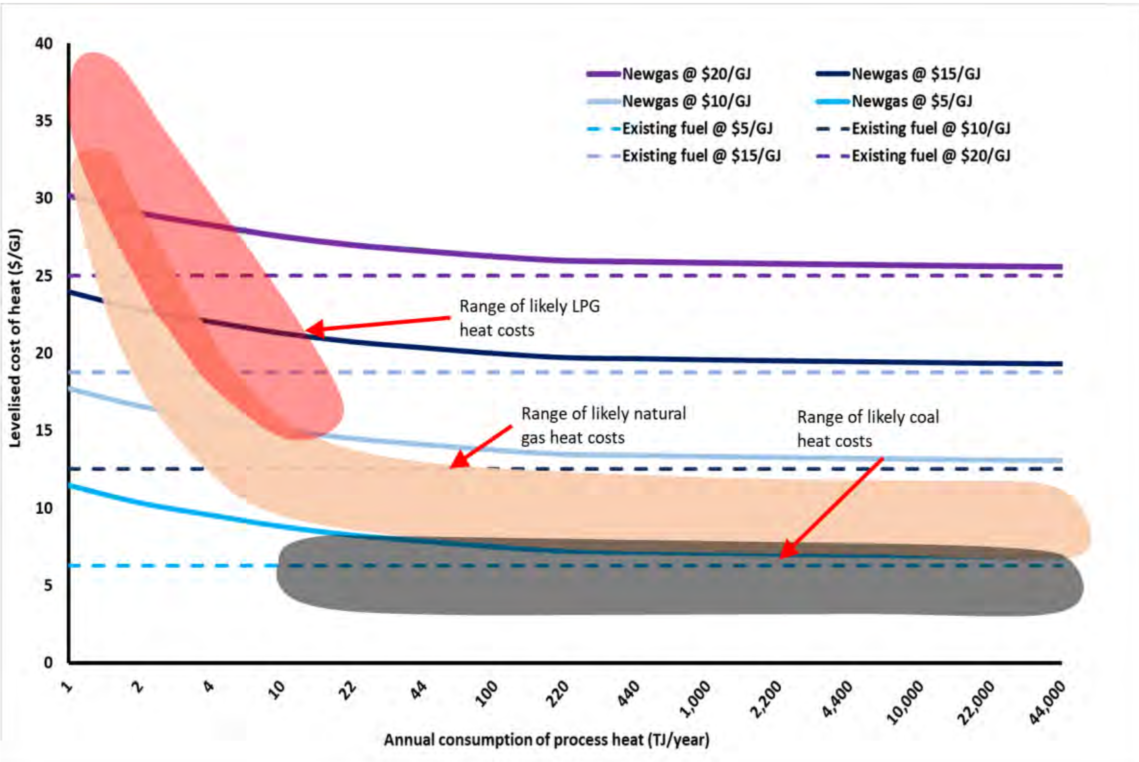


Figure 22: Cost of heat from fossil-fired process energy production considering either new build or amortised systems, together with a mapping of expected cost of heat based on coal, gas & LPG price dependence on user demand levels.

Bioenergy

The capital costs of biomass-fired boilers, biomass gasifiers and biomass digestors are discussed in Appendix C, with a power law fit to size also applying. In this section, bioenergy options are considered as a single class with capital costs taken as those of combustion boilers and used as indicating the average performance of the other configurations.

Figure 23 shows LCOHs of new build bioenergy systems against fossil-fired systems whose capital costs are fully depreciated. For biomass, a likely price range of $0 to $15/GJ is used, while for existing fuels, prices are likely in the range of $5 to $20/GJ. Note that lower cost for biomass fuel compared to natural gas is an obvious but crucial prerequisite for a bioenergy system to be cost-competitive (ignoring any subsidies for renewable energy).

The width of the shaded lines represents the uncertainty in the determination. It follows an estimated +-20% uncertainty and site-specific range to the capital cost estimates. Further it is assumed that the economies of scale according to the cost-scaling coefficient of 0.7 for less than 10 MW and 0.9 for greater than 10 MW is used for bioenergy. 10 MW_{th} capacity at 80% capacity factor corresponds to 250 TJ/year of annual process heat consumption.

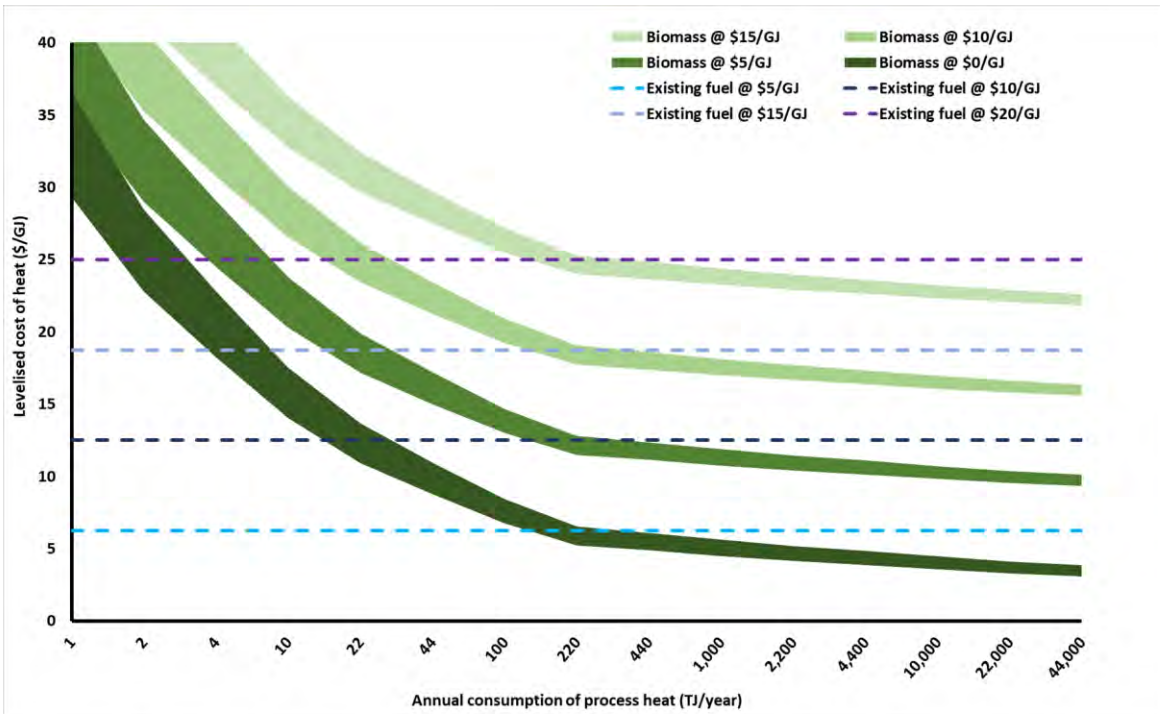


Figure 23: LCOE of existing gas and new build biomass process heat plants.

The LCOH curves for biomass are seen to cross and become less than those of gas-fired systems that are already amortised at various size points. The larger the plant, the more attractive a biomass solution is compared to gas of a given price, due to the size-dependent capital cost contribution that favours larger plants. It should be noted however that higher capacities can also result in more complex biomass supply chain issues and potential increase in input fuel cost if fuel is not available within a certain distance. Whilst biomass LCOHs are much higher for small systems, the increase is almost in direct correlation with the higher fossil fuel prices seen by smaller users (Figure 22), thus there is no apparent favourable size-based niche market apparent from this analysis. It appears that any situation where biomass is available at $5/GJ or less should be quite competitive. It should also be noted that small bioenergy systems may be selected because they provide waste disposal capability, rather than because they are competitive with fossil fuels (this is sometimes included by assigning a negative cost to the bioenergy fuel).

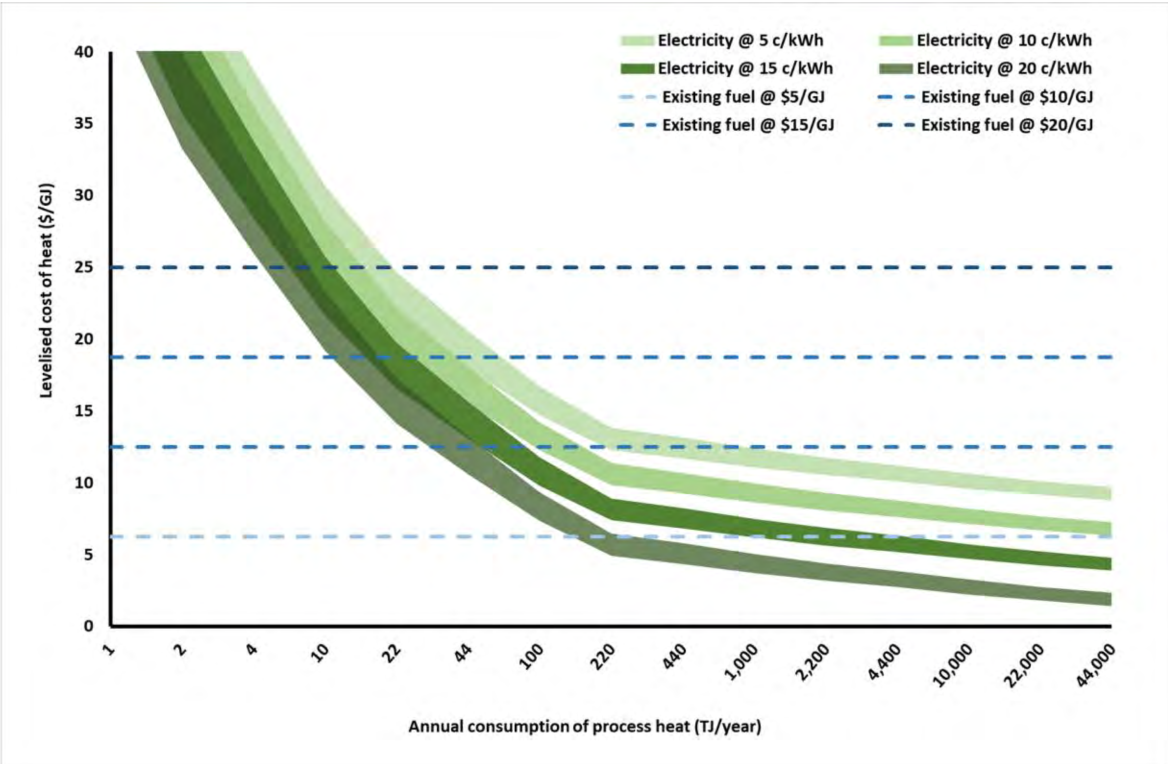


Figure 24: LCOH of biomass CHP plants; electricity prices ranging from 5 to 20 cents/kWh and biomass at $5/GJ.

A biomass CHP system sized to meet the process heat demand at a user site produces additional electricity while supplying process heat and is thus more efficient and offers two sources of value. Figure 24 shows LCOH curves for biomass CHP systems for a range of average electricity prices. The power conversion efficiency of the turbine depends on the extraction pressure of the steam from the turbine for introduction to the process; a nominal power conversion efficiency of 15% is assumed in this graph. The LCOH of the CHP system is derived by subtracting an implied revenue from the generation of electricity from the annual fuel costs. Thus, the higher the electricity price the lower the effective LCOH is.

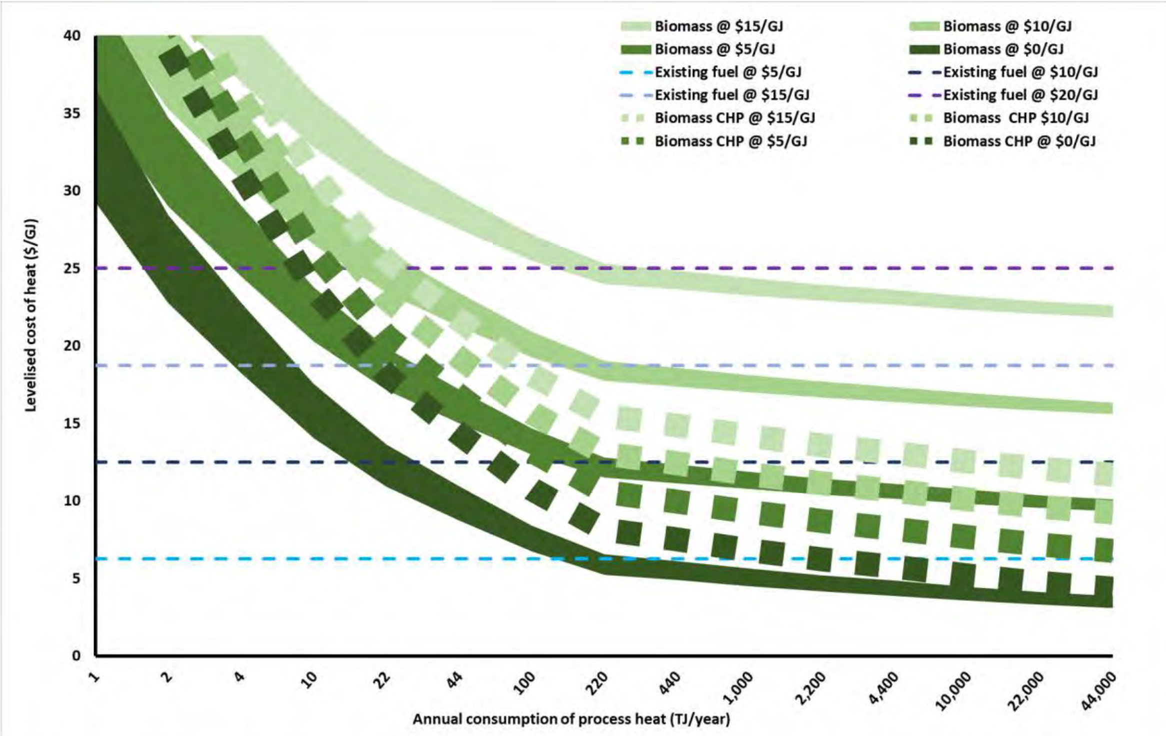


Figure 25: LCOH of biomass CHP vs biomass process heating plant; electricity price 10 c/ kWh.

Figure 25 shows the comparison of the LCOH of a CHP system against a process heat only system for the specific case of 10c/kWh electricity price. The LCOH of a CHP system is lower than that of a heat-only system for fuel cost greater than $0/GJ, for a sufficiently large system. On the other hand, if both biomass fuel costs and electricity costs are low, small systems do not justify the extra capital investment, however in general a CHP configuration is well worth investigating.

Renewable electrical heat

Either electrical resistance heating or heat pumps can be contemplated for direct substitution and it is instructive to examine indicative LCOH values for some particular cases. It should be emphasised that some of the more attractive opportunities for electrical options involve low effective efficiencies of use and that benefits can result from installation of electric technologies directly at the point of use.

A further issue with electrically-driven systems is the cost of electricity. The analysis below considers some representative average costs of electricity. All the industrial users in the scope of this study are assumed to be grid connected, even though increasing number may have their own behind the meter PV systems. The effective cost of electricity will depend on the source for it and may well change during the course of the day according the nature of their electricity supply contract, which in the future may also result from direct contracts with renewable electricity generators.

A time varying cost of electricity raises the question of when an electrically driven heating system should be operated. Demand for heat may be variable also and may or may not correlate with daytime business hours. Operating a heat system for a reduced period could be accommodated with the addition of thermal energy storage. Reduced hours of operation (i.e. lower capacity utilisation factor) will however increase the contribution of capital amortisation to LCOH. For example, an electrical heater limited to operate only when output from an onsite PV system was available would work with a capacity factor of just 15 -20%, with a consequent higher LCOH, whereas a unit relying on grid electricity could follow the high capacity factors of many industrial gas-fired installations.

Electrical resistance

Figure 26 shows the LCOH curves of electrical resistive heating system at 95% conversion efficiency and 80% capacity utilisation factor.

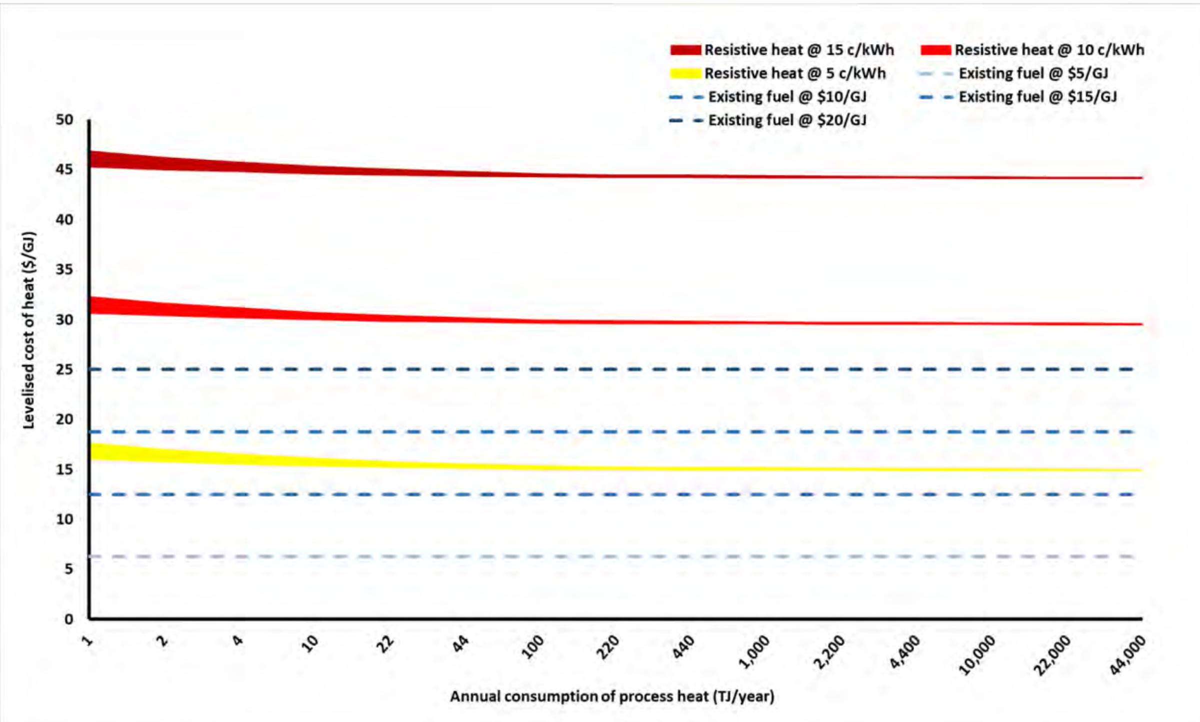


Figure 26: LCOE of existing gas vs new build electrical resistive heating plants; electricity prices at consumer end ranging from 5 to 15 cents/kWh; efficiency 95%.

The width of the curves reflects uncertainty in the Capex at ± 10%. An electrical resistance heating system maintains the same efficiency almost independent of temperature. The flat curves indicate the dominant dependency of LCOH on electricity prices as the Capex contribution is small. On the whole, very low costs of electricity relative to competing options will be required to make resistance heating competitive. However, situations where direct application of heat replaces an extremely inefficient heat transfer process from a central boiler, could be competitive.

A further observation is that the low Capex contribution to LCOH means that the penalty for operating at low capacity factor is substantially reduced, this raises the idea of combining resistive heating with other sources of heat, with resistive heating used to take advantage of possibly intermittently available very low cost electricity[16].

Heat pump

For a heat pump run with a high capacity utilisation factor, the determinants of LCOH are the Capex, the electricity price and the coefficient of performance. The coefficient of performance is determined by the temperature lift required, and the thermodynamic efficiency of the heat pump relative to ideal. Figure 27 depicts the LCOH for a heat pump supplying heat with a temperature lift of 80°C (e.g. output at 100°C from an input at 20°C), operating at a capacity factor of 80%, with electricity price ranging from 5 to 15 c/kWh.

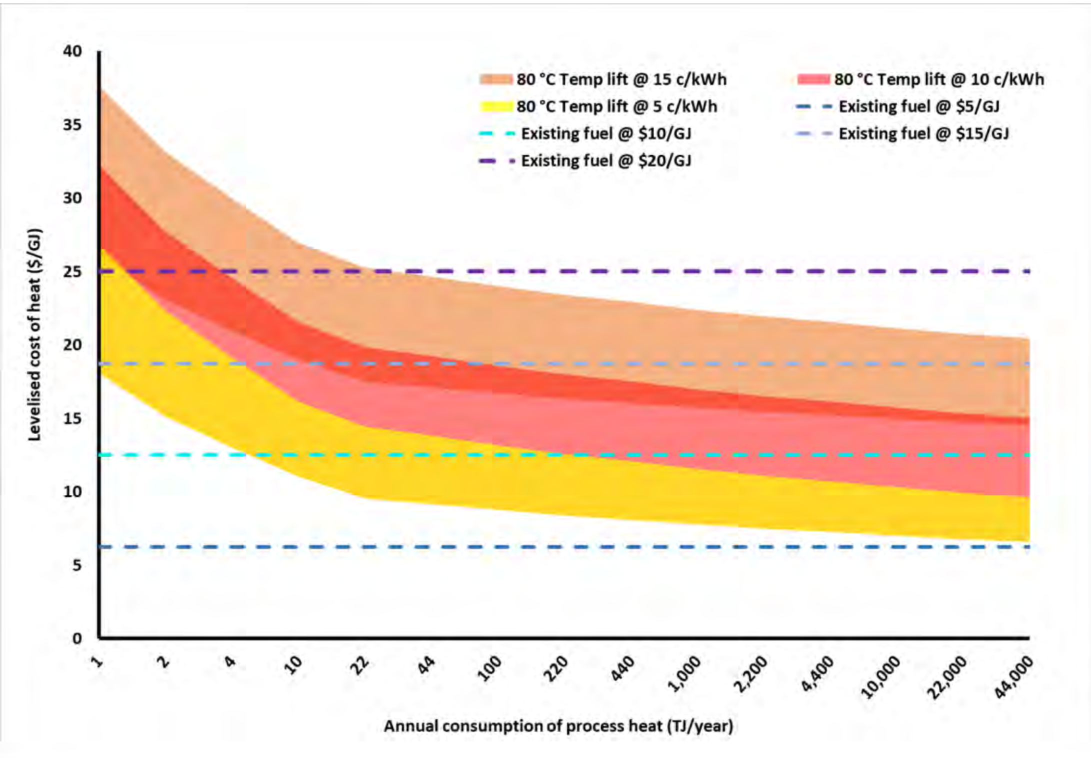


Figure 27: LCOH of heat pumps for electricity prices ranging from 5 to 15 c/kWh, thermodynamic efficiency 65%.

For this analysis, thermodynamic efficiency was assumed to be 65%, i.e. COP set at 65% of the maximum theoretical value for the upper and lower temperatures in question. Capex figures were

[16] In the NEM there are already times when wholesale prices are negative in correlation to high wind generation and low demand. Large future deployment of PV is predicted to result in very low midday wholesale prices during high solar days.

taken from Appendix E. The bands of spread result from a combination of uncertainty and spread in cost and COP of ±10%.

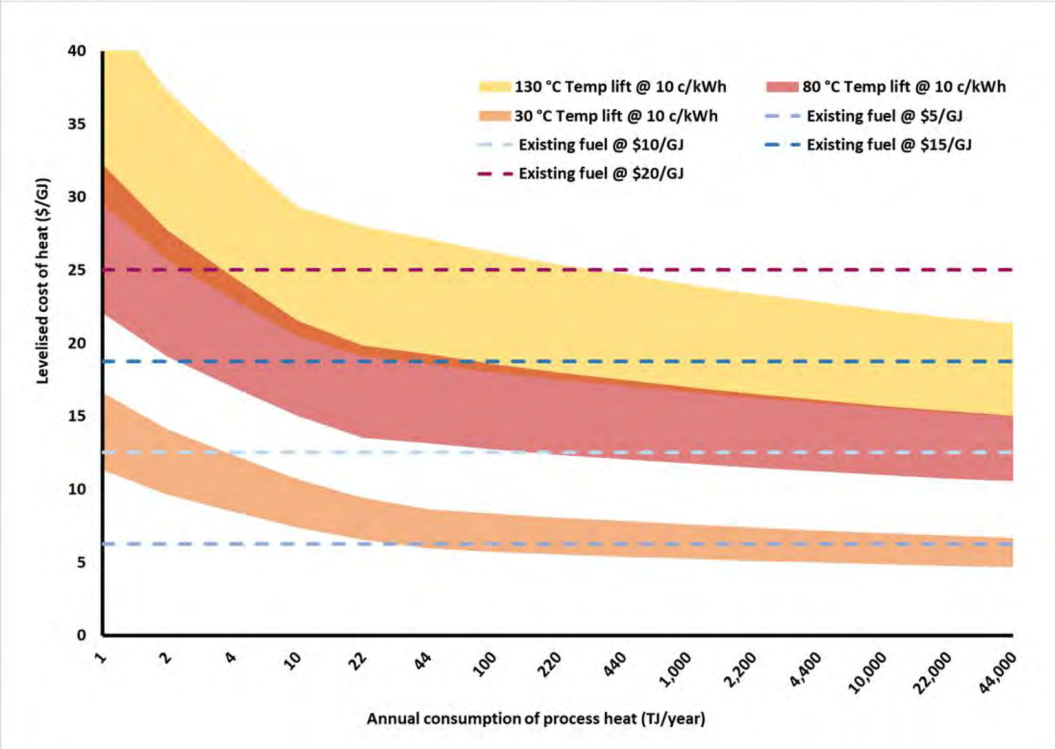


Figure 28: LCOH of heat pumps for heat supply temperature lift ranging from 30 to 130°C; electricity price at 10 c/kWh, thermodynamic efficiency 65%.

Figure 28 shows the impact of temperature lift and hence COP on the LCOH of heat pumps[17]. Note that it is the difference in temperature of source to output that determines COP, so if a higher temperature source is available, the LCOH of output heat will be reduced. At low temperatures lifts, heat pumps can be seen to be highly competitive with other options. As discussed above, the COP and the electricity price largely determines the LCOH and hence the cost of energy. The effective fuel-related cost of heat from a heat pump can be thought of as the electricity price divided by the COP, while the fuel-related heat cost for an existing fossil-fuelled system is the fuel cost divided by the energy delivery efficiency.

The input energy costs being the main determinant of cost effectiveness, in mathematical terms, a heat pump solution is worth detailed investigation if:

(cost of electricity)/COP < (cost of fuel)/(energy delivery efficiency)

Where the costs are converted to the same units using 1 kWh = 3.6 MJ.

[17] If a 20°C source temperature were assumed these would correspond to output temperatures of 50 – 150°C

Figure 29 examines the effect of capacity utilisation factor. The capacity factor, indicating the utilisation of the heat pump, can be seen to impact the LCOH as well as the shape of the LCOH curves. At higher utilisation, the LCOH flattens out toward the effective fuel cost more quickly than the lower utilisation LCOHs.

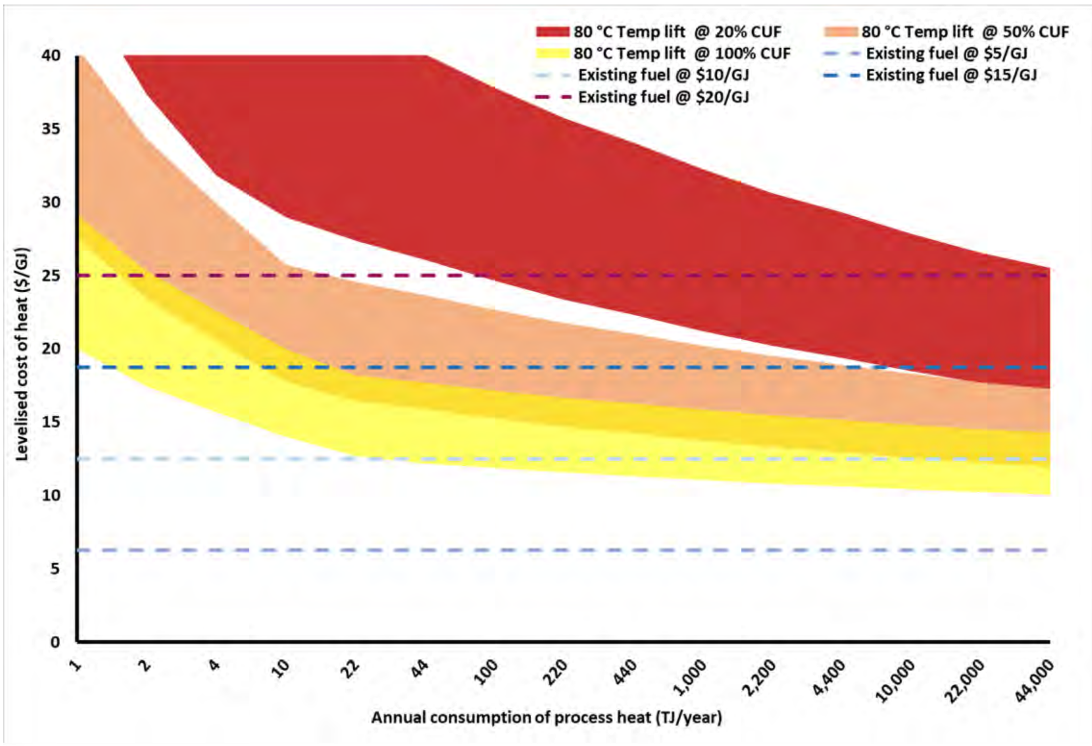


Figure 29: LCOH of heat pumps at different CUF; electricity price 10 c/kWh, thermodynamic efficiency 65%.

With increasing capacity factor, the same capital cost is amortised over a higher energy output, and hence the LCOH approaches the lower limit sooner. This is relevant to the sourcing of electricity. If it is desired to use behind the meter self-generation using PV, or to source low cost renewable electricity from the grid at times of high generation, it needs to be understood that the LCOH penalty of a low capacity factor can negate an apparent electricity cost advantage.

The overall conclusion is that heat pumps are a very promising solution for industrial heat users needing process heat below 100°C (or 80°C lift) with high-capacity utilisation. The main determinant is the ratio of electricity price to existing fuel prices together with the energy conversion efficiency of the competing processes.

Geothermal

The economics of sedimentary aquifer geothermal energy are largely dictated by the local resource and the utilisation of this resource. A shallow resource can be tapped at less expense than a deeper resource, and the higher the temperature and flow rate of the resource, the greater the energy available to the user. If the flow rate and temperature determine the amount of energy available at any one time, the utilisation refers to the amount of time this available energy can be used in processes.

Flow rates depend on the porosity of the aquifer, and the power of pumps applied. Pump loads have an electricity cost that can become prohibitive if flow rates are driven too high. However, for a properly designed well into a suitably porous aquifer, pumping loads are a small fraction of the total heat yield. Hence, electricity costs contribute only slightly to LCOH.

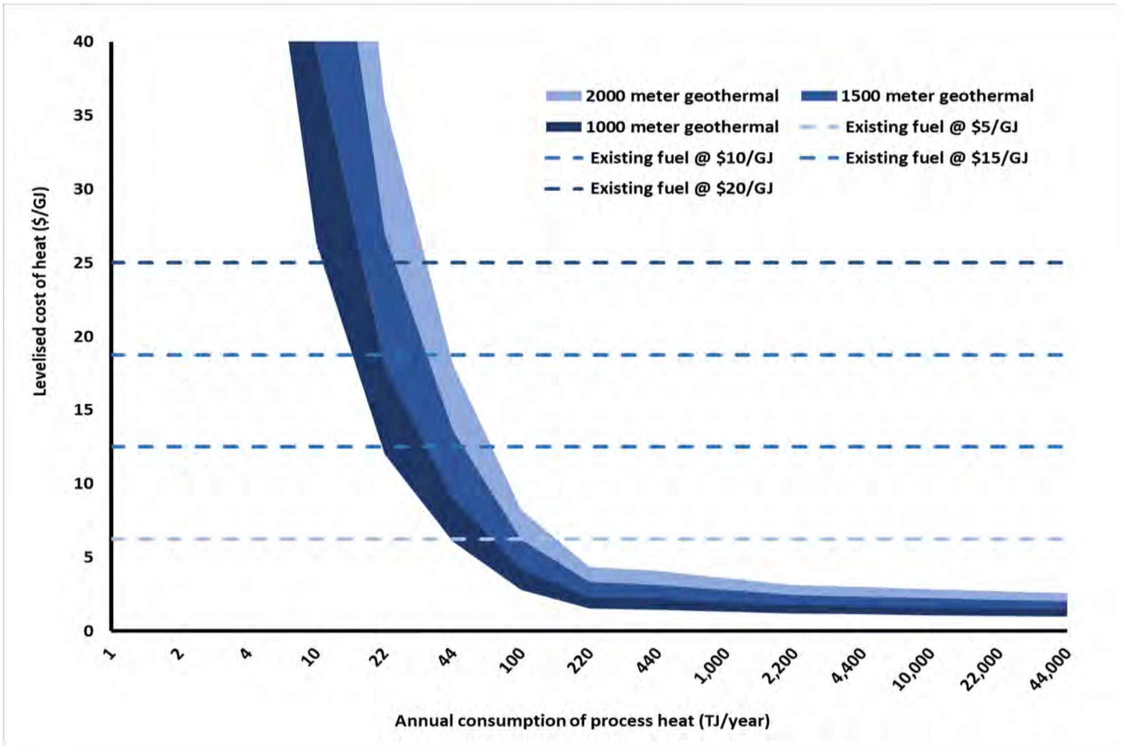


Figure 30: LCOH of hot sedimentary aquifer geothermal plants at different well depths; Flow rate is 30 l/s and process supply temperature is 75°C.

When compared to low-temperature solar thermal, biomass and heat pump systems, capital costs are high and increase with depth. However, the energy is available on a 24-hour continuous basis and if the utilisation factor is high, the economic performance will be best. Hence, resource depth and utilisation is the major determinant of the LCOH. LCOH curves are shown in Figure 30 for depths of 1000m, 1500m and 2000m, and for the typical case of 30 L/s flow rate, 10c/kWh electricity. The width of the curves reflects uncertainty in cost of wells and achievable flow rates. The estimated capital cost variation is at +/-20%. The LCOH's correspond to one pair of wells being utilised up to 80% at ~170,000 GJ/year, before a discontinuity at the point where it is assumed that a second pair of wells would be required.

For an industrial heat user, geothermal is only an option if they are located on a sedimentary basin and then the suitability of an aquifer is largely a question of whether it is hot enough for the process. Only temperatures up to 95°C are achievable in Australia. Given the low costs of heat that could result however, it is worth considering geothermal as a preheat that is supplemented by other technologies for further heating such as heat pumps for example. The overall conclusion from this analysis is there is a very strong crossover point of annual energy demand above which a geothermal solution can be very cost-effective, below that point it is not. Although only applicable to a minority of users, it should definitely be investigated where low temperature heat is used.

Solar thermal

For a comparison of solar thermal options against fossil fuel, a range of specific temperatures have been individually examined. As a starting point and an example of a location with a ‘reasonable’ solar resource level, Brisbane QLD has been selected for the analysis. Figure 31 shows LCOHs for 100, 200, 400 and 600°C systems.

The shaded bands for the results for solar thermal are indicative of the possible range of values due to the various uncertainties and variations in system configurations possible. These are larger than they are for bioenergy or electrically-driven technologies as there is no input energy cost so the fractional uncertainty in capital cost translates directly to that of LCOH. The estimated capital cost variation is also larger at +/-20% and there is a strong site dependence of the solar resource available. No cost of land has been included as it is assumed that the user takes advantage of existing land or roof space[18]. Operation and maintenance costs are assumed to be 2% of capital cost per year. A cost-scaling exponent of 0.7 for less than 20 MW and 0.9 for greater than 20 MW is used for solar thermal. 20 MW_{th} capacity at 80% capacity factor corresponds to 500 TJ/year of annual process heat consumption.

It is apparent that solar thermal systems for temperatures below approximately 150°C should be quite competitive on this basis with fossil-fired solutions over almost the entire size range at current gas prices. In claiming this, reference is made again to the observation that small users already pay much higher prices for energy than large ones. Looking at the higher temperatures, systems at around 200°C (small trough or Fresnel concentrators) appear to have some prospects if wholesale gas prices remain around $12/GJ. At 400°C present costs for solar technology are too high for viability even at likely future gas costs. At 600°C and above there is an even larger cost gap.

[18] There is also no allowance for structural reinforcement of roofs, which may be required in some cases.

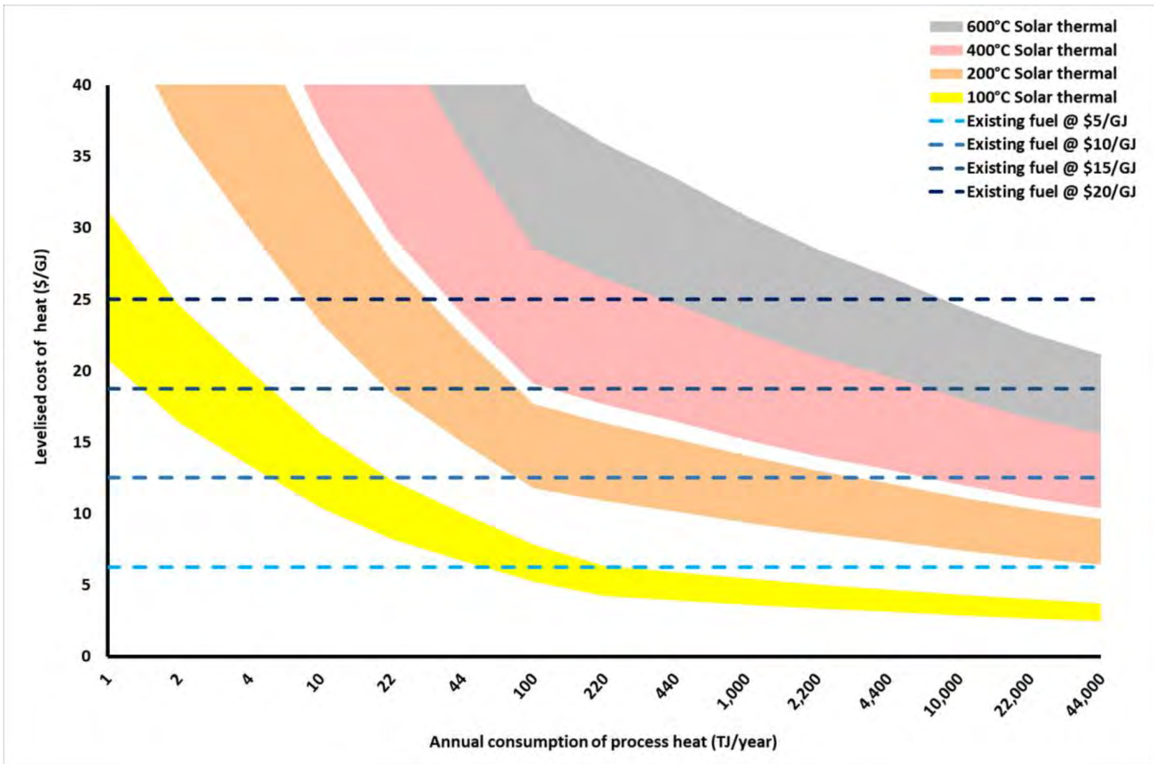


Figure 31: Solar thermal LCOE v gas LCOE, with capacity factors of 31.1% for evacuated tube collector (100°C) and 14.1% for concentrator (200, 400 and 600°C); zero land cost assumed; site: Brisbane.

