Renewable energy options for industrial process heat

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APPENDICES

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Prepared for

ARENA

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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 –

APPENDICES

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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This document is a continuation from the main report

The main report document and the appendices can be downloaded from

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APPENDIX A. REVIEW OF 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 as well as their application sectors. Several previous studies were discussed in our initial study (Lovegrove et al., 2015a, 2015b). Here we provide an overview of recent pertinent studies since the release of our initial study in 2015.

A.1. ITP

A.1.1. Renewable Energy Options for Industrial Gas Users

In 2015, a team led by ITP, in collaboration with Pitt&Sherry and the UTS Institute for Sustainable Futures, and commissioned by ARENA, conducted the first comprehensive study about Renewable Energy Options for Australian Industrial Gas Users, consisting of a summary report and a detailed technical background report (Lovegrove et al., 2015a, 2015b). These reports illustrated the opportunity for industrial gas users of switching to renewable energy, depending on their current and prospective natural gas price. It provided an overview of the range of renewable energy options, including bioenergy, solar thermal, and others (including geothermal and heat pumps). The study was accompanied by a number of real-world examples of renewable energy integration in industries including food and beverage, mining, waste utilisation, and building heating and cooling.

A.2. Australian Energy Resources Assessment

The AERA, produced by Geoscience Australia and the Department of the Environment and Energy, with support from ARENA, provides a scientific and economic assessment of Australia’s non-renewable and renewable energy resources (Geoscience Australia, 2018). This up-to-date online resource provides an overview as well as resource specific information and data on the Australian energy landscape and past and future trends in energy generation, supply, export and domestic use, to inform industry and policy makers.

A.3. International Energy Agency

A.3.1. Renewable Energy for Industry

In 2017, the International Energy Agency published Renewable Energy for Industry—From green energy to green materials and fuels (Philibert, 2017). The report provides an overview of the current and potential future renewable energy solutions to reduce GHG emissions originating from industrial processes. Current renewable energy technology options for process heat applications discussed are bioenergy, solar thermal and power to heat. Options for renewable energy via electricity discussed include renewable energy power procurement/generation and electrification of steam- and gas-driven components, such as compressors, pumps and valves by replacing them with electric drives.

The recent decrease in electricity costs from PV and wind was highlighted as a particular opportunity for renewable energy integration either via electrification and electric heat generation or the production and use of hydrogen-rich chemicals and energy carriers, including liquid hydrogen, ammonia, methanol, dimethyl ether (DME) and organic hydrides (such as methyl-cyclohexane (MCH), typically via water electrolysis. An additional benefit of increasing electric power use by the industry sector may be the additional flexibility provided for the integration of variable renewables to the power grid.

The report argues that in ideal locations with very high solar, wind and hydro resources, hydrogen production through renewable water electrolysis is cost-competitive with steam methane reforming, and ammonia could be produced at costs that are competitive with current market costs in some regions (such as Europe and Asian markets).

It is estimated that in the event of a large-scale electrification of industrial processes, several terawatts of additional electric power capacity would need to be installed, in addition to the new capacity installation already projected in IEA´s long-term low-carbon scenarios.

Potential new technologies that lead to reductions in GHG emissions discussed include using hydrogen as the reducing agent (instead of coke) in the production of pig iron from iron ore. In cement manufacturing, replacing fossil energy (coal, oil and gas) with solar and (renewable) electric heating, molten carbonate electrolysis or electrolysis of solubilised limestone, with the potential to produce methanol and carbon nanotubes as by-products.

A range of policy and market mechanisms are discussed that could promote the uptake of renewable energy technologies in industry. At the national level, these target improved access and use of renewable electricity and economic incentives for the development and adoption of renewable energy technologies. Internationally, discussed measures to increase trade of clean materials include global and sectoral renewable energy standards, customs tax schemes based on carbon intensity of traded goods, and procurement of carbon-free materials by industries and the public to reduce the grey energy content of final manufactured products.

A.3.2. Solar Heat Worldwide

This annual report provides an overview of the trends in solar heating worldwide and highlights projects that are of particular interest (Weiss & Spörk-Dür, 2018). It provides data on installed solar thermal capacity based on data collected from 66 countries, representing approximately 95% of the global solar thermal market. Technologies covered include all types of stationary and concentrating solar collectors.

In 2017, solar thermal heat provided 388 TWh of heat with an installed capacity of 472 GW_{th}, compared to 1,430 TWh and 494 TWh of electricity by Wind and PV, respectively and compared to 5 GW_e for CSP. This corresponds to 134.7 Mt-CO_2 emissions savings.

Globally, most of the installed solar thermal capacity derives from the traditional mass markets for solar water heaters for residential applications. However, there has been growing interest in solar thermal for district heating and industrial applications, with solar district heating systems having reached a total installed capacity of 1.14 GW_{th} worldwide by the end of 2017, with multiple large projects completed in Denmark. By the end of 2017, the area of solar heat for industrial processes (SHIP) had grown to over 600 systems with total installed collector area over 600,000 m^2 (>400 MW_{th}), and system sizes ranging from small demonstration projects to plants of over 100 MW_{th} capacity (Miraah EOR plant in Oman). 2017 saw a growth of 25% in the number of installed SHIP plants and 46% growth in installed collector area.

The majority of current and new installed solar thermal systems remain thermosiphon systems, typically used for water heating.

Worldwide, the solar thermal industry has an annual turnover of around USD $19.2 billion and provides around 700,000 jobs.

The IEA Solar Heating and Cooling Programme (http://task49.iea-shc.org/) provides publications on technically relevant topics such as (Frank et al., 2012, 2015).

A.3.3. Solar Heat for Industrial Processes, Technology Brief

This report provides an overview of solar thermal technology status and opportunities for industrial processes requiring up to 400°C (IEA-ETSAP / IRENA, 2015b). The report contains an overview of installed capacity, performance and cost data, information about the economics and a list of industrial process steps suitable for solar process heat. It further provides insights to the barriers for the uptake of SHIP technologies and recommendations for specific policy actions to promote the uptake of solar thermal process heat in industry. Barriers include:

- short payback time expectations (<3 years)
- relatively low fossil fuel prices charged in the industrial sector
- risk accompanied with integrating solar thermal into existing complex industrial processes
- rooftop space and finance opportunities for the upfront costs (esp. for SMEs.

Benefits include:

- reduced dependence on volatile fossil fuel prices
- solar thermal technologies can be produced by local manufacturing, creating additional economic stimulus, particularly in developing countries, where labour costs are significantly lower than in the developed world.

The uptake of SHIP technologies can be facilitated if solar thermal systems are integrated during the construction phase of new industrial plants. Policy actions and support to promote the uptake of SHIP technologies include:

- create more awareness of the benefits of solar industrial process heat
- provide design guidelines and tools
- provide financing mechanisms to cover upfront costs
- consider whether support for solar thermal could be an alternative to fossil fuel price subsidies to national industries.

A.3.4. Biomass for Heat and Power, Technology Brief

Similar to the IEA/IRENA Technical Brief for SHIP, this report summarises the technology, status, costs, benefits, barriers and potential enablers, including policy measures, for further uptake of biomass energy production systems (IEA-ETSAP / IRENA, 2015a).

The report summarises the biomass energy technology mix, which currently consists of around 50% (27 EJ) traditional woodstoves in developing countries, with the remainder a mix of:

- power generation and CHP (using fixed or fluidised bed combustors)
- biomass co-firing in coal power plants
- anaerobic digestion of wet biomass with CHP.

Biomass energy production has unique aspects and challenges to it, including:

- biomass feedstock is available in some form and to some extent in most parts of the world
- nexus of biomass for food, feed, fibre and energy
- competing potential impacts on the environment may include biodiversity, GHG emissions, landscape development, soil and water.

The key to bioenergy production is to ensure the sustained supply of appropriate biomass feedstock sources (in terms of quality, quantity, cost, location) over the planned lifetime of a biomass energy system.

Current installed costs for bioenergy systems are:

- power generation and CHP: <USD $4000-7000/kW
- retrofitting co-firing of biomass in coal power plants: USD $140-850/kW
- anaerobic digestion: USD $2574-6100/kW.

Annual O&M costs in % of CAPEX are:

- large capacity: 3-5%
- small capacity: 6-6.5%
- co-firing plants: 2.5-3.5%.

Typically, the biomass feedstock costs contribute 40-50% of the energy production costs and range as follows:

- waste: <US$0-0/GJ
- processing residues: US$0-4/GJ
- locally collected feedstock: US$4-8/GJ
- international traded feedstock: US$8-12/GJ.

In addition, increasing competition for biomass feedstocks may increase its price in the future.

Policy actions and support to promote the uptake of SHIP technologies include:

- national biomass power generation (and possibly process heat) targets
- feed-in-Tariffs (with suitable tariff degression over time)
- tax credits
- policy stability
- sustainability criteria for biomass as a fuel / certification systems for sustainable forest management.

A.3.5. General requirements and relevant parameters for process heat collectors and specific collector loop components

The IEA Solar Heating and Cooling, Task 49 (in collaboration with SolarPaces Annex IV) provides guidance for solar process heat collectors design and installation. It consists of the following subtasks (Frank et al., 2012):

A: Process heat collectors: aims to improve all types of collectors and develop recommendations for standardised testing procedures; first aim is to increase knowledge about general requirements and relevant parameters of process heat collectors and their improvement.

B: Process integration: aims at development of advanced pinch and storage management tools; survey of integration methodologies for solar process heat; develop system concepts and integration guidelines.

C: Design Guidelines: establish design guidelines, simulation tools, performance assessment methodology, monitoring of demonstration/best practice projects;

A.4. International Renewable Energy Agency

A.4.1. Renewable Energy Policies in a Time of Transition

This comprehensive document, jointly prepared by IRENA, IEA and REN21 (Renewable Energy Policy Network for the 21st Century), provides an in-depth description of the policy options that policymakers around the world have available to support the development of renewable energy (IRENA / IEA / REN21, 2018).

The document reviews the status of policies and targets globally and provides policies for each of the sectors in heating and cooling, transport and power. It also provides an updated classification and terminology for renewable energy policies.

Although the largest of the three main energy sectors (by final energy), the heating and cooling sector is the least regulated. Existing policy measures include mandates and obligations, fiscal and financial incentives and carbon and energy taxes.

A.5. US Department of Energy

A.5.1. Bandwidth Studies

Since 2015, the US Department of Energy´s Advanced Manufacturing Office has commissioned a series of so called Energy Bandwidth Studies across 16 industry sectors (Energetics Inc., 2017):

- Advanced high-strength steel (AHSS)
- Aluminium
- Carbon fibre
- Cement
- Chemicals
- Food and beverage
- Glass
- Glass fibre
- Iron & Steel
- Magnesium
- Mining (conducted in 2007 with potential deviations in methodology)
- Petroleum refining
- Plastics and rubber
- Pulp and paper
- Seawater desalination
- Titanium.

All reports are publicly available and can be downloaded free of charge from the US Office of Energy Efficiency and Renewable Energy's website: https://www.energy.gov/eere/amo/energy-analysis-data-and-reports.

These studies provide a systematic and comparable analysis of the energy use and trends and energy savings potential across energy-intensive industrial processes in the US. The goal of the Bandwidth Studies is to use a consistent methodology across all sectors to enable intra- and cross-sectoral comparisons. The studies analyse the 'bandwidth', i.e. the range in energy consumption for specific industrial processes to establish current typical energy consumption, state-of-the-art energy productivity, practical minimum energy requirement and energy reduction potentials.

A.5.2. Other Resources

The DoE Office of Energy Efficiency and Renewable Energy further provides two-page diagrams, mapping the manufacturing energy and carbon footprints for a range of industries: https://www.energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs

Besides these technical publications, the DoE coordinates researchers and other partners to deliver innovative technologies and, maintains projects, analyses, protocols and strategies to reduce industrial energy intensity and carbon emissions. It further offers various software tools, such as the Process Heating Assessment and Survey Tool (PHAST) and the Steam System Modeling Tool (SSMT), available at http://energy.gov/eere/amo/software-tools, a Sankey diagram tool to compare and explore energy flows across US manufacturing and within 15 key subsectors at https://www.energy.gov/eere/amo/dynamic-manufacturing-energy-sankey-tool-2010-units-trillion-btu, as well as training and other guidance to industry tailored to the individual industry sectors. The following websites contain more information, details and links:

https://www.energy.gov/eere/renewables

https://www.energy.gov/eere/amo/industries-technologies

Although these reports, tools, etc. were prepared in the US context, they may also serve as useful information sources and references for energy standards and savings potential in international industries operating in Australia.

A.5.3. Other recent studies

In addition to the Bandwidth Studies, the US DoE has published a number of other relevant publications.

Technology Assessments – Process Heating

This report, along with 13 other technical assessments, was prepared in support of the 2015 Quadrennial Technology Review of the area of Innovating Clean Energy Technologies in Advanced Manufacturing (US DoE, 2015d).

The report shows a Sankey diagram of process energy flow (from steam, electricity and fuels to applied energy and process end use losses) in the US manufacturing sector. It shows that the largest portion, around 70%, of process energy (7.6 EJ), is used for process heating. Industry-specific process heat demands, process specific temperatures and heat demands and process heat saving opportunities are presented. The report contains a description of existing (non-renewable) process heating technologies via combustion or electricity. It outlines improvement potentials for process heating subsystems, including components and enabling technologies, discusses potential for R&D and provides insights to barriers for industrial process heat integration. The report also contains two case studies about infrared and microwave heating to reduce energy use and improve product quality.

Technology Assessments – Waste Heat Recovery

This document is similar to the technology assessment for process heating. It provides an overview of major waste heat sources along with their typical temperature ranges and cleanliness (US DoE, 2015e).

The report then summarises and comments on several previous reports on energy efficiency and waste heat recovery published by the US DoE. Previous reports cited include:

- Oak Ridge National Laboratory (ORNL), Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities, Arvind Thekdi (E3M Inc.) and Sachin Nimbalkar (ORNL), ORNL/TM-2014/622, January 2014. Available at: http://info.ornl.gov/sites/publications/files/Pub52987.pdf. This report provides a current, comprehensive assessment of WHR technologies, and sections of this report are excerpted in this Technology Assessment.
- Energetics Incorporated and E3M, Incorporated, Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing & Mining, prepared for the U.S. Department of Energy, Industrial Technologies Program, December 2004. Available at: http://energy.gov/sites/prod/files/2013/11/f4/energy_use_loss_opportunities_analysis.pdf
- BCS, Incorporated, Waste Heat Recovery: Technology and Opportunities in U. S. Industry, prepared for the U.S. Department of Energy, Industrial Technologies Program, March 2008. Available at: http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf
- Pacific Northwest National Laboratory (PNNL), Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions, prepared for the U.S. Department of Energy, April 2006. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-15803.pdf
- Lawrence Berkeley National Laboratory (LBNL), Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries: An ENERGY STAR® Guide for Energy and Plant Managers, prepared for the U.S. Environmental Protection Agency, February 2015. Available at:
- http://www.energystar.gov/sites/default/files/tools/ENERGY_STAR_Guide_Petroleum_Refineries_20150330.pdf
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- Energetics Incorporated for Oak Ridge National Laboratory, U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis, prepared for the U.S. Department of Energy, Industrial Technologies Program, 2012. Available at: http://www.energy.gov/eere/amo/downloads/usmanufacturing-energy-use-and-greenhouse-gas-emissions-analysis.
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- Oak Ridge National Laboratory (ORNL) and E3M Inc., Technologies and Materials for Recovering Waste Heat in Harsh Environments, Sachin Nimbalkar, Arvind Thekdi, et.al., ORNL/TM-2014/619. Available at: http://info.ornl.gov/sites/publications/files/Pub52939.pdf

The report further shows typical heat losses of industrial process types. Process heating is shown to have around 25% end use losses.

It reproduces a list of waste heat recovery opportunities in harsh environments, such as in steel, glass, aluminium, and cement industries.

The report further contains a list of barriers to the implementation of waste heat recovery in industry.

Areas for further R&D are identified at the very low-temperature (<120°C) and very high-temperature (>870°C) ranges. Very low temperatures present challenges with economics, while at high temperatures streams are often contaminated, which poses challenges with the materials of a waste heat recovery system in contact with the waste heat source. At intermediate temperatures (around 300 to 650°C), opportunities exist for enhanced waste heat recovery.

The report than reviews existing waste heat recovery technologies and their limitations, potential emerging technologies and technology opportunities. It concludes with a detailed set of R&D opportunities.

Improving Process Heating System Performance

This Sourcebook is intended as a practical guide for industry to review and identify opportunities for reducing energy demand for process heat (US DoE, 2015c). It is a companion for some of the other resources offered by the DOE, such as the technology assessments and software tools described above.

Barriers to Industrial Energy Efficiency

This report explores barriers to the accelerated uptake of energy efficiency measures in the industrial sector, shows opportunities to overcome the barriers and gives examples (US DoE, 2015a).

Annual Reports of the Geothermal Technologies Office (GTO)

The GTO promotes RD&D of geothermal technologies in the US. The annual reports provide updates on technology status, R&D activities, projects and market developments for geothermal energy in the USA (US DoE, 2018)

The goal of the GTO is to reduce costs and risks of geothermal energy technology, with a focus on the areas:

- Hydrothermal resources – exploration of natural geothermal sites
- Enhance geothermal systems – creation of man-made geothermal reservoirs
- Low temperature and coproduced resources – low-temperature (below 150°C) geothermal resources
- Systems analysis – technology progress monitoring and addressing of challenges

The GTO further maintains a data repository of their projects, a mapping tool for siting of utility-scale power projects, a regulatory roadmap, as well as performance, cost and economic impact analysis models, and several reports.

A.6. National Renewable Energy Laboratory (US)

A.6.1. Generation and Use of Thermal Energy in the US Industrial Sector and Opportunities to Reduce its Carbon Emissions

Industry contributes 20% of total US GHG emissions, with half of it originating from fuel combustion to produce hot gases, steam for process heating, process reactions, and process evaporation, concentration and drying (McMillan et al., 2016).

Challenges to minimising GHG include:

- heterogeneity and variations in the scale of US industry
- complexity of modern supply chains.

Solutions:

- energy efficiency
- material efficiency
- switching to low-carbon fuels.

Energy solutions:

- nuclear (small modular reactors)
- solar thermal industrial process heat)
- geothermal energy
- electrical heating
- hydrogen.

The study analysed energy use across 14 industries in the US, using data from the US EPA GHGRP for the 960 companies within the 14 industries that were required to report their emissions, together contributing 5% of US total GHG emissions in 2014. It found:

- within these 14 industries (and the companies represented in the study), 70% of the heat demand was for CHP and steam generation
- process heat integration typically via steam jackets, heating coils, and indirect heat exchangers (mostly from combustion gases to process reactors)
- for solar industrial process heat, technical and economic feasibility depended on solar insolation and space availability for the solar thermal system at (or nearby), the industrial facility
- besides being a fuel source, hydrogen should also be considered for petroleum refining and as a potential substitute for coke as a reducing agent in steel-making

Recommendations of the report include:

- additional nuclear-renewable hybrid energy system case studies
- assessment of industry electrification options
- evaluation of thermal energy storage buffers and heat-transfer systems
- detailed evaluation of SHIP and geothermal energy resource potential for industrial heating
- technical/economic assessment of the benefits of hydrogen production for industrial use.

A.7. Oak Ridge National Laboratory (US)

A.7.1. Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities

This report focuses on waste heat recovery from industrial plants, which correspond to 25-55% of total energy use in industry ((Thekdi & Nimbalkar, 2014)). It shows sources and characteristics, such as temperature, of waste heat and discusses existing and emerging technological solutions, challenges (such as quality/cleanliness of waste streams, low temperatures, costs, lack of on-site use) and R&D opportunities (e.g. micro-size heat exchangers, new corrosion-resistant materials) for waste heat.

A.8. UK Government

The UK Department of Energy and Climate Change and the Department for Business, Innovation and Skills commissioned a series of Industrial Decarbonisation and 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. The reports then set out a range of techno-economic and business decision-making evidence on the decarbonisation issues that are most relevant to that sector. This evidence is synthesised to produce a series of potential pathways for emissions reduction (WSP Parsons Brinckerhoff, 2015).

The UK Business, Energy & Industrial Strategy Department recently published a study investigating the potential of switching to alternative fuels in energy intensive industries (Lyons et al., 2018). The study focuses specifically on the situation in the UK and mainly considers process heat applications. Main alternative fuel options considered are biomass and waste, hydrogen and electricity. In addition, carbon capture utilisation and storage (CCUS) is considered.

Fuel-switching technology options for each application of process heat are given. The total technical potential for fuel switching was estimated to be 89 TWh per year by 2040 with the potential to save up to 16 Mt of CO_2, out of a total consumption of 320 TWh.For 2030, the technical potential was estimated to be 56 TWh.

Largest sectors identified 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, together accounting for 86% of the demand that is in principle suitable for fuel switching. In contrast, the commercial potential, i.e. the potential to reach discounted payback times of five years or less, is estimated to be only about 20% of that, i.e. 11 TWh by 2030.

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 suitable technologies. However, biomass use is found to be likely limited by supply and concomitant cost constraints.

Time scales are estimated for the commercialisation of different fuel-switching technologies across the major industries, including time required for developing, testing, demonstration and investment decision for new energy solutions.

The study finds that in the absence of a carbon emissions price, the most likely cost-effective fuel-switching options are low-temperature indirect heating applications with solid biomass, or heat pumps for smaller-scale applications of several hundred kW. For direct heating applications, biomass or hydrogen are expected to be more cost effective than electric options.

It was further found that, if a carbon emissions price is taken into account (assumed at £77/t-CO_2), in certain cases combining fuel switching with CCUS can lead to cost-effective achievement of negative emissions and even negative costs, particularly when combined with bioenergy. In addition, hydrogen production combined with CCUS co-located with potential large-scale applications of hydrogen (i.e. in furnaces and kilns) is recommended for further investigation.

A.9. Germany's Solar Payback Program

Solar Payback is a three year program (2016-2019) financed by the German Federal Environment Ministry's International Climate Initiative (IKI), to promote the uptake of solar thermal industrial process heat (SHIP) in South Africa, India, Mexico and Brazil. The program aims to raise awareness about the technical and economic potential of SHIP technologies by providing clear and transparent information on their costs and benefits. It further helps to build selected reference systems in the target countries and cooperates with financial institutions to assist stakeholders and investors in securing access to financing.

Solar Payback published a pamphlet on SHIP. The opportunity for SHIP is presented in terms of global low to medium-temperature (up to 400°C) process heat demand (approx. 1400 GW), compared to current global solar process heat installed (0.28 GW). A break-down of industrial heat demand by industry and temperature is provided, together with an overview of the temperature levels of significant industrial processes (Solar Payback, 2017).

Current barriers for SHIP perceived by turnkey suppliers and drivers for the uptake of SHIP are listed. A number of operational systems in the target countries (except Brazil) are showcased and a list of global SHIP suppliers with a record of completed projects is provided.

The Solar Payback website contains a map tool showing SHIP technologies suppliers worldwide, and can be found at: https://www.solar-payback.com/suppliers/.

A.10. Australian Alliance for Energy Productivity

The Australian Alliance for Energy Productivity published a guide for businesses on replacing steam with electricity technologies to boost energy productivity (Jutsen et al., 2018).

A.11. Zero Carbon Industry Plan – Electrifying Industry

Beyond Zero Emissions' Zero Carbon Industry Plan – Electrifying Industry focuses on electrically-heating industrial processes through a range of heating processes (Lord, 2018). This report has provided much of the background for the material on electric heating in Appendix E.

APPENDIX B. ANALYSIS OF ENERGY USE

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 coke, coal by-products and brown coal briquettes. Biomass fuels have a significant existing role for particular niche applications.

The most comprehensive source of energy statistics 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).

B.1. Fuel use for process heat in Australia

Natural gas consists of almost pure methane, often containing small quantities of CO_2 (always less than 2% by volume), nitrogen, and sometimes ethane. The term natural gas is applied to gas found in underground reservoirs, almost always in association with varying amounts of other hydrocarbons such as ethane, propane and butane. Over the past fifteen or so years gas has also been produced from coal seams, and in eastern Australia natural gas supplied to consumers may consist of either gas produced from so-called conventional sources and coal seam gas. Natural gas first became available to consumers, initially only in Brisbane, Melbourne and Adelaide, in 1969. Over the subsequent fifty years it has become more widely used than any other source of energy, across the entire range of energy using activities. As a clean burning and readily controllable fuel it is used directly for low-temperature processes, such as cooking, and high temperature processes, in kilns and furnaces. It is also used indirectly to produce useful heat in the form of hot water and steam, and as a fuel for combustion engines, including both internal combustion engines and gas turbines.

It is these characteristics that have made gas by far the most important source of process heat for Australian industry. Figure 74 shows quantities of natural gas used by the various sectors of economic activity. Total consumption was 1,517 PJ in 2016_17.

It will be seen that three sectors, electricity generation, oil and gas extraction and processing, and residential, account for about two-thirds of total consumption. Electricity generation and residential consumption are outside the terms of reference for this study.

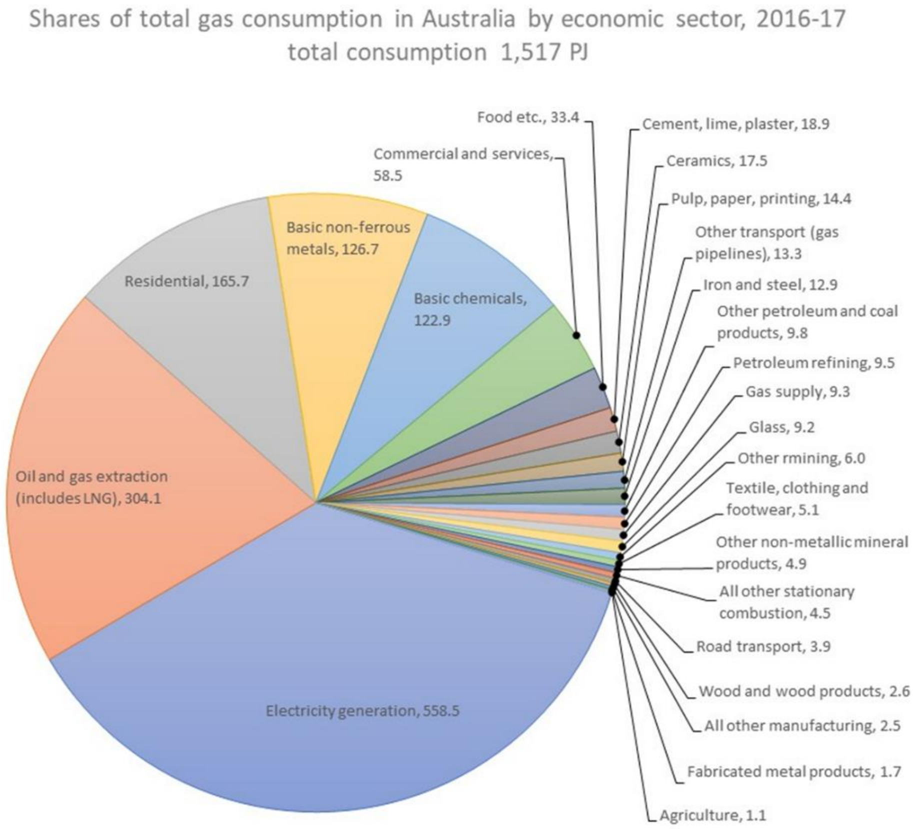

Figure 74: Gas consumption in PJ, Australia, 2016-17. Data from Australian Energy Statistics.

The great majority of gas used in what is defined in Australian Energy Statistics as the oil and gas extraction industry is in the processing of raw gas for domestic market use and in the further processing of gas to produce LNG for export. Australian Energy Update 2018 states that in 2016-17 production of LNG used 239 PJ of gas, excluding gas used to generate electricity, which is reported in Australian Energy Statistics under Electricity generation. This implies that the remaining 65 PJ of gas is consumed at gas processing plants servicing the domestic gas industry. Note that Australian Energy Statistics departs from ANZSIC in its classification of LNG production, which ANZSIC classifies in Division C, Manufacturing, as part of Subdivision 18, Basic chemical manufacturing.

Some of the particular processes used to remove impurities in the raw gas stream, prior to further processing to either pipeline gas or LNG, require thermal energy input. However, the great majority of the energy used in gas processing takes the form of motive power to drive compressors. Gas processing plants use one of a relatively small number of proprietary processes, in which energy flows within the plant are closely integrated. Most of this motive power is provided by gas turbines, consuming some of the gas input to the plant, with waste heat used to meet thermal energy requirements. Electrical energy requirements are supplied by on-site generation, also powered by either gas or linked steam turbines, i.e. in a combined cycle configuration.

For these reasons, we consider there is very little scope to replace plant gas use with renewable energy, notwithstanding the opportunity cost value of gas consumed within the plant.

Other, somewhat smaller uses of gas in Australia are also outside the scope; these include Other mining, Pipeline transport, Road transport, Gas industry (meaning supply of gas to the domestic market), and Construction. Other mining is excluded because Australian Energy Update 2018 states that all gas consumption in this sector is used for electricity generation. Gas industry and Construction are grouped as “All other stationary combustion” in Figure 74. Figure 75 shows the distribution of gas consumption between the remaining sectors, with all the above consumption categories removed.

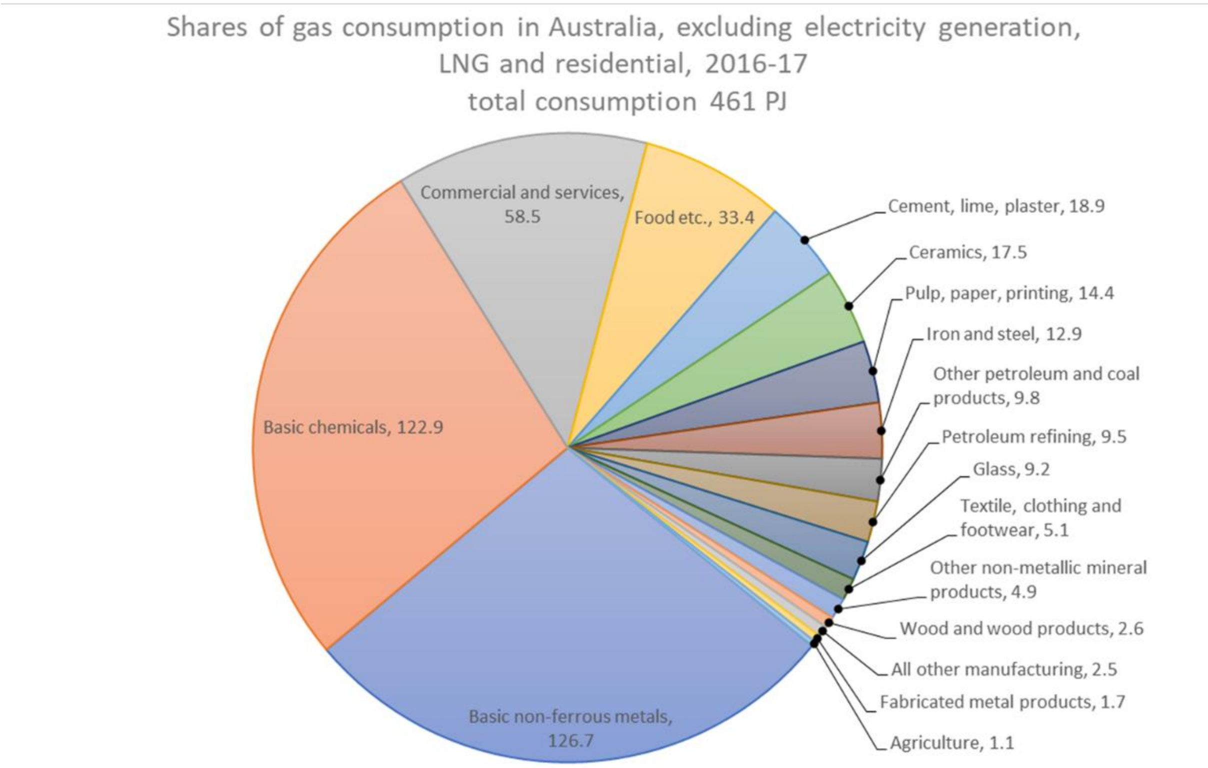

Figure 75: Shares of gas consumption in PJ, Australia by relevant economic sector in 2016-17; total consumption: 461 PJ. Data from Australian Energy Statistics.

In the Commercial and services sector most gas consumption is for space heating (in cooler parts of south east Australia), hot water, and cooking (outside the scope of this study). However, Commercial and services, as defined in ANZSIC, also includes commercial laundries, which are classified under Division S, Other services, Subdivision 95, Personal and other services, Group 953, Other personal services, Class 9531, Laundry and dry-cleaning services. Commercial laundry businesses are large users of gas to produce hot water and steam, as evidenced, for example, by the severe disruption of service to hospitals and hotels in Perth caused by the explosion at the Varanus Island gas processing plant, and resultant loss of gas supply. We know of no public data on the total quantity of gas used by laundry services and have therefore excluded the whole Commercial and services sector from subsequent figures and graphs. However, some data on commercial laundry services is examined later in this chapter.

The overall effect of the exclusions discussed here is that all the remaining sectors, with the sole exceptions of Agriculture, ANZSIC Division A, fall within ANZSIC Division C, Manufacturing. Figure 76 shows trends in annual gas consumption by these sectors since 2008-09.

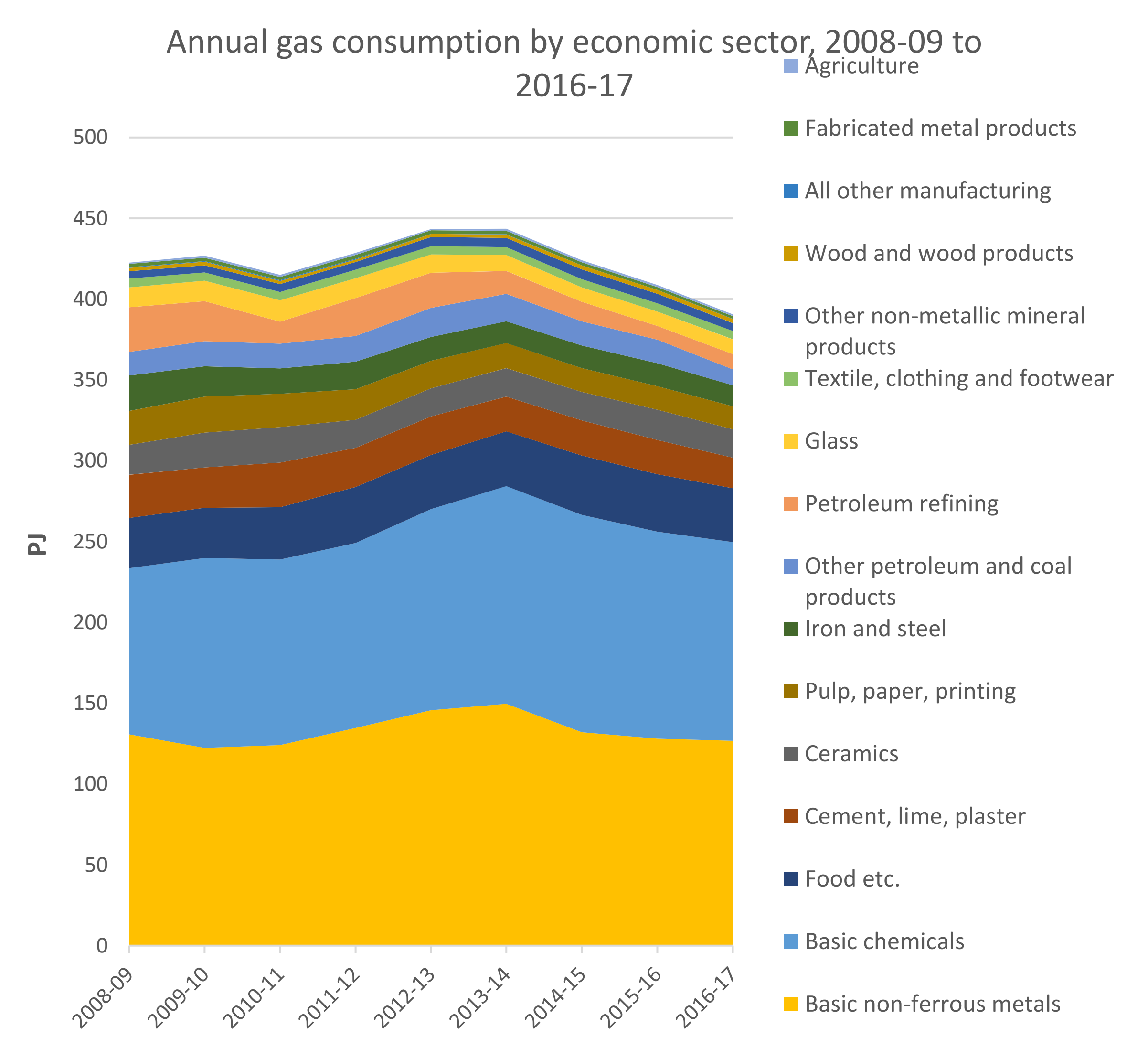

Figure 76: Development of annual gas consumption by sector since 2008-09.

