HIGH TEMPERATURE HEAT PUMPS for the Australian food industry:

Opportunities assessment

August 2017

AUTHORSHIP OF THIS REPORT

This report is published by the Australian Alliance for Energy Productivity (A2EP). A2EP is an independent, not-for profit coalition of business, government and environmental leaders promoting a more energy productive and less carbon intensive economy.

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Note: Acknowledgement of this support does not indicate stakeholders' endorsement of the views expressed in this report.

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Executive Summary

The purpose of this report was to define the likely feasibility, and range of applications for heat pumps in the food industry, with a focus on high temperature (HT) heat pumps delivering useful heat at 66°C-150°C.

This work is a continuation of the 2xEP project investigating the opportunities for innovation in technology/business models that could transform energy productivity in the food value chain (http://www.2xep.org.au/innovation-next-wave.html). The first overview report defined one key transformative change as being the electrification of food processing, displacing fossil-fuel fired boilers and steam systems. One central technology required for this transition is the application of heat pumps to recover heat from waste streams to boost temperatures, displace steam, and in some cases simultaneously provide process cooling.

This work is particularly important at a time when East Coast Australian companies have seen a significant rise in gas prices in the last two years, with prices often more than doubling. As heat pumps effectively use electricity to harness heat from waste heat streams or the environment at efficiencies of over 300%, they can cost effectively displace gas when gas prices are high (and when the cost of renewable electricity is falling rapidly – as solar PV can be used to power heat pumps).

The project team consulted extensively with stakeholders and conducted research to define international best practices in heat pumps technology and application globally and to understand the experience and capacity in Australia. We then evaluated the likely economic return from using heat pumps in a range of applications locally. This evaluation is at pre-feasibility level. Based on a successful outcome of this project, we could potentially pilot heat pumps in the most promising applications with strong replication potential.

The key findings of this project are:

High temperature industrial heat pump technology has developed rapidly in the past decade. There are now many commercial products for industrial processes, including the food processing industry. Thousands of units are now in service, in Japan, South Korea and (to a lesser extent) Europe to supply heat at up to 95°C. And the technology has also extended to development of heat pumps delivering steam at up to 150°C. At the same time, there are barely a handful of high temperature (over 65°C) industrial installations in Australia.

High temperature heat pumps could play an important role in Australian industry to recover heat and displace steam/hot water generated from natural gas (and LPG). With the rapid escalation in gas prices and potential gas supply constraints, and the need to move to low carbon energy solutions, high temperature heat pump technology could play an important role in Australian industry.

The most economically attractive applications occur where heat pumps can be used to upgrade heat from waste streams and/or capture latent heat, (like waste water, hot humid air (e.g. from dryers), condenser heat from refrigeration systems), and where simultaneous heating and cooling duties can be delivered. Classic applications of high temperature heat pumps in food processing include:

- Food drying and washing processes, where the heat pump cool side captures latent heat in the exhaust stream as well as sensible heat to provide hot, dry inlet air, water or steam at the required temperature;

- Heating process or cleaning water by upgrading waste heat from a waste heat stream or a refrigeration system; and,
- Pasteurisation where the heat pump may provide heating and cooling duties to displace steam.

The economics of high temperature heat pumps have improved due to gas price escalation, technology development and early stage economies of scale, and now appear broadly viable. While, there is a significant capital cost for high temperature heat pumps, the development of packaged 'Eco cute' units in Japan provides relatively economical volume manufactured units for heating water and air to 90°C. Economic analysis should consider all the value streams. Many international case studies only report the direct energy benefits. The value derived from using HT heat pumps may include four types of energy productivity benefits:

- Direct energy savings from the COP of heat pumps of 3 or more (and where simultaneous heating and cooling is possible, this can double). A generalised comparison of the cost of generating heat with heat pumps indicates that heat pumps may generate heat with up to 50°C+ temperature lift at say $10/GJ (based on $160/MWh power); significantly lower than a typical boiler and steam system using natural gas – at $12/GJ gas cost, heat delivered to process would typically cost over $15/GJ from a steam system (>$25/GJ for an inefficient system).
- The recovery of sensible and in some cases also latent heat, which would otherwise be wasted.
- Use of heat pumps as stepping stones towards complete replacement of boilers and steam systems, generating potentially much greater savings, where existing systems have low efficiency.
- Additional energy productivity benefits including enabling increased plant throughput, better heating control leading to product quality improvements and greater reliability than steam systems.

While the economics of HT heat pumps are application and site specific, it appears that there will be many heat pump solutions that pay back within six years (delivering over 15% per annum internal rate of return) just based on direct energy benefits. Where these installations allow retirement of boilers and steam systems, or where the heat pump fulfils a cooling and heating duty simultaneously the systems could pay back in less than 3 years. Given these rates of return, there is potential for well-designed financing mechanisms to provide low upfront cost, cashflow-positive finance packages for heat pumps.

There are significant barriers to implementation of HT heat pumps which explains the very small number of installations to date. Some barriers to implementing HT heat pumps in the Australian food industry include:

- Historically cheap coal and then gas prices, which have supported the continuation of central, steam based heat supply systems and under-investment in end use efficiency improvement;
- Lack of business knowledge of the application of this technology as there are almost no local examples and limited local supplier expertise;
- Limited incentives to implement the technology (which were central to rapid deployment in Japan and Korea);

- There is skill required to optimally implement HT heat pumps (other than in applications that just directly replace a heating source) including using 'pinch' thermodynamic analysis, and determining how to extract the greatest total business benefit. This expertise is not widespread in the Australian market.

These barriers have been overcome in Japan and Korea through government support including information provision, technical support incentives, and investment incentives.

The project team believes that there is sufficient potential for application of HT heat pumps to displace natural gas and deliver an attractive return for the Australian food industry that further work is justified to develop the market. This may include part-funding the conduct of detailed feasibility studies and case implementation projects, to demonstrate the application in applications where there is substantial replication potential.

A list of recommended actions is provided Section 8 Conclusions and next steps**.**

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1 Purpose and context of this report

This report was prepared by the Australian Alliance for Energy Productivity (A2EP). A2EP is an independent, not-for profit coalition promoting doubling the energy productivity of the economy by 2030.

This report examines the feasibility of utilising industrial heat pumps producing output fluids at 66°C-150°C for food processing.

This work is a continuation of the 2xEP project investigating the opportunities for innovation in technology/business models that could transform energy productivity in the food value chain from plate back to farm. This project follows from our finding that one key transformative change would be the electrification of food processing, displacing fossil fuel fired thermal processes. One key element of this change was seen to be the application of distributed heat pumps to recover heat, displace boilers and steam systems and in some cases simultaneously provide process cooling.

This work is particularly important at a time when East Coast Australian companies have seen a rapid escalation of gas prices in the last two years, with many companies seeing contract prices double from $6/GJ to $12/GJ or more. In addition, renewable electricity costs have fallen and there is an increasing focus on demand-side energy productivity improvement. Increasing numbers of businesses are investing in 'behind the meter' renewables and improvements in process efficiency, while beginning to recognise the many business benefits of innovation. As heat pumps effectively use electricity to harness heat from waste heat streams or the environment, they can very cost effectively displace gas when domestic prices as these factors play out.

Our aims from this work were to:

- Understand the availability of heat pump technology;
- Determine whether heat pumps are likely to be economical in Australian food processing applications;
- Define barriers to be overcome to allow increased application; and finally,
- Define the next steps that should be taken to fulfil the potential of this technology in the local market.

What is energy productivity?

Energy productivity (EP) refers to the value created from using a unit of energy. To improve EP, we can increase economic value added by using energy more effectively, or use less energy – in short, do more with the energy we use.

EP = Value added ($)/Energy (primary, GJ)

The ideal commercially sustainable applications for heat pumps in industry will have both productivity as well as energy benefits, for example, improved plant reliability, reduced maintenance, enhanced controllability, improved product quality or increased throughput. This could be directly through application of the technology or through enabling the partial or complete replacement of central steam and hot water systems with highly automated local heating systems using heat pumps and other highly productive electro-technologies. Boilers and steam systems often have surprisingly poor system efficiencies, and high maintenance burden.

2 Scope of work and process for developing the report

This report was prepared using the approach set out below.

Scope of work and methodology

1. Examine international best practice and work done to date in Australia on high temperature (HT) heat pumps through web research and direct contacts.
2. Develop a stakeholder group of parties interested in HT heat pump technology applications including equipment suppliers, researchers, potential end-users, and government. We also invited our 65-person 2xEP Innovation working group to provide input. We interviewed a range of key stakeholders to understand the current market and some of the key technology options and barriers (see Appendix A: Heat pump stakeholder contributors).
3. Define ideal applications of industrial heat pumps in Australian food processing, taking into account Australian conditions such as: the small scale of the market and the fact that most companies make a variety of products in short product runs; the competitive situation, profitability and investment plans of local businesses; energy prices and trends – and the impact of rapidly escalating gas and grid electricity prices, falling on-site government energy and carbon policies, declining costs of renewable electricity, climatic conditions (and range of conditions in NSW and Victoria by season); and, other factors identified in the course of the work.
4. Select the most promising applications and conduct pre-feasibility analyses including first cut costs and benefits. It proved difficult within the time period to develop real life case examples, and there are so few in the market this was challenging and we had to try to get case examples from linking companies with sites.
5. Extrapolate the findings from 3. and 4. to define the larger scale opportunities and challenges for HT heat pumps in the food processing industry. Define potential gas displacement potential and greenhouse gas savings potential.

Deliverables

1. Draft report covering the defined scope, distributed to stakeholders for comment.
2. Workshop conducted by phone, inviting the key stakeholders to discuss the draft.
3. Final report, delivered to funders and stakeholders and posted on the A2EP website.
4. Four fact sheets - one page case summaries of 3 Australian case studies and a 1 page overview fact sheet on high temperature heat pumps for the food industry.

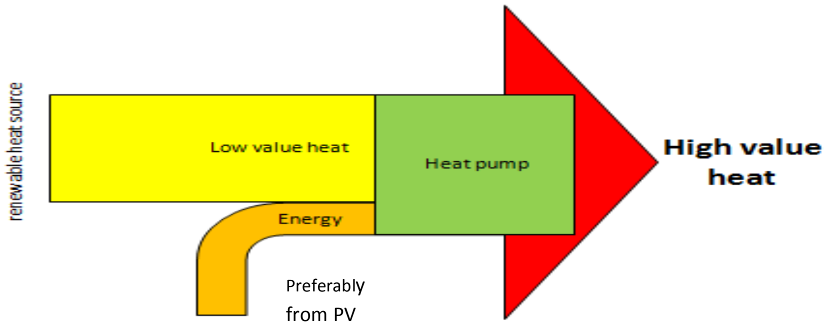
3 High temperature heat pump technology and overview of applications

3.1 Technology overview

3.1.1 Basics

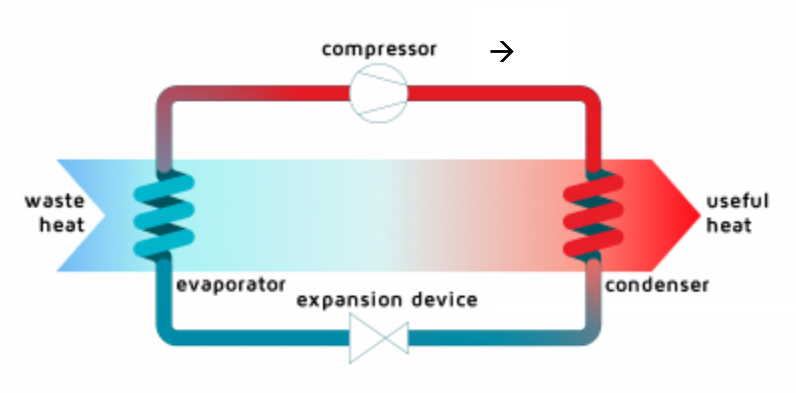
Industrial heat pumps use a refrigeration cycle to very efficiently transfer heat from the environment to waste heat streams. Heat pump technology (driven by electricity) can displace gas and upgrade heat (both sensible and latent) from waste streams such as waste water, hot humid air (e.g. from dryers) and condenser heat from refrigeration systems, for utilisation in a range of applications like blanchers, dryers and pasteurisers, as depicted in Figure 1 and 2 below.

Figure 1 – Heat pump leverage: Most input from lower grade heat streams or renewable sources



Source: Pachai, A C 2013, *Applying a heat pump to an industrial cascade system*

Figure 2 – Heat pump components



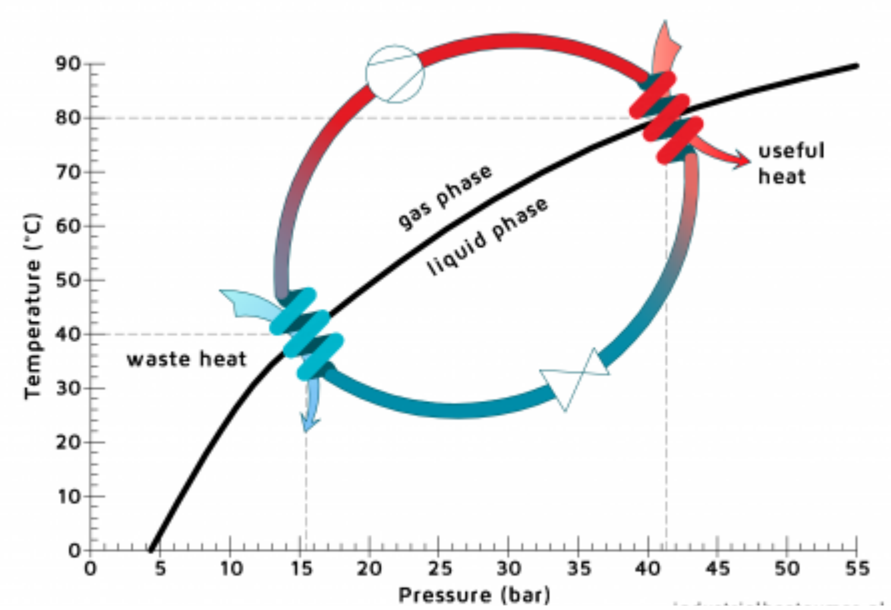
Source: De Kleijn 2017, www.industrialheatpumps.nl

Heat pumps can play a number of roles:

- Raise the temperature of a fluid.
- Simultaneously cool a fluid, which can also be used for dehumidifying.
- Recover waste heat from a stream, including latent heat from water vapour.