With the high-temperature systems, the possibility exists to build them as CHP systems by using back pressure steam turbines to produce both electricity and lower temperature process heat. As with bioenergy CHP, this will yield lower-cost heat than a heat only system in some cases, again depending on system size and value of electricity.

It is instructive to consider the effect of solar resource level on these conclusions. Figure 32 presents the results for a 200°C system modelled for Melbourne (9.6% capacity factor), Brisbane (14.1% capacity factor) and Alice Springs (21.7% capacity factor), representing the range of possible Australian locations. It is apparent that such a system would be at borderline viability in Brisbane but would look quite competitive in a location like Alice Springs. On the other hand, application in a location with a lower solar resource (e.g. equivalent to Melbourne) would not make economic sense, unless the user is in a regional area and already pays very high prices for gas.

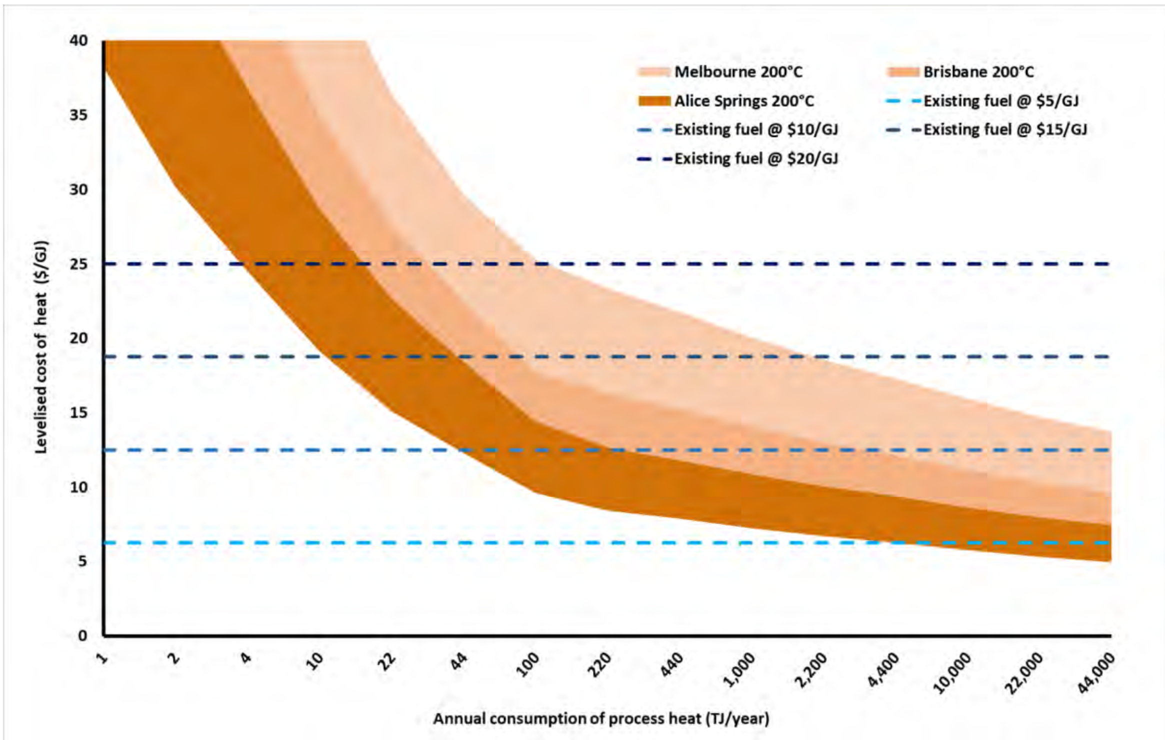


Figure 32: Solar thermal LCOH for 200°C process heat for poor, reasonable and excellent solar resource locations.

3.7.2. Process redesign

There is a segment of the industrial process heat market, particularly in mid-sized manufacturing, where the actual efficiency of process heat use from centralised boiler facilities distributed around the site can be quite low. These are opportunities for process re-design. They can be particularly suited for alternative ways of introducing energy that is electrically driven. Electromagnetic processes or heat pumps at the point of use are key examples.

In addition to this, it is apparent that in the very large heat use sectors of iron and steel and chemicals a serious shift to renewable energy is going to require a major process redesign.

Unlike direct substitution approaches, it is not possible to offer meaningful simple LCOH comparisons by technology for process redesigns. While LCOH could be evaluated for a specific site once energy use efficiencies are known, it would not be a meaningful metric if significant investment in process redesign was needed. For any given situation, all options need to be considered with careful analysis of the potential internal rate of return or lifetime net present value of cost.

3.8. Resources

Bioenergy feedstocks include: agricultural residues, energy crops, forestry residues, urban wastes, sewage gas, landfill gas and woody weeds. Whilst the handling technologies are mature on a global scale, in Australia supply chains are still largely undeveloped. There is considerably more potential than is currently utilised. The location of current resources is specific and linked to current land use.

Much of the continent has sedimentary aquifers below the surface, many with elevated temperatures. Identifying accessible geothermal resources is harder and reliant on the skills of experts in the field.

Solar resources are well known at an average level and are higher towards the inland of the continent. There are key issues of day to day and seasonal variability. Australia's overall solar resource level is close to the best in the world.

There is a reasonable but not ideal correlation between the location of industrial heat users and geothermal, solar or biomass resources. The majority of industrial gas users would be able to identify some level of solar and / or biomass resource that could in principle be used.

Electricity-based heating, however, has a key advantage that grid connection allows it to be used in any location, with renewable electricity provided from elsewhere. Massive use of solar-derived hydrogen in the future will likely be targeted at production in high solar resource areas. This would assume that pipeline transmission and distribution would be carried out in the same way as it presently is for natural gas. This would not only remove the geographical limitations on use, but also provide inherent daily energy storage using the volume of the pipe network itself.

4. ALUMINA AND OTHER NON-FERROUS MINERALS

4.1. Overview

The AES reports energy use for ANZSIC groups 213 – 214 within the manufacturing division and refers to them as Basic non-ferrous metals. This is the category discussed in this chapter, renamed with an emphasis on alumina as it is the alumina refineries that are the largest users of process heat in the sector.

Other important contributors to heat use in this sector are copper, nickel, and zinc refineries. The sector also includes four aluminium smelters that further process alumina to metal aluminium using the Hall-Héroult electrolytic process. This is electrically-driven so these plants are not major users of heat. Smaller, though not insignificant quantities of high temperature heat are used in the process of baking carbon anodes.

4.1.1. Site location and intensity of heat use

Figure 33 shows the location of plants in this sector and their approximate annual energy use. It indicates that there are a relatively small number of large energy use sites. Figure 34 provides more detail on the location of alumina refineries relative to the sources of bauxite that they process.

There are currently six operating alumina refineries in Australia, producing mostly smelter grade alumina from five bauxite mines for both the domestic and export markets. According to the Australian Aluminium Council, Australia is the world's second largest producer and exporter of alumina, with 22% of global production. In 2011, Australia produced 19.1 Mt of metallurgical (smelter grade) alumina and around 0.5 Mt of chemical grade alumina. As shown in Figure 34, four alumina refineries are located in the southwest of Western Australia and two near Gladstone, Queensland, with the following alumina production capacities:

- Yarwun, QLD (Rio Tinto Alcan): 3.4 Mt/year
- Queensland Alumina Ltd (QAL), QLD (Rio Tinto Alcan, Rusal): 3.95 Mt/year
- Worsley, WA (South32 - Worsley Alumina): 4.6 Mt/year
- Kwinana, WA (Alcoa of Australia): 2 Mt/year
- Pinjarra, WA (Alcoa of Australia): 4.2 Mt/year
- Wagerup, WA (Alcoa of Australia): 2.6 Mt/year.

A seventh refinery at Gove, Northern Territory (Pacific Aluminium) suspended operation in 2014. As can be seen from Figure 34, these alumina refineries tend to be located in relative proximity to bauxite mines. Notable exceptions are the mine at Weipa and nearby locations on Cape York Peninsula, which is not close to a refinery, and the refineries in Gladstone that in turn are reliant on bauxite delivered by ship from Weipa or Gove. The reason for this separation is that there is no suitable large source of conventional fossil fuel within hundreds, if not thousands, of kilometres of Weipa, whereas Gladstone is close to major supplies of both coal and gas.

According to industry experts, the alumina sector in Australia is expected to grow at a rate of around 1-2% per year.

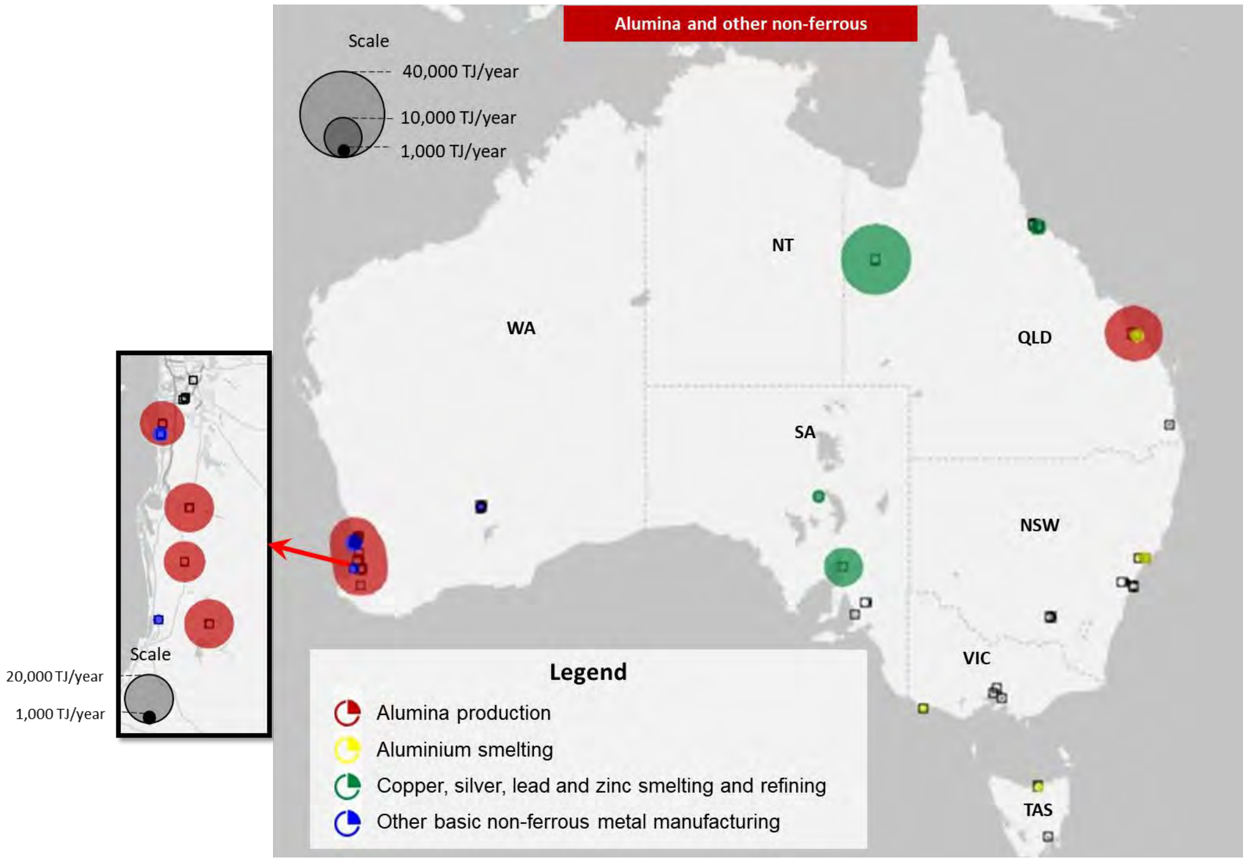


Figure 33: Location and volume of heat use for alumina and non-ferrous metal processing facilities.

Other major energy use sites are the copper refinery at Mt Isa, QLD, the copper and uranium operation at Olympic Dam in mid-South Australia and the multi metals smelter at Pt Pirie, SA, that processes ore from mines in Broken Hill. Smaller quantities of thermal energy use are associated with the nickel smelter at Kalgoorlie, WA, the nickel refinery at Kwinana, WA, the currently closed nickel refinery at Yabulu, QLD, and the initial processing of zinc concentrate at the electrolytic zinc refineries at Risdon (Hobart), TAS and Townsville, QLD.

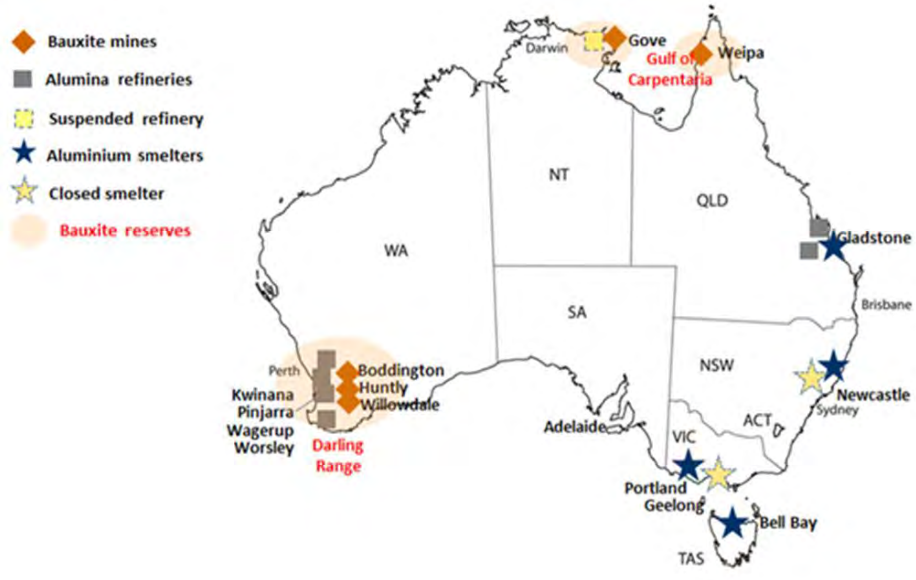


Figure 34: Overview of bauxite mines and reserves, alumina refineries and aluminium smelters in Australia. Reproduced from Australian Aluminium Council.

4.1.2. Processes that use heat

Energy is consumed at all stages in the production of metals. The processing of ore to metal can involve various combinations of beneficiation, refining and metal production. Processing and refining of the ores consumes the most energy and mining the least. While most of refining is carried out at high temperatures in furnaces, low-temperature processes (<250 °C) are identified as leaching, drying, anode and cathode washing and electrolyte heating, which are common to most of the non-ferrous extraction processes. The energy consumed in such processes can be estimated to vary from 10% to 20% of the total energy (Rankin, 2012). Some mineral ores may be difficult to leach and require roasting to expose the valuable mineral. The roasting temperatures can vary from 500 to 700°C with multi-hearth and roasting kilns used (Adham & Lee, 2012).

Production of alumina from bauxite, the main aluminium-containing ore, using the Bayer process involves two major energy-intensive process steps. The first process step involves the digestion of bauxite in a sodium hydroxide solution to produce aluminium hydroxide. This process step requires steam at around 200°C and consumes about two-thirds of the thermal energy input to the alumina refining process. The remaining one-third is required in the second step, the calcination of aluminium hydroxide to produce alumina (anhydrous aluminium oxide). The calcination occurs at temperatures above 800°C and heat is generally provided directly to the reactor by the combustion of natural gas or coal. The energy intensity of alumina refining in Australia is between 4 and 8 GJ/t. The exact energy demand depends on the quality of the bauxite and the energy efficiency of the refinery. The theoretical minimum is approximately 1.3 GJ/t.

Besides alumina, Australia is a large producer of copper. Mount Isa, QLD, Olympic Dam, SA and Prominent Hill, SA, have the largest processing facilities. Copper sulphide ore is concentrated in a hydrometallurgical process, with some heat used for drying before smelting and refining in furnaces at around 1200°C.

Australia also accounts for one-third of the world's nickel production (Chemlink, 2019). The largest producing facilities are in Kalgoorlie, WA, Kwinana, WA and Yabulu, QLD. As with copper production, an initial concentrating process is followed by high-temperature smelting. Hydrometallurgy processes use hot 250 ºC sulfuric acid at a pressure of 4.5 atmospheres to dissolve the nickel and cobalt.

Zinc production begins with concentrates fed into the fluidised bed roaster with oxygen at 950°C to convert to acid-soluble zinc oxide. Zinc oxide is leached by electrolytes containing sulphuric acid in reactors at 85°C and atmospheric pressure (Moyes et al., 2002). Zinc metal is produced by electrolysis and then melted in an electric furnace and cast into ingots.

4.1.3. Existing heat supply

Overall sources of the heat used by the sector are show in Figure 35. The total of 171 PJ/year is an estimate of the heat use based on an average conversion efficiency of 80% applied to the fuels used for heat production.

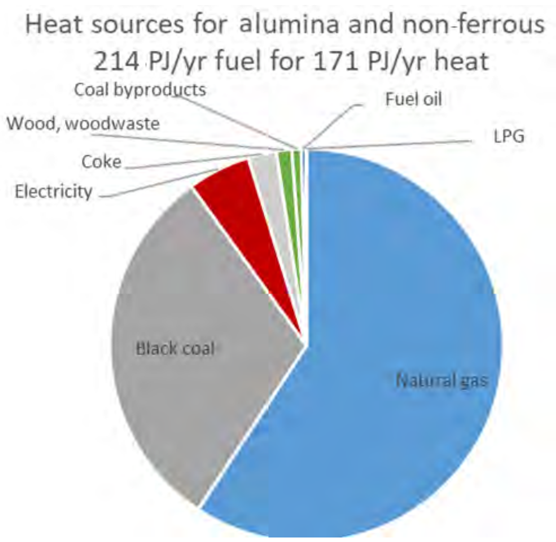


Figure 35: Existing sources of heat in the alumina and non-ferrous sector.

Natural gas dominates, with coal also a significant source. Electricity plays a role in some facilities and other fuels make a minor overall contribution.

The Queensland Alumina and Yarwun refineries, both at Gladstone in QLD, and the Worsley refinery in WA, use coal for steam raising and gas for other processes, while the other three refineries use gas for all their requirements. Smaller quantities of coal are used in the production of some other non-ferrous metals.

Australian Aluminium Council data for 2013 (the most recent year for which data are available on the Council's website) indicate that the alumina industry used 153 PJ of gas and 46 PJ of coal. These figures compare with total consumption for the sector as a whole in 2012-13 of 146 PJ of gas and 52 PJ of coal reported in *Australian Energy Statistics*. It is likely that the apparent discrepancy between the two gas consumption figures is caused by the different treatment of gas used to generate electricity, some of which *Australian Energy Statistics* allocates to the electricity generation industry sector. Yarwun, Pinjarra, Wagerup and Worsley all host large CHP facilities.

The electricity use for heat is assumed to be for melting and casting in foundries and similar activities.

The facilities in this sector are among the biggest users of energy in the country. Their costs of energy are likely to be close to the wholesale prices prevailing. Thus, the overall cost of supply of gas in 2019 would be around $8-10/GJ, coal around $3-4/GJ, and electricity around $100/MWh (equivalent to $28/GJ).

4.2. Renewable energy options

Typical average continuous heat demand of the facilities in this sector is in the order of several hundred megawatts. The large scale limits the renewable energy options that have the potential to substitute significant shares of fossil fuel. Solar thermal, renewable electricity and renewable fuels are the most likely options to decarbonise this sector.

Whilst the plants in WA and possibly Mt Isa are located over sedimentary aquifers, the temperatures that would be obtainable are only comparable to the temperature of waste heat that those plants currently emit to the environment, so geothermal is discounted as a viable option for the sector.

Biomass has been used as a partial replacement for coal for steam raising (Nathan et al., 2019). However, the scale of demand in large alumina refineries (>500 MW_{th}) means that bioenergy is unlikely to be capable of supplying the bulk of the energy input for alumina production. There are currently only a handful of biomass plants in the world at this scale, mostly running on either wood pellets or wood chip. In the locations of Australia's plants, the local supply of biomass (bagasse) is both limited and seasonal. For example, in Queensland, while there is still room for some expansion, the sugar industry has already looked to supplement bagasse with other woody materials in order to keep their own generators going all year.

A 36 MW_e (approx. 100MW_{th}) waste-to-energy plant is currently under construction in the Kwinana Industrial Area by Phoenix Energy. This plant will produce baseload power using steam turbines to power up to 50,000 homes. Waste heat from this plant could potentially be transferred as steam to the Kwinana alumina refinery, which is a few kilometres north, and upgraded for the Bayer digestion process.

4.2.1. Solar thermal

Solar thermal technologies for steam generation for the digestion process include:

- linear Fresnel
- parabolic trough
- tower systems
- parabolic dish.

In addition, there is the possibility for combined heat and power generation with back-pressure steam turbines. This would require steam at 400°C or more in order to achieve significant electrical power outputs.

Potential solar thermal technologies for process heat integration in the calcination process are:

- tower systems
- parabolic dish

A research project, supported by ARENA, is investigating integrating solar thermal energy into the Bayer process. This project aims at introducing solar energy into both the lower-temperature digestion process, requiring around 200°C (see case study below), as well as into the calcination process taking place at above 800°C. The lower-temperature integration can be accomplished by substituting gas-fired boilers with a solar-thermal heated steam generator. For high-temperature solar energy integration into the calcination reaction, the process is either conducted directly in a high-temperature solar receiver reactor (demonstrated at the lab-scale, see (Davis et al., 2017)), or the calcination reactor is heated using solar heat indirectly with a heat transfer medium, such as inert particles, air or steam. Solar thermal use for pre-calcining at 400-500°C has been proposed as a potential transition path (Nathan et al., 2019).

The level of solar resource for the WA and Gladstone alumina refineries is quite good (average DNI ~2100 kWh/m^2/year). The resource at Mt Isa and Olympic Dam is on the other hand close to the best in Australia (~2500 kWh/m^2/year).

If a new greenfield refinery were to be built using solar thermal energy as a major heat source, the choice of plant location would play a large role in the economics, as the solar thermal production increases in proportion to the local solar resource (DNI). In a recent analysis, the economic potential of solar thermal heat for co-generation in alumina refining was compared between the southwest of WA with good solar resource and the western tip of WA with best domestic solar resource (>2600 kWh/m^2/year). The results indicate a large difference in the economic results and, while the economics are not yet fully feasible for the southwest of WA, there is very good potential for economic feasibility in locations with best solar resources (see also case study below).

It may also be possible to apply the solar concentrating technologies to dry and smelt copper concentrate (Gallo et al., 2015).

4.2.2. Mechanical vapour recompression

The most prospective renewable electricity approach for lower-temperature heat use in this sector is mechanical vapour re-compression.

Alumina digestion occurs in a series of steam-fed digestors with each successive digestor taking progressively lower-temperature steam flashed off the previous one. The highest temperature digestor requires steam at around 200°C (sometimes lower, depending on the nature of the ore) The final digestor discharges steam at approximately 60°C, which is condensed in a cooling tower. Traditionally, steam is supplied to the digestion process from gas-fired boilers or as the discharge from the steam turbine of a combined cycle power plant used to produce electrical power for the site.

Mechanical vapour recompression (MVR) represents an attractive means of upgrading and reusing the low-temperature steam otherwise condensed in the cooling towers. MVR captures the latent energy of the low-temperature steam and reduces the volume flowrate of input steam required from the steam turbine. To achieve this, waste steam at sub-atmospheric pressure must be compressed to ~10 bar using electrically-driven compressors. A multi-staged compression process is required, as centrifugal fan compressors are typically limited to a pressure ratio of less than two. Inter-cooling is also required between successive compression steps to reduce the superheat of the steam and keep temperatures to metallurgically imposed limitations (without inter-cooling, steam temperatures would exceed 700°C).

4.2.3. Renewable fuels

Renewable hydrogen produced through water electrolysis could in principle be used to substitute natural gas in alumina refining but is not yet cost-competitive with natural gas for process heat applications.

Concentrated solar-driven steam methane reforming is a proven method to enhance the energy content of the products from steam methane reforming. In conventional (non-solar) SMR, part of the feedstock is combusted to provide the enthalpy input for the endothermic reforming reaction. If concentrated solar heat is introduced to the process, the product yield of the process is increased and solar energy is captured in the process, reducing the carbon intensity of the process. CSIRO is moving ahead in this area and have demonstrated the process on a solar tower at up to 500 kW.

Solar reformed natural gas (i.e. syngas) can be used to displace natural gas for steam production. Alternatively, it could be introduced to the high-temperature calcination of alumina. Syngas from coal gasification has already been used commercially for calcination in alumina production (Nathan et al., 2019).

4.3. Case studies

4.3.1. Renewable energy options for the digestion step in the Bayer alumina process

Figure 36: Overview of typical Alumina refinery site, with major infrastructure (Reproduced from JLW Group Holdings P/L).

Two main renewable energy options for the digestion step of alumina refining, solar thermal and MVR, have been analysed and compared for a refinery in southwest WA as part of an ARENA funded project led by the University of Adelaide. A typical site overview is shown in Figure 36.

For solar thermal, integration of 500 tph (392 MW_{th}) steam at 470°C, 80 bar, for power generation using back-pressure steam turbines, followed by introduction into the digestion process at 210°C, was considered.

Alternatively, waste steam from the refinery, currently rejected to the atmosphere at around 53°C/0.14 bar, can be upgraded to 210°C/8.9 bar using multi-stage MVR. Eight compression stages are required with water injection after each stage for de-superheating. The net work input to generate 500 tph of steam is estimated at 115 MW_e, delivering a thermal power of 385 MW_{th}, corresponding to a COP of 3.3. A limitation of the flow rate of steam that each compressor can process leads to a requirement for parallel MVR systems to be installed to match the total mass flow rate of process steam required by the digestion process.

Figure 37 compares the economics of solar thermal and MVR steam supply in terms of Internal rate of return, calculated based on mitigated gas and CO_2 emissions costs. For MVR, the reduced power output of the CHP system leads to additional power purchase costs.

For solar thermal, the two cases shown are for a 392 MW_{th} tower system with 14 hours of thermal energy storage (49% capacity factor) based on 2018 cost estimates and for a 392 MW_{th} tower system without TES (20% capacity factor) based on 2023 cost estimates.

The calculated IRR of MVR depends on the electricity price assumed, but positive values are achievable. The comparison of solar thermal and MVR strongly depends on the assumed electricity price. Solar thermal is predicted to yield favourable economics for electricity prices above around 7 c$/kWh$_e$ while MVR is predicted to be more favourable below that.

Figure 37: Comparison of IRR for solar thermal with MVR steam production (Assumptions: lifetime: 20 years, gas price: $10/GJ, boiler efficiency: 82%, CO_2 emissions cost ($29/t in 2020 to $131/t in 2050, O&M cost: 2% of capex per year).

Summary

Location	South West, WA
Application of process heat	Steam for the digestion step in the Bayer alumina refining process
Temperature	210°C
Energy resource	Solar (DNI: ~5.8 kWh/m^2/day) / Grid power
Technology options	Concentrating solar thermal with thermal storage / Mechanical vapour recompression
Designed to deliver	500 tph of steam / 390 MW$_{th}$
Energy/emissions saved	Solar thermal: potential to displace up to ~6 PJ p/year of natural gas MVR: potential to displace up to 12 PJ p/year of natural gas
Other aspects	Sufficient buffer land available at the refinery site for a solar plant.

4.3.2. Electric infrared preheating in aluminium forging

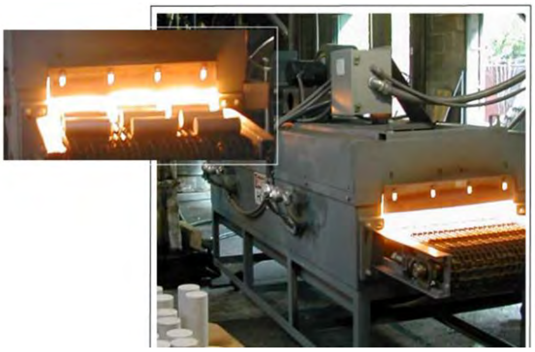


Figure 38: Hybrid rapid infrared preheating furnace, processing aluminium billets. (Reproduced from Kadolkar et al [19]),

Queen City Forging in Ohio, US makes components for transport and agricultural equipment. The company heats aluminium billets to 425°C prior to hot-forging. Previously this preheating was achieved using gas-fired convection furnaces in batch processes. By switching to a new electric powered convection-infrared hybrid preheating furnace, the company has reduced costs and energy use, while increasing throughput, quality and consistency.

The new hybrid system uses only 1.16 GJ (323 kWh) per tonne of product compared to 3.49 GJ (969 kWh) with the conventional convection-based batch system, a two-third energy saving which led to cost savings of 40-50%. Queen City Forging was also able to greatly increase output as preheating time reduced from 6 hours to 18 minutes, and heat treatment time reduced from 10 hours to 1 hour. In addition, the IR-processed materials showed improved strengths and fatigue resistance compared to the conventionally processed material.

Summary

Application of process heat	Preheating of aluminium billets for forging in the production of aluminium machine parts
Temperature	425°C
Energy resource	Grid power
Technology	Continuous belt type hybrid convection-infrared preheating furnace (custom design)
Designed to deliver	77 kW of heating power (optimised combination of convection and radiant heating); tungsten-halogen IR heating filaments at >2,200°C
Energy/emissions saved	Energy demand reduction of 645 kWh per tonne of product (65%) 40-50% energy cost savings
Construction	Start of development project in 2001

[19] *Application of rapid infrared heating to aluminium forgings, Oak Ridge National Laboratory, 2004.*

4.3.3. Solar process heat in copper mining

Figure 39: Trough collectors and thermal storage tanks at Minera El Tesoro. Reproduced from Abengoa.

Abengoa Solar have installed 1280 parabolic trough modules on six hectares of land adjacent to the Minera El Tesoro copper mine in the Atacama Desert. The plant cost US $12 million and supplies heat to the copper refining process. The maximum operating temperature is 260ºC.

A heat transfer fluid (water with a corrosion inhibitor) is circulated through the solar collectors and a heat exchanger is used to deliver this heat to the storage tanks and the electro-extraction process used to produce copper.

The solar thermal system is designed so that it can store energy in the form of pressurised hot water. This allows the system to operate after sunset and on partially cloudy days. The system controls automatically select the solar field, the thermal tanks, or both as the sources of heat for the electro-winning process.

Summary

Location	Atacama Desert, Antofagasta region (Chile)
Application of process heat	Electrowinning process in copper production
Temperature	260°C
Energy resource	Solar thermal (DNI: ~9.5 kWh/m^2/day)
Technology	Solar parabolic trough collectors; pressurised hot water storage
Designed to deliver	10 MW_{th}; displacing 55% of diesel use
Energy/emissions saved	~10,000 tonnes of CO_2 per year saved
Construction	Commissioned in 2012
Investment	US $12 million
Other aspects	Thermal storage allows for provision of heat outside of daylight hours

5. FOOD AND BEVERAGE

5.1. Overview

ANZSIC classifies Food product manufacturing as Subdivision 11, under Division C, Manufacturing, and further divides it into the following groups:

- Meat and meat processing (111)
- Seafood processing (112)
- Dairy product manufacturing (113)
- Fruit and vegetable processing (114)
- Oil and fat manufacturing (115)
- Grain mill and cereal product manufacturing (116)
- Bakery product manufacturing (117)
- Sugar and confectionary product manufacturing (118)
- Other food product manufacturing (119).

In addition, Group 121, Beverage manufacturing, includes the manufacture of cordials, beer and spirits, all of which require low-temperature thermal energy input. It is these groups combined that are covered by the AES data for food and beverage and which are examined in this chapter.

5.1.1. Site location and intensity of heat use

Figure 40 indicates the distribution and approximate level of process heat use in the sector, further divided into subsectors, with more specific data in Table 8. Overall, the locations mirror the population distribution and the location of the primary production that supplies them. There are a considerable number of establishments within capital cities but also a lot in regional areas. The sugar mills along the Queensland and northern NSW coasts are notable large heat users and are largely responsible for making this sector overall one of the biggest users of heat.

Many of the establishments falling into Groups 111, 113 and 114 are located outside metropolitan areas, making them potentially suitable for the use of renewable energy. Sugar mills, which fall into Group 118, are also located in non-metropolitan areas, and have access to a large, zero (or even negative) cost source of biomass energy in the form of bagasse, which is well established as a renewable energy source. Indeed, the NSW/QLD sugar mills host nearly 60% of Australia’s bioenergy capacity in the form of bagasse CHP.

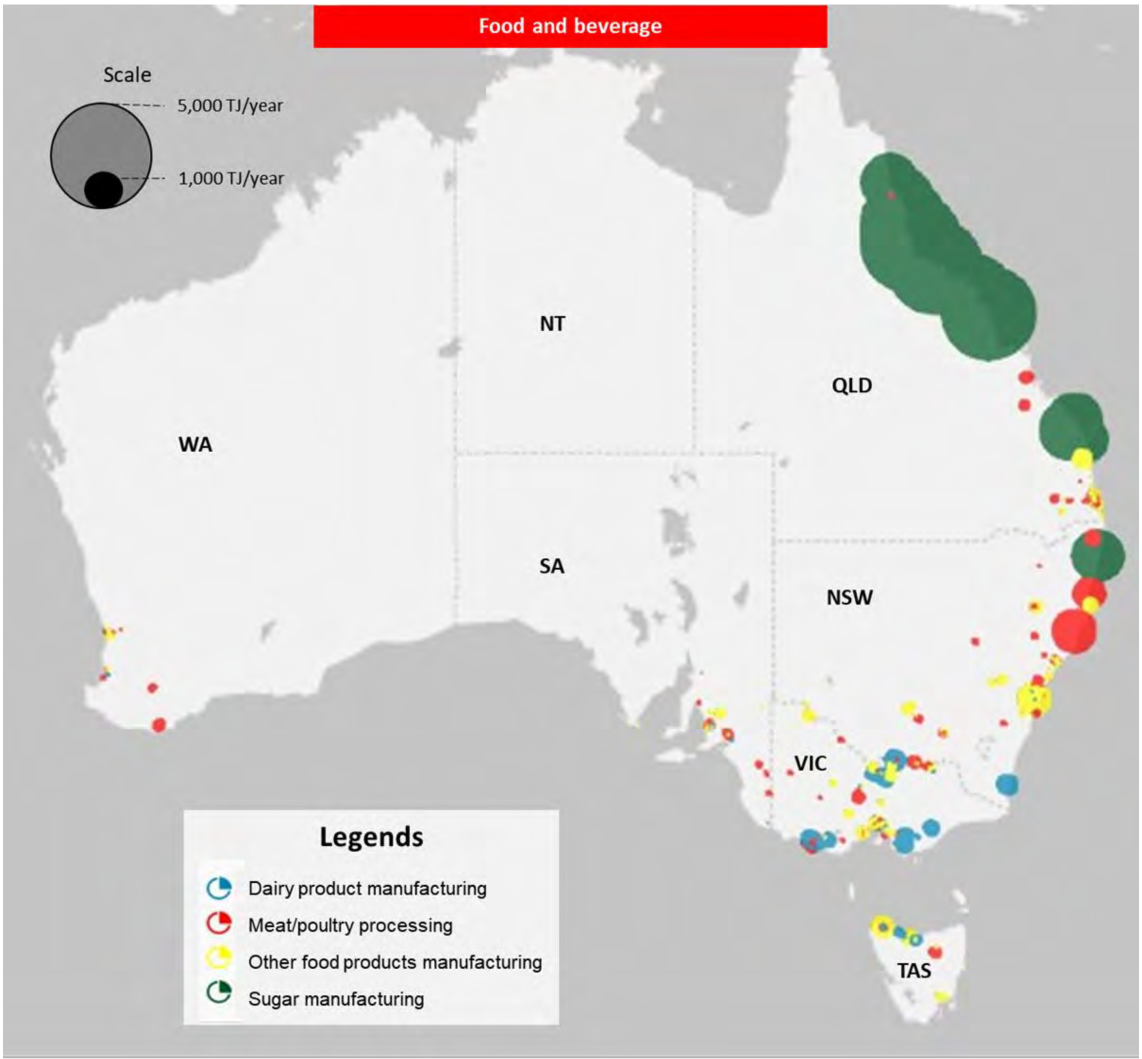


Figure 40: Location of food and beverage sites and their volume of heat use.

The Australian dairy manufacturing sector includes farmer-owned co-operatives and multinational companies. The six largest dairy firms are Murray Goulburn, Warrnambool Cheese and Butter (both now owned by Saputo Australia), Fonterra, Lion, Parmalat and Bega Cheese, which between them process roughly 90% of the Australia's raw milk. It is seen to be concentrated in Victoria and Tasmania.

Meat processing is also a major subsector, with many sites in regional areas inland from the coastal population centres.