Coal and related products, until about fifty years ago the main, indeed almost only source of energy for process heat throughout the economy, has long since been displaced by gas as the fuel of choice for process heat. However, as Figure 77 shows, using the same Y-axis scaling as Figure 76, very large quantities of coal and coal products are still used in some industries. By far the largest user of coal is the iron and steel industry. Here coal, or, more precisely, coke, which is a coal product, is used as the reducing agent to convert iron oxide to metallic iron (in the form of pig iron) in blast furnaces, which is the first stage of what is called integrated steel production. Australia has two integrated steel mills, at Port Kembla, NSW and Whyalla, SA. Coke ovens (where coal is converted to coke) and blast furnaces produce large volumes of coal by-products, in the form of coke oven gas and blast furnace gas, and these are the major source of process heat in integrated steel making. Coal is both a process raw material and a source of process heat. A somewhat similar situation applies in the case of other coal products, which include brown coal briquettes.

The other main coal using sectors are non-ferrous metals and cement. Details of how and where coal is used are provided in the next section.

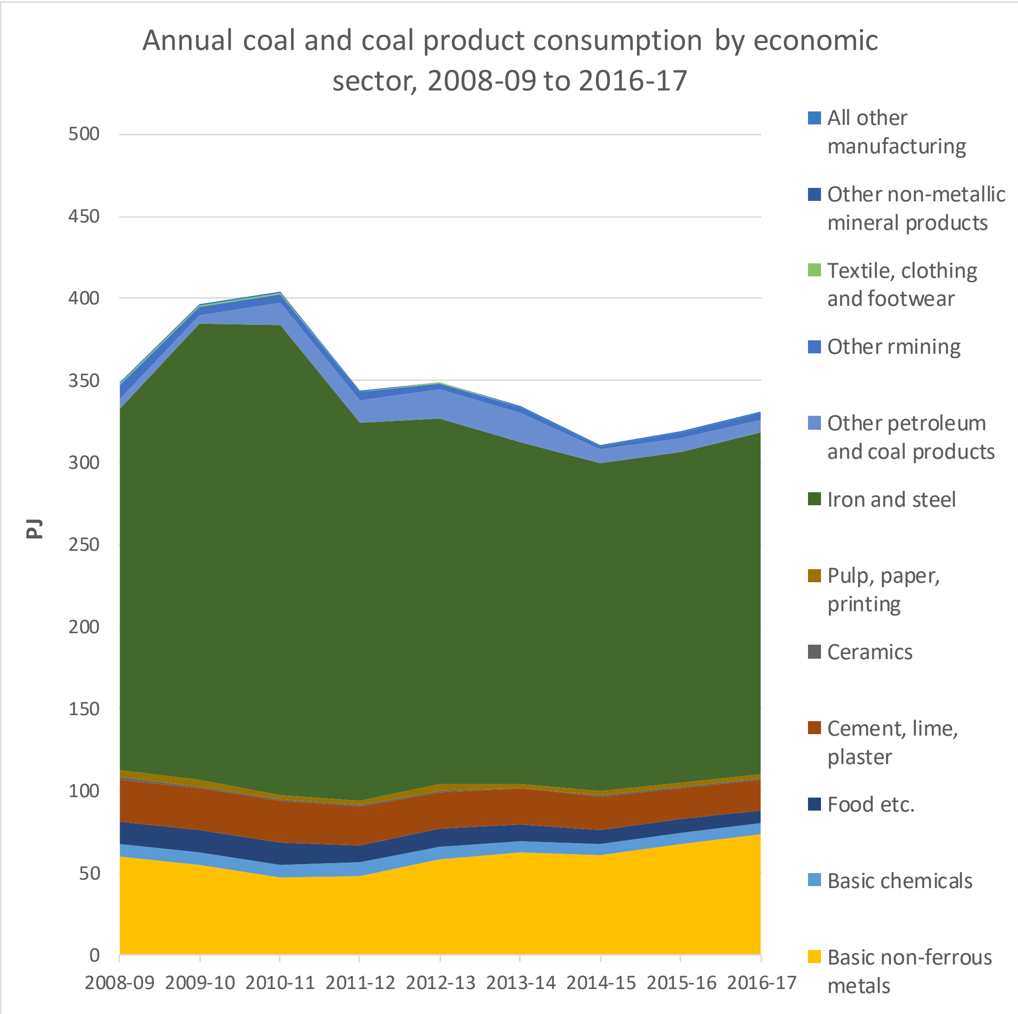

Figure 77: Development of annual coal and coal product consumption by sectors since 2008-09.

The third fossil fuel used to provide process heat is LPG. Figure 78, presented on the same scale as Figure 76 and Figure 77, shows LPG is a very minor fuel, compared with gas and coal. Although it is used in a wide range of sectors, total quantities in each are very small. Most LPG users in industry are small establishments, located in areas without a reticulated natural gas supply. They use LPG because electricity-using options are either too expensive or not suited to the particular applications they require.

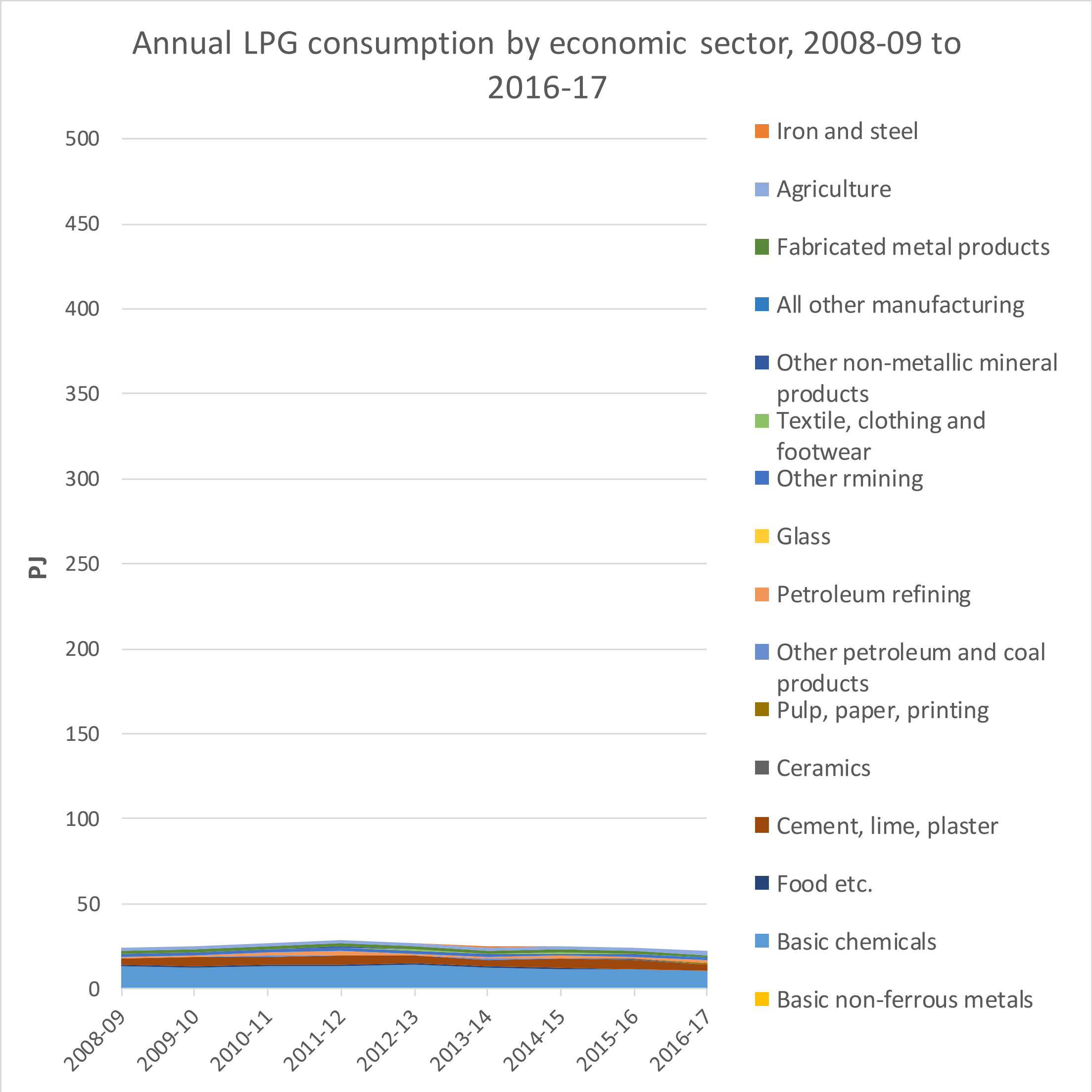

Figure 78: Development of annual LPG consumption by sectors since 2008-09.

Finally, the use of biomass fuels to provide industrial process heat should not be forgotten. Biomass is particularly important in two industries, sugar milling (part of the large Food sector) and paper pulp production. In both of these industries biomass materials constitute large volume waste by-product streams, and are used to generate steam, which is used in both thermal processes and to generate electricity for use on site. A number of sugar mills also export electricity that is surplus to their own requirement. The cement industry uses timber construction waste as a supplementary kiln fuel, and fuel wood is also used in some parts of the chemicals, ceramics and non-ferrous metals industries.

Overall, natural gas is by far the most important fuel currently providing what might be termed 'normal' process heat for industry. LPG use, because of its cost and location, may provide attractive smaller-scale opportunities for substitution by renewable process heat.

It is striking that almost all the sectors shown in Figure 76 appear to have reached peak gas consumption in 2013-14, since when consumption has declined. Basic non-ferrous metals and Basic chemicals, when combined, account for almost two-thirds of the total gas consumption in 2016-17. In order to see the trends more clearly, Figure 79 shows gas consumption trends in all sectors other than Basic chemicals and Basic non-ferrous metals.

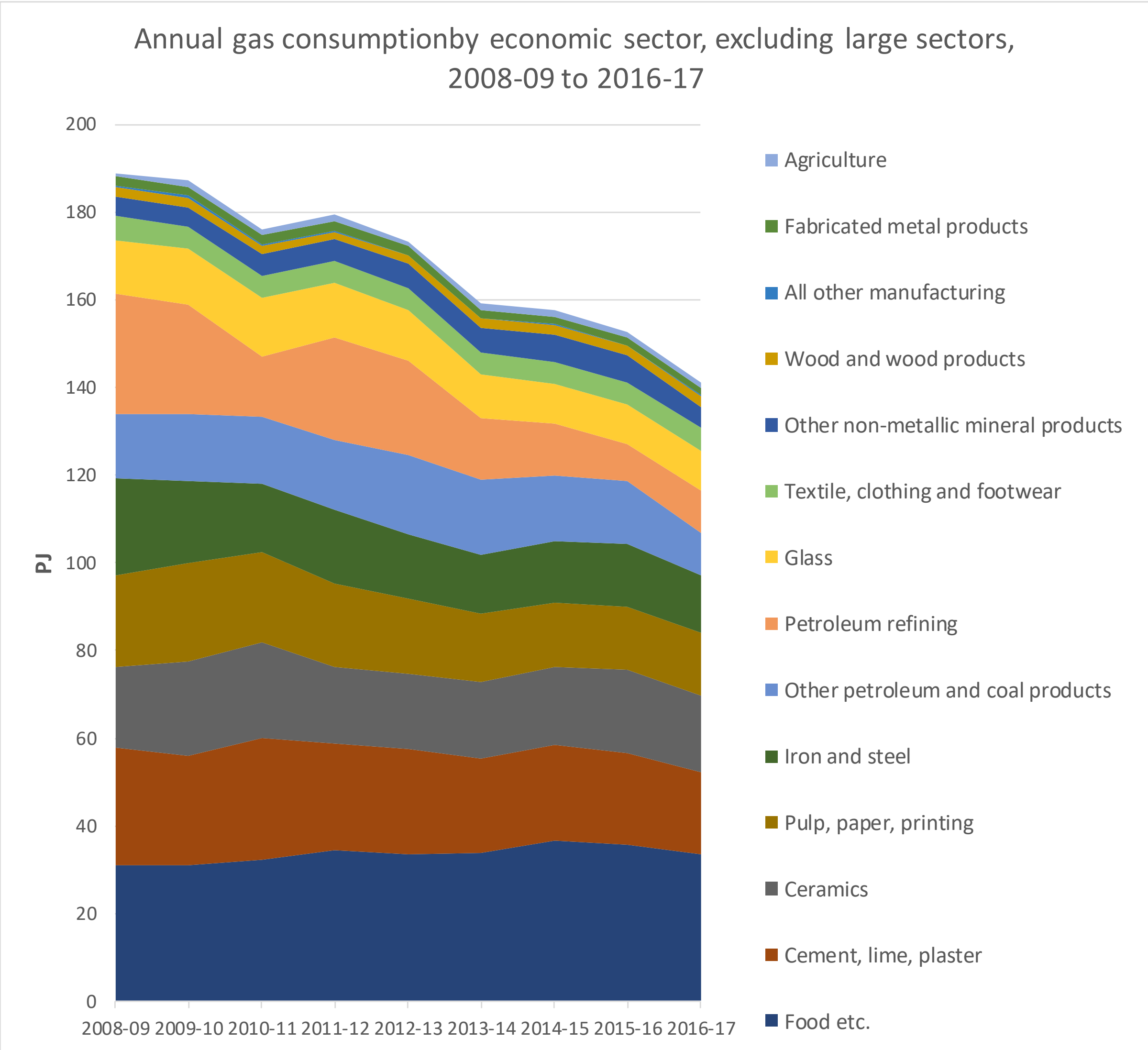

Figure 79: Development of annual gas consumption by sectors since 2008-09, excluding the sectors Basic chemicals and Basic non-ferrous metals.

It can be seen that gas consumption decreased between 2015-16 and 2016-17 in all sectors, though by varying relative amounts. There can be little doubt that this reduction in consumption was largely driven by the very large increase in wholesale gas prices over the same period. It is likely that, when data for 2017-18 becomes available, further falls in consumption will be observed. It is also noteworthy that in some sectors there has also been a decline in consumption over a much longer period, probably reflecting structural changes in the industries concerned. These will be discussed in more detail in the following section.

In the previous report, some slightly more disaggregated data on gas consumption by industry sector was presented. These data were sourced from an ABS publication, which has not been repeated, meaning that no new data are available. However, we have been able to develop rough estimates of gas consumption by indirect means from another data source at the individual site level. The results of this analysis are presented in the third Section of this Chapter.

B.2. Identifying locations and intensity of process heat use by industry

The location of specific industry facilities and level of energy use by them is a key input to assessing of the potential for renewable energy use based on available resources and land use restriction, and the economics of specific applications linked to levels of energy demand.

Restrictions arising from commercial confidentiality requirements mean that most gas consumption data at state levels are available from AES only at highly aggregated levels. Figure 80 shows trends in total natural gas consumption in the whole manufacturing sector at state levels. Consumption in the NT is reported as zero.

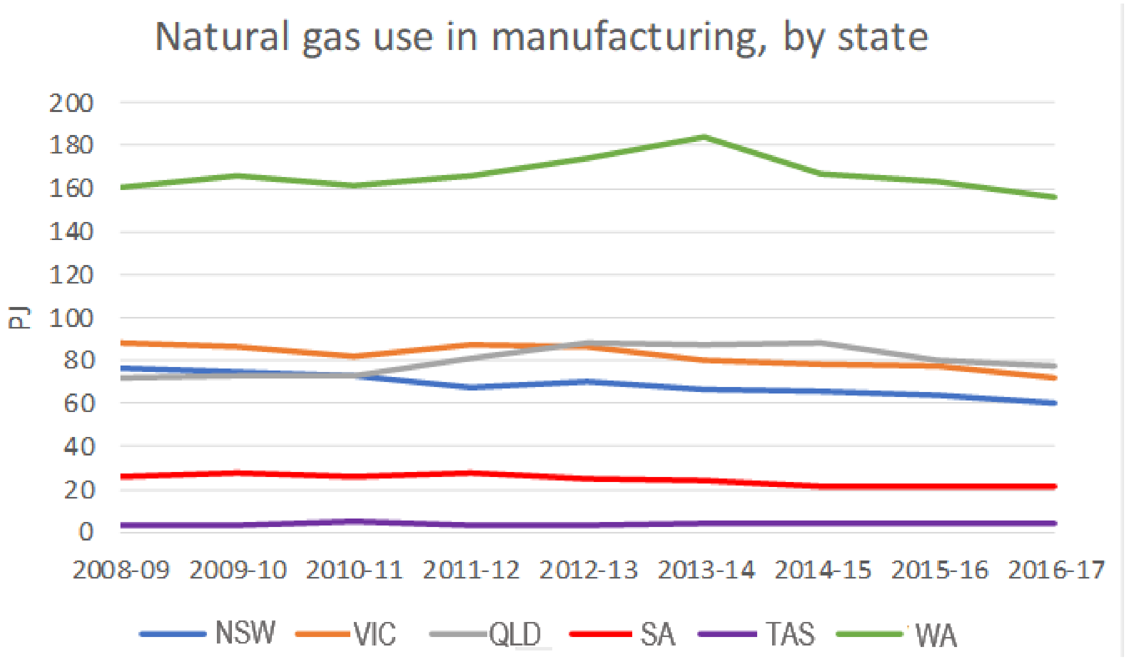

Figure 80: Natural gas use in manufacturing by state.

The consumption levels shown in Figure 80 for WA and QLD are dominated by consumption by the alumina and ammonia industries. In the other four states gas is used by a more diverse range of manufacturing sectors.

Figure 81 shows the combined consumption of natural gas and LPG in food manufacturing by state. The dominance of VIC and NSW is particularly striking.

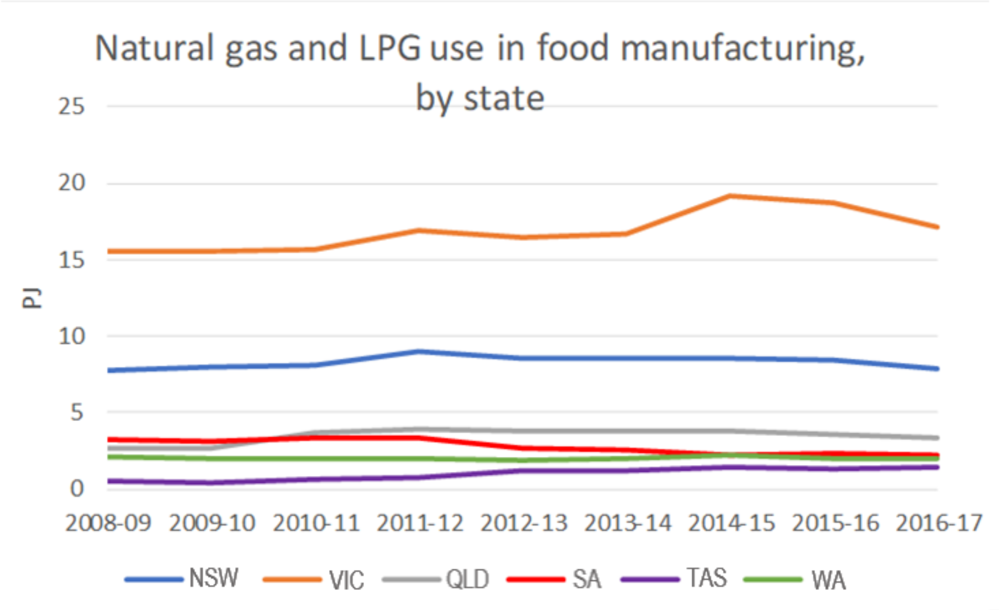

Figure 81: Natural gas and LPG use in food manufacturing, by state.

Further information about energy use and, specifically, consumption of gas and coal used for stationary combustion activities can be inferred from two other public data sources. These are the National Greenhouse and Energy Reporting Scheme (NGERS) public reports, and the National Pollution Inventory (NPI).

NGERS public reports cover all legally liable entities responsible for annual greenhouse gas emissions, which in total (Scope 1 plus Scope 2) exceed 50 kt CO_2-e in the reporting year. In 2016-17 there were 385 such responsible corporate entities. The data that NGERS liable organisations are required to report publicly is very limited. It includes organisation name, total Scope 1 emissions, total Scope 2 emissions and total net energy consumption. It is possible, however, with some understanding of emission factors and emission calculation methodology, to use these data to ‘reverse engineer’ estimated consumption of energy other than electricity and identify the predominant fuel used. We applied this approach to the data reported by the 385 reporting organisations in 2016-17.

The NPI provides much more detailed public reports of emissions to the environment of a large number of pollutants, at the individual facility level rather than, as for NGERS, at the responsible corporate entity level. The most recent NPI contains pollutant emissions data from 4,146 separate sites across Australia, with the exact locations provided. The NPI however does not provide the amounts of energy consumed. This must be approximately deduced from other information on the relevant industry or back calculated from the levels of those pollutants that can be linked to the combustion of fuels. The calculation first determined whether the fuel used was likely to be natural gas, oil or coal, based on the ratio of sulphur dioxide to carbon monoxide in the reported emissions. It then calculated energy consumption on the basis of fuel-specific emissions factors for carbon monoxide, sulphur dioxide, nitrogen oxides and particulates. We recognise that this process is subject to high uncertainty, because site emission levels may vary widely from the assumed default averages because of differences in pollution control equipment. The more obviously inaccurate results were adjusted by reference to the NGERS analysis results and the AES data.

With those qualifications in mind, we consider that the results of the NPI analysis provide valuable guidance as to the sites, and hence also the types of industry, likely to offer the most promising opportunities for using particular renewable energy approaches to displace fossil fuel consumption. In our first pass analysis we selected from the total population of NPI sites the 800 with the highest apparent gas and coal consumption, as estimated by the above procedure.

B.2.1. NGERS public data

Drawing also on our knowledge of Australian industry, the analysis was able to identify the following major gas-using businesses by sub-sector in the food and beverages sector.

A similar analysis was not possible for other sectors, because of the more complex mix of fuels used, e.g. including biomass, coal, and/or the diverse range of industry sectors in which reporting companies are active. That said, for manufacturing industry sectors with highly concentrated ownership in Australia, the analysis was able to confirm the identity of businesses that account for the great majority of energy use. Such sectors include iron and steel, alumina, pulp and paper products, glass and cement.

In addition, the analysis identified individual businesses in other sectors that appear to consume large quantities of gas, and the location of their major facilities. Examples include selected businesses specialising in:

- non-ferrous metals primary production, other than alumina, such as lead, zinc, copper, nickel, and lithium
- titanium dioxide and related chemical products
- building products
- wood products
- other non-metallic mineral products.

Table 29: Major gas using businesses by sub-sector in the food and beverages sector.

Industry sector	Number of businesses	Approximate gas consumption (PJ)
Abbattoirs, other meat processing, chicken meat and eggs	7	5
Dairy processing/ milk products	4	7
Canning, freezing and downstream processing	2	2
Beer and soft drinks	4	3
Other food processing	5	4
Starch products and fuel ethanol (Manildra)	1	5
Total food and beverage		**26**
Ammonia and downstream products	5	98

B.2.2. NPI data

The NPI provides a comprehensive list of pollutants and facilities classified at ANZSIC class level. The pollutant data was used to judge the energy intensity or consumption pattern by sector. Sites identified by the NPI were sorted by industry sector and sub-sector, with the results shown in Table 30.

Table 30: Industry sector and number of sites with $CO/SO_2/NO_x$ emissions.

Industry Sector	No of sites
Food and beverage	320
Commercial and services	108
Wood and wood products	44
Glass and glass products	11
Other mining	374
Textile, clothing and footwear	11
Machinery and equipment	26
Agriculture, forestry and fishing	24

Electricity, gas, mining, transport, residential	486
Water and sewage	175
Other non-metallic and mineral	9
Fabricated metal products	49
Other hydrocarbon products	54
Alumina and other non-ferrous	37
Cement, lime products	43
Iron and steel	12
Petroleum refining	10
Pulp and paper	44
Bricks and Ceramics	33
Oil and Gas extraction	98
Ammonia and other chemicals	90
Total	2,058

All Australian industrial facilities that meet the National Pollutant Inventory (NPI) reporting criteria are required to submit annual reports of their emissions of substances (NPI, 2019). NPI mandates reporting of 93 priority toxic substances as pollutants and currently excludes reporting carbon dioxide currently, which is the main product of fossil fuel combustion (besides H_2O). The other products of combustion are oxides of nitrogen (NO_x), sulphur dioxide (SO_2), particulate matter and carbon monoxide (CO), that are reported in the NPI.

As per the NPI, 2042 industrial facilities emit the combustion products. Emissions include pollutants from biofuels such as bagasse, landfill gas and biogas. NPI provides consolidated emissions arising out of processes, combustion of fuels, as well as diffused emissions i.e. distributed energy use, cars and other domestic activities. Some facilities that are excluded include scrap metal handling, petrol stations, mobile emission sources operating outside the boundary of facilities and dry-cleaning facilities that employ less than 20 peoples.

From the NPI data, NSW, QLD and WA are the largest polluters, signifying energy intensive industries. Though Victoria has a considerable number of industrial facilities, pollutant quantity is low, indicating lower energy intensity.

Considering the vast number of sites to be analysed, a rough methodology to arrive at an order of magnitude of energy consumption (at each site) was devised. As per studies from the US Environment Protection Agency (data shown in Table 31), the proportion and quantity of emissions is directly related to the quality and quantity of fuel. For example, when combusted, coal and oil release higher levels of sulphur dioxide and particulate emissions than natural gas. This was used to determine and calculate the energy consumed at a site.

Table 31: Fossil fuel emission levels converted to SI units (kg per TJ of energy input; data source: (NaturalGas.org, 2018)).

Fossil Fuel Emission Levels converted to SI units (kg per TJ of energy input)			
Pollutant	**Natural Gas**	**Oil**	**Coal**
Carbon dioxide	50,301	70,507	89,424
Carbon monoxide	17.20	14.19	89.42
Nitrogen oxides	39.55	192.60	196.47
Sulfur dioxide	0.43	482.37	1,113.93
Particulates	3.01	36.11	1,179.70

The calculation first determined whether the fuel used was likely to be natural gas, oil or coal, based on the ratio of sulphur dioxide to carbon monoxide in the reported emissions. It then calculated energy consumption on the basis of fuel-specific emissions factors for carbon monoxide, sulphur dioxide, nitrogen oxides and particulates from Table 31. Then the results were multiplied by the ratio of AES process heat (assuming a rough process efficiency) to the AES total energy consumed by the sector to eliminate emissions from other fuels such as diesel, electricity etc.

For sectors where public data / production quantity / process data and specific energy consumption are known, such as alumina, sugar and oil and gas, a weighted average of known data and emissions-based energy data was considered, of which a major weightage was given to known data. Sites that were known to have suspended operations such as the Gove Alumina Refinery and a cement plant in Western Australia were removed. Then a sector wide subtotal was calibrated with the AES subtotal. This method is approximate and provides an order of magnitude accuracy that can be plotted on a map to provide a sense of the scale and comparison of each site and sector.

B.3. Fuel cost trends

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. Wholesale gas markets in eastern Australia, i.e. excluding WA, have seen dramatic increases in wholesale gas prices, starting around the middle of 2016. Figure 82 shows quarterly averages of the daily gas prices in the VIC wholesale gas market. Figure 83 shows quarterly average prices in the short-term trading markets (STTM) in Brisbane, Sydney and Adelaide. Both graphs are sourced from the Australian Energy Regulator (AER). There is no similar (comparatively transparent) wholesale price data for WA.

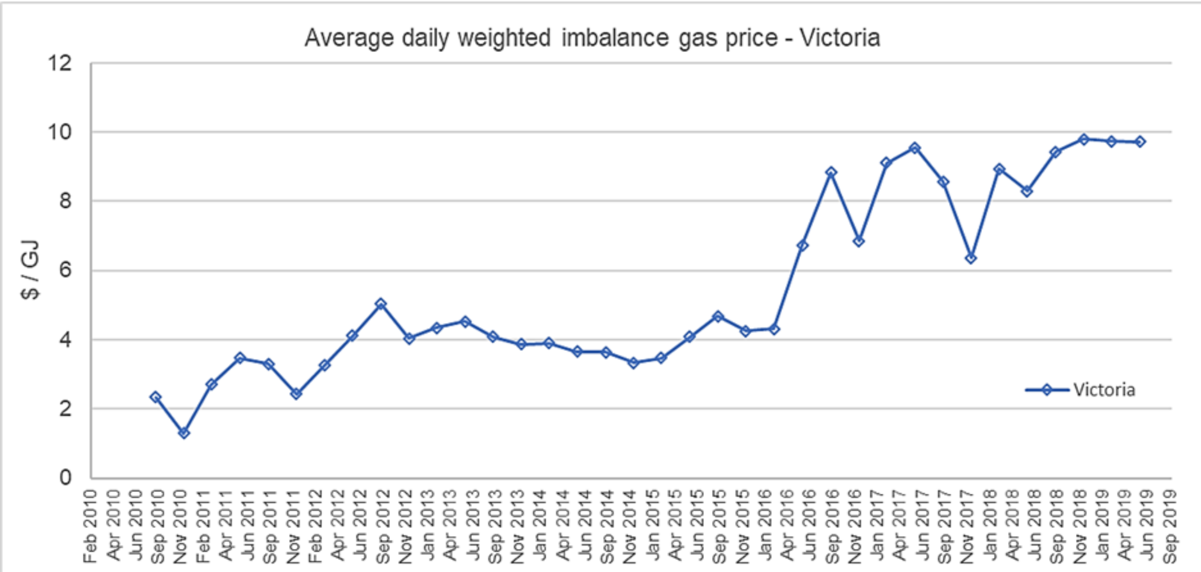

Figure 82: Development of the quarterly average daily gas price in the Victorian wholesale gas market.

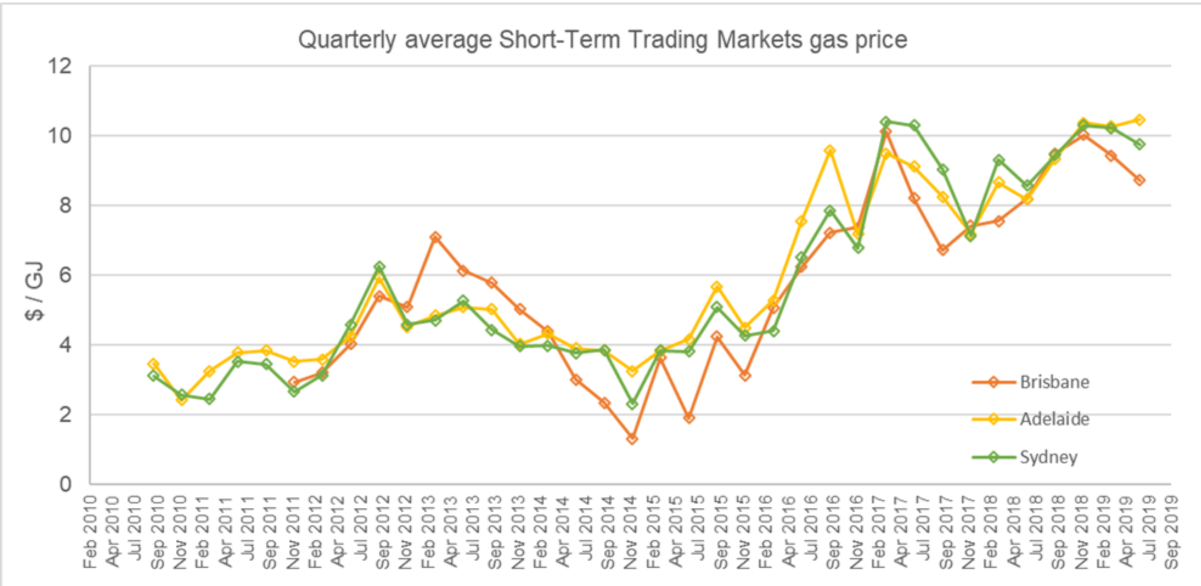

Figure 83: Development of the quarterly gas prices in the short-term trading markets in Brisbane, Sydney and Adelaide.

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. These have nearly tripled underlying demand for gas as shown in Figure 84.

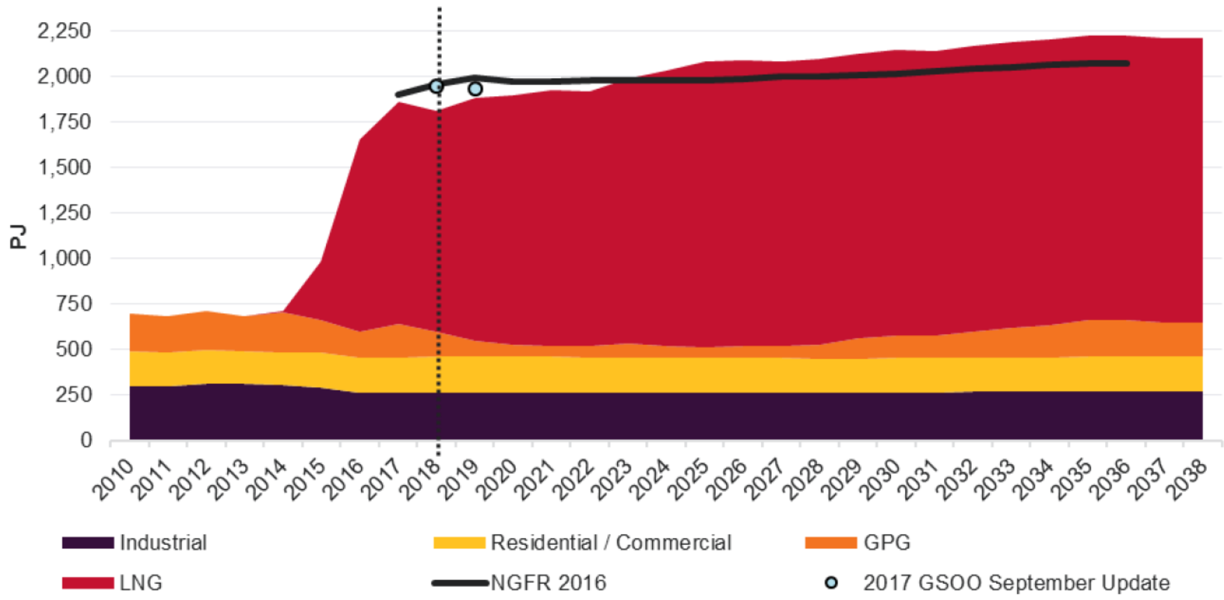

Figure 84: Gas consumption actual and forecast. (Reproduced from, AEMO[27].)

Pipelines supplying gas to these plants are connected to the wider eastern Australia pipeline network, which connects gasfields 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 85).

[27] 2018 Gas Statement of Opportunities https://www.aemo.com.au/-/media/Files/Gas/National_Planning_and_Forecasting/GSOO/2018/2018-Gas-Statement-Of-Opportunities.pdf.

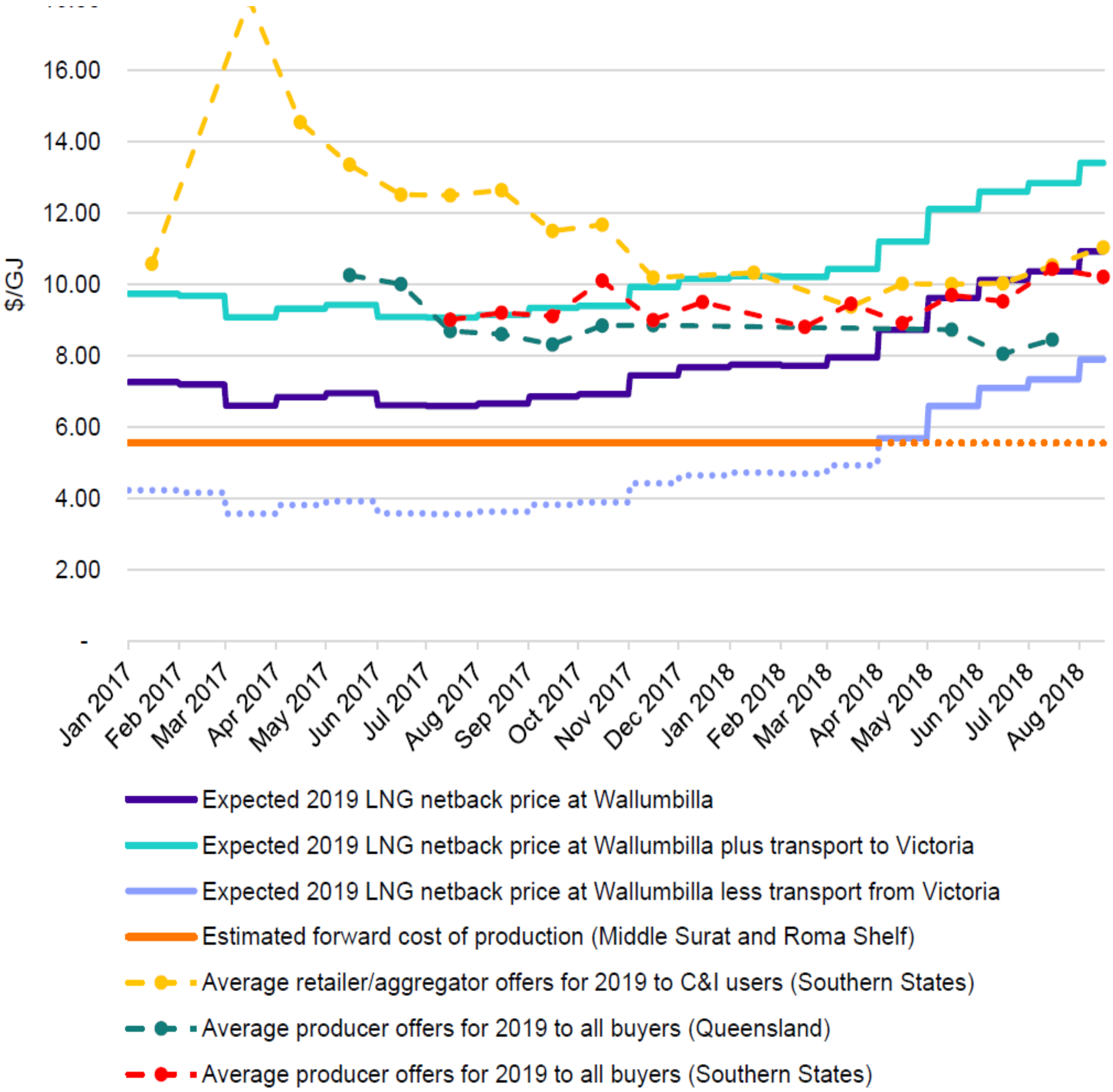

Figure 85: Monthly average gas prices offered for 2019 supply against expectations of 2019 LNG netback prices. Reproduced from (ACCC, 2018).