A low temperature waste heat flow can be upgraded to useful high temperature heat using a heat pump. The mechanical heat pump driven by an electric motor is the most widely used. Its operating principle is based on compression and expansion of a refrigerant. A heat pump has four main components: evaporator, compressor, condenser and expansion device. In the evaporator, heat is extracted from a waste heat source by evaporating the refrigerant at low pressure. The gas is compressed and its temperature increases (just like in a bicycle pump). In the condenser, this heat is delivered to the process at a higher temperature as the refrigerant condenses and releases its latent heat. Electric energy drives the compressor and this energy is added to the heat that is available in the condenser. The efficiency of the heat pump is denoted by its 'coefficient of performance' (COP), where a COP of 3 means three times as much heat energy is delivered as the amount of mechanical work input from the compressor.

Figure 3 – The thermodynamic cycle (using ammonia)



Source: De Kleijn 2017, www.industrialheatpumps.nl

In the figure above, the black line shows the relationship between pressure and boiling point of Ammonia. At low pressure and temperature Ammonia is evaporated in the evaporator, absorbing heat as the liquid is converted into gas – storing the latent heat of vaporisation. The energy needed for this is provided by a waste-heat stream. The compressor increases the pressure of the Ammonia vapour, increasing its temperature (like in a bike pump). The vapour is then condensed at high pressure and temperature inside the condenser, releasing its latent heat of vaporisation. During the condensation of Ammonia, heat is released at a higher temperature: a useful source of energy. The liquid Ammonia is transported to the expansion device that lowers pressure. The low temperature, low pressure Ammonia flows to the evaporator where it again absorbs heat energy as it evaporates.

3.1.2 Efficiency - Coefficient of performance

The efficiency of refrigeration systems and heat pumps is denoted by the coefficient of performance (COP). The COP is the ratio between energy usage of the compressor and the amount of useful cooling at the evaporator (for a refrigeration installation) or useful heat extracted from the condenser (for a heat pump). Most of the electric energy needed to drive the compressor is released to the refrigerant as heat, so more heat is available at the condenser than is extracted at the evaporator of the heat pump. For a heat pump a COP value of 4 means that the addition of 1 kW of electric energy is used to achieve a release of 4 kW of heat at the condenser. At the evaporator side 3.0-3.5 kW of heat is extracted and additional heat from the electricity input to run the motor/compressor is added, so that a total of 4 units of heat is delivered when only 1 unit of electricity (or mechanical energy) is used.

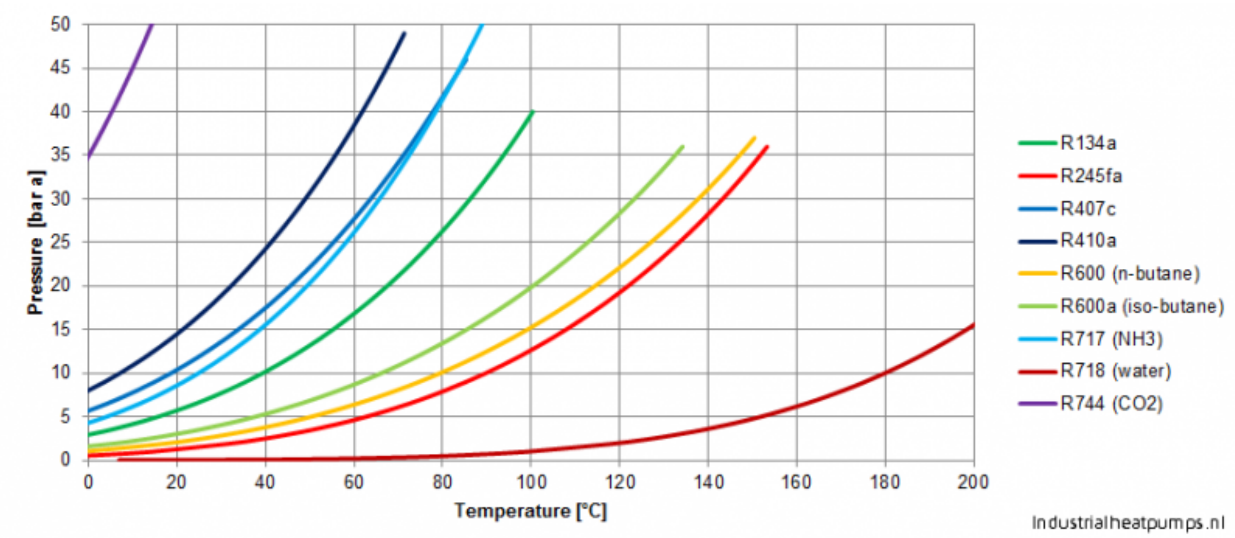
For more information on COP see Appendix C: Coefficient of performance background Information.

3.1.3 Refrigerants

A variety of refrigerants are available for usage in mechanical heat pumps. Improved refrigerants are being developed over time. Even water can act as a refrigerant if the pressures and temperatures are managed appropriately: in fact, because it has a very high latent heat of evaporation it can be very effective. Depending on their characteristics, different refrigerants are suitable for different temperature ranges, and have different efficiencies. Selection is based on several criteria:

Pressure: At a given temperature the condensation pressure is different for different refrigerants.

Figure 4 – Refrigerant characteristics: temperature versus pressure



Source: De Kleijn 2017, www.industrialheatpumps.nl

Critical temperature: Above a certain temperature a refrigerant reaches its supercritical area. Within the supercritical range the fluid and gaseous phase of the refrigerant can no longer be distinguished.

Energy efficiency: The efficiency of a heat pump depends on the choice of refrigerant.

Natural versus synthetic refrigerants: Most synthetic refrigerants (mostly HFCs, as CFCs, which also damaged the ozone layer, have been phased out) contribute strongly to the greenhouse effect. This impact can be 3,000 times higher than CO_2. Natural refrigerants with very low climate impact are available, and these may work more efficiently than the refrigerants they replace. Synthetic refrigerants with lower climate impacts are also being developed. Since different refrigerants have differing heat transfer capacity and latent heat, changing refrigerants may affect the overall heating or cooling capacity of a system. This may lead to a need to replace equipment, or to implement energy saving measures that reduce the amount of heating or cooling required.

Other selection factors include investment costs, required size of the installation and safety and permits. For more information on natural refrigerants see Appendix D: High temperature heat pumps with natural refrigerants.

Figure 5 – Characteristics of a selection of refrigerants

Refrigerant	Pressure at 15 °C [bar a]	Pressure at 70 °C [bar a]	Pressure ratio [bar a / bar a]	Heat of evaporation at 70 °C [kJ/kg]	Density at 15 °C [kg/m3]
R134a	4,9	21,2	4,3	124	23,8
R407c	7,5	35,0	4,7	107	31,9
R600 (n-butaan)	1,8	8,1	4,5	307	4,5
R600a (isobutaan	2,6	10,9	4,2	269	6,8
R717 (NH3)	7,3	33,1	4,5	939	5,7
R410A*	12,5	47,7	3,8	45	48,0
R744 (CO2)	50,9	Critical temperature is 31 °C			160,7

* Critical temperature R410A is 71 °C

Source: De Kleijn 2017, www.industrialheatpumps.nl

3.1.4 Developments in heat pump technology

Heat pump technology has rapidly developed in the last decade, particularly HT heat pumps to deliver temperatures of over 80°C (and up to 140-150C° for cascaded or multi-stage heat pumps). Because heat pumps are more efficient when operating across a smaller temperature difference (about 2-4 percent per degree reduction), systems that use multiple heat pumps in series (cascading or multi-stage) can achieve large efficiency improvements, so they can operate across larger overall temperature differences at high efficiencies, although they are more complex and expensive. These developments have greatly extended the range of applications. HT industrial heat pump technology development in Japan has focused on:

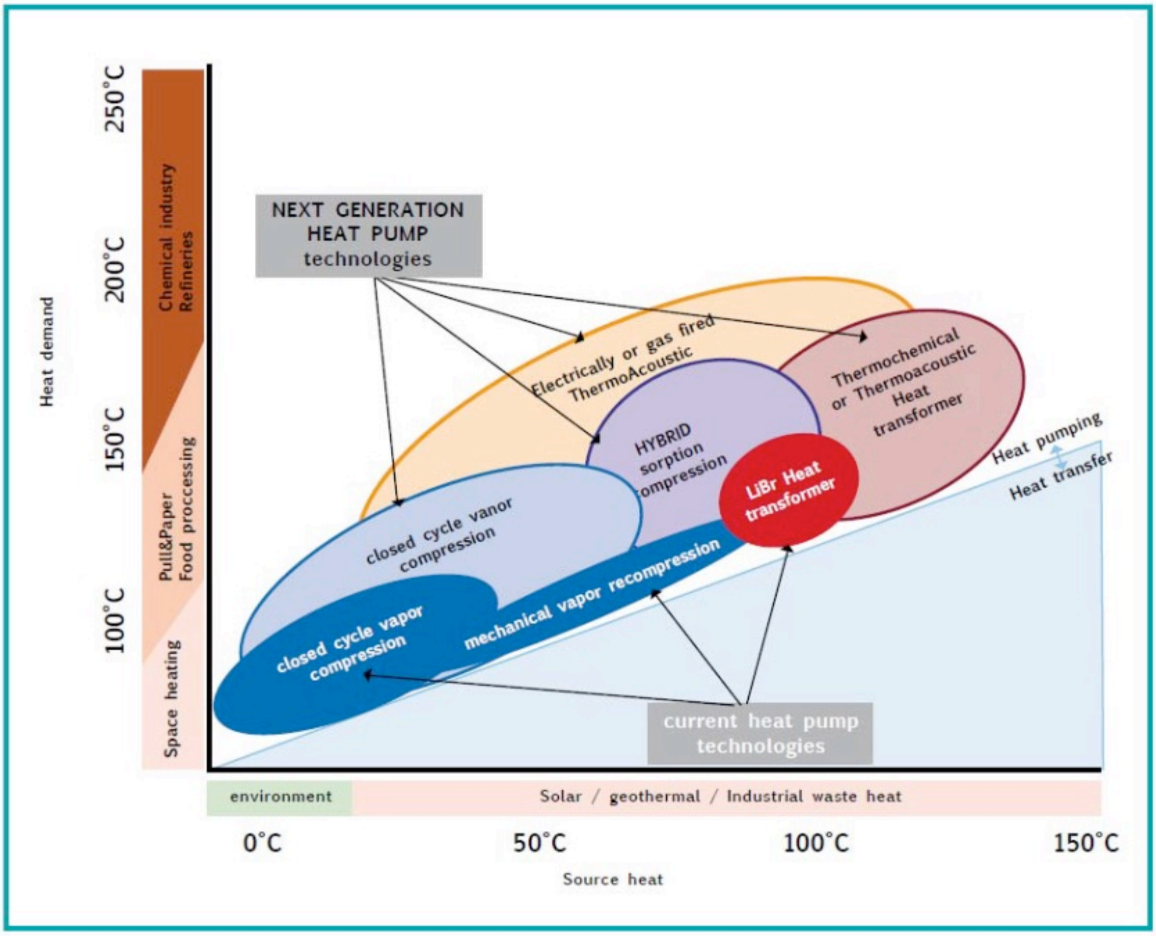
- Hot water and hot air supply, using CO_2 refrigerant. These packaged 'Eco-Cute' heat pumps can produce hot water at up to 90 °C with a heating capacity of up to 72kW, and have been commercialized in Japan and sold globally.

- CO_2 heat pumps, capable of generating hot air to 100 °C with a heating capacity of 110 kW, have been also commercialized in Japan.
- Heating and cooling of circulating water and steam generation using 'Reverse Rankine' cycle.
- The Japanese have also reported on development of industrial heat pumps that can provide steam at 120 to 165°C using cascading or multi-stage approaches.

Improving technologies and economies of scale of production of packaged units are making heat pumps more competitive, supported by declining costs of renewable electricity (and energy storage) and increasing costs of natural gas.

Some examples of the use of these technologies are provided on the following pages.

Figure 6 – Heat pump developments



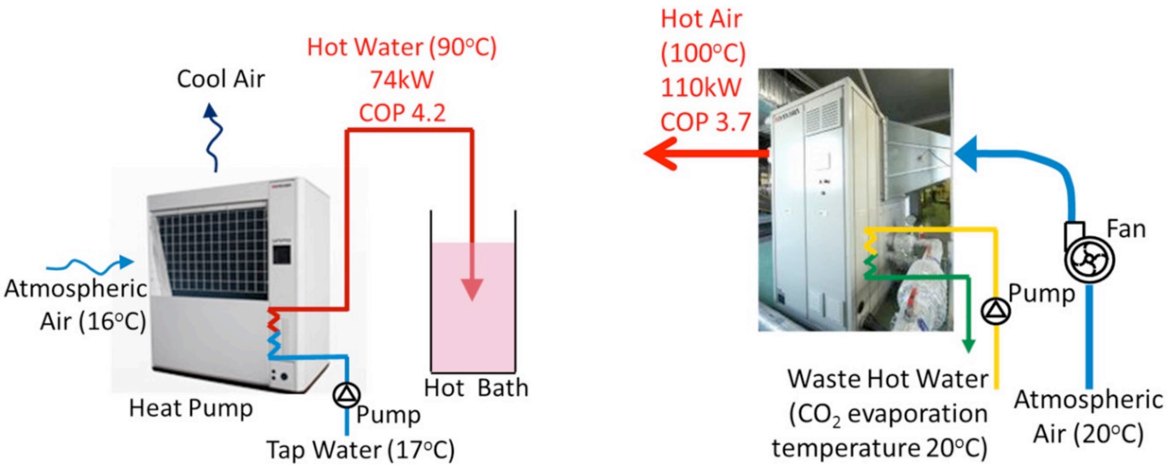
Source: IEA HPP Annex 35 2013, Application of Industrial Heat Pumps, Task 3

3.1.5 Examples of new technology applications

Packaged CO_2 heat pumps

Figure 7 (left) shows a typical arrangement and energy flows of a CO_2 refrigerant air-source heat pump (with reciprocating screw compressor) supplying hot water, delivering hot water at a temperature of 90°C, and with a heating capacity of 74kW and COP of 4.2. Figure 7 (right) shows the typical arrangement and energy flows of a CO_2 refrigerant water source heat pump when used for the supply of hot air, which can generate hot air at a temperature of 100°C, with a heating capacity of 110 kW and COP 3.7.