Table 8. Food and Beverage sector size distribution by sites

Industry Sector, PJ/year (MW$_{th}$ range at 80% CUF)	< 0.1 (< 1 to 4)	0.1 to 0.5 (5 to 20)	0.5 to 1 (21 to 40)	1 to 5 (41 to 200)	5 to 45 (201 to 1800)	Total no. sites	Total heat use PJ/y	Main Fuel
Sugar mills	1	1	-	14	7	23	95.8	Bagasse
Dairy product	35	15	-	-	-	50	4.6	Natural gas
Meat/poultry processing	71	14	1	1	-	87	7.8	Natural gas
Other food products manufacturing	137	22	-	1	-	160	8.6	Natural gas

5.1.2. Processes that use heat

A comprehensive summary of the various processes, temperatures and shares of heat use encountered in the various subsectors has been assembled in a study for the Victorian Government (McLeod et al., 2005). Key results are shown in Table 9.

Table 9: Temperature distribution of energy use for specific food and beverage subsectors (McLeod et al., 2005).

Meat industry	Temp	Share
Hot water	40 to 60°	14%
Rendering/fat melting - Gas	50 to 140°	40%
Hot water: e.g. cutting, deboning, sterilisation - Gas	80 to 90°	29%
Other - Gas	Various	16%
Dairy industry	**Temp**	**Share**
Evaporation - Gas	60°	47%
Pasteurisation - Gas	72°	24%
Drying - Gas	120°	29%
Fruit & vegetable	**Share**	**Share**
Boilers - Gas	40 to 60°	12%
Hot water low temp - Gas	40 to 60°	13%
Hot water med temp - Gas	60 to 80°	19%
Steam high temp - Gas	80 to 200°	28%

Ovens - Gas	250 to 400°	25%
Other - Gas	Various	3%
Beverage & malt manufacturing	**Temp**	**Share**
Malt germination - Gas	15°	4%
Malt kilning curing - Gas	30 to 40°	13%
Hot Water – e.g. cleaning, heating, warming - Gas	40 to 60°	7%
Pasteurisation - Gas	60 to 90°	10%
Hot water – e.g. CIP, cleaning, sterilisation - Gas	60 to 100°	20%
Beer brewing - Gas	140 to 210°	21%
Malt kilning - Drying - Gas	180 to 200°	25%

Examining the major subsectors in more detail:

Sugar

Australia has 24 sugar mills, owned by eight companies and Queensland produces 94% of the country's cane sugar. As of 2017, approximately 35 million tonnes of sugarcane are processed to produce 4.5 million tonnes of raw sugar and 10 million tonnes of bagasse in a season (June to November). Bagasse is a fibrous waste, and a by-product in sugar mills that is used as fuel in CHP power plants to produce electricity and steam for process operations. Sugar mills are self-sufficient in energy and, depending on the efficiency of their equipment, may export to the local electricity network a significant proportion of the renewable electricity they generate. Figure 41 illustrates the principles of such an energy balance.

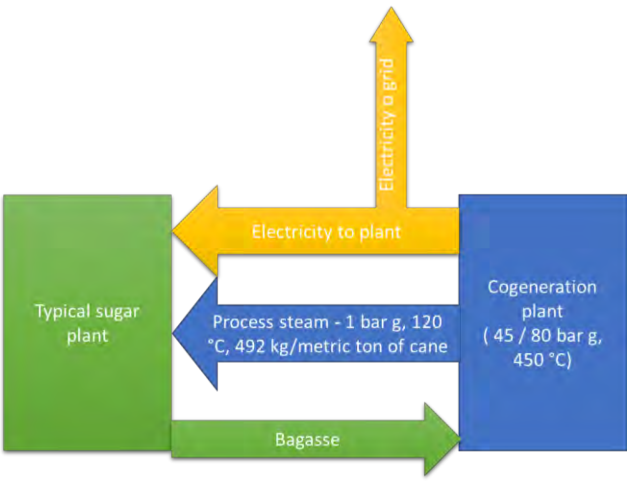


Figure 41: Sugarcane CHP process (Data: (Tully Sugar Ltd, 2009)).

Some mills have been modernised/rebuilt to become much more efficient, meaning they are able to export a significant proportion of the electricity they generate. Doing this at all sugar mills is an untapped potential source of more dispatchable renewable electricity.

Primarily electrical energy is used to run drives and machinery, and steam is utilised to evaporate the sugar cane juice to crystallise out raw sugar.

Dairy products

Manufacturing processes that use intensive thermal energy in dairy manufacturing include:

- standardising, pasteurising (hot water) and homogenising of raw milk to drinking milk
- removing moisture from milk, using evaporators and spray dryers (hot air) to manufacture milk powders
- separating milk fat from liquid milk, and then pasteurising (hot water) to manufacture cream
- disinfecting and cleaning production areas, packaging bottles

Table 10. Energy Consumption in the Dairy Industry (Dairy Australia, 2006).

Description	Dairy manufacturing Milk & desserts, cheese & whey products	Dairy manufacturing, milk powder
Energy consumed per 1,000 litres of raw milk	653 MJ	715 to 2,478 MJ
Electricity	32 to 50%	9 % to 48%
Thermal energy (Deduced from percentage of electricity use)	50 to 68%	52% to 81%
Heat to power ratio	**1.0 – 2.1**	**1.1 - 4.26**

Electricity is required to support general plant operations, such as refrigeration and lighting, and thermal energy (including energy sources such as gas, coal and biomass) is used for pasteurisation and evaporation processes. The main sources of energy are natural gas (68%) and grid electricity (26%). The output product affects the amount of energy consumed and ratio of heat to power. From Table 10, dairy powder manufacturing units have high heat to power ratio as there is need to operate spray dryers and evaporators. The wide range indicates different manufacturing unit's varying process efficiency. It also indicates that there may be a significant potential reduction in overall heat demand if all plants were upgraded to best practice standard.

Predominately natural gas-fired steam boilers are used to meet thermal energy needs and electricity is used to run chillers and other machinery.

Meat processing

The meat industry consumes a significant amount of energy. As reported by Meat & Livestock Australia the sources of energy are grid electricity (31.6%), natural gas (37%) and coal (19%). The major energy consuming activities are refrigeration (from electricity) and the production of steam and hot water (Meat & Livestock Australia, 2019).

According to the AMPC "Energy use varies between processing sites and is influenced by factors such as the type of species processed, the throughput, the extent of rendering activity, the amount of refrigeration and the level of further processing. Cattle and sheep abattoirs tend to need significantly less hot water than pig plants. Around 80% of total energy use at pig abattoirs is for thermal energy generation (e.g. for heating scalding tanks, raising steam, singeing), as opposed to just 30–77% at cattle and lamb abattoirs. Sheep processing generally uses less than pigs or cattle principally because the animal is less bulky and less energy is required for chilling" (Tang & Jones, 2013).

Table 11: Typical specific energy consumption in meat industry (Tang & Jones, 2013; Wiedemann et al., 2012).

Industry	Energy usage GJ / tonne HSCW	% Electricity	% Thermal energy	Heat to power ratio
Beef & veal	1.3 to 5.2	23-47%	53-77%	1.1 - 3.3
Sheep	3.6 to 6.7	23-47%	53-77%	1.1 - 3.3
Pork	14.9 to 17.5	20%	80%	4.0

Steam and hot water is produced by boilers powered by natural gas, coal, electricity or oil.

Other food manufacture

The other food manufacturing sectors include grains, horticulture, seafood, confectionery and beverages including wine. Typical processes involved are deep frying, steam cooking, baking, chilling, etc. Typical gas consumption can be in the range < 1 to 500 TJ/year depending on the size of the facility. Mostly gas-fired heaters, steam boilers and electrical equipment are used in the processing of food. From Figure 6, process temperatures can range from 60 to 350°C and occasionally higher for some applications. Many facilities have centralised heating and cooling systems with low efficiencies of supply of energy to the point of use. Some use electrical heaters to generate hot water and steam for processing, and this increases the GHG emissions where non-RE electricity is used. Most of the existing standard equipment are heated by simple heat exchangers, which allow retrofitting of renewable energy systems.

5.1.3. Existing heat supply

The various sources of the estimated total of 115 PJ/year of end use heat for the food and beverage sector are shown in Figure 42. The total is an estimate of the heat use based on an average conversion efficiency of 80% applied to the fuels use for heat production.

The use of bagasse for the process heat needed in sugar mills dominates at close to 70% of the total.

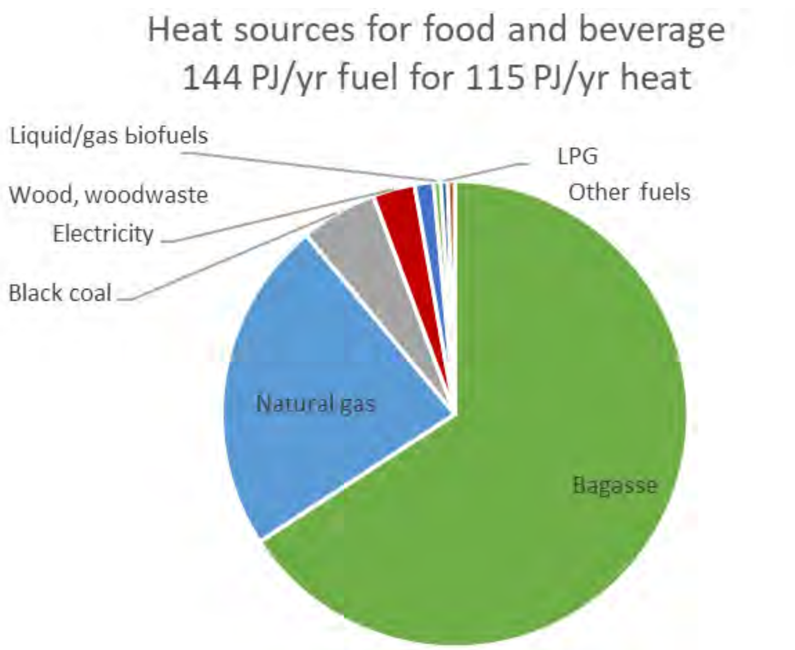


Figure 42: Existing sources of end use heat in the food and beverage sector.

Tis sector is a large user of gas and, unlike many other sectors of manufacturing, total gas consumption has actually increased slightly over the past decade, with the exception of a slight fall in 2016-17, which was almost certainly related to recent large gas price increases. Virtually all gas used in this sector is for low temperature processes, most notably hot water and low-pressure steam, but also in ovens. Significant quantities of electrical energy are also used, particularly for refrigeration and general mechanised processes, but also for heat in bakeries and processed food preparation. In addition to gas and electricity, smaller amounts of heat are provided by coal, wood waste, LPG and other fuels. LPG is likely to be used in ovens and cooktops, but coal and other fuels are almost certainly used for steam and hot water.

The food and beverage sector includes businesses that range from small energy consumers up to reasonably large users. This means a similar range in the energy costs encountered, at the smallest sizes, energy costs will be close to domestic supply prices, with gas at around $30/GJ, and even higher costs for those needing LPG supply and electricity around $300/MWh ($83/GJ). At the larger-end gas prices would be expected to be around $10 to $15/GJ and electricity around $120/MWh ($33/GJ). Those sites choosing to use coal as a heat source are presumably sufficiently large and able to access cost-effective supplies such that prices around $5/GJ may prevail.

5.2. Renewable energy options

In the food and beverage sector, all renewable energy options are worth consideration. Bioenergy dominates the current use of renewable energy in the sector. In any situation where a waste or low-cost biomass resource is available, it is likely to offer a positive return on investment.

Electric heat pumps or other technologies depend for economic performance on the ratio of electricity to other fuel costs and the overall efficiency improvement they can bring to the process. Many businesses in this sector have already installed on-site rooftop PV systems to replace some of their consumption of purchased grid electricity.

Solar thermal and geothermal options are worth considering, with economic performance depending on the resource at the site plus the temperature of use for the required heat.

Table 12: Operating bioenergy plant: waste water (abattoirs, meat processing, dairy).

Project name/ location	Technology	Feedstock	Capacity
Dinmore meat processing Dinmore, QLD	Covered anaerobic lagoons	Meat processing wastewater	Installed biogas train to existing 10 MW boiler
Warrnambool Cheese and Butter Allansford, VIC	Hot water heater	Wastewater	2 MW_{th}
Castlemaine Perkins Water Recycling plant Brisbane, QLD	Water recycling plant, 130 m^3 gas per day	Brewery waste water	Heat only; substitutes for natural gas in boiler
AJ Bush Bioenergy Project (ReNu Energy) Beaudesert, QLD	CAL, CAT engine	Waste water from rendering	Electricity only, 1.1 MW_e
Goulburn Bioenergy Project, ReNu Energy Goulburn, NSW	n/a	Wastewater (rendering and abattoir)	Electricity only, 1.6 MW_e
Oakey Beef Exports Pty Ltd, QLD	CAL, boilers	Meat process wastewater	50,000 GJ/year
Thomas Foods International Murray bridge, SA	n/a	Abattoir effluent	n/a
Leongatha Dairy, VIC	n/a	Food and agricultural wet waste	Electricity only, 0.76 MW_e

The sector has a wide range of sizes of sites by energy use and as noted above this leads to a wide range in current prices paid for energy for process heat, with smaller sites paying two or three times as much as larger ones. This is in almost exact correlation with the LCOH of renewable options being higher at small size and lower at large size. The LCOHs achievable are certainly within the ballpark of providing a positive return on investment, so every energy user in this sector should give all available renewable options serious consideration.

Table 13: Bioenergy - woody and solid waste feedstocks (horticulture, food processing, livestock, meat)

Project name & location	Technology	Feedstock	Capacity	Cost
Voyager Craft Malt heat plant Whitton, QLD	Pyrocal continuous carbonisation with fire tube water heater	Walnut shells	0.5 MW_{th}	$550,000
Suncoast Gold Macadamia Gympie, QLD	6 MW steam boiler, high pressure (40bar and 380-400°C)	Macadamia nut shells	1.5 MW_e 6 MW_{th}	$3 million
Unigrain Wagin, WA	Combustion; Organic Rankine Cycle	Oat husks	Cogneration: 0.8 MW_e	n/a
MSM Milling, Manildra, NSW	4.8 MW steam boiler (7,147 kg/h, 16 bar)	Wood chips + wood fines, sawdust, bark	Process heat	$5.8 million
Australian Tartaric Mildura, NSW	CHP, Rankine cycle	Grape marc	0.6 MW_e 8 MW_{th} (10 tonnes steam/hr)	$11 million
Greenham Meats Smithton, TAS	Conversion of existing coal boiler (process steam)	Pyrethrum waste	10 MW_{th}	$1.2 million
Macca Feeds Williams, WA	Gasification boiler supplying process steam	Wood chip (waste wood and mallee)	1.7 MW_{th}	$0.75 million
Meredith Dairy Meredith, VIC	Hot water boiler	Senescent pines on farm, chipped	240kWth	$120,000
Fletcher International abattoir Albany, WA	Combustion boilers (moving grate)	Woodchips	Two biomass boilers with 4,640 kW_{th} capacity	$4.5 million
Baida Poultry Beresfield, NSW	n/a	Poultry waste and litter	Cogen, 1 MW_e	

5.2.1. Bioenergy

The use of bioenergy is well established in the food and beverage sector, as shown in Table 12 - Table 13. Bioenergy is most likely to be economic when the bioenergy uses a waste that otherwise requires treatment, as evidenced in Table 12.

However, there are also facilities that use solid waste, as shown in Table 13, with both woody wastes and horticultural wastes (grape marc) being used. There is also an example of a poultry litter plant; use of this feedstock is much more commercially developed in Europe.

5.2.2. Electrical

The competitiveness of an electrical solution depends on the relative prices of electricity and the fuel that it potentially replaces, as well as the cost of electricity infrastructure changes that may be needed to increase supply. As noted above, these vary over a wide range.

Many businesses in this sector have already installed on-site rooftop PV systems to replace some of their consumption of purchased grid electricity.

In most cases an electrical option makes most sense where the energy efficiency of the process can be considerably improved. The food and beverage sector has many established businesses in which the efficiency of heat transfer to the actual process is quite low using current systems.

Heat pumps

The electrical heating technology with greatest potential in the food sector is heat pumps. Commercially available heat pumps can supply hot air, hot water or steam at the temperatures required for most food production processes. As well as achieving high efficiency, heat pumps can deliver heat at a precise temperature, improving product quality.

There may be additional efficiency advantages of heat pumps where there is a need for cooling or refrigeration. Heat pumps can provide simultaneous heating and cooling with a good COP. The meat processing subsector is a clear example of a combined need for hot water and chilling.

Whilst there is not yet wide use of heat pumps in the Australian food and beverage sector, Table 14 lists examples of heat pumps used in the food and beverage sector around the world.

Table 14 Examples of electric heat pump applications in the food and beverage sector (IEA, 2014).

Product	Company, location, heat pump make	Heating capacity (kw)	Temp-erature uplift	Coefficient of performance	Heat pump application
Food - chocolate	Nestle, UK Star Neatpump	1,250	5°C > 60°C	6 (combined heating & cooling)	Simultaneous cooling and hot water for chocolate production. Saving $200,000 in energy costs
Frozen noodles	Shikoku Island, Japan	144	83°C > 98°C 10°C > 3°C	3.0 (heating) 2.1 (cooling)	Hot water for boiling noodles, and cold water for the cooling process before freezing
Milk powder	Arla Arinco, Denmark Industri Montage	1,250	40°C > 85°C	4.6	Preheats air to 85°C for drying milk powder. A gas boiler completes the temperature uplift to 150°C. Payback – 1.5 yrs
French fries	McCain, Netherlands Grasso 65	500	> 70°C	5-8	Recovers and recirculates heat from drying french fries before cooking. Provides most of the heat for drying. Payback – 4 yrs
Beer	Mohrenbrauerei, Austria COFELY Kältetechnik	370	> 77°C		Reuses waste heat from chillers to supply all process and space heating. Payback 5.7 yrs. Energy saving 18%

Infrared

Infrared heating has many roles in food production and can be three times more efficient than gas ovens. Infrared systems can be used for frying, roasting, baking, pre-heati thawing, blanching and pasteurisation. One of the advantages of infrared heating is that it can heat the surface of a food (e.g. a pie crust) without cooking it through.

Microwave

Microwave heating is used in the food industry for rapid defrosting, cooking, pasteurisation and drying. It is particularly useful for drying foodstuffs, such as fruit, vegetables and herbs, due to the speed and uniformity of its drying (Punathil & Basak, 2016). Sometimes microwave drying is used in combination with other drying methods such as hot air.

Electrical resistance

Almost any food production processes could be carried out using electrical resistance heating. For example, a gas-fired oven for baking food could be replaced by ovens using electrical resistance heating. Any requirement for hot water or steam in food production could be met with an electrical resistance boiler.

5.2.3. Geothermal

Geothermal heat in Australia is limited to temperatures below 95°C from hot sedimentary aquifers. The food and beverage sector has considerable use for heat in this range so geothermal options should be considered. To justify the minimum fixed costs of a single pair of wells, annual heat use must be greater than 10 TJ/year, which a large number of sites are. The site also needs to be located on a suitable aquifer, as detailed in C.3.2. There are meat processing sites located inland on theGreat Artesian Basin aquifers for example that would be good candidates for geothermal heat use. The case study in 5.3.2 provides a good example.

5.2.4. Solar thermal

From Figure 40, food and beverage sites are spread between the coast where solar radiation levels are lower, to inland regional areas, where they are higher. However, this sector requires predominantly low to medium-temperature heat, making solar thermal likely to be economic when compared to natural gas use, even at sites with intermediate solar resource, as shown in Figure 31.

A potential limitation is that many facilities in this sector are within city industrial areas, which can limit the space for deploying solar thermal collectors. Solar heating systems can be deployed on free rooftop space to minimise land use. Structural upgrades may be required to carry the load in the order of ~30 kg/m^2 of collector and wind induced forces on the support structure.

Operating hours in facilities vary from 8am to 5pm, 5 days per week to 24 hours a day, 7 days a week. Facilities operating 8-5/5 are better aligned with solar energy availability, which reduces the demand for thermal storage and hence reduces capital investment and LCOH. However they suffer significantly from lower utilisation due to operating two days a week without load. The optimal thermal storage size to capture energy over the weekend depends on the storage type used and its associated cost.

In the sugar industry, solar thermal could be employed to generate steam, preheat boiler feed water, dry bagasse, dry raw sugar and heat juices (Krog, 2018). This would be logical if there was insufficient bagasse available or a higher value use had been identified for it[20].

Combined heat and power renewable systems are advantageous as they have higher efficiency and generate electricity and process heat simultaneously. These systems typically produce more heat than power, which matches the demand of many facilities in this sector well.

Solar collectors to generate heat at low to medium temperatures (up to 150°C) include glazed/unglazed flat plate collectors and evacuated tube collectors with or without mirror (Table 7). These technologies are commercially mature and used worldwide for water heating at an installed capacity of around 500 GW_{th} (Weiss & Spörk-Dür, 2018). Evacuated tube collectors dominate the market with over 70% share.

Hot water storage is the least expensive method for storing heat at up to 180°C. Below 100°C, the tank doesn't need pressurisation that makes this technology particularly inexpensive.

Despite thermal storage, solar thermal typically needs to be complemented with a backup solution, such as bio- or natural gas, to compensate for variations in solar availability.

5.2.5. Process redesign

Several alternative processes exist that can reduce the process heat demand in food and beverage processing. While these processes often shift the energy demand to electricity, they can also result in substantial energy savings.

Major process heat demands occur in dewatering/drying as well as in pasteurising.

In addition to the application of energy electrically as discussed above in section 5.2.2, electric alternatives to conventional evaporation processes include (Jutsen et al., 2018; Lord, 2018):

- ambient forced or natural evaporation
- centrifuging
- pressing
- reverse osmosis / membrane filtration
- mechanical vapour recompression

Pasteurising is traditionally accomplished via short-term heating to ~70°C. Alternative processes for non-thermal pasteurising include:

- high-pressure processing
- membrane filtration
- microwave

[20] Some sugar mills use coal in combination with bagasse.

- ultrasonic
- irradiation (UV, X-ray)
- pulsed electric fields.

Membrane filtration can be used to filter pathogens (bacteria, spores) from liquid food products. Different membrane sizes are used for different process steps. In the dairy industry, choice of membrane pore size can be used for the removal of bacteria, fat, different proteins, NPN, lactose, and more. In addition, reverse osmosis can be used for dewatering and for water reclamation.

Another emerging technique is high-pressure processing (HPP), which isthe sterilisation of food by subjecting it to very high pressures of up to 6,000 bar. For full sterilisation, an additional temperature increase is required (Matser et al., 2004). HPP is considered to result in better product quality with respect to texture, flavour, retention of nutrients and shelf life than conventional heat sterilised products (Matser et al., 2004). However, it does not necessarily result in a reduced energy requirement.

A recent study (Rodriguez-Gonzalez et al., 2015) estimated the specific energy demand to remove E. Coli bacteria from apple juice using different alternative food processing technologies and compared it to conventional thermal pasteurisation. The study found that membrane filtration and UV irradiation have the potential for energy reductions of up to 1000 and 10,000 times, respectively, compared to conventional high-temperature pasteurisation. For HPP, the electric energy demand was estimated to be 338 to 483 J/g, mainly for compression of water, which is around 1.5 to three times higher than the thermal energy demand in conventional pasteurisation (167 to 228 J/g). They estimated the potential for energy savings in HPP to be up to 50% in an alternating two vessel configuration, while additional energy may be required for chilling or preheating.

5.2.6. CHP and hybrid systems

In a recent study for a food sector client carried out by ITP, a heat solution combination of renewable energy technologies was identified. Solar PV and solar thermal CHP with bioenergy for backup have potential to provide energy independence for small-scale industries in the food and beverage sector as illustrated in Figure 43.

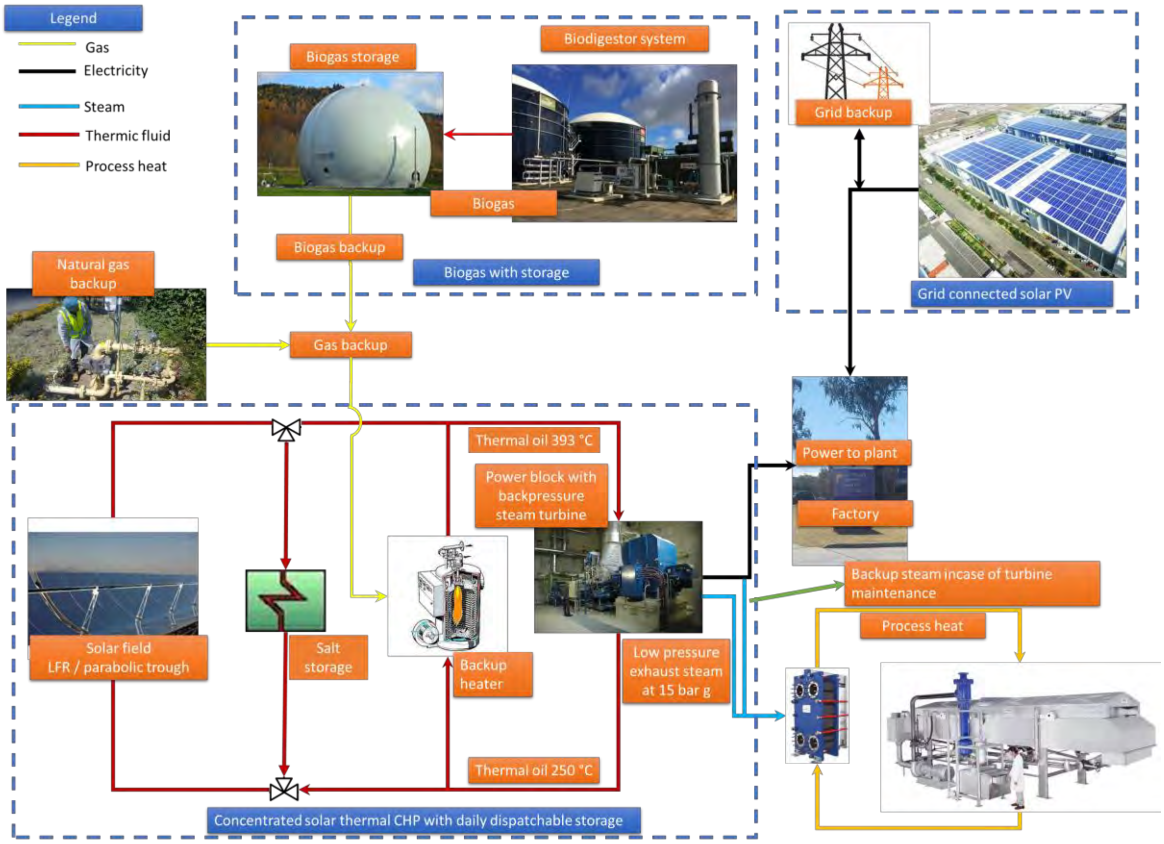


Figure 43: Solar CHP system with bioenergy backup for food and beverage industries[21].

For this case with an annual gas consumption of close to 350 TJ/ year, a solar thermal field sized to meet the plant's heating demand during the day can potentially have a 1.0 MW_e backpressure steam turbine as the power block. A turbine with a typical electrical generation efficiency of 5 to 10%, also supplying heat at 150 to 200 °C to process is possible. Adding 10 hours storage provides a better capacity factor. If new build plants are in locations with good solar radiation the LCOH can be close to $10 to 12 /GJ when the value of electricity is assumed to be around 11c/kWh, thus increasing the viability of the solar thermal system.

Alternatively, as shown in Figure 43, where wet organic waste is available, it can be consumed in an anerobic digestor to produce methane. The methane and / or natural gas can be used to run an engine or microturbine to produce electricity and process heat. These systems have close to an efficiency of 70 to 90% depending on the utilisation of exhaust gas and engine cooling water. The simple payback periods are less than four years and can provide heat and power 24/7 on demand. Engines and microturbines can have sizes from 50 kW_e to 12 MW_e or higher and are very modular.

[21] ITP diagram using images adapted from Snackbrands, Evo Energy, PV-tech, Biogass Renewables.

5.3. Case studies

5.3.1. Solar heat for winery

Figure 44: Evacuated tube collectors and storage tanks. (images from Apricus).

As part of a bottling line expansion, De Bortoli Winery installed a solar thermal evacuated tube collector system at its Griffith winery in 2013. This system was designed to reduce gas consumption for hot water by more than 80% over the year.

The evacuated tube collectors are mounted at a tilt angle of 37 degrees to optimise performance in high demand periods and two 6000 litre stainless steel storage tanks are used to store the hot water. Two high-efficiency, 350kW gas-fired backup boilers were also installed to ensure bottling can be scheduled as required. A programmable smart control system was installed by De Bortoli Wines, which maximises daily gas savings.

The winery also installed a 230 kW photovoltaic system that was forecast to produce about 349 MWh per year. The simple payback on the photovoltaic system was estimated to be about three years. De Bortoli Winery received a $4.8 million Clean Technology Food and Foundries Investment Program grant to contribute to the plant upgrade and expansion that was forecast to cost $14.5 million.

Summary

Location	Griffith, NSW
Application of process heat	Hot water in wine making
Temperature	95°C
Energy resource	Solar (GHI: ~5.6 kWh/m^2/day)
Technology	100 × 30 tube collectors evacuated tube solar collectors 2 × 6000 litre hot water storage tanks 2 × 350 kW condensing boilers 230 kW_e of photovoltaic modules
Designed to deliver	~12,000 litre/day of water preheated to 95°C / 200 kW_{th} 350 MWh_e/year of electric power from PV system

Energy/emissions saved	~1,120 GJ p/year. by solar thermal system (more than 80% of hot water load)
Construction	Start May 2013, commissioned August 2013, further control system optimisation Oct 2013
Investment	~$14.5 million (total investment for expansion)
Simple payback	~6 years, before grant funding
Other aspects	Roof needed to be strengthened The solar thermal project was a small part of a larger energy efficiency upgrade project across multiple sites

5.3.2. Geothermal & CHP plant for abattoir

Figure 45: Midfield Meats Co-Generation system, Victoria. (image from Midfield Meats).

Midfield Meats is an abattoir in Warrnambool, VIC. The site is forward thinking in its mix of energy sources. The Midfield Meats plant integrates a geothermal bore with a natural gas-fired CHP plant to reduce reliance on mains water, natural gas and electricity.

Water is drawn from the bore at 42°C (30°C above the mains temperature). It then enters a filtration plant to filter out mineral content, which would otherwise lead to scale build-up in piping. After sand filtering, UV filtering, and finally reverse osmosis (RO), the water is at 38°C and is split into two streams; one for washing by hand, and one for further boosting through the CHP plant.

Approximately 1 ML of water is drawn each day by the bore from the Dilwyn aquifer, with the balance being supplied by the municipal water supply. The bore was originally drilled to 900 m depth, though the most suitable extraction point was later determined to be at 700 m.

The CHP plant operates 24 hours a day, 5 days a week, and comprises a V16 Deutz engine that produces electricity through the internal combustion of natural gas. Waste heat is transferred to the filtered geothermal bore water via the engine's cooling and exhaust gas, raising it to 70-75°C. It is subsequently fed to the gas boilers, which raise it to 90°C for washing and sterilisation purposes. At the design point, the CHP plant produces electricity at a rate of 1,550 kW_e and heat at a rate of 1,700 kW_{th}.

The capital cost of the bore was around $1 milion. The RO plant (costing ~$400, 000) and the CHP plant (costing ~$1.5 million) were originally owned and operated by the energy performance contractor, with Midfield Meats paying only for the supply. The RO plant was subsequently purchased by Midfield Meats as in-house engineers were comfortable with the technology. Ownership of the CHP plant remains with a third party. The project has avoided investment in additional natural gas boilers that would otherwise have been required owing to production increases.

The primary driver for installation of the bore was water. The system now provides 55% of the sites water requirements. The economics of the heat alone would not have carried the project however. The economics of the water would. The site needed heat and water but the way in which this business viewed it is that once the capital cost of the bore was sunk, the water supply was then significantly cheaper than municipal water (i.e. a focus on ongoing operational costs).

Summary

Location	Warrnambool, VIC
Application of process heat	Washing and sterilising in meat production
Temperature	~40°C / 70-75°C / 90°C
Energy resource	Geothermal (Dilwyn aquifer) Natural gas
Technology	Single bore geothermal water from 700 m depth CHP with internal combustion engine Gas boilers
Designed to deliver	Geothermal: 1 million litres per day of water at 42°C CHP: 1550 kW_e / 1700 kW_{th}
Energy/emissions saved	Geothermal: ~28,000 GJ_{th}/year / ~1,800 t-CO_2/year (estimates) CHP: 60% of electricity demand; 9,600 tonnes of CO_2 savings p/year
Construction	CHP: commissioned in 2009
Investment	Geothermal: ~$1M + $400,000 for Reverse Osmosis CHP: ~$1.5 million
Other aspects	Geothermal primarily implemented for water extraction

5.3.3. Heat pump system for distillery

Figure 46: Left: Shene Estate and Distillery, TAS; Centre: Example of a Mitsubishi Q-ton unit; Right: hot water storage tank coupled to Q-ton unit. (Reproduced from Mitsubishi Heavy Industries).

The Shene Estate and Distillery in Pontville, TAS makes gin and whisky. Every day the distilling process consumes ~6000 litres of hot water at temperatures between 64 and 90°C.

Historically the distillery heated water using an instantaneous electric heater, but rising electricity costs led the business to consider cheaper alternatives. Although the distillery considered a gas boiler, this option was hampered by a lack of connection to the gas grid. Instead, the business decided in 2018 to install an air-to-water hot water heat pump (Mitsubishi Heavy Industries, Q-ton).

The heat pump uses outside air as its heat source and can operate in temperatures as low as-minus 25°C. It uses a two-stage compressor to raise the outdoor air temperature, delivering up to 30 kW of heat. For an air input at 16°C it can deliver 65°C water with a COP of 4.3. The distillery also runs the heat pump during off-peak electricity periods, storing hot water for later use. It is expected that the heat pump installation will reduce operation energy costs by ~60%, compared to the electric resistance water heater.

Summary

Location	Pontville, TAS
Application of process heat	Distilling in liquor production
Temperature	64-90°C
Energy resource	Ambient air, can operate at ambient temperatures down to -25°C
Technology	Two-stage air-to-water heat pump (refrigerant: CO_2) Hot water storage tank
Designed to deliver	Up to 30 kW_{th}
Energy/emissions saved	Electricity reduction by ~60%

6. AMMONIA AND OTHER CHEMICALS

6.1. Overview

The AES category of ANZSIC subdivisions 18-19 is ‘basic chemical and chemical and rubber product manufacturing’. Here we refer to it as ‘Ammonia and other chemicals’, reflecting the high significance of ammonia in the overall energy consumption of the sector.

The chemical industry involves a large and diverse range of manufacturing activities. These can be divided into two groups: basic chemicals and chemical products. Basic chemicals are for the most part single chemical compounds which, as the name suggests, are the basis from which a wide variety of complex products are manufactured. Basic chemicals can be further divided into two groups: petroleum and coal products and other basic chemicals.

Other basic chemicals manufacture typically involves very large manufacturing facility producing bulk chemicals such as sulphuric acid, ammonia, chlorine, other industrial gases and basic polymers, like polyethylene and polypropylene. The raw materials from which many of these products are made include natural gas, ethane, oil refinery by-products (such as propylene), and salt.

There is considerable interest in the feasibility of using renewable energy as an alternative energy source for ammonia production. Some feasibility studies are currently underway, notably at the Yara plant on the Burrup Peninsula in the Pilbara.

6.1.1. Site location and intensity of heat use

The sites for activity in the Ammonia and chemicals sector with their indicative intensity of heat use are shown in Figure 47.

Production of ammonia is by far the largest user of gas in the whole chemicals sector. There are currently seven major ammonia plants in Australia as listed in Table 15. Ammonia plants are widely dispersed, including one at Phosphate Hill, near Mount Isa in north west QLD, one at Moranbah and one in Moura, (both in central QLD), one in Brisbane, one in Newcastle, one in Kwinana, and one in the Pilbara.

Methane is both a feedstock and a source of energy used in the production of ammonia. In this analysis, we consider only the fraction of energy that can be attributed directly to the process heat.

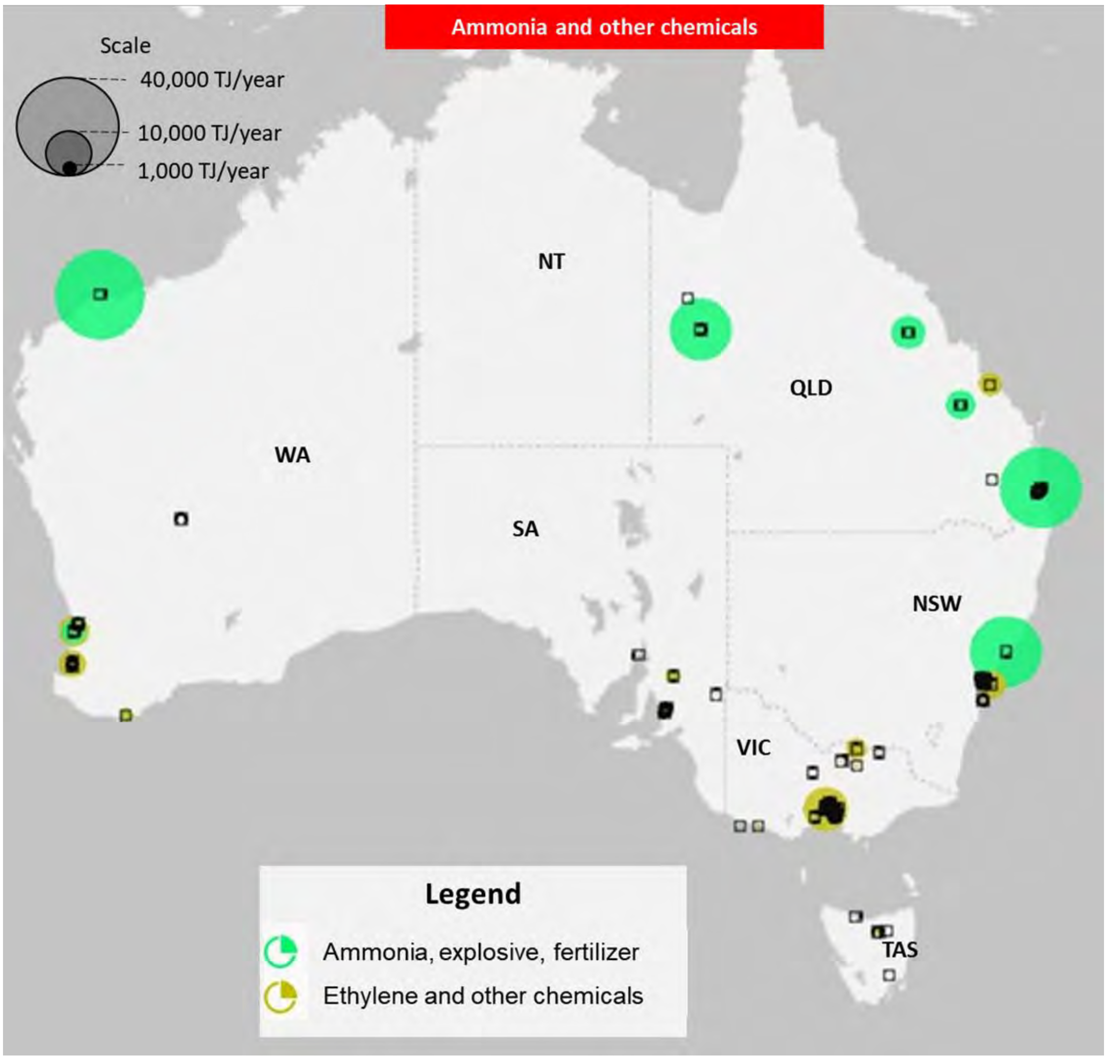


Figure 47: Location and volume of heat use for ammonia and other chemicals.