Events since then have been summarised by the Australian Competition and Consumer Commission (ACCC) in its fifth interim report (ACCC, 2018) from the inquiry into gas supply arrangements in eastern Australia, in the following terms:

> *"As we reported in the July 2018 report, a number of short-term factors came together in 2017 to significantly disrupt the operation of the East Coast Gas Market at a time when it was already undergoing significant change. As a result, gas prices offered by suppliers in the East Coast Gas Market in 2017 were well in excess of export parity prices and there was a significant gap in prices being offered by retailers/aggregators and gas producers.*

> *"In the July 2018 report, we observed that early price data for 2019 indicated that the short-term factors had eased. By the end of the first quarter of 2018, the prices offered in the domestic market for gas supply in 2019 had converged with export parity prices." (p. 15)*

This suggests that the ACCC expects average wholesale prices to be slightly lower in 2019 than in 2018. If the expectation that domestic prices have 'converged' with export parity prices is realised, 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, and are always likely to be, well above the former level of Australian domestic prices.

APPENDIX C. BIOENERGY TECHNOLOGY

A variety of thermochemical, physiochemical and biochemical technologies are available to convert biomass feedstocks to thermal energy, as shown in Figure 86.

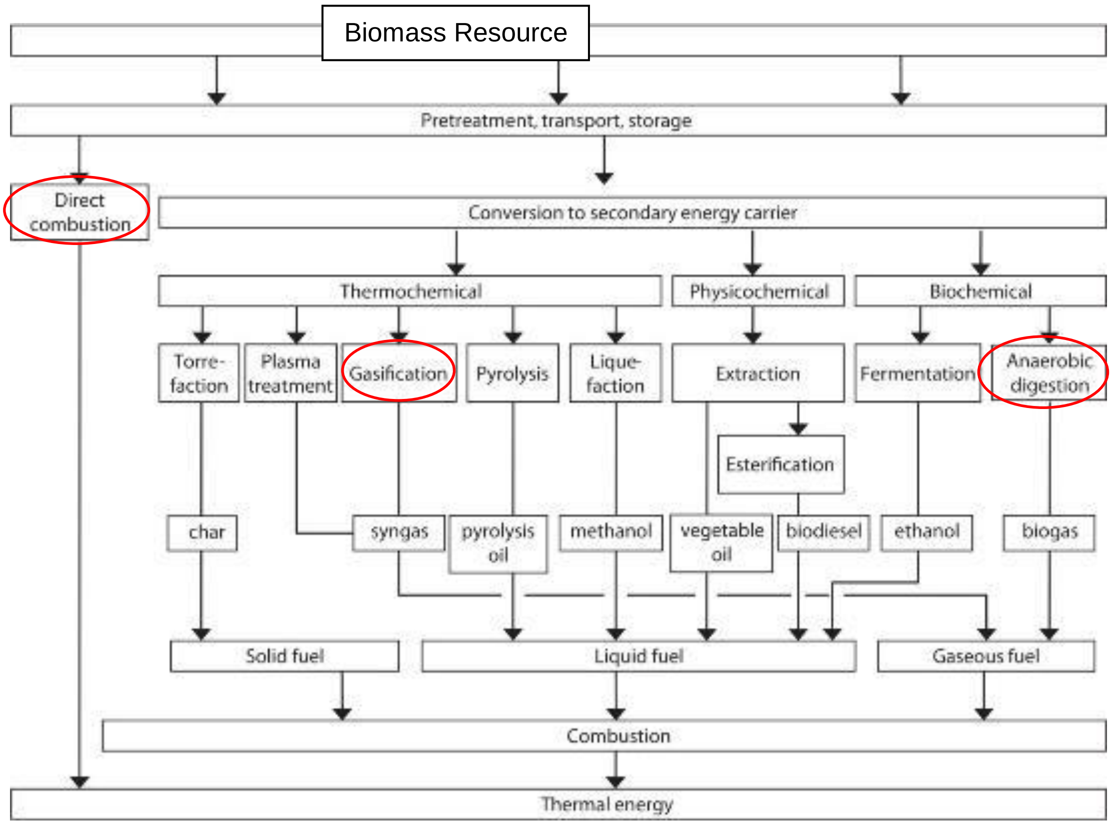

Figure 86: Energy from biomass conversion technologies. Reproduced from (Kaltschmitt, 1998).

Table 32 gives a summary of operating bioenergy plant by sector in Australia. Both systems primarily design for heat and those primarily designed for electricity generation are included.

Table 32 Operating Australian bioenergy plants by industry sector as at end 2018.

SECTOR	NO OF PLANT	ESTIMATED TOTAL SECTORAL ELECTRIC CAPACITY (MW_e)	OUTPUT	AVERAGE CAPACITY	
				MW_e	Thermal
MINERAL PRODUCT MANUFACTURING	4	-	3 heat only 1 unknown		93,750 GJ/year
FOOD & BEVERAGE, LIVESTOCK	39	8.0	25 cogen 4 electric only 10 heat only	0.31	1.5 MW_{th}
Of which food & beverage	*10*	*4.9*	*3 cogen* *1 electric only* *6 heat only*	*1.20*	*4.4* MW_{th}
Of which piggeries	*20*	*3.2*	*20 cogen*	*0.16*	*1,385 GJ/year*
PULP AND PAPER	4	79.0	4 cogen	19.8	
FOREST PRODUCTS	8	0.5	1 cogen 7 heat only	0.50	6 MW_{th}
HORTICULTURE	6	0.1	1 cogen 5 heat only	0.10	4 MW_{th}
OTHER	3		3 heat only	0.0	0 MW_{th}
Subtotal	**64**	**88.0**			
SUGAR	24	463.0	24 cogen	19.30	
WATER/ SEWAGE	23	52.0	13 cogen 10 unknown	2.30	
LANDFILL GAS	53	171.0	Most electric only	3.20	
Subtotal	**100**	**664** MW_e			
OVERALL TOTAL	**164**	**751** MW_e			

Data from Bioenergy Australia survey data, ISF analysis and additional research

C.1. Overview of technologies

C.1.1. Anaerobic digestion

Anaerobic digestion is a commercial technology that involves a series of biological processes in which micro-organisms break down biomass feedstock in the absence of oxygen. The process is best suited to wet biomass (typically dry solid content is between 5-30%) thus a common feedstock is livestock effluent. The resulting biogas is typically 60% methane (CH_4) and 40% carbon dioxide (CO_2), which can be used for heat and/ or electricity production, or upgraded to produce a renewable natural gas (with approximately 95% CH_4) for direct injection into gas pipelines (Wall et al., 2018).

Table 33: Anaerobic digestion technologies.

Technology type	Temperature range	Other requirements	Applications
Covered anaerobic lagoons (US EPA, 2002)	25-40°C (mesophyllic)	Hydraulic retention time between 30-60 days pH between 6.6-7.6 Alkalinity from 1,000-5,000 mg/litre	Rural applications, generally for livestock or process effluent
Heated agitated (high-rate) lagoons (Calli, 2012)	45-60°C (mesophyllic)	Hydraulic retention time <15 days	Sewage sludge, or where a higher rate of digestion is desired
In-vessel digester (US EPA, 2002)	Both mesophyllic (e.g. plug-flow digesters) and thermophyllic (complete mix digesters)	Dependent on technology. Retention time can be as low as 1-2 days for high-rate systems	For higher energy output or a smaller footprint e.g. municipal sludge

The majority of biogas in Australia is derived from landfill gas, which is generally used in electricity only plant and accounts for nearly 25% of bioenergy electrical capacity. However, in recent years there has been an expansion of smaller-scale anaerobic digestion, in particular for livestock farming and water utilities. A key driver of this growth has been through initiatives such as Australia’s Pork CRC Bioenergy Support Program, which has helped 16%of the national herd’s manure effluent be directed to biogas systems, increasing from 2% in 2012 (Pork CRC, 2018). There are also examples of commercial digesters using sewage waste as a feedstock, for example Sydney Water and Melbourne Water.

However, there are still challenges to deployment. Two key barriers to further uptake of anaerobic digestion of waste streams are: 1) the energy density of waste feedstocks is not well understood[28] but is generally low; and 2) projects struggle to reach economies of scale since farm operations are often small operations and cannot aggregate sufficient quantities of feedstock (Lukehurst & Bywater, 2015).

There are a number of commercial operators looking at the Build, Own, Operate Maintain (BOOM) model for bioenergy and other renewable energy plant in order to reduce deployment costs. For example, the company ReNu has installed an anaerobic digestor at Southern Meats in Goulburn using the BOOM model, with a twenty year power purchase agreement for the power (Bioenergy Insight, 2018).

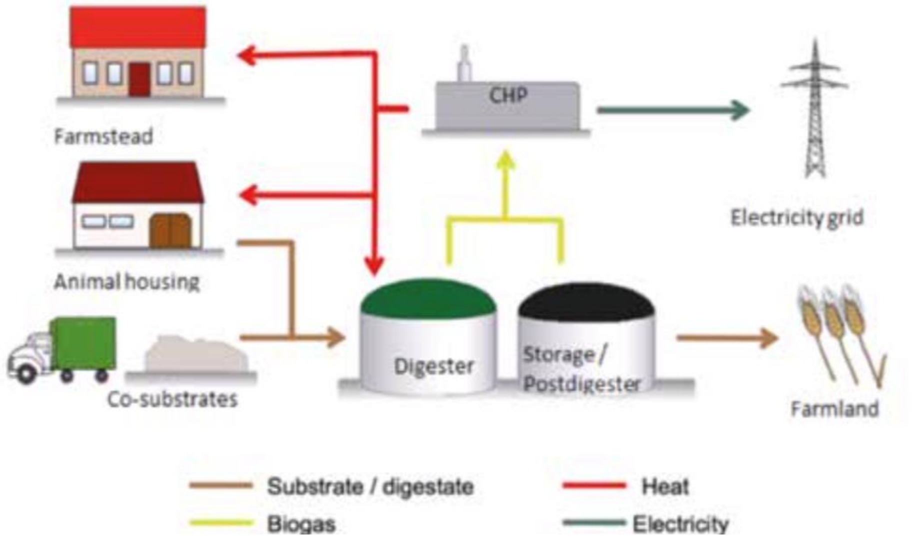

Figure 87: Schematic layout of an anaerobic digestion plant. Copied from (Lukehurst and Bywater, 2015)*.*

C.1.2. Combustion

Combustion technology, including combined heat and power (CHP), is generally categorised into fixed bed and fluidised bed technologies (Bain & Overend, 2002). Fixed bed combustion technologies include fixed crate, moving grate and vibrating grate options, which are determined based on the feedstock. For example, the Caboolture sawmill boiler uses a fixed grate to generate process heat from dry wood waste. Fluidised bed combustion allows for more feedstock flexibility and can be more efficient. However fluidised bed combustion is a more expensive option, so is often better suited to large (>20MWt) operations.

[28] At a recent industry workshop on energy research priorities, representatives from both Sydney Water and Veolia as well as the Managing Director of FIAL, specifically expressed that further work is needed to characterise the energy content of different waste streams.

Table 34. Combustion technology types.

Technology type	Temperature range	Other requirements	Applications
Fixed bed boiler	800–1000°C	Moisture content of feedstock <50% Conversion efficiency of 20-40%	Dry feedstock Smaller operations e.g. underfeed stokers are attractive <6 MW_{th} and grate furnaces for <20 MW_{th}
Fluidised bed boiler	760-870°C	Low NO_x emissions can be achieved	Dry feedstock Large operations >30 MW_{th}

C.1.3. Gasification

High-temperature gasification is an alternate conversion pathway, involving a complete thermal breakdown of biomass to produce a medium- or low-calorific value gas which can be upgraded for heat or other energy products (IEA Bioenergy, 2018). The main gas components are CO, CO_2, H_2O, H_2, CH_4 and other hydrocarbons. Biochar is a solid by-product of the process. This method is better suited to dry feedstock (dry solids content greater than 40%), which is most often woody biomass (Wall et al., 2018).

Gasification systems can offer technical benefits over combustion systems, as they produce a synthesis gas that, after suitable cleaning, is compliant with standard gas engines and gas turbine specifications, thus allowing the use of highly-efficient electricity generation. Co- and trigeneration are also possible but the overall cycle efficiency would not be higher than in a conventional combustion type plant.

Gasification technologies are further separated into gasification/combustion and gasification technologies (Lamers et al., 2013). In gasification/combustion the raw gas is later burnt in a boiler with additional air to achieve a stoichiometric combustion. A variety of commercial gasification/combustion plants operate worldwide, such as the 140 MW_{th} plant in Vaasa in Finland (Metso Corporation, 2013) and the 25 MW_e Weyerhauser CHP plant in Uruguay using wood waste (Berkes, 2019) as well as the 20 MW_e Fukuyama plant in Japan using refuse-derived fuels (JFE, 2011).

Gasification plants include equipment to clean the produced raw gas to a quality suitable for high-efficiency conversion in gas engines and gas turbines. The high efficiency for electricity generation is promising but the technology has not seen much commercial use over the past 20 years, largely due to the complexities involved in cleaning a biomass derived raw gas, e.g. tar condensation. Only a few gasification plants operate in combination with gas engines or turbines, and Australian applications are still at the demonstration stage, for example Renergi's advanced biomass gasification project in Perth, WA.

Table 35: Gasification technology types.

Technology type	Temperature range	Other requirements	Applications
Gasification/ combustion i.e. through fixed-bed or fluidised-bed gasifiers	750–900°C to avoid ash melting at higher temperatures	The final gas composition is strongly dependent on the amount of oxygen, air or steam admitted to the reactor as well as the time and temperature of reaction	Lower cost options for process energy use. Higher conversion efficiency (40-50%) can be achieved when combustion/heat recovery is integrated
Gasification for syngas production,	High temperatures: above 1200ºC – 1700ºC Or low temperature: 400ºC – 900ºC with subsequent catalytic reformer	High temperature processes produce higher concentration of H_2 and less tar and char. Low temperature processes produce a mixture of H_2, CO, and CO_2 and a range of heavy hydrocarbons, which require subsequent cracking to produce syngas	Syngas has approximately half the energy density of natural gas can be converted to natural gas (CH_4) and range of other hydrocarbon fuels

C.2. Bioenergy resources

There have been a number of reviews of the bioenergy potential in Australia, including for example, Geoscience Australia (Geoscience Australia, 2014), and the Clean Energy Council's Bioenergy Roadmap (CEC, 2008). Both focus on electricity generation rather than heat. The short-term potential is given as approximately 11 TWh_e from approximately 97 PJ_{th} of heat from biomass combustion and the long-term potential is estimated to be seven times that amount, including a 47 TWh_e contribution from agricultural stubble. Even excluding stubble, the long-term potential is assumed to increase by 250%, with the biggest growth in animal and urban wastes, which both approximately double. Table 36 shows each feed stock's contribution to the roadmap target at 2020 (the same data is summarised in Figure 13).

Table 36: Australian bioenergy potential at 2020 (electricity) and estimated heat potential (CEC, 2008).

	Base unit for projection		2020 electricity potential GWh/year	2020 heat potential PJ/year
LIVESTOCK				
Poultry	94,384,000	population	297	2.7
Cattle (feedlots)	870,025	population	112	1.0

	Base unit for projection		2020 electricity potential GWh/year	2020 heat potential PJ/year
Pigs	1,801,800	population	22	0.2
Dairy cows	1,394,000	population	22	0.2
Abattoirs	1,285,000	tonnes	337	3.0
SUBTOTAL			**790**	**7.1**
OTHER AG RESIDUES				
Nut shells			1	0.009
Bagasse	5,000,000	tonnes	3000	27.0
Sugarcane trash	4,000,000	tonnes	165	1.4
SUBTOTAL			**3166**	**28.0**
ENERGY CROPS/ WOODY WEEDS				
Oil mallee			484	4.4
Camphor laurel			20	0.2
SUBTOTAL			**504**	**4.6**
FOREST RESIDUES				
Native forest (public and private)	2,200,000	tonnes		
Plantation (public and private)	3,800,000	tonnes		
Sawmill and wood chip residues	2,800,000	tonnes		
SUBTOTAL			**2442**	**22.0**
PULP AND PAPER MILLS WASTES				
Black liquor			365	3.3
Wood waste			85	0.8
Recycled paper wet wastes			8	0.07
Paper recycling wastes			48	0.4
SUBTOTAL			**506**	**4.576**
URBAN WASTE				
Food and other organics	2,890,000	tonnes	126	1.1

	Base unit for projection		2020 electricity potential GWh/year	2020 heat potential PJ/year
Garden organics	2,250,000	tonnes	262	2.4
Paper and cardboard	2,310,000	tonnes	38	0.3
Wood/timber	1,630,000	tonnes	295	2.7
SUBTOTAL			**721**	**6.5**
LANDFILL/ SEWAGE GAS				
Landfill gas	9,460,000	tonnes	1880	16.9
Sewage gas	735,454	tonnes	901	8.1
SUBTOTAL			**2781**	**25.0**
Overall total			**7294**	**101.0**

Bagasse, sewage gas, and landfill gas together account 56% of the 2020 target, and stubble accounts for more than 60% of the long-term target. While stubble is potentially a very large resource in the long-term, it is unlikely to be developed at large scale in the medium term, as the requirements for collection and compaction impose considerable costs relative to other biomass and energy sources. It is therefore unlikely to provide a viable alternative for large-scale industrial gas use in the medium term. Small plants for rural heat applications may be feasible, as occurs in the UK for example.

Urban bioenergy resources offer significant energy potential but are likely to be utilised at centralised collection points. The current focus of applications is on the export of electricity for sale, rather than substitution for industrial gas, owing to the higher value of electricity.

For biomass resources, the AREMI maps contain data developed and maintained by the Australian Biomass for Bioenergy Assessment (ABBA) project, funded by ARENA (AREMI, 2019). This ongoing project, led by AgriFutures Australia (formerly Rural Industries Research and Development Corporation) in collaboration with several state departments, aims to develop a national database of biomass resources for bioenergy generation, including the types, volumes and locations of potential bioenergy feedstocks, to catalyse investment in this sector and increase the uptake of biomass sources for energy.

For sugarcane bagasse and total sugarcane trash, national data is available. The actual data is concentrated in QLD and the northern tip of NSW, which may reflect the concentration of this industry in these regions. Data is provided in terms of dry tonnes per year.

National data further includes residues from piggeries, including conventional flush manure and spent bedding, calculated as tonnes of volatile solids per year on a dry basis and tonnes of dry matter per year. Residues do not include direct waste from meat production. In addition, the national data includes winery waste.

At the state level, a range of biomass data is available. Data availability and format varies somewhat from state to state, which, again, may reflect the differences in local industries among the states.

It should be noted that many bioenergy resources may also have an agricultural use and value, e.g. as fertiliser to return nutrients and pesticides to the soil. Hence, there may be competing interests for energy generation and agricultural uses.

AREMI also provides mapped data of the locations of biogas facilities, projects and people involved in the biogas space.

C.3. Capital and operational costs

Most costs available in the literature are for CHP plant, which include both the boiler or gasifier and the generator or gas engine. This reflects the more common use, and that most Australian bioenergy plants produce electricity, as shown in Figure 88. This may result from the historic situation where electricity has been the higher-value output. However, the capital cost of heat-only plant is much lower, as they do not include the turbine or gas engine, so increasing gas costs may see a rise in heat only plant.

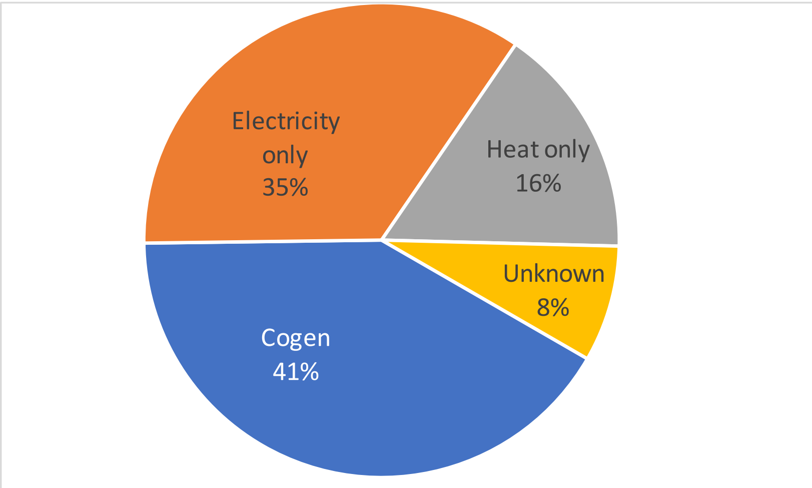

Figure 88: Outputs types from Australian bioenergy plant (by numbers of plant).

C.3.1. Bioenergy technology costs

Typical capital costs for CHP plant are given in Table 37 (from Lovegrove et al, 2018) along with the range of costs found in the literature. The cost is related to plant size, with a size dependency of cost proportional to size ^0.7. The full list of sources and costs is given in Table 37 through to Table 41 present installed cost information for, in turn, combustion-based CHP plant, gasification-based CHP plant, anaerobic digestion-based CHP plant and combustion-based heat only plant.

Table 37: Typical CAPEX for CHP plant, and range in literature.

DESCRIPTION	POWER OF SAMPLE PLANT MW	O&M FIXED % of Capex	CAPEX A$/ MW	Range A $m/ MW of literature ($MW_e$ sample plant)
Anaerobic digestor	2.5	5.2%	$5.10	$3 (1 MW_e) - $22 (300 kW_e)
Direct combustion: boiler plus steam turbine	15.0	3.6%	$4.91	$2.50 (15 MW_e) - $16 (7.5 MW_e)
Gasifier	n/a	3.6%	n/a	$4.07 (15 MW_e) - $8.10 (0.5 MW_e)

From Lovegrove et al, 2018. Single point costs are average of a wide range.

Table 38 Capital cost range - direct combustion CHP plant cost (steam turbine).

DATA SOURCE, COUNTRY	DESCRIPTION	POWER MW_e	O&M FIXED % of Capex	CAPEX(1) AUD m$/ MW_e
(Lovegrove et al., 2018) Australia	Direct combustion: boiler plus steam turbine	15.0	3.6%	$4.91
(Stucley et al., 2012a) Australia	Generic, steam turbine using bagasse or woodchip	5.0	5.7%	$5.40
(Stucley et al., 2012a) Australia	As above	20.0	5.4%	$3.15
(IRENA, 2015) OECD	BFB/CFB boiler; average of large number of plant, power rating median from US and Europe	15.0		$4.19
(IRENA, 2015) OECD	As above for stoker boiler	15.0		$5.20
(McGahan et al., 2013) Australia	Darwalla, Chicken litter, combustion	7.5	13.0%	$16.00
(BREE, 2012) Australia	Reference plant, boiler and steam turbine, wood waste	2.0		$5.00
(BREE, 2012) (Australia)	As above	20.0		$6.00
(Bridle, 2011) Australia	Feasibility study, fluid bed combustor/boiler and steam turbine, feedlot solid waste	4.1	3.3%	$6.80
AETA Model_2013-2 (Excel) Australia	Generic, high-pressure boiler firing stored bagasse, condensing steam turbine	32.0	3.1%	$4.00
AETA Model_2013-2 (Excel) Australia	Generic, high-pressure boiler firing wood, condensing steam turbine	18.0	2.5%	$5.00
(US EPA, 2007) US	Generic, stoker boiler, configured for power only	15.5	2%	$2.48
(US EIA, 2017) US	Reference plant	50.0	2.9%	$5.04
(Arup, 2016) UK	Average of seven dedicated bioenergy plant plus published sources, condensing boiler	22.9	2.2%	$5.52
(Kallis, 2016) Australia	Yorke, biomass	15.0		$6.00

Table 39 Capital cost range - direct combustion with gasification (CHP plant).

DATA SOURCE, COUNTRY	DESCRIPTION	POWER MW_e	O&M FIXED % of Capex	CAPEX(1) AUD m$/ MW_e
(Stucley et al., 2012a) Australia	Generic, gasifier package	0.5	5.4%	$8.10
(IRENA, 2015) OECD	Gasifier, average of large number of plant, power rating median from US and Europe	15.0		$4.07

Table 40 Capital cost range, anaerobic digestors (CHP plant).

DATA SOURCE, COUNTRY	DESCRIPTION	POWER MW_e	O&M FIXED % of Capex	CAPEX (average) A$M/ MW_e
(Lovegrove et al., 2018) Australia	Anaerobic digestor	2.5	5.2%	$5.10
(Arup, 2016) UK	Average of 14 AD plant	2.3	10.8%	$6.12
(IRENA, 2015) OECD	Average of large number of AD plant	0.5	3.7%	$5.77
(McGahan et al., 2013) Australia	Feasibility, centralised AD digestor for poultry litter	4.6	5.7%	$6.25
(Bridle, 2011) Australia	Feasibility, AD of feedlot liquid effluent, based on building new contact digestor and gas engine	0.3	3.1%	$21.91
AETA Model_2013-2 (Excel) Australia	Generic, landfill gas reciprocating gas engine	1.0	5.0%	$3.00
(Oliff et al., 2012) Australia	Generic, reciprocating gas engine	0.007	0.7%	$20.40
Foster, A (2018), Australia (Fortune, 2018)	Installed plant, reported cost, anaerobic digestion of wastewater NB Electricity only	1.6	n/a	$3.4

Table 41 CAPEX for Australian bioenergy heat plant, reported costs.

Project	Feedstock [technology]	Thermal capacity (MW_{th})	Capital cost (million $)	$m/ MW_{th}
Murphy Fresh Hydroponics	Waste hardwood logs [combustion]	6	$0.60	$0.10
Greenham Meats (NB conversion of existing coal boiler)	Pyrethrum waste [combustion]	10	$1.20	$0.12
Gelliondale Nursery	Sawmill residues [combustion]	1.5	$0.28	$0.19
Macca Feeds	Wood chip [combustion]	1.7	$0.75	$0.44
Fletcher International abattoir	Wood chip [combustion]	9.3	$4.5	$0.48
Pyrenees Timber boiler	Sawmill residues [combustion]	0.24	$0.120	$0.50
Meredith Dairy	Woodchips [combustion]	0.24	$0.12	$0.50
Dinmore meat processing facility	Wastewater [anaerobic digestion]	10	$8.80	$0.88
Voyager Craft Malt heat plant	Walnut shells [combustion]	0.5	$0.55	$1.10
MSM Milling (replacement of existing LPG boilers)	Wood chip [combustion]	4.8	5.8	$1.2

Data from Bioenergy Australia survey 2018, ISF analysis (note cost data has not been verified).

It can be noted that some of the specific cost numbers in Table 41 are implausibly low (i.e. ten times less than others). It is assumed that this is because there are other unexplained contributions to the financing of those particular projects.

C.3.2. Process heat plant cost model used

Cost curves for process heat plant were modelled in Lovegrove et al, 2015, using publicly available project cost data to verify the model. These have been updated based on industry knowledge and the data listed above and are shown in Figure 89, including the complete process heat plant cost (water tube boiler systems, plant equipment, civil works, installation, piping, 14 day fuels storage and plant commissioning). These cost models have been used in the analysis in section 3.7

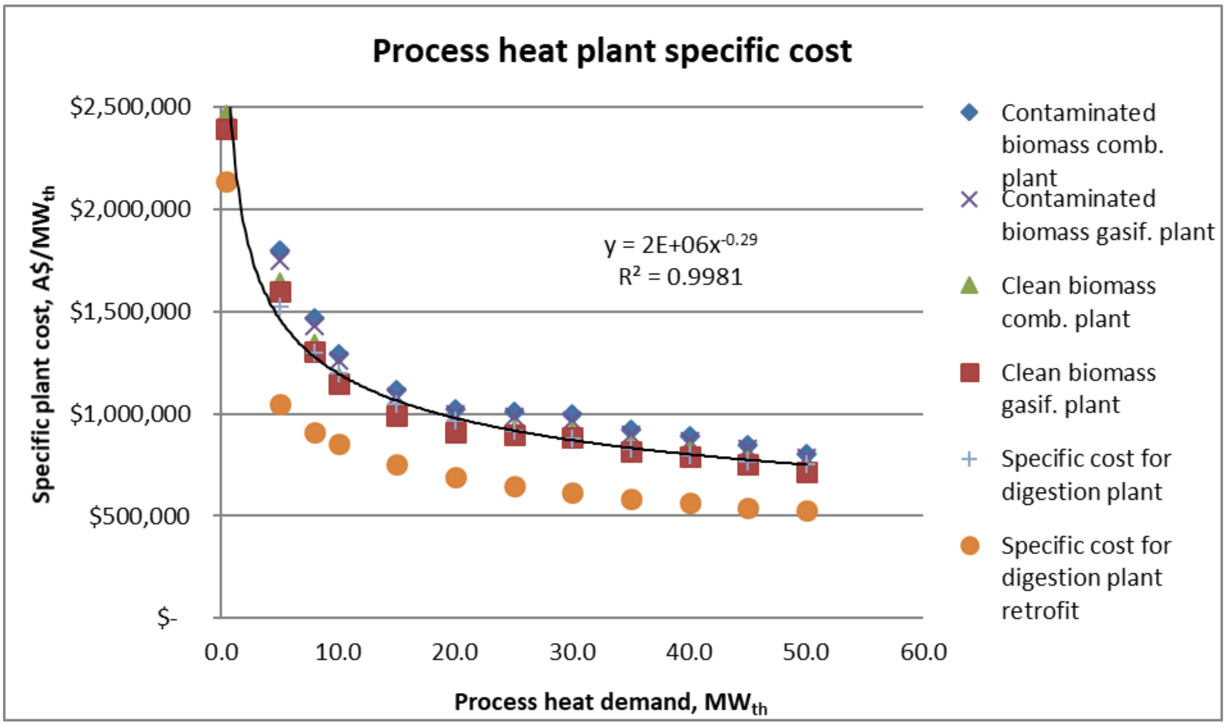

Figure 89: Installed cost models for process heat from various biomass technologies A$ 2019.

The cost difference between combustion and gasification/combustion plants results mainly from the lower amount of excess air that a combustion/gasification plant requires. The smaller amount of excess air results in a smaller flue gas volume and hence smaller boiler and flue gas cleaning components. However, the overall impact is marginal, as this affects two cost components only, and does not affect efficiency in a process heat plant. There is a greater effect in electricity-only plant as gasification systems can lead to higher Rankine cycle efficiencies. However, gasification plants generally have much stricter feed requirements than combustion plants.

The cost difference between clean and contaminated biomass feedstocks derives mainly from the additional flue gas cleaning equipment that contaminated fuel plants require, e.g. flue gas scrubbing systems.

The specific capital cost curve for retrofitting an anaerobic digestion plant is generally significantly lower than the other biomass alternatives. However, this requires the existing boilers to be able to burn biogas without adverse effects on the boiler lifetime, and some contaminants in biogas can have an adverse effect on boilers if they are not removed. If a new biogas-fired boiler is required with the anaerobic digestion plant, the specific costs may be similar to clean biomass combustion plants depending on the relative costs of gas collection and cleaning and solid biomass feed handling. The cost of small biogas plants increases significantly because of the relatively higher cost of small digestion tanks. Small biomass boilers can be provided as modular units with minimal on-site installation.

C.3.3. Bioenergy feedstock costs

The ongoing fuel costs for bioenergy plant have a significant effect on the overall economics. The cheapest bioenergy feedstocks will be those that occur on site and require handling for waste disposal. These fuels will be zero cost, so the cost of replacing existing energy sources with bioenergy is almost entirely dependent on the capital cost of the technology. Conversion at the time when existing boilers require replacement is likely to be the most cost effective. Note however that many residues created by the saw milling industry have existing markets, for example in the horticulture and livestock industries.

Table 42 gives indicative costs per GJ for selected feedstocks. Note that costs for wastes that do not arise on site will always have to cover transport, and any processing that occurs.

Table 42: Indicative costs per GJ for various bioenergy resources (from (Lovegrove et al., 2018, p 184)).

Resource	Indicative cost A$/GJ
Animal wastes, sewage sludge, landfill gas	Generally zero, and may be negative if disposal costs are avoided
Bagasse	$0 - $0.8
Short cycle crops (such as oil mallee)	$4.2 - $7.0
Wood pellets	$11.0
Agricultural residues such as straw	$1.7 - $5.7
Forest residues	$1.3 – $2.6
Wood waste	$0.4 – $2.5

APPENDIX D. GEOTHERMAL TECHNOLOGY

ARENA has examined the potential for geothermal energy in Australia in a comprehensive manner. Three major reports have been released:

- Barriers, Risks and Rewards of the Australian Geothermal Sector to 2020 and 2030, a report for ARENA by the International Geothermal Expert Group Members (Grafton et al., 2014)
- Competitive Role of Geothermal Energy near Hydrocarbon Fields, a report by Evans & Peck (2014)
- Geothermal Energy in Australia, a report produced by CSIRO (Huddlestone-Holmes, 2014).

Although the focus of these reports is largely directed at the potential for power generation, relevant material from the reports is reviewed here.

In Australia, geothermal heat largely originates from radionuclide decay in deeply buried granites. Where an overlying rock strata has low thermal conductivity, it forms an insulating cap and allows rock temperatures to rise significantly as a consequence of the heat generated over long time periods. As a rough rule of thumb, temperatures increase between 20°- 35°C per kilometre in depth in Australia (Pujol & Bolton, 2015). Accessing this heat depends on the circulation of water to the hot rock, either naturally occurring or by artificially injecting it. In other countries water can be naturally in contact with heat sources that are connected with seismic or volcanic activity.

(Huddlestone-Holmes, 2014) provides a categorisation into three basic situations as illustrated in Figure 90:

A)shallow direct use

B) deep, natural reservoirs

C) enhanced geothermal systems.

The distinction made between the three types is based on depth and the temperatures available.

Shallow direct use and deep natural reservoirs, together referred to as hot sedimentary aquifers, require establishing boreholes for water extraction. These resources have been accessed to a limited degree in Australia but to a much greater extent in other countries, e.g. New Zealand. They typically offer temperatures between 60 and 110°C.

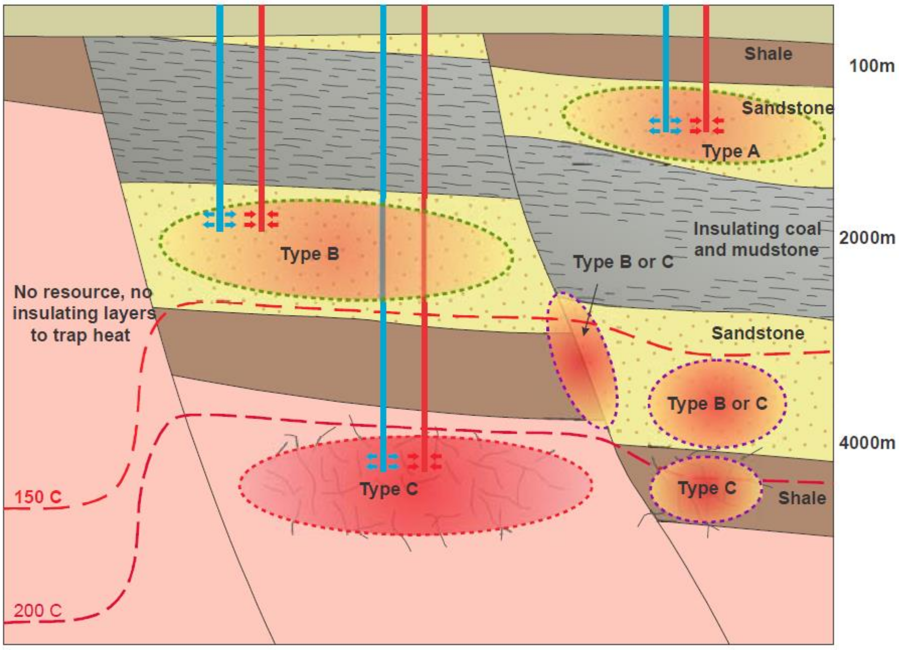

Figure 90: Geothermal resources and the three main types of use. Reproduced from CSIRO, (Huddlestone-Holmes, 2014).

The deeper, enhanced geothermal systems[29] can access higher temperatures between 200 and 250°C. To achieve this requires drilling bores to in excess of 4000m, close to technically achievable limits. Drilling is then followed by artificial fracturing of the rock (fracking) to establish a high surface area permeable region between the injection and extraction wells.