Figure 7 – CO_2 heat pumps for heating water and air (Mayekawa)



Source: IEA HPT Annex 35 2014, Application of Industrial Heat Pumps, Pioneering Industrial Heat pump Technology in Japan

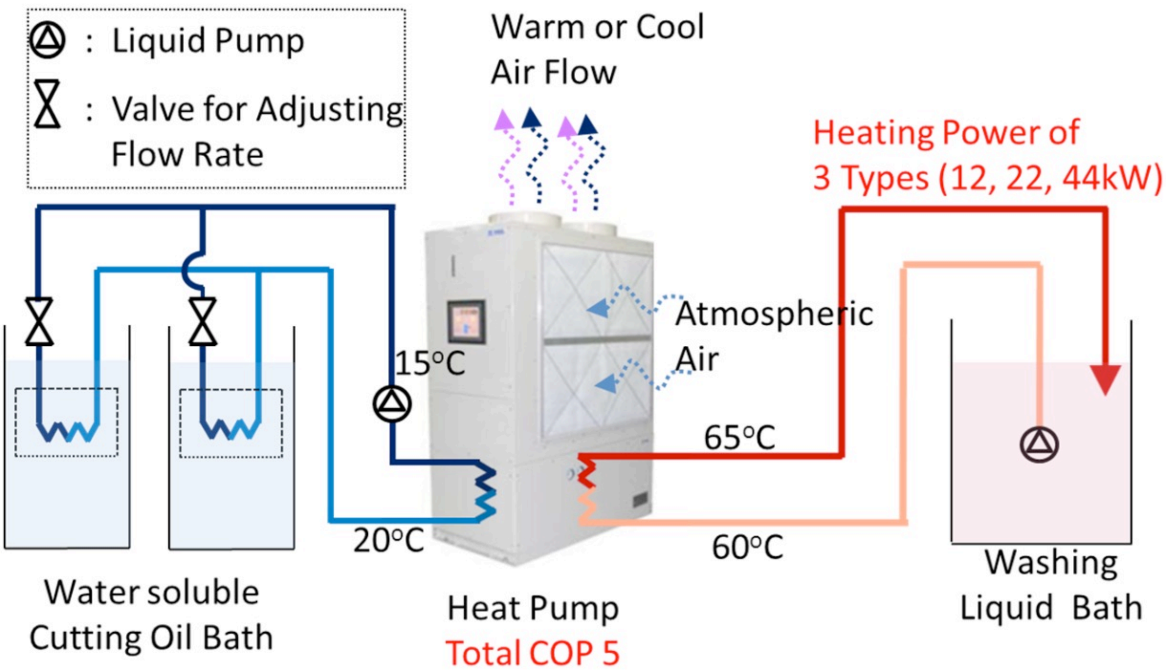
Heating circulating hot water

In many industrial processes, hot water after being cooled by 5 to 10°C is reheated and circulated. The reverse Rankine cycle is well suited used for heating circulating hot water at 60 to 80°C, and delivers a high COP.

Figure 8 shows a schematic of a typical application of the reverse Rankine cycle air- or water-source heat pump with HFC-134a refrigerant. While cooling water-soluble cutting oil, this heat pump heats the liquid, which washes the machined parts, thus providing simultaneous cooling and heating. Three operating modes - heating mode, cooling mode and heating and cooling mode - are available, using the heat exchanger between the air and refrigerant in either direction of heat flow, as required. The total COP in heating and cooling mode reaches 5.

As an example of the effect achieved using these heat pumps, a reduction of 84% in primary energy consumption and 80% in CO_2 emissions compared with the conventional combination of cooling by chiller and heating by boiler steam, has been reported. At factories producing cars or auto parts, many heat pumps of this type are starting to be adopted.

Figure 8 – Typical application of reverse Rankine heat pump



Source: IEA HPT Annex 35 2014, Application of Industrial Heat Pumps, Pioneering Industrial Heat pump Technology in Japan

Cascading/multi-stage heat pumps for steam generation

Cascaded or multi-stage heat pumps and other options to achieve larger temperature increases while maintaining efficiency are being developed in Japan (see 9). By using heat pumps in series, the temperature difference across each unit is reduced: efficiency improves by 2-4% for each degree reduction in the temperature difference, so large efficiency gains can be achieved, although equipment cost is increased. Alternatively, larger temperature increases can be achieved at similar efficiency.

Figure 9 – Cascaded or multi-stage heat pumps (KOBELCO: SGH series)

Source: IEA HPP Annex 35 2013, Application of Industrial Heat Pumps, Task 3

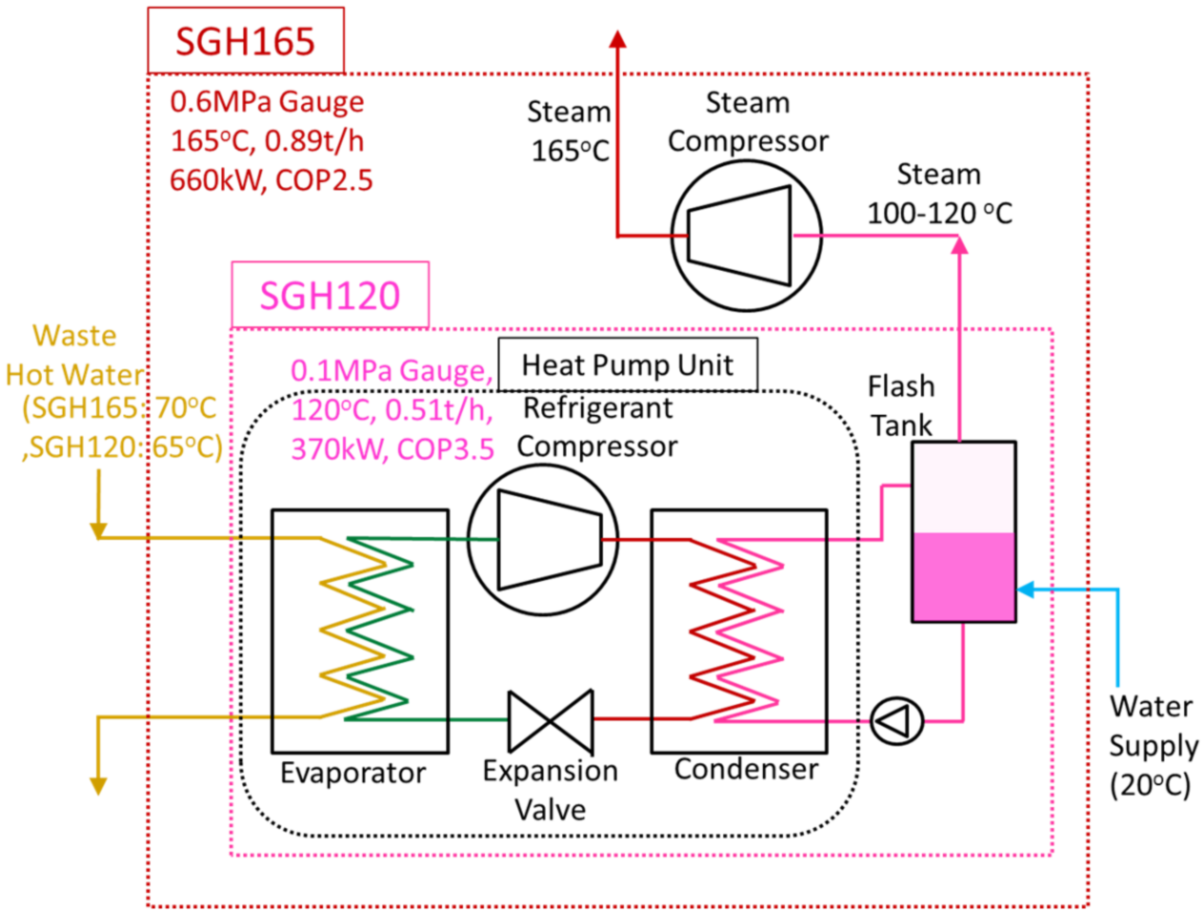
Example of steam generation using heat pumps

Since an HFC-245fa refrigerant has a critical temperature exceeding 150°C, a single-stage compression or two-stage compression heat pump can be used for re-heating circulating hot water at a temperature exceeding 80°C, or steam generation at a temperature exceeding 100°C. The dual cycle, which consists of an HFC- 245fa cycle for the high-temperature side, and another refrigerant (HFC- 134a or HFC-410A) for the low-temperature side, is also efficient.

Figure 10 shows a schematic diagram of two models of a steam-generating heat pump. The SGH 120 version generates steam initially by heating pressurised water and evaporating it in a flash tank after leaving the heat pump unit. This model generates steam at 120°C, with a flow rate of 0.51 t/h and a COP of 3.5 from a waste hot water input temperature of 65°C.

The SGH165 model generates steam at 165°C. After the heat pump unit generates steam, the steam compressor increases the steam pressure and temperature still further. The flow rate of the steam is 0.89 t/h and the COP reaches 2.5 from a waste hot water temperature of 70°C. The SGH120 model has a single stage compressor with a flash tank, and the SGH165 model has adds a steam compressor. HFC- 245fa is selected as the refrigerant of the SGH120 model, and a mixture of HFC-245fa and HFC-134a is selected as the refrigerant of the SGH165 model, considering the capacity per unit refrigerant flow.

Figure 10 – Steam generation pump: a mixture of HFC245fa and HFC134a refrigerant (Kobe Steel)



Source: IEA HPP Annex 35 2013, Application of Industrial Heat Pumps, Task 3

4 Heat pump applications for Australian food processing

Typical heat pump applications are summarised in the table below:

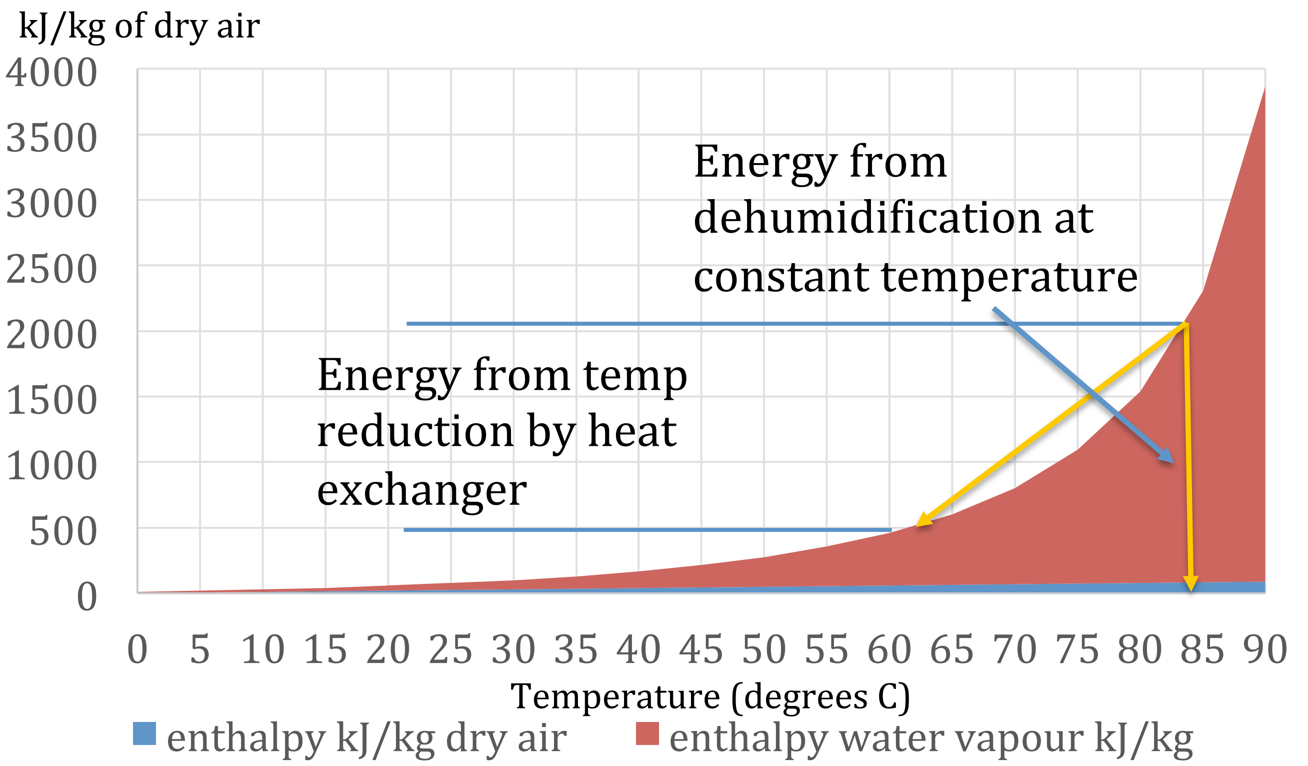
Application type	Features	Typical Industries
Dryers	Capture sensible and latent heat from exhaust streams	Milk, pasta, noodles…
Food washing	Capture sensible and latent heat (water vapour) from exhaust streams	Potatoes, vegetables, fruit
Water heating for process and cleaning	Capture waste heat from process or refrigeration (or air) compressors	All food
Pasteurisation	Can be heating and/or cooling role	Milk, juices, …..
Combined process heating and cooling	Ideal applications use the condenser for heating and evaporator for cooling simultaneously	An example is bread - product cooling and proving

Drying

Food dryers generally use air heated with steam, gas or hot water. Warm air picks up moisture from the wet product, and generally this humid warm air is exhausted and wasted. Conventional heat exchangers can only capture a proportion of this waste heat. A heat pump can extract heat from the humid air - both sensible heat and latent heat by condensing the water vapour. The now dry cool air is heated by the heat pump for reuse in the dryer. (Note that the latent heat accounts for most of the available energy in the humid warm air streams).

The figure below shows the latent and sensible heat content of saturated air, and how a heat pump can recover it. As noted elsewhere, the heat pump can also upgrade the temperature of the heat it recovers.

Figure 11 –Energy content of air and water vapour in saturated air (kJ/kg of dry air)



Source: Pears A 2017, *Identifying Heat Recovery Opportunities*, Plant Energy Efficiency Conference, 22-23 May, Hilton Melbourne South Wharf

Heating process water with waste heat from a refrigeration system

Waste heat from a refrigeration system typically has a temperature of 25 to 30°C. With the use of an add-on heat pump, waste heat from the condensing side of the refrigeration system is used to heat water to temperatures up to 80°C, at COPs of 4 or higher.

Pasteurization

The pasteurisation process requires products to be heated above 70°C, and then cooled. Heat exchange (regeneration) between cold and hot product flows is already implemented, but is limited by heat exchanger efficiencies and equipment design. Extra heating to bring the product to pasteurisation temperature is typically provided by steam, and product cooling after heat exchange is provided by externally sourced chilled water. A heat pump can extract heat from the product to be cooled (displacing cooling from chilled water) and supply this heat at a higher temperature to product to reach pasteurization temperature (displacing steam). This is an example of a heat pump simultaneously heating and cooling a process. In these cases, the effective COP can be particularly high, but this benefit needs to be balanced with scheduling challenges.