Some of the ammonia produced at each plant is converted to nitric acid, which is then reacted with ammonia to produce ammonium nitrate, one of the main products of the seven plants. Ammonium nitrate has two main uses; as an agricultural fertiliser and as a blasting explosive for use by the mining industry. The plants at Moranbah and Moura produce only explosives, the plants at Brisbane and Phosphate Hill produce only fertilisers and the plants at Newcastle and Kwinana produce both explosives and fertilisers. The Pilbara plant produces mainly ammonia, which is exported as a bulk commodity. Ammonia is an important internationally traded commodity.

Table 15: Major ammonia-based fertiliser and explosives plants in Australia (AN: Ammonium nitrate, DAP: diammonium phosphate, AS: ammonium sulphate).

Company	Suburb	State	Main activities	Production capacity ton per year
Yara	Burrup	WA	Ammonia	850,000
Orica	Kooragang	NSW	Ammonia + AN +nitric acid	360,000
Incitec	Gibson Island	QLD	Fertilisers	Ammonia: 360,000, Urea: 280,000, AS: 200,000
Incitec	Phosphate Hill	QLD	Ammonia for DAP production at Mt Isa	>950,000
Incitec	Moranbah	QLD	AN	330,000
CSBP, Incitec	Moura	QLD	AN	210,000
CSBP	Kwinana	WA	Ammonia, AN	260,000

Polyethylene is produced in large volume at both Botany and Altona.The ethane feedstock is supplied through dedicated pipelines from Moomba and Longford respectively.

The third subsector of the chemicals industry involves the manufacture of an enormous diversity of products including pharmaceuticals, cleaning products, cosmetics, paints, pesticides and herbicides, fertilisers, and plastic and rubber products of all kinds. As a broad generalisation, most of these manufacturing activities are not particularly energy intensive, use mainly gas and electricity for their energy requirements, and take place at a large number of individual factories, many of which are quite small. There are major concentrations of these activities in Sydney (Botany), Melbourne (Altona) and nearby at Geelong, and Perth (Kwinana).

6.1.2. Processes that use heat

Figure 48 shows the typical fertiliser production process from different raw materials. Ninety per cent of the energy used in the fertiliser industry is used for ammonia production (Gerlagh & Van Dril, 1999). Although ammonia production overall is a large energy consumer, the Haber Bosch ammonia synthesis step itself is an exothermic process. Heat recovered is used to generate high pressure steam to run CHP units, thus increasing the overall efficiency of the process. Figure 49 shows typical energy use in an ammonia plant.

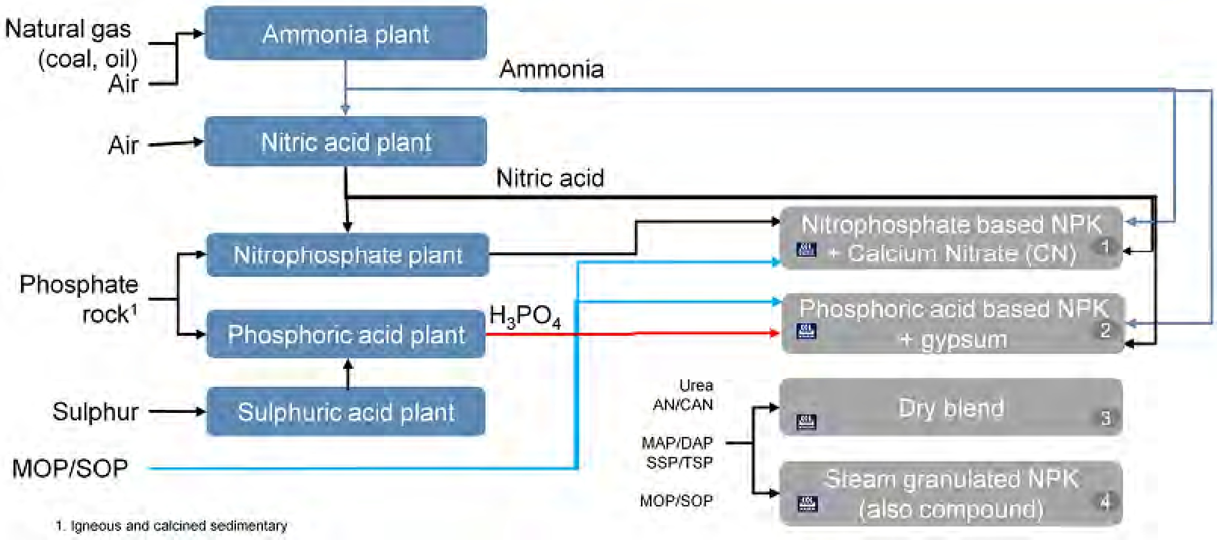


Figure 48: Fertiliser production routes. (Reproduced from Yara Fertilisers.)

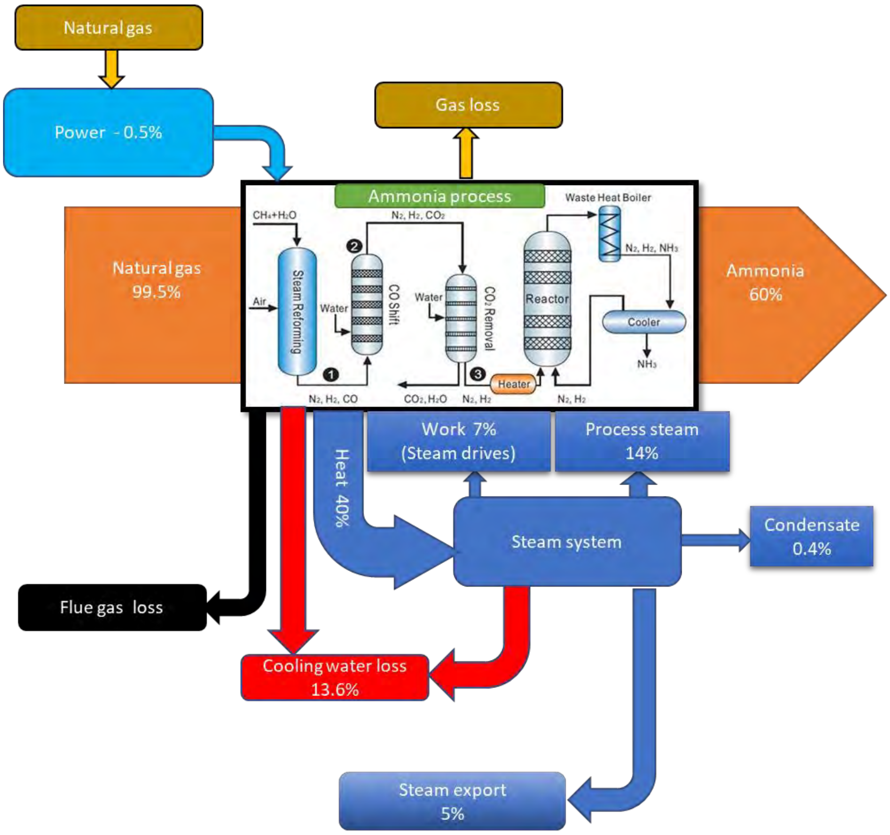


Figure 49: Typical energy use in ammonia plant[22].

Almost 60% of the natural gas is used as feed stock and the balance is used as energy for steam reforming of methane (SMR), which occurs in catalytic reactors at around 800°C. Electric power use is a small portion of the total energy consumption, as high-pressure steam generated from the exothermic heat produced by ammonia synthesis reactors is typically used in turbines that directly drive large compressors and pumps etc. Where ammonia plants are integrated with fertiliser production, steam can also be exported to the downstream process.

Approximate natural gas consumption in ammonia production is 35 GJ/tonne of NH_3, of which 20 to 22.6 GJ/tonne is used as feedstock and the balance is fuel used in the primary reformer and auxiliary boiler (ENERGY STAR®, 2017; Yara, 2017).

Australia has two plants that manufacture polyethylene and polypropylene products. The Altona and Botany Bay plants process ethane feedstock from Bass Strait and Cooper Basin into around 205,000 t/ year and 250,000 t/ year of ethylene (www.qenos.com). The processing of ethane can be divided into the following steps:

[22] Data and ammonia process schematic adapted from *(Noelker & Ruether, 2011)*

- steam/furnace cracking and quenching: Ethane, in the presence of steam and heat (750 to 900°C) changes to other hydrocarbons. The gases from the furnace are immediately quenched in a quench tower
- the cracked gases are then compressed to 3500 kPa and liquified for distillation
- the cracked gas is chemically treated to remove impurities in a caustic tower and dried using a molecular sieve desiccant drier
- dried gas is cooled and liquified and the liquid stream is distilled / fractionated to separate the components (Qenos, 2015).

The major energy consuming process is conversion of ethane to ethylene. The specific energy consumption for process and feedstock is 24.5 and 47.3 GJ/tonne of product (Neelis et al., 2008). As of 2010, fuel used in the furnace and boilers accounted for 90% of GHG emissions at both sites and is estimated at around 11,000 TJ/ year (Qenos, 2010). In 2013, the Altona facility launched a CHP plant that produces 21 MW_e of power and 88 tph of steam (The Fifth Estate, 2013).

6.1.3. Existing heat supply

Figure 50 provides a breakdown of heat sources for the Ammonia and other chemicals sector. The total of 42 PJ/year is an estimate of the heat use based on an average conversion efficiency of 80% applied to the fuels applied to heat production. This does not include the further 86 PJ/year of natural gas that is transformed as feedstock and appears as the hydrogen component of the ammonia.

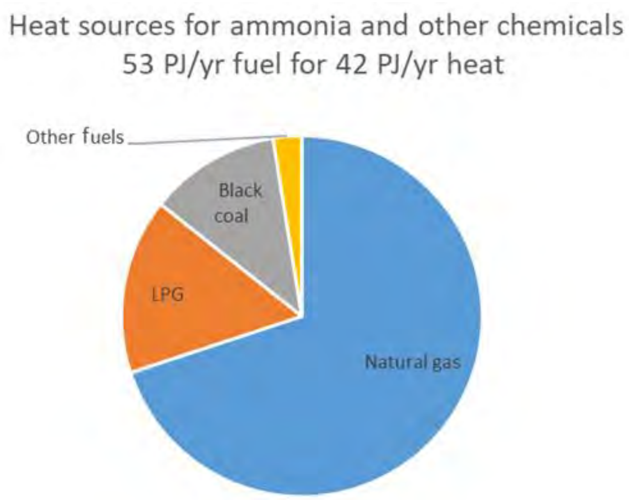


Figure 50: Existing sources of heat in the ammonia and other chemicals sector.

A small number of large petrochemical and ammonia manufacturing establishments use gas in large volumes, both as a source of energy and as a feedstock. The feedstock use includes methane and ethane, both of which the AES classifies as natural gas. Methane is used as feedstock for the manufacture of ammonia at six plants located in Queensland, NSW and WA.

Manufacture of many, though not all of these chemicals requires the significant input of thermal energy. Several of these plants use large volumes of steam; the Botany site is serviced by a centralised coal fuelled boiler.

The large plants in this sector are among the biggest users of energy in the country. Their costs of energy are likely to be close to the prevailing wholesale prices.. Thus, the overall cost of supply of gas in 2019 would be around $8-10/GJ, coal around $3-4/GJ, and electricity around $100/MWh (equivalent to $28/GJ). On the other hand, there are also many small plants, using gas at around $30/GJ, with even higher costs for those needing LPG supply and electricity around $300/MWh ($83/GJ).

6.2. Renewable energy options

In principle, renewables could substitute for either the heat to drive reforming of methane or the feedstock for ammonia or both. Regarding chemical manufacturing other than ammonia or ethylene, the German Society for Chemical Engineering (DECHEMA) has estimated that the fuel used to generate steam accounts for 60% of the total fuel used by the European chemicals industry (Bazzanella & Ausfelder, 2017). Steam can be produced with renewable energyincluding solar thermal, bioenergy and electrical solutions, in particular heat pumps driven by renewable electricity from solar and wind.

Several renewable approaches exist for hydrogen production as a feedstock. The nature of chemical synthetic industries is such that substitution of feedstock requires high levels of purity and an associated high capital investment in process development to meet stringent modern quality standards. The mixed and variable product streams from biomass gas technologies, for example, would face considerable challenges for this use.

Research groups around the world have demonstrated pilot-scale solar thermal-driven steam reforming of methane, including the CSIRO at Newcastle. This has the potential to replace a major proportion of the identified process heat if methane continues to be used as a feedstock. Currently around 30% of gas consumption is for combustion to provide the heat for steam reforming reactors at around 800^{o}C. This appears to be an encouraging future prospect worthy of continued effort, which is not too far from being economically viable at current costs of natural gas.

Hydrogen could be produced by biomass gasification if there was a sufficient resource available. It would need major investment in post processing and purification of the gas to be acceptable. It is hard to see the volumes required being available in Australia.

McKinsey, in examining the decarbonisation potential of various sectors, concludes that ammonia production could be one of the most cost efficient applications for carbon capture and storage (de Pee et al., 2018). This arises because the process of hydrogen production from methane inherently produces a concentrated CO_2 stream, so capture is essentially built in. If ammonia production is located close to gas production, then the opportunities for CO_2 reinjection should also be facilitated. In this context, the solar thermal steam reforming of methane could form part of a total zero emissions approach.

Production of pure solar hydrogen by electrolysis for use as a fuel is still several times more expensive than natural gas but is likely to have a future role to play. Technically, it could readily be accepted into an existing ammonia plant, as long as it was free of water vapour. This route of renewable hydrogen use is more attractive than general substitution of natural gas in other sectors as it removes / reduces the need to operate the steam reforming step and could avoid that aspect of investment cost for a new plant.

6.2.1. Ammonia production from electrolysis

There is considerable global interest in the production of ’green ammonia’, as ammonia production is currently responsible for approximately 1.7% of global CO_2 emissions, with most production destined for fertiliser use (The Royal Society, 2018). The dominant process is steam reforming of fossil fuels, with feedstock accounting for approximately half the emissions. Global consumption is expected to increase considerably by 2050, with some authors projecting a tripling to allow for the expanded role of ammonia as an energy carrier for transport and stationary energy sectors (Brown, 2018b).

The two main process alternatives to reduce emissions are using CCS at the point of production, and producing hydrogen (the main ammonia precursor) by electrolysis (de Pee et al., 2018). Steam reforming combined with CCS offers a CO_2 reduction of 70-90%, while electrolysis powered by renewable electricity reduces emissions to zero (The Royal Society, 2018). Electrolysis is expected to be cheaper than the CCS route at electricity prices below USD50/MWh (de Pee et al., 2018). Newer electrolysis processes are at the late stage of commercialisation, with pilot plants established or being developed in Australia (the Yara plant in the Pilbara and Port Lincoln in SA, see case studies below), Japan, Germany, the UK and the US (Brown, 2018a).

Long-term growth in global demand for hydrogen is likely to be driven by the requirement to decarbonise transport and as an energy storage medium, with Australia’s potential share of this market already highlighted as being very significant (Brown, 2018b; Hydrogen Strategy Group, 2018; van Wijk et al., 2017).

In the near term, however, the production of green ammonia provides a stepping stone, and is likely to be the market in which renewable hydrogen first becomes competitive.

Given the likely global demand for renewable hydrogen and Australia’s trading partners’ decarbonisation targets, efforts focussed on a process change to zero carbon production are likely to be much more effective in the long-term, than substitution of a proportion of fossil fuel heat with renewables within the current steam reforming process.

6.2.2. Renewables for steam and hot water

Where sufficient amounts of low-cost biomass (< $5/GJ) are available, bioenergy is likely to be a viable option for process heat integration, particularly with CHP for lower temperature hot water or steam generation. At sufficiently large plant sizes (see section 3.7) bioenergy offers the benefit of continuous operation, which is suitable for chemical production plants, which typically operate around the clock.

Solar thermal and thermal energy storage are most cost-effective at lower temperatures up to ~150°C. Hence solar thermal could be viable for hot water and steam generation in chemical production in locations with a good solar resource. Where renewable hydrogen is to be produced with seawater, solar thermal can also be used for seawater desalination, for example via solar-heated multi-effect distillation, requiring temperatures only a little over 100°C and allowing for inexpensive water storage to overcome intermittency.

6.2.3. Electric heating

Separately to the consideration of using electrolysis for green hydrogen for ammonia, it would also be possible to construct steam reforming reactors that were electrically heated.

For steam and other lower-temperature process heat needs in smaller general chemicals manufacturing plants, the four main electrical alternatives to fuel-based steam systems are:

- heat pumps
- mechanical vapour recompression
- electric resistance boilers
- microwaves.

Closed-cycle heat pumps can produce steam at up to 160°C and are therefore likely to have a large number of potential applications in the Australian chemicals sector. These will be most advantageous where they can be fed with a source of waste heat and achieve a coefficient of performance of three or higher.

Open-cycle mechanical vapour recompression is most applicable where waste streams, e.g. steam, can be re-integrated into the process after upgrading to higher temperature and pressure. They are particularly effective where only small temperature lifts are required in order to reuse the energy contained in the waste stream and a single stage MVR unit can be used. For larger temperatures increases, they can be combined in series.

Electric resistance boilers are an alternative technology for hot water production. They can replace gas-fired boilers with little modifications to the overall system. Electric boilers are less energy efficient than heat pumps for hot water generation but have a very fast response time, which allows taking advantage of cheap renewable electricity.

Microwaves have been used for many years in the pharmaceutical and fine chemical industries. Microwave heating offers fast start, stop, speed up and control of chemical reactions that can reduce energy use and improve product quality compared to gas-fired heating. Large-scale use of microwave heating in the production of plastics, biodiesel, chemicals and pharmaceuticals has long been limited due to the high cost of scaling up microwave-based synthesis. However, more recently continuous microwave heating systems have been applied in larger processes with production capacities of hundreds of kilograms, for example in the production of plastics, plasticisers, resins and lacquers. Japan’s Microwave Chemical, for example, has developed microwave systems to produce a variety of specialist chemicals including a microwave-based process to turn waste vegetable oil into fatty-acid esters used to make coloured ink for the newspaper industry. The heating process uses three times less energy, and is ten times faster, than the conventional fuel-based process.

6.2.4. Green ammonia projects

Several recent studies have pointed out the potential of green ammonia production as a commodity and potentially as an energy carrier for green hydrogen (ACIL Allen Consulting, 2018; Bruce et al., 2018; Hydrogen Strategy Group, 2018; Philibert, 2017). Philibert, 2017 illustrated that ammonia production using hydrogen from water electrolysis with renewable electricity has the potential to become cost-competitive with hydrogen from conventional steam methane reforming in regions with strong solar and wind resources, including Australia.

Two green ammonia projects are under development in Australia. In Port Lincoln SA, the company H2U, with financial support from the SA government, is developing a green hydrogen and ammonia demonstration plant including a 15 MW electrolyser and ammonia production facilities. The ammonia is planned to be supplied as a fertiliser to the region’s agricultural sector.

In the Pilbara region in WA, Yara Pilbara Fertilisers, part of Yara International, has been producing ammonia through steam methane reforming since 2006. The company, in collaboration with Engie Energy Services, is currently exploring the feasibility of converting part of their operations to using renewable hydrogen. A 2.5 MW solar PV trial system is underway, with a 100 MW solar array planned to be operational by 2021.

The Pilbara region boasts excellent solar as well as wind resources and has attracted interest from other consortia to build large-scale solar and wind farms for renewable energy export to Asia via sub-sea cables and hydrogen (or its derivatives).

6.3. Case studies

6.3.1. Green ammonia demonstration plant

Figure 51: Siemens green ammonia pilot project at Rutherford Appleton Laboratory, near Oxford, UK. (Image from ammoniaindustry.com.)

Internationally, Siemens is among a range of European companies pursuing green ammonia both as a form of energy storage and for fertiliser production. In collaboration with the University of Oxford, Cardiff University and the Science & Technology Facilities Council, Siemens is operating an all-electric ammonia synthesis and energy storage demonstration facility near Oxford, UK (Figure 51). The plant includes an ammonia synthesiser with a capacity of ~30 kg/day, ammonia storage facility and an internal combustion engine adapted to ammonia to generate electricity.

Thus, the pilot plant is designed to demonstrate the full round-trip of renewable electricity from power to ammonia and back. With the pilot system, Siemens aims to explore the business case for ammonia in various applications, including as a long-term large-scale electricity storage medium, for demand-side response, or to sell as an input to fertiliser production, chemical feedstock, or fuel.

Summary

Location	Rutherford Appleton Laboratory, Oxford (UK)
Energy resource	Grid electricity
Technology	PEM electrolyser Air separation unit (pressure swing absorption) Haber-Bosch ammonia synthesis reactor Pressurized ammonia storage facility 30 kW internal combustion engine (3-cylinder spark ignition)adapted for ammonia, coupled to electric generator
Designed to deliver	30 kg/day of ammonia

Construction	Completed in 2018
Investment	£1.5 million ($2.7 million)
Other aspects	Facility serves as a learning and demonstration plant

7. IRON AND STEEL

7.1. Overview

In the analysis of Figure 4, Iron and steel is the third-largest sector for industrial process heat use. This analysis treats all coal inputs to iron production as being process heat. Much of the energy is required for the chemical reaction that removes oxygen from the iron oxides. In this study we treat that energy as process heat rather than ‘feedstock’ i.e the energy provides the heat needed to break the oxygen bonds. The role is not limited to the use of carbon and the carbon does not become part of the final product to any significant extent[23]. Whilst the sector is dominated by the iron production it also includes further processing to steel and the transformation of steel to derivative products. The Australian iron and steel industry produces about six million tonnes of steel and 14 million tonnes of greenhouse gases (mostly carbon dioxide) a year. This is about 2.5 per cent of Australia’s total annual emissions.

Iron and steel are essential to industrial society and whilst technically and economically challenging, it is possible to identify technically feasible paths to fully renewable energy-based production.

7.1.1. Site location and intensity of heat use

The sites for activity in the Iron and steel sector with their indicative intensity of heat use are shown in Figure 52. Table 1 shows the major iron and steel companies with their production capacity.

Most thermal energy use by the Australian iron and steel industry occurs at the country’s two integrated steelworks: the Bluescope plant at Port Kembla and the Liberty Steel (formerly Arrium) plant at Whyalla. Most of the thermal energy required comes from the coke use in blast furnaces to reduce iron oxide to pig iron, together with the coke oven gas and blast furnace gas produced as by-products of the respective operations. Natural gas is used essentially as supplementary fuel to these gases, and its use is integrated with the overall operation of the plant. Integrated steel mills are very large operations, producing large quantities of steel. In the most recent years about three million tonnes were produced at Port Kembla and a little over one million tonnes at Whyalla.

There has been a decrease in coal consumption seen in this sector between 2010-11 and 2013-14, associated with a drastic fall in sales, leading to the closure of one of the two blast furnaces at the Port Kembla plant.

[23] This is in distinction to the analysis of the natural gas for ammonia production that is directly providing the essential feedstock of hydrogen which becomes part of the ammonia, as well as the process heat.

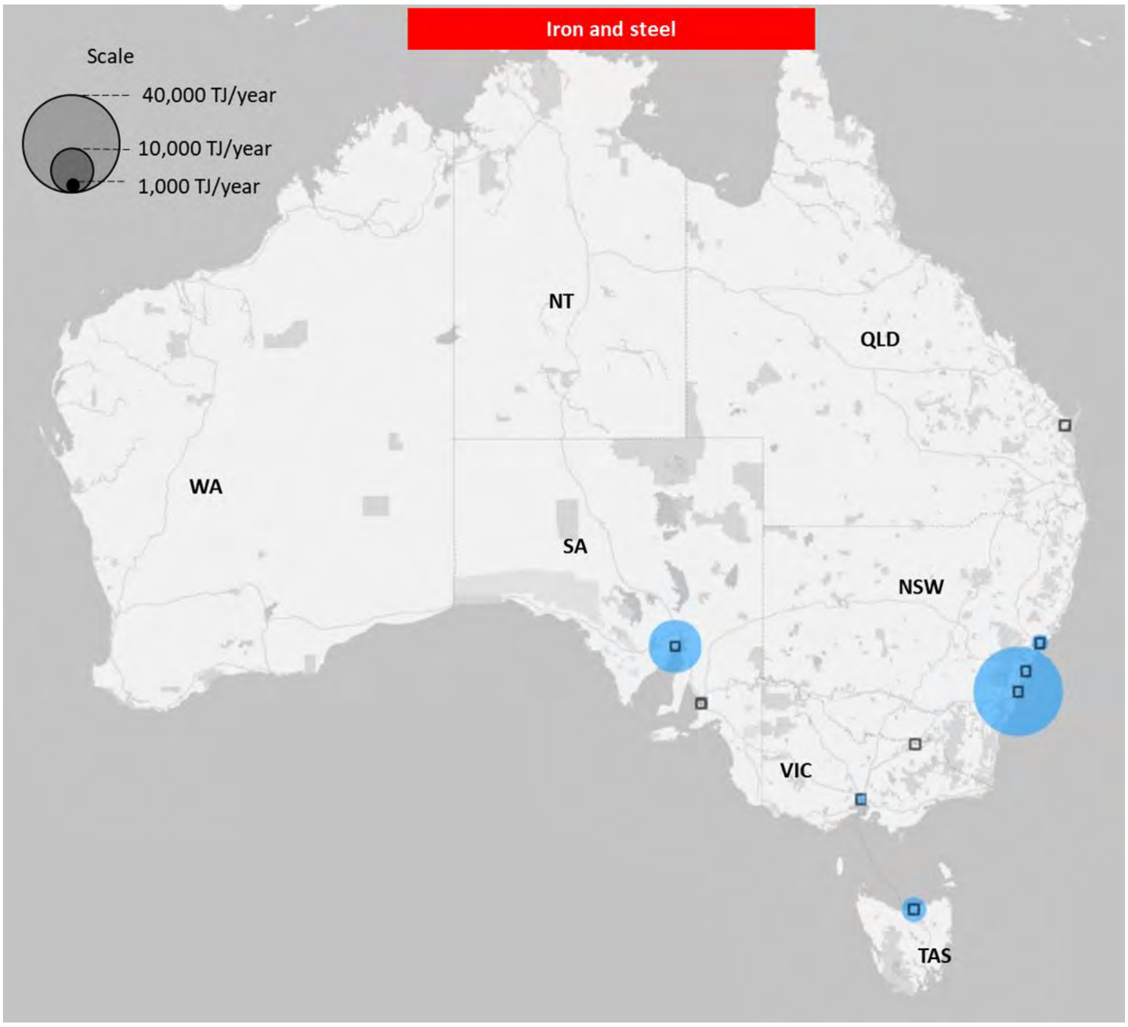


Figure 52: Locations of activity and intensity of heat use in the iron and steel sector.

Table 16: Major iron and steel companies in Australia (BF: Blast Furnace; BOS: Basic Oxygen Steelmaking; EAF: electric arc furnace).

Company	Suburb	State	Main activities	Production technology	Production capacity per year, in million tons	Energy use per year in PJ
Bluescope Steel (AIS) Pty Ltd, Port Kembla steel works	Port Kembla	NSW	Primary iron and steel manufacture	BF, BOS	2.6	**52**
Bluescope Steel Limited, - Springhill	Port Kembla	NSW	Integrated steelworks, flat products	BF, BOS	-	**-**
Commonwealth Steel Company Ltd, MolyCop Waratah	Waratah	NSW	Secondary steel manufacture	EAF	1.7	34
Onesteel Manufacturing Pty Limited, Whyalla Steelworks (Arrium)	Whyalla	SA	Integrated steelworks, long products	BF, BOS	1.28	-
OneSteel	Rooty Hill	NSW	Secondary steel manufacture	EAF	0.625	-
OneSteel	Waratah	NSW	Secondary steel manufacture	EAF	0.33	-
OneSteel	Laverton	VIC	Secondary steel manufacture	EAF	0.74	-
Tasmanian Electro Metallurgical Co Pty Ltd, TEMCO	Bell Bay	TAS	Manganese ferroalloy smelter	EAF	-	-

7.1.2. Processes that use heat

Figure 53 presents an overview of the main elements of integrated iron and steel production. Three routes are shown; primary steel making via the blast furnace route; primary steel making via direct reduction, and secondary steel making based on scrap steel recycling.

Australian integrated steel plants use the blast furnace approach. Key steps in this are:

- coke production in a coke oven battery via high-temperature partial combustion. This also produces a range of by-product chemicals and gases, some of which have a market value and some of which are redirected as fuel sources to other parts of the process.
- sinter plant agglomerates iron ore dust with other materials at high temperature, to create pellets that can be fed to the blast furnace along with lump iron ore. Temperatures range from1150 to 1250 °C in the ignition zone, 900 to 1000°C in the soaking zone
- the blast furnace, which is fed mainly with coke, supplemented with natural gas, along with the iron ore and flux (usually limestone and dolomite) plus injection of pure oxygen to combust the fuel. This operates at temperatures of around 1500°C, up to over 2000°C.

The oxygen is pulled from the iron ore and reacts with carbon or hydrogen in this hot reacting environment, while the flux reacts with impurities in the iron ore. The products are molten pig iron and blast furnace slag

- molten iron along with scrap steel transfers to either a basic oxygen furnace (BOF), which is also called basic oxygen steel (BOS) plant, or an open-hearth furnace (OHF) to complete the process of steelmaking.

The Direct Reduction approach is employed at scale around the world and employs ahigh-temperature furnace typically operated on natural gas only to reduce the oxides to iron. The iron produced is then further processed to steel along with scrap material in an electric arc furnace (EAF).

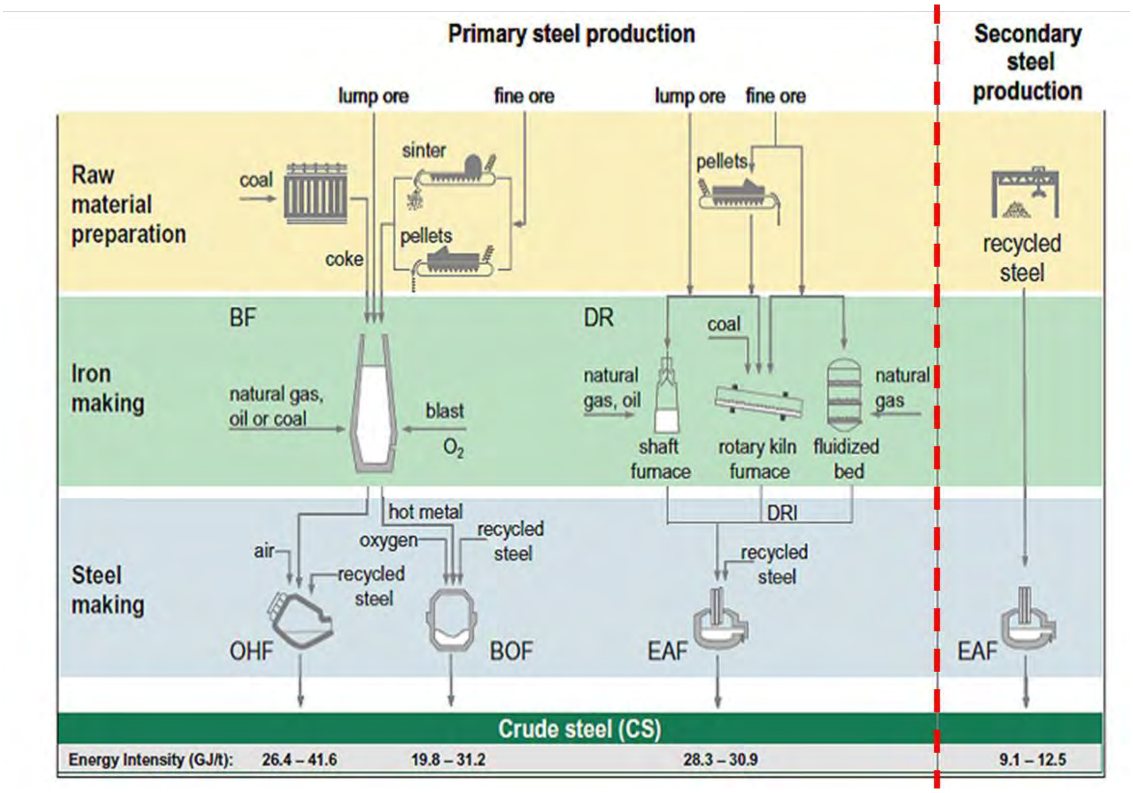


Figure 53: Primary and secondary steel production routes. Reproduced from World Steel Association.

CSIRO reports that the energy intensity of the primary steel production route is around 20 GJ per tonne of crude steel (Rankin, 2012).

Considerable volumes of combustible gases (blast furnace gas and coke over gas), consisting mainly of carbon monoxide, are produced from blast furnaces and steel making furnaces as well as coke production. These are recycled for use as fuel at various parts of the plant, often supplemented with purchased natural gas. Integrated power production using steam turbines also is typically included, with waste heat recovery contributing to steam production.

The secondary steel production route does not require a coke or a sinter plant because the recycled steel scrap is melted directly in an electric arc furnace (EAF). The energy intensity of this route is around 9.7 GJ per tonne of steel (Rankin, 2012).

7.1.3. Direct reduced iron

Currently, blast furnaces are used to process most iron ore. A potentially cost effective and lower-emissions alternative is direct reduced iron processes (DRI), particularly in countries where high-quality coking coal is not readily available. DRI tends to have lower installed cost and operating costs than blast furnaces. DRI based on natural gas is a well-established technology, operated at scale in many countries although not yet in Australia.

In DRI, iron ore in solid form is reduced with syngas (CO, H_2) as the reducing agent. If the process is conducted with renewable hydrogen as the reducing agent instead of syngas, CO_2 emissions could be eliminated (see below). Energy savings can be achieved if the hot DRI is directly fed to a nearby EAF.

7.1.4. Existing heat supply

Figure 54 illustrates the sources of process heat for the iron and steel sector. The total of 94 PJ/year is an estimate of the heat use based on an average conversion efficiency of 80% applied to the fuels used for heat production. Clearly coal dominates, supported by natural gas and then electricity that is used in electric arc furnaces.

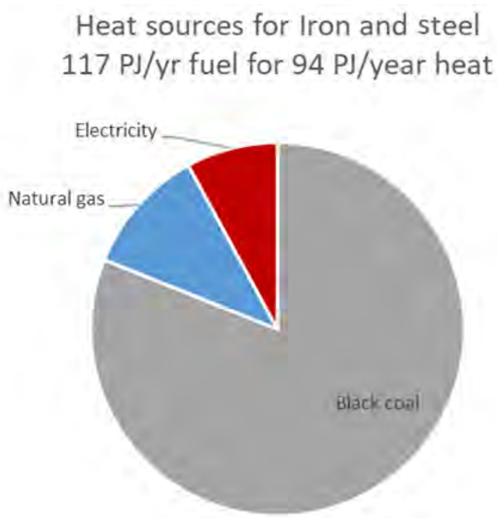


Figure 54: Sources of process heat in the iron and steel sector.

With just two major integrated steel plants, it is difficult to generalise on likely costs of energy, however the closest to wholesale prices might again be expected for these. Thus, the overall cost of supply for gas in 2019 would be around \$8 -10/GJ, coal around \$3-4/GJ, and electricity around \$100/MWh (equivalent to \$28/GJ). It may be that the facilities with electric arc furnaces have secured more competitive contracts for electricity supply.

7.2. Renewable energy options

There is scope for the replacement of some of the current energy uase in iron and steel manufacturing with renewable energy. Current natural gas use could be substituted by other renewable gases and some share of the coal use could in principle be substituted by biochar. Current electricity use can migrate to electricity of renewable origin without any process change.

Given the relatively low energy prices that integrated steel plants would currently experience, it is unlikely that any source of biochar could be economically competitive on present terms. It may be possible that some use of municipal solid waste could be contemplated, possibly gasification, with the product gases then substituting for natural gas use given that a blast furnace could be assumed to be insensitive to gas composition.

Beyond this there are new processes for future zero emissions iron and steel production that are at various stages of commercial maturity. Adoption of these implies major investments in new plants either at existing sites or as new greenfield developments. With Australia being a major iron ore exporter, leveraging renewable energy sources to increase the amount of value adding via the steps of iron and steel production would be logical, given Australia's strong renewable energy resources. This, however, is contingent on the growth of a market for zero emissions iron and steel and / or market forces that put a high price of carbon dioxide emissions.

7.2.1. Bioenergy potential in existing processes

One of the established techniques for bioenergy use in iron and steel making is to use biochar to replace coal and coke in steel making and thereby reduce emissions without substantial modification in the steel making process. This is the most significant source of emissions in blast furnace primary iron production.

The use of charcoal is well established in Brazil, which produces somewhere between 25% and 30% of iron using charcoal (Scarpinella et al., 2011), using an estimated 190,000 tonnes per year of charcoal (Hu et al., 2011). Provided the biochar has suitable attributes, this can even result in process improvement compared to coke (Scarpinella et al., 2011). This substitution has great potential for CO_2 emissions reduction provided the charcoal is from sustainable plantations. However, there are significant issues with current charcoal production in Brazil, which has been associated with deforestation, and there are efforts underway to ensure that the charcoal is produced from renewable biomass sources (Profor, 2017). With the caveat regarding the wood source, process substitution of biochar for coking coal can be a more effective pathway for bioenergy contribution to iron making than the substitution of bioenergy for fossil heating fuel.