Enhanced geothermal systems offer the greatest long-term potential but are still in the R&D phase. It is hot sedimentary aquifers that could potentially represent a renewable energy alternative for industrial process heat in the near term.

D.1. Technical approaches for hot sedimentary aquifers

Harnessing a hot sedimentary aquifer resource requires drilling bore holes. This is a standard practice with an established industry that is usually targeted at constructing bore holes to provide water resources. Holes are drilled at chosen diameters and steel casings are then lowered in sections, with each section screwed to the next. The gap between casing and the side of the hole is filled with cement grout pumped in under pressure. A perforated screen is lowered into the bottom of the hole in the active part of the aquifer to allow water to flow but keep rocks and sediment out.

[29] Sometimes referred to as Hot Dry Rock geothermal.

The water in an aquifer is typically under some pressure, which will cause it to rise up the bore hole to an equilibrium at 50 or 100m below the surface. Consequently a submersible pump is lowered down to this level to produce the flows needed.

Bore holes can be drilled and cased in a range of diameters. Holes are often initially drilled at a small size and then ‘reemed’ to a larger size. For deeper holes, a hole may be drilled and cased to an intermediate depth and then continued further in a smaller diameter.

If the goal is to provide process heat, then the approach that offers the most sustainable use of a resource is to have two boreholes, one for extraction and one for reinjection. Aquifer water is brought to the surface and heat extracted via a heat-exchanger for the process, and the water is then reinjected to the aquifer as illustrated in Figure 91.

The alternative is to simply extract the water from one bore, extract the heat and dispose of it. This is clearly cheaper and there are geothermal heat projects that have done this and simply discharged water into a river or drain. If the water is needed for a town supply or irrigation purposes, then there is a stronger argument for the single bore approach.

The extraction rate achievable is limited by the ability of the aquifer to replace the extracted flow, determined by both the permeability/porosity and the thickness of the reservoir. Pumping requirements will also increase with increasing well depth and decreasing well diameter. Extraction rates and pumping loads have a significant impact on project economics.

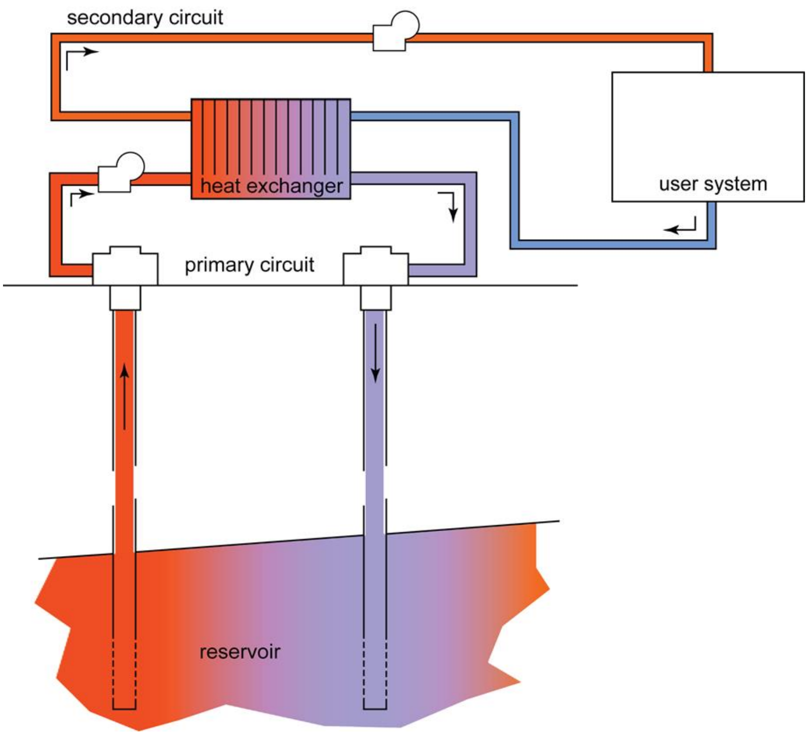

Figure 91: Typical geothermal 'doublet', i.e. a pair of injection and extraction bore holes. Reproduced from (Pujol & Bolton, 2015).

Significant uncertainty exists during geothermal project development regarding the temperatures that exist at depth and the achievable water flow rates from a well. As a result, geothermal project development involves probabilistic resource assessment by hydrogeological consultants.

Together with the temperature of the resource, the flow rate determines the thermal power that can be extracted.

$$\text{Power (kW}_{th}\text{)} = \text{mass flow rate (kg/s)} \times \text{specific heat (kJ/kg/°C)} \times \Delta T \text{ (°C)} ,$$

where the specific heat of water is 4.186 kJ/kg/°C and ΔT (°C) is the temperature difference between the extracted groundwater at the inlet and outlet of the heat exchanger.

It can be seen that thermal power increases linearly with temperature and flow rate, and that even a ‘small’ geothermal project with a flow rate of 10 litres/s and ΔT = 10°C gives thermal power of 420 kW_{th}. While increasing well depth (and hence cost) is most often required to attain higher temperatures (and thermal power), the flow rate achievable is mostly a property of the aquifer although higher flow rates can be achieved at the expense of increased pumping power requirements. Where the thermal load exceeds that which can be met by a single pair of wells, further wells can be added. However they must be suitably separated to avoid locally lowering the temperature of the aquifer. The result is that project economics are highly dependent on flow rate.

D.2. Geothermal resources

‘Geothermal Energy in Australia’ (Huddlestone-Holmes, 2014), the CSIRO report to support ARENA’s geothermal research, includes the resource map in Figure 92.

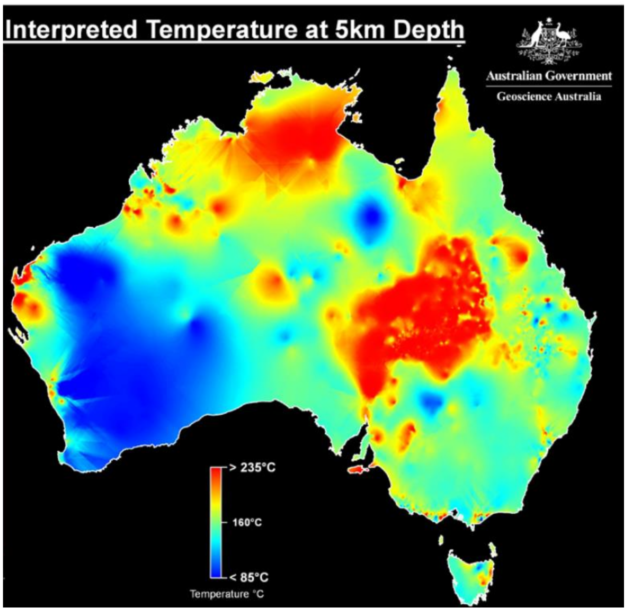

Figure 92: Interpreted crustal temperature at 5 km depth. Reproduced from Geoscience Australia.

This is an indication of the underlying resource that may potentially be targeted by enhanced geothermal systems. The hottest region in central Australia (indicated in red) lies within the Great Artesian Basin that extends from QLD to north-west NSW and northern SA. It has been subject to numerous bores beyond 1000 m depths that have yielded water temperatures of over 100°C (Huddlestone-Holmes, 2014).

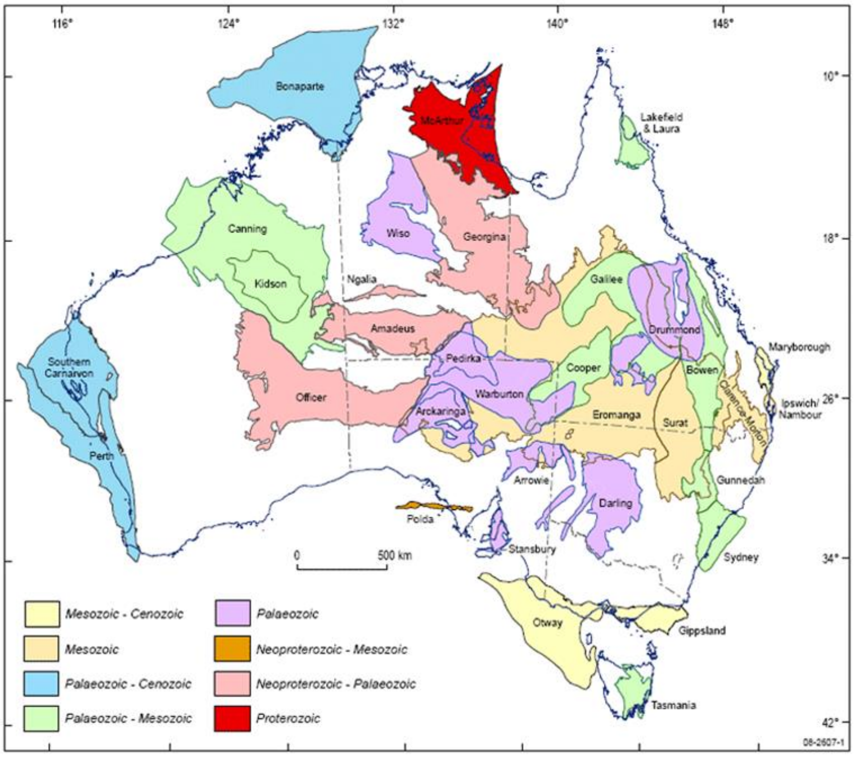

Figure 93: Distribution of onshore sedimentary basins in Australia. Reproduced from Geoscience Australia.

In regards hot sedimentary aquifers, resources can be found at approximately 30% probability in areas within sedimentary basins. This means on average around 5% of the continent is likely to be sitting on a useful resource. Figure 93 shows the distribution of sedimentary basins in Australia. Unfortunately, resource supply is not co-located with resource demand in most cases. The Great Artesian Basin, indicated in Figure 94, is notable as it covers a very large area of the continent and is actually a combination of several of the sedimentary basins shown in Figure 93. Almost any location within the basin can be expected to yield hot water. Temperatures can be up to 90°C and depths are 1000 – 1500 m. The Artesian basin is used to a high degree as a source of water for townships and farms and in many cases water that comes to the surface at an elevated temperature is simply allowed to cool before use.

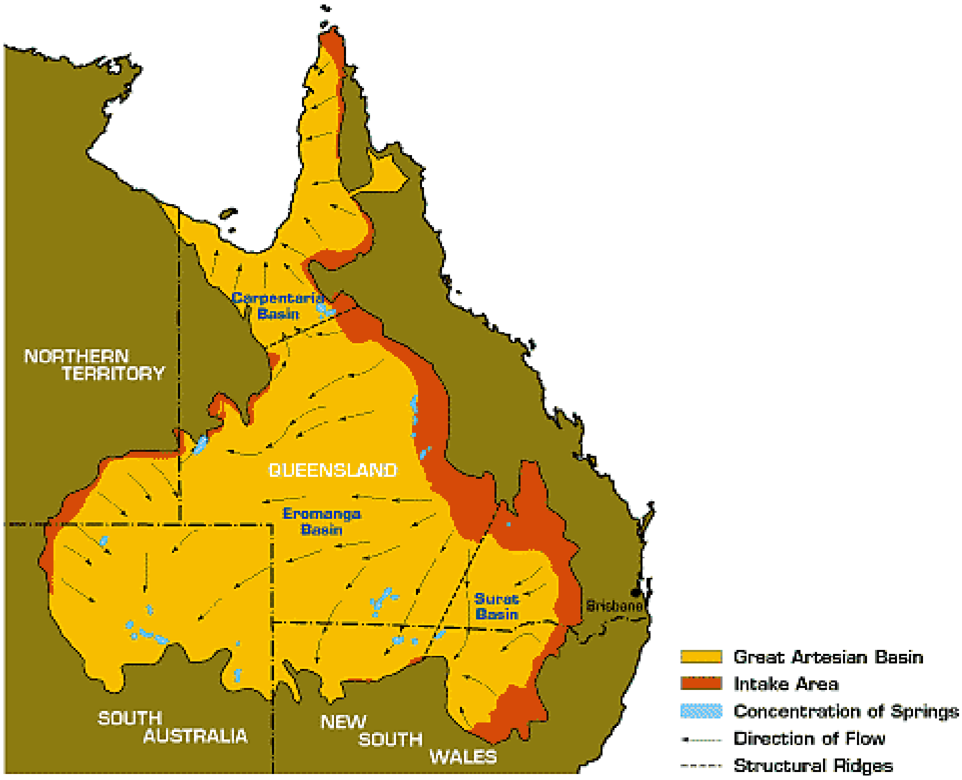

Figure 94: The Great Artesian Basin. Reproduced from travelling-australia.info.

Despite the large land area involved only a minority of industrial operations are located near the Artesian basin.

The Yarragadee basin in the Perth region is also notable. This is a reliable source of hot water in the range of 40°C at depths of 800 – 1000 m and has been used in a range of projects for pool heating and space heating and cooling.

There is an interesting example of the Otway basin in the Latrobe Valley in VIC. It lies beneath the brown coal deposits at depths of 700 – 800m, extends some 50km, and offers temperatures up to 75°C (Driscoll & Beardsmore, 2011).

For much of the eastern part of the continent, between the Artesian basin boundary and the coast, where a majority of gas users are located, the presence of a hot sedimentary aquifer resource is a low but not zero probability. Assessing the potential would require use of geological / hydrology expertise. State government departments with water resource responsibilities have considerable background knowledge. Assessment becomes a sequential analysis of probabilities that includes: is the location on a sedimentary basin; will water be present, will it be at an elevated temperature, and will the strata allow reasonable rates of extraction.

Geoscience Australia have estimated that the amount of geothermal energy at temperatures above 150°C and at depths of up to 5 km is over 1.9×10^{10} PJ and hence several orders of magnitude higher than Australian primary energy consumption. However, the economic extraction of geothermal energy depends on the depth of the drilling, the water flow rate through the geothermal well and the pumping power associated with pumping water through the system to the earth’s surface. In addition, the limited temperatures of geothermal energy at accessible depths limits the technology´s application for process heat applications. Hence, the potential to use geothermal energy depends very much on the local variables and can only be determined with a combination of an in-depth analysis of the process heat requirements, the geological site and exploratory drillings to confirm the estimated potential.

D.2.1. Resource data

For geothermal energy, AREMI allows us to visualise the national map of interpreted underground temperatures at 5 km depth shown in Figure 92 (righthand side). However, the maps in AREMI currently display as temperature ranges without absolute temperature scales. The absolute temperature scale can be seen in Figure 92. For NSW, AREMI additionally provides temperature maps at 2, 3 and 4 km depth.

D.3. Technology selection and design considerations

Figure 95 provides an overview of selected heat applications of geothermal energy for industrial processes.

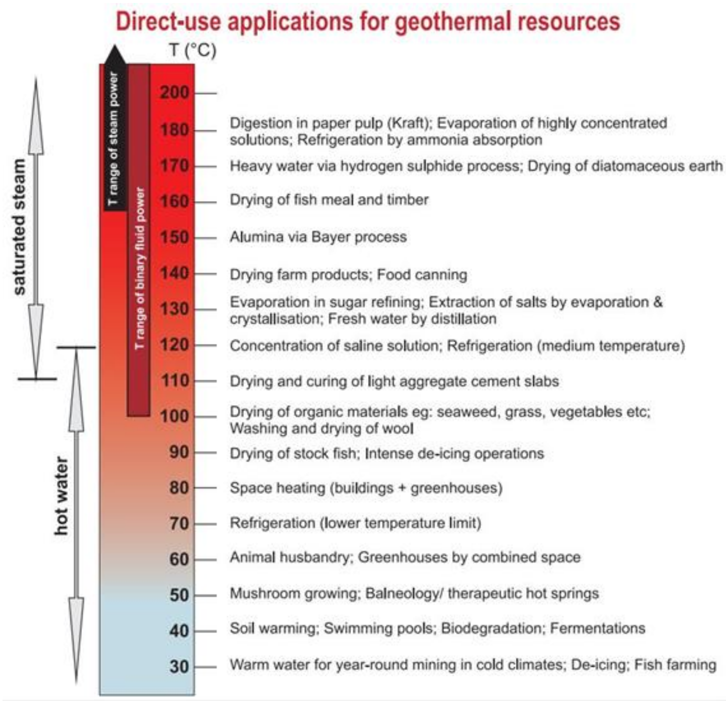

Figure 95: Direct use applications of geothermal energy versus geothermal source temperature. (Reproduced from Geoscience Australia).

In addition to providing a source of heat at elevated temperatures, even at a depth of a few metres below the ground, the ground temperature is quite constant over the course of a year and this surface region may provide a stable thermal reservoir for heating and cooling via ground source heat pumps (Geoscience Australia, 2018).

D.4. Costs and opportunities

The Competitive Role of Geothermal Energy Near Hydrocarbon Fields report (Evans & Peck, 2014) provides the following cost forecasts:

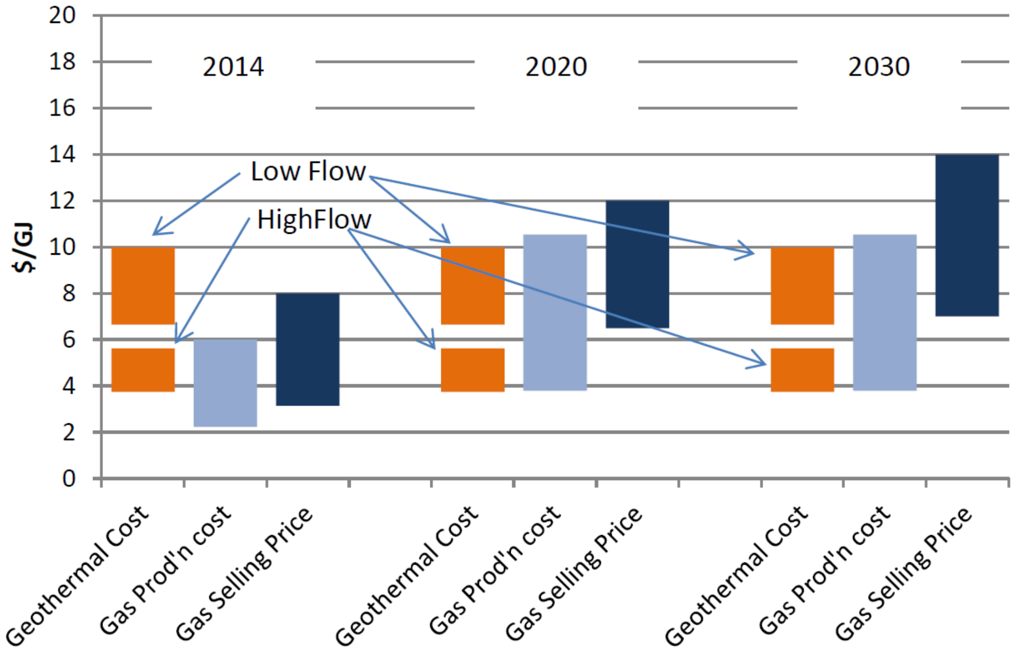

Figure 96: Comparison of geothermal energy cost, gas production cost and gas selling price at Moomba. (Reproduced from (Evans & Peck, 2014)*).*

Evans and Peck conclude that by 2020, enhanced oil and gas recovery, processing facilities and various utilities could cost effectively be run with geothermal direct heat. Urea production and carbon capture processes are hypothetical new processes that could be viable by 2020 in Moomba.

The report identifies alumina production as a potential application but indicates that an enhanced geothermal system in the Cooper Basin that is remote from the bauxite is not a viable way to reducing energy costs.

The Evans & Peck report indicates that pulp and paper production is an application that might be suitable for regions that have feedstocks in proximity to geothermal resources. There is an example of a major direct geothermal heat application in New Zealand’s pulp and paper sector.

Table 43 quotes geothermal heat costs before allowing for a heat exchanger and injection costs to sustain circulation. However, Evans & Peck claim that this provides a valid comparison to the gas fuel price, as this does not include the cost of a gas fired-boiler system. Evans & Peck conclude that even in a high-flow scenario, geothermal heat would be too risky an investment in 2014 but should be viable by 2020.

Table 43. Geothermal heat production costs, from Evans & Peck, June 2014.

	Low flow (40kg/s/well pair) $/GJ heat	High flow (80kg/s/well pair) $/GJ heat
Optimistic well cost	6.66	3.75
Optimistic well cost + 50%	9.99	5.62

In the Cooper basin, 2020 could mark a turning point for considering geothermal solutions as many existing facilities will come to the end of their working life and need to be replaced.

The analysis of the potential for use of geothermal heat for assisting gas production at Moomba notes that 8%of gas is needed to provide the energy for production plant operations.

The Barriers, Risk and Rewards of the Australian Geothermal Sector to 2020 and 2030 report indicates that the most prospective markets for geothermal energy in Australia out to 2030 are in remote locations that are off the grid, and where there are commercial-scale applications for either electricity or direct heat. It also notes that where an identified geothermal resource is co-located with gas processing and recovery facilities, there may be opportunities for use of geothermal heat.

The cost parameters can be used to deduce the capital investment required for industrial heat applications. The thermal capacity of systems can be calculated from the power plant conversion efficiencies and their rated electrical power output.

For Table 44, the costs of the power plant have been removed for thermal applications. Instead an allowance for balance of plant aspects at 10%of the quoted power plant cost is used to produce the specific cost estimates.

Table 44: Cost estimates for thermal energy developed from figures in (Grafton et al., 2014).

Parameter	Enhanced geological systems	Hot sedimentary aquifer
Thermal capacity	550 MW_{th}	420 MW_{th}
Total cost	$450 million	$240 million
Fixed O&M costs	2% of total capital costs	3% of total capital costs
Specific coat	$818/$kW_{th}$	$571/$kW_{th}$

An internal report provided by Rockwater Consultant Hydrogeologists (Pujol & Bolton, 2015) gave the following capital cost estimates:

> "*For recent geothermal projects undertaken in the Perth Basin of Western Australia at depths ranging from 500 to 1500 m, the total capital costs ranged from $1350/m to*

> *$1850/m (average $1700/m). These costs exclude heat exchanger and circulation pumps in the secondary circuit that would be required regardless of the chosen heating method. Costs include insurance (typically 1%), supervision, testing and control (13%), pipework (5%), headworks and submersible pump (10%) and all drilling related costs (71%)." "… for projects deeper than 1500 m heavy duty oil and gas drill rig will be required. It is estimated that these costs might be in the order of $2500/m ± $500."*

The latter figure is consistent with the figure of $9.3 million per 4,000m deep production well given in (Grafton et al., 2014). In the economic modelling provided in Section 3.7, we have used $1,700/m capex for wells up to 1,500m in depth, and $2,500/m beyond that. An injection well is assumed to be 60% of the depth of the production well, and a cost-size scaling relationship has been assumed for drilling of multiple wells on one site.

APPENDIX E. RENEWABLE ELECTRIC HEATING TECHNOLOGY

E.1. Heat pumps

E.1.1. Introduction to the technology

In nature, heat naturally flows from a hot ‘source’ towards a cold ‘sink’. Heat pumps are devices that can reverse the direction of this heat flow by manipulating a working fluid known as a refrigerant. They are widely used to provide heating and cooling for residential, commercial and industrial applications. Heat pumps can utilise a range of different sources of heat including ambient air, the ground, water or a waste stream of fluid and can efficiently produce hot air, hot water or steam.

There are many different types of heat pump, all requiring a certain work or heat input. For every unit of energy input, a heat pump can deliver multiple units of thermal energy. This makes heat pumps an efficient device for upgrading low-grade ‘waste’ heat into higher-value heat for use in an industrial process.

The basic concept of a closed cycle vapour compression heat pump is illustrated in Figure 97.

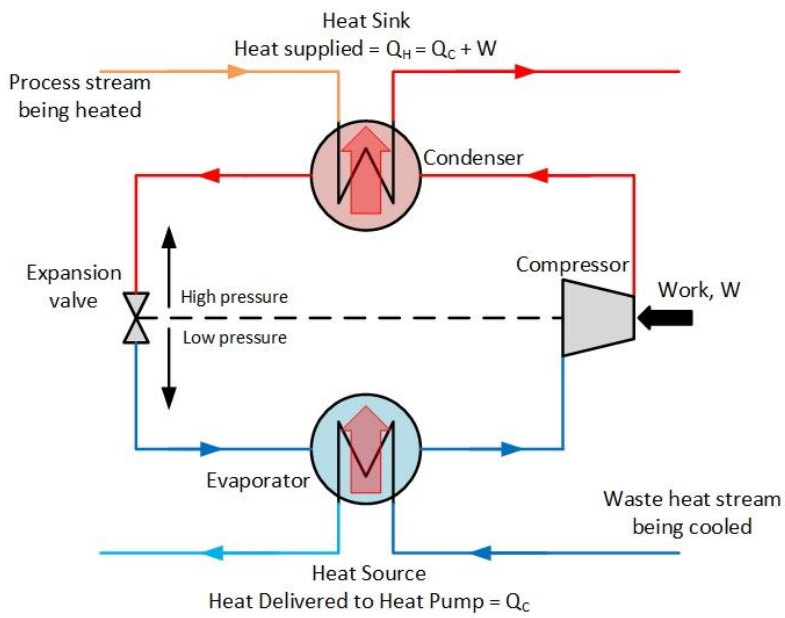

Figure 97: Schematic of a closed-cycle vapour compression heat pump.

In heating mode, the refrigerant is compressed so that its temperature increases, and then passes through a heat exchanger to deliver heat to the application as it condenses to liquid form. The working fluid is then expanded to lower its temperature below that of the source heat temperature (e.g. ambient air or waste heat). The fluid can then travel through another heat exchanger to collect heat from the source to evaporate it.

There are a range of different thermodynamic cycles available that can perform the role of a heat pump, each of which is suited to different applications. A summary of the different technologies is listed below.

Mechanical vapour compression (MVC) heat pumps are the most widely used and commercially successful and are broadly used in refrigerators and air conditioning systems. A mechanical compressor is used to drive the flow of a refrigerant and pump the heat from the source to the sink.

Mechanical vapour recompression (MVR) is a special type of heat pump that compresses the vapour form of the fluid being processed (usually water) directly in an open cycle, rather than using a refrigerant in a closed cycle. In the most common MVR system, low pressure process steam is extracted and compressed to a higher pressure and temperature. This steam is then fed back into the process so that the latent heat from the expended process fluid can be captured and delivered back to the target process.

MVR achieves COPs as high as 60 for small temperature uplifts of 5 to 10 degrees. For higher temperature uplifts they can be used in series, to achieve temperatures of 200°C or higher.

Common MVR applications include concentration of a process or effluent stream, drying or distillation in industries such as chemicals, pharmaceuticals, paper making, sewage treatment and desalination.

Thermal vapour recompression (TVR) systems achieve heat pumping through the use of an ejector and high-pressure vapour. A TVR heat pump is driven by heat rather than mechanical energy.

Thermo-acoustic (TA) heat pumps are still in the development phase. They use acoustic energy to upgrade waste heat to usable process heat at the required temperature (Spoelstra & Tijani, 2005).

Industrial heat pumps are commercially available for heat processes up to 160°C. Higher temperatures outputs are currently the target for several manufacturers but require further development of both refrigerants and the compressor technology (Section 0).

E.1.2. Global prevalence of heat pumps

Heat pumps are a well-established technology with thousands of industrial units in service around the world, with the highest prevalence in Japan and Europe. However, there are very few industrial heat pumps operating in Australia.

Analysis of European markets has shown approximately 2000 TWh of industrial heat demand. Of this demand, 174 TWh could be met by industrial heat pumps, 74.8 TWh of which was classified as high temperature (80–150°C) (IEA, 2014). Globally, the industrial heat market is predicted to continue to increase, with low to medium-temperature heat (below 400°C) accounting for 75% of this growth in heat demand in industry by 2040 (IEA, 2017). It has been estimated that widespread use of heat pumps in both the residential and commercial sectors could reduce CO_2 emissions by 1.25 billion tonnes by 2050 (IEA-ETSAP / IRENA, 2013).

E.1.3. Process types and temperatures

A comprehensive list of applications for industrial heat pumps has been provided in several studies (IEA, 2014; McMullan, 2003; Watanabe et al., 2017). These applications include:

- drying: e.g. products such as timber (40-100°C), air for milk powder (80°C), potatoes (70°C), malt (35°C), painted parts (up to 120°C), french fries (70°C).
- washing: e.g. food industry (65-90°C), metal/plastic parts (60°C)
- process water: e.g. brewing (85°C), boiler feedwater (90°C), hospitals (75°C)
- pasteurisation: milk, butter and cheese (73°C)
- concentrating: wort boiling, milk, sugar solution (75-80°C), amino acid
- space heating: e.g. circulated hot water (50°C), district heating (70-90°C).

E.1.4. Efficiency of heat pumps

The principle benefit of heat pumps over other heating technologies is their efficiency, i.e. they can produce more units of heat output than they consume in electrical energy. This efficiency is measured by the Coefficient of Performance (COP), defined as the ratio between electrical energy used and the heat produced:

$$COP_{HP} = \frac{Q_H}{W_{in}}$$

where Q_H is the heat delivered by the heat pump to the process and W_{in} is the energy or ‘work’ supplied by the compressor.

Figure 98 shows typical heat pump COPs for a range of realistic source and process stream temperatures. The values of COP are heavily dependent on the difference in temperature between the source of the heat and the output temperature required of the heat pump, also called temperature lift. The larger the temperature lift required, the lower the performance of the heat pump and vice versa.

	Process Temperature (°C)																						
Source Temperature (°C)	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160
30	11.3	9.0	7.4	6.3	5.5	4.8	4.3	3.8	3.5	3.2	2.9												
35	15.1	11.2	8.9	7.3	6.2	5.4	4.7	4.2	3.8	3.4	3.1	2.8											
40	22.6	15.0	11.1	8.8	7.3	6.2	5.3	4.7	4.2	3.7	3.4	3.1	2.8										
45	45.2	22.4	14.8	11.0	8.7	7.2	6.1	5.3	4.6	4.1	3.7	3.3	3.0	2.7									
50		44.9	22.3	14.7	10.9	8.6	7.1	6.0	5.2	4.6	4.0	3.6	3.2	2.9	2.7								
55			44.5	22.0	14.6	10.8	8.5	7.0	5.9	5.1	4.5	4.0	3.5	3.2	2.9	2.6							
60				44.1	21.8	14.4	10.7	8.4	6.9	5.9	5.0	4.4	3.9	3.5	3.1	2.8	2.6						
65					43.7	21.6	14.2	10.5	8.3	6.8	5.8	5.0	4.3	3.8	3.4	3.1	2.8	2.5					
70						43.2	21.3	14.0	10.4	8.2	6.7	5.7	4.9	4.3	3.8	3.3	3.0	2.7	2.4				
75							42.7	21.1	13.9	10.2	8.1	6.6	5.6	4.8	4.2	3.7	3.3	2.9	2.6	2.4			
80								42.1	20.8	13.7	10.1	7.9	6.5	5.5	4.7	4.1	3.6	3.2	2.8	2.6	2.3		
85									41.6	20.5	13.5	9.9	7.8	6.4	5.4	4.6	4.0	3.5	3.1	2.8	2.5	2.2	
90										41.0	20.2	13.2	9.7	7.7	6.3	5.2	4.5	3.9	3.4	3.0	2.7	2.4	2.2
95											40.4	19.8	13.0	9.6	7.5	6.1	5.1	4.4	3.8	3.3	2.9	2.6	2.3
100												39.7	19.5	12.8	9.4	7.3	6.0	5.0	4.3	3.7	3.2	2.8	2.5
105													39.0	19.1	12.5	9.2	7.2	5.8	4.9	4.2	3.6	3.1	2.8
110														38.3	18.8	12.2	9.0	7.0	5.7	4.8	4.0	3.5	3.0

Figure 98: Indicative COPs (heat pump efficiencies) as a function of source and process temperatures.

The theoretical maximum efficiency of an ideal, or Carnot-cycle heat pump can be expressed in terms of the heat delivery temperature and the temperature lift across the heat pump as:

$$COP_{Carnot} = \frac{T_H}{T_H - T_C}$$

where T_C and T_H are the temperature, in degrees Kelvin, at which the heat pump receives heat in the evaporator and delivers heat in the condenser respectively. It is important to note that these temperatures are not the process operating temperatures but the refrigerant temperatures. A temperature difference is required between the evaporator and the heat source, and the condenser and the process temperature, to drive the heat transfer. For this reason, the effective temperature lift in the process streams (process fluid outlet temperature minus source side temperature in) will be less than the temperature lift internal to the heat pump. The actual heat pump coefficient of performance can be expressed in terms of the Carnot-cycle (ideal) performance as:

$$COP_{HP} = \eta \cdot COP_{Carnot} = \eta \cdot \frac{T_H}{T_H - T_C}$$

where η is the system thermodynamic efficiency. Modern commercially available heat pumps will typically be between 65 and 75% of their theoretical maximum efficiency.

In certain circumstances heat pumps can be used for simultaneous heating and cooling. In this case a combined coefficient of performance, $COP_{combined}$, can be expressed as the ratio of total useful thermal energy supplied/removed to the electrical input:

$$COP_{combined} = \frac{Q_H + Q_C}{W_{in}}$$

where Q_C and Q_H are the heat extracted from the source and delivered to the process respectively, and W_{in} is the energy or "work" supplied by the compressor.

An example of this is a heat pump used to produce hot water for food production, whilst extracting the heat from a stream of brine, which is used for chilling, thereby offsetting the energy required in the chiller unit. Such installations can result in combined COPs higher than nine and a very high return on investment for the business. However, challenges in aligning the requirement for heating and cooling in smaller plants can lead to a requirement for thermal storage buffers of cold and hot process fluids.

Several factors influence the COP of a heat pump. These include;

- **temperature lift:** the difference between the cold and hot side of the unit has the greatest impact on efficiency; the larger the temperature difference, the lower the COP
- **temperature glide:** the magnitude of the temperature change within the refrigerant as it changes phase from liquid to vapour in the evaporator or condenser
- **refrigerant type**: each refrigerant has unique physical properties, such as boiling temperature, critical temperature and volumetric capacity, that influence the efficiency of a heat pump operating between given source and sink temperatures
- **Compressor type:** scroll, screw, centrifugal, and reciprocating are the main compressing technologies for commercial heat pumps. They vary in capacity, cost, and efficiency. Selecting the suitable compressor is a multi-faceted design optimisation process.

Additionally, it is also important to consider any energy consumption from necessary ancillary equipment such as fans and pumps (e.g. evaporator fans for air source heat pump). Whilst this load does not strictly influence the COP (as the energy to drive these is not part of the expression), it will impact the overall energy required by the unit.

E.1.5. Heat pump refrigerants

Closed cycle heat pumps transfer heat by compressing and expanding a refrigerant fluid. This refrigerant's characteristics should include a high latent heat when in gaseous form, and good ability to transfer this heat.

Two significant classes of refrigerants, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), have mostly been phased out due to their role in destroying the earth's ozone layer. CFCs and HCFCs have been replaced by hydrofluorocarbons (HFCs). HFCs do not deplete ozone, but many of them do have a very high global warming potential – often thousands of times higher than CO_2. For this reason all governments have agreed to drastically reduce use of HFCs by mid-century.

There is a shift in the heat pump industry towards natural refrigerants such as CO_2, ammonia and water, as well as some newly-developed HFCs with low global warming potential. Manufacturers should aim to deploy environmentally benign refrigerants. However, the indirect consequence of a possible lower COP, which can increase their indirect emissions depending on the origin of grid electricity, should also be considered.

The choice of refrigerant depends primarily on the temperature levels of the process. CO_2 (R744) is a common refrigerant usable for heat processes up to 120°C. As a refrigerant CO_2 has several beneficial properties – it is non-toxic, non-flammable, non-corrosive, is not ozone depleting and has a GWP of only 1. CO_2 heat pumps can also operate with more compact compressors, and heat exchangers, despite operating at high pressures (Nekså, 2002). However, its low critical temperature of 31.0°C means that the temperature of the heat source must not be higher than about 30°C.

For most refrigerants other than CO_2 it is important to have a critical temperature that is sufficiently above the highest heat rejection temperature desired.

E.1.6. Implementation of heat pumps

For some applications, such as process water heating, heat pumps can be implemented with little modification of existing plant and equipment. Here the heat pump would typically replace either steam (jacketed vessel or heat exchanger) or electricity (resistance elements) used to produce hot water. Generally, the interfacing of the heat pump in these cases requires a small amount of additional insulated piping. However, the removal of steam as a water heating source can often allow for the removal of some steam piping, with an associated reduction in heat losses.

The physical footprint of the heat pump depends on the heat pump type and heating capacity of the unit. CO_2 heat pumps are modular units designed to be installed in parallel to increase total capacity, with each unit only occupying 1-2 m^2 of floor space. The small footprint of these units allows them to be located close to the process requiring the heat. Ammonia heat pumps tend to occupy larger areas (5-20 m^2) and are more commonly installed in a plant room away from the process (potentially close to the heat source such as refrigeration plant). This means they require more insulated piping for process integration.

E.1.7. Installed costs of heat pumps

Assessing the costs of heat pump systems can be challenging. It is important to consider the capital and installation cost of the unit, as well as the achievable COP. The COP will depend on operational conditions including supply and delivery temperatures, feed water temperatures, and ambient temperatures, together with consideration of whether the heat extracted from the source (i.e. cooling) is also a value (e.g. can this offset chiller loads).