Water heating for process and plant cleaning (including cleaning in place – CIP systems)

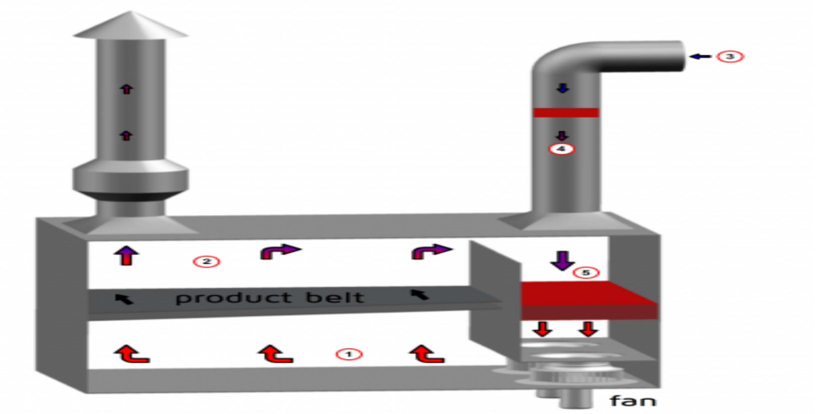
Water is needed at elevated temperatures – typically 65°C + for cleaning process plant, including using cleaning in place (CIP systems), as well as for process needs at temperatures up to 80°C +. Heat pumps are well suited to this duty. The Japanese 'EcoCute' heat pumps that use CO_2 as refrigerant are well suited to providing heat at these temperatures with a high COP.

4.1 Drying processes

The most common dryer type is one in which air is heated with steam, gas or hot water and then circulated over the wet product. As the air picks up moisture from the wet product, its humidity increases and the energy contained in the warm vapour stream may make it a useful heat source. Indeed, since evaporation consumes over 2.3 MJ/litre, there is usually a large amount of potentially useful energy available from condensing the water vapour (see Figure 11 which shows the energy content of saturated air). Normally this humid air is exhausted. With a heat pump, heat can be extracted from the humid air. The air is cooled down and dehumidified in the evaporator. The extracted heat can be upgraded in temperature by the heat pump and used to heat the dryer. So, the heat pump serves two purposes - heat the dryer and dehumidify and recirculate air, delivering high energy efficiency.

The figure below shows a typical traditional dryer. Hot air (1) at 70°C, is circulated over a product belt inside the dryer. The hot air is used to evaporate water from the product, and the temperature of the air decreases and its humidity increases. The cool, humid air (2) is then partly exhausted, however, the main part of the air is recirculated in the dryer. To compensate for exhausted humid air, fresh dry outside air is brought into the cycle (3) and preheated (4). After preheating this air is mixed with the recirculated humid air and the mixture (5) is then heated to the required process temperature.

Figure 12 – Conventional drying process



Source: De Kleijn 2017, www.industrialheatpumps.nl

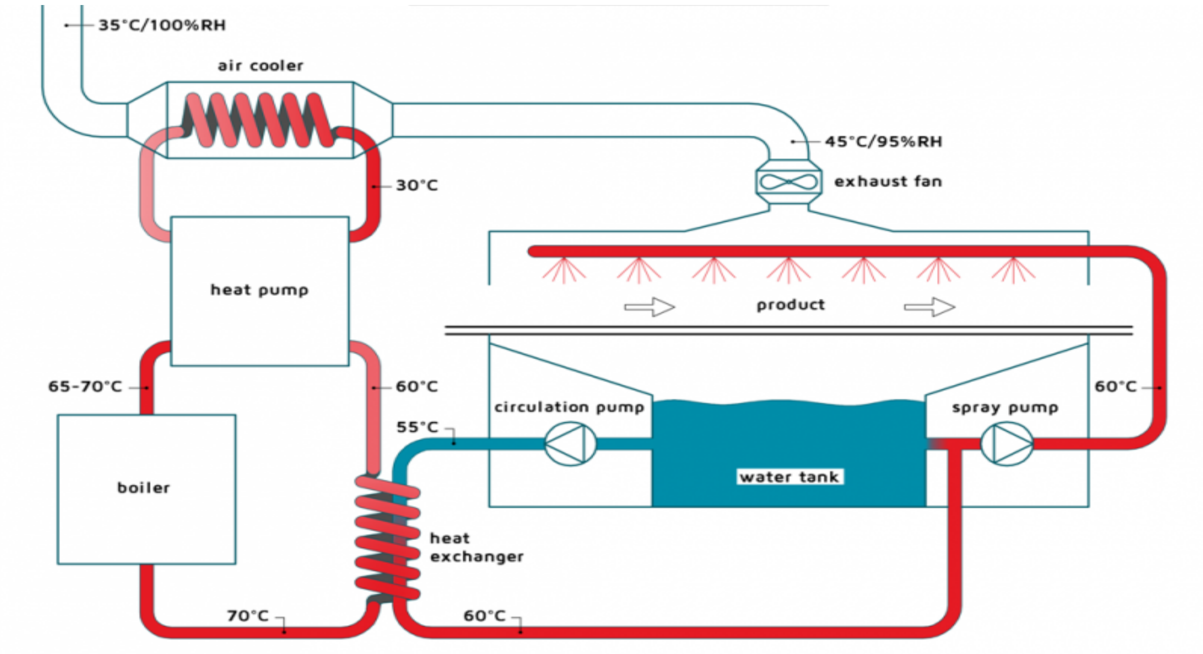
The exhausted humid air contains a lot of energy. The temperature level of this air is low and direct reuse inside the dryer is therefore not possible. Application of a heat pump gives the possibility for waste heat recovery. With a heat pump the extracted latent heat from the exhaust air is upgraded to a higher temperature level and reused to heat the dryer.

This approach is now used in domestic heat pump clothes dryers, which now achieve energy savings of 60 to 75% relative to traditional resistive heating dryers. These dryers do not need venting, although the condensed water must be removed or pumped away.

4.2 Washing processes

Washing of food normally involves spraying hot water, sometimes mixed with a solvent, over the product. A conventional washing machine is show below. The washing water is pumped through a heat exchanger and is heated by a gas-fired boiler. The washing water is pressurized with a spray fan and sprayed over the product. Some washing water will evaporate in the air, but most flows back to the water tank. The washing installation is often equipped with an air discharge fan to prevent the installation from vapour flowing out through the openings in the washing machine. The air discharge blows humid hot air to the atmosphere and maintains a negative pressure inside the washing machine. The discharge air contains a large amount of energy.

Figure 13 – Industrial washing machine with heat pump



Source: De Kleijn 2017, www.industrialheatpumps.nl

Using a heat pump, it is possible to reuse the heat from the discharge air to heat the washing water. A washing machine with heat pump is shown above. The evaporator (cold side) of the heat pump is placed inside the air discharge duct. In the evaporator, humid air is cooled down below the dew point. The temperature level of this waste heat is increased by the heat pump. In the condenser, this heat is used to heat the central heating circuit of the washing machine. It will still be necessary to use some steam (or heat from another external source) to heat washing machines of traditional design. But a highly insulated unit should, in principle, not need additional external heat, as the heat from the electricity input driving the motor could offset modest heat losses. It is also possible to directly heat the washing water with the condenser. However, when a washing machine has more than one washing section, it is easier to heat the central heating circuit.

To achieve a high efficiency, it is important that the discharge air has a high relative humidity. This can be attained by controlling the amount of discharge air based on the relative humidity or the pressure inside the washing machine. This means that, without a heat pump to capture that latent heat, efficiency is low.

The heat demand of the washing installation depends on:

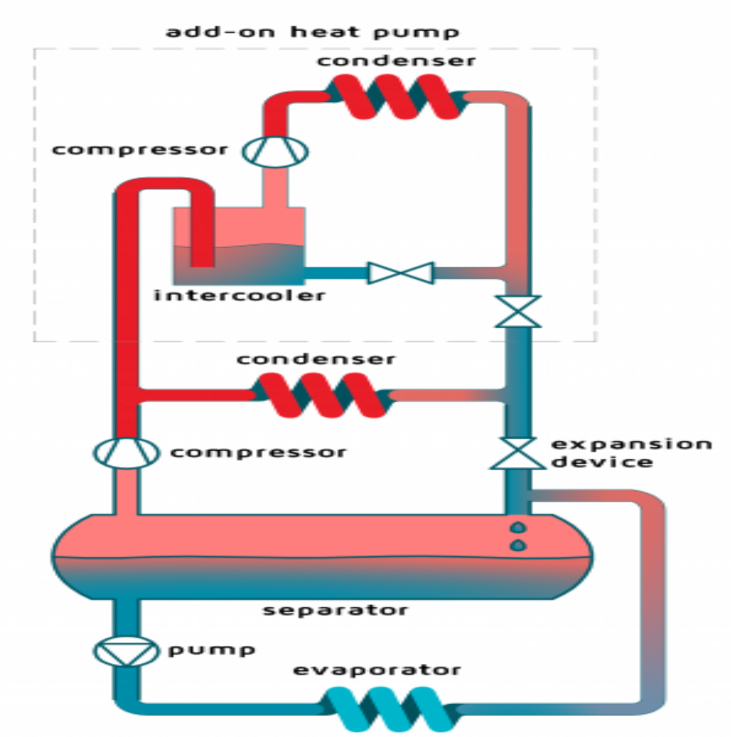
- In-outgoing temperature of the product.
- Amount of vapour that is evaporated and discharged.
- Heat losses through surface of washing machine.

Based on the size of each of these heat flows, it is possible to determine if the complete washing machine can be heated with a heat pump.

4.3 Heating process water using an add on heat pump to a refrigeration system

Typically, the food industry needs to cool/freeze products before transport. Hot water is needed for the process and for cleaning purposes. Waste heat from a refrigeration system typically has a temperature of 25 to 30°C. With the use of an add-on heat pump, waste heat from the condensing side of the refrigeration system is used to heat water to temperatures up to 80°C. The add-on heat pump will further increase the pressure of the refrigerant from the refrigeration system to achieve high condensation temperatures.

Figure 14 – Add-on heat pump



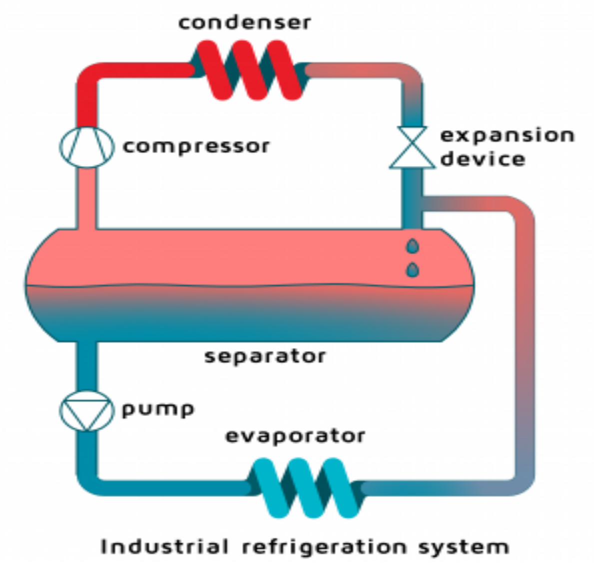
Source: De Kleijn 2017, www.industrialheatpumps.nl

The figure above shows an industrial refrigeration installation on which an add-on heat pump is installed. Two pipes connect the add-on heat pump to the refrigeration system. The compressor of the add-on heat pump is positioned in series with the compressor of the refrigeration system. The heat pump compressor will further increase the pressure of the compressed gases from the refrigeration system. A condensation temperature of 70°C results in cleaning water of 65-70°C. The pressure of the condensed refrigerant at the outlet of the condenser is reduced and it flows back to the refrigeration system.

The discharge gases of the refrigeration system condensate at a temperature of 25 to 30°C, however, due to compression they are superheated up to 60 to 100°C. The superheated gases are cooled down by an intercooler before they are further compressed by the heat pump. Cooling occurs by mixing liquid refrigerant from the condenser with the superheated gases. Because the gases are cooled, compression will be much more efficient. Moreover, discharge gas temperatures of the heat pump compressor are not too high. Too high temperatures may demolish compressor oil.

The capacity of the heat pump compressor is controlled by the heat demand of the cleaning water flowing through the condenser. The capacity and thus the amount of compressed gases flowing through the heat pump compressor varies due to this control system. The refrigeration condenser takes care of condensation of the remaining compressed gases. Only the required heat is processed by the add-on heat pump.

Figure 15 – Refrigeration system



Source: De Kleijn 2017, www.industrialheatpumps.nl

The figure above shows a typical type of refrigeration installation. The separation vessel contains fluid as well as gaseous refrigerant. The fluid refrigerant is circulated over evaporators with the use of a pump. The refrigerant temperature is lower than the process that needs to be cooled. Therefore, the refrigerant can extract heat out of the process at the evaporator. The heat causes the refrigerant to partially evaporate. The gas/liquid mixture is then led to the separation vessel. To maintain a constant pressure level inside the vessel, gas is extracted from the separator by the compressor. Due to the compression, both the pressure and the boiling point of the refrigerant are increased. Due to this higher boiling point compressed gases can release heat towards their environment. This heat release takes place inside the condenser of the refrigeration system. Because of the heat that is removed the refrigerant will condense (become liquid – [both gas or liquid can be called a fluid]). The pressure of the fluid refrigerant is then lowered and it is transported back to the separation vessel. Hence, yet another cycle can be started.

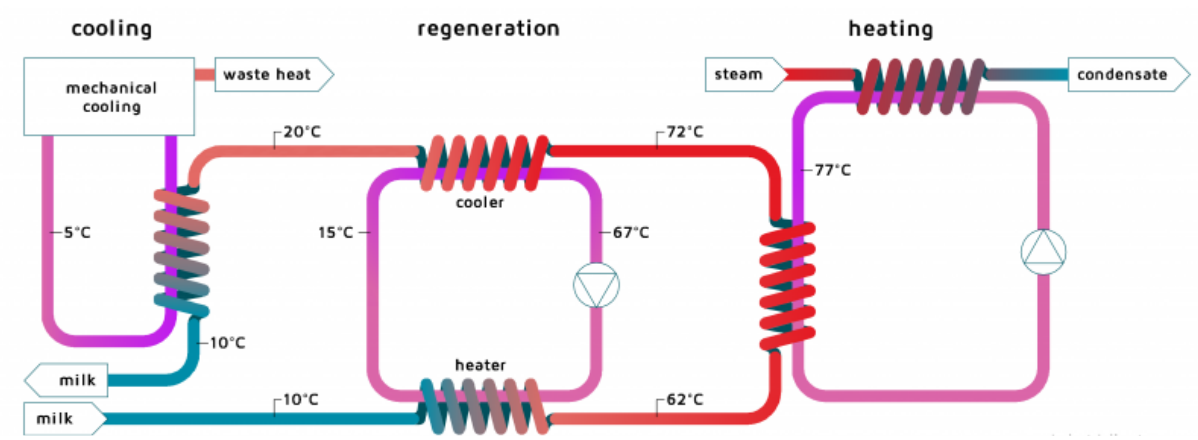
The amount of waste heat that is released at the condenser side is almost equal to the heat that is extracted from the product that needs to be cooled. The difference is additional energy due to electric energy used for the refrigeration compressor. In general, the waste heat extracted at the condenser side has a temperature that is too low to be useful. Application of an add-on heat pump gives the opportunity to efficiently upgrade the waste heat to a useful temperature level.