Based on the current charcoal production from Brazil's eucalypt plantations, it could take somewhere in the order of 700,000 ha of plantation forest to produce sufficient biochar for Australia's current iron production (Scarpinella et al., 2011). This is equivalent to 36% of the current area of commercial plantation.

7.2.2. Electrical

Indications are that large scale offtake agreements for renewable electricity are increasingly competitive with grid electricity. The Liberty Onesteel operation in Whyalla under its new management has notably announced major initiatives to source renewable electricity. This can be applied to existing uses or potentially expanded.

The most likely route to complete decarbonisation of primary steel making is through hydrogen-based direct reduction (Lord, 2018). The second stage of this method of steel making will involve an electric arc furnace. Direct-reduced iron will be melted in an EAF and mixed with a source of carbon. The EAF consumes approximately 686 kWh to produce one tonne of steel.

The process presents no technical challenges as it is very similar to current use of EAF, which are used widely to recycle steel scrap and convert direct-reduced iron into steel.

Hydrogen-based direct reduction of iron ore requires heating in fluidised beds to 650-750°C. This could potentially be aided with direct electrical resistance heating. However, it should be noted that some reducing agent (e.g. carbon or hydrogen) is still essential for the chemical conversion.

7.2.3. Advanced zero emissions processes

Companies in Sweden have announced the start of a long-term research project aimed at developing a production method for steel based on the use of hydrogen generated from carbon emission-free energy sources, including hydro and wind power, to replace coal/coke or natural gas in the blast furnace process (Otto et al., 2017).

Similar efforts have commenced in other countries in Europe. In Germany and Austria, companies including ThyssenKrupp Steel, Salzgitter and Voestalpine have been investigating new methods, in particular hydrogen-based iron reduction (Knitterscheidt, 2019).

CSIRO has developed a new process to recover the waste heat from cooling of blast furnace slag and save water (CSIRO, 2015). Currently, the slag is cooled from ~1400°C in a wet-granulation process, which results in a heat rejection to the environment of around 1.8 GJ/tonne (~700,000 TJ/ year globally). In the new dry-granulation process this heat can be recovered by an air flow. A similar solution has been developed by a group of engineering and industrial companies in Europe (McDonald & Werner, 2015).

At a much earlier stage of development, researchers at George Washington University have developed solar thermal electrochemical photo (STEP) energy conversion. This is a new process that uses electricity and the chemistry of iron to convert iron ore to iron metal. Conventional iron extraction process is carried out at ~2000°C, when the carbon in the coke reacts with oxide in the ore and is removed as CO and CO_2. According to the new research, iron ore at 600 to 1000°C is more soluble than previously expected and this principle is used in an electrolysis arrangement that requires much less energy. The process can be powered by renewable electricity to eliminate CO_2 emissions.

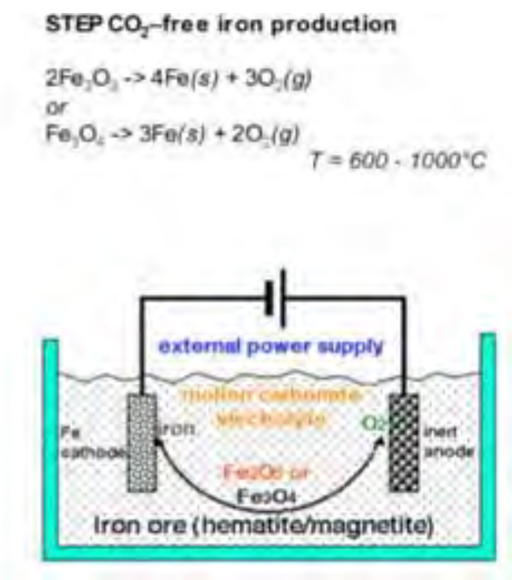


Figure 55: The STEP carbon dioxide-free production of iron (Berger, 2010)*. (Reproduced from Nanowerk.)*

Also at an early research level, the carbothermal reduction of iron oxide using concentrated solar energy as a source of process heat has been considered (Steinfeld & Fletcher, 1991).

Adopting new technology in Iron and Steel, is challenging as the plants are large and the technical risk substantial. The Iron and steelmaking industry in Australia has a history of trial and error with new processing technologies. Rio Tinto invested over $400 million over several years in the development of the HISmelt technology, which is a direct smelting process for making iron straight from the ore. Fine iron ores and non-coking coals are injected directly into a molten iron bath contained within a smelt reduction vessel (SRV), to produce high-quality molten pig iron. The excess gas produced during the process is used for power generation, production of direct reduced iron, or as fuel gas.

The process can be considered both as a potential replacement for the blast furnace and as a new source of low-cost iron for BOS or EAF steelmaking. The technology offers potential advantages such as lower operating costs; lower capital intensity, lower environmental impact, and greater raw material and operational flexibility (Institute for Industrial Productivity, 2019).

The technology is currently considered “technically acclaimed but financially unviable” (Klinger, 2011). Operation of the Kwinana, WA plant was suspended in 2008 and in 2011 it was announced that the plant would be closed. The plant was dismantled, and part of the equipment shipped to China (Mininglink, 2019).

Another innovative project that ultimately was discontinued was the BHP Billiton Hot Briquetted Iron plant in the Pilbara, discussed next.

7.3. Case studies

7.3.1. Hot Briquetted Iron plant, Port Hedland

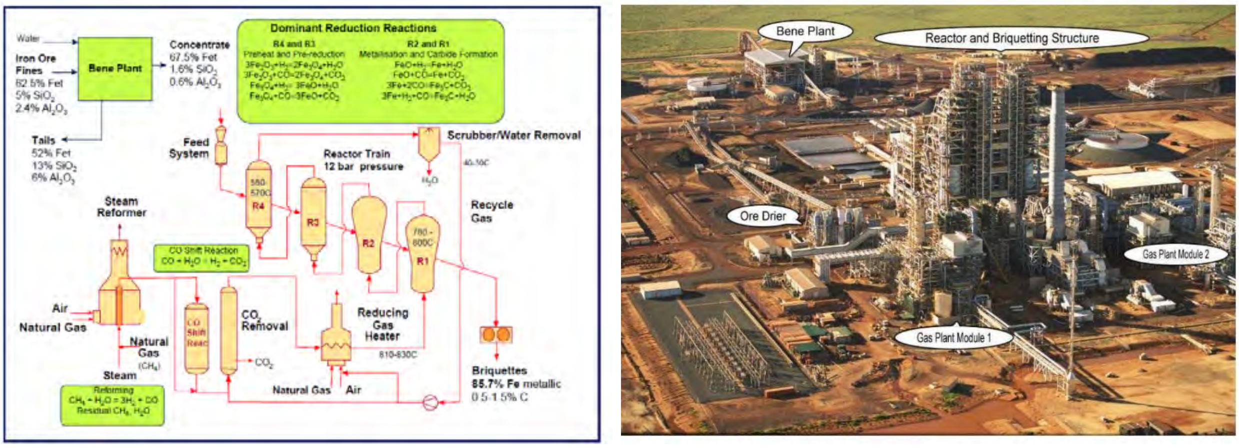


Figure 56: Left: Finmet process flow sheet of the Boodarie Iron plant; right: photograph of the plant (Brent et al., 1997).

In 1999, BHP-Billiton completed the construction of a Hot Briquetted Iron (HBI) production plant near Port Hedland, WA, (named Boodarie Iron). The plant operated until 2004, when a fatal gas explosion led to the decision to shut down the plant. In 2007, it was announced that the plant would be demolished. BHP-Billiton stated unmanageable risks to be the reason for the decision.

The facility produced HBI using the Finmet process, which is shown schematically in Figure 56. The Finmet process is a direct iron reduction process. Iron ore fines are reduced in a series of fluidised bed reactors operated at 800-1200°C, with syngas (CO, H_2) as the reducing agent. In the Boodarie Iron plant, the syngas was produced on site via steam reforming of natural gas.

The specific energy use of direct iron reduction (~3.6 MWh per tonne of crude steel) is significantly lower than that of the conventional blast furnace/basic oxygen furnace process route (~5 MWh per tonne). The process could be decarbonised by adapting it for substitution of renewable hydrogen (Philibert, 2017).

The hot fine iron is compressed into briquettes the size of a cake of soap with over 90% iron content and shipped overseas for use as a supplement for pig iron and scrap in electric arc furnace steel mills. HBI is a relatively new product, which may help replace pig iron from blast furnaces.

Finmet is one of several alternative direct reduced iron (DRI) processes, accounting for 2% of iron production from all DRI processes. Together, the DRI processes provide 4% of all iron input to steel making, while hot metal from blast furnaces constitutes 58% and scrap constitutes 38% (Lockwood Greene Technologies, 2000).

BHP-Billiton reported persistent commissioning difficulties, large cost overruns and significant operational issues, that led to a complete write-off of the plant value of $1.7 billion during the period from 1998 to 2000. After an explosion in 2004 in an area of the plant that had been shut down for scheduled maintenance, plant operation was suspended and in 2007 the plant was eventually demolished.

An independent team of experts investigated the incident, "*indicating that the accident was caused by a series of dust explosions, at least one of which was initiated and stimulated by hydrogen formed during the cleaning process*."

According to BHP, the decision to demolish the plant was based on the conclusion that the plant did not reach its financial and technical targets and that proposals for a conversion of the plant into other operations involved major capital investments.

Overall the experience with this project illustrates that advanced steel production systems can be built in Australia but that the technical and financial challenges should not be underestimated.

Summary	
Location	Port Hedland, WA
Temperature	800-1200°C
Energy resource	Natural gas
Technology	Direct reduced iron (Finmet): carbothermal reduction of iron ore with syngas (H_2, CO) obtained via steam methane reforming
Designed to deliver	2.3M tonnes p/year. of hot briquetted iron
Energy/emissions saved	Direct reduction of iron: 3.6 MWh / ~1.7 t of CO_2 emissions per tonne of crude steel (averages) (Philibert, 2017)
Construction	Commissioned in 1999, operational until 2004
Investment	~$1.7 billion

8. CEMENT AND LIME

8.1. Overview

The major energy and CO_2 intensive step in the production of concrete is the production of clinker in cement kilns (thermal energy demand ~3.4 GJ/t of clinker). Cement constitutes around 7 to 15% of concrete by weight, the rest being mostly gravel, sand and water (NRMCA, 2008).

Clinker is produced mainly from limestone (primarily calcium carbonate),mixed with a second silica-containing raw material. The mixture is heated up to around 1450°C, which results in the formation of calcium silicates, which is the main product and constituent of Portland cement. In this process, large amounts of CO_2 are released, mainly from the calcination of calcium carbonate.

In cement kilns, gas or coal is conventionally combusted with the clinker in the kiln to provide the required process heat, leading to additional CO_2 emissions. Globally, on average around ~0.53 tonnes of CO_2 are emitted per tonne of cement produced, with approximately half due to the combustion of fossil fuel to supply the process heat and the other half evolving from the calcination process itself. Part of the CO_2 released in the manufacturing of cement is re-absorbed during the use of the cement (NRMCA, 2008).

8.1.1. Site location and intensity of heat use

The sites for activity in the Cement and lime products sector with their indicative intensity of heat use are shown in Figure 57.

After a series of closures of older, less efficient cement kilns, Australia now has only five integrated cement mills, producing both clinker and cement. These are located at Gladstone, QLD, Berrima, NSW, Railton, TAS and Birkenhead and Angaston, SA. All except the Birkenhead plant are located outside major metropolitan areas. The Gladstone, Berrima and Railton plants use coal to supply heat, while the Birkenhead and Angaston plants use natural gas. In the Birkenhead plant, natural gas has partially been displaced with process engineered fuels from waste (see case study below). A similar partial conversion is underway at the Berrima plant.

Over recent years the energy efficiency of Australian cement kilns has increased significantly due to the closure of the older kilns using less efficient manufacturing processes. Converting limestone to lime requires much lower temperatures than the manufacture of cement. Public data on the location of operating Australian lime kilns is limited, but most are in rural areas with good access to limestone quarries. It is assumed that most lime kilns use natural gas, while some use other fuels such as LPG. It is not known whether any use coal. Total consumption of thermal fuels by the sector in 2016-17 was 45 PJ.

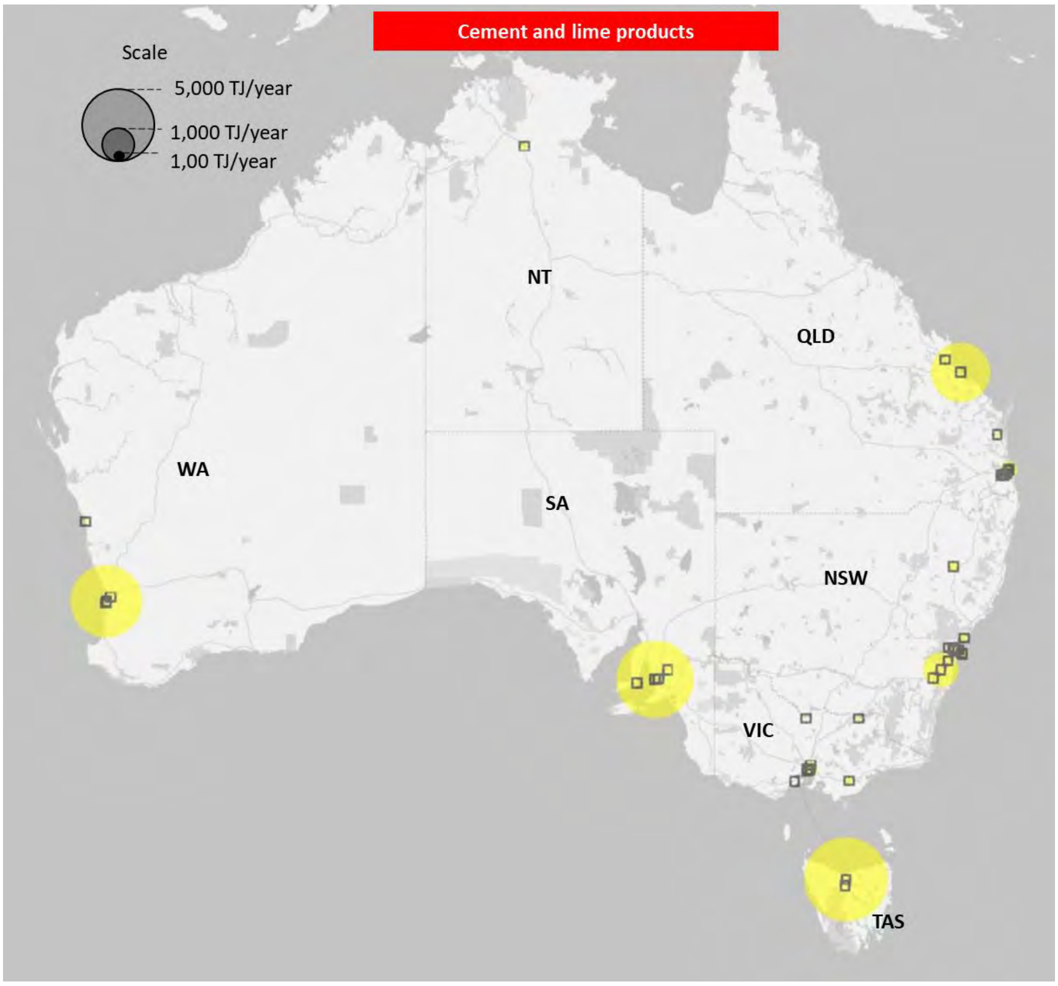


Figure 57: Location and volume of heat use for cement and lime products.

According to data published by the Cement Industry Federation, production of clinker has decreased from about 7.1 million tonnes in 2008-09 to about 5.6 million tonnes in 2016-17. Over the same period fuel use per tonne of cement has decreased by about 20%. The available data suggest that this result has been achieved by a combination of enhanced energy efficiency in clinker production, greater use of extenders mixed with clinker to make cement, and increased imports of clinker from negligible levels in 2008-09 to about one million tonnes in 2016-17.

A large cement kiln at Kwinana in WA has closed and now operates as a clinker grinding plant.

8.1.2. Processes that use heat

Production of cement consists of two main process stages. The first stage is production of cement clinker in cement kilns, which is where almost all thermal energy consumption occurs. The second stage is grinding clinker to cement, which uses mainly electricity.

There are several sequential processes and reactions involved in the production of clinker. A major heat input is required for the calcination of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$; reaction enthalpy ~1.8 GJ/t), which occurs at around 850 to 1000°C.

8.1.3. Existing heat supply

The cement and lime products sector used an estimated total of 35 PJ/year of heat in 2016-17. The breakdown of contributions of the various sources for this heat is shown in Figure 58. This total is an estimate of the heat use based on an average conversion efficiency of 80% applied to the fuels applied to heat production.

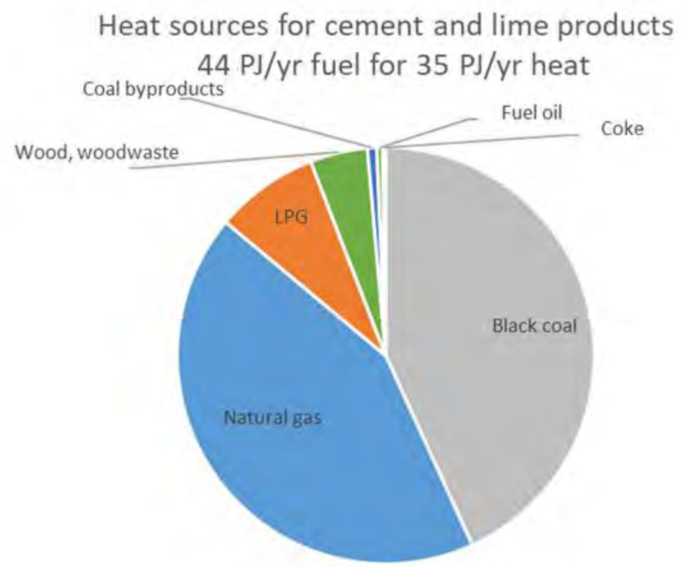


Figure 58: Existing sources of heat in the cement and lime products sector.

Prices are assumed to be low for coal and gas for these large users, around $4/GJ and $10/GJ respectively.

8.2. Renewable Energy options

8.2.1. Bioenergy

Biofuels and waste materials (such as process engineered fuel; see case study below) are viable alternative fuels that already contribute 5% to the cement industry's energy demand, with the remainder provided by coal, electricity, oil and gas.

Cement and lime kilns are particularly suited to using mixed wastes as a consequence of their high temperatures and the nature of the process in which all the ash and impurities (included for example traces of iron) end up as part of the product. This has the added benefit of absorbing elements that are difficult to be disposed of, such as chlorine (Nathan et al., 2019).

It seems clear that this is the obvious route for growth of renewable energy use in the sector. Waste materials are used at several cement kilns today, indicating that they are cost competitive with gas and even coal.

Hence, renewable fuels, including upgraded and recycled waste materials and biofuels, appear to be the most viable renewable energy option.

8.2.2. Electrical

Electric furnaces are capable of providing process heat at the temperatures required for cement production but are not currently available at the required scale. Vattenfall and Cementa are aiming to develop electrified cement production by 2030 within project CemZero (Philibert, 2017).

Australian company Calix is currently developing an electric version of its direct separation Reactor, a flash calciner capable of processing limestone, clay and other minerals (Lord, 2018). Calix is exploring how, by electrifying this step, they can facilitate the capture and storage of carbon dioxide from the calcination of limestone (Edwards, 2017).

The rotary kiln stage of cement production requires higher temperatures of 1450°C. This is technically possible to achieve using electrical resistance heating, but it would be a major challenge to match the capability of a gas-fired rotary kiln to process many tonnes of cement per hour. A more promising possibility for the electrification of rotary kilns is a plasma arc furnace, which can generate temperatures higher than 5000°C. This approach is the subject of an on-going Swedish collaboration between cement-maker Cementa and power company Vattenfall, the aim of which is to electrify cement production.

Molten carbonate synthesis is another potential electric route to cement manufacturing, which is currently under R&D (Chery et al., 2015).

However, given the low costs of other fuels accessed by cement and lime, electricity would have to be as cheap as 2c/kWh to be worth considering. It may be that hybrid kilns could be constructed that take very cheap electricity at times when wind or PV generation exceeded demand, with fuel use applied at other times. However, the high temperatures and thermal inertia of kilns would not be suitable to intermittent operation.

8.2.3. Geopolymer cement

A major issue in discussing the cement and lime product sector is that irrespective of the source of heat used, the reduction of calcium carbonate inherently produces a very large amount of CO_2. Other than a carbon capture and storage solution, the only way to avoid this is to adopt alternative products to replace traditional lime-based cements.

Geopolymer cement is an alternative cement that has been used successfully in Australia and overseas in a wide range of applications including major infrastructure and multi-storey buildings (Lord, 2017).

Geopolymer cement is not limestone-based and is not made in a cement kiln. In fact the principal reactions involved in its manufacture take place at room temperature, thus avoiding the need for heat altogether. (Though precast geopolymer concrete is sometimes cured with the aid of low-temperature steam.)

The manufacture of geopolymer cements results in far lower emissions than ordinary cement. Most of its embodied emissions are associated with a key ingredient – an alkaline solution known as the alkali activator. This alkaline solution tends to be a high-emissions product due to the large amount of electricity required to drive its production through the electrolytic chlor-alkali process. However, most of these emissions could be eliminated simply by using renewable electricity to power the electrolysis.

8.2.4. Solar thermal

Calcination of limestone with concentrated solar thermal energy has been demonstrated at the 10 kW scale at PSI in Switzerland (Meier et al., 2006), and is currently developed further at the pilot scale (Project SOLPART) at the PROMES/CNRS solar furnace research centre in Odeillo, France and other solar research centres. The high temperatures required in cement production require high-concentration solar thermal collectors, either solar tower or parabolic dish concentrators. The temperature of calcination (~850°C) is amenable for CST, while the sintering temperature (1,450°C) could only be reached efficiently on a solar dish with current technology.

As costs of solar thermal energy increase with increasing temperature (see Appendix F), this technology is not yet cost competitive with fossil fuels and unlikely to be a preferred path.

8.2.5. Renewable gas

Any renewable gas, either from biomass or solar hydrogen could be substituted for natural gas consumption. However, this would be a long way from being cost competitive and such gases would be of greater value if applied as chemical feedstocks or in other sectors.

8.2.6. Process changes and carbon capture

Cement manufacturing has already achieved large reductions in CO_2 emissions, from around 1 tonne of CO_2 per tonne of cement a number of years ago to around 0.5 tonne

Besides the use of low-carbon fuels and renewable energy, further CO_2 emissions reductions can be achieved by increased incorporation of fly-ash from coal power stations into cement manufacturing, which does not require the energy-intensive calcination process (Nathan et al., 2019).

Carbon capture and storage is another path to curb CO_2 emissions. This can be achieved through oxy-combustion, which also has efficiency benefits. This may offer an opportunity to utilise oxygen from renewable hydrogen production to avoid the need for air separation. Negative CO_2 emissions would be achieved if CO_2 emissions from cement manufacturing are eliminated altogether, while CO_2 is absorbed by the concrete through carbonation during its use. Alternatively, the captured CO_2 may be utilised for synthetic fuel production or enhanced gas recovery (Nathan et al., 2019).

8.3. Case studies

8.3.1. Alternative fuel in cement manufacturing

Figure 59: Construction and demolition timber processing and supply to the Birkenhead cement plant, (images Adelaide Brighton).

Adelaide Brighton's Birkenhead, SA gas-fired cement kiln has the capacity to produce 1.3 million tonnes of cement product per year. In 2003, the kiln commenced using more than 70,000 tonnes of recycled construction and demolition timber per year as a supplement to natural gas. The receival, storage and feed systems were upgraded in 2005.

To deliver the recycled timber, a designated processing plant was built in the vicinity of the cement plant. The plant was built by SITA-ResourceCo and is capable of converting up to 350,000 tonnes of raw material into 150,000 to 200,000 tonnes of alternative fuel each year.

Summary

Location	Birkenhead, SA
Application of process heat	Cement production
Temperature	up to ~1,450°C
Energy resource	Process engineered fuel (recycled construction and demolition timber)
Technology	Co-firing of cement kiln with recycled wood
Designed to deliver	~1.2M GJ (HHV)
Energy/emissions saved	20% reduction in natural gas consumption
Construction	Implemented in 2003
Other aspects	Waste recovery plant built near cement kiln to minimize transport costs

8.3.2. Waste to process engineered fuels production facility

Figure 60. Waste treatment facility (left) and process engineered fuel product (right).(images ITP)

In 2018, Cleanaway ResourceCo opened a new waste recovery plant in Wetherill Park, NSW. The plant diverts waste from landfills and provides a fuel intended to displace coal usage at the Boral cement plant in Berrima, NSW as well as for other industrial customers. ResoureCo received debt financing from the Clean Energy Finance Corporation and a grant from the NSW Environmental Trust for construction of the plant.

The facility is designed to process residues from recycling, commercial & industrial waste and small amounts of construction & demolition into process engineered fuel. This typically includes non-recyclable plastics, cardboard, paper and textiles as well as certain difficult-to-recycle waste timber materials.

All incoming materials are sorted, separated and shredded. Non-combustibles, such as metals and aggregates, are recovered for re-use. Plastics are then separated by hoppers, and two fuel streams are created, one with a high plastic content with a higher calorific value and high combustion temperature, which is sent to cement kilns, and a stream with high timber content, suitable for bioenergy boilers.

The plant employs 50 full-time staff and processes ~250,000 tonne per year of waste materials over an expected lifetime of 20 years. It reuses over 90% of the waste, with the remainder disposed of in a landfill.

The fuel products have a density of 200-300 kg/m^3 uncompressed and ~800 kg/m^3 when compressed for shipping. The calorific value of the produced fuels is in the order of 17 GJ/tonne. Products are sold and shipped to cement kilns in Australia and southeast Asia as a substitute for coal. At the Boral, NSW cement kiln, it is expected that 100,000 tonnes of process engineered fuel from the Wetherill Park plant will replace 50,000 tonnes of coal each year.

The Cleanaway ResourceCo plant in Wetherill Park is the second plant of its kind in Australia. The first plant has been operational since 2003 in South Australia, providing fuel to the Adelaide Brighton Cement kiln in Birkenhead, SA (see case study above).

Summary	
Location	Wetherill Park, NSW
Application of process heat	Cement kilns
Temperature	up to 1,450°C
Energy resource	Residues from recycling, commercial and industrial waste, and small amounts of construction and demolition waste
Technology	Waste recovery plant, producing process engineered fuels and metals
Designed to deliver	~250,000 tonnes p/year
Energy/emissions saved	~200,000 to 400,000 t/year of CO_2 emissions saved
Construction	2018
Investment	Finance from CEFC
Simple payback	n/a
Other aspects	First of its kind in NSW Around 50 full-time jobs 20 years lifetime Fuel is more cost effective than coal High transport costs of fuel, hence most effective for nearby use

9. PULP AND PAPER

9.1. Overview

The Pulp and paper sector is highly capital intensive and concentrated in a few key regions. Five major companies operate 22 mills across Australia. These mills produce almost 65% of Australia's newsprint requirement, over 30 per cent of our printing and writing paper, over 95% of Australia's industrial packaging, and the majority of our tissue and sanitary paper needs. More than half of all fibre used in Australia to make paper now comes from recycled material, thus reducing overall energy use.

9.1.1. Site location and intensity of heat use

The sites for activity in the Pulp and paper sector with their indicative intensity of heat use are shown in Figure 61.

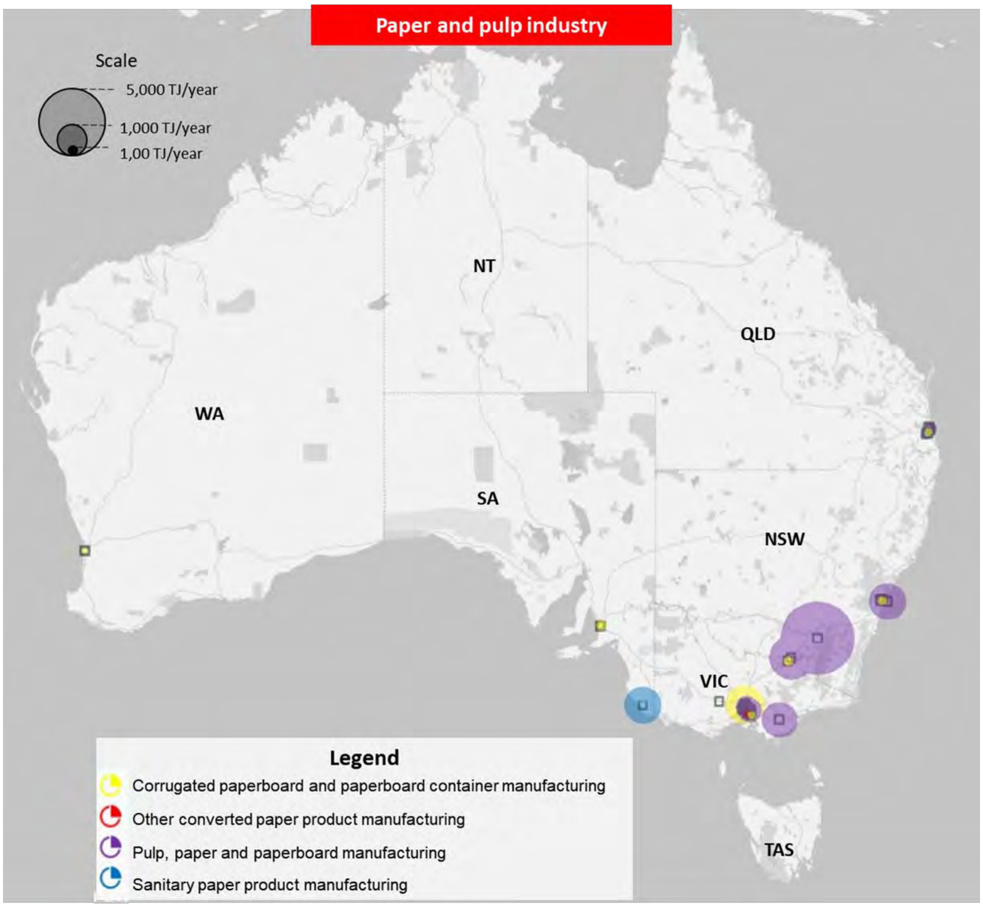


Figure 61: Location of paper and pulp manufacturing facilities and their heat use.

Australia now has only five mills that produce pulp from timber, located at Albury and Tumut in NSW, Maryvale (near Morwell) in VIC, Boyer (near New Norfolk) in TAS, and Millicent in SA. A sixth mill, at Tantanoola, in SA, was closed in 2011. It is probable that the decrease in consumption of gas (and other fuels) between 2010-11 and 2012-13 was in part due to the closure of this plant. All five of the remaining pulp and paper mills are located in rural areas. The industry sector also includes a number of plants, mostly located in or on the outskirts of major metropolitan areas, which make paper and cardboard products from pulp, which is a less energy intensive activity, though still requiring steam.

The large pulp plants have heat use in the range 1,000 – 5,000TJ/year, while the smaller paper products sites are in many cases less than 100TJ/year of consumption.

9.1.2. Processes that use heat

This sector is a large user of steam and hot water, and most use of gas and other fuels is for this purpose.

Figure 62 shows the power and heat generation for process use in a typical conventional integrated paper and pulp mill.

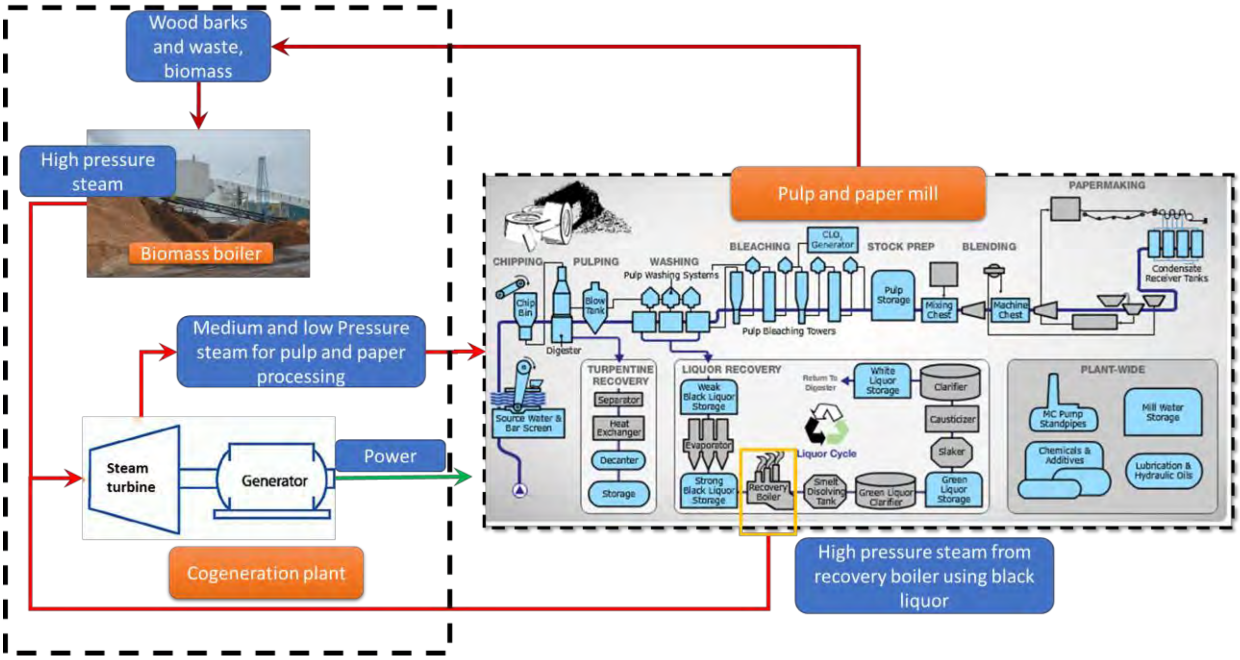


Figure 62: Power and Heat generation in an integrated pulp and paper mill[24].

The most energy intensive part of this industry is the production of pulp from timber, which is the source for all of biomass fuels used by the industry.

There are a range of processes for producing pulp for paper making, using various combinations of chemicals, heat and mechanical actions. Australia has a variety of pulping processes. Notably

[24] ITP schematic using Pulp and paper mill process diagram reproduced from Hai Quynh Co., Ltd. Biomass boiler image reproduced from Pulp and paper Canada.

the Kraft chemical pulping process is used in Maryvale and thermomechanical pulping is used in the Boyer and Albury plants. Black liquor is a by-product of the Kraft pulping process. Table 17 shows the energy use breakup of a typical modern Kraft paper mill.

Table 17: Steam and electricity use in a modern Kraft paper mill (Francis et al., 2002).

Process	Steam	Electricity
Energy use per air dried tonne of pulp	**GJ/t**	**kWh/t**
Chip conveying	-	20
Digester	1.7	40
Washing and screening	-	30
Oxygen delignification	0.5	75
Bleaching	2.3	100
Pulp machine	2.3	141
Black liquor evaporators	3.1	30
Power plant parasitics	2.3	60
Kiln and recausticising	-	50
Hot water supply from machine heat recovery	-	32
Waste-water treatment	-	30
Miscellaneous	-	30
Total Energy Consumed	**12.2**	**638**
Energy Generated via Recovery Boiler (CHP unit)	**15.8**	**655**

The drying stage consumes one third of the energy required to make virgin paper and 81% of the energy required to make recycled paper (Kinstrey & White, 2006). The conventional drying process relies on the production of steam at 120-125°C (Kinstrey & White, 2006).

The overall energy use for chemical pulp-based paper is around 42.5 GJ/t and for recycled paper it is around 13.5 GJ/t (Laurijssen, 2013). However, this can be offset by the share of energy that is produced internally from waste bioenergy streams.

Table 18 shows an overview of varying energy use in different processes in the paper and pulp industry.

Table 18. Overview of energy use and generation of different processes in the US pulp and paper industry (Laurijssen, 2013).

Process	Energy use			Energy generation	
	Electricity	Steam	Fuel	Electricity	Steam
Energy use per air dried tonne of pulp	**kWh/t**	**GJ/t**	**GJ/t**	**kWh/t**	**GJ/t**
Cutting & chipping	15	-	0.173	-	-
Mechanical pulping	2,200	-	-	-	5.4 (a)
Chemical pulping	700	22.2 (c)	-	1,580	22.2 (b)
Recycled pulping	85- 500	0.02- 0.6	-	-	-
Paper making(f)	180-550	4.5- 5.5	-	-	-
Production of additives	192	1.05	-	-	-

a - It is assumed that 3.1 GJ is available as excess heat from the pulping process and 2.3 GJ from the burning of bark.
b - It is assumed that 18 GJ is available from black liquor and 4.2 GJ from bark burning.
c - Conversion efficiency of 24 & 34%, Based on energy content wood (18 GJ/t).

9.1.3. Existing heat supply

The pulp and paper sector used an estimated total of 21 PJ/year of process heat in 2016-17. The breakdown of contributions of the various sources for this heat is shown in Figure 58. This total is an estimate of the heat use based on an average conversion efficiency of 80% applied to the fuels use for heat production.

The data show that over the period 2009 to 2017, there has been a modest decrease in natural gas consumption. The complete data also show a modest decline in the use of other thermal energy fuels.

The pulp and paper sector includes businesses that range from small energy consumers up to reasonably large. At the larger end gas prices would be expected to be around $10 to $15/GJ and electricity around $120/MWh ($33/GJ). Those sites choosing to use coal as a heat source are presumably sufficiently large and able to access cost effective supplies such that prices around $5/GJ may prevail. At the smallest sizes, energy costs will be close to domestic supply prices, with gas at around $30/GJ and electricity around $300/MWh ($83/GJ).