Table 45 below presents purchase price information for a range of industrial heat pumps currently available in Australia. Prices have been supplied by personal communication with each of the manufacturers/suppliers and are accurate as of December 2018. Values represent purchase price only, non-inclusive of GST, freight, commissioning or installation[30].

Installation costs are difficult to generalise as they are highly dependent on the specific application of the heat pump, the quantity of additional piping required, requirements for electrical capacity upgrades, controls integration etc. For small units such as CO_2 heat pumps (e.g. Mayekawa, Mitsubishi Heavy Industries) this is estimated at between $5,000 - $10,000. These prices are based on examples, such as the MHIA Qton installed at Shene Distillery in Tasmania, and direct communication with suppliers.

For larger systems the costs of installation are much harder to estimate and depend heavily on the specifics of the project. All suppliers approached for this report were reluctant to quote firm figures and there are few large high temperature systems installed in Australia to use as benchmarks. A recent assessment of heat pump opportunities in the Australian food industry (Jutsen et al., 2017) detailed the costs associated with the installation of a 630 kW Mayekawa ammonia heat pump at the Lobethal Abattoir in South Australia. The total cost of the installation was $900,000 ex. GST, which included multiple compressors, VSDs, acoustic enclosure, ammonia detection and ventilation system, wiring, electronics and control, piping integration and commissioning. Extrapolating prices from this and other large heat pumps systems installed in Europe (IEA, 2014), installation costs can be expected to be between approximately 1-2 times the purchase price of the heat pump.

As a general guide, the purchase price of a heat pump system costs around $500 - $2000 per kilowatt of heating capacity for heat pumps with capacity below 500 kW, and around $300-$500 per kilowatt for systems of 1 MW and above. Including the cooling capacity of the unit as well (which is application specific) the costs are around $300 - $1300 per kilowatt of combined heating and cooling capacity for units with capacity below 500kW, and around $150 - $250 per kilowatt of combined heating and cooling capacity for units with capacity between 500 kW - 1MW.

[30] These additional costs could not be obtained in this study, as they are highly site and application dependent.

Table 45: Industrial heat pump specifications and purchase costs in Australia 2018-19.

Brand	Model	Refrigerant	Compressor type	Nominal capacity (kW)	Unit Cost ($AUD)	$/kW (heat)	$/kW (heat + cool)	Source[1]	Sink[1]	Source temperature (°C)[2]		Sink temperature (°C)[2]		Scenario[3]				
										T_{in}	T_{out}	T_{in}	T_{out}	1	2	3	4	5
Mitsubishi Heavy Industries	Qton	R744	rot+scr	30	$25,000	$833	-	A	L	-	-	5-63	60-90	X		X		
Automatic Heating[4]	iTomic CHP15HF	R744	recip.	15	$28,000	$1,867	-	A	L	-	-	5-60	65 or 90	X		X		
Mayekawa	Unimo AW	R744	recip.	72	$48,100	$668	-	A	L	-	-	5-65	65 or 90	X		X		
Automatic Heating[4]	iTomic CHP26H4	R744	recip.	26	$50,000	$1,923	-	A	L	-	-	5-60	65 or 90	X		X		
Mayekawa	Unimo WW	R744	recip.	107	$58,500	$547	$301	L	L	-5-37	-9-32	5-65	65 or 90	X	X	X	X	
Automatic Heating[4]	iTomic CHP080Y2	R744	recip.	78	$70,000	$897	-	A	L	-	-	5-60	65 or 90	X		X		
Viessmann	Vitocal 350-G Pro	R134a	recip.	32	$71,316	$2,263	$1,348	L	L	-7-25	-10-22	30-73	35-73	X	X			
Mayekawa	Unimo AWW	R744	recip.	82	$74,900	$916	$525	L/A	L	-2-37	-7-32	5-65	65 or 90	X	X	X	X	
Mayekawa	Eco Sirocco	R744	recip.	89	$75,000	$843	$500	L	A	0-40	-5-35	-10-43	60-120	X				X
Viessmann	Vitocal 350-G Pro	R134a	recip.	66	$80,643	$1,222	$724	L	L	-7-25	-10-22	30-73	35-73		X			
Viessmann	Vitocal 350-G Pro	R134a	recip.	112	$104,207	$928	$549	L	L	-7-25	-10-22	30-73	35-73		X			
Viessmann	Vitocal 350-HT Pro	R1234ze	recip.	104	$110,903	$1,072	$652	L	L	0-50	-3-47	20-73	35-90	X	X	X	X	
Viessmann	Vitocal 350-HT Pro	R1234ze	recip.	134	$125,040	$932	$567	L	L	0-50	-3-47	20-73	35-90	X	X	X	X	
Viessmann	Vitocal 350-G Pro	R134a	recip.	180	$127,005	$707	$420	L	L	-7-25	-10-22	30-73	35-73		X			

Viking Heat Engines[5]	HBS4	R245fa/ R1336mzz	recip.	200	$139,500	$698	$379	L	L				80-160					X
Viessmann	Vitocal 350-HT Pro	R1234ze	recip.	182	$143,046	$786	$481	L	L	0-50	-3-47	20-73	35-90	X	X	X	X	
Viessmann	Vitocal 350-G Pro	R134a	recip.	234	$156,603	$670	$398	L	L	-7-25	-10-22	30-73	35-73		X			
Viessmann	Vitocal 350-HT Pro	R1234ze	recip.	273	$175,023	$641	$392	L	L	0-50	-3-47	20-73	35-90	X	X	X	X	
Johnson Controls	HeatPAC24V	R717	screw	307	$199,768	$651	$353	L	L	10-40	5-35	40-60	70-85	X	X			
Johnson Controls	HeatPAC28V	R717	screw	612	$285,305	$466	$253	L	L	10-40	5-35	40-60	70-85	X	X			
Johnson Controls	HeatPAC106S	R717	screw	1046	$318,579	$305	$166	L	L	10-40	5-35	40-60	70-85	X	X			
GEA	Red Astrum HE	R717	recip.	420	$380,000	$905	$571	L	L	-10-40	5-35	40-60	55-80	X	X			
GEA	Red Astrum ML	R717	recip.	1200	$650,000	$542	$319	L	L	-10-40	5-35	40-60	55-80	X	X			

Notes:
1. A = Air source/sink, L = liquid source/sink.
2. Process stream temperatures listed are the range accepted/produced by the heat pump.
3. Scenarios correspond to the generic operational scenarios used in this study for operational cost comparison purposes only.
4. Automatic heating units are sold as a complete system (includes circulation pump and control unit).
5. Refrigerant is chosen based on optimising performance for the given application.

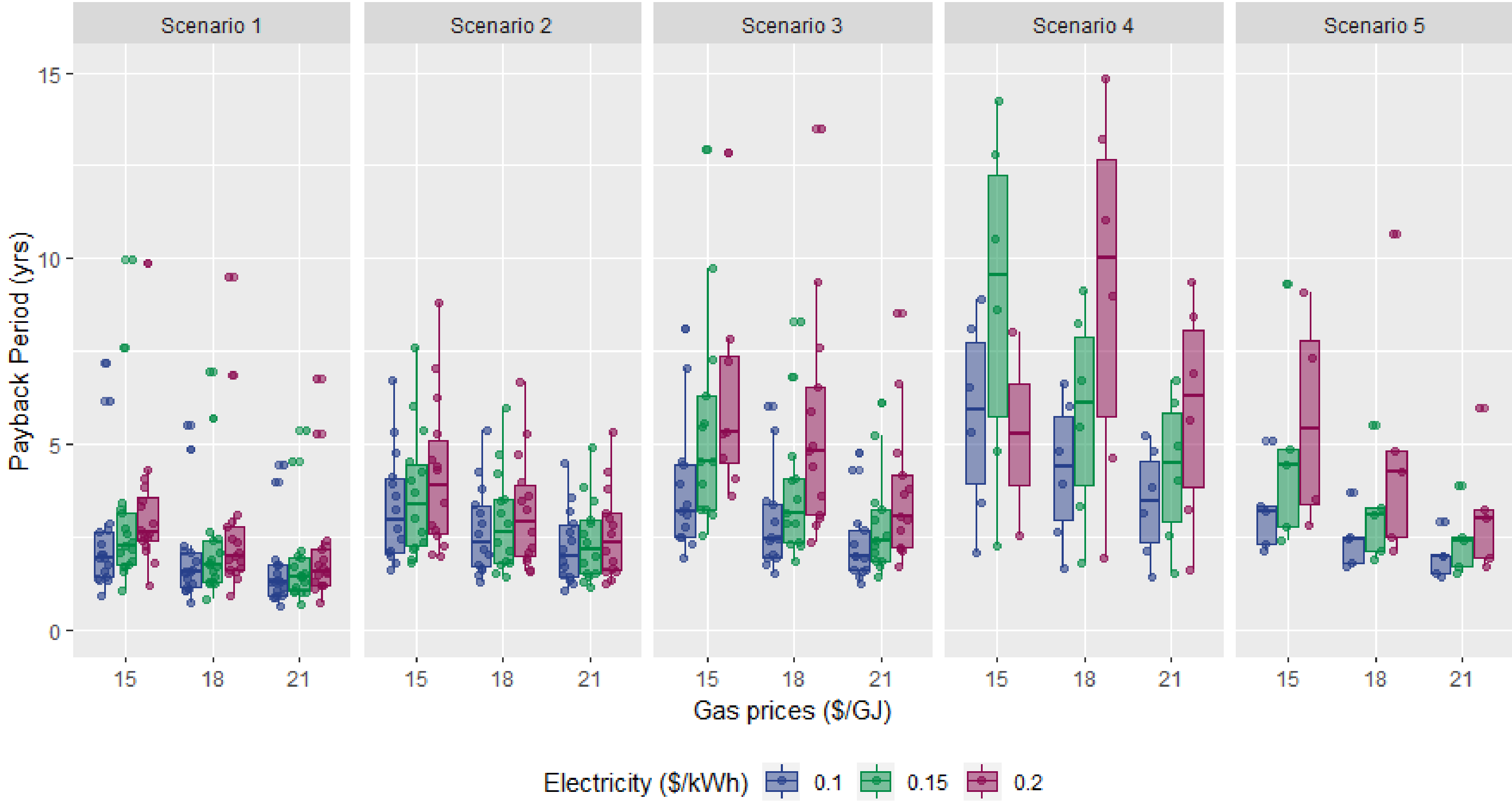

Figure 99: A box and whisker plot of payback period for the five operating scenarios listed in Table 46. Assumed 5000 hours operation/year, boiler efficiency 65%..

Scenario modelling for payback periods

Payback periods for each heat pump installation will depend on the COP at the source and sink temperatures, and unit costs of electricity and gas. To provide a guide to the operating costs that can be expected, five different generic scenarios have been considered here, summarised in Table 46. These scenarios attempt to capture typical heat pump applications, as well as the breadth of performance available. In the description of these conditions, the following definitions are used:

- Source temperature entering/exiting the evaporator = $T_{S,in}$ / $T_{S,out}$
- Process fluid temperature exiting the condenser = $T_{P,out}$

Table 46: Heat pump scenarios considered.

Scenario	$T_{s,in,}$, °C	$T_{s,out,–}$ – °C	$T_{P,out}$, °C	Description
1	37	32	65	medium-temperature water production using waste heat; no cooling (COP based on heat delivered only)
2	12	7	65	like scenario 1, but cold side of the heat pump is used to produce chilled water/brine
3	37	32	90	like scenario 1, but higher process temperature
4	15	12	90	like scenario 3, but cold side of the heat pump is used to produce chilled water/brine
5	?	?	>120	hot water production using waste heat streams of up to 100°C; no cooling

Figure 99 shows the simple payback period for various fuel costs (electricity: $0.10/kWh - $0.20/kWh, gas: $15/GJ – $21/GJ) for the five broad heat pump scenarios above. Data points with payback periods longer than 15 years have been excluded from the plot, as these would not represent commercially viable projects. The existing heat source replaced by the heat pump is assumed to be a gas-fired boiler operating at a steam system efficiency of 65% and 5000 hours of annual operation.

For scenario 1 and 2 there are many heat pumps currently available in the market that can achieve payback periods between 2-5 years for each of the fuel cost variations. For scenario 3 there is still several units that can achieve sub 5-year payback periods, particularly for situations with high gas costs.

Scenario 4 is more complex as it involves assumptions of the energy offsets associated with the cooling loads (cooling produced from the heat pumps is assumed to offset an electrically-driven chiller with a COP of 4). The COP for heat pumps in this scenario is naturally lower than the previous three scenarios, given the large temperature lift. Despite this, several heat pumps still achieve sub 5-year payback period. However, the data is far more dependent on the details of the installation and the value captured by the cold stream. This indicates that the application of heat pumps for this scenario requires careful consideration of the unit's capacity for the desired temperature lift, heat source and process temperatures.

Finally, scenario 5 is for heat pumps producing high-temperature outputs. The data shows that provided a suitable waste heat source is available (up to 100°C), payback periods of less than 5 years are achievable for a range of fuel costs.

E.1.8. Potential future improvements to heat pumps

There are a range of potential improvements for industrial heat pumps. These may include the continued development of heat pumps for natural refrigerants and advances in compressor materials allowing higher compressor discharge pressures (higher condenser temperatures). This advancement may provide a means for water to be used in closed-cycle MVC heat pumps supplying process temperatures up to 200°C.

However, the largest improvement may indeed be behavioural. For a long time, Australia has enjoyed gas prices that have encouraged complacency around process design. This period now appears to have ended and there is increased attention on energy costs savings. This will be a driver for efficiency improvements and should see Australia learn from leaders in other parts of the world and begin to adopt heat pump technologies broadly across our manufacturing sectors.

E.1.9. List of potential suppliers of heat pumps

Table 47: Industrial heat pump supplier details.

Manufacturer	Model	Contact Details
Current Australian suppliers		
Johnson Controls	HeatPAC HeatPAC HPX	www.johnsoncontrols.com Ricardo Hoffmann
Mitsubishi Heavy Industries Australia	Qton - ESA30E-25 ETW-L (future) ETW-H (future)	http://mhiaa.com.au Trent Miller
Viessmann	Vitocal 350-HT Pro Vitocal 350-G Pro	www.viessmann.com C.T. Kwok
Mayekawa	Unimo AWW, Unimo AW Unimo WW, Eco Sirocco	www.mayekawa.com.au Peter O'Neil
GEA	RedAstrum RedGenium	www.gea.com Greg Clements
Automatic Heating	iTomic Eco Cute	https://www.automaticheating.com.au/
International suppliers		

Viking Heat Engines	HBS4	http://www.vikingheatengines.com/ Ingrid Lofnes
Star	Neatpump	http://www.star-ref.co.uk/ Dave Pearson
Likido	LikidoONE	https://www.linkedin.com/pulse/likido-heat-pump-assisted-distillation-stuart-cox/ Stuart Cox
Kobelco	SHG120 SGH165	Nishioka Daiki Do not currently service Australia
Hybrid Energy	Customised systems	https://www.hybridenergy.no/ Jostein Henriksen
Calefa	Custom	http://www.calefa.fi/ Antti Porkka

E.2. Electromagnetic heating

Electromagnetic heating mainly refers to infrared, induction and dielectric technologies. Ultraviolet processing is a non-thermal electromagnetic technology that can replace some energy-intensive industrial applications such as curing or water treatment. Although industry has used these technologies for decades, we have only scratched the surface of their true potential.

These technologies typically use electromagnetic waves to transfer energy to a target material or process without the need for any heat transfer medium. The frequency of the wave associated with each technology is presented in Figure 100.

Frequency	50 Hz - 500 kHz	10-100 MHz	200-3000 MHz	30-400 THz		1-30 PHz
Wavelength						
	Induction	Radio	Microwave	Infrared	Visible light	Ultra-violet
Max temp °C	3000	2000	2000	2200		N/A
Power density (kW/m²)	50,000	100	500	300		100
Efficiency	50-90%	80%	80%	60-90%		
Application	Rapid internal heating of metals.	Rapid internal heating of large volumes.	Rapid internal heating of large volumes.	Very rapid heating of surfaces and thin material.		Non-thermal curing of paints and coatings.

Figure 100: Different electromagnetic process heating technologies (Figure BZE).

The main advantage of electromagnetic heating technologies is the accurate delivery of energy to the point of need, which can reduce energy waste, speed up the process and improve plant productivity. Electromagnetic processing transfers energy directly through air or vacuum into the target material, without the need for any energy transport material. As a result, it can be more efficient than conventional indirect heating in which a heat transfer medium, usually air, steam, solid surfaces, or oil, is heated first to then transfer the thermal energy to the target material through convection or conduction (Figure 101).

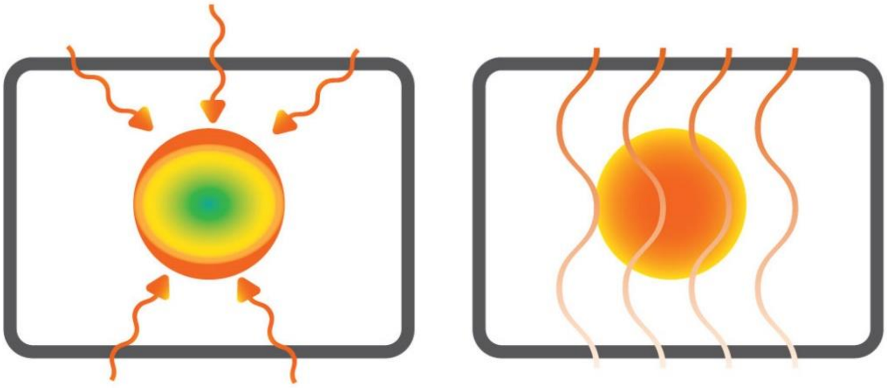

Figure 101: Conventional heating (left) compared to electromagnetic heating (right). (Figure BZE).

Beyond efficiency, electromagnetic heating has the following potential advantages:

- **Rapid start up:** Unlike steam systems, they have low thermal mass and are fast-response heating systems
- **Greater flexibility to be controlled:** due to their fast response, they can be varied efficiently to produce a more consistent output with insignificant energy losses during intermittent processes
- **Less material waste:** as there is no contact with combustion gases and other substances, there is less contamination, thereby reducing material wastage
- **Compact size:** taking up less space on the factory floor
- **Safety:** producing less noise and on-site pollution.

Moreover, implementing electromagnetic technologies enable industrial plants to

- facilitate the integration of renewable electricity in their manufacturing processes
- sign up and respond to demand side management programs
- improve the enterprise productivity through better energy flow monitoring and optimisation (Decarb Europe, 2017).

E.2.1. Dielectric heating

In dielectric heating, the target material is placed within a high-frequency oscillating electromagnetic field that causes the molecules/particles inside the material to agitate rapidly.

Dielectric heating is divided into two distinct categories based on the electromagnetic frequency: radio-frequency (10-100 MHz) and microwave (200-3000 MHz).

Microwave systems are more expensive but are better suited to smaller products and materials with an irregular shape. On the other hand, radio-frequency systems heat material more uniformly than microwaves and with greater depth of penetration, and work best with objects of a regular, simple shape. Radio-frequency heating power can reach 900 kW whereas microwave generators are limited to around 100 kW.

Potential advantages of dielectric heating are:

- the heating power can be adjusted according to the load requirement. For example, as a product dries, the energy input can be reduced
- high heating density – can deliver more heat in a smaller region
- faster processing times – reduces the overall heating time
- instant start-up – full power is available in seconds
- relatively uniform heating throughout a mass of material
- reduced equipment size – dielectric heaters are smaller than convection ovens required to do the same work (down to 20%)
- lower required temperatures vs other techniques
- safety – no hazardous gaseous by-products of combustion
- possibility of reaching high temperatures - up to 2000°C
- ability to drive chemical reactions – such as adhesive curing.

Global prevalence of dielectric heating

It is estimated that well over a million radio-frequency heating systems have been installed around the world in the last 60 years (Koral, 2008). Many of these systems are for drying applications. Interest in microwave systems started to increase in the 1980s to improve productivity and reduce the cost in mainly food manufacturing plants.

Process types and temperature

Dielectric heating works well with materials such as paper, cardboard, textiles and wood that are electrically non-conductive but have polar particles such as water molecules. Conventional methods heat these bulky materials slowly and unevenly because the heat must travel from the surface to the interior via conduction.

In general, both microwave and radio-frequency heating are efficient for drying because water is an excellent absorber of this range of the electromagnetic spectrum. Drying some materials with dielectric heating can reduce the risk of cracking compared to conventional methods due to a faster drying rate.

Table 48 shows applications for dielectric heating including heat processes such as drying, sintering, calcining, cooking, curing and pre-heating.

Table 48: Industrial process applications of dielectric heating (RF: radio-frequency; MW: microwave).

Material	RF	MW	Process
Biodiesel		✔	Separation
Ceramics	✔	✔	Drying, enhancing chemical reactions
Chemical, medical & pharmaceutical	✔	✔	Drying, heating, separation, enhancing chemical reactions, diathermy, treatment of biological tissues, curing, - gas recombination, - synthesis
Food	✔	✔	Drying, heating, boost heating, cooking and pre-cooking, tempering, thawing of frozen food, vacuum heating and drying, pasteurising, sterilising
Various materials (Jones et al., 2002)	✔	✔	Heating, drying, thermally assisted comminution, carbothermic reduction of oxide minerals, leaching, roasting/smelting, pre-treatment, coal treatment
Plastics	✔	✔	Drying. heating. enhancing chemical reactions
Paper		✔	Drying, heating
Rubber		✔	Separation, heating, vulcanising
Textiles	✔	✔	Drying, heating
Timber	✔	✔	Drying, heating
Waste treatment (Jones et al., 2002)		✔	Waste volume reduction, selective heating, treatment of hazardous materials

Efficiency of dielectric heating

The general efficiency of wave production in radio-frequency technology is similar to that of microwave (70%). Industrial microwave systems operate at a significantly higher efficiency than domestic microwaves. However, some losses occur when the mains power frequency is converted to the specific frequency required by the system, e.g. 915 MHz.

Table 49: Component and system efficiency of microwave heaters (MKS Instruments, 2014b).

Component	Efficiency		Note
	Domestic (<2 kW)	**Industrial (>50 kW)**	
Frequency conversion	85%	>95%	Large systems have higher efficiency
Magnetron	68%	85-90%	Larger water-cooled magnetrons have higher efficiency
Waveguide and cavity	90%	95%	Well-tuned cavity has higher efficiency
Overall efficiency	**52%**	**76-81%**	

The efficiencies listed in Table 49 are not always achieved due to additional losses caused by non-ideal coupling between the generated wave and the target material. For many applications, we can expect a total heating efficiency of ~50% and ~65%, respectively, for microwave and radio-frequency.

Cost of dielectric systems

The general cost of dielectric heating systems is difficult to estimate because the microwave and radio-frequency units are often part of a larger system that can include batch processing conveyor belts, presses/hydraulic equipment and packaging subsystems. This section provides some indicative values for the associated costs.

The cost figures for microwave systems have been acquired from two local and one international microwave system supplier as well as peer-reviewed published data. The cost of radio-frequency systems has been gathered from the literature and suppliers' websites.

The cost of dielectric systems is composed of:

1. capital cost of a microwave's three major components (MKS Instruments, 2014a):
   - microwave generator – a function of the type of generator, cooling mechanism (air or water), power level, and power control mode (fixed or variable)
   - control system
   - mechanical components – for material handling, including the batch processing cavity and/or conveyor belt
2. operational costs – including energy, tube replacement, general maintenance, and inventory floor/space cost.

The indicative installed cost of a complete microwave system with material handling units is in the range of A$4000 - 8500 per kW of microwave power output (Koral, 2013; National Research Council, 1994). This includes the cost of microwave generator, housing, control units, waveguides, safety features, conveyor, system design and commissioning. The lower and upper bounds of the price range correspond to large (~100 kW) and small systems (<20 kW). The installation cost typically contributes 5-15% of the total cost.

The microwave generator costs between around 1,500 and 3,200 AUD per kW of delivered microwave power (Table 50). The lower and upper bounds correspond to large (~100 kW) and small (<20 kW) power units. In Australia, a 100 kW microwave generator can be purchased for A$150-200k from European and US suppliers. These are industry standard microwave systems that use 915 MHz frequencies.

Assigning an indicative price to the material handling subsystem in microwave and radio-frequency heating systems is very difficult because they are often designed bespoke and vary significantly, as a result of various factors such as cavity size, throughput, safety features, ventilation requirements, etc.

However as a general rule, in comparison to conventional heating systems, microwave technology can use smaller components for material handling thanks to its higher heating density leading to a lower cost of equipment and factory floor area that reduces the system capital cost (Table 50).

Table 50: The capital equipment, installation, and consumable cost of microwave heating systems; converted from US dollars using 2018 average exchange rate of 0.74 (Mujumdar, 2014).

	Capital equipment (A$/kW)		Consumable equipment (A$/kW)
Microwave generator	**Control system**	**Material handling**	**Magnetron tube**
1,500-3,200	250-400	System dependent, but less than the cost of material handling in conventional systems	120-1000

The main consumable component of a microwave generator, the magnetron tube, has a limited lifetime and needs to be replaced periodically. Magnetrons can be used in two different modes to adjust their output power. Magnetrons with a switch mode, which adjust the power output by switching between on/off modes, last for 6,000-8,000 hrs. A magnetron using a linear mode power supply with continuously variable output lasts for 4,000 to 6,000 hrs.

Costs of replacing magnetrons with different power levels are listed in Table 51. A larger 100 kW magnetron tube can be replaced for about A$12,500 to 15,000. By refurbishing the used magnetron, instead of replacing it, the cost can be reduced by about 50%.

Table 51: Microwave tube replacement cost (Mujumdar, 2014).

Size (kW)	**Type**	**Frequency (MHz)**	**Life (hrs)**	**Actual Cost (A$)**
3.0	Magnetron	2,450	8,000	2,300
6.0	Magnetron	2,450	8,000	3,500
15.0	Magnetron	2,450	5,000+	5,800
30	Magnetron	915	8,000	9,000

The economics of microwave processing are strongly dependent on the application of the technology. A return on investment of 12-24 months and a 25-30% increase in the production capacity has been reported for microwave pre-drying with current energy prices in the US (Industrial Microwave Systems, 2019).

In general, radio-frequency systems are cheaper and cost about A$1,800 to 4,000 per kW of output power for a full system installed (Table 52). This includes the cost of radiofrequency generators, housing, conveyor belts and design. The cost of replacing the consumable radiofrequency tube (triode) and corresponding lifetime is listed in Table 53.

Table 52: The capital equipment, installation, and consumable cost of radio-frequency heating systems.

	System Size	**Smaller than 20 kW**	**Larger than 100 kW**
Capital equipment ($A/kW)	**Radio-frequency generator**	2000	1000
	Control system	Cost of control system for conventional heating +400	Cost of control system for conventional heating +250
	Material handling	System dependent	System dependent
	Total	~4000	~1800
Installation cost ($A/kW)		500	200
Consumable ($A/kW)		500	190

These cost figures are very sensitive to customisation and can increase substantially (by up to 100%) when the client requirement deviates from the manufacturer's standard design.

Table 53: Radio-frequency tube replacement cost; converted from US dollars using 2018 average exchange rate of 0.74 (Mujumdar, 2014).

Size (kW)	Type	Frequency (MHz)	Life (hrs)	Cost (A$)
10	Triode	<100	10-20,000	$5,000
50	Triode	<100	10-20,000	$9,800
100	Triode	<30	10-20,000	$15,000
200	Triode	<30	10-20,000	$38,000

List of potential suppliers and contact details.

Table 54: Industrial microwave heater suppliers.

Company	Country	Website and contact details	Note
Simultech	Australia	www.simultech.com.au Tel: 03 9735 9816	
Advanced Microwave Technologies	Australia	www.amtmicrowave.com/ info@amtmicorwave.com	Commercialisation, research and development, project consultation, microwave rental
Weisstechnik	Germany	www.weiss-technik.com/en/ Local contact: Simultech Australia	
Ferrite Microwave Technologies	USA	ferriteinc.com Tel: 1-800-854-1466	
Thermex Thermatron	USA	thermex-thermatron.com Mark@thermex-thermatron.com Local Contact: Columbit (www.columbit.com.au) colfoods@columbit.com.au	Drying and curing, modular industrial heaters
Fricke und Mallah	Germany	www.microwaveheating.net info@microwaveheating.net	For industrial drying, pasteurisation-heating of wood products, foaming – preheating, plastic treatment
MAX Industrial Microwave	China	www.maxindustrialmicrowave.com info@maxindustrialmicrowave.com	Food processing, sterilisation, drying, dehydration, insect drying and sterilisation, roasting, curing
KERONE	India	www.kerone.com info@kerone.com	
Sairem	France	www.sairem.com commercial@sairem.com	Food processing, sintering, thermosetting, polymerisation.

Table 55: Radiofrequency heater suppliers.

Company	Country	Website and contact details	Note
Thermex Thermatron	USA	thermex-thermatron.com Mark@thermex-thermatron.com	Various applications and processes
KERONE	India	www.kerone.com info@kerone.com	Food processing, textile, preheating plastics, preheating rubber, drying ceramics, wood and paper
Stalam	Italy	www.stalam.com stalam@stalam.com Heat and Control - Mount Gravatt Tel: 07 3877 6333	Textile, food processing, pharmaceutical and cosmetic
Radio-frequency Co.	USA	www.radiofrequency.com rfc@radiofrequency.com	Food processing, fabric and textile, drying fibreglass, sterilisation of medical waste
Sairem	France	www.sairem.com commercial@sairem.com	
PSC (part of C. A. Litzler Co., Inc.)	USA	www.pscrfheat.com	Tempering, drying, fibreglass package dryer, foam, ceramic, food, coatings
Litzler	USA	calitzler.com	

E.2.2. Infrared heating

Electrical infrared (IR) heaters have been used in industrial processes since the 1930s. They use radiative elements such as an infrared lamp that heats up using electricity and emits thermal radiation at wavelengths longer than 0.7 micrometres. IR heaters can be classified into three different types based on their wavelength (Table 56).

Table 56: Infrared heater categories.

	Wavelength	Emitting temperature	Applications
Near infrared	0.76-2 µm	1800-2500°C	Drying coatings, paper, textiles. Deeper penetration for baking, roasting etc.
Med infrared	2-4 µm	800-1800°C	Efficient surface heating of glass, plastic, water
Far infrared	4-10 µm	400-600°C	Food processing. Space heating in buildings such as factories.

IR heating is a very suitable technology for fast heating of simple and flat surfaces. With more sophisticated arrangements of IR heating elements, complex shapes such as curved plastic pieces and car bodies can be also heated (Figure 102).

Infrared heating elements can be made of different materials:

- **Ceramics:** low-cost heating materials with emission in the range of 2-10 micrometres
- **Quartz:** reaches higher temperatures, heats up almost instantaneously, can be formed into complex contours, emission in the range of 1.5-8 micrometres
- **Metal sheathed:** provides high flexibility for the peak emission and shape at low cost.

Figure 102: Quartz Infrared heating element for deburring of plastic products. (Reproduced from Heaeus).

Global prevalence of infrared

Infrared process heating was initially used by Ford Motors in the mid-1930s for curing paint on automotive body parts. Since then, various systems and infrared heating elements have been developed leading to significant growth in the market. Infrared heating is currently considered a mature and well-developed process heating system and is adopted across different sectors of the manufacturing industry.

Process types and temperature

IR systems are designed according to the temperature requirement and the ability of the target material to absorb infrared radiation. In general, shorter wavelengths correspond to higher power densities and can reach very high temperatures of over 2000°C. The temperature and intensity of IR heaters can be adjusted for different products and can even heat different sections of an object to different temperatures.

Table 57 lists several thermal processes in various industries that can be suitable for IR heating. In the food industry, IR can be used for frying, roasting, baking, thawing, blanching and pasteurisation.

Table 57: Thermal processes that are suitable for infrared heating.

	Curing	Drying	Gluing	Laminating	Melting	Preheating	Shrinking	Soldering	Sterilising	Tempering
Automotive	√	√	√	√	√	√	√	√		
Ceramics	√	√	√			√				√
Electronics	√	√	√	√		√		√		
Flooring	√	√	√	√	√	√				√
Food		√			√	√			√	√
Glass		√	√	√		√		√	√	√
Metal	√	√	√	√	√	√		√	√	√
Packaging		√	√	√		√	√			
Paper	√	√	√	√		√	√			
Photovoltaics	√	√	√	√	√	√		√	√	√
Plastics	√	√	√	√	√	√	√			√
Powder coating	√	√			√	√				
Rubber	√	√	√	√	√	√	√			√
Semiconductors		√	√	√	√	√		√		√
Textiles	√	√	√	√	√	√	√			
Wood	√	√	√	√		√	√			

The advantages of Infrared heating include:

- **rapid heating rate** (see Table 58)
- **fast response:** can be switched on and off relatively quickly due to its insignificant thermal mass, which is particularly suitable for intermittent processes
- **compact size:** for example an IR dryer will be less than one metre long compared to 10-30 metres for a typical convection heating system
- **precision:** ability to control temperature and target a precise area (+/-0.5°C compared to +/-5°C for gas oven)

- **large thermal gradient:** infrared heating can generate high heating power impinging upon the target surface creating a sharp temperature change within the material close to its surface. This is suitable for some applications such as in food industry e.g. the surface of a food product (e.g. a pie crust) can be heated without cooking it through.
- **modular design:** easy to integrate into existing production systems.
- **low cost:** often several times cheaper than a convection or other heating system. IR heaters usually cost less than $1000 per kilowatt
- **low maintenance:** long life and little maintenance except scheduled cleaning of reflectors and replacement of emitters
- **clean products** - through eliminating the need for circulating air or flame gases – circulating air in convection ovens can cause contamination
- **worker safety** – reduces heat and emissions; eliminates risk of carbon monoxide poisoning.

Table 58: Comparing the heating rate of different materials using convection and IR heating.

	Steel (0.13 cm thick)	Aluminium (0.13 cm thick)	Plastic (0.64 cm thick)	Wood (0.64 cm thick)
	Time taken to reach 150°C (seconds)			
Gas convection (at 220°C*)	210	138	460	365
Electric infrared	30	20	14	8

**A gas oven must be heated to 220°C to heat its contents to 150°C.*

Efficiency and performance

The efficiency of an infrared heating system is strongly dependent on:

- how well the emitter radiates within the desired wavelength suitable for the target material – governed by the emitter temperature and material
- how well the target material absorbs the radiation striking its surface – governed by the absorption coefficient.

The absorption coefficient of the target material needs to be carefully considered when an infrared heating system is selected. A low absorption coefficient can lead to high reflection or transmission losses leading to significant waste of radiant power. For example, plastic parts and water (Figure 103) are strong IR absorbers whereas polished metals are not.

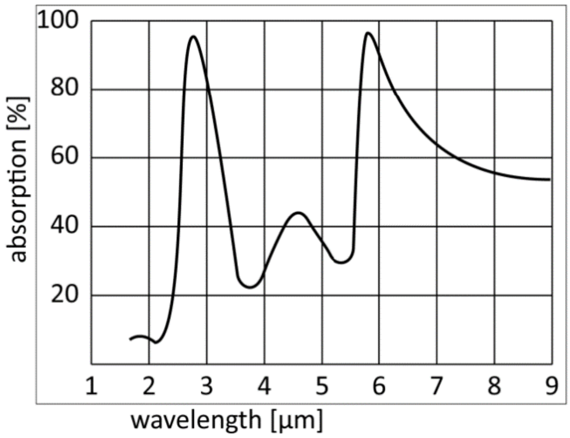

Figure 103: The absorption coefficient of water as a function of wavelength (reproduced from Leonardo Energy[31]).

A short-wavelength radiator converts electricity into radiation power at an efficiency of about 90%. About 70% is directed to the target surface after being reflected by the bulb back reflectors and transmitting through the cover. The amount of heat generated at the target material is highly dependent on its surface absorption. The performance of different infrared heating elements is presented in Table 59.

Table 59: The performance of different infrared heating element (Chromalox, 2019; Fostoria, 2019).

	Quartz lamp	Quartz tube	Metal sheathed rod	Wide area panel	
				Ceramic coated	Quartz face
IR category	Short wave	Medium wave	Long wave	Medium wave	Medium wave
Source temperature (°C)	1600-2200	1000	760	90-870	Up to 930
Electricity to IR conversion efficiency	72-86%	40-62%	45-56%	45-55%	45-55%
Peak wavelength (µm)	1.16	2.3-2.8	2.8-3.6	2.25-7.9	2.5-6
Response time	seconds	30 sec-2 mins	2-4 mins	5-8 mins	6-10 mins
Illumination profile	Point - line	Line	Line	Wide area – uniform	Wide area - uniform

[31] Application note Infrared heating www.leonardo-energy.org

In general, it can be assumed that the specific energy consumption of infrared heating is several times smaller than convection-based systems (Callebaut, 2014). Moreover, an infrared emitter is a large resistive load that has a favourable effect on power factor.

Installed costs of infrared heating

IR heating is simpler and cheaper than dielectric and induction heating because IR heating elements don't need expensive frequency converters. Table 60 shows the cost of IR heating elements. Ceramic elements' cost is sensitive to their size and power, so the high end of the cost range corresponds to smaller, low-power units.

Note that these figures don't include a complete IR heating system. A full oven may be comprised of a cavity, material handling units such as conveyer belts, sensors, heating elements, and controller. The cavity and material handling units are usually custom-designed but, in general, they are smaller for IR ovens in comparison to convection-based systems.