4.4 Pasteurisation

Product needs to be heated above 70°C for pasteurisation, after which is cooled. Most pasteurisers utilise heat exchange between the cold and hot product flows. The cold product before pasteurization is used to pre-cool the product directly after pasteurization, or looking at it the other way around: the hot product is used to pre-heat the cold product. In addition to this extra heating and cooling are needed for pasteurization. This is normally provided by, for example, steam injection and a flow of chilled water. In many systems, the efficiency of heat recovery is low. A heat pump can be the ideal solution to extract heat from the product that needs to be cooled and supply this heat at a higher temperature to the product that needs to reach pasteurization temperature.

The figure below shows a typical milk pasteuriser. Milk comes in at 10°C and is preheated to 62°C degrees with regenerative heat from milk being cooled after pasteurisation. The milk is then heated to 72°C with hot water, often produced from a steam heater. After this desired pasteurization temperature is reached, the milk needs to be cooled down back to 10°C. At first cooling is supplied by regeneration with fresh milk to 20°C. To reach the desired milk temperature of 10°C, a cold water circuit is used. This circuit is cooled with the use of a refrigeration system. The cooling circuit releases waste heat at its condenser site.

Figure 16 – Conventional pasteurization process

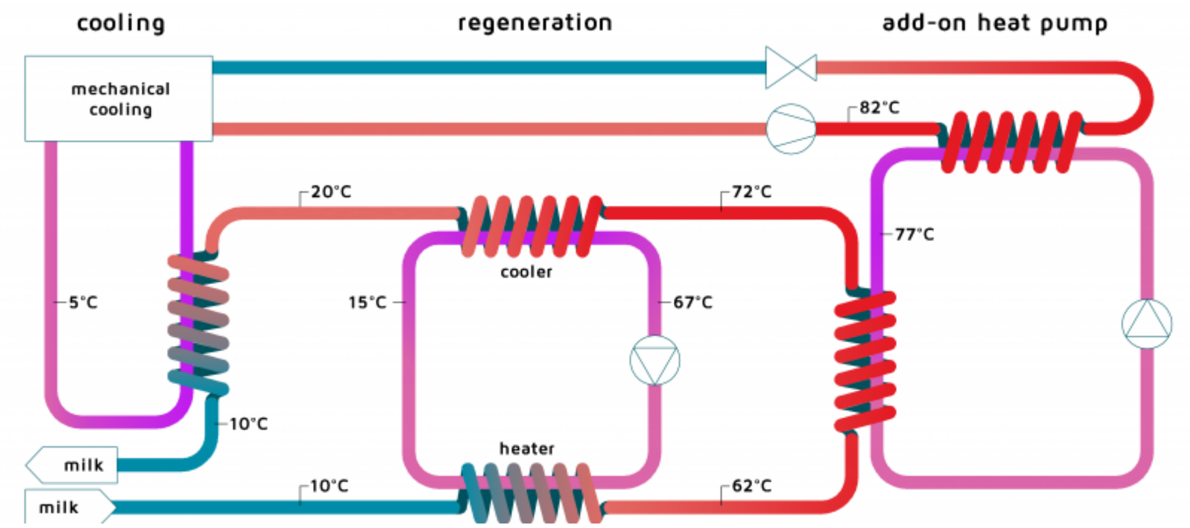


Source: De Kleijn 2017, www.industrialheatpumps.nl

Pasteurization with the use of an add-on heat pump

Application of a heat pump enables the opportunity to reuse the waste heat from the mechanical cooling system in the pasteurization process. The add-on heat pump replaces steam for the pasteurization process. Compressed gases from the refrigeration installation have a condensation temperature of 25 to 30°C. The heat pump compressor increases the pressure of the gaseous refrigerant further so the condensation temperature is over 80°C. Heating for pasteurization is thus supplied by the heat released at the condenser of the refrigeration system. After condensation of the refrigerant in the refrigeration system, its pressure is reduced inside an expansion element after which the refrigerant is sent back to the original cooling cycle.

Figure 17 –Pasteurization process with add-on heat pump



Source: De Kleijn 2017, www.industrialheatpumps.nl

5 Commercial feasibility factors and barriers to implementation

5.1 Commercial feasibility factors

Heat pumps can be used in many industrial processes to upgrade and thus recover waste heat from waste water streams, hot humid air, and condenser heat from refrigeration systems, for reuse in process or cleaning. Where waste heat flows have higher temperatures than potential uses, direct heat exchange is possible, and a heat pump is not justified. Where the users need heat at higher temperature than is available from a waste heat stream, then it could be feasible to use a heat pump. In complex industrial applications, a pinch analysis may be required to assess the suitability of waste heat integration. (See Appendix E: Pinch analysis, which provides additional information on this approach). For less complex applications, the method following will help evaluate the benefits:

Overall economics of heat pumps

The primary factors influencing the economics of heat pump use are:

- The **relative price of electricity and available fuels** (see next section for details), or more accurately the delivery cost of heat pump services compared to those from alternative forms of heating. The actual competition is not between the cost of natural gas and electricity, but the effective delivered cost of heat at the temperature required at the location it is needed. Where distributed heat pumps and other direct heating can displace a boiler and steam system, this can release large amounts of hidden savings, as these systems typically have large losses and so the effective cost of delivering heat to a process can be deceptively higher than expected after accounting for these losses. Note that natural gas boilers also have significant electricity consumption for ancillaries like fans and pumps, which is often forgotten.

  In country areas, gas transmission charges can be particularly high, or natural gas may not be available and then LPG or other expensive heat sources are used, which makes heat pumps more competitive. Note also that renewable electricity generation on-site can now be cheaper than grid electricity, and will become increasingly attractive over time.

- The **lift temperature** of the application (between the waste stream temperature and the process need). See Figure 20 for an indication of this effect.

- The **capital cost of the heat pump**, and the installation cost of the heat pump as a new project or retrofit. The capital cost will be impacted by the need for redundancy for plant reliability. One strategy to achieve at least partial redundancy without a cost penalty is to install multiple smaller standard units instead of one large heat pump. This can be more economical as use of modular, mass produced heat pumps may deliver unit capital savings, and reduced maintenance costs from use of standardised equipment and spares.

- Economics of heat pumps should factor in all business benefits, not just the value of energy savings – see section below for discussion of broader business benefits.

- Financing options: where a heat pump is perceived to have an unacceptably long payback period, it may still deliver a worthwhile internal rate of return. And, if finance can be accessed at an acceptable interest rate over a longer time period, the project may offer a positive cash flow using borrowed funds. And its impact on reducing overall businesss costs means that it can also increase business asset value as soon as the savings are visible.

Financiers are becoming more interested in financing energy productivity and on-site renewable energy projects as they improve their understanding of them. The Clean Energy Finance Corporation has played a major role in the change, and partners with financiers to offer attractive finance packages.

Heat pump costs should decline as economies of scale and standardisation are captured, designers and installers become more skilled and supply chains mature. Timing of installation to match equipment retirement, plant expansion, development of new plants, etc. can also help economics.

- The ability of the heat pump to **simultaneously deliver multiple functions** e.g. heating and cooling, or heating and dehumidification, can enhance economic benefits of HT heat pumps.
- **Operating hours** – retrofitting heat pumps is quite expensive, so a good return on investment is facilitated by high operating hours - ideally 3 shifts/7 days (i.e. 24/7 operation). Alternatively, availability of cheap electricity from solar PV and increasing peak demand charges may improve economics for operations with largely daytime operating hours, but the capital still must be repaid with less operating hours. Overnight and weekend off-peak tariffs can also improve economics.
- The amount of water vapour in a waste heat gas stream for drying applications.
- Process efficiency improvements implemented in parallel with installation of a heat pump that reduce the energy waste of the process. This may include upgrading insulation of process equipment, installation of variable speed drives, sensors, monitoring systems and controls to support smarter operation, optimisation of maintenance regimes, etc. Improving process efficiency reduces the size and capital cost of the heat pump, as well as the operating cost.
- Installation of renewable energy and/or energy storage systems (which can store thermal energy, not just electricity), establishment of contracts to purchase renewable energy, and contracts to manage demand and export electricity. These are often cost-effective individually, but can achieve synergies with heat pumps and other energy efficiency measures.
- The relative capital and operating costs of the heat pump against alternatives, as well as process and business benefits, discussed below.
- Also, as noted earlier, if a heat pump can provide both heating and cooling, its efficiency is very significantly improved: and thermal storage can help to match heat or cooling available to demand.

Understanding energy productivity benefits delivered by a heat pump application

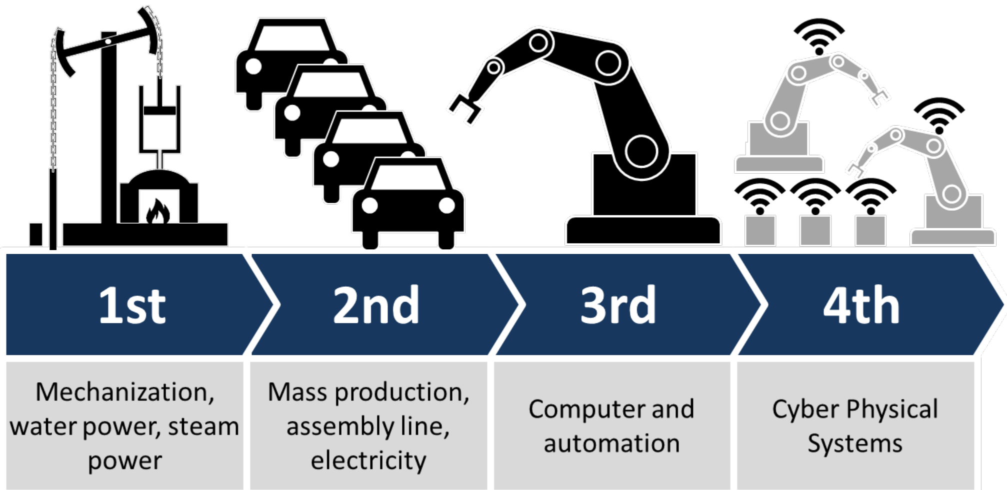
Heat pumps can often deliver value to the production process in addition to replacing a steam heating system. Another set of key economic determinants of success come from using heat pumps to generate increased business value. For many applications to be attractive and commercially sustainable, heat pumps will not only be required to effectively recover waste heat, but will also need to deliver some level of broader business benefit.

These benefits may include enabling:

- Improved plant reliability (partially dependent on redundancy)
- Reduced system maintenance (particularly where it displaced all or a significant part of steam reticulation system)
- Enhanced controllability leading to improved product quality
- Increased throughput
- Reduced water bills, where the heat pump condenses water that can be utilized on-site
- Reduced environmental management costs e.g. boiler blowdown and chemicals.
- Space savings compared to a boiler and steam system
- Improved working conditions – less noise and heat

This may be achieved directly through application of the technology or through enabling the partial AND ultimately complete replacement of central steam and hot water systems (Industry 1.0) with highly automated local heating systems using heat pumps and other highly productive electro-technologies with high levels of real time monitoring, smart control and optimization (industry 4.0). Combining installation of a heat pump with process efficiency and other measures, as noted earlier, can amplify the overall business benefits.

Figure 18 – Transition from Industry 1.0 to Industry 4.0



Source: https://en.wikipedia.org/wiki/File:Industry_4.0.png

Other capital and related maintenance benefits that should be taken into consideration in an evaluation of a heat pump project

There can be a case for installation of a heat pump to replace specific processes or parts of a steam system where losses are particularly high (for example, processes at the end of long steam pipe runs or poorly insulated pipes), or where times of use differ (for example, required for longer operating hours) from times when steam is needed for other processes and the steam system could be shut down if this process was converted from steam. Note also that where condensate return from processes to boilers involves long pipes, the use of point-of end use heat pumps to replace condensate return may be worthwhile. If the plant has limited steam capacity, for example, due to a need to increase production, there may be additional value generated by use of heat pumps in parts of a system, and other energy efficiency improvement strategies.

A heat pump can also avoid the cost of the infrastructure (and energy use of fans or pumps) to remove waste heat and humid air from a process. It can provide potentially useful water through condensing. It may reduce costs of meeting environmental standards (for example, odours or liquid wastes) by recirculating air or condensing water instead of exhausting it, and provide for improved dryer product quality from effectively converting the dryer to a closed process as make-up air is not required.

The impact of relative energy prices of electricity and fuels on direct energy cost savings

Figure 19 – Relative cost of electricity to gas in European countries

Country	Ratio
Austria	2.74803
Belgium	2.68827
Bulgaria	1.81882
Czech Republic	3.28846
Denmark	1.34661
Estonia	2.41489
Finland	1.62201
France	2.0554
Germany	2.21645
Hungary	2.69643
Ireland	2.13351
Italy	3.93987
Latvia	3.09091
Lithuania	2.89744
Luxembourg	1.49882
Netherlands	2.44648
Poland	2.56748
Portugal	2.21408
Romania	2.90667
Slovakia	3.14368
Slovenia	1.74831
Spain	2.78157
Sweden	1.43411
United Kingdom	3.62963

This table shows the relative cost of electricity to gas in European countries (2015). The lower the ratio, the better the competitive position for using heat pumps. The ratio in East coast Australia is currently 3.3-4, depending on the specific prices available. As can be seen this ratio is still higher than much of Europe, but substantially lower than it has been in the past.

Note that this table is just a guide to relative delivered energy costs, and does not account for steam system efficiencies, and in Australia this would typically be significantly worse than countries like Germany.

Figure 20 below is adapted from the US Department of Energy[1] to give an indication of the relative costs of heating liquids using boilers and heat pumps. As can be seen, the economics is heavily influenced by the amount that the temperature is to be increased between the original waste heat temperature and the temperature required by the ultimate process, that is, the lift. The higher the lift, the lower the COP and the worse the economic case for using a heat pump.

Typical new contract industrial electricity prices in the east coast of Australia in 2017/18 are 15-17.5c/kWh, after recent energy price escalation. **Note:** where a plant has installed PV their average electricity price can be lower, particularly if a larger proportion of plant operating hours are in day time and grid electricity contracts incorporate peak demand charges and time of use pricing.