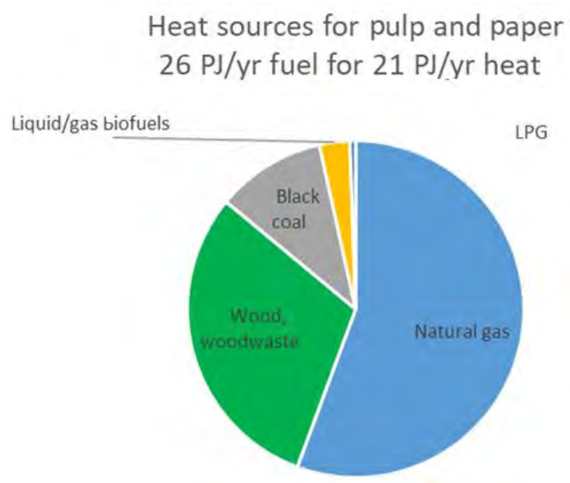


Figure 63: Existing sources of heat in the pulp and paper sector.

9.2. Renewable energy options

This sector has made substantial use of its own wood-waste for process heat, however, the extent to which coal and gas are also used is an indication that there is insufficient easily accessible wood-waste for all heat demands. This suggests the need to look at alternative renewable sources for the easier low temperature applications and reserving the biomass material for higher-temperature process heat. Solar thermal, geothermal, and heat pumps can all be considered for lower-temperature heat.

9.2.1. Bioenergy

The use of bioenergy for process heat and CHP is well established in both the pulp and paper and forest products industries in Australia, as shown in Table 19.

Table 19: Operating plant details; pulp and paper and forest products.

Project name	Location	Technology	Feedstock	Capacity
Visy Paper	Tumut, NSW	Cogen	Black liquor	20 MW_e
Visy Paper	Brisbane, QLD	Cogen	Black liquor	2 MW_e
Visy Paper	Campbellfield, VIC	Cogen	Wood waste	3 MW_e
Visy Paper	Maryvale, VIC	Cogen	Black liquor	54 MW_e

There is still considerable potential for additional heat provision from forest residues, which could provide a similar scale of energy resource as provided by bagasse. Pulp and paper wastes are probably closer to their long-term potential, with only a 40% increase projected for the potential energy supply from these wastes at 2050 (Geoscience Australia, 2014).

9.2.2. Solar thermal

Solar thermal can be substituted cost-effectively for all low-temperature tasks, such as preheating boiler feed water. It could also supplement high and medium-pressure steam for the CHP turbine during the day. This could reduce the demand for bioenergy and limit its use for periods with a lack of available solar energy.

Solar collectors to generate heat at low to medium temperatures (up to 150°C) include flat plate collectors and evacuated tube collectors with or without mirrors (Table 7). These technologies are commercially mature and are used worldwide for water heating at an installed capacity of around 500 GW_{th} (Weiss & Spörk-Dür, 2018). Evacuated tube collectors dominate the market with over 70% share.

Hot water storage is the least expensive method for storing heat at up to 180°C. Below 100°C, the tank doesn't need pressurisation which makes this technology particularly inexpensive.

The relatively low energy demand at the smaller facilities, combined with remote locations and the need for low-to medium-temperature heat may favour the use of solar thermal to complement bioenergy and eliminate natural gas from the energy mix.

9.2.3. Electrical

Heat pumps

Paper drying is a particularly promising application for heat pumps due to the relatively low temperature uplift required, as paper drying systems expel waste, and humid air at 100°C. A heat pump, such as Viking's HeatBooster, could reheat this air to 125°C with a coefficient of performance (COP) of around 4.5.

At least one real-world example exists of heat pumps being used in this way. At Smurfit Kappa's paper factory in the Netherlands, a heat pump upgrades waste heat from paper drying, reusing it at different steps in the production process and achieving a COP of 4.

Infrared

Infrared heating is an alternative way of drying paper. Electric infrared is widely used for drying coated paper. It would be reasonably straightforward to retrofit an existing conventional steam dryer with electric infrared emitters, using the two heat sources in combination to dry paper. This type of hybrid drying system has several advantages:

- It could enable some paper mills to produce all their steam using thermal energy recovered from the pulping process, reducing or eliminating the need for supplementary natural gas.
- Infrared is particularly useful towards the end of the drying section because the efficiency of evaporation declines as the paper dries.
- Adding infrared to an existing steam-drying system can increase productivity by 10-15%.

9.2.4. Geothermal

Geothermal heat in Australia is limited to temperatures below 95°C from hot sedimentary aquifers. Pulp and paper plants could make use of heat at such a temperature. However the location of current plants suggests the likelihood of being located on a suitable aquifer is low. Nonetheless it could be worth investigation.

9.2.5. Process changes

Where large drying processes are involved at relatively low temperatures, mechanical dewatering solutions could be considered as a lower-energy alternative.

9.3. Case studies

9.3.1. Heat and power from black liquor for paper manufacturing

Figure 64: Australian Paper's Maryvale plant. (image from sprinter.com.au.)

The Australian Paper plant in Maryvale is the largest integrated pulp and fine paper manufacturing site in Australia, producing over 600,000 tonnes of paper per year. In addition, the plant is also Victoria's biggest generator of renewable baseload energy with black liquor biofuel created as a by-product of the Kraft pulp and paper manufacturing process.

Black liquor is fed into two boilers to produce high pressure steam for cogeneration using a steam turbine. This system produces ~240 GWh_e/year of electricity and ~1800 GWh_{th}/year of thermal energy for their processes. The renewable energy system is complemented with purchases of ~6 PJ of natural gas and 30 MW_e of electricity from the grid.

The Maryvale bioenergy plant contributes to the operation's carbon neutral certification. The bioenergy project offsets approximately 50% of the energy requirements for onsite production, which is approximately 18 PJ per year.

A challenge in this project is to maintain certification under the National Carbon Offset Standard (NCOS), which is a resource-intensive process (data and robust analysis).

Summary

Location	Maryvale, VIC
Application of process heat	Combined power and steam generation
Temperature	~125°C steam from turbine exhaust
Energy resource	Black liquor (by-product from wood pulping)
Technology	54.5 MW_e / ~400 MW_{th} bioenergy (black liquor)-fuelled CHP plant
Designed to deliver	~240 GWh_e/year, ~1800 GWh_{th}/year

9.3.2. Waste to energy plant in paper manufacturing

Figure 65. Visy's waste to energy plant in Coolaroo, VIC. (Reproduced from protechwelding.com.au.)

Visy's waste to energy plant is located at their Coolaroo facility in Campbellfield in the northern outskirts of Melbourne. The project is the first of its kind in Australia and faced many of the normal hurdles for unusual projects but had the advantage that there are multiple facilities like this overseas. However, overseas facilities are not without their problems and each one has unique aspects of its technology and integration with the waste chain, so that the lessons learnt there may not always translate to another site. That meant the designs could not simply be duplicated in Australia.

The project was commissioned in 2011. The combined heat and power (CHP) plant generates electricity and process heat from the combustion of unrecyclable paper and plastic waste. There is a 30 MW_{th} fluidised bed boiler that raises steam to 64 bar and 460°C. This steam then goes through a let-down phase by passing through a 1.5 MW_e steam turbine. The steam exits the turbine at 3 bar and 200°C, which is the required temperature for use as process heat in the plant.

The project cost approximately $50 million and received $2 million in grant funding from Sustainability Victoria, and generated a lower return on investment than normal for Visy. The primary economic drivers for the project were (in order of significance):

- Reducing landfill charges - reduction in landfill volumes and their corresponding charges and this extending to the mass of water contained in the feedstock which is up to 50% contribution to waste dumping costs.
- Reducing natural gas use - provision of steam for process, replacing packaged gas fired boilers.
- Reducing electricity use - electricity is only 5% of the load and was not the driver of this project.

Technical challenges for this project involved removing metals and PVC from the waste stream. Metals can foul the sorting and handling machinery, particularly the feed to boilers. PVC would release chlorine upon combustion leading to undesirable environmental outcomes.

The project was the subject of detailed preliminary work. It was eventually brought together as an in-house construction with only one component, the major thermal equipment (boiler and feed) as a turnkey item. This meant there was significant technical risk even though all other pieces of equipment for the project were developed from conventional parts. They were brought together on a ‘for project’ basis and this introduced bespoke design risks. These risks were mitigated by bringing in someone with previous overseas experience.

Summary

Location	Campbellfield, VIC
Application of process heat	Heat (steam) and power for paper production
Temperature	200°C
Energy resource	Unrecyclable paper and plastic waste
Technology	CHP with 30 MW_{th} fluidised bed boiler and 1.5 MW_e steam turbine
Designed to deliver	Power: 1.5 MW_e, remainder heat (steam)
Energy/emissions saved	up to ~13 GWh_e/year electricity / ~200 GWh_{th}/year heat
Construction	Commissioned in 2011
Investment	$50 million ($2 million grant from Sustainability Victoria)
Other aspects	Project was motivated by a combination of factors, including energy cost savings as well as reductions in landfill charges and natural gas and electricity usage

10. OIL, GAS AND PETROLEUM

10.1. Overview

Oil and gas extraction and petroleum refining are analysed as separate sectors in Figure 4.Both are indicated as substantial users of process heat. Here they are discussed together as they have key common features.

In both cases, these are industries that process a huge amount of a fuel, which is then either exported or used in the transport or power generation sectors. Thus, their heat use, despite being large in absolute terms, is a modest fraction of the total amount of energy they process.

Following on from this, they have access at lowest cost to their respective inflow unprocessed fuels. Their processes also generate streams of waste products that can be employed to provide the process heat they need. Thus, in the context of a discussion of the potential for renewables providing process heat, there is technical potential and it may be possible that situations will arise where the economics for some renewable use can be favourable. However, the bigger picture question is how might these sectors transform in total and move towards a zero emissions world.

The main activity under petroleum products is petroleum refining, but this group also includes the production of chemicals derived from coal, commonly as a by-product of coke manufacture. These industries are in long-term decline in Australia: for example, over the past 15 years the number of oil refineries has been reduced from eight to four; one in Perth (Kwinana), one in Melbourne (Altona), one in Geelong and one in Brisbane.

10.1.1. Site location and intensity of heat use

The sites for activity in the oil gas and petroleum sectors with their indicative intensity of heat use are shown in Figure 66.

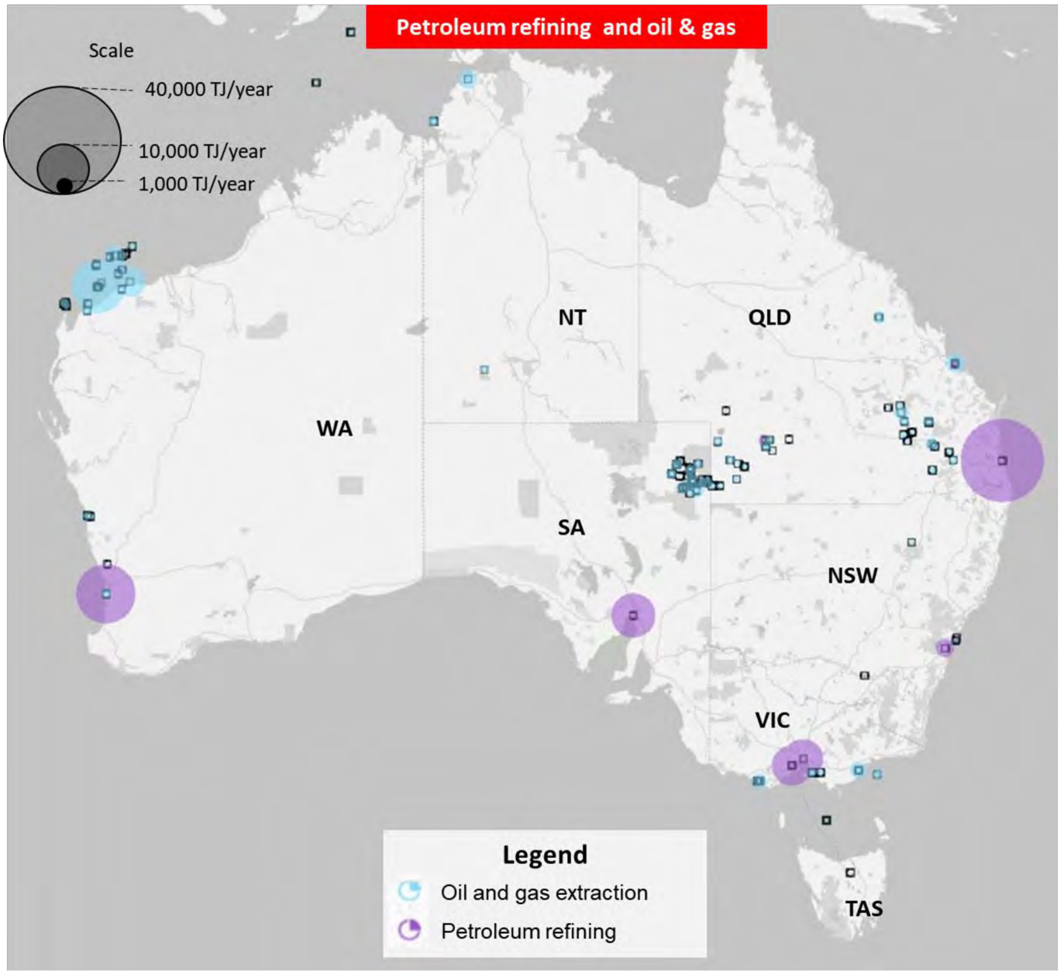


Figure 66: Location and volume of heat use for oil and gas and petroleum refining facilities.

10.1.2. Processes that use heat

Petroleum refining and other petroleum and coal products

Natural gas is used as a supplementary fuel in some, but not all, of Australia's four remaining oil refineries (Kwinana, Geelong, Altona and Lytton (in Brisbane)). The decreasing consumption of gas is related to the closure of three other refineries in Sydney and Brisbane between 2013 and 2015. Refineries mostly use heat at medium temperatures for crude oil distillation, thermal cracking of heavy hydrocarbons and similar types of operation. Use of gas means that more of the hydrocarbons derived from the crude oil can be converted to higher-value petroleum products. Refineries are very large and very closely integrated production facilities.

Oil and gas

In the oil and gas sector, most of the activity is related to gas production and processing. A large amount of gas is consumed in gas turbines at production facilities that directly drive compressors for pipeline transport. Also counted in this sector are the LNG production facilities. In these, gas is consumed in gas turbines to drive the compressors of the various refrigeration stages.

At onshore gas fields (including coal seam gas fields), most of which are in QLD and SA, energy requirements are almost entirely to drive compressors and pumps. Historically, gas engines have been used to provide this energy, but in recent years there has been a decisive move to electric motors, supplied either from the grid, in the QLD coal seam gas fields (with a consequent large increase in consumption of coal fired electricity), or PV, in the remote conventional gas fields of SA and south west QLD.

At offshore production platforms, which are the source of almost all the conventional gas produced in VIC, WA and the NT, larger quantities of gas are consumed in gas turbines to power compressors. These are used in both processes to separate out some of the various hydrocarbons in the raw gas stream and transport the gas through subsea pipelines to onshore processing facilities (mainly LNG plants).

The actual heat use in this sector comes from two different activities. One activity is the removal of CO_2 to the levels needed to meet the (different) specifications for either pipeline quality domestic gas or LNG. The conventional gas fields have varying levels of CO_2 content, e.g. Gorgon and Moomba have notably high levels. This must be removed to give a gas composition that meets pipeline specifications. At the LNG facilities, the feed to liquification must have close to zero CO_2 content to avoid it freezing within the process. CO_2 scrubbing is achieved by amine absorption or other processes. The scrubbing material is regenerated by heating to around 120^{o}C to drive off the CO_2.

The other activity is separation of the various components of the associated liquid hydrocarbons (LPG, condensate).

Depending on the configuration of the plant, heat may be provided bywaste heat from the compressors combustion of some of the gas, or both. Although gas plants vary greatly in the volume of CO_2 stripped and vented, combustion emissions per production are very similar in all plants. To the extent that there are differences between plants, these appear not to be in any way correlated with the volume of CO_2 stripped. This implies that the gas turbine waste heat is used to regenerate the organic solvent used to strip CO_2, which has no useful function in plants processing raw gas with very low CO_2 content has no useful function. It follows that this industry would not be a very attractive candidate for renewable heat on a simple substitution basis. On the other hand if electrical drives are adopted for compressors and plant, and these are powered using renewable electricityto improve environmental outcomes, then seeking renewable methods for providing the process heat would also make sense.

10.1.3. Role for renewables

Whilst there may be niche roles for renewables to provide process heat in petroleum refining, this is secondary to society transitioning away from these fuels, as will be needed to reach longer term emissions targets. Use of the fuels is, after all, the primary source of emissions, rather than their refining. The trend is also towards Australia increasingly importing refined fuels rather than crude oil. Refineries in Adelaide and Sydney have closed in previous years.

Renewable ethanol already plays a role in automotive fuel as does biodiesel. The potential for 'drop-in' renewable fuels has received considerable attention, but is outside the scope of this study. Electrification of transport through battery electric vehicles has a major potential to substitute renewable electricity in the place of fossil petroleum. Hydrogen for fuel cell electric vehicles also clearly has a role to play. There can be a conversion of these developments also through advanced catalytic fuel synthesis via the Fischer Tropsch gas to liquids process or methanol synthesis.

In gas processing, the thermal loads for regeneration of CO_2 scrubbing systems would be technically very suitable for the application of solar thermal systems for example. However as noted it is apparent that there is already waste heat available that can be applied to these processes and there would be no benefit in applying renewable energy. If however compressor systems currently driven by gas turbine direct drives were converted to an electric drive, then it would become logical to look at renewable sources for the heat load.

10.1.4. Innovative processes

The traditional process for removal of carbon dioxide from natural gas streams is via an amine absorption process where the amines are recycled for use with the introduction of large quantities of heat.

Low-energy alternatives are available for this process across the world, and one of them is the use of membrane separation. The gas stream is passed over membranes of specific qualities (mostly pore size) that allow one component to pass through while retaining the other. The separation usually requires high pressure. Membrane technology in a number of areas (not just CO_2 removal) has developed rapidly in the past 30 years and commercial systems are in place across the world. Use of membranes will require power consumption to maintain the pressure difference across the membrane.

Using microwave rather than other heating to regenerate amines is another approach still in the experimental phase.

11. OTHER SECTORS

11.1. Overview

The sites for activity in the remaining other sectors with their indicative intensity of heat use are shown in Figure 67.

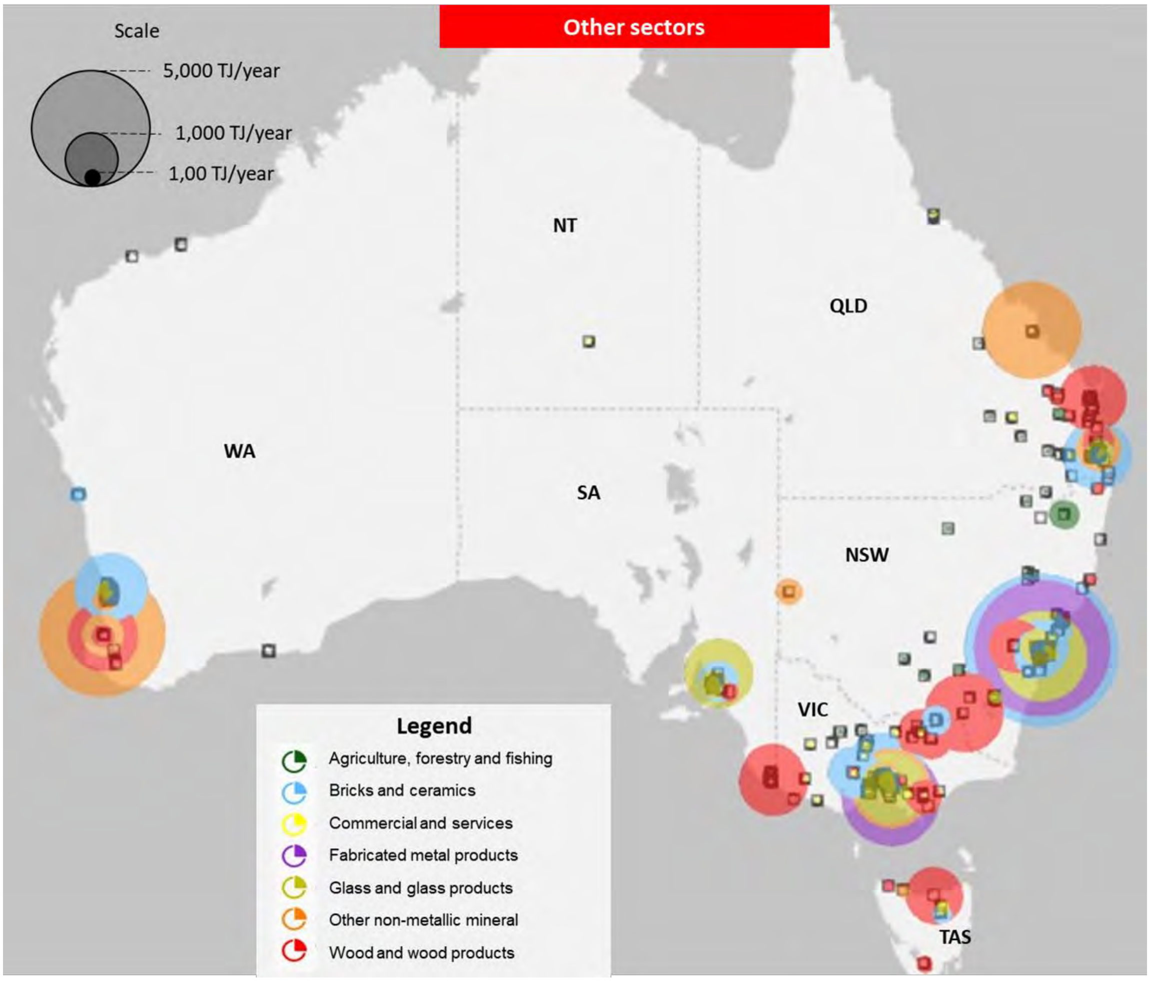


Figure 67: Location and volume of heat use for other sectors not covered in previous chapters.

The remaining sectors include businesses that range from small energy consumers up to a few that are reasonably large. Natural gas dominates as the source of heat. At the smallest sizes, energy costs will be close to domestic supply prices, with gas at around $30/GJ, even higher costs for those needing LPG supply, and electricity around $300/MWh ($83/GJ). At the larger end gas prices would be expected to be around $10 to $15/GJ and electricity around $120/MWh

($33/GJ). Those sites choosing to use coal as a heat source are presumably sufficiently large and able to access cost effective supplies such that prices around $5/GJ may prevail.

11.2. Key subsectors

11.2.1. Ceramics, glass, other non-metallic mineral products

These subsectors use natural gas almost exclusively as their preferred fuel source for the high temperature thermal processes that they use. The advantages of gas are that it burns cleanly and can be easily controlled, allowing a high level of process control, and making it easier to deliver consistent, high-quality products. In each of these industries, consumption of gas and other combustion fuels has fallen quite dramatically since 2010. We are unable to locate any public data on total production volumes of any of these products, making it difficult to determine whether reduced energy consumption is attributable to a structural decline in output, increased energy use efficiency, other factors, or a mix of these factors.

Structural decline in output could be caused by changes in building methods, technologies and materials. It is important to understand the factors at work, because an industry in structural decline is unlikely to be interested in shifting to new manufacturing methods, such as the use of renewable heat.

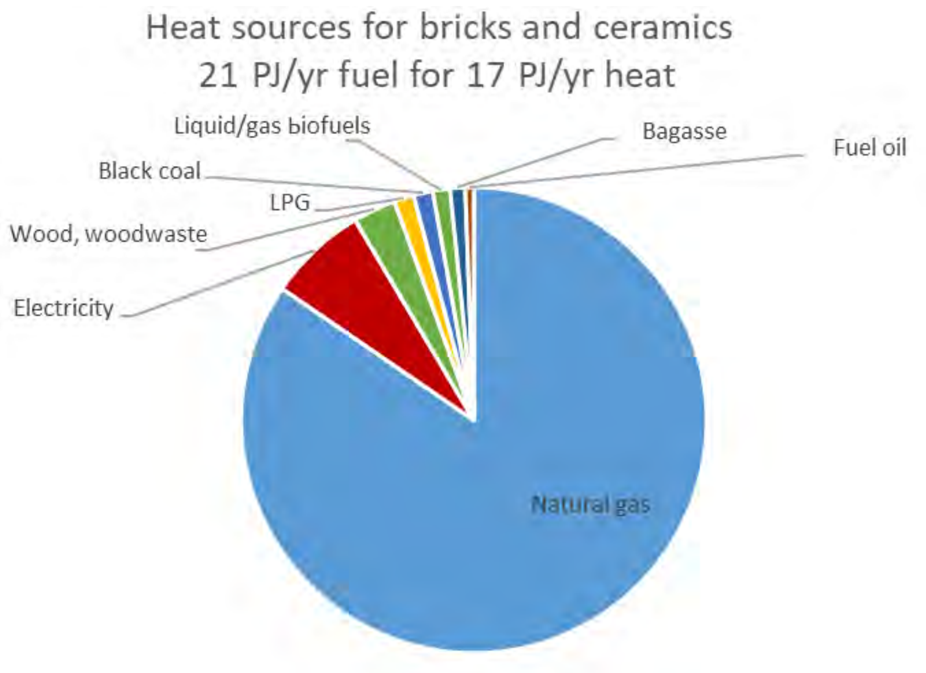


Figure 68: Existing sources of heat in the bricks and ceramics sector.

More than 75% of the energy consumed in brickmaking is thermal energy for the firing process (Carbon Trust, 2008). Brick firing often occurs in long tunnel kilns through which bricks are moved steadily over 40 to 70 hours. The bricks are heated to a maximum temperature of 1040°C but both heating and cooling must occur slowly to avoid damaging the bricks (Lord, 2018).

There are already several brick manufacturing plant that fuel their kilns with bioenergy (see Table 20). In addition to replacement of gas fuel in the kiln, energy use can be reduced by replacement of a proportion of brick material (clay) by biosolids. This has a significant effect on the energy used during firing due to self-combustion of the organic materials. The biosolids may include a wide range of materials, from sewage sludge to sawdust (Muñoz Velasco et al., 2014). Research at RMIT in Melbourne found there was between 12% and 50% reduction in external energy use at 25% biosolids concentration, depending on the specific composition of the biosolids (Bartolo et al., 2019). There are other benefits, primarily reduction in the need for clay excavation (with associated energy savings), and disposal of biosolids. Two of the brick plants in Table 20 include biosolids in bricks as a way of reducing their energy use and environmental footprints.

Table 20 Australian brick manufacturing plants with bioenergy fired kilns

Project name	Location	Technology	Feedstock	Energy output (GJ/year)	Cost
Austral Bricks	Horsley Park, NSW	Heat only (brick kiln)	Landfill gas	240,000	Plant 1: $1.1 million Plant 3: $5.3 million
Austral Bricks	Rochedale, QLD	Heat only (brick kiln) Incorporation of biosolids into brick mixture (1)	Sawdust and timber products waste	5000	$7.7 million (2)
Austral Bricks	Longford, TAS	Heat only (brick kiln)	Sawdust	130,000	N/A(3)
Brikmakers	Guildford, WA	Incorporation of grain dust as biosolids in bricks	Grain dust	n/a	n/a

(1) Replacement of setting machine allowed a reduction in energy consumption and incorporation of biosolids (sawdust) into brick material.
(2) This includes other energy efficiency upgrades.
(3) The kiln has been fired with sawdust for many years, however a recent program of energy efficiency allowed operations to be fired almost exclusively by biomass. This enabled Austral Bricks to be certified carbon neutral by purchase of carbon credits for the remaining emissions.

Brick – microwave assistance

Several pilot studies have shown that the time and energy required to fire bricks can be reduced by using microwaves to supplement conventional kiln firing.

In a microwave-assisted kiln the bricks are heated simultaneously from the outside by conventional heating, and from the inside by microwave heating. This means the bricks can be heated rapidly and evenly, ensuring no damage occurs. Faster firing means less heat is wasted and energy efficiency is increased.

In one UK study a conventional gas-fired tunnel kiln was fitted with two 60 kW microwave emitters. It was found that this tunnel kiln, with microwaves supplying just 10% of the total firing energy, reduced energy consumption by 50%. The microwave assistance also reduced the firing time from 46 hours to 16.75 hours – an increase in production speed of 174% (UK Government, 1999).

Microwaves could be retrofitted to most existing brick kilns, and the technique could also be applied to almost any kiln-fired ceramic product, such as tiles and kitchenware.

Glass – electrical resistance

All stages of glass production could be electrified and indeed there is commercially-available equipment to enable this (Lord, 2018). The most energy-intensive step in glass making is melting the raw materials, which accounts for around 75% of the energy requirement. Globally, many modern gas-fired glass melting furnaces are fitted with electric boosting, which contributes 5-20% of the heat (Worrell et al., 2008).

All-electric glass melting furnaces are available and have been used in the glass industry since the 1920s. Today all-electric glass furnaces are mostly used to make special glass, such as glass for displays, tableware and cookware, and in the production of glass wool, but they could be used for any type of glass.

The biggest advantage of electric glass melters is their energy efficiency. By passing a current through the raw materials, they generate heat within the charge through electrical resistance. This results in lower heat losses, and the best electric glass furnaces can achieve an efficiency of 87%, which is a 37% improvement on an average conventional gas-fired furnace. Electric glass furnaces have several other advantages including higher-quality output, reduced capital cost, less maintenance and lower toxic emissions.

Several manufacturers offer large electric glass melters capable of melting over 100 tonnes of glass per day. However, one advantage of electric glass melters is that, unlike gas-fired furnaces, efficiency is not strongly related to larger capacity, making smaller, modular installations more viable.

11.2.2. Textiles, clothing and footwear

The main use of fuels for heat is in the textiles part of this sector, where both hot water and low-pressure steam are used in scouring and some types of dyeing operations. Most establishments involved in these sectors are relatively small, at least compared with steelworks, oil refineries and the like. These factors mean that renewable energy may be an attractive option to reduce dependence on gas for textile industry businesses.

Depending on their location and resource availability, all of the renewable options should be considered.

11.2.3. Commercial and services

The ‘commercial and services’ sector includes every ANZSIC category from F to Q. This covers wholesale, retail trade, communications, finance and insurance, property and business services, government administration and defence, education, health, community services, recreation, hospitality and other services. It also includes all schools and hospitals.

In this study we are not concerned with building heating, which is very significant in this sector. The process heat use that has been estimated is that associated with steam and hot water use in commercial laundries and hospitals.

Depending on their location and resource availability, all of the renewable options should be considered.

11.2.4. Wood and wood products

The sawn timber sector is the largest processor of wood in Australia. Almost 50%of wood is converted to sawn timber. This sector is the most geographically dispersed and accounts for over 20% of the industry's employment. There are around 1070 hardwood sawmills. Many are small, labour intensive and independently owned. By contrast, the 235 softwood mills are generally large-scale and operated by larger companies. A number of new investments in sawmilling are either underway or being considered.

The wood-based panels sector consists of 37 mills. They produce a range of products including particleboard, plywood and medium-density fibreboard (MDF). Particleboard and MDF are made from residue and lower-grade pulp logs. Production of these materials is usually either integrated with plantation or native forest-based sawmills. Plywood manufacturers, in contrast, use high quality sawlogs. This sector has been growing quickly in recent years. With international investors building new production facilities predominantly aimed at export markets.

Wood products production already makes use of wood waste material as illustrated in Table 2.

Table 21 Operating wood and wood products operations using bioenergy.

Project	Technology	Feedstock	Capacity	Cost
Caboolture Sawmill, QLD	Fixed grate combustion (heat only)	Waste wood (dry) from operations and external suppliers	Plant 1: 10 MW_{th} Plant 2: 6 MW_{th}	Replacement cost (REPEX) estimated $10 million
Pyrenees Timber boiler, Chute, VIC	Biomass boiler (heat only)	Sawmill wood residues	240kWth	$120,000
Colac sawmill heat plants, Colac, VIC	Plant 1: Stepped oscillating grate Plant 2: Pile grate (heat only)	Sawmill waste (green sawdust and dry shavings)	Plant 1: 12 MW_{th} Plant 2: 6 MW_{th}	Estimated REPEX Plant 1: $10 million Plant 2: $6 million
Mt Romance Sandalwood, Albany, WA	Biomass boiler (heat only)	Woodchips	6 MW_{th}	n/a
Auswest Timbers, Bussleton, WA	Biomass boiler (heat only)	Sawdust generated onsite	22,000 GJ p/year	n/a

Microwave drying

Microwave drying is at R&D, pilot, and early-stage commercial stages. Tests of microwave drying of Australian sawn timber sections has been conducted by the Forest and Wood Products Corporation and others, and a product developed in the 2000s. The product is however quite different from normal timber (http://www.misaltech.com/microwave.html). It is important to note that Australian native hardwoods do not behave during drying in the way that many overseas species do.

Microwave heating

Microwave heating during the final stages of MDF formation is also at the R&D stage, and is focused on replacing convective / radiative heating during the press and curing stage. The drying stage that occurs before this is likely to use the majority of the heat in the process and is not the focus of research.

11.2.5. Agriculture

The main uses of natural gas and LPG in agriculture are for glasshouse heating and for heating of poultry sheds. Interestingly, AES statistics show that more LPG is used than natural gas, possibly reflecting that many agricultural enterprises do not have access to distributed gas. Although relatively small in terms of total energy use, these would appear to be a highly prospective applications of renewable energy.

Poultry and pig farms use thermal energy for rearing animals. Some poultry farms use natural gas for heating and pig farms use radiant lamps for sheds and crates. The heat lamps in a piggery contribute to roughly 75% of total energy consumption. Alternatively, gas can be a cost effective source of heat for pig rearing (farrowing and weaning) when compared to electricity (McGahan et al., 2018).

All these uses are for heat at low temperatures. The full range of renewable energy sources should be considered and will most likely be competitive with gas or certainly LPG. For large installations with a suitable aquifer, geothermal is an option. Low-temperature solar thermal should be considered. It would however have the disadvantage of producing more energy in summer months when it is not needed. Electrically-driven heat pumps would benefit from high COPs for the modest end-use temperatures. Waste or low-cost biomass-fired heating would be competitive if the feedstock is available.

Bioenergy is the dominant renewable approach that is increasingly adopted for these applications. Table 22 lists installations of anaerobic digestion systems adopted at piggeries both to solve waste disposal issues and provide energy. In many cases covered anaerobic lagoons (CAL) are used as the effluent has traditionally been collected in lagoons in any case. The biogas produced offers the greatest value when used in a CHP system based on a reciprocating gas engine for power generation with heat recovery from the exhaust gases, and this has been employed in the systems listed.

Table 22: Operating bioenergy plants: piggery effluent.

Project name/location	Technology	Capacity	Cost
Berrybank Farm Piggery Windemere, VIC	Mixed tank	1,125,686 kWh/y, 6,754,118 MJt/y	n/a
Bears Lagoon Piggery Bendigo, VIC	CAL	1,294,539 kWh/y, 7,767,235 MJt/y	n/a
Kia Ora Piggery Yarrawalla, VICc	CAL	450 MWh + 2.701 GJth pa.	~$1million
Blackwood Piggery Trafalgar, VIC	CAL	375,229 kWh/y, 2,251,373 MJt/y	n/a
Blantyre Farms Piggery Young, NSW	4 x CAL, 3 x 80 kW generators		~$1million
Rivalea Australia Corowa & Bungowannah, NSW	40 ML CAL 500 kW CHP	4,127,516 kWh/y, 24,765,098 MJt/y	n/a
	CAL	900,549 kWh/y, 5,403,294 MJt/y	n/a
Cameron Pastoral Lundavra, QLD	Hybrid CAL	1,941,809 kWh/y, 11,650,852 MJt/y	n/a
Tong Park Piggery Warra, QLD	Hybrid CAL	3,377,059 kWh/y, 20,262,353 MJt/y	n/a
Bettapork Piggery Biloela, QLD	Mixed tank	1,125,686 kWh/y, 6,754,118 MJt/y	n/a
Signium Piggery Ellangowan, QLD	Hybrid CAL	3,151,922 kWh/y, 18,911,529 MJt/y	n/a
Urrbrae Piggery Netherby, SA	CAL	1,970 kWh/y, 11,820 MJt/y	$109,700
SunPork Piggery Brinkley, SA	CAL	1,711,280 kWh/y, 8,800,871 MJt/y	n/a

Table 23 lists examples of biomass combustion systems for greenhouse heating. In this case various low-cost waste biomass materials are combusted in hot water boilers exclusively for heating purposes. Heated water is stored and circulated as needed. CHP configurations based on back pressure steam turbines are found to be uneconomic given the small size of the systems.

Table 23 Operating bioenergy plant details; horticulture.

Project name	Location	Technology	Feedstock	Capacity	Cost
Family Fresh Farms glasshouse	Peat's Ridge, NSW	Justsen Energieteknik hot water boiler	Forest residues	5 MW_{th}	n/a
Hills Transplants glasshouses	Devonport, TAS	Energence heating plant	Wet woodchips	2.5 MW_{th}	n/a
Gelliondale Nursery	Alberton, VIC	3-pass hot water boiler connected to a multicone grit arrestor and I/D fan into flue	Wet sawdust	1.5 MW_{th}	$280,000
Gippsland Greenhouse Produce	Gippsland, VIC	Polytechnik biomass heater plant	Wood residues	2 MW_{th}	n/a
Murphy Fresh Hydroponics	Mansfield, VIC	Hot water boiler	Waste hardwood logs	6 MW_{th}	$600,000

11.2.6. Fabricated metal

Metal casting involves melting batches of metal, often several tonnes, and then pouring or injecting small amounts into a mould.

Metal can be melted in an electrical induction furnace with higher efficiency than a gas-fire furnace. For example, a coreless induction furnace melts aluminium with an efficiency of 68%, compared to less than 50% for the most efficient type of gas-fired furnace (BCS Inc., 2005). Another advantage of induction furnaces is that they combine the melting and holding tasks, removing the need for a separate energy-intensive holding stage.

Melting in an induction furnace also leads to lower yield losses because, unlike gas-fired furnaces, there are no exhaust gases to contaminate the metal. Induction furnaces can also be designed so that a smaller surface area of the charge is exposed to air (Lord, 2018).