*Table 60: Typical lifetimes and costs of IR heating elements (*price varies linearly with size).*

Heating element geometry	Type	Rated life (hrs)	Price (A$) *
Wide area	Ceramic	25,000	3,400 (for 18 kW) – 1,200 (for 1.8 kW)
	Quartz faced	25,000	320 (for 4 kW) – 390 (for 1.6 kW)
Linear	Ceramic	5,000	190 (for 5 kW) - 380 (for 1 kW)
	Metal sheathed	5,000	220 (for 15 kW)-280 (for 2 kW)
	Quartz Tubes	5,000	~60 (for 1 kW)

As a rough estimate, a complete IR oven cost is around 1,250 A$/kW (for a 330-kW system) to 3240 A$/kW (for a 16 kW system) indicating the large range of system price variation (Intek, 2019). It is expected that 5-15% of the total cost is due to installation.

List of infrared suppliers and contact details

Table 61: List of infrared heating suppliers.

Company	Country of origin	Website and contact details	Notes
Infralight	Australia	http://www.infralight.com.au/ Email: iruv@infralight.com.au	Supplies heating elements, control systems and system design services
Cynebar	Australia	https://cynebar.com.au/ office@cynebar.com.au	Bespoke and standard heating element and system design
CALDAN	Australia	https://www.caldan.com.au info@caldan.com.au	Infrared halogen quartz heater for plastic processing – variable output power from 1% to 100%
Simultech	Australia	http://www.simultech.com.au/ Tel: 03 9735 9816	Long wave and shortwave IR heaters for 300°C to 3000°C range
Philips	Australia	http://www.lighting.philips.com.au Tel 1300 304 404	Industrial heating, e.g. drying, baking, carbonising, melting etc.
Tobin electrical components	Australia	www.tobins.com.au info@tobins.com.au	IR heating elements
Furnace Engineering	Australia	http://www.furnace.com.au/ info@furnace.com.au	Wide range of heating technologies including IR ovens
Fostoria Industries Pty Ltd	Australia	http://www.fostoriaindustries.com.au/ Tel: 02 97722166	Design, manufacture & supply infrared process heating systems
TECHSPAN	Australia	https://www.techspan.com.au/ sales@techspan.com.au	IR heating elements supplier
Chromalox	USA	https://www.chromalox.com Tel: 1 800 443 2640	Supplier of Metal Sheathed Radiant Heaters
WECO	USA.	https://wecointernational.com/ weco@wecointernational.com	Supplies IR heating system using Ceramicx heating elements
Weisstechnik	Germany	https://www.weiss-technik.com/en/ Local supplier: Simultech Australia	Infrared elements, modules, ovens, bespoke system design
Star Progetti	Italy	http://www.starprogetti.com Local supplier: SBH Solutions (http://www.sbhsolutions.com.au) info@sbhsolutions.com.au	Adjustable heat output IR Helios Radiant
KERONE	India	http://www.kerone.com info@kerone.com	?
Litzler	USA	https://calitzler.com sales@calitzler.com	?

E.2.3. Induction

Induction is another non-contact heating technology for efficient and very fast heating of metals and other electrically conductive materials. In this method, the target material is placed within an electric coil through which a high frequency alternating electric current flows. The oscillating magnetic field generated by the coil heats up the bulk of the target material (Figure 104).

Material heating occurs due two effects:

- hysteresis losses: happens in magnetic materials such as iron and nickel in which the target atoms are continuously magnetised in different directions creating internal friction that dissipates energy as heat
- eddy current*:* the alternating magnetic field creates electric current within the material that dissipates energy due to the electric resistance of the target material.

The depth of eddy currents in the material can be controlled by the frequency of the magnetic field; higher frequencies generate currents closer to the surface.

Induction heating can be used for different applications such as melting, brazing, vacuum heating, and surface hardening. Properties of induction heating include:

- applicable only for electrically-conductive materials
- heats up the bulk of the target material
- can penetrate through materials that block infrared radiation such as glass and plastics to heat up the internal metallic components.

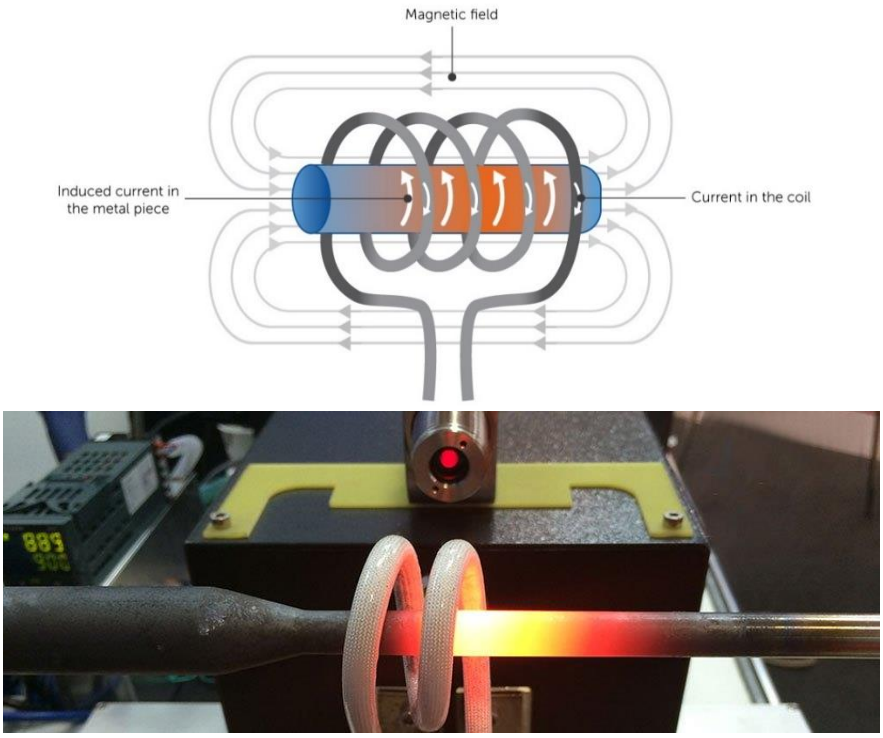

Figure 104: Induction heating using an oscillating magnetic field that induces electric current in the target material: Top: schematic of principle, Bottom: induction heating of a steel part. (Reproduced from ultraflexpower.com.)

Advantages of induction heating:

- **highly precise and repeatable:** suitable for those processes that require accurate repeatability
- **fast response:** enabling higher energy productivity in highly variable production lines
- **rapid heating:** it directly heats the target materials with minimal or no waste heat and almost a zero-thermal mass
- **high efficiency:** efficiencies above 90% attainable with proper design and operation (higher than IR)
- **penetration through crucible:** can heat up materials in crucibles with low thermal and electric conductivity.
- **high energy productivity when used in batch processing:** induction heating can replace ovens and furnaces that need to be heated 24/7 to ensure they are operational when needed. It can be used upon the need for heat, eliminating the idle time energy losses.

Table 62 lists several thermal processes that can be suitable for induction heating.

Table 62: Process types that can benefit from induction heating (source: ultraflexpower.com).

Process	Material	Application	Temperature
Annealing	Aluminium, carbon steel, carbide, copper, stainless steel	Wire processing, precision tool forming, tube forming	400-800°C
Bonding	Steel, stainless steel, Kovar	Optics, medical, gaskets to metal casing, dental (metal to plastic)	Up to 400°C
Induction brazing	Copper, steel, aluminium, – brass	Heat exchanger manufacturing, tubing, metal fabrication	400 - 1200°C
Casting	Titanium, gold, ceramic, Inconel etc	Wide range of application including medical, pressure casting	1600°C
Crystal growing	Silicon, sapphire	Photovoltaic cells; sapphires and silicon for integrated circuits	Above 950°C
Curing and coating	Epoxies, adhesives, ink, powder coating	Bonding materials	50 - 1000°C
Forging	Steel, brass, etc	Metal forming	>1000°C
Hardening	Steel	Quenching	<1000°C
Hot forming	Steel, raphite	Metal and quartz forming	Up to 2000°C

Efficiency of induction heating

The electrical efficiency, η_e, of an induction heater is defined as

$$\eta_e = \frac{\dot{Q}_{th}}{\dot{W}_e}$$

In this equation, $\dot{Q}_{th}$ is the heating power generated in the target specimen and $\dot{W}_e$ is the electrical power consumed by the power supply. The overall efficiency of induction heating is a function of the losses in power supply and capacitors. Significant energy can be lost during the frequency conversion. Different types of frequency converters, as presented in Table 63, are used to generate the alternating current with various frequency ranges. Low frequencies are generally associated with higher conversion efficiencies.

Table 63: Efficiency of various frequency converters.

Frequency converter	Thyristors	Transistors	Vacuum Tubes
Efficiency	90–97%	75–90%	55–70%
Frequency range	100 Hz–10 kHz	Up to 500 kHz	Up to 3000 kHz
Power range	Up to 10 MW	Up to 500 kW	Up to 1200 kW

Additional losses include:

- power transmission losses: the cables need to carry large electrical currents that cause resistance losses
- thermal losses from the target material: heat is conducted, convected, and radiated away from the target region on the specimen. This is more significant in those applications that include high temperature and/or materials with high thermal conductivity. The heat loss to the ambient can be reduced with the use of a refractory around the specimen.
- losses in the coil: this is more significant when heating materials with very low electrical resistance such as aluminium.

Although the overall efficiency of induction heating can reach 80-90% in some cases, many typical applications suffer losses in each stage, leading to an overall efficiency of 60-70%. The efficiency of induction furnaces can be as high as 75% (Kermeli et al., 2016). The dissipated energy at each section is usually taken away by a coolant such as air or water.

Installed cost of induction heaters

The equipment cost of induction heaters varies based on the output power, frequency, and the associated accessories. The indicative costs of induction heaters and induction furnaces are provided in Table 64 and Table 65.

Table 64: Cost of induction heating systems, excluding the installation cost; converted from US dollars using 2018 average exchange rate of 0.74 (Across International, 2019).

Frequency (kHz)	Price (A$/kW)	Application
High	560-1250	Heating small parts, melting metal powder
Medium	280-420	Heating small parts, cutting, soldering copper, heat-treating, annealing

Table 65: CAPEX of induction furnaces for melting steel, copper, gold, silver, and aluminium (Across International, 2019).

Frequency (kHz)	Capacity (kg)	Price (A$/kW)
Medium	200	230
	500	170
Low	10	640
	15-30	680
	60-80	490
	100-150	530

In many cases, water cooling equipment is required to cool the power components and the coil of the induction heating systems. This can cost from A$5,000 to A$25,000 for 33 litres/min to 117 litre/min capacities.

A list of induction heating suppliers and contact details is provided in Table 66.

Table 66: Industrial induction heater suppliers.

Company	Country of origin	Website and contact details	Notes
Australian Induction Heating	Australia	http://www.inductionheating.com.au/ aih@inductionheating.com.au	Forming, forging, metal hardening, tempering, brazing, soldering, drying, metal melting
Welding Industries of Australia	Australia – USA	https://www.welding.com.au/ Tel:1300 300 884	Refinery, process piping, pressure vessels, power piping, petrochemical, preheat parts up to 315˚C, 35 kW power output
I & R Pauk HIS	Australia	http://www.pauk.com.au/ ipauk@pauk.com.au	
Furnace Engineering	Australia	http://www.furnace.com.au info@furnace.com.au	
RDO Induction	USA	https://rdoinduction.com info@rdoinduction.com	From 1.5 kW to 500 kW in frequency ranges from 1kHz to 1.0mHz
Australian Coating Removal	Australia	http://www.acrtech.com.au/ Tel: +61 410 185 797 James@Acrtech.com.au	Induction coating removal from steel, pipeline, buildings, ship marine, bridges, storage tanks
Miller	USA	https://www.millerwelds.com/ Tel: +1 920 734 9821	
Ultraflex Power Technologies	USA	https://ultraflexpower.com/ Tel: +1 631 467 6814	Heating, melting,casting
Radyne	USA	https://radyne.com Local supplier: Inductotherm Group Australia Pty Ltd https://inductotherm.com.au furnaces@inductotherm.com.au	Annealing, brazing ,hardening, coating ,soldering, heat treatment, tempering -

E.2.4. Ultraviolet

Ultraviolet processing is considered a non-thermal technology that can replace energy intensive applications. Many consumer products are coated to improve durability, provide protection or enhance appearance. Most of these coatings are dried and cured in gas-fired ovens. Ultraviolet processing is an alternative room-temperature method of curing coatings.

UV processing is used to cure:

- coatings applied to wood, metals, paper, plastics, vinyl flooring, and wires
- inks as part of printing operations
- adhesives used in packaging and plastics
- polymers used to print on circuit boards and other electronic parts (Gellings, 2011).

These systems require special UV-curable coatings and a custom-made lamp system. UV coatings are more expensive than traditional solvent-based coatings, but this extra cost is offset by several benefits:

- lower energy use: typically 75% less than thermal gas-fired systems
- faster processing: curing in seconds, rather than minutes or hours
- near-elimination of toxic volatile organic compounds emitted by solvent-based coatings
- better control over the result.

UV processing is also applied in other areas such as food processing and waste treatment. UV radiation at short wavelengths such as 0.25 micrometres destroy the DNA of microorganisms such as bacteria, fungi, viruses.

In the food industry, UV radiation can indirectly improve energy productivity by improving the shelf life of the produce, thus minimising waste.

E.3. Electric resistance heating

Many types of industrial ovens, furnaces and kilns can be powered either by a fuel or by electricity (just as a domestic oven can be gas or electric fuelled). This section outlines significant types of electric heating technologies that can replace a fossil fuel oven, kiln or furnace.

The simplest and oldest electricity-based method of heating is (ohmic) 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 and efficiency, which can approach 100% (EPRI, 2007). 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.

Indirect resistance provides a straightforward alternative to many gas-fired heating systems because it delivers heat in a similar way. For example, any gas-fired oven for baking food or firing ceramics could operate just as well using electrical resistance heating (Figure 105). In fact, electrical resistance furnaces used to be even more common in industry before natural gas became readily available in Australia (early 1970s).

Electric resistance boilers could replace many centralised gas-fired steam systems. Electric boilers can produce hot water or steam (up to 220˚C), are available in any size (up to 100 MW) and are almost 100% efficient (Cleaver Brooks, 2018). They have a very fast response time and some manufacturers in Europe already operate electric boilers flexibly to take advantage of low-cost intermittent power supply from renewables (Bazzanella & Ausfelder, 2017). Another advantage of electric boilers is that they can directly replace a gas-fired boiler with little modification to the overall system.

Electric resistance could power high-volume, high-temperature processes such as calcining. Australian company Calix is developing an electric version of its flash calciner, which can process limestone, clay and other minerals, by heating them to around 1000˚C.

Electric resistance lacks some of the benefits of other electric heating technologies, such as the high COPs of heat pumps or the high heating rates of induction. But its importance is its ability to replace an extremely wide range of gas-fired ovens, furnaces and kilns.

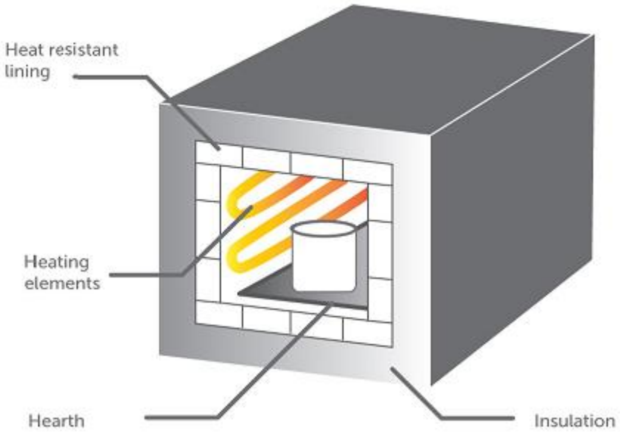

Figure 105: A furnace heated by indirect electric resistance heating elements (figure BZE).

Different configurations of indirect resistance heating are:

- **Electric furnaces:** use high temperature heating elements, usually made of SiC, $MoSi_2$, nichrome that can reach temperatures in the range of 1000-2000°C
- **Electric ovens:** the ohmic heating elements mounted in the oven heat the products through convection and radiation. Forced circulation of the air may be required for uniform and more rapid heating
- **Electric boilers:** are available in a wide range from kWs to MWs. Unlike their combustion-based counterparts, electric boilers don’t produce any harmful gases and hence can be installed near the point of use. Individual boilers can be turned on and off independently.

By replacing the central boiler with smaller units, the plant is likely to be more flexible and efficient.

- **Circulation heaters:** are compact heating devices for liquids and gases. They have ohmic heating elements immersed in the fluid stream.

Efficiency of electric resistance heating

In ohmic heating, 100% of the consumed electrical energy is converted into heat inside the element, but not all of it is necessarily delivered to the target material. The immersion configuration is the only one that transfers the entire generated heat to the target material. In the other configurations some energy is lost to adjacent elements such as the ambient air or the oven/furnace enclosure.

Electric crucible furnaces are far more efficient than their gas-fired counterparts. Energy requirements for melting aluminium in different types of furnaces are provided in Table 67.

Table 67: Energy required for melting aluminium in different furnace types (Kermeli et al., 2016).

	Gas-fired crucible	Ohmic crucible	Induction crucible
Energy intensity (kWh/kg)	1.627-2.603	0.466 - 0.577	0.511-0.577

Advantages of electric resistance heating

- low capital and maintenance costs
- suitable for frequent start and stop situations
- quiet operation
- high efficiency heating
- wide range of operating temperatures, from low to above 1000°C
- absence of combustion gases at the point of use
- accurate energy flow monitoring.

Disadvantages of electric resistance heating

- presence of residual heat in the heating element
- not as productive as heat pumps at low temperatures.

Cost of electric resistance heating

The costs of electric furnaces and ovens are highly dependent on size, features, temperatures, throughput, heating process, etc. They are typically custom designed. A price range for different types of furnaces is provided in Table 68. Usually, building an electric furnace is less expensive than building a gas-fired one.

Table 68: The capital cost of various ohmic heating systems; some costs converted from US dollars using 2018 average exchange rate of 0.74 (Bacchetti et al., 2018).

		CAPEX
Furnaces	Crucible furnace	10.66 – 18.45 (A$/ton)
	Reverberatory furnace	1.62 – 17.80 (A$/ton)
	Tower furnace	3.12 – 20.41 (A$/ton)
Circulation heaters (Chromalox, TEMPCO)	Non-corrosive fluids	80-280 A$/kW
	Corrosive fluids	280-980 A$/kW
Electric ovens (Intek)	Electric resistance	4000-5500 A$/kW
Electric boiler 90°C water (incl. installation)	500 kW	200-300 A$/kW
	1000 kW	170-190 A$/kW
	1800 kW	140-160 A$/kW

E.4. Electric arc furnaces

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. Recycling steel in an electric arc furnace requires only 10% of the energy required to produce primary steel (Carpenter, 2012). Electric arc furnaces are also used to convert direct-reduced iron into steel.

Electric arc furnaces melt steel by generating an electric arc[32] from a graphite electrode to the metal load. It is a scalable technology, with furnaces available in capacities up to about one million tonnes per year. They can be rapidly started and stopped, allowing a manufacturer to vary production according to demand.

[32] An electric arc occurs when an electrical current jumps between electrodes. As the current passes through air (or another gas) it produces a plasma discharge, generating heat and light. Lightning is a natural form of electric arc.

Other types of electric arc furnace include the indirect arc furnace, common in the production of copper alloys, and the submerged arc furnace used to produce various metals such as silicon and iron alloys.

APPENDIX F. SOLAR THERMAL TECHNOLOGY

This section provides a description of the main solar thermal collector technologies that are commercially available, in order of increasing concentration ratio.

F.1. Overview of technologies

Unglazed flat plate collectors

Unglazed collectors are simple panels of black material containing channels for heat transfer fluid, usually water (see Figure 106).

Figure 106: Unglazed collector for an indoor pool at the Australian Institute of Sport, Canberra. (Reproduced from Sunbather).

Unglazed collectors are suitable for temperatures of around 20°C above ambient temperature and are often used for swimming pool heating. For this application, they are typically fabricated from EPDM rubber or PVC. The simple design results in high thermal losses for a given temperature, however their low cost makes them an attractive option in low temperature applications like pool heating. Unglazed panels made from sheet steel have been demonstrated for air heating, however such products are not readily available commercially.

Glazed flat plate collectors

Addition of a sheet of glass in front of a flat panel solar collector plus an insulating material behind it are simple ways for reducing convection and conduction heat losses. Flat plate glazed collectors are the dominant technology in the Australian domestic solar hot water market. They are a mature technology. Traditionally applied to the domestic market, commercial systems are deployed via the assembly of standard panels in arrays as illustrated in Figure 107. Annual output is maximised if the collector is tilted toward the equator at an angle equal to the latitude of the site.

Figure 107: Commercial flat plate collector array. (Reproduced from solarproductcn.com).

Thermosiphon (passive) collectors dominate the Australian domestic market. In this case the storage tank is mounted above the panels and as the name implies, the hot fluid from the panels circulates naturally to transfer heat to the water in the storage tank. This design although simple, adds significantly to the loading of the roof.

In commercial systems, a split-system comprising a ground mounted tank and roof-mounted collectors is normally preferred due to the larger tanks employed. Circulation pumps and controls are needed to circulate water or heat transfer fluid (HTF) through the panels and to the tank.

Flat plate systems often require frost protection in cooler climates where ambient temperatures drop below zero. This may be in the form of a HTF with antifreeze properties, or via a pump which circulates water from the tank when system sensors detect sub-zero temperatures.

Evacuated flat plate collectors

These are a new type of stationary (non-tracking) collector. They aim to combine the benefits of lower costs and the installation and modularity advantages of flat plate collectors with the higher performance of evacuated tube collectors. The space between absorber plate and glass cover is evacuated to suppress convection heat transfer between plate and glass. This reduces the overall heat losses from the collector, allowing it to operate at higher temperatures than non-evacuated collectors. The collector panels can deliver up to 200 °C without mirrors or concentrators but efficiencies start reducing at these temperatures. Like all non-concentrating collectors, this collector converts both diffuse and direct beam radiation. The construction details of an evacuated panel are shown in Figure 108.

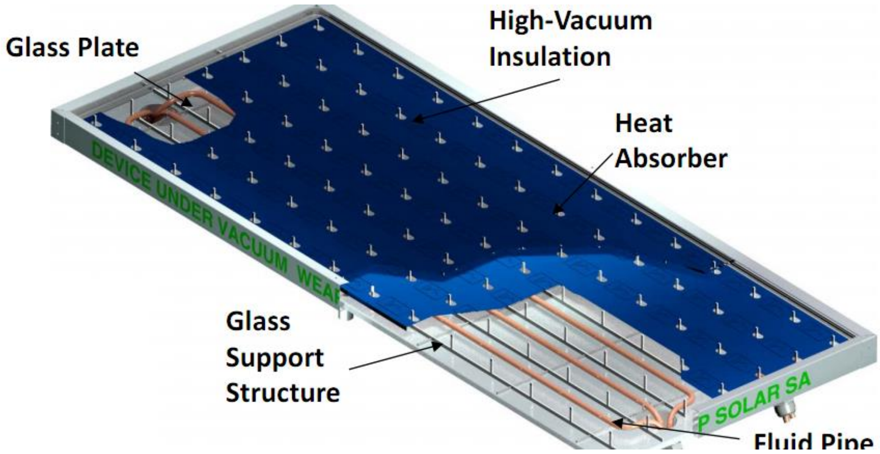

Figure 108: *Cross sectional view of a high-vacuum flat plate collector. (Reproduced from TVP Solar).*

Non-concentrating evacuated tube collectors

Evacuated tube collectors are the competing solar technology for domestic and commercial solar hot water. A series of individual tubes are mounted together in panels as shown in Figure 109. It is a less mature technology than flat plate collectors and systems tend to cost more, but are typically recommended over flat plate collectors in cooler or less sunny locations where thermal losses become more significant relative to the amount of solar radiation absorbed. As with flat plate collectors, commercial-scale systems utilise the same components as domestic systems, and scale easily.

As with flat plate collectors, annual output will be maximised if the collector is tilted toward the equator at an angle equal to the latitude of the site. However, in Australia, the low thermal losses of evacuated tube collectors make them prone to summer overheating. To mitigate this risk, collectors will often be mounted at greater angles, levelling seasonal output by increasing winter output at the expense of summer output. Increased tilt angles will also increase hail resistance of the tubes, which are typically designed to withstand a 25mm diameter hail stone incident at 90km/h. Frost protection is not commonly required owing to the same insulating properties that allow the collector to generate high temperatures.

Figure 109: Evacuated tube collector array. (Reproduced from stage3renewables.com).

CPC evacuated tube collectors

Compound parabolic concentrators (CPC) are an example of a non-tracking concentrator. They utilise evacuated tube receivers with an arrangement of stationary mirrors to gather more radiation than is directly incident on the tube. This reduces the tube size and hence the surface area for heat losses. Concentration levels of around two times are possible and so have the effect of boosting operating temperatures to around 150°C above ambient temperature. Multiple tubes are arranged in panels as illustrated in Figure 110.

Figure 110: A CPC collector. (Reproduced from andyschroder.com).

Parabolic trough collectors

In parabolic trough concentrators, the tubular receiver is fixed to the focal line of a concentrating trough-shaped mirror that tracks the sun along one axis throughout the day. Modern parabolic trough systems achieve radiation concentration by a factor of around 25-50 and are capable of reaching up to 500°C, but are typically used for temperatures between 150 to 400°C. Trough systems either heat a HTF such as synthetic oil, or generate steam for process heat or power generation.

Key components of a trough concentrator are illustrated in Figure 111. As tracking occurs, the receiver at the focal point of the trough must also move. This creates the necessity for dynamic joints through which the HTF must be circulated, adding complexity. The receiver tubes can be simple metal tubes. Adding a glass tube cover to limit convection losses improves performance or alternatively using an evacuated tube as the receiver gives the best possible performance.

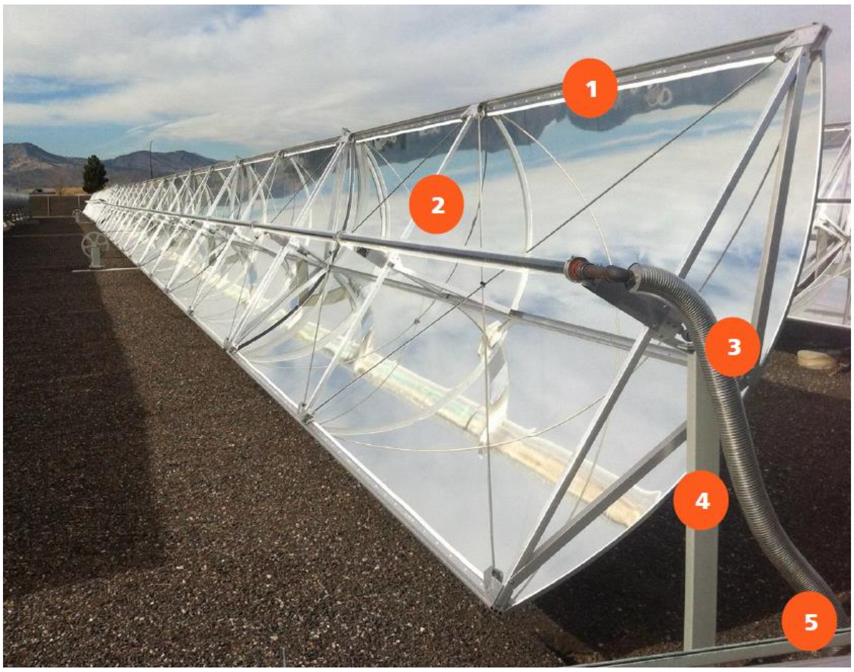

Figure 111: Parabolic trough collector construction, 1 Concentrator with aluminium or glass mirror, 2 Receiver tube, 3 Flexible coupling, 4 Pylons, 5 Header piping. (Figure from Abengoa).

Whilst parabolic troughs could be made in any length and aperture width, there has been an evolution in commercially available products in two directions: large aperture units for solar thermal power generation and smaller systems for process heat.

Use of large troughs with aperture widths of around 5.8 m and high-quality evacuated tube receivers has become standard practice for concentrated solar power generation. These large trough arrays use heat transfer oil in the receivers and collect heat at around 400°C. Arrays with peak thermal capacities from around 30 MW_{th} up to 1 GW_{th} have become a mature technology, with the hot oil used to raise steam for power generation (Figure 112).

Large trough collectors can also be used for process heat. Arrays down to 1 MW_{th} are technically feasible, however large trough suppliers typically have less interest in such small systems. Globally there are a number of companies who offer small aperture, lightweight troughs specifically for mid-range process heat, as illustrated in Figure 113.

Figure 112: Parabolic trough field in a large CSP plant (image K. Lovegrove).

Figure 113: Small aperture parabolic trough collectors, suitable for rooftop application. (image from NEP Solar).

Linear Fresnel reflectors

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 tracked independently to focus direct beam radiation on a linear focus that is fixed on a stationary tower (Figure 114). Manufacturers of LFR systems claim they offer advantages over trough concentrators by having reduced structural costs, mirrors that are easier to manufacture and clean plus the benefits of a fixed focus that does not require flexible coupling for the HTF. Against these advantages their overall average optical efficiency is lower.

As with troughs, receivers can be evacuated or non-evacuated. Whilst less commercially mature than troughs, the split of commercial offerings into large scale units used for power generation (but also available for process heat) and smaller units particularly aimed at medium temperature process heat can be observed.

The fixed receiver and low profile of the mirrors works to make the smaller LFR systems suitable for rooftop integration as shown in Figure 114.

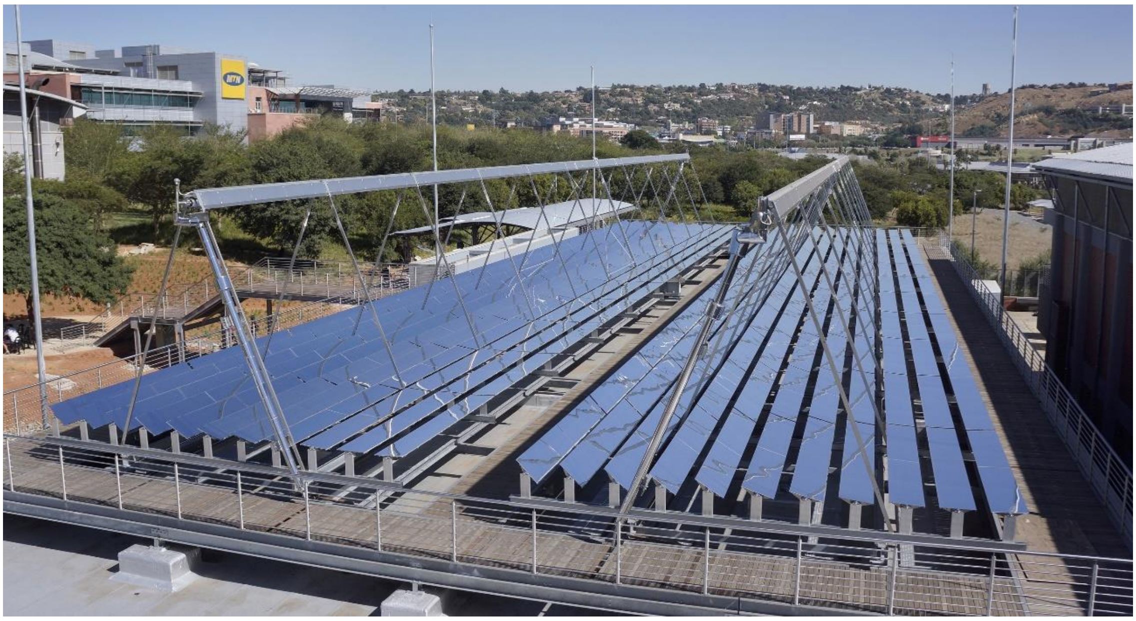

Figure 114: Linear Fresnel Collector. (Image from Industrial Solar).

Tower systems

In the concentrated solar power sector, the heliostat field / central receiver approach is gaining wider support. It offers higher temperatures (matching available steam technology) and can also utilise the molten salt energy storage solution more effectively because of the higher temperature difference.

The most commercially mature systems are large in thermal capacity (over 300 MW_{th}) and have so far been used only for power generation. However, there are also commercial players developing smaller systems down to a few MW_{th} in size that can be applied to process heat. For a process heat application, the use of molten salt as both a HTF and thermal storage medium is readily adaptable and offers heat at temperatures up to 580°C.

Figure 115: Aerial view of the Gemasolar solar tower plant in Spain, thermal capacity 400 MW_{th}. (Image from Torresol Energy).

There is ongoing work at the pilot stage on applying tower systems to directly drive high temperature chemical processes. A key relevant example is the solar driven steam reforming of methane to produce hydrogen or syngas mixtures. The CSIRO solar group in Newcastle is a pioneer in this area.

Paraboloidal dish concentrators

Figure 116: Australian National University's prototype 500m^2 paraboloidal dish concentrator (image K Lovegrove).

Paraboloidal dishes are the least mature of the large-scale solar thermal technologies but also provide high concentration ratios and low thermal losses. Dishes are double axis tracking and have the highest concentration levels and efficiencies of the concentrator system options. Dishes are also modular and have the capacity to be mass manufactured to minimise project engineering costs. They are mentioned here for completeness as there is no real commercial provider in a position to offer solutions for immediate application to industry for process heat as yet.

F.2. Solar resources

The direct beam is quantified by measuring direct normal irradiation (DNI), meaning the intensity of radiative flux on a surface that is assumed to be always perpendicular to the sun. Figure 117 (upper map) illustrates the annual average distribution of DNI across the continent.

The total (direct beam and indirect diffuse) irradiation is quantified by measuring global horizontal irradiation (GHI), meaning the intensity of radiative flux on a surface that is horizontal to the ground. Figure 117 (lower map) illustrates the annual average distribution of GHI across the continent.

There is a strong correlation between the DNI and GHI, however the northern tropical areas show a tendency to higher GHI relative to DNI as a consequence of the increased amount of moisture in the atmosphere even under sunny conditions. The highest solar intensity regions in Australia are amongst the highest in the world. Most of the natural gas use, however, is located nearer to the population centres around the coast, not in the highest solar resource areas.

In a very approximate sense, any areas with an annual average daily irradiance of around 16 MJ/m^2/day or better (either GHI or DNI as most relevant) might be considered to have reasonable prospects for solar technologies, which includes most of mainland Australia, except for some coastal regions where some of the large population centres are located.

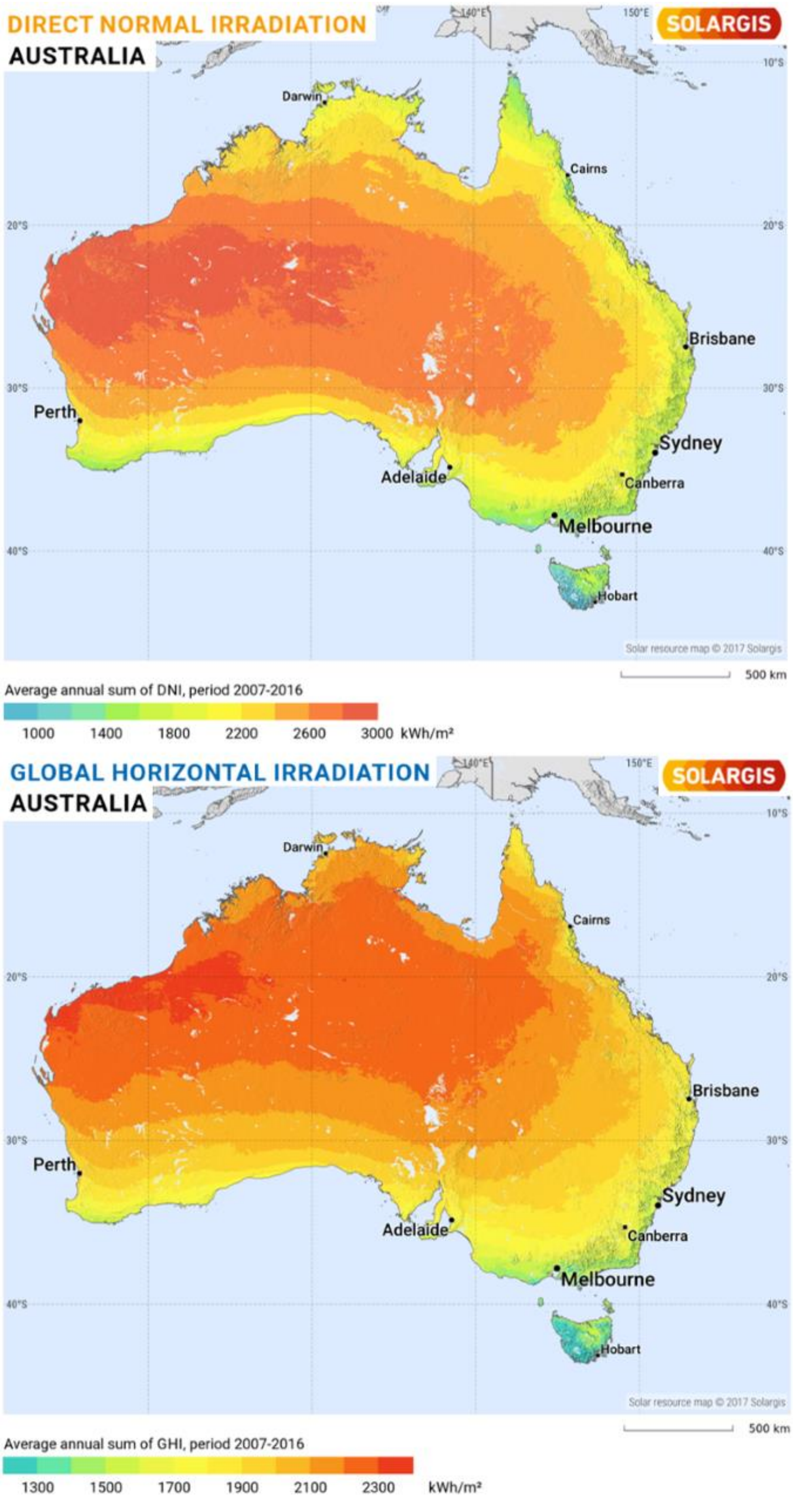

Figure 117: Australian solar irradiation resources. Left: Direct Normal Irradiance, right: Global Horizontal Irradiance. Solar resource map © 2019 Solargis.