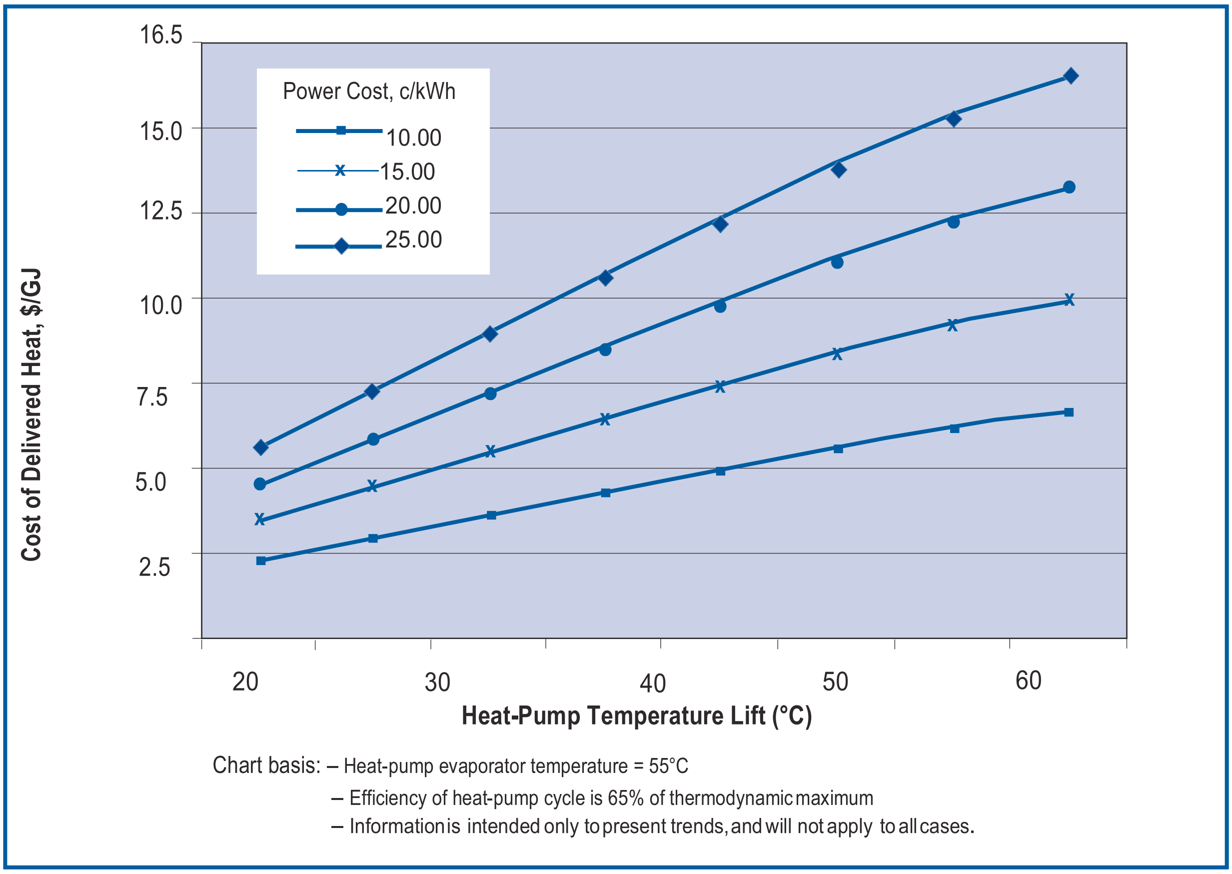
Typical industrial gas prices in east coast Australia in 2017/18 are $10-$12/GJ and often significantly more for some 2017 contracts, after doubling due to supply constraints brought on by high LNG exports from Gladstone.

Due to gas price escalation relative to power in the last two years and potential gas shortages, for a 40°C lift in the example in the diagram with a 16.5c/kWh power price, heat would be generated at say $7.75/GJ by a heat pump. This can be compared to an alternative gas boiler: at a gas cost of

[1] https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/heatpump.pdf

$12/GJ and even assuming a high 75% efficiency for delivery of heat from the boiler system to the application, this would result in a cost of heat delivered of over $16/GJ. Even if you required a 60°C lift and the heat pump COP was thus lower or a more expensive multi-stage or cascaded heat pump was needed to achieve high efficiency, the effective cost of heat delivered from the heat pump would be about $11/GJ, significantly cheaper than the delivered heat from the gas-based steam alternative.

Figure 20 – Heat pump temperature lift versus cost of delivered heat



Adapted from: US Department of Energy
https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/heatpump.pdf

The efficiency of the conversion and delivery of heat from gas (or other heat source) is also a very significant factor in the comparison. Many boiler systems run at under 50% efficiency, effectively more than doubling the cost of heat relative to the gas price.

Note: Be cautious about simplistic comparison of the ratio of gas to electricity cost as a determinant of likely project economics as this approach can lead to rejection of a potentially profitable application of heat pumps. Systems thinking that combines improvement of end-use efficiency to reduce the size of the heat pump required, or takes advantage of unique features of heat pumps can make a big difference to heat pump costs. Use of cascaded or multi-stage heat pumps and MVR could also work better than a single stage heat pump where bigger temperature lifts are required or where higher efficiency can be justified due to high costs of alternative heat sources.

Another way of looking at a very basic comparison for the operational costs to heat water:

Hot Water Requirement	Energy Source	Efficiency: Avg COP	Energy Consumption	Cost of Source	Cost of Hot Water Requirement	Heat Pump savings
1 KWh	Natural Gas Boiler	0.33-0.8 delivered	1 KWh / 0.8 = 1.25-3 KWh	$12/GJ = $0.0432/ KWh	1.25-3 kWh x $0.0432 / kWh = $ 0.054-0.13	
1 KWh	Water Cooled Heat Pump	6.0	1 KWh / 6.0 = 0.167 KWh	$0.15-$0.18 / KWh	0.167 kWh x $0.15-$0.18 / kWh = $0.025 - $0.03	44 - 75+% At COP 4, 17 - 50+%

CO_2 footprint reduction:

Hot Water Requirement	Energy Source	Efficiency: Avg COP	Energy Consumption	CO_2 Source Emissions*	Carbon Footprint	Heat Pump CO_2 footprint reduction
1 KWh	Natural Gas Boiler	0.9 diff from previous table	1 KWh / 0.9 = 1.11 KWh	185g CO_2 / KWh	1.11 KWh x 204g CO_2 / KWh = 226 g CO_2	
1 KWh	Water Cooled Heat Pump	6.0	1 KWh / 6.0 = 0.167 KWh	1090 g CO_2 / KWh – VIC 840g CO_2 / KWh – NSW & ACT 780 g CO_2 / KWh – QLD 530 g CO_2 / KWh – SA	0.167 KWh x 1090g CO_2 / KWh = 182 g CO_2 – VIC 0.167 KWh x 840g CO_2 / KWh = 140 g CO_2 – NSW & ACT 0.167 KWh x 780g CO_2 / KWh = 130 g CO_2 – QLD 0.167 KWh x 530g CO_2 / KWh = 89 g CO_2 – SA	-11% VIC -31% NSW & ACT -36% QLD -56% SA Greater where electricity is from renewables

Note: while official NGGI data suggests Tasmania have very low emission intensity, this is an average value. At the margin, the Basslink cable links Tasmania into the National Electricity Market. A change in consumption of a unit of electricity leads to a reduction (or increase) in production of a unit at the marginal greenhouse intensity of the NEM.

Note that across the NEM as the renewable power component grows (expecting 42% by 2030), the carbon savings from using heat pumps will grow. However, at fringe of grid, and at times of peak demand, higher power line losses increase the carbon intensity of electricity, especially where SWER lines are involved. If the plant used all renewable energy from solar (plus batteries) then the coefficient would be zero. Note also that if the COP is lower, then CO_2 savings are lower (except in the renewables cases).

The extra benefits that can accrue if you can completely replace centralised steam systems, using heat pumps and non-thermal process:

While heat pump systems are inherently efficient due to their ability to utilise atmospheric or waste heat (relative to a base temperature of minus 273C) and upgrade it with leverage using an electric motor, there is another compelling efficiency benefit where local distributed heating can be implemented which is suited to specific applications. Through this, centralised boiler and steam distribution systems (using natural gas/ other fossil fuels) can be displaced. Local application often means that waste heat can be recovered from a process, its temperature upgraded, and it can be reused in the same location. This can avoid distribution losses and facilitate more precise and flexible management.

Why transition from "Industry 1.0" (the steam age) to "Industry 4.0" (automation, high controllability, real time process monitoring and optimisation and high quality):

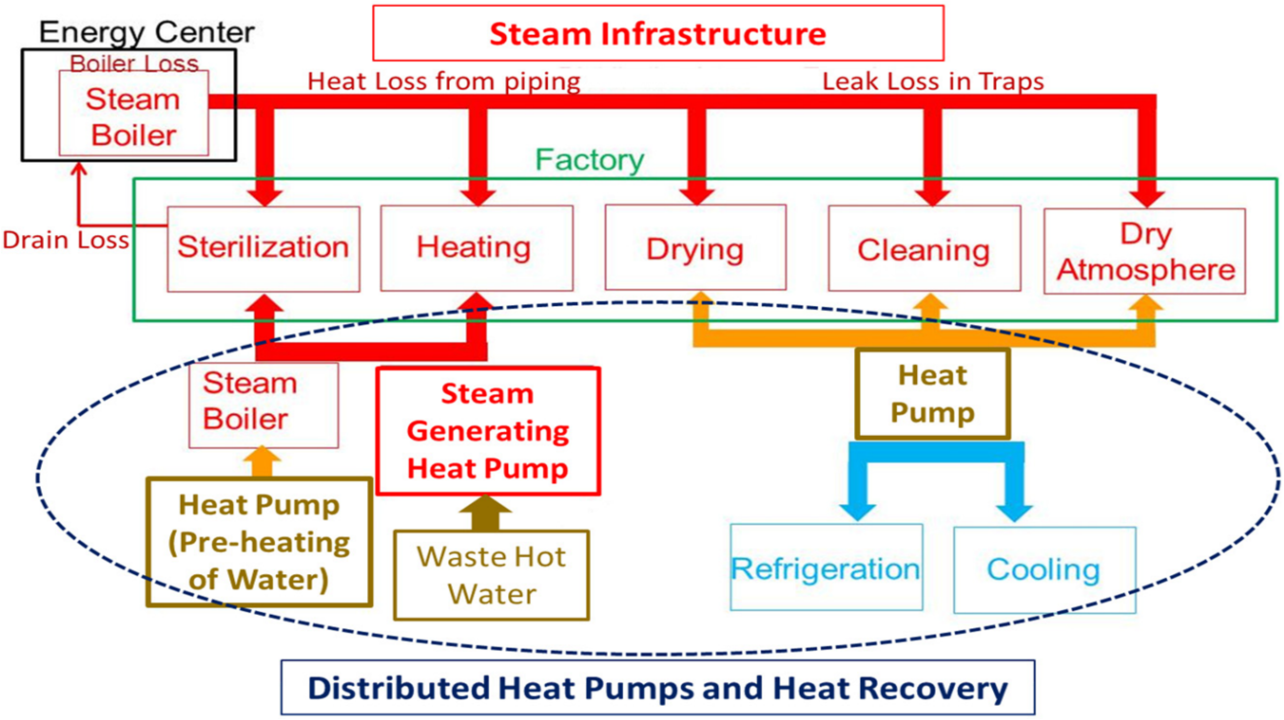
Steam systems are notoriously inefficient. They have excessive losses in most cases due to poor insulation of lines, failure to recover all available condensate, condensate heat losses, boiler blowdown losses, leaking steam traps and steam leaks. Boilers themselves typically have 15%+ losses in flue gases and radiation losses, unless they have installed condensing economisers and are kept in very good tuning with flue gas monitoring and control systems. They also suffer turndown and cycling losses at lower loads and respond slowly to changed operating conditions. Standby losses are also typically significant. So, few centralised boiler systems are much more than 60% efficient, and some barely achieve 25% efficiency overall, though this is seldom recognised due to lack of gas and steam monitoring and data.

Steam systems also have considerable maintenance costs and impacts on plant reliability. It is also not recognised often that there are substantial electricity costs associated with boiler fans, pumps, and other ancillaries.

Using electric heat pumps designed for specific heating/cooling loads, installed locally to these applications, means simplified operations can be achieved with very much higher overall system efficiencies.

Avoiding the need for steam in some applications, particularly remote from boilers, can mean that some steam pipes can be decommissioned, reducing pipe losses. And reducing the need for steam reduces energy wasted from providing heat at far higher temperatures than are often needed.

Figure 21 – Infrastructure in a factory using distributed heat pumps



This diagram shows how a series of local heat pumps (in the bottom half of the diagram) can be used to displace an entire boiler and steam system including all the traditional infrastructure (top quarter of the diagram) in a food processing plant. (Note that in this case the steam boiler pre-heated by the heat pump seems was a booster for the small load left to supply a legacy process still needing high temperature steam).

In the original case steam is produced in the boilers in the energy centre, and supplied to all areas of the factory for use in the manufacturing process. Overall energy efficiency is low, due to boiler losses, heat losses from piping, steam leakage losses in traps, and drain recovery losses.

Significant energy savings are achieved by replacing steam infrastructure and electric resistance heaters with distributed HT heat pumps for hot water/air supply, heating of circulating hot water and steam generation. Heat recovery and simultaneous cooling and heating using of waste heat using heat pumps is also utilized.

It may not be necessary to replace a whole steam system in one go to gain some benefits – for example by using a heat pump to replace a long steam and condensate pipe run (or a chilled water or glycol pipe to a remote part of a site), substantial reduction in losses may be achieved.

Potential benefits from using thermal storage with heat pump systems to deliver demand management

If heat generated with heat pumps or waste heat exhausted in plants can be stored in a heat storage material, the effective use and control of the heat is enabled. Daytime (peak time) and night time (off-peak time) power loads can be rebalanced or the storage can be used to support demand response, and waste heat may be further utilized. Thermal energy can be stored during daytime heat pump operation on solar, for use at night or when solar input is lower. At present, water or ice are normally used as thermal storage materials. However, thermal storage materials such as molten salt, organic material or hydrated salt can store heat over a wide temperature range from -10 to 250°C. Phase Change Materials (PCMs) are improving and declining in cost. They can reduce the storage volume needed, and deliver heat at a fairly stable temperature as they solidify.