The speed of induction melting presents a more innovative opportunity. Instead of melting large batches of metal, induction could melt small quantities of metal quickly, just enough metal for a single casting (Salonitis et al., 2016).

Once melted, the metal would be injected immediately into the die casting system. This potential approach has several advantages including reducing failed castings, increasing energy efficiency, reducing material losses from metal oxidisation and eliminating the need to keep any metal hot (Salonitis et al., 2016).

11.3. Case studies

11.3.1. Bioenergy-heated glasshouse

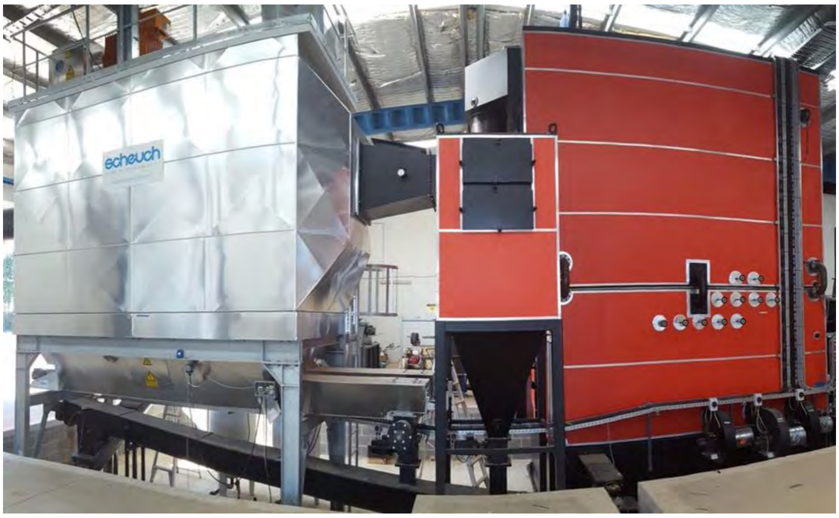


Figure 69: Biomass boiler (right) with exhaust gas treatment system (left). (Reproduced from Justsen Pacific.)

Family Fresh Farms' greenhouse in Peats Ridge, NSW produces cucumbers all year around in a four-crop cycle, with a yield of up to 24 tonnes per week. This is enabled by the farm's integrated heat control system which keeps the greenhouse at a temperature of 18°C during the night.

Heat is provided by a hot water system that runs in a series of pipes through the greenhouse. Family Fresh Farms chose to use a Justsen Energiteknik hot water boiler fuelled by sawmill waste from a nearby source to heat the water. Wood chips are delivered weekly by a semi-trailer with a moving floor that can be unloaded automatically. This technology was favoured due to its lower costs compared to LPG and better environmental performance compared to coal.

The wood chips storage system is managed autonomously by a distributor system and chips are automatically fed to the boiler by a conveyor belt and an auger. The 5 MW_{th} boiler is coupled to a 1000 m^3 hot water storage tank with 60 MWh of capacity, delivering up to 10 MW_{th}. The storage provides enough energy to heat the greenhouse through one cold night. The system uses around 4000 tonnes of wood chips per year.

The boiler operates autonomously, based on the storage filling status and forecast heat demands by the greenhouse. Exhaust gases are cleaned by a cyclone separator and a Scheuch electrostatic filter system.

Wood chips are one of the cleanest biofuel sources, producing very little ash residue and hence result in low maintenance. The boiler can operate with most biomass and waste fuel sources, and moisture contents of up to 55%. However, with less pure fuel sources, such as fuels from waste, the complexity and cost of the exhaust gas treatment system increases. Operating a bioenergy plant of this sort requires approval by the EPA (Environment Protection Authority). If the fuel source changes, the exhaust treatment system may have to be expanded and a new approval may have to be sought.

Summary

Location	Peats Ridge, NSW
Application of process heat	Heating of glasshouse for cucumber production, to maintain temperature above 18°C
Temperature	Hot water at up to 90°C
Energy resource	Sawmill waste (wood chips)
Technology	5.5 MW_{th} biomass-fuelled boiler delivering hot water at up to 105°C Hot water storage tank of up to ~90°C with 60 MWh_{th} capacity Scheuch exhaust gas treatment unit
Designed to deliver	Up to 10 MW_{th} of hot water at up to 90°C
Energy/emissions saved	Up to 4,000 t of CO_2 emissions saved per year
Construction	Commissioned in 2017
Other aspects	Boiler operates autonomously Due to low ash content of fuel, ash container only needs to be emptied 1-2 times per year Boiler fuel can be changed to other biomass sources (potentially requiring an upgrade of the exhaust gas treatment system)

11.3.2. Biomass-heated pine nursery

Figure 70: Left: Pine seedlings in HVP nursery. Reproduced from HVP; Right: sawdust delivery and storage. (Reproduced from Rural Industries Research and Development Corporation).

Gelliondale Nursery in Alberton, VIC was constructed in 2010 and grows pine saplings for nearby plantations. The site uses a biomass boiler to provide space heating for the greenhouse in which the saplings are grown. Wet sawdust provided by local sawmills is used to feed the 1.5 MW_{th} boiler, though other organic fuels can be used (i.e. olive pits). In total, the greenhouse covers an area of 4,700 m^2. As a greenfield site, all energy options were on the table for the site.

The nursery is outside of the gas distribution network and so, prior to construction, LPG was considered as a fuel source. The capex of an LPG boiler and associated heat exchangers, feed systems, distribution systems etc. was estimated at $80,000, compared to the biomass boiler at $550,000. However, ongoing fuel costs were expected to be $170,000 per year. for LPG, and only $30,000 per year. for sawdust. These estimates gave the biomass option a payback of 3 to 4 years compared to the LPG option, with a GHG saving of around 400 tonnes per year.

The major technical challenge was the varying moisture content of biomass feedstock, which necessitated air flow moderation to maximise efficiency. This was an important issue dealt with during commissioning of the equipment, hence the right balance of technical knowledge was vital.

Project development barriers were noted as largely:

- a lack of familiarity with the technology internally
- a perceived difficulty in finding information on the technology
- a perceived difficulty in finding any applicable grants.

For mitigating risks, the proponent undertook a number of measures that included:

- Gelliondale engaged a consultant (in this case the eventual supplier was the consultant).
- Senior staff visited existing biomass boiler sites, two of which were horticulture operations and one a timber operation.

- Other divisions of the company were experienced with pelleting operations (which engage some similar processes – biomass combustion and feed systems) which helped significantly.

Overall the internal ‘selling’ of the idea was quite easy. As a timber grower the company has long-term vision and long-term paybacks are the norm. The overall project to establish the greenhouse (not just the boiler) had an expected payback of 20 years, so this fitted in easily and improved the anticipated outcome.

Summary

Location	Alberton, VIC
Application of process heat	Space heating for greenhouse to grow pine saplings
Temperature	~20°C
Energy resource	Wet sawdust from local sawmills
Technology	1.5 MW_{th} biomass boiler
Designed to deliver	~7,300 GJ of heat per year
Energy/emissions saved	~400 t of CO_2 per year saved compared to LPG
Construction	commissioned in 2010
Investment	Biomass boiler: $550,000
Simple payback	3-4 years
Other aspects	Facility not connected to natural gas distribution network Biomass system instead of LPG improved overall economics of this greenfield system

11.3.3. Solar thermal-driven absorption chiller for hospital cooling

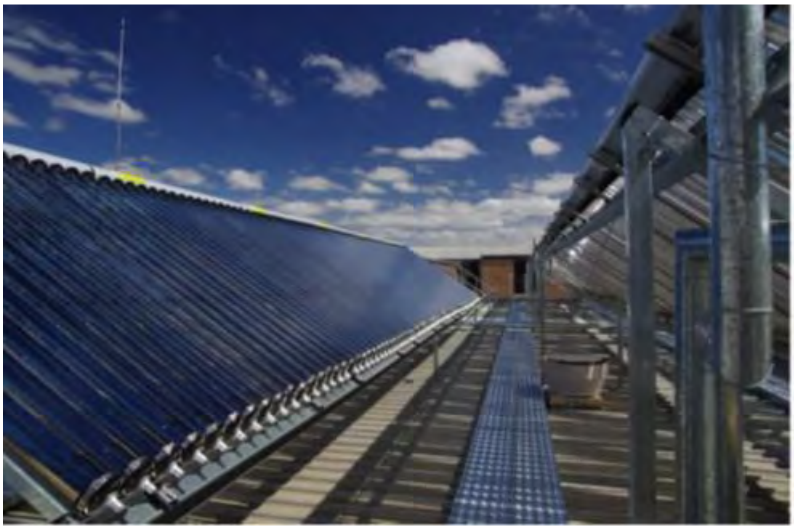


Figure 71: Solar evacuated tube collectors (image Greenland systems).

In March 2011, a solar thermal-driven cooling system was commissioned at Echuca Hospital in regional VIC. The solar field creates heat which is then used to operate an absorption chiller to cool water. The water is then used to cool circulating air in the HVAC system.

The system comprises a single-stage absorption chiller, which feeds 6°C water to the hospital building for space cooling. The absorption chiller is fed by 95°C water from a 300 m^2, 460 kW evacuated tube solar field – the largest in Australia – with natural gas backup. Two 5,000 L tanks store excess hot water when demand from the absorption chiller is low. This water can be used to substitute the normal hot water supply, or for space heating.

Annual heat generation from the solar field is estimated at 700 MWh (2,520 GJ), a capacity factor of 17.4% for the solar collectors. Net energy cost savings are estimated at around $60,000 per year, with electricity use having fallen by 1,373 MWh per year, substituted by natural gas and solar.

However, with a total project cost of $2.2 million, the primary economic driver for the project was not the marginal cost of energy savings, but rather the avoidance of electricity infrastructure upgrades that would otherwise have been necessary due to hospital expansion, with cooling provided by electric HVAC systems.

- Economic considerations included:– A lack of power infrastructure at the site was mooted with doubling of overall hospital beds. This project avoided a ~1,000 KVA transmission line upgrade and associated substation and other infrastructure. This was ~$1 million of avoided infrastructure alone.
- The project used 3740 solar collectors which required independent modelling as per CER procedure.

- Integration into the existing HVAC systems was relatively simple, with an injection circuit into the return line from the absorption chiller. In this system there was a default control built in. If the solar field can do the work, the existing heat exchanger senses the circulating temperature and doesn't need to turn on.
- Maintenance was simplified with the removal of 180 standalone split system air conditioners.

The system has proved itself so well in operation that a second system has now been funded (with help from ARENA) on the same site.

The initial system was funded by an internal capital grant for replacement of ageing infrastructure supplemented by funding from Sustainability Victoria. The internal proponent (the engineering manager) enjoyed a relatively high degree of autonomy and was able to pursue the outcome, even though using unconventional means, as long as the outcome was part of the internal strategic engineering plan.

The funding for the second system has been largely made possible through the success of the first.

Summary

Location	Echuca, VIC
Application of process heat	Absorption chiller for space cooling at a hospital in rural Victoria
Temperature	95°C hot water used in absorption chiller to cool water to 6°C
Energy resource	Solar thermal (GHI: ~1,800 kWh/m^2/year)
Technology	300 m^2 of evacuated tube solar collectors 2 × 5000 litre hot water storage Natural gas backup boiler
Designed to deliver	460 kW of hot water at 95°C from solar collectors (~700 MWh$_{th}$/year)
Energy/emissions saved	Electricity use reduced by 1,373 MWh/year (due to solar and gas)
Construction	Commissioned in 2011
Investment	Total project cost: $2.2 million
Other aspects	Solar thermal system avoided need for electricity infrastructure upgrade (~$1 million + of avoided costs)

11.3.4. Radio frequency glue curing

Figure 72: Kallasøe radio-frequency timber press (reproduced from: Kallasøe Machinery).

Most engineered wood products (EWPs), such as glulam and cross-laminated timber, are made from separate timber pieces held together with strong adhesive. This glue must cure before it develops full strength. Some manufacturers of timber products cure glue by heating the EWPs in a gas-fired kiln for up to eight hours, Table 24 (Lord, 2018).

Table 24: Comparison of processing time and energy input for setting adhesive in glulam.

Curing technique*	Energy per 1 m^3 timber (kWh)	Processing time per batch
Gas-fired kiln*	200+	up to 8 hours
Radio-frequency$^{\Delta}$	6-11	18-26 minutes

** Gas-fired energy estimate based on Wood Solutions' Environmental Product Declaration for glulam. $^{\Delta}$ RF energy depends on amount of glue in the product and moisture content in the timber.*

In Europe, EWP manufacturers increasingly use radio-frequency heating to cure glue. Danish company Kallesøe Machinery makes equipment that uses radio-frequency heating to cure and set EWP glues in less than 20 minutes, many times quicker than any alternative curing process. Radio-frequency curing is also extremely energy efficient as it heats only the glue, without heating the wood at all. Compared to curing in a gas-fired kiln, it uses less than 10% of the energy.

Summary

Location	Europe, global
Application of process heat	Curing of glue (e.g. melamine formaldehyde (resin)) in manufacture of cross-laminated timber engineered wood products (e.g structural timber elements)
Temperature	~120-150°C
Energy resource	Grid electricity
Technology	Up to 200 kW radio-frequency curing oven
Designed to deliver	Process heat for curing of glues/adhesives
Energy/emissions saved	90% reduction in energy demand for curing, compared to gas-fired curing oven

12. MOTIVATIONS AND CHALLENGES

A focus of this investigation was to establish, through interviews, the attitudes and experiences of stakeholders in industry. The intent was to determine the major motivating and demotivating factors for significant change in their energy mix. To obtain views of both present renewable energy users and future possible renewable energy users, our questions were posed in a general energy sense while eventually drawing out responses on renewables specifically where required or pertinent. Appendix H provides more detail on the interview questions and sectors targeted. Before summarising the interview outcomes, it is useful to examine the international context.

12.1. Barriers to energy innovation

Examining the literature on barriers to energy innovation in the industrial sector more generally can provide some guidance on motivating change.

UNIDO (Table 25) categorises barriers into:

- risk
- imperfect information
- hidden costs
- access to capital
- split incentives
- bounded rationality.

The USDOE (Barriers to Industrial Energy Efficiency - Report to Congress July 2015) itemises barriers into just three main groups, which encompass the six categories identified by UNIDO, even if not included in the specific examples provided;

- Economic and financial (includes risk, hidden costs, access to capital, split incentives)
- Regulatory (risk, hidden costs, split incentives)
- Informational (imperfect information, bounded rationality).

The same USDOE study provides examples of actions to overcome the barriers within these groups, including information provision in various forms, facilitation of new skills development (including new commercial relationships both in and outside a business), and a number of measures that seek to restructure the financial or reward relationships (or recognise hidden existing aspects of those relationships) between parts of a business, a business and its employees or a business and its customers. A summary is provided in Table 26.

Table 25. Taxonomy of barriers to energy efficiency (Sorrell et al., 2011).

Barrier	Claim
Risk	The short paybacks required for energy efficiency investments may represent a rational response to risk. This could be because energy efficiency investments represent a higher technical or financial risk than other types of investment, or that business and market uncertainty encourage short time horizons
Imperfect information	Lack of information on energy efficiency opportunities may lead to cost-effective opportunities being missed. In some cases, imperfect information may lead to inefficient products driving efficient products out of the market
Hidden costs	Engineering-economic analyses may fail to account for either the reduction in utility associated with energy efficient technologies, or the additional costs associated with them. As a consequence, the studies may overestimate energy efficiency potential. Examples of hidden costs include overhead costs for management, disruptions to production, staff replacement and training, and the costs associated with gathering, analysing and applying information
Access to capital	If an organisation has insufficient capital through internal funds, and has difficulty raising additional funds through borrowing or share issues, energy efficient investments may be prevented from going ahead. Investment could also be inhibited by internal capital budgeting procedures, investment appraisal rules and the short-term incentives of energy management staff
Split incentives	Energy efficiency opportunities are likely to be foregone if actors cannot appropriate the benefits of the investment. For example, if individual departments within an organisation are not accountable for their energy use they will have no incentive to improve energy efficiency
Bounded rationality	Owing to constraints on time, attention, and the ability to process information, individuals do not make decisions in the manner assumed in economic models. As a consequence, they may neglect opportunities for improving energy efficiency, even when given good information and appropriate incentives

Which approaches can help to bridge the gap between motivation and action? Governments in Australia generally act by changing the environment in which businesses operate. This is managed through enabling programs to assist businesses in the environment they currently occupy, and through legislation to alter that environment. This chapter and the interview process in particular examines what steps will have a functional effect.

Examples of approaches to bridging the gap between motivation and action are provided in Table 26.

Table 26. Opportunities and successful examples for end-use energy efficiency modified from (US DoE, 2015b).

Type	Description of barrier	Opportunities and/or successful examples
Economic and financial		
	Internal competition for capital	Provide / support alternative financing Example: Cummins efficiency capital fund
	Corporate tax structures	Example: Netherlands - accelerated depreciation for energy efficiency
	Program planning cycles	
	Split incentives	Example: J.R. Simplot – recognising the “split incentive” program
	Failure to recognise non-energy benefits of efficiency	Guidance / papers on approaches. Pilot projects.
	Energy price trends	-
Regulatory		
	Utility business model	Opportunity: Align customer and utility incentives
	Lack of industrial participation in funded energy efficiency programs	Collaboration: Utilities and industrial customers Evaluate participation Energy efficiency in policy standards
	Failure to recognise non-energy benefits	-
	Energy efficiency not in resource planning	Efficiency as part of utility and state planning Proper accounting for energy efficiency
	Environmental permitting	End-use efficiency improvements within the legal framework.
Informational		
	Adoption of systematic energy management system	Example: Nissan energy management system
	Lack of awareness of incentives	Increase outreach Technical and economic potential studies
	Metering and energy consumption data	Example: 3M and PPG Industries allocate energy costs to individual business units
	Lack of in-house technical expertise	Assistance to industrial facilities

12.1.1. Economic barriers

For much of the technology that industry is interested in and is likely to implement, it is important to focus beyond technologies in the R&D phase when assessing future actions that will achieve a major impact in the next 5-10 years. For example non-R&D policy actions ensuring biomass market stability, say through feed-in tariffs, are the primary recommendation of the IRENA biomass report as summarised in Table 27 (IEA-ETSAP / IRENA, 2015a).

A reduction in competing subsidies for other fuel sources (fossil fuels) is also mentioned by others (Taibi et al., 2010) (IEA-ETSAP / IRENA, 2015b; IRENA / IEA / REN21, 2018) and is part of the IEA's concerns (IEA, 2012). The latter also notes "internationally aligned sustainability requirements" as the second plank of their summary recommendations for policy. This factor ultimately leads into social licence, feedstock market stability, economic and environmental sustainability of the solution.

Table 27: Recommended actions from IRENA for the example biomass (IEA-ETSAP / IRENA, 2015a) .

IRENA recommended actions for biomass example	Timing
Overcoming economic barriers	
Create a stable, long-term policy framework for bioenergy, to increase the investor confidence and allow for the sustainable expansion of bioenergy production	2012-30
Phase out inefficient fossil fuel subsidies and introduce CO_2emission pricing schemes to ensure a level playing field for bioenergy	2012-30
Introduce mandatory sustainability requirements and quality standards based on credible internationally-aligned certification schemes	2012-15
Analyse and introduce appropriate accounting in CO_2 pricing schemes for negative emissions related to CCS on biomass-based installations	2012-30
Adjust economic incentives over time, as bioenergy moves towards competitiveness with fossil counterparts	2020-40
International collaboration	
Enhance efforts to introduce internationally-aligned certification schemes for biomass feedstocks based on commonly agreed sustainability indicators	2012-20
Increase efforts to align technical standards for biomass intermediates to reduce trade barriers and infrastructure compatibility problems	2012-20
Expand international RD&D collaboration, making best use of national competencies	2012-30
Enhance exchange of technology and deployment, including best practices for sustainable bioenergy production	2012-30

Transaction and hidden costs

One factor that receives considerable attention from many small businesses for instance are transaction costs: the cost of making the change to normal business processes. Such costs are often 'hidden' from the business cases formed when (especially) long-term cost of energy is calculated for review papers. Such costs are not overcome by addressing a skills shortage as the risk is fundamental to operation of increasingly complex technologies and many (but certainly not all) businesses simply do not wish to take that path. This view is partly size dependent – very large usage often entails the same number of moving parts, valves, sensors etc. and the same number of operators and control software as a very small system of the same kind. The difficulty of operations and the risks of downtime are no greater but the rewards substantially more and the skills basis and scope for action of the larger business greater.

This is partly the reason why combined heat and power has not taken off to its full economic potential (if every project were assessed only on payback), while scale of operations, and the scale of integration into the wider grid and local networks are noted as the major barriers for this industry (USDOE 2015 Chapter 6: Combined Heat and Power Systems). These technologies are extremely mature and yet there are major barriers to be overcome by designated R&D actions.

The Garnaut Climate Change Review (2008) for Australia makes significant reference to transaction costs, including the allocation of staff time and skills, and their strong role in smaller investments, and smaller businesses, where the transaction cost undermines the investment returns (Foxon et al., 2007). In particular we suspect (and our interviews confirm) that the position referred to by Garnaut that businesses “*generally only search for incremental improvements to existing ‘routines’, which would satisfy existing evaluation criteria, and so neglect carbon accounting*” has not significantly altered except that there is now an almost universal awareness of climate change and a strong (though not universal) thread of personal motivation to change in the business and energy leaders we interviewed.

12.1.2. Regulatory barriers

Biomass reports mirror Australian business concerns when describing market stability (for feedstock) as a crucial issue. The most recent high-profile examples include corn for ethanol in the US and, while only partly renewable, waste for energy shortages in some European countries, where some plants have survived by taking waste from other countries. This would be unworkable in Australia as the transport of biomass over distance quickly becomes uneconomic. This suggests that new facility development, if unchecked, may occur beyond the scale afforded by the economic catchment area of the resource. The dynamics of demand and supply of feedstock between different industries as occurred for the corn industry (not corn waste) in the US during the early 2000s is the other side of this coin (Nunez, National Geographic). Both effects drive the price of raw material upwards and both are (somewhat) foreseeable.

These lessons on supply and demand have been learned over time with some earlier reports having missed lessons from later experiences. One such lesson is from the corn sugar to ethanol experience in the US. Variations in the mandated renewable fuel substitution targets created another major commercial pressure (resource competition) at that time and this had flow on effects in other areas. Interestingly these lessons are born of experience in the mid-2000s and neither are mentioned in the Australian Bioenergy Roadmap of 2008 (CEC, 2008). These lessons follow market development and maturity, and should be considered in addition to the recommendations of that 2008 report, which mostly suited an undeveloped market and experimental or pilot-scale technologies.

12.1.3. Information barriers

Information provision is currently considered adequate by most businesses for their purposes, but the proper interpretation of this attitude is that the current level of information for businesses on new technologies, pilot studies and demonstration plants should be continued, not decreased. It also does not preclude the idea that for aspects of some technologies, industry does not know what it does not know. This could be the case for recent trends and innovations and technologies that are not yet well accepted.

While the businesses themselves see information provision as adequate, this does not mean they are static. They are open to new ideas and new approaches and nothing in the statement above indicates that information providers should not continue to provoke new thoughts, to educate about alternative ways to deal with old problems, and to bring information from other countries etc. to their attention. This is an underlying expectation of the status quo.

Social licence

Ensuring that measures are sustainable in environmental and social dimensions (‘GHG reductions, food security, biodiversity, and impact on soil and water’) is the second focus of the IRENA report after feedstock stability, and of a later Australian report Bioenergy in Australia (Stucley et al., 2012b). These authors note “aesthetic, recreational, biodiversity, water cycle management or carbon stock qualities” must also be satisfied along with the GHG licence afforded by renewable substitution. Such public perceptions were also a factor in driving US government policy during the corn ethanol market crisis.

Information provision, a major plank of recommendations in many earlier studies, may now have a different role in educating public perception and establishing that social licence is real, rather than the earlier role for information provision almost solely around commercial risk assessment. This comment especially applies to biomass where burners, gasifiers and digesters can be seen as polluting, while missing the focus on the benefits. This societal role can be extended to many areas of renewable energy in relation to social licence and understanding. For instance, public perception is often that major commercial building owners should be able to achieve much more than they do. It is often not apparent to the casual passer-by that many medium and high-rise commercial buildings have very limited potential for solar collection – having small roof area relative to their occupancy, and with sides being shaded by nearby buildings. The latter results in a very poor commercial argument when coupled with high (per kW) integrated solar façade prices.

Bounded rationality

An inference around bounded rationality is that sometimes the bias involved is unconscious or at least not conscious of the factors being neglected. We have in general found that this ‘unconsciousness’ is not so. The strict definition of bounded rationality is that decisions are made with limited information, limited time and limited mental capacity. While clearly this exists, most business owners / managers / energy champions interviewed were aware of the logical shortcuts they had taken to reach their conclusions.

The limitations were accepted as part of the process and overcoming the limitations (perhaps with the exception of limits to mental capacity, which is a circular argument related to one’s inability to objectively view oneself and must exist at any level and for any person) appears to have been considered by most. Freeing up more time, or throwing more people at a decision making task, and gathering more information were core parts of the interview conversations. These options were generally described as having been pursued to a point of an (informal) judgement of the limit in the benefit cost ratio of further efforts to reduce the risk.

12.2. Level of technology development

One dominant factor of this study is the level of development of the technologies. This is illustrated in Figure 73 for various types of risk, information gaps, and ultimately access to capital (where the success of investment appraisals or external capital raising is intimately related to the assessment of risk). Business adoption of new technologies faces risks (yellow arrows) in achieving appropriate scale up of the technology, in the measured achievement of their own growth and in changes to the value chain as the technology is more broadly adopted by others.

Some of the technologies we discuss in this paper are in the fledgling stages of development, the less risky in the second tier of Figure 73. The figure is adapted from an OECD publication on manufacturing priorities and policies and we have attempted to simplify the position of businesses in this study. The more developed the technology, the more developed the businesses using the technology, and the more developed the market, then the less risk there is. The red line indicates the very broad positions covered by different technologies discussed in this study and the adopter (business) sits in a position where it must carefully weigh the risk in both dimensions. The size of a business and the size of the change to operations is a significant factor also reflected in the figure.

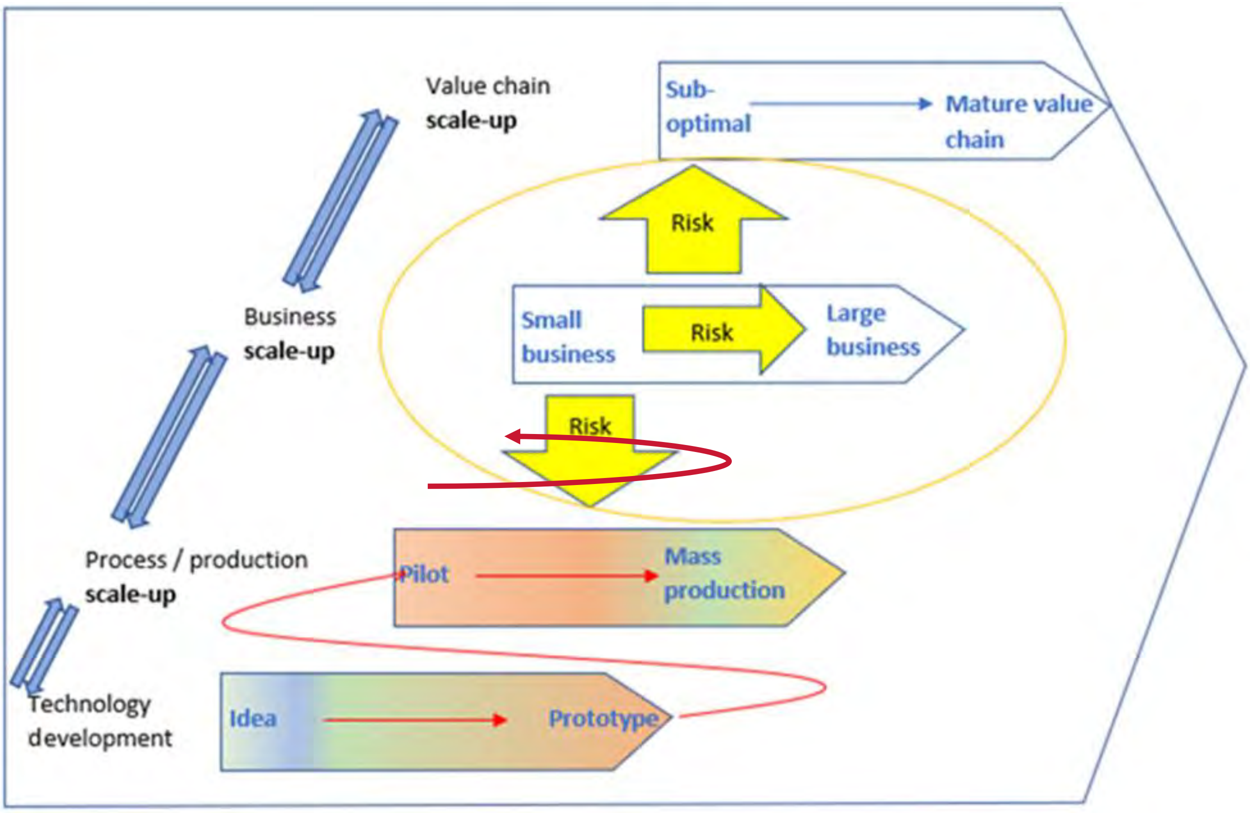


Figure 73: Dimensions of scale-up. The greatest risk is in the lower left of the figure. The least risk (and perhaps the least opportunity) is in the top right with mature technologies in mature industries. Adapted from (OECD, 2017).

A recent report (IEA Bioenergy, 2017), with a technical rather than policy focus, pointed to three items for action:

- Mandatory obligations for deployment of sustainable novel fuels and for specific subcategories that are at different stages of technical and market maturity.
- Appropriate and dedicated financial mechanisms and instruments to facilitate technological development and subsequent market deployment. These can include loan guarantees, and ways of bridging the initial cost differences between the novel energy sources and more established ones (fossil or other bioenergy).
- Support for RD&D focused on priorities identified in previous sections.

The latter R&D point appears to be not particularly relevant to the businesses in this report as industry is generally not interested in large-scale uptake of R&D. It may however be highly relevant to achievements.

A role in policy and target setting for R&D is relevant to longer-term achievement in areas where the technologies need to move through and past the pilot and demonstration plant stages – and this is a necessary first step for the ultimate uptake by any (non-R&D) business. Areas where this matters are very new technologies, and this seems very relevant to the substitution of heat by some alternative processes. Various R&D actions are the primary recommendations for action for the replacement of heat in the chemical industry with catalysis (IEA 2013, Technology Roadmap Energy and GHG reductions in the Chemical Industry via Catalytic Processes). Late stage R&D / product standards / market acceptance work is similarly a primary recommendation for changes of processes for production in the cement industry (IEA, 2018).

This type of role, and the actions associated with it, are similarly highly relevant for areas where major change is possible but simply too great for any single industry player to risk, or where the combined issues extend well beyond the boundaries of a single business into the supply chain and/or market. Two examples of this are capable of creating a major change to non-renewable fuel usage in Australia:

- the substitution of coal usage by hydrogen in the production of steel
- the substitution of natural gas usage by hydrogen in the production of ammonia.

Both of these are unlikely to proceed in Australia without action by governments to address a number of the barriers noted above and assist with development of stable, local supply chains.

While the relevant actions from the above will be brought together in the summary to this chapter, the following discussion relates to business interviews. The interest of businesses interviewed was not focussed on the early R&D / technology development stages.

Ultimately from a business perspective what matters to them are issues on a day-to-day basis. This is what can be relied upon to continue to create a bankable business case up to and well beyond the identified payback period. As noted by IRENA, to make it to an investment stage “policy stability is the first criterion for investors and project developers to evaluate the … market during the project’s lifecycle”.

12.3. Stakeholder interviews

Business categories

Businesses can be categorised into large, medium, small and micro. Various government agencies categorise small businesses as having less than 100 (or 200) employees and large businesses above this. For this discussion we also add the micro category - those with less than 10 employees. It is the general relationship of the business size to the state of planning sophistication, capitalisation, succession planning and access to capital that makes the size of the business a useful indicator of how they may react to a particular opportunity. Small businesses tend to have many competitors, lower business valuations, less access to capital and fewer staff to smooth out year to year and generational succession planning. This limits the level of experimental capital that they can or will employ. The risk factors – business continuity, market and technology – are generally considered equally by businesses of all sizes.

Background on energy use

Interviewees in general were not questioned in detail about the distribution of process heat at various temperatures. They were asked to separate their major energy uses in their thinking and responses to our questions. This resulted in a fairly predictable mix of thoughts about multiple energy needs for those with a greater variety of processes and usually a dichotomy for those (usually large businesses in the rank 1 to 3 of Figure 73) whose processes focussed on a single large stream of energy use. For many businesses with multiple end temperatures (generally food and beverage) there was a reluctance to split thinking down to substitution of one small energy stream separate from others. This is a subset of the thinking mentioned above on small-scale opportunities. There is simply no desire to introduce an entirely separate piece(s) of equipment with all the associated operational hurdles, skills gaps, contractual, purchasing, managerial and maintenance issues to provide energy, no matter how green or cheap, to a small use within a complex factory. Smaller energy streams within a large plant are seen as best serviced by one or two large energy plants whose output is piped in some way to the multiple different uses. The overall desire for simplification of processes appears universal and is obviously soundly based in contemporary management theory and practice.

All respondents were aware of the major final temperature requirements for their processes and where relevant in discussion were able to outline the efficiency limitations of their chosen prime movers and the various step downs from there on through their manufacturing processes.

The overall considerations / concerns / approaches for the businesses interviewed were remarkably diverse. While almost appearing contradictory at times, the differences were not irrational or in any way difficult to understand in the context of each business's unique circumstances. Some of these are provided as specific examples below, categorised under the headings discussed above: economic, regulatory and informational, with the added heading of level of technology development.

12.3.1. Economic

Capital (internal and external)

The majority of businesses interviewed used predominantly internal capital. This was either from prior (unusual) or current cash flow through profit reserves. The provision of capital was not seen as a significant barrier by most where the project passed other relevant hurdles. Ease of this, however, varied with the scale of the investment. In general businesses with multiple sites / plants (such as food and beverage), the total investment in a change at one plant was easier to manage. Notably the attitude of some, in minerals processing, coincided with other previous and current project interviewees, in waste and chemicals, where the focus was on a single large item of plant with a long lifetime. Here capital is a major investment and for some cannot be easily funded, where they exist in a commodity industry (price takers, export exposed) or have other significant risk factors that make financial return on a long plant lifetime highly risky. A very pertinent example of this is the (still present) inability to obtain a workable gas contract in the eastern Australian gas market – even for very large gas users. The inability to obtain a one to two year gas contract is a stark contrast for a business that has a major item of plant with a 50 or 60 year lifetime.

Renewable energy purchase agreements were not seen by most as alleviating this issue. The long-term nature of such agreements requires careful management of ongoing liabilities in the face of the generally short-term investment focus of many companies. In an industry where plant may have a lifetime of 50 years it is difficult to imagine confidence in a financial instrument or company under the control of others when we see business names, ownership, sector focus, senior management, culture and boards change dramatically over much shorter time periods for even very large companies. The few respondents comfortable with the concept spoke about carefully constructed contracts with large companies of long history.

Long equipment lifetime also amplifies the limits to obtaining capital, whether external or internal, for areas where there is any technology or market risk.

Competition for capital between projects in a business is common. This can be because of limits to the capital. In many cases when fully explored (e.g. by proposing accessing external capital or use of an energy purchase agreement to relieve the business of needing a capital investment) the issue was revealed to be ultimately one of managing the availability of staff to manage the change and / or simply managing the pace of change. In some cases the individual business units must fund their own capital for improvements.

Project timing

All business surveyed had a robust approach to project timing that reflected an experience base. The usual cycle is one of yearly investment budgets, yearly promotion or assessment of various competing opportunities and then implementation with a full view to the time taken for construction and implementation. Long lead times are part of the decision making process and are not seen as a barrier. This may have been different if there was a specific subset of businesses that pursued more experimental change but this was not seen in the interviewees. There were no special considerations around renewable or non-renewable energy changes in this context. Renewable opportunities were not seen as more difficult – but this is primarily due to the exclusion of any more experimental approach to (any) change. Only proven technologies were considered by the interviewees, with considerations as to what constitutes ‘proven’ discussed below in section 12.3.4.

Opportunity and opportunity cost

Interviewees were no more or less excited by renewable projects as an opportunity. Their analysis was always around the business case and maintaining business continuity. In some cases, their interest in the opportunity was around a possibility for renewables to provide a more stable source of energy, energy pricing, and energy continuity in the face of market, environmental and legislative changes.

The concept of opportunity cost featured in most discussions. Energy and renewable projects compete at all times for capital, skills and time investments as noted above. They do so with no special considerations – however it was noted that in some industries the use of (own) waste biomass had the potential to reduce costs in other areas and hence become part of the consideration.

Risk (primarily to operations)

Operational risk is a high-level consideration of the businesses interviewed. They were all cognisant of the potential for what might seem initially a minor consideration in a technology change to impact on the ability to consistently produce product and /or consistently produce quality product. The highly structured approach to change and managing risk noted in the 'Information' section is used to mitigate this risk universally. Hence while the potential outcome may be disastrous, the risk of occurrence is apparently in all cases tightly managed to an acceptable level.

Payback

Desired or essential paybacks vary widely but with a strong focus on the two year timeframe. There is a strong and unsurprising tie of paybacks to the nature of the industry's market or production cycle. A useful example is the timber industry, whichwas noted as the only one happy to accept project payback lifetimes in the order of 8 to 15 years. This makes inherent sense in an industry where their stock (trees) take at least 20 years to grow. The long-term nature of the investment is inherent. This is in contrast to, as an example, the poultry industry where the product is grown in months. Here the nature of the processes for growth, slaughtering and even downstream vertically integrated feed production change rapidly. This is a situation exacerbated by the difficult physical environment (highly corrosive). The genetics of the stock even alter sufficiently to routinely require changes to the processing equipment such that lifetime and payback of any equipment must be very short. Paybacks must be 2 to 3 years in this industry.