The higher the level of average irradiance at a site is, the higher the utilisation of a given solar system will be and hence the more favourable the economic performance will be. For an approximate indication, it is sufficient to simply estimate annual average from one of these maps.

F.2.1. Resource data

For a more accurate feasibility study for a particular user / site, a range of data sources are available. Depending on the depth of a study, annual average values can be used, and month by month average values can be examined. For the most detailed examination, annual data sets of values in one hour or shorter time steps, along with associated temperature, humidity and wind-speed and other data can be used in complex models such as SAM (NREL, 2018). Such year-long data files can be real years that are identified as being typical or best or worst extremes of variability, or alternatively typical meteorological years (TMY) synthesised out of segments of real year data chosen to reproduce the most representative one-year data set for the location. The following are available sources of solar energy related data.

AREMI

For solar energy, AREMI (Australian Renewable Energy Mapping Infrastructure) provides long-term average daily DNI and GHI maps, which are derived from satellite images that are processed to extract radiation exposure data and validated with a limited number of (currently around 20) ground-based measurement stations. Moreover, AREMI also provides an open-source TMY data file creation tool (AREMI, 2019).

Bureau of Meteorology

The Australian Government's Bureau of Meteorology (BOM) has satellite-derived data sets of DNI and GHI (and other climate data) available. Hourly solar exposure data is available for the period from 1990 to present (new data periodically added). The resolution of the data is 0.05 degrees (approximately 5 km by 5 km). The BOM also provides one-minute ground station-based measurement data for those stations that measure it (BOM, 2019).

Additional data used for solar system performance predictions, including dry bulb temperature, dew point temperature, relative humidity, atmospheric pressure, wind speed and wind direction, is available from the Bureau of Meteorology based on hourly or half-hourly measurements over several years (depending on the operation period of each weather station) across a network of around 700 ground-based weather stations in Australia.

Data sets with solar and weather data can be purchased from the BOM on an external hard drive at cost-recovery charges for the hard drive and shipping.

Others

Additional sources of solar radiation data include NASA (NASA, 2019), Meteonorm (Meteonorm, 2019), Vaisala (Vaisala, 2019) and SolarGIS. The NASA website service allows solar data to be downloaded freely for any grid reference across the globe. The data is in the form of monthly averages and is derived from 22 years of satellite data with an effective 30 km grid. Hourly data is derived using a calculation procedure based on an average day for each month.

Meteonorm, Vaisala and SolarGIS are commercial providers of modelled datasets of solar and wind resources across the globe. For solar, the most comprehensive data set includes hourly GHI, DNI, DIF (diffuse horizontal irradiation) and weather data. These providers also offer synthesised ‘typical meteorological year’ (TMY) files that have hourly data for a hypothetical year that matches long-term average solar resource levels.

F.3. Global status and trends

Based on recent available IEA market data, the global installations of solar thermal systems worldwide have grown to a total capacity of 472 GW_{th} and a yield of 388 TWh_{th}/year by 2017, up by a factor of 7.6 compared to 2000 (62 GW_{th}, 51 TWh_{th}/year) (Weiss & Spörk-Dür, 2018). Hence, the level of installed capacity for solar thermal is comparable to those of wind and photovoltaics (Figure 118).

However, 99% of installations are for water heating (mostly for domestic hot water use and pool heating) in residential and commercial buildings, with largest markets in China and Europe, as illustrated in Figure 119. These traditional markets are declining due to the growing competition of heat pumps and photovoltaics, resulting in a decreasing growth in solar thermal installations worldwide. The majority of 72% of water heating installations use evacuated tube collectors, with China the major manufacturer and consumer, while glazed flat plate collectors account for 22% and unglazed collectors for 6%, as shown in Figure 120. In Australia and New Zealand, currently around 6.5 GW_{th} in capacity is installed, with the majority unglazed and evacuated tube collectors.

The number of jobs in production, installation and maintenance of solar thermal systems was estimated at 708,000 worldwide in 2016.

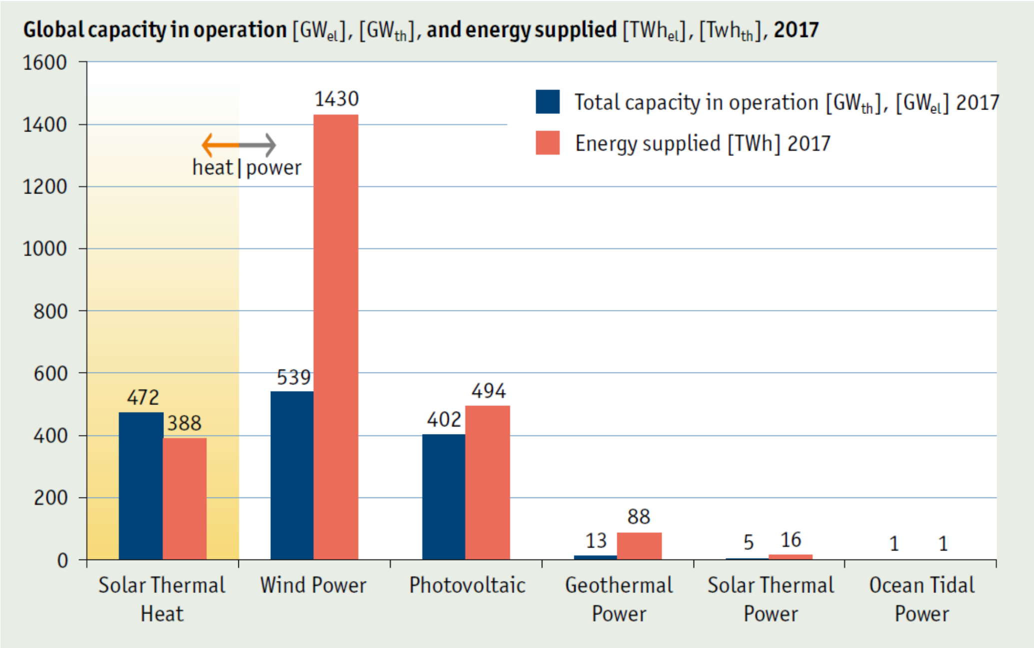

Figure 118: Global installed capacity and energy yield of solar thermal compared to other major renewable energy technologies. Note that solar thermal is in GWth/TWhth while the other technologies are in GWe/TWhe. Reproduced from (Weiss & Spörk-Dür, 2018).

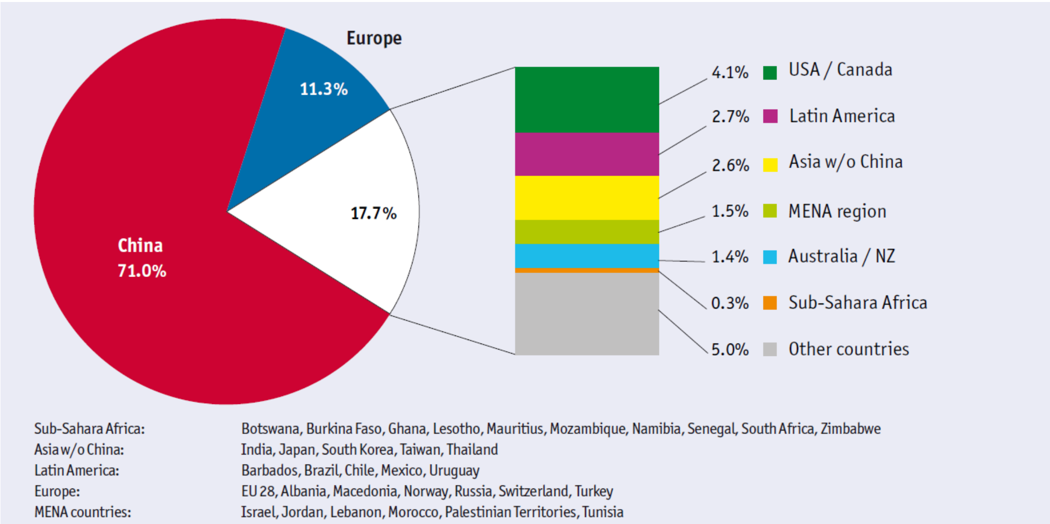

Figure 119: Breakdown of solar water and air heating collector market by country, as of 2016. Total installed capacity was 457 GWth. Reproduced from (Weiss & Spörk-Dür, 2018).

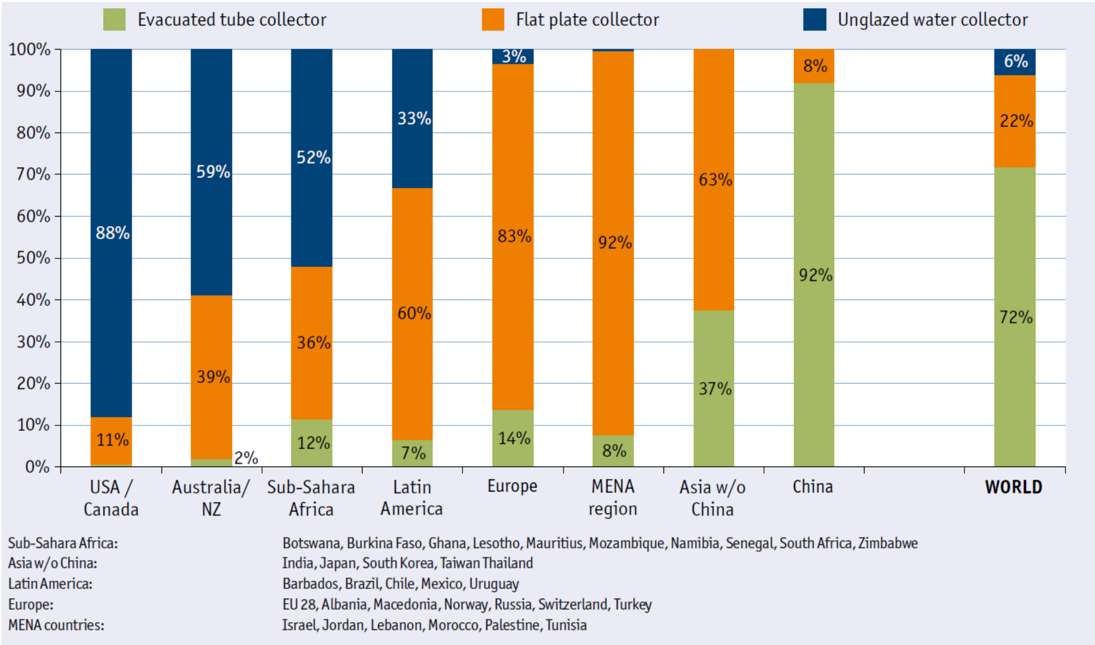

Figure 120: Solar thermal technology share by region and technology as at the end of 2016. Reproduced from (Weiss & Spörk-Dür, 2018).

In contrast to water heating, the total installed capacity of solar heat for industrial processes is currently at around 280 MW_{th}, less than 1% of total solar thermal capacity (Solar Payback, 2017). Consequently, concentrating solar collectors, such as Trough and Fresnel, that are geared towards providing heat at temperatures beyond those required for water heating, have experienced low growth over past years. As a result, their costs haven't dropped as much as for other renewable technologies, including evacuated tube solar collectors, that have been deployed at a scale of several hundred GW globally. Until now, the main application of medium and high-temperature solar thermal technologies has been for concentrated solar thermal power generation. However, this market is also still at an early stage of development with a current total installed capacity worldwide of around 5.2 GW_e (equivalent to around 15 GW_{th}).

However, there appear to be signs of a shift in solar thermal, from the traditional water heating applications towards an increasing number of solar process heat applications. The largest project to date, the Miraah Enhanced Oil Recovery plant in Oman, uses a novel parabolic trough technology, and has reached a capacity of over 100 MW_{th}, with plans for further expansion up to around 1 GW_{th}. In 2017, a total of 193,000 m^2 of new collector area for solar process heat was installed, corresponding to around 135 MW_{th} of new capacity.

Besides the Miraah project, Denmark has had the strongest growth in solar heat installations with a 110 MW_{th} district heating system using flat plate collectors completed in 2016, along with two new and three extended solar thermal systems in 2017 adding capacity of around 6 MW_{th}. A significant amount of around 111,000 m^2 in new parabolic trough collectors was installed in 2016 and 2017.

The number of solar process heat projects has grown from around 200 projects totalling 42 MW_{th} in 2010 to around 500 projects totalling 280 MW_{th} (400,000 m^2) in April 2017 (Solar Payback, 2017; Weiss & Spörk-Dür, 2018). The system size currently averages at around 560 kW_{th}, up from 210 kW_{th} in 2010.

The small-scale concentrator systems operating in the range 150 - 250ºC are virtually invisible in these statistics. Whilst the technology has been thoroughly proven and commercial installations exist, they are still in very small numbers, reflecting the fact that traditionally gas in particular has offered a cheaper solution. In contrast, concentrated solar thermal systems for power generation are constructed in large arrays in the order of 10s to 100s of MW_{th} capacity. The learnings are however applicable for larger higher-temperature process heat applications.

The International Energy Agency (IEA) has a program devoted to solar heating and cooling (SHC) that is directly concerned with solar heat, with much of its activity at lower temperatures. A separate IEA program, SolarPACES (Solar Power and Chemical Energy Systems) is concerned with high-temperature concentrating systems primarily for power production but also for direct solar-thermal driven chemical processes. The two programs combine for a shared task to promote small concentrators for the medium-temperature range process heat applications.

F.4. Technology selection and design considerations

An overview of selection criteria for solar thermal technology is provided in Table 69. Technology selection should start with the required final process heat temperatures, which together with the return temperatures to the solar field, determine the choice of solar collectors (Table 7). To illustrate this, Figure 121 provides an overview of typical industrial processes and corresponding process heat temperatures and collector types.

Table 69: Aspects to consider in the selection and design of solar thermal systems.

Selection criterion	Notes
Supply and return temperatures	See Table 4
Choice of heat transfer fluid / process integration	See Table 4
HTF pressure	Compressed water up to 180°C below 8 bar
HTF storability and costs	To consider: freezing, unit costs, pressure, need for inert gas
Roof load	Including collectors and HTF
Technology certifications	See Table 70

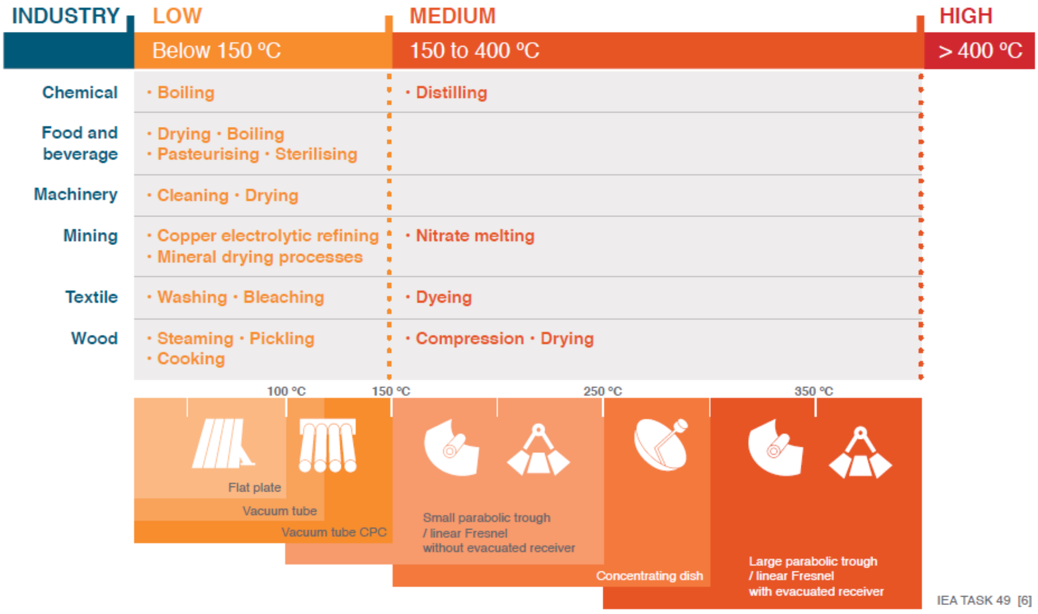

Figure 121: Temperatures and solar collector types for a selection of industrial processes. Reproduced from (Solar Payback, 2017).

The selection of the heat transfer fluid goes hand in hand with the collector selection as the choice of heat transfer fluid depends on the operating temperature of the collector and not all collector types have been developed for all potential heat transfer fluids. Table 7 lists typical heat transfer fluids for all collector types.

Several national or international certification standards exist, which verify the performance claims made by the collector manufacturers. An overview of standards is provided in Table 70.

Table 70. National or international certification standards for solar collectors (Solar Payback, 2017).

Country/region	Certification standard
Europe	Solar KEYMARK
USA	Solar Rating and Certification Cooperation, SRCC
India	Bureau of Indian Standards (BIS)
Mexico	NMX-ES-001-NORMEX *
South Africa	South African Bureau of Standards (SABS) *
Brazil	National Institute of Metrology, Quality and Technology, INMETRO *
China	Chinese National Standard *

*These standards do not yet include concentrating collectors.

Additional aspects to consider in the selection of solar collectors include (Solar Payback, 2017):

- energy output certified by accredited third party
- enough pressure resistance
- adequate stagnation handling and overheating prevention
- suitable weight for rooftop installation or appropriate size for ground-mounting.

The performance of a given solar system depends on the location, due to variations in available direct and diffuse solar radiation, latitude, collector orientation, temperature, wind, etc. For an in-depth economic analysis, the annual performance of a solar collector system needs to be determined. This can be done for example with hourly performance simulations using software such as the NREL System Advisor Model (NREL, 2018). This requires local solar irradiation and weather data (including dry bulb temperature and wind speed). For locations in Australia, this data can be obtained from AREMI and the Bureau of Meteorology, as described in section F.2.

Further, the experience level of a potential supplier and their expected reliability to deliver technology and maintenance should be considered when planning a new project.

F.5. Solar thermal equipment suppliers

Whilst the solar thermal technologies are all well progressed into commercialisation, it is only the evacuated tube and flat plate systems that can be described as commercially mature. In Australia, the supply chain and market for systems operating below 100°C is strong, however for operation above 100°C the supply chain is still nascent. Nonetheless, technology providers either local or from overseas can be found for industrial gas users seeking alternative energy sources.

Table 71 contains a non-exhaustive list of solar thermal technology suppliers, both within Australia and, where necessary, internationally, for each of the technologies.

Table 71: Solar thermal technology suppliers.

Technology supplier	Country of origin	Website	Notes
Non glazed			
Sunbather	Australia	https://www.sunbather.com.au/commercial-service/	HiPEC PVC
Glazed flat plate			
Rheem	Australia	http://www.rheem.com.au/commercialsolarwaterheaters	Major flat plate vendor in Australia. Standard efficiency (NPT200) or high-efficiency (Bt Series) flat plate collectors. A number of commercial systems completed. Edwards, a long-term provider of domestic systems featuring stainless steel tanks are now also part of the Rheem group

Rinnai	Australia	http://www.rinnai.com.au/commercial/	Commercial flat plate and evacuated tube systems with instantaneous gas boosters.
Solahart	Australia	http://www.solahart.com.au	Solahart is more focused on the domestic sector where it is a leading player. The company is owned by Rheem
Chromagen	Europe / Australia	www.chromagen.com.au	Australian distributors of a brand with presence around the world. Domestic and commercial systems
Evacuated tube			
Apricus	Australia	http://www.apricus.com.au/commercial-hot-water/	Has the majority market share in Australian evacuated tube systems. Tubes manufactured in China, and a number of commercial systems have been completed. Gas or electric boosting
SolarArk	Australia	http://www.solarark.com.au/	As above, components manufactured in China and assembled locally. A number of commercial systems completed
Endless Solar	Australia	https://www.endless-solar.com.au/	Evacuated tube system vendor with instantaneous gas boosting.
Greenland	Australia	http://www.greenlandsystems.com.au/	High-temperature evacuated tube for commercial applications
CPC plus tube			
Ritter Solar	New Zealand	http://xlsolar.co.nz/large-scale-solar-systems	Linuo Paradigma are a major manufacturer in China, who trade under the brand name Ritter Solar and Ritter XL internationally. The Australasian office is headquartered in NZ
Solfex	UK	http://www.solfex.co.uk/Product/1-cpc-inox/	Manufactured Ritter Solar GmbH in Baden-Württemberg-Germany
Evergreen Energy Solar	Europe	http://www.evergreenenergy.ie/cpc6.htm	Online retailer of wide range of renewable heat systems
Evacuated flat plate			
TVP Solar	Europe	https://www.tvpsolar.com/	Systems up to 180ºC targeted at industrial applications
Small parabolic trough			
New Energy Partners	Australia / Switzerland	http://www.nep-solar.com/	NEP are originally Australian based and have developed a small trough product for process heat with demonstration systems in Newcastle
Soliterm	Germany	http://www.solitem.de/	Coated aluminium troughs in a range of aperture widths to maximum 4m
Smiro	Germany	http://smirro.de/smirro/index.php/de/solare-konzepte/produkt-smirro	3.4 m^2 collector modules using lightweight aerofoil like structure

Abengoa	Spain / USA	http://www.abengoasolar.com/	As well as its major role in large scale CSP systems, Abengoa Solar has smaller light weight trough systems for industrial process heat applications
Large parabolic trough			
Abengoa	Spain	http://www.abengoasolar.com/	Market leader in large (5.8m aperture) glass reflector based trough systems operating with evacuated tube receivers and oil HTF
Sener	Spain	http://www.sener-power-process.com/ENERGIA/solar-power/en	A large Spanish engineering company that has featured prominently in the CSP industry globally
Skyfuel	USA	http://www.skyfuel.com/home.shtml	Offering a large lightweight trough product using their propriety 'Reflectec' film for mirror surfaces
Aalborg CSP	Denmark	https://www.aalborgcsp.com/	Have some significant CHP and district heating projects in Europe, also provided the tower based system for Sundrop farms in Australia
Sener	Spain	http://www.sener.es/revista-sener/en	A large Spanish engineering company that has featured prominently in the CSP industry globally
Small linear fresnel			
Industrial solar	Germany	www.industrial-solar.de	A small LFR system targeted at process heat. 12 sites around the world are identified as reference installations
Rioglass	Europe	https://www.rioglass.com/rioglass-sun-2-heat-solutions/	A major provider of CSP components also has a LFR system targeting industrial heat
Large linear fresnel			
Frenell		http://www.frenell.de/	Global leader in large LFR systems for CSP plants
Heliostat tower			
Abengoa	Spain	http://www.abengoasolar.com/	A major player in commercial CSP power station projects
Solar Reserve	USA	http://www.solarreserve.com/	Large tower salt receiver systems
Sener	Spain	http://www.sener.es/revista-sener/en	Responsible for Gemasolar 20 MW_e first ever commercial salt tower system, and Noor 3 100 MW_e system
Brightsource	Israel / USA	http://www.brightsourceenergy.com/	Developer of large tower based CSP systems

Vast Solar	Australia	http://www.vastsolar.com/	A startup company offering modular small tower systems, currently operating first demonstration system

F.6. Capital costs

Solar thermal costs and performance vary strongly with temperature. At higher temperatures specialised collector technology is required to mitigate the increased thermal losses associated with high temperatures. Each technology provided by a given supplier will have a certain cost per unit area. At the same time, as discussed further in Section F.7, the efficiency will be very dependent on operating temperature, starting at a high value at low temperatures and dropping off to zero at some maximum temperature for the technology in question. The cost per m^2 must be divided by the efficiency to determine an installed cost per unit capacity for a particular temperature. Since each technology can operate over a range of temperatures, the result is a series of curves of installed cost per unit capacity versus temperature that is indicatively as shown in Figure 122.

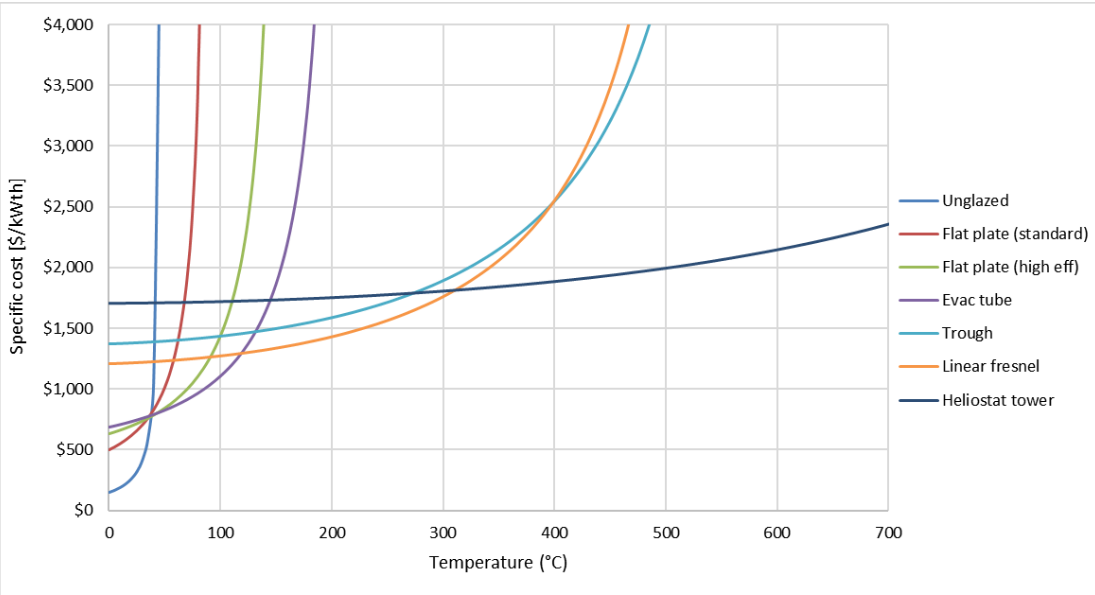

Figure 122: Indicative capital costs with temperature.

Establishing reliable cost data points for as-built systems is challenging in solar thermal owing to the extensive balance of plant costs and the different amounts of storage required. Systems have cost contributions from the collector array and the storage system (if any) and the overall cost is strongly dependent on the amount of storage chosen.

Ideally a costing basis of cost per unit area for each collector type plus cost per unit capacity for thermal energy storage would be established together with a size dependency. However it is apparent that the supply chain and the number of relevant projects for supply temperatures above 100°C is low, particularly in Australia. The information that is available is rather in the form of cost per unit capacity for particular systems with ‘typical’ levels of thermal storage, with ‘typical’ equated to approximately one day of thermal load.

As well as the storage medium, storage cost will depend on the size of the tanks employed, and storage size will depend on the needs of the customer. A hypothetical customer whose heat demand matched the solar resource exactly would require no storage. An industrial gas user considering a system as a partial fuel saver, that could be covered within the turndown ratio of an existing gas fired system, could also consider having no storage.

Installation costs per unit capacity will decrease with increasing system size, but will also depend on issues such as site access, remoteness, height etc. The procurement process will also impact this component significantly, as this is often where contractors will apply their margin. For an industrial customer, a competitive tender process is slower, but it is more likely to result in lower installation costs than simply selecting a supplier and requesting a design and quote.

The information that has been obtained for solar, biomass and natural gas technologies appears to be consistent with an accepted power law fit to costs with an exponent of 0.7 (Perry & Green, 1999), i.e.:

$$Cost(capacity\ x) = Cost(capacity\ y)\left[\frac{x}{y}\right]^{n}$$

Where: x = plant capacity of interest

y= base case plant capacity

n = exponent less than 1

What has been done is to collect cost data points from a combination of: information from suppliers to commercial in confidence projects in Australia, previously published reports and known system case studies. Data from previous years has been escalated at 2.5%/year. Overseas data has been converted at current exchange rates. The power law size cost scaling discussed above has been assumed to be valid and all data points normalised in system size to 1 MW_{th} on that basis. The results are shown in Table 72 and plotted as a function of operating temperature in Figure 123.

It is apparent that a linear fit to this data is a reasonable approximation for the purposes of a rule of thumb approach to assessing economics at an initial screening stage. The indication of an approximate linear fit suggests that the hypothetical cost versus temperature relationships suggested in Figure 122 do arrange in such a way that the locus of most cost effective choices line up in such a manner. It can be concluded, however, that the linear fit is only valid up to about 600°C and from that point must steepen to vertical as it follows the trajectory of the relationship for towers or dishes.

The fact that data from disparate sources and times can be normalised in a reasonable manner to 1 MW_{th} supports the proposed power law relationship with size. The data set is however too limited to draw any firm conclusions on the value of the exponent other than to say it is not incompatible with a commonly suggested value of 0.7.

Based on this fit to the 1 MW_{th} case, the power law size dependence can be reapplied to generate the family of cost estimation curves shown in **Figure 17**.

Table 72. Solar thermal system costs normalised to 1 MW_{th} and A$ 2019.

Source	Cost per kW	Size (kW_{th})	Temp.	Cost per kW at 1MW_{th} base capacity
Small trough A	$2,720	200	200°C	$1,678
Small trough A	$2,040	1,000	200°C	$2,040
Tubes plus CPC A	$1,760	200	150°C	$1,086
Domestic SHW	$5,500	2	60°C	$816
Tubes plus CPC B	$2,095	147	150°C	$1,180
Queanbeyan Pool flat plate	$6,206	13	70°C	$1,680
Tubes, De Bortoli Winery Griffiths NSW	$3,672	143	95°C	$2,061
Australian Institute of Sport	$397	720	40°C	$359
Tower plus heliostat	$1,152	100,000	600°C	$4,585
Domestic (10m^2) pool heating	$1,375	5	40°C	$277
Queanbeyan Pool unglazed (340m^2)	$550	282	40°C	$376
Small LFR A	$1,469	1,000	250°C	$1,469
Large troughs A	$1,152	100,000	400°C	$4,585
Large troughs B	$1,590	1,900	370°C	$1,928
Large troughs B	$857	92,200	370°C	$3,328
Large troughs C	$3,681	200	220°C	$2,271
Large flat plate A	$353	864	100°C	$338
High performance tubes	$2,549	200	200°C	$2,271
Small trough B	$1,029	1,441	150°C	$1,148
Evacuated flat plate A	$,831	210	150°C	$1,146
Large troughs D	$568	20,000	550°C	$1,395

Large troughs D	$512	20,000	200°C	$1,258
Large troughs A	$919	75,000	280°C	$3,357
Large troughs A	$1,250	20,000	280°C	$3,069
Large troughs A	$827	250,000	280°C	$4,334
Small LFR A	$919	20,200	215°C	$2,265

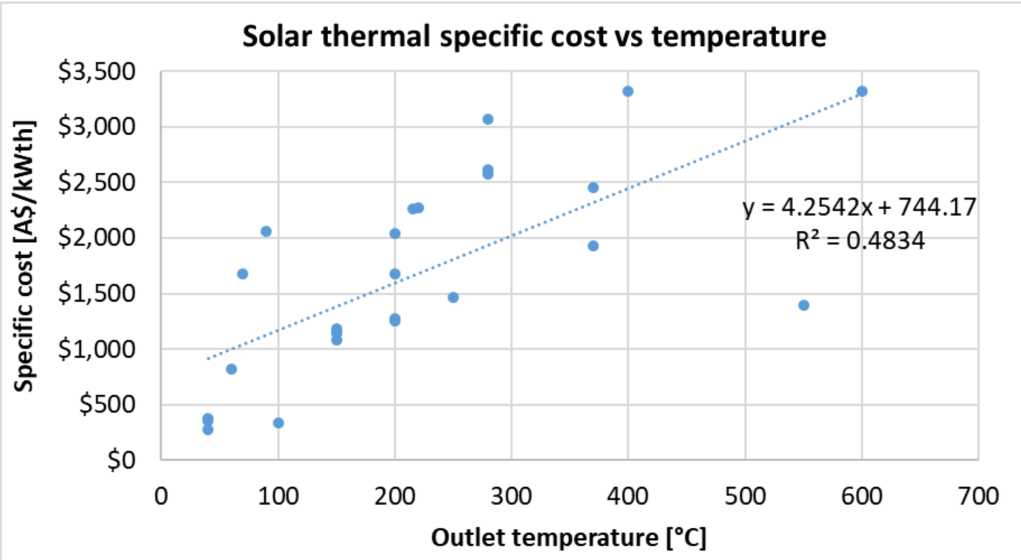

Figure 123: Solar thermal specific cost versus temperature, normalised to a 1 MW_{th} system and expressed in A$ 2019.

This data has been used to assemble the illustration of installed cost dependence on both temperature and system size in **Figure 17**.

F.7. Performance analysis of solar thermal systems

Solar thermal systems are subject to the variability of solar input, through the diurnal cycle, cloud variability and seasonal variations. Predicting their performance is a more complex process than it is for other technology options. Overall analysis of economic potential requires an estimate of annual output. Assessing the integration issues associated with matching production to load requires prediction of output on an hour by hour basis.

The determinants of instantaneous energy production can be summarised as:

- The thermal losses that are directly linked to the instantaneous temperature of the system are largely independent on the level of solar radiation absorbed. As a consequence, at low solar input, efficiency drops.

- The level of solar radiation absorbed, which is determined by both the instantaneous intensity of radiation and the angle at which it strikes the collector aperture. The output of a fixed collector will be at a maximum when the sun rays are perpendicular to the surface of the collector (typically around midday). At lower sun angles the solar gain will be reduced due to the lower projected collector area presented to the sun. Tracking collectors also experience incidence angle effects. For a single axis concentrator, seasonal sun movement away from perpendicular to the tracking axis reduces output[33].
- Dynamic effects such as lags due to the thermal capacity of components and minimum operational thresholds.

The following sections examine, firstly, the determination of peak efficiencies for the various collector types, followed by an examination of the modelling of the semi-dynamic behaviour of the systems over a full year, leading to some indicative results that best inform further economic comparisons for this study.

Peak performance

The efficiency of a solar collector refers to the heat output for a given heat input and can be defined as:

$$\eta = Q_{out}/Q_{in}$$

AS/NZS 2535, ISO 9806 and the IEA SHC use the following second-order equation to model collector efficiency.

$$\eta = \eta_0 - a_1(T_m^*) - a_2 G (T_m^*)^2$$

where:

η = collector thermal efficiency
η_0 = "optical efficiency" - collector thermal efficiency at $T_m^* = 0$
a_1 = first order loss coefficient (W/m^2/°C)
a_2 = second order loss coefficient (W/m^2/°C)
T_m^* = reduced temperature difference = $(T_{fluid} - T_{ambient})/G$
G = solar irradiation (W/m^2)

The constant η_0 is indicative of the optical efficiency of the collector under direct normal irradiance, while the two coefficients a_1 and a_2 describe the increasing thermal losses of the collector with increasing temperature.

Derivation of the coefficients for this equation is addressed by many collector testing laboratories around the world and, if the area of the collector is known, the equation can be used to determine the output of the collector at a particular irradiance and temperature.

[33] Angle effects are often quantified by a scale factor on peak efficiency called the Incidence Angle Modifier (IAM), this can be plotted as a function of time of day or be quoted as an annual average.

Representative coefficients for Uunglazed, glazed flat plate, and evacuated tube solar thermal technologies are listed in Table 73.

Table 73. Efficiency coefficients for various solar thermal technologies (for gross area).

Collector Type	η_0	a_1	a_2	Source
Unglazed	0.840	18.00000	0.00000	IEA SHC via Energetics
Flat plate	0.608	5.47000	0.01260	SRCC – Solahart L Series
Evac tube	0.456	1.35000	0.00380	SRCC – Apricus AP-20
CPC	0.554	0.81180	0.00307	SRCC – Ritter 18 OEM
Trough	0.720	0.15000	0.00170	SANDIA via Energetics

The efficiency curves that result from the efficiency equation and the coefficients provided in Table 73 are shown in

Figure *124*.