Figure 22 –Heat pump without thermal storage tank

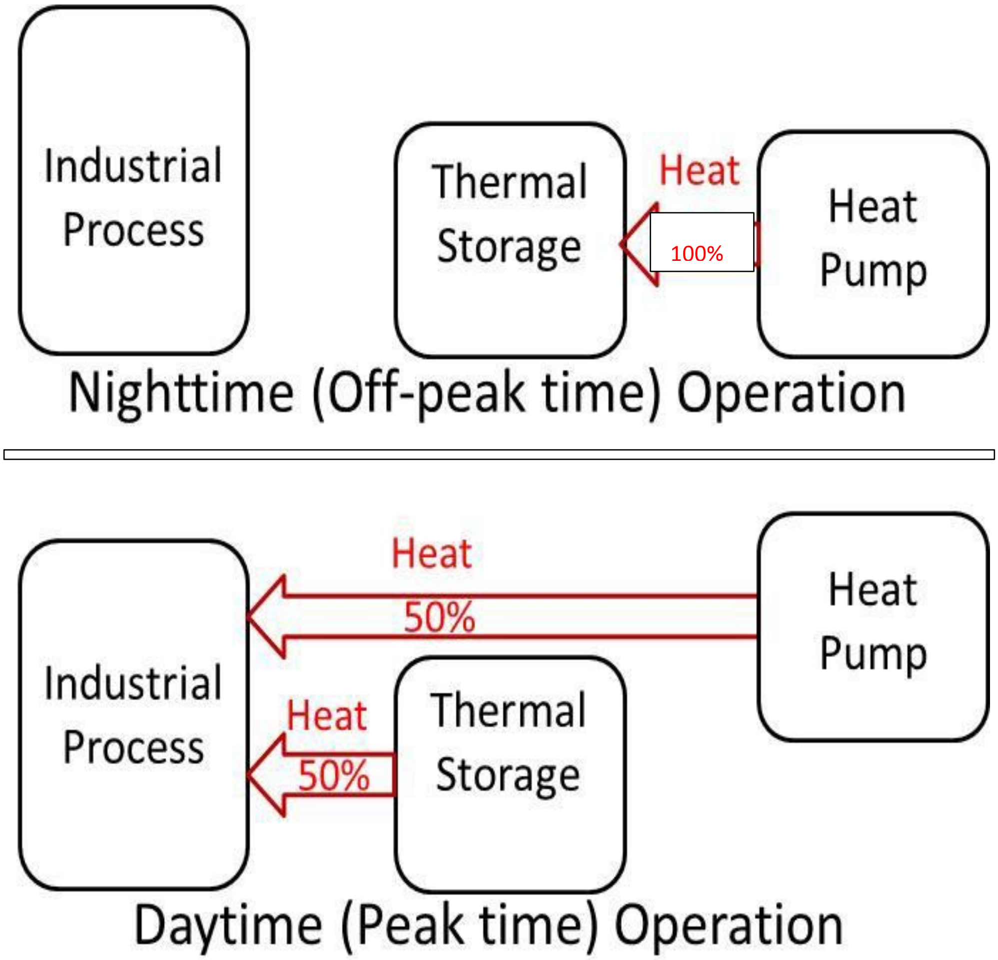


Figure 23 –Heat pump with thermal storage tank

Source: IEA HPP Annex 35 2013, Application of Industrial Heat Pumps, Task 3

Heat pumps and renewable energy

Heat pumps offer several advantages over solar thermal technologies. They can run on electricity from any source including the grid, so they can be integrated into the core production processes of a plant. They also 'feed off' low grade waste heat sources, reducing total energy inputs to processes. Heat pumps work consistently: clouds or cold winter weather have little impact on their performance.

Heat pumps can be modular, and benefit from economies of scale for production and installation. The skills required to maintain them are more widely available because the can use the refrigeration industry's labour force. By using two or more units in parallel, reliability can be improved, as loss of a single unit will only reduce output, not lead to a plant shutdown. Also, because heat pumps are more likely to be distributed around a plant, they can offer higher reliability than a central boiler. Many plants already have back-up generators, which can be used to keep heat pumps operating (and provide waste heat to improve their efficiency) at times of grid outages or limited supply during peak electricity demand.

Heat pumps can work with, and enhance the economics of renewable energy:

- Heat pumps can run on solar PV, wind, bioenergy generation, stored electricity or the grid, so they can be integrated into an on-site renewable energy system, or draw power from regional wind, hydro, pumped hydro or other electricity supply. Biofuels or solar thermal systems can be used to raise the input temperature to heat pumps, improving their efficiency, or (with biofuels) to 'top up' heat pump output to deliver higher temperatures.
- Low cost, mass produced, efficient solar thermal collector technologies can be used, instead of more complex and less efficient high temperature collectors, to produce low temperature heat that can be upgraded by heat pumps. Where solar thermal systems raise the temperature of waste heat from on-site sources, they improve the efficiency of a heat pump, so their contribution helps to increase the heat output from the heat pump. It is cheaper and easier to store low grade heat (at under 100°C) as an input for heat pumps than to store high temperature heat.

Capital cost of equipment

It is difficult to provide generic capital costs and economic analysis as heat pumps' specifications depend on the temperatures, and the installation costs can vary greatly, particularly retrofits, but the following provides some guide on order of magnitude costs. This discussion must be seen in a context of potential for significant price reductions through economies of scale, learning by installers and ongoing technology development. With experience, the perceived business value of the broad benefits of heat pumps, and perceptions of risk may change, niche markets may be identified, and development of tailored financing packages could underpin great adoption.

One important issue is the need for plant redundancy, which would be required if the original heating (and in some cases cooling) system was not retained for standby. If you were starting from scratch with a distributed heat pump system and no fossil fuel boiler system, you would need redundancy, lower cost backup or other options, but you would save the marginal cost between the distributed system and the substantial cost of installing a complete boiler and steam system with associated heat exchangers and piping infrastructure. Also, the use of multiple, smaller, standardised package heat pump units may provide a more economical solution than a large customised unit and also provide redundancy. Where both heating and cooling are needed, the COP of a heat pump significantly improves, so its economics can improve.

Mayekawa supplies a packaged CO_2 transcritical Eco-Cute hot water heat pump (up to 90°C water), with about 90kW heating capacity costs about $75,000 plus installation – so maybe $100,000-125,000 installed in a retrofit. There is one installed in a Tofu plant in Australia. Mayekawa also supplies R717 heat pumps capable of producing hot water up to 80°C in larger quantities. They also locally supply CO_2 trans-critical units that heat air to 120°C, also around the $75,000 mark plus installation. Johnson Controls supplies ammonia units in Australia. A large scale hot water unit installed supplying water at 70°C was $300,000.

Mitsubishi Heavy Industries offers a 30 kW CO_2 refrigerant heat pump hot water service with a COP of 3-4 for commercial and small industrial applications. These cost around $25,000, and are attractive replacements for LPG hot water services, as running cost is from 40 to 60% lower. They are not designed to utilise heat recovery or provide active cooling while heating.

The payback for some projects in Europe is around two years. In Australia, the best projects are likely to come in around 2+ years payback on energy cost savings alone, but as seen in the previous section we have a higher electricity to gas price ratio in Australia than many countries and we would expect paybacks here to typically be more like 4 years, with a lot of variability, and potential for improvement in future with cost reductions due to higher sales volumes. Note also that these paybacks do NOT include the impact of energy productivity enhancing value streams, nor do they account for additional efficiency benefits that accrue from replacement of poor efficiency steam systems (or part thereof). Development of financing schemes that could provide equipment with little or no upfront cost and a positive cashflow could increase adoption rates.

The Australian Renewable Energy Agency (ARENA) has released its new Investment Strategy, and energy productivity is one of the four key priorities. ARENA will be looking for good projects that show innovation in the context of Australia and an industry, and also where there is good replication potential. The initial applications of high temperature heat pumps for industry in Australia, particularly in new applications/industries for this country, potentially fit the bill and could be able to apply for grants of up to 50% of the installed capital cost of the project.

Some state governments are also providing funding through specific programs as well as broader application of their energy efficiency certificate schemes – though usually these schemes do not offer incentives for changing energy forms. Well-designed heat pump systems, especially those combined with process efficiency improvements, can deliver carbon emission reductions, the basis on which the size of incentives is calculated. We will need to test the ability to apply for funding for heat pump applications.

Maintenance requirements: High temperature heat pumps have tended to have greater maintenance requirements than lower temperature units as the higher temperatures require higher system pressures and thus put a higher stress on components. Inspections are required twice annually and recommended replacement periods for small packaged HP compressors are 30,000 hours (about 4 years if run 3 shifts, 7 days) at a cost for a small packaged compressor unit of about $25k. Ongoing evolution of remote real time monitoring and data analysis offer potential to reduce or facilitate improved coordination of routine maintenance visits.

5.2 Barriers to implementation

The following is a brief assessment of the key issues preventing the larger scale implementation of high temperature heat pumps in the food industry.

1. ***Lack of awareness and knowledge of how to achieve the most economically attractive applications:*** Based on interviews with stakeholders, most manufacturing businesses have very limited knowledge of high temperature heat pumps and potential applications. One large and sophisticated food producer held a phone workshop with key staff and a 2xEP researcher, and identified half a dozen very prospective opportunities in half an hour, none of which has been explored previously. The fact that gas and electricity prices have only reached a point where heat pumps have become economically attractive in the last year is a major reason for this lack of awareness.

   We also see evidence in the local market of simplistic assessments of heat pump applications where the total business value for implementing them is not understood and only the direct energy cost comparisons for the application are assessed.

2. ***Capital cost:*** Heat pump projects require capital investment. Australian manufacturers typically have short payback requirements and exhibit very low levels of capital investment in their facilities, and this acts against retrofitting heat pumps. Financial analysis also rarely incorporates the value of the potential multiple business benefits, as this requires more sophisticated analysis. The perception that a business is 'behind' until the payback period is reached is also a pervasive barrier to many energy productivity investments. In practice, these investments can increase asset value by a multiple of purchase cost so, if the business was sold, it would gain a higher price. An additional potential capital cost is the need for equipment redundancy in the ideal situation where the existing heating/cooling infrastructure is not going to be retained, for example, in the situation where a boiler and steam system are being replaced by distributed local heating. This is not an issue where the equipment selected for the application is multiple identical packaged heat pumps, and this is looking like the most economical option in many cases. Boilers also need redundancy but this capital cost is generally already sunk (and note that standby boilers tend to have much bigger standing heat losses.

3. ***Lack of energy efficiency incentives and government promotion:*** Confusing and rapidly changing policy settings at a Commonwealth level and a lack of incentives and promotion of heat pumps has hampered application of this technology.

   In Japan and South Korea this technology has become widely applied in industry based on **strong and consistent long term support for the development and tech transfer of heat pumps**.

4. ***A business culture which does not encourage innovation and change:*** As there are few installations in Australia, and lack of an experience base, many companies would perceive higher risk from these installations. In addition, to gain the greatest benefit from distributed high energy productivity electricity technologies, ideally you would aim to replace central boilers and steam systems entirely, but this would require a further leap of faith and Australian businesses generally are highly risk averse. Technical professionals also lack experience and relevant skills: this reduces the likelihood of them recommending heat pumps.

About 15 to 20 years ago, several reports (for example, *Industrial Heat Pumps – Experience, Potential and Global Environmental Benefits*, IEA Heat Pump Centre) pointed out the advantages of industrial heat pumps and quoted the technical and economical performances of various types. Disadvantages and obstacles for applications were also identified:

- Lack of knowledge of the potential benefits of industrial heat pumps
- Lack of experience in different types of industries.
- Lack of hardware for some types of potential applications.
- Lack of combined process and heat pump technology knowledge (or, lack of understanding of process integration).

Many of the same arguments apply today outside Japan and South Korea, where applications are very common in the food industry.

The last point on lack of understanding of process integration is important, as when heat recovery is part of a heat pump retrofit project – and particularly in the case of simultaneous heating and cooling applications, to get the best outcomes, a pinch study should be conducted and these thermodynamic engineering skills and experience are in short supply in Australia (see Appendix E: Pinch analysis). This understanding would overcome the simplistic drive towards plant changeout decisions.

Other potential barriers:

- Lack of local experience and infrastructure. While there are at least four companies that have come forward in stakeholder meetings with the interest and theoretical capacity to supply high temperature heat pumps in Australia, there are only a relatively small number (probably less than five) of installations in the Australian food industry. This means that there is limited local experience in the specification, installation and maintenance of the machines in Australia.
- Technical competency required to identify optimal applications. To find the ideal applications for heat pumps the following skills are often required:
    - Pinch analysis to define the best place to locate heat pumps to gain the best outcome, particularly to find simultaneous heating and cooling applications.
    - Business understanding to define the value streams from the projects on top of the basis energy savings.
- Ability to effectively schedule combined heating and cooling duties. In situations where heat pumps gain the maximum COP by combining heat and cooling duties, there may be challenges scheduling both duties unless in the same process (like a pasteuriser), without installation at additional cost of hot/cold storage tanks.

6 Industrial applications and case study examples

6.1 Sample international industrial applications

6.1.1 Heat pump on a French fry dryer

A manufacturer of French fries installed a heat pump that will provide the heat for a French fry dryer. A belt dryer that operates at a temperature of 70°C is using its own waste heat due to the use of a heat pump. As a result, an energy saving up to 70% is realized in the energy consumption of the dryer.
Source: De Kleijn 2017, www.industrialheatpumps.nl

6.1.2 Add-on heat pump in the food industry

At a leading company in the food industry a heat pump is installed 'on top of' an existing refrigeration system. This construction is called an add on heat pump. It is a mechanical heat pump that uses the refrigerant of an existing refrigeration system, in this case Ammonia. With the use of an add on heat pump the pressure of the gaseous Ammonia is increased. This causes the refrigerant to condensate at a higher temperature. In this case the add on heat pump is used to heat a water circuit up to 65°C. Application of a heat pump enables several processes to benefit from the waste heat of the refrigeration system. Source: De Kleijn 2017, www.industrialheatpumps.nl