For most other businesses there were reasons, though less obviously or continuously compelling, for a similar aim. We had in a previous report discussed the example of installing two energy efficiency initiatives in a major dairy plant only to have the markets change, leading product lines to be altered, to the point that the initiatives did not even operate for as long as their intended payback (three years).

The attitude to removing payback altogether as a consideration, through energy purchase agreements with independent commercial operators providing heat, was raised with interviewees. For the companies interviewed this approach was not appealing except in one case. This was due to multiple considerations, mostly around the complexity of ensuring that such agreements were sustainable as noted above in section 12.3.1. There is no doubt that moving a large capital cost item on to an advantageous operating cost line is financially attractive, but where the item provided (energy) is mission critical there are considerable risks that must be considered. This is contrary to some views expressed in various forums, however we can only report that our interviewees were overwhelmingly concerned by the long-term risk posed when critical supplies of energy are in the hands of another company rather than a regulated entity. All companies change over time and five or ten years is a long time for effects on management and board composition effects on financial stability and staff competency in changing markets. Even with the best will in the world it is easily conceivable that these would affect the resources and ultimately the ability of a supply partner. Unlike electricity, with an over the fence heat supply the energy user cannot easily go to market for an alternative supplier if problems arise. It is possible that this is an area that will mature with time and experience in the Australian context.

Payback also interestingly, but not surprisingly, became irrelevant in discussions with some industries where business survival is a pressing concern. On a smaller scale, product line survival was also mentioned – with the example given of technology changes needed to maintain the social licence for a product (removing palm oil from a process being the example given). These considerations override payback.

Decision cycles (especially for long-life equipment)

There was little discussion arising on the role of decision cycles. As noted above businesses had standard processes – usually based around an annual cycle. Part of the decision making process, e.g. for mining, involves a decision made on the basis of annual budgets but also for a 'life of mine' budget (say 20 years). This is simply an expression of the obvious – that there is little point in a measure making a positive change year on year if there is only three or four years of business life remaining because the primary resource is going to run out.

Exactly the same consideration is evident in the thinking mentioned above for businesses with longer-term challenges in other areas. As described these clearly revolve around the relationship with the lifetime of the investment required (and return) in the long-lasting assets.

12.3.2. Information

It is obvious that the first step in assessing a new opportunity is awareness that the opportunity exists. The role of information providers in stimulating awareness of new technologies is ongoing. This role is in part to overcome the limitation, noted above, that for some aspects of some technologies, industry does not know what it does not know.

Once aware, the level of development of the technology is perhaps the next key piece of information about a technology or approach.

In discussing their pursuit of opportunities very few businesses identified a lack of information as a barrier to innovation or uptake of opportunities. It was acknowledged as obvious that available information is sometimes limiting for these decisions. The majority , if not exclusive view, was that contemplation of a major technology change was accompanied by a commitment to obtaining all the information available and performing the appropriate analysis. The means of achieving this were typically identified, (and usually in this order) as;

- internal engineering analysis using published reviews, data sheets, case studies, manufacturers information, cost data
- visits to demonstration plants or if lucky enough fully operational plants using the technology
- use of external resources;
  - manufacturers of equipment (seen as conflicted but still a starting point)
  - consultants specialising in the technology or area of interest
  - hires from other companies who have used the technology
- establishment of small pilots either as
  - a true pilot plant or
  - modification of part of an existing process line
  - either of the above on an increasing scale of operations over a time period
- modification of one of multiple sites that a business may have.

There was a universal commitment to obtaining the information required. There was a universal preference for increasing surety in terms of being, to quote one interviewee, “leading edge, not bleeding edge”. The presence of pilot plants was usually insufficient in itself but moving up the hierarchy towards larger demonstration plants, fully working single plant examples and preferentially multiple working plants with the appropriate technology displayed created more surety.

At that point of the scale some businesses were happy to see the technology working in a different application or industry. Others with very specific product qualities / highly fine-tuned production processes and /or where product differentiation between multiple market players was important, were more stringent in requiring information that arose from the use of the new technology in the same industry, with the same operating parameters, and even in the same geographic region.

Skills (internal and external)

Internal skills were often seen as limiting. This is in a qualitative sense where experience with a particular technology is lacking – and hence the inclusion of external consultants in the above list. It is in a quantitative sense in many cases where businesses keep their own engineering teams who can be spread too thin.

It is clear that an idealised concept where an external team swoops in to make change does not exist, or at least does not alleviate the engineering team or managers of their responsibility to manage change. This is regardless of the attractiveness of the financial case.

For some, the skills gap simply translated to a need to keep the technology simple. Regardless of the teams that may be brought together to construct and implement a change, there still needs to be a team to run the technology. One interviewee, with operations in jurisdictions across the Pacific and not always have the same relatively ready access to technicians and engineers that is enjoyed in Australia. As a result he sought out only to install technologies that are simple and easy to run and repair in these jurisdictions. This same approach applies in many smaller businesses in Australia, though this operational skills side was not noted as a barrier for the medium to larger businesses with Australian sites that were interviewed in this survey.

12.3.3. Regulatory

Regulation as a barrier was generally a short and underwhelming conversation – with the exception of long-term government legislation as related to subsidies and pricing. The relationship of this to long-term financial performance was seen as very important.

Perhaps the most topical challenge was ensuring east coast gas supply and price security. Companies interviewed indicated that obtaining suitable long-term contracts remains a problem.

Non-market pricing

Non-market pricing inclusions for such as environmental levies or subsidies was not considered by any to be a barrier in itself. The continuity and longevity of pricing and legislation around the item was however important to any confidence in the business case.

12.3.4. Level of technology development

Internal innovation incentives

Several of the businesses interviewed had internal innovation incentives or energy cost reduction incentives. This is either through internal processes that institutionalise innovation or through personal or group KPIs (more common in larger companies). None of the companies interviewed had explicit renewable energy incentives or renewable energy targets, although many had energy reduction or greenhouse targets to be met through efficiency programs. Some businesses had dedicated innovation teams. More than one (mining, food, beverage) had energy teams at one or both of plant and national level. Most businesses sought out innovation to some degree. At the low end of this, for one company that exists at the very mature end of the business development cycle, the very strong market (price) competition left them with slim margins and no room for expenditure on internal research.

Where present it was apparent that the KPIs or achievement milestones were treated as serious aims and part of the fabric of the way the company did business. The internal incentives were framed in terms of energy productivity (output per unit energy) or cost productivity. Discussion of the processes indicated that at no time was the thinking around an issue limited or blinkered and all ancillary considerations (such as side stream advantages in productivity or costs) were able to be taken into account.

There seems to be little to improve in this general approach.

Supply chain limitations

To be acceptable, a renewable energy concept has to have been proven to an acceptable level somewhere in the world, and hence the required equipment will have gone through several production iterations. Hence, once a decision had been made to pursue a concept, no practical limitations were noted for the supply of equipment. Many of the companies interviewed were national and multinational with technical and purchasing reach and knowhow beyond Australia. For smaller companies the situation may differ and experience has shown that this can be an issue. For our interviewees, the issue of supply of equipment, like the construction and implementation considerations, were seen as merely practical issues that form part of a well-developed business plan on a proven technology. This situation may have been different if any of the businesses involved were considering a more experimental, less proven, technology.

There were real supply chain considerations around the renewable energy source. While solar is self-limiting (due to space constraints) for many businesses this is not the case for externally-sourced renewable energy. Specific examples discussed were municipal waste to energy and forest biomass. These were chosen as they are sources likely to be able to provide energy on a large and continuous scale. Municipal waste was seen as contractually risky and inconsistent. Even though examples of long-term forest residue contracts were provided as examples, this did not seem to alleviate concerns about the available volume and economics of provision over distance.

This latter concern might be addressed and be fruitful for modelling works for larger energy users.

Scale (too small and too big)

Very-small projects were not routinely discussed, but where mentioned it was noted that they failed to inspire. This was due to the lack of reward for the time that would be spent on them. The primary factors in this are the associated operational hurdles, skills gaps, and contractual, purchasing, managerial and maintenance issues associated with providing energy for a small use within a complex factory.

Very few interviewees agreed that there was a size of technology change project that was simply inherently too big. There was no inherent reluctance to change noted. Where payback was adequate then it was generally agreed that capital could be raised – even if it meant going to outside capital in a business that usually used internal capital. The issues that were ‘show stoppers’ for larger changes were around the technology risk and the potential interruption to business continuity. These were also usually wrapped up – for very large changes – in the issue of dealing with a generational change to an energy source in one of the larger ‘single line’ businesses for equipment that might have a very long lifetime. The difficulty lies in the assurance of the future of the business as related to other much broader issues such as international trends, legislative certainty, price competition from other technologies that might have a cheaper marginal cost, and product substitution (either through obsolescence or alternative approaches to the final user need).

One ‘exception’ to this was in challenging businesses in the very large users category (steel and alumina) to think around radical alternate energy sources. An example used was substitution of coking coal with hydrogen or biogas, or the concept of a biomass replacement for coal on a very large scale. In this case the ‘too big’ component was not really about the scale of the investment but rather the multiple challenges to be overcome to make such a change happen.

Data on new technologies

Interviewees were in the main comfortable with, and supportive of the existing level of provision of data through fact sheets, case studies etc. This attitude was in relation to the review of technologies as they fit into the acceptable risk profiles discussed above – or to know that the technology is not acceptable (not suitable or not enough known or done). This is not to suggest that further work on various technologies to establish new data is not seen as a worthwhile task. Rather it was the pragmatic attitude of working with what is known, that such further work is research and that research is not part of their energy choices.

As examples: there was a relatively high level of comfort with their own existing knowledge level of CHP technologies, as many businesses had looked at this in their own feasibility assessments. For energy storage, steam accumulators were seen as a mature technology requiring an implementation study if desired but not requiring further data. On the other hand, newer technologies for thermal energy storage like molten salt were seen as too experimental (despite a track record in other industries) and thus there was no real desire for more data. Batteries were seen as too small-scale or as too low a return for implementation.

13. OPPORTUNITIES

Our investigations suggest that prospects for renewable energy-based industrial process heat in Australia may be categorised under three timeframes:

- Short-term, 0-5 years: Application of existing technology that is already used in other markets, is immediately economic while working with businesses to address the various barriers.
- Medium-term, 5-10 years: Process optimisation plus further uptake of borderline economic opportunities. Now past R&D phase but no or few demonstration plants exist and mechanisms are needed to spur industry uptake.
- Long-term,10-20+ years: Long-term vision to emissions free industry. Hydrogen substitution in steel and ammonia and other large energy use industries - Major structural change required, with a role for R&D, policy and funding to create the value chain that will make this happen.

13.1. Specific industry opportunities

In each industry sector, the potential opportunity for renewable energy uptake and process optimisation is defined by the current level of fossil fuel use. The nature of use and volume of heat use in each sector determines the level of challenge involved and the applicable renewable energy approaches that are suitable. Table 28 summarises the estimated potential opportunity by sector in these three timeframes and the most applicable renewable energy technologies in each case. The allocation of potential between timeframes is an indicative estimate of the authors, it is not a rigorous quantitative assessment based on a defined method. Here we discuss each sector further in more detail.

Alumina and other non-ferrous

In this sector, heat use is split between modest temperatures (digestion) and very high temperatures (calcining). The low temperature portion could be provided by either solar thermal or electrically-driven mechanical vapour re-compression. It is estimated that there are some niche cases where renewable solutions will be taken up in the near term. At current energy prices the rate of return on large-scale approaches appears to be positive but below the typical investment threshold of the companies involved. It is estimated that this is accessible in the medium term if the barriers are overcome. The high-temperature processes could be addressed by large-scale production of renewable gas (hydrogen) for substitution. However, there is a large cost gap to bridge. Further R&D effort could also develop advanced electrical or solar thermal approaches for the high temperatures, however this long-term potential requires a substantial global demand or mandate for zero emissions products.

Table 28. Potential for renewable heat by sector

Sector	Total fossil heat use in PJ/year	Opportunity potential (ST - 0 to 5 yrs potential; MT - 5 to 10 yrs potential; LT- 10 to 20+ yrs)		Key process	Key renewable technologies: Bioenergy	Geothermal	Heat pump	Other electric	Solar thermal	Hydrogen	Comments
Alumina and other non-ferrous	169	ST	9	Alumina digestion, calcination			✓		✓		Low temperature portion is accessible in medium term if barriers overcome. High temperature processes need R&D and global demand for zero emissions product
		MT	67				✓		✓		
		LT	93				✓		✓	✓	
Iron and steel	94	ST	0	Iron ore reduction, steel production							Needs global demand for zero emissions products, will require major investment in new plants
		MT	5		✓						
		LT	89					✓		✓	
Oil and gas extraction	87	ST	4	CO2 scrubbing regeneration, steam							If drives are electrified, low temperature heat can be addressed by other techs. In LT, linked to future of transport fuels
		MT	18				✓		✓		
		LT	65							✓	
Petroleum refining	65	ST	3	Distillation, hydrogen use							Some MT opportunities at medium temperatures. LT linked to future of transport fuels
		MT	13		✓		✓	✓	✓		
		LT	49							✓	
Ammonia and other chemicals	42	ST		Steam reforming of methane, steam							Needs global demand for zero emissions products, could be first segment to adopt renewable hydrogen as energy input.
		MT	8						✓		
		LT	34							✓	
Food and beverage	37	ST	7	Hot water, frying, steam, baking	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	19		✓	✓	✓	✓	✓		
		LT	11		✓	✓	✓	✓	✓	✓	
Cement, lime products	34	ST	10	Calcining, roasting	✓						Strong existing use of bio waste can grow. Long term future of the sector unknown
		MT	16		✓						
		LT	8							✓	
Commercial and services	18	ST	9	Steam	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	9		✓	✓	✓	✓	✓		
		LT			✓	✓	✓	✓	✓	✓	
Bricks and ceramics	16	ST	3	Kiln heating	✓						Well suited to bioenergy if resource is available. Some electrification potential also
		MT	8		✓						
		LT	5		✓					✓	
Pulp and paper	14	ST	2	Hot water, process steam	✓						Strong use of bioenergy already, Progress may be limited by biomass supply, leverage other RE technologies for lower temperature processes
		MT	6.3			✓	✓	✓	✓		
		LT	6			✓	✓	✓	✓		
Other mining	14	ST	3	-	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	4		✓	✓	✓	✓	✓		
		LT	7		✓	✓	✓	✓	✓	✓	
Glass and glass products	7	ST	0	Glass melting							Progressive switch to electric resistance heating plus bioenergy
		MT	3		✓			✓			
		LT	4					✓		✓	
Other sectors	31	ST	6	-	✓	✓	✓	✓	✓		Low temperatures first, all RE technologies have a role
		MT	9		✓	✓	✓	✓	✓		
		LT	16		✓	✓	✓	✓	✓	✓	
Total	**628**	**ST**	56								
		MT	185.3								
		LT	387								

Iron and steel

Options for Iron and steel are limited, however the volume of energy involved is very large. It is estimated that there is very little if any short-term potential. Overseas experience shows that wood based charcoal can substitute directly for coke in iron production and renewable gases could substitute for natural gas. There is some medium-term potential for actions in this area however the volume of material available in Australia is likely to be limited. In the long-term there is great potential for new advanced systems based around direct reduction of iron using hydrogen followed by steel production in electric arc furnaces. This will require very large investments in new plant and there is also a very large energy cost gap. This long term potential is contingent on a global demand or mandate for zero emissions steel products.

Oil and gas extraction

A significant heat use at modest temperatures has been identified as part of the regeneration of CO_2 separation systems. At present this is economically met from the waste heat from gas-fired turbines that directly drive compressors and pumps. If drives are electrified, this low temperature heat could be delivered by other renewable technologies, specifically electrically-driven heat pumps or solar thermal systems. However, in the long-term the evolution of this sector is intimately linked with the future of transport fuels. It may be that it progressively transforms into or is replaced by large-scale hydrogen approaches.

Petroleum refining

Petroleum refining has some potential for medium-term use of renewables for process steam, distillation and possibly hydrogen feedstock. Bioenergy, heat pumps, other electrical approaches and solar thermal could all technically contribute. Use of renewable hydrogen as a feedstock could reduce the emissions profile of conventional fuels. However as with the oil and gas sector, the long-term evolution of this sector is intimately linked with the future of transport fuels. It may be that it progressively is replaced by large scale hydrogen approaches or electric vehicle use.

Ammonia and other chemicals

The short-term potential in this sector is only for modest amounts of steam needed for various processes. In the long-term, the potential is very large and linked to the replacement of natural gas by renewable hydrogen as both a heat source and feedstock. Ammonia production is likely to be the first sector where renewable hydrogen becomes economic. Hydrogen is not just an energy source but an essential feedstock. Supplying renewable hydrogen saves on the need to invest in and operate steam reforming of methane.

There is a medium-term potential for replacing the heat required for steam reforming of methane. Solar thermal systems can do this, and they could be adopted in a transition strategy in which they were subsequently adapted to support pure hydrogen production.

Given the likely global demand for renewable hydrogen and Australia's trading partners' decarbonisation targets, efforts focussed on a process change to zero carbon production are likely to be much more effective in the long term than substitution of a proportion of fossil fuel heat with renewables within the current steam reforming process.

Food and beverage

Much of the heat use in Food and beverage is already renewable as a consequence of bagasse use in sugar refineries. Some mills have been modernised/rebuilt to become much more efficient, meaning that they are able to export a significant proportion of the electricity they generate. Doing this at all sugar mills is an untapped potential source of more dispatchable renewable electricity.

The remaining potential is much less due to the sector's total heat use. There are many sites and heat uses ranging from high to low temperature. Given this, every renewable option should be considered on a case by case basis. Bioenergy is being adopted already where fuel availability is adequate and secure (in addition to sugar refineries). Low-temperature geothermal heat should be considered by inland sites where appropriate. Solar thermal has potential. Electrically driven heat pumps and electromagnetic and resistance-based heating can be substituted. This sector has great potential for process re-design and optimisation also. Overall, most of the potential has been assessed as medium-term.

Cement, lime products

This sector has a strong and growing existing use of waste based bioenergy. It seems clear that this is the obvious route for growth of renewable energy use in the sector and much of this potential is assessed as medium-term. Waste materials are used at several cement kilns, indicating that they are cost competitive with gas and even coal. However, the long-term future of this sector is unknown. In transitioning to a net zero emissions scenario, the inherent CO_2 production will need to be addressed by sequestration, offsets or adoption of innovations like geopolymer cements.

Commercial and services

The relevant aspects of this sector are steam, hot water and other processes in large laundries and kitchens. The potential is assessed as short or medium-term and achievable. Given the range of temperatures and sites, all the renewable technologies should be considered on a case by case basis, along with consideration of redesigns and optimisations. The low-temperature applications will have the most options and greatest potential of being economically favourable in the short term.

Bricks and ceramics

The operation of high temperature kilns limits the renewable options, but is well suited to bioenergy if the resource is available. There are some innovative electrical approaches requiring process redesign. Direct resistance heating is also possible and could be operated in a hybrid fashion at times of low electricity prices. Much of this potential is assessed as medium-term.

Pulp and paper

This sector has a strong use of bioenergy already with further uptake likely in the short and medium-term. At some point progress may be limited by biomass supply. For the lower-temperature applications, other renewable technologies, such as heat pumps and solar thermal offer good potential to supplement the bioenergy use.

Other mining / other sectors

Given the range of temperatures and sites, all the renewable technologies should be considered on a case by case basis, along with consideration of redesigns and optimisations. The low-temperature applications will have the most options and greatest potential of being economically favourable in the short term.

Glass and glass products

The operation of high-temperature glass furnaces limits the renewable options. Renewable gas, either bio based or hydrogen could be substituted. Electrical resistance heating is also possible and could be operated in a hybrid fashion at times of low electricity prices. The challenges in this sector suggest that the potential is assessed as dominantly long term.

13.2. Examples of international initiatives

Developing policies to promote renewable heat has more challenges than those for renewable electricity (Sharma et al., 2017):

- heat is a local resource and, unless district heating or similar systems are in place, surplus production cannot be fed back into a grid, so supply must match local demand
- while electricity is a homogeneous energy carrier, heat demand shows different temperature levels per technology and application.
- renewable heat supply is often variable over time (diurnal, seasonal). For industrial applications, this means that supplementary energy sources are required if demand is constant

- difficulty in integrating solar process heating systems into existing, optimised process heating streams
- tailor made solutions are often required for each specific industry
- upfront costs can be high for small and medium-scale industries
- qualified and competent designers, installers and software support can be difficult to source locally
- unavailability of adequate policy and regulatory support (as compared to renewable energy power generation systems)[25].

A range of strategies are being pursued internationally to overcome these challenges. Member states of the European Union have introduced targets for specific shares of renewable heating and cooling, while other countries such as India, China, Tunisia and Mexico target the use of solar collectors for buildings and process heat (REN21, 2018; IEA 2019). Tunisia is an interesting new example, with its Prosol program using a combination of low-interest loans, investment subsidies, quality control and freer markets to meet its 2020 goal of 14,000m^2 of solar process heating panels to replace fuel oil and gas (REN21, 2018). Annual installations have increased seven-fold.

Overall, renewable heating and cooling targets exist in at least 48 countries and at least 21 countries have heat obligations/mandates in place at the national or state/provincial level to promote the use of renewable heat technologies (REN 21), although many of these are for space or district heating in cold countries.

Industrial energy users are used to paying for gas as they use it, with the capital costs for gas infrastructure having been raised and amortised by governments and utilities. Consequently, industrial users show little appetite for investing their own funds to convert to renewables. Many of the large industrial gas displacement projects undertaken worldwide involve significant up-front capital cost, tax or other assistance, and/or a third party raising the funds and providing energy via a leasing or energy purchase agreement.

The most relevant strategies for the purposes of this study are described below.

13.2.1. Capital subsidies and loans

Government subsidies and loans not only assist with the cost, but also provide a level of public confidence in a new technology and its take-up. Examples of support for renewable energy capital subsidies for the industrial sector include[26]:

- Germany - 25% of initial investment cost subsidy for industrial heat

[25] For instance, REN21 2018 notes that 48 countries have renewable heating and cooling targets and 24 have incentives or mandates, while 146 countries have renewable electricity targets and 128 have incentives or mandates.
[26] REN21 2018, DSIRE 2019

- Netherlands - grants under the Sustainable Energy Investment Subsidy Scheme to support renewable heating installations
- India – loans for industrial heat from biomass. Cogen systems can also claim Renewable Energy Certificates
- Brazil – has the world's highest rate of bioenergy for heat and uses loans and subsides for industrial heat and CHP from bagasse
- California – Up to 85% (max $250,000) of the cost of new commercial or industrial energy saving technologies.

In the past, Australia had various programs, such as the Clean Technology Program (which included the Clean Technology Investment Program, the Clean Technology Food and Foundries Investment Program, and the Clean Technology Innovation Program), which assisted small to medium-sized industry with planning and implementation of energy efficiency and renewable energy deployment. Grants were available for research, development and commercialisation of clean technology products and to support investments in energy efficiency machinery and equipment. Large industry was assisted and motivated by the requirements to assess and report on energy efficiency opportunities in the Energy Efficiency Opportunities program, although this did not specifically target renewables.

13.2.2. Renewable energy targets or portfolio standards

Targets for renewable energy have been widely used by state and central governments as a means of encouraging diversification, cleaner generation of meeting greenhouse gas targets. The mechanisms used to achieve the targets vary (Watt & MacGill, 2014). They can be set as a capacity target, ramping up at a set rate over time, or as a percentage by a particular year. They can be renewable energy technology neutral, have separate targets for a specified list of technologies, or provide different levels of support for each technology, depending on cost, stage of development or percentage penetration, for instance. Many operate via a tradable renewable energy certificate scheme, which has a market independent of the main energy market. Such target mechanisms expose renewable energy projects to wholesale or retail energy market signals while providing an additional production incentive for renewable energy production. They remain a potentially strong driver for establishing renewable energy markets where conventional supply is entrenched and market access is otherwise difficult. Targets often operate in conjunction with other support mechanisms, especially where certificate prices are low and would therefore not provide sufficient revenue for new technologies.

Examples of target mechanisms used for renewables in the industrial sector include (IEA SHC Annual Reports, 2014, 2017 and REN21, 2018):

- Chinese solar thermal obligations – enacted by provinces, in line with the 11th and 13th Five Year Plan for New Energy and Renewable Energy Law of China, plus coal bans in 28 cities

- European targets for an annual 1% increase in renewable energy for heating and cooling. This mostly targets buildings, but some countries, such as Netherlands, have included biogas, biomass, and geothermal under its heat tariffs and UK includes renewable energy heat under its FIT policy, with 20 year tariffs available for businesses.

Interest in supporting the transition to renewables has increased at the local level, driven by environmental concerns, job creation aims and a broader interest in sustainable and self-reliant communities. Many cities have set targets independently of state or federal government initiatives (REN21, 2018), with several setting industrial heat targets:

- Chandigarh, India – Mandatory solar water heating for industry and other buildings
- Munich, Germany – 80% reduction in heat demand between 2009 and 2058, including process heat
- Osnabrück, Germany – 100% renewable heat by 2050
- New York, USA – 20% biofuel blend in heating oil by 2034
- Vienna, Austria – 50% solar thermal heat by 2050.

Other cities, including Berlin and Schönau in Germany and Boulder, USA have plans to buy back their electricity systems, so that they can be managed at a local level, using local, renewable energy resources. This trend means that industries operating in these areas will need to transition to renewable options, and will accelerate technology development and uptake.

However, industries themselves are increasingly setting their own targets. As of early 2017, 48% of the US-based Fortune 500 companies and 63% of Fortune 100 companies had at least one climate or clean energy target, and 10% of the Fortune 500 companies had set a specific renewable energy target (REN21, 2018). By early 2019, more than 166 leading global corporations had joined the RE100 initiative, a network of corporations committed to using 100% renewable energy (http://there100.org/re100).

Until recently, companies adopted renewable energy solutions mainly as an act of corporate social responsibility. However, significant reductions in renewable energy costs, as well as maturing market and policy environments, have made renewables cost competitive and attractive sources of energy in their own right. The economic benefits of sourcing renewables may also include long-term price stability, security of supply, reduction of energy-related expenses and the possibility of new business opportunities (REN21, 2018).

13.2.3. Technology demonstration

Demonstration systems are an important stage of technology and market development, providing developers the opportunity to manufacture and test new products at pilot or expected final scale, whilst also allowing prospective users an opportunity to see the product and process in operation. Demonstration systems allow fine tuning of processes, monitoring of performance under real-world conditions and hence better estimation of O&M and life cycle costs. It is difficult, if not impossible, to develop a market without demonstration systems and in Australia there are currently very few renewable energy demonstration systems for industrial heat.

Demonstration systems can also be installed at designated demonstration sites or ‘parks’. Although not necessarily in ‘real-world’ industrial conditions, this can allow:

- a range of different technologies to be tested under the same conditions
- easy access for prospective customers to inspect technologies (which can sometimes be difficult at industrial sites due to safety and commercial considerations)
- shared monitoring, O&M staff, load management, storage and other facilities, which can reduce costs for technology developers
- sharing of knowledge amongst system developers, with benefits for all technologies
- prospects for development of shared supply chains and industry infrastructure in future market development.

As an example, the South African SOLTRAIN Initiative focuses on solar thermal training and demonstration, but has found that subsidies are still required for industrial deployment (REN21, 2018).

13.2.4. Tax incentives

Tax incentives can operate at a number of levels, for instance, as exemptions from taxes, such as sales, payroll or import taxes; as tax deductions for individuals or businesses; via accelerated depreciation; or as tax credits. See for instance (KPMG, 2011).

Exemptions from tax have most commonly been used during the industry development phase, although more recently, taxes on imports are being used in Europe and the US to protect local industry against cheaper imports, where these are considered to result from industry support programs introduced by other governments. Tax deductions or credits are more focused on the end user and on deployment.

Examples include:

- The US has used tax credits of 30% for businesses as its key federal government support mechanism for renewables. The tax credit is deducted directly from tax payable and any unused amount can be carried forward to the next tax year.
- Many countries provide exemptions from sales taxes or GST (VAT) for renewable energy system components.
- China uses a range of tax incentives, including reduced tax rates for renewables, VAT refunds at different levels for various renewables, and tax credits for energy conservation.
- The Netherlands offers tax deductions up to 41.5% for renewable energy investments under its Energy Investment Allowance, as well as accelerated depreciation for environmentally friendly assets.

- Canada offers accelerated capital allowances for specified renewables, including industrial process heat and fuels from waste.

13.2.5. Building and Planning Codes

Although not directly targeting industrial heat, building codes can provide a useful indirect incentive for renewables. Current building and planning codes tend to focus more on residential and commercial buildings than industrial settings, but could be extended.

Energy rating schemes that provide credits for renewables have been used in NSW, to meet the BASIX requirements for new buildings or substantial renovations. Germany, France and other countries have provided higher incentives for innovation, such as building integrated or dual function products that provide electricity plus light, heat, or shading. As the building's envelope and HVAC systems improve, regulations can address other installations and renewable energy (IEA, 2008).

Planning codes can also be useful in encouraging optimum orientation for new developments, which is critical to the opportunities then available for solar devices. Solar access regulations are increasingly important to prevent future overshadowing problems as more building owners invest in solar products.

13.2.6. Carbon Pricing

Putting a price on carbon in the economy can be the most broad-based means of encouraging carbon emissions reduction, with policies targeting renewables, energy efficiency, etc. acting as indirect or supporting policies, often with their own additional drivers. There are a number of different carbon pricing policies in operation internationally, while some have operated in Australia in various forms over the past two decades.

Carbon taxes are the most direct application of a carbon price signal. A tax is charged at a set rate of $/t of CO_2 equivalent emissions.

Issues can arise around tax avoidance, write-off against other losses, the treatment of trade-exposed industries, foreign owned companies etc.

Carbon trading schemes

The ability to trade carbon emissions is considered one way to minimise overall abatement cost, since not all emitters will be able to access low-cost emission reduction options.

Baseline and credit schemes allocate a baseline emissions level to a sector or entity and should set a target for reducing this over time. Liable parties must reduce their emissions or purchase emission credits from approved sources if they exceed their annual baseline. Issues can arise with establishing baselines and with agreeing on approved sources (e.g. whether they can be purchased on the international market) and on the additionality of those sources (e.g. whether or not they correspond to abatement that is additional to what would have happened otherwise). The current Direct Action scheme is a baseline and credit scheme, with liable parties bidding through a reverse auction process for funds to undertake emission reduction projects.

Cap and trade schemes impose a cap on total emissions, which reduce over time. Liable entities or sectors must reduce their proportional emissions over time, purchase equivalent emission certificates or face penalties. The carbon pricing scheme that operated in Australia from 2012 to 2014 was a cap and trade scheme, initially with a fixed carbon price. It was repealed before it transitioned to having a market-based price for carbon certificates.

13.2.7. Equipment performance standards

Minimum energy performance standards (MEPS) can be used to increase the energy efficiency of appliances, lighting and equipment. In Australia they are used to set the performance levels of key household appliances, such as refrigerators, and can be gradually tightened over time. Given the high emissions intensity of Australian electricity, improving energy efficiency has the added benefit of reducing emissions.

In Australia, the *Greenhouse and Energy Minimum Standards (GEMS) Act* covers MEPS and the associated Energy Rating Labelling (ERL) requirements (GEMS Regulator, 2012). Similar standards could be used to improve the efficiency of industrial equipment. This could mean that industrial energy use requirements reduce over time, as equipment is upgraded, whether or not processes are changed. Reductions in the energy requirements of a site can in turn change the cost-effectiveness of supply options and could accelerate adoption of renewable energy.

14. CONCLUSIONS

The extensive discussion of issues around electricity supply in the community has overshadowed consideration of industrial process heat in recent times. The large increases in gas prices that have followed the expansion of the LNG export industry, combined with Australia's commitments to reduce greenhouse gas emissions eventually to near zero, mean that greater attention to alternatives to heat supply are required. Current higher east coast gas prices are likely to continue into the future and the ability of industrial customers to secure contracts for supply remains challenging. The carbon risk with fossil fuel use in general also continues.

At present, industrial process heat is predominantly provided by gas combustion with coal the second biggest source. Renewable energy is already a significant contributor via bagasse from sugar production, wood waste and other bioenergy, and provides a share of the electricity that is already used for heat. Smaller companies as a rule pay higher costs of energy for gas and other fuels, which makes renewable alternatives more competitive, but this is countered by the fact that smaller renewable energy systems are more expensive per megawatt than larger ones.

In this report we have investigated the economics of heat supply from; bioenergy, geothermal, renewable electricity, renewable hydrogen and solar thermal, and compared these with the range of costs that industry currently faces with fossil fuels. While renewable hydrogen is still an expensive option at this stage, it is found that there are situations where each of the other renewable approaches can be economic at the present time. There are more options available for lower-temperature process heat. There are also many examples where process redesign can reduce energy use and facilitate the conversion to renewable sources.

So far, bioenergy is the big achiever in the supply of renewable heat. As well as high-profile use of sugar cane and wood waste within the respective industries, systems continue to be installed in many industry sectors and the visibility of and confidence in working systems grows. Low-temperature geothermal systems appear attractive in areas where hot aquifers exist. Solar thermal solutions appear to have great potential but have so far not gained traction and must deal with the chicken and egg problem of an industry reluctance to adopt systems for which there are not many visible examples. Low temperature lift heat pumps are already economically attractive if used at high capacity and particularly when providing simultaneous heat and cooling functions. Resistance heating offers the advantage of low installed cost, and electromagnetic systems can bring efficiency advantages when process redesign is contemplated.

There are demonstrated renewable energy technologies available for every application of process heat. However, the level of industry experience remains low and so uptake represents a challenge. In seeking to advance the uptake of renewable heat in industry, it is important to understand the drivers and barriers that industry faces. There are a range of technology and business risks that managers must deal with to avoid the bad outcomes that can have major consequences to ongoing business viability. In addition, whilst positive internal rates of return are apparent for many renewable energy solutions, companies typically expect simple payback times of just a few years for their energy investments. However, against this there are examples that show that when issues become an existential threat, higher levels of technical risk are considered acceptable and investments may be much longer term.

The renewable process heat options covered in this report can be placed into two categories. The most straightforward involves adapting the heat sources and processes used in thousands of existing industrial plants. These are incremental changes based on new but technically proven technologies. These changes have the potential to convert around half of industrial energy use and are within the grasp of single businesses, sites, or corporations. Nevertheless, they are likely to be pursued over time only under major refits, or if supported by an appropriate market or incentive. There are a number of policy measures identified in this report that can accelerate the uptake of these technologies.

The second category, a very large part of the opportunity for major change in Australia, is in long-term change to a few processes that notably consume the most energy. This change requires an appetite to tackle issues that are beyond the reach of any single business. These opportunities include the replacement of fossil fuels in ammonia, alumina and steel manufacture, and in the cement industries. These businesses exist as a small number of corporations and with a few large plants, rather than a plethora of small plants and businesses. They also tend to be more directly exposed to international competition and hence have been largely exempt from greenhouse gas reduction measures to date.

Attitudes to change in businesses involve a complex assessment of perceived risk that has different nuances for every business, even in the same industries. Implementing change in this second category is difficult. Large-scale material change in these industries cannot be funded by single entities and requires assistance and at least coordination as well as a pace of change that does not expose Australian businesses to damaging differences in competitiveness.

Hydrogen has received a lot of attention in the past year or so as a future fuel for industry, transport and export. It appears to have enormous potential, however realising this potential will depend on developing a major production industry to drive the cost down and develop the distribution approaches. Iron and steel, ammonia and chemicals, and the high-temperature aspects of alumina and non-ferrous metals production are very large sectors for heat use where concepts exist for renewable energy use via hydrogen for example. The economic gap is however currently large in Australia. Progress in these areas depends on the emergence of a global market for emissions free versions of the products. If this happens, then Australia, having both the raw materials and excellent renewable energy resources, should be in a position to produce them at a lower cost than other countries. This will require massive investments in new plants and processes.

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16. LIST OF ABBREVIATIONS

ABS	Australian Bureau of Statistics
ACCC	Australian Competition and Consumer Commission
AERA	Australian Energy Resources Assessment
AES	Australian Energy Statistics
ANZSIC	Australian and New Zealand Standard Industrial Classification
ARENA	Australian Renewable Energy Agency
AUD	Australian Dollars
CHP	Combined heat and power
COP	Coefficient of performance
CPC	Compound parabolic concentrator
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrated solar power
CST	Concentrated solar thermal
DNI	Direct normal irradiance (W/m^2)
DRI	Direct reduced iron
GHG	Greenhouse gas
GHI	Global horizontal irradiance (W/m^2)
GWP	Global warming potential
HBI	Hot briquetted iron
HTF	Heat transfer fluid
IEA	International Energy Agency
IRR	Internal rate of return
ISF	Institute of Sustainable Futures
ITP	ITP Renewables/Thermal
LCOE	Levelised cost of energy
LCOH	Levelised cost of heat
LNG	Liquified natural gas
LPG	Liquified petroleum gas
NGERS	National Greenhouse and Energy Reporting Scheme
NPI	National Pollutant Inventory
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Cooperation and Development
ORC	Organic rankine cycle
PJ	Petajoule (1 PJ = 10^{15} Joule)
PV	Photovoltaics
RE	Renewable energy
SAM	System Advisor Model (by NREL)
SHIP	Solar heat for industrial processes
TMY	Typical meteorological year
UNIDO	United Nations Industrial Development Organisation

US DoE	United States Department of Energy
USD	US Dollars

Energy unit conversions and prefixes

kW	Kilowatt, unit of power equal to 1,000 W
kWh	Kilowatt-hour, unit of energy (1 kW generated/used for 1 hour)
kWp	Kilowatt-peak, unit of power for PV panels tested at standard test conditions
MW	Megawatt, unit of power equal to 1,000 kW
MWh	Megawatt-hour, unit of energy (1 MW generated/used for 1 hour)
MJ	Megajoule, unit of energy equal to 10^6J
GJ	Gigajoule, unit of energy equal to 10^9J (1,000 MJ)
TJ	Terajoule, unit of energy equal to 10^{12}J
PJ	Petajoule, unit of energy equal to 10^{15} J
EJ	Exajoule, unit of energy equal to 10^{18} J
e	As a subscript on any of above indicates electricity
th	As a subscript on any of above indicates thermal

Appendices in a separate file.

Both this main report document and the appendices can be downloaded from

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