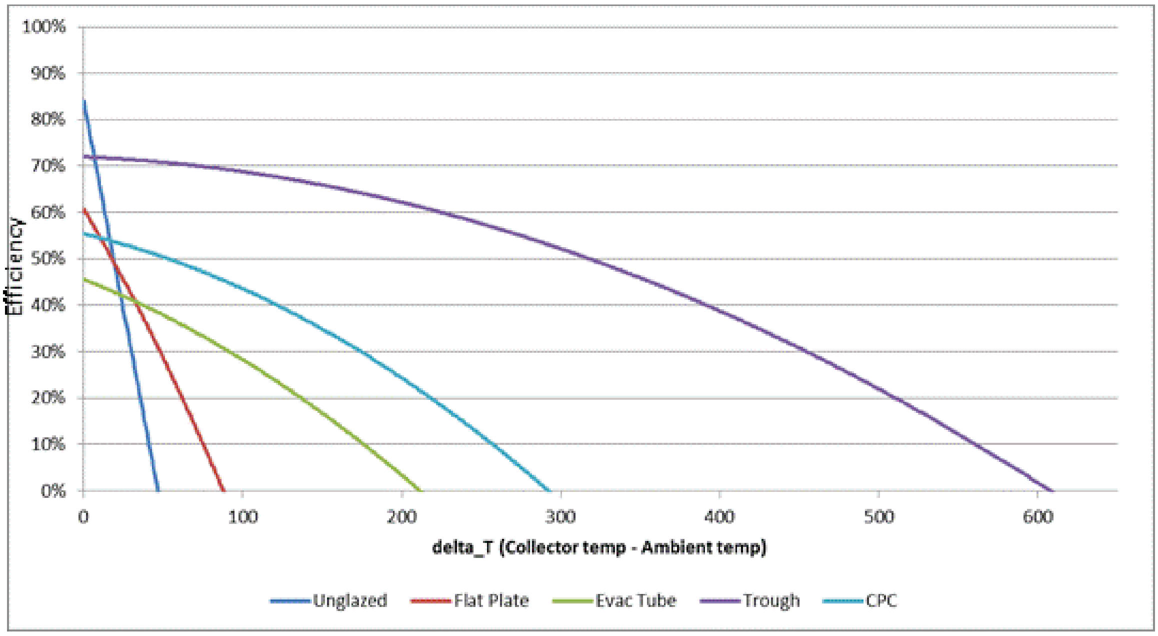

Figure 124: Peak efficiency at 1000 W/m² irradiance (GHI or DNI as appropriate) vs temperature.

As the temperature of the fluid increases, so too do the losses, until the efficiency drops to zero for some limiting temperature. This limit is low for unglazed collectors, restricting them to low temperature applications such as pool heating. Unglazed collectors can be seen to have the highest optical efficiency, but also the highest thermal losses for a given temperature.

A glazed flat plate collector has lower optical efficiency than an unglazed collector due to the small amount of radiation reflected by the glass. However, this glass prevents losses to the ambient air and also reduces re-radiative losses, with the glass transmitting high wavelength solar radiation, but blocking low wavelength thermal radiation (the greenhouse effect). Lower thermal losses are the result, and higher temperatures are thus attainable.

Evacuated tube collectors will tend to have lower optical efficiency (based on gross collector area) than flat plate collectors on account of the spacing between tubes. The spacing plus the curved surface of the absorber tubes however means that they maintain their performance at close to peak levels for longer hours of the day.

The efficiencies considered in this study are based on gross area of the collector. There can often be confusion, particularly in the comparison between flat plate systems and evacuated tubes, between efficiencies defined around the gross area of the collector, the aperture area, or the absorber area. Gross area refers to the footprint of the collector, and so includes the frame and manifold of the collector. Aperture area refers to the glazed area of a flat plate collector, and to the diameter multiplied by length of the glass tubes in an evacuated tube collector. Absorber area is the exposed absorber area of a flat plate collector, and the total diameter multiplied by length of the cylindrical absorbers within an evacuated tube collector.

When gross area is considered, evacuated tube collectors will tend to appear less efficient than flat plate collectors at low temperatures (low thermal losses), owing to spacing between tubes and the evacuated space within each tube collecting no energy from incident radiation. When absorber or aperture area is considered, the efficiency of tube systems will appear relatively higher.

Annual performance analysis

To assess collector performance in different locations around Australia, the System Advisor Model (SAM) developed by the US Department of Energy’s National Renewable Energy Laboratory (NREL) has been used (NREL, 2018). SAM models the hourly performance of a solar thermal system using a range of parameters specified by the user, alongside a solar and weather data file that includes hourly irradiance and ambient temperature information for a specific location.

SAM contains a range of default models for different solar thermal technologies. A solar hot water model can be configured for glazed and unglazed flat plates and evacuated tube systems. High temperature concentrator system thermal performance can also be considered in SAM by examining solar field output in separate models for parabolic trough, Linear Fresnel and heliostat tower based-concentrating solar thermal power systems.

In the solar hot water model, the collector can be specified according to the area and the efficiency parameters described previously. Default values were used in this study, including levels of thermal storage and assumed load profiles.

The solar data files used represent average years from the Australian Bureau of Meteorology database for a given location.

SAM results are in the form of hourly time series data over the course of a year. An excerpt from the flat plate collector modelling is depicted in Figure 125. The graph shows three consecutive days with different irradiance conditions (above), and the resulting collector output (below).

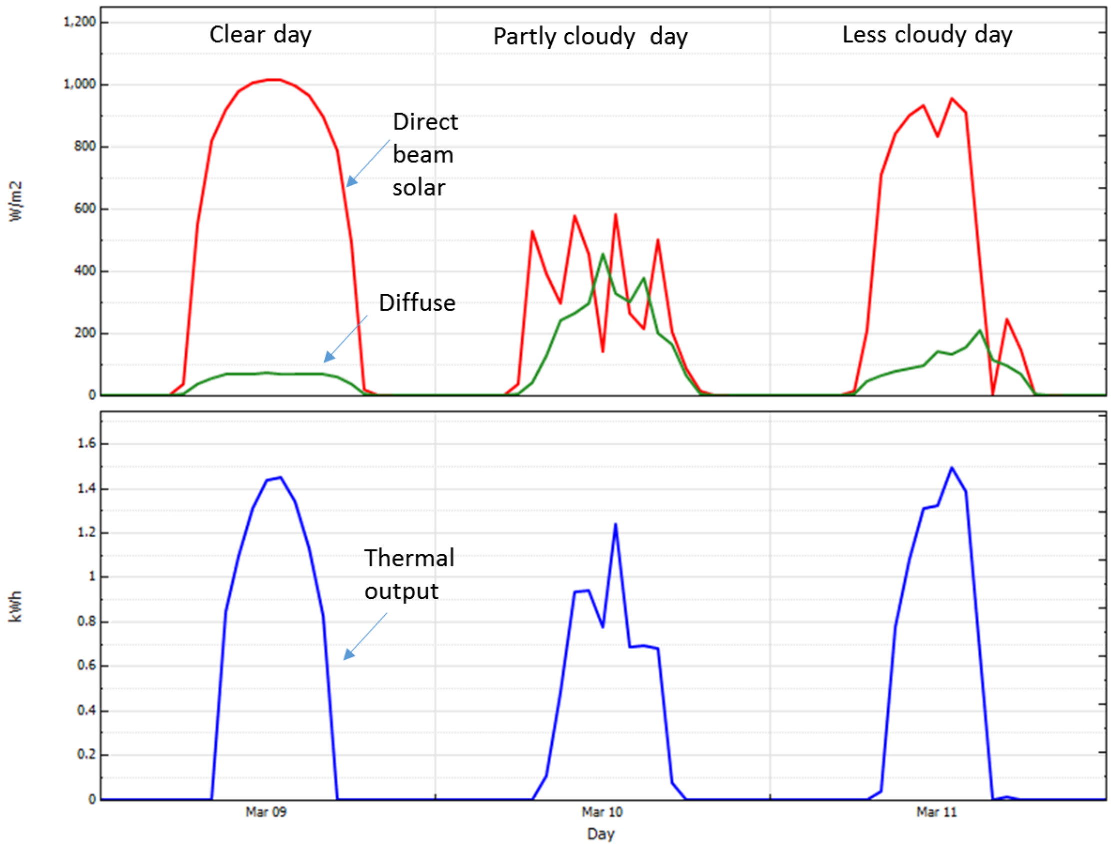

Figure 125: SAM time series results for a flat plate hot water system for three representative days.

Seasonal variation is deduced from the time series results, as shown in Figure 126. This excerpt from the flat plate modelling shows the impact that reduced irradiance and ambient temperatures have on collector performance from month to month.

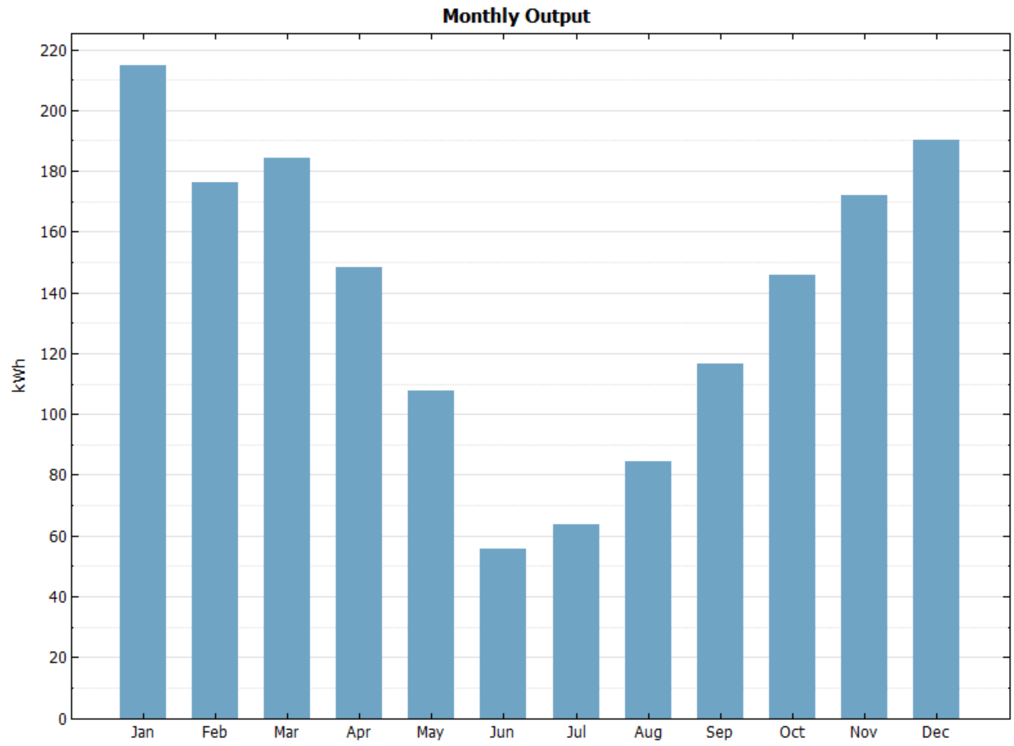

Figure 126: SAM monthly results.

The performance of a 10 m^2 north-facing unglazed collector at raising water to 25°C was modelled. The collector tilt was set to 20°, which was assumed to be the typical roof pitch. This was not altered between locations owing to the inability to frame-mount non-rigid unglazed collectors. Storage parameters were set to model a pool such that volume and thermal losses are high.

For the flat plate and evacuated tube models, the performance of 2.96 m^2 collectors at raising water to 55°C was assessed. The collectors were oriented due north and tilted at the latitude of the site. A typical 300 litre hot water tank was assumed for storage, and the ambient temperature surrounding the storage tank was set to the average annual ambient temperature of the location.

It should be noted that SAM modelling of solar water heaters is simple. The default settings do not include seasonal variation of load but rather a constant 200 litre/day, and modelling assumptions such as a mixed tank can result in understatement of performance for the type of solar water heaters that are used in Australia.

Whilst these examples are sized for domestic applications, the predictions of output per unit area are equally valid for larger commercially sized systems.

The collector efficiency parameters that were used in the modelling are those shown in Table 73. The results in terms of annual output per square metre are depicted in Table 74 and Figure 127.

Table 74. Collector annual output by location.

Location	GHI [kWh/m²/year]	Average Ambient Temp [°C]	Unglazed [kWh/m²/year]	Flat Plate [kWh/m²/year]	Evac. Tube [kWh/m²/year]
Hobart, TAS	1389	12.5°C	1038	541	838
Melbourne, VIC	1469	15.0°C	1105	551	861
Albany, WA	1582	14.7°C	1155	600	981
Sydney, NSW	1773	18.4°C	1270	668	1076
Brisbane, QLD	1828	19.8°C	1341	699	1096
Perth, WA	1913	18.0°C	1419	736	1084
Rockhampton, QLD	2012	22.1°C	1440	762	1215
Darwin, NT	2114	27.3°C	1370	750	1262
Alice Springs, NT	2256	21.2°C	1706	877	1256

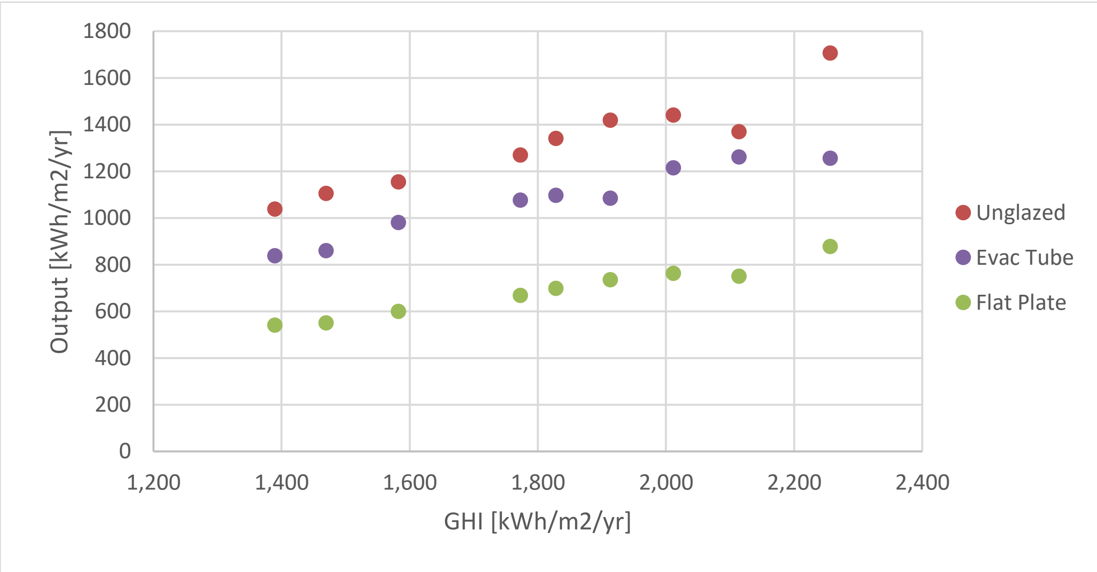

Figure 127: Collector output vs GHI by location.

As expected, the annual output for these three technologies shows strong dependence on annual GHI. Due to varying thermal losses in collectors, variation could be expected on account of ambient temperatures and other localised meteorological characteristics. Such effects are responsible for the scatter that is observed, however it is apparent that for a good rule of thumb, output is linear in the GHI.

If annual output is compared to the output expected at a design point GHI of 1000 W/m² maintained 24 hours a day, 365 days per year, the result is the relationship of capacity factor to annual GHI shown in Figure 128. These linear trends are used to support the economic analysis in Chapter 3.7.

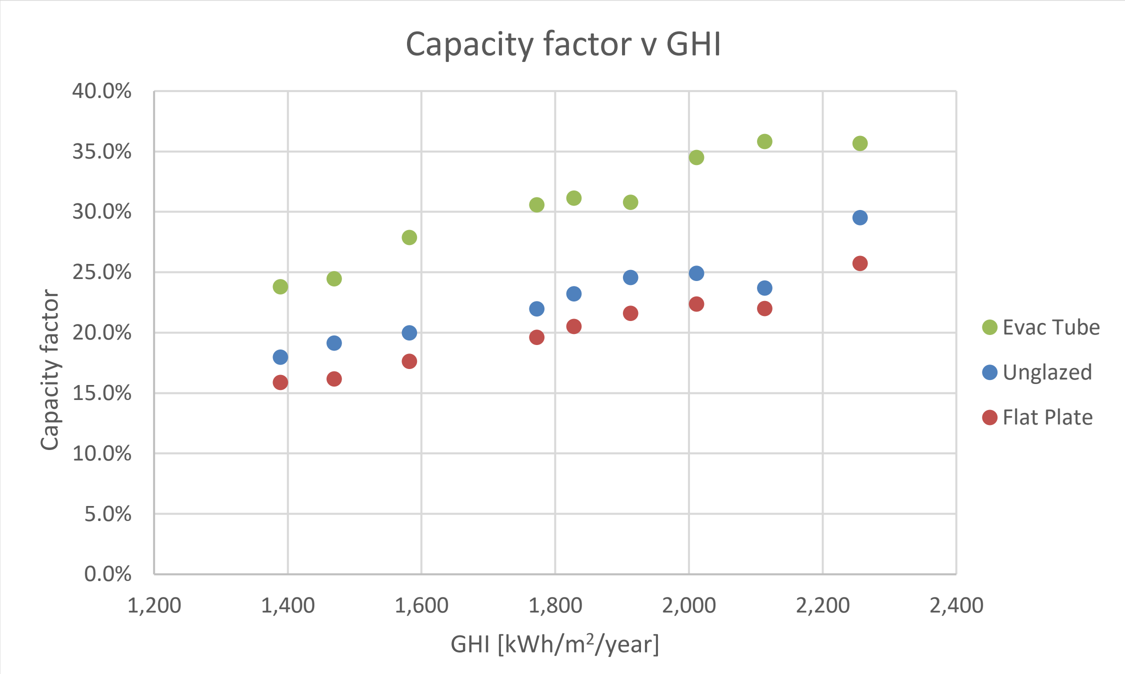

Figure 128: Collector capacity factor vs GHI by location.

Parabolic Trough

The ‘physical trough’ parabolic trough CSP plant model within SAM was also used to estimate capacity factor at various locations around Australia. (Figure 129).

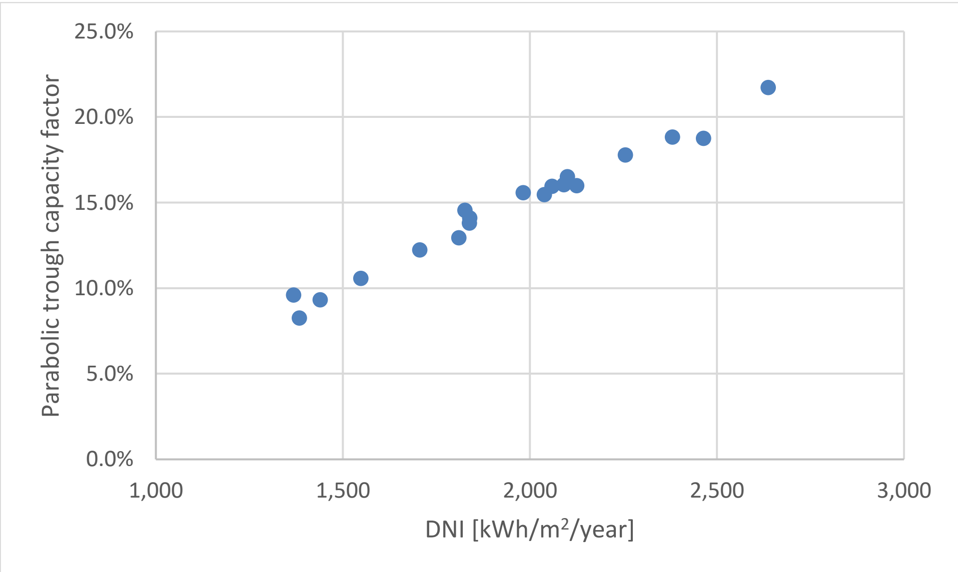

Figure 129: Trough capacity factor without storage vs DNI by location.

Again, a strong correlation can be observed against solar resource (in this case measured with DNI).

It has been assumed that trough capacity factors are a good approximation for Fresnel systems and also, to a lesser extent, heliostat systems. Although the performance of a trough system is strongly temperature dependent, it is assumed that the capacity factor is not.

APPENDIX G. THERMAL STORAGE TECHNOLOGY

G.1. Hot water

Water as heat storage and heat transfer medium is inexpensive. Hot water circuits are similar to thermic fluid circuits in design and operation. Below 100°C process temperatures, water is heated and stored in unpressurized tanks. The stored thermal energy is retrieved when there is a process requirement. Above 100°C pressurized hot water can be used. Compressed air or nitrogen is used to pressurize the tank above the saturation temperature of water (based on steam tables) to keep it in a liquid state. Hot water storage is economical and simple to operate for small-scale applications up to 180°C. The temperature difference in the process circuit is directly proportional to the storage vessel size. Above 180°C, it is expensive to manufacture, heat treat and deploy pressure vessels with high plate thickness. Examples are shown in Figure 130.

Figure 130: Unpressurized hot water storage tank operated between 65 and 85°C. (reproduced from Agricultural Projects Holland B.V).; right: pressurized storage tank. (Reproduced from I.VAR. Industry).

G.2. Steam accumulators

Steam accumulators are basically pressure vessels designed as per ASME or local boiler regulations to store pressurised hot water. Surplus steam at high pressure is charged into the tank with hot water and is stored at a particular set pressure. When there is demand for steam, the accumulator releases steam by opening the main stop valve. The pressure drop causes the high pressure water to ‘flash’ to steam. The discharge steam from the accumulator is saturated steam at lower pressure (Figure 131).

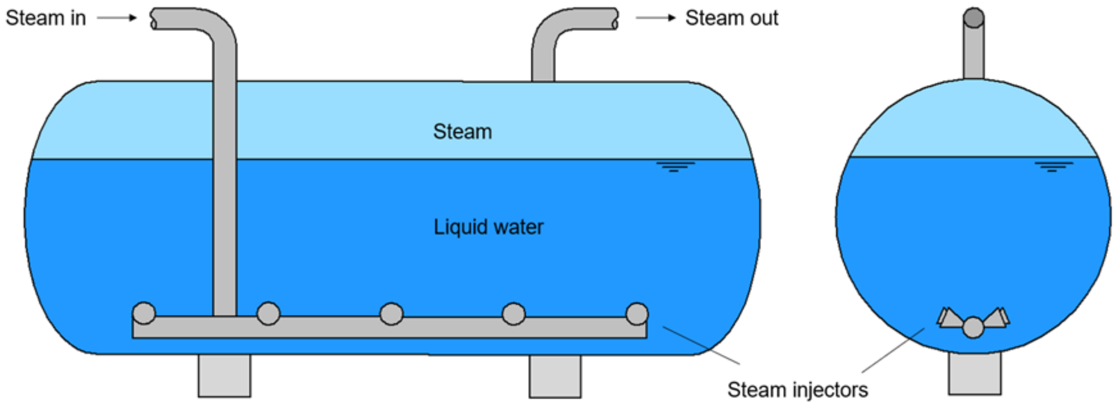

Figure 131: Steam accumulator (figure ITP).

Cost of steam storage accumulators

The cost of the accumulator depends on the volume of the tank and the steam pressure. Other costs include the piping system, safety valves, control valves, instruments etc. for operation of the tank.

A cost example for a steam accumulator used in a solar thermal power system is shown in Table 75. The storage system is designed to store steam for 1 hour of full-load operation of the power block at 147 MW_e. Assuming a thermal efficiency of ~40% for the steam turbine power block at the given inlet steam conditions, the thermal energy input to the power cycle is estimated to be 367.5 MW_{th}. Based on the given data, the cost per unit of storage can then be estimated to be 104.7 $A/$kWh_{th}$.

Table 75: Example of steam accumulator, including cost, assuming AUD/USD = 1.35 (Prieto et al., 2018).

Description	Values
Design gross power	147 MW_e
Turbine inlet conditions	100 barg, 540°C
Tank volume (base accumulator)	1 x 4,500 m^3
Superheater accumulator	1 x 1,500 m^3
Steam discharge pressure from base accumulator	35 barg
Steam discharge pressure from superheater accumulator	22 barg
Cost of 1-hour storage system	38,470,287 A$
Specific storage cost per unit of thermal energy stored	104.7 A$/$kWh_{th}$

Experience for steam storage

Steam accumulators have been used as a storage system in some plants, but it should be noted that the pressure from the steam accumulator keeps dropping when the stored steam is drawn from the accumulator. This must be taken into account in the system design. Further, above 285°C, it may not be economical to build large accumulators as the thickness of the vessels tends to be excessively large and it becomes difficult to manufacture, heat treat and deploy such vessels. It may have to be assembled as multiple units on site.

For these reasons, application of steam accumulators is usually limited to short term storage (up to ~1-2 hours), primarily to bridge short-term intermittency in steam generation (e.g. due to intermittent clouds in case of a solar thermal system), in the absence of another thermal storage system such as molten salt. It tends to be uneconomical as well as inefficient to store large quantities of high-pressure steam. For example the PS10 solar thermal plant in Spain uses a steam accumulator with a storage capacity of 50 minutes, to store saturated steam at 40 bar g / 250 °C to feed an 11 MW steam turbine.

It is possible to purchase steam accumulators from suppliers worldwide, or get the system designed by a reputable engineering contractor for the required storage capacity and have it fabricated by a local manufacturer.

Figure 132: Steam accumulators at the PS10 Abengoa solar tower plant in Seville, Spain. (Reproduced from pole-derbi.com).

G.3. Molten salt

Sensible heat storage in molten salt is a commercially proven and cost-effective thermal storage technology for temperatures above those achievable with water storage. Molten salt storage systems typically consist of two storage tanks, a ‘cold’ and a ‘hot’ tank and a heat exchanger to transfer heat to and from the storage system (Figure 133). Systems with only one tank and a moving divider are also possible. The storage system is ‘charged’ by circulating molten salt from the cold tank to the heat exchanger where it is heated, before it is stored in the hot tank. To ‘discharge’ the storage and utilise the stored energy, the flow direction is reverted and the cooled-down salt returns back to the cold tank. Storage periods are typically several hours but can be up to a week.

A potential challenge with molten salts is related to its operating temperature limits. The lower limit is given by the melting/freezing point of the salt, while the maximum operating temperature is limited by the chemical stability of the salt and corrosion limits of the containment materials in contact with the salt.

Freezing point of salts can be as low as 52°C, but most commonly used molten salts have a freezing point between around 130 to 230°C (e.g. Hitec HTS, Solar Salt). The upper temperature limit is typically between around 450 and 600°C (Bradshaw & Siegel, 2008). Hence, the salt composition used should be selected based on the temperature requirements of the process heat application.

The relatively high freezing point of molten salts also requires that the storage tanks are fitted with electric heating elements to prevent solidification during extended periods without energy input. In certain cases, the electric heaters have been utilised to store low- (or even negative-) cost excess power from the grid that would otherwise have been curtailed during periods of oversupply from variable renewables.

There are limited suppliers in the world to supply a complete molten salt storage system. It is also possible to get the system designed from engineering contractors, to procure, assemble, commission and operate it.

Molten salt storage systems are currently operational in the Gemasolar and Crescent Dunes CSP tower systems, where salt is heated directly in the solar receivers up to 565°C, as well as in several parabolic trough plants around the world with indirect heating of the salt up to around 390°C via heat exchange with heat transfer oil running through the solar receivers.

Frenell GmbH are actively promoting direct salt heating with Fresnel systems, stating that they have a modular approach to salt tank systems, and SkyFuel Inc is promoting a parabolic trough collector with molten salt heated directly inside the receiver tubes.

Figure 133: Image of a large-scale molten salt storage system used in a parabolic trough solar power plant. (Reproduced from Heliocsp).

G.4. Synthetic/mineral oil

The principle of operating an oil-based thermal storage system is similar to that of a molten salt system except for the different storage medium. Synthetic oils are expensive but have a good lifetime, and operational ease, i.e. good heat transfer and flow properties and a freezing point in the range of 0 to 12°C. Hence, heat transfer oils are a good candidate for small- or medium-scale thermal storage in the temperature range between around 180 to 393°C.

Potential downsides of heat transfer oils include their flammability, which requires the system to be designed accordingly (Kuravi et al., 2012). In addition, the highest allowable temperatures for long-term operation are limited to around 400°C with the most high-temperature-stable oils, which are at the same time the most expensive storage medium and result in relatively high unit costs of thermal storage.

Mineral oils have been suggested for thermal storage at temperatures up to around 315°C. They are a low-cost alternative to synthetic oils with similar heat transfer properties but lower temperature stability.

Oil storage is a relatively simple technology and process engineering contractors can design and provide specifications for the system. The materials can be purchased and assembled to give the required output.

To date, only one large-scale solar thermal system (SEGS I) has been built with an oil-based thermal storage system, which, however, was damaged in 1999 in a fire and was not replaced subsequently. Since then, all storage systems in solar thermal systems have used molten salt due to its cost and safety advantages.

G.5. Concrete

Concrete-based thermal storage is an upcoming thermocline energy storage system that has received a lot of R&D effort and for which there appears to be at least one commercial offering (Figure 134). Heat transfer tubes with fin plates are run through concrete blocks. The heat transfer fluid (HTF) is passed through the tubes to store sensible heat in the concrete block. As the HTF flows through the concrete block, is cooled due to the heat transfer to the storage medium (concrete), which creates a temperature gradient (thermocline) in the concrete block, with the inlet region being at the highest temperature and the outlet region at the lowest temperature. To discharge the storage, the HTF is run in the opposite direction, thereby taking advantage of this temperature gradient in the concrete. Thus, the initial HTF temperature (up to ~600°C) can nearly be attained during discharge.

Figure 134: Concrete thermal energy storage. (Reproduced from DLR).

G.6. Packed bed

Packed bed storage systems operate in a similar manner as concrete storage, but they use a granular medium such as pebbles or rocks as the storage mediums, contained in an insulated vessel (Figure 135). Hot air is passed over the packed bed to store energy and the air is passed in opposite direction when energy is needed for power generation. They can operate at up to 800°C and may be used to run hot air turbines. It is possible to use packed bed in low temperature storage applications, however, the additional cost of the hot air ducting system, air heat exchangers and pumping losses have to be taken into consideration in their economics. Packed bed and concrete-based storage systems have the potential to be among the lowest cost thermal storage options at intermediate- and high-temperatures, but are yet to be fully exploited commercially at large scale.

Figure 135: Packed bed thermal storage system. (Reproduced from Airlight Energy).

G.7. Phase-change materials

Latent heat storage in phase-change materials (PCM) is a potential new thermal storage technology. The benefits of PCM storage include the potential for high-energy storage density and high storage temperatures and the release of heat at a constant temperature.

PCM storage systems are also considered as a low-cost option for storing electric energy in the form of thermal (latent) energy. The stored thermal energy can either be converted back to electricity via a thermal power cycle or used directly as a source of high-temperature process heat.

In the former case, this offers a potential alternative to batteries as an electricity storage technology. The round-trip efficiency of storing electric energy via the intermediate form of thermal energy is low (due to the inherent heat rejection during the conversion of thermal energy back to electric energy). However, there may be a chance that such a system results in lower levelised cost of electricity compared to electricity storage in batteries, due to the potential for significantly lower capital costs compared to batteries.

On the other hand, if electricity is used for process heating, then the PCM storage concept may be an efficient energy storage technology and potentially a viable alternative to sensible heat storage technologies.

Currently, company 1414°, based in South Australia, is commercialising a PCM storage system heated with electricity using molten silicon as the phase-change storage material, converting electricity to latent heat stored at 1414°C.

G.8. Thermal energy storage suppliers

Table 76 contains a non-exhaustive list of thermal storage technology suppliers.

Table 76. Thermal storage technology suppliers.

Supplier name	Technology specifications	Website
	Steam accumulators	
Terrajoule	Steam pressure: 18 Bar g	www.terrajoulecorp.com
Spirax Sarco	-	www.spiraxsarco.com
Novatherm	-	www.thermodyneboilers.com
Thermodyne	-	www.novathermboiler.com
East Coast Steam	-	www.eastcoaststeam.com
Simons Boilers	-	www.simonsboiler.com.au
	Molten salt storage systems	
Linde Bertram		https://www.the-linde-group.com
Frenell		http://www.frenell.de/
Flagsol (Engineering contractor)		www.flagsol.com
Idom (Engineering contractor)		https://www.idom.com
	Synthetic/mineral oil systems	
Idom		https://www.idom.com
Flagsol		www.flagsol.com
	Concrete / solid systems	
Energy Nest	Temperature: <600 °C	http://www.energy-nest.com
Aalborg CSP tie up with Energy Nest		http://www.aalborgcsp.com/
Solastor	Graphite-based system	https://solastor.com.au/
	Packed bed systems	
Airlight Energy	Temperature: <600°C	www.airlightenergy.com
	Phase change material systems	
1414°	Temperature: 1414°C	https://1414degrees.com.au/

APPENDIX H. STAKEHOLDERS CONTACTED

A focus of this report 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.

Discussions were free ranging in order to draw out pertinent examples and insights and sought to always include the following issues:

- Barriers
  - capital (internal and external)
  - information
  - skills (internal and external)
  - regulatory
  - non-market pricing
  - project timing
- Motivations
  - opportunity and opportunity cost
  - risk (primarily to operations)
  - internal incentives and habits
- Sanitising (essential) factors
  - payback
  - scale (too small and too big)
  - decision cycles (especially for long life equipment)
  - supply chain limitations
- Specific items where relevant
  - data on technologies
  - data on CHP technologies
  - data on RE storage (batteries, molten salt, PCM, steam accumulators) and impact on other options
  - temperature based opportunity capture if relevant to the industry / business.

Our approach to achieving a meaningful cross-sectional outcome was to target both the focus areas noted by ARENA and to ensure that the larger sectors of use were covered. To do this we:

- updated the *natural gas energy usage by industry sector* of the 2015 ITP report by adding in other forms of likely thermal usage (coal, diesel, lpg) and bringing up to the last ABS data available (2016-17)
- used this update to create a prioritised list for industry sectors under the ANZSIC system by energy used
- used this list and ARENA's nominated sectors to assign prior contacts, new contacts from ARENA workshop attendance and team contacts from recent work to targeted industry sectors – focussing on national / international scale businesses in the main
- introduced the context and aims of the project to these selected stakeholders (~27) and sought interviews
- interviewed senior management of companies including ALCOA, Nyrstar, Pacific Aluminium (Rio Tinto), Orora, Timberlink, Inghams, Lion, Coca Cola Amatil, Nichols Poultry, Grange Resources, Boral, Austral Bricks, Simplot as well as individuals with recent experience at Colgate Palmolive, Origin Energy, AGL, Murray Goulburn and BHP. Covering the categories alumina, aluminium, non-ferrous metals, primary metals, basic chemical and chemical product manufacturing, food and beverage, dairy product manufacturing, meat and meat products, wood and wood products, fabricated metal product manufacturing, glass and glass products, paper and converted paper product manufacturing, and non-metallic mineral products

The prioritised sector list (Table 77) differs considerably in focus from the previous report on gas users only. Here the top five sectors identifiable in the ANZSIC / ABS data contribute 85% of the opportunity – and most importantly a very large percentage of that opportunity is in replacement of coal and other non-renewables rather than gas.

Table 77: Prioritised sector list for stakeholder interviews.

Delivery	Main ASIC sector	PJ Gas	Notable subsectors	PJ thermal	%age	rank	cumulative %age	focus area
Transmission	Primary metal and metal product manufacturing	14	Primary metal and metal product manufacturing (excl Alumina)	254	26%	1	26%	y
Transmission	Primary metal and metal product manufacturing	148.2	Alumina	251.8	26%	2	51%	y
Transmission	Basic chemical and chemical product manufacturin	86.2	-	127.4	13%	3	64%	y
Distribution	other Mass market mfg	119.7	-	119.7	12%	4	77%	-
Distribution	non-metallic mineral products	23.9	o 203 Cement, lime, plaster and concrete	76.9	8%	5	84%	y
Distribution	Food product manufacturing	19.6	All other food product manufacturing (by subtraction)	45	5%	6	89%	y
Distribution	Pulp, paper and converted paper product manufac	14.5	-	23.3	2%	7	91%	y
Distribution	non-metallic mineral products	16.5	o 202 Ceramics	18.5	2%	8	93%	y
Transmission	Petroleum and coal product manufacturing	13	-	13	1.3%	9	95%	-
Distribution	non-metallic mineral products	11.5	o 201 Glass and glass products	11.9	1.2%	10	96%	y
Distribution	Food product manufacturing	7.2	Dairy product manufacturing	7.2	0.7%	11	96%	y
Distribution	non-metallic mineral products	5.6	o 209 Other non-metallic mineral products	5.8	0.6%	12	97%	y
Distribution	Wood product manufacturing	3.2	-	4.6	0.5%	13	98%	-
Distribution	Food product manufacturing	4.5	111 Meat and Meat Product Manufacturing	4.5	0.5%	14	98%	y
Distribution	Textile, leather, clothing and footwear manufactur	2	-	3.6	0.4%	15	98%	-
Distribution	Beverage and tobacco product manufacturing	3.4	-	3.4	0.3%	16	99%	y
Distribution	Transport equipment manufacturing	3	-	3	0.3%	17	99%	-
Distribution	Fabricated metal product manufacturing	2.8	-	2.8	0.3%	18	99%	-
Distribution	Food product manufacturing	2.4	Sugar and confectionery manufacturing	2.4	0.2%	19	100%	y
Distribution	Machinery and equipment manufacturing	2.2	-	2.2	0.2%	20	100%	-
Distribution	Polymer product and rubber product manufacturing	1.4	-	1.4	0.1%	21	100%	-
Distribution	Printing (including the reproduction of recorded me	0.9	-	0.9	0.1%	22	100%	-
Distribution	Furniture and other manufacturing	0.2	-	0.2	0.0%	23	100%	-

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