6.1.3 Hybrid heat pump at slaughterhouse

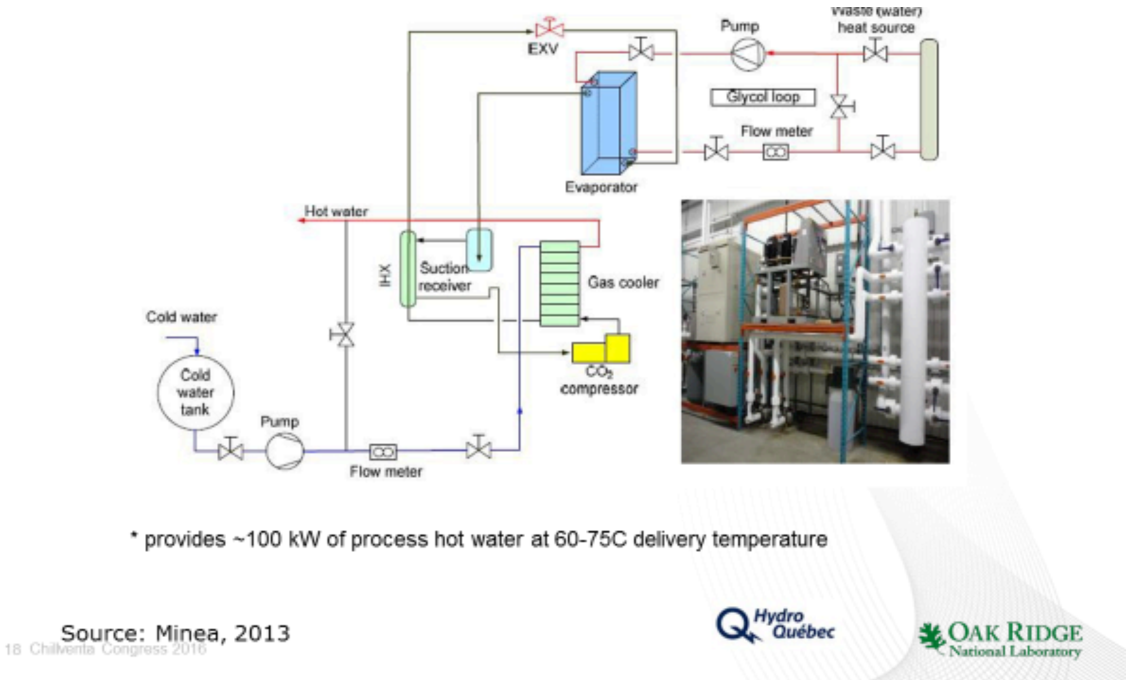
At a Norwegian abattoir, a hybrid heat pump with 650 kW of power was installed in 2007. The hybrid heat pump is used to heat water to a temperature of 83°C. This water is used for cleaning and sterilisation purposes. Heat is extracted out of a refrigeration installation. Installation of the hybrid heat pump resulted in an annual energy saving of 500,000 litres of oil. Source: De Kleijn 2017, www.industrialheatpumps.nl

6.1.4 Add-on heat pump for sports centre

At a sports centre, an add on heat pump has been installed. The add-on heat pump is used to upgrade the heat that is rejected from of an ice rink to keep the ice surface intact. The heat is transported towards a swimming pool. The installation of the add-on heat pump was made possible because of a collaboration between authorities, the company and the installer of heat pump. The heat pump, installed June 2012, enables the use of waste heat from the ice rink by increasing the pressure of the refrigerant in its refrigeration system. As a result, more energy is available at the condenser of the refrigeration system that can be used in the heating system of the swimming pool. Source: De Kleijn 2017, www.industrialheatpumps.nl

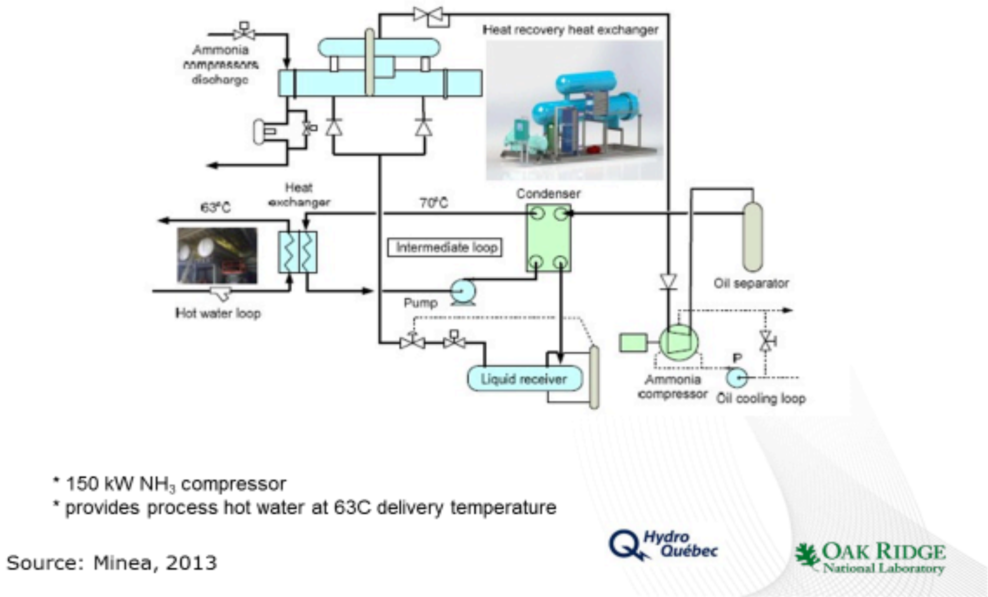
6.1.5 Canadian dairy plant 1

Figure 24 – CO_2 trans-critical industrial heat pump in Canadian dairy plant



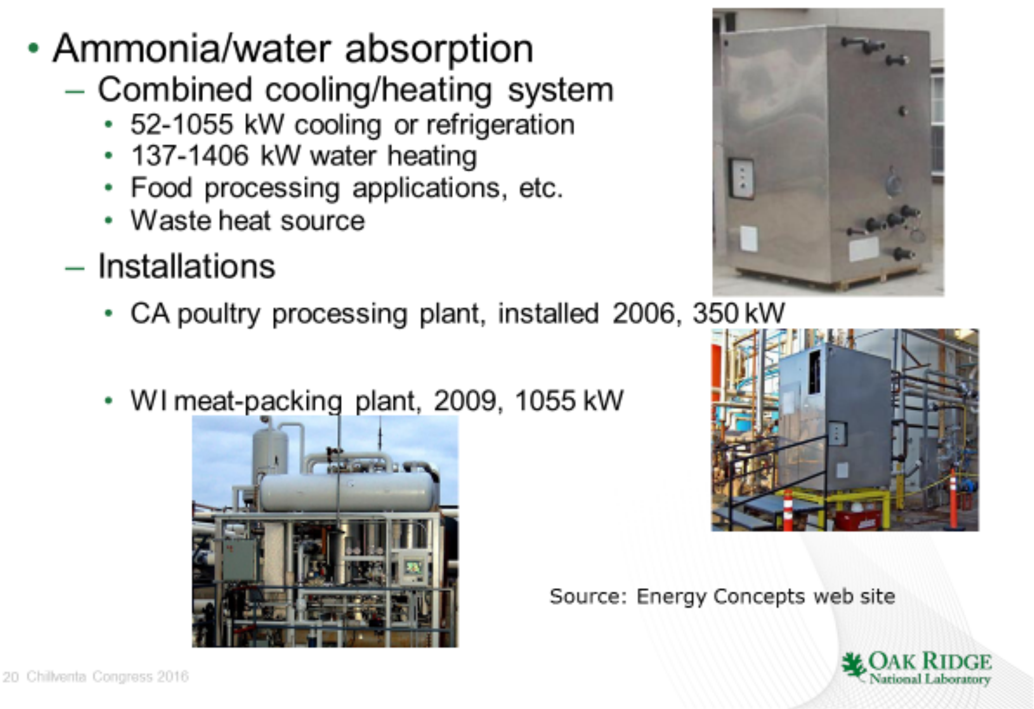
6.1.6 Canadian dairy plant 2

Figure 25 – NH_3 heat recovery heat pump in a Canadian dairy plant



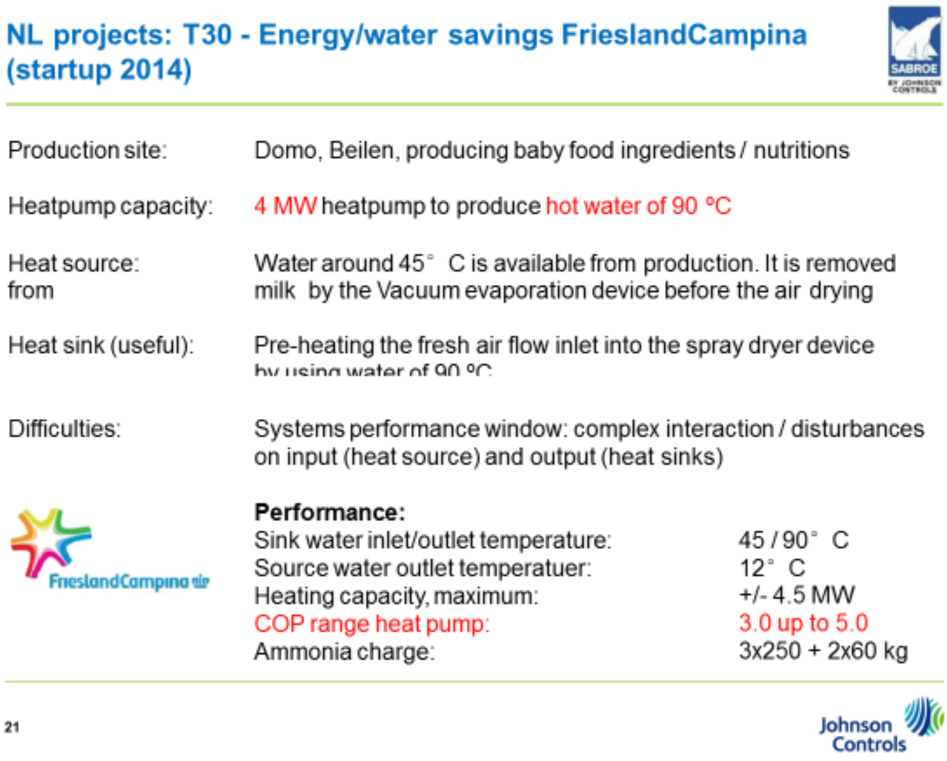
6.1.7 Poultry processing and meat packing plants

Figure 26 – Combined cooling/heating using heat pumps in two example applications



6.1.8 Baby food processing plant

Figure 27 – Energy/water savings at baby food plant



There are many more examples of industrial heat pump applications internationally in the IEA Annex 35 found at http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/ .

See also Appendix B: International technology review for a summary of a selection of international case studies.

6.2 Australian case studies

As discussed throughout in this report, at present there are very few examples of high temperature heat pumps being utilised in the Australian food industry. Several case studies are presented in this section: Lobethal Abattoir in South Australia, where a heat pump was installed in 2012; Shene Estate Distillery in Tasmania, where a heat pump was installed during the course of this project being conducted; and two sites for which heat pump installations have been proposed and preliminary assessments have been conducted. The first of these sites is a food processing plant on the outskirts of Melbourne and the second is a salt processing facility in regional Victoria. Further detailed feasibility assessments are planned for both sites.

Lessons learned from local experience

The following observations have been made about the heat pump installed at the South Australian abattoir:

- The heat pump tends to have relatively higher maintenance cost and higher capital cost than the boiler (though not when you consider the whole steam system).
- The heat pump in this case is an add-on heat pump to the freezer compressor, which becomes a problem when the product mix is favouring chilled not frozen products, so the freezers are not producing enough base waste heat for the heat pump to run at full load. The abattoir does not have rendering facilities and as such is not typical of most large abattoirs, which tend to have adequate recovered flash steam for these heating duties. As a result, heat pumps are generally not usually viable for sites with rendering using present approaches.
- The maximum hot water temperature achievable is 85°C; optimal operation is at 80°C.
- The following are operational experience gained by site engineers with this particular installation:
    - The heat pump requires a stable load to ensure good operation – ideally sized for 60 to 80% of total heat rejection available from refrigeration plant.
    - Heat pump controls on main plant discharge pressure, not water output temperature when load from main plant is insufficient.
    - Plant had to install automatic isolation valves on both inlet and outlet of ammonia on the evaporative condenser as in cold weather the condenser was providing approximately 350 kW of condenser capacity through natural air flow with no pump or fan running.
    - Theory said site needed the heat pump surge vessel 3m above the main plant liquid receiver, but in practice they needed a direct liquid line feed from the heat pump surge drum to the main plant chiller accumulator to avoid liquid backing up in the heat pump surge drum.
    - It is very important to have a high efficiency air purger installed and operating – careful design and installation to ensure air is removed from the heat pump without exposing air purger to excess pressure as only takes a small amount of air in the system to shut down the heat pump.

- Ensure heat pump compressors are on variable speed drives to allow effective regulation of capacity.
- Heat pump reciprocating compressors are noisy – design enclosure to suit.
- Complex programming required to ensure integration and optimisation to main refrigeration system.

A study of an Australian dairy plant assessed for heat pump suitability found the following:

- The dairy plant characterised as a typical dairy factory with 18.8 GJ thermal load. The assessment was for using heat pumps to replace gas fired steam to heat water from 15 to 60°C. The assumed gas price was $11/GJ (though some sites are now paying $15/GJ).

- The assessment results were 6-8 year payback. (This is beyond the 2-4 year payback typically expected. However, it is equivalent to a rate of return on investment of 10-15% pa: with appropriate financing and risk management, this could be viable: indeed, this rate of return would be considered acceptable for large energy supply investments.) Other negatives included: complex design; difficulty matching demand with supply of waste heat; and increased electrical demand (though this was presumably included in the financial calculations).

What was NOT included in the assessment on the positive side is further benefits such as thermal savings from replacing all or part of the steam reticulation system, opportunities for simultaneous cooling any productivity benefits from using far more controllable local heating, and potential synergies from combining a heat pump with energy (thermal and/or electric) storage and renewable energy.

6.2.1 Lobethal Abattoir, South Australia

Context of heat pump installation

- Thomas Foods International's Lobethal Abattoir is located approximately 35km west of Adelaide.
- In 2012 a two stage ammonia heat pump was installed to utilise waste heat expelled by the condensers of new freezer plant.
- Heat pump heats approx. 250,000L of water/day from 11°C to 75°C and is an alternative to heating water with a gas-fired boiler.
- Hot water produced is delivered to a thermal storage tank and is used partly during the night for sterilisation and cleaning purposes and partly during the day for processing e.g. sterilising knives.

Equipment installed

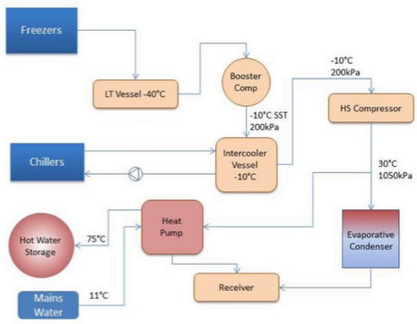
- Mayekawa Plus+ Heat ammonia heat pump
- COP: 4.8 – 6.5

Costs and benefits of heat pump compared to gas boiler

- Cost to supply and install 630kW high stage ammonia heat pump onto an existing refrigeration plant similar to Lobethal approximately $900,000 + GST *
- First of kind in Australia, so high R&D costs incurred
- Energy cost: 40% reduction in LPG costs in line with reduction in LGP use for water heating
- Water use: reduction in water evaporated in evaporative condensers by as much as 119 kL per week
- Carbon emissions: significant reduction of 7 tonne of CO_2 per week
- Ammonia is non-ozone depleting and has a global warming potential of zero (as compared to alternatives such as the synthetic refrigerant R-134a, which a has a GWP of 1,300. As ammonia is caustic leak detection systems were installed to minimise safety risk.

Comments

- It should be noted the Lobethal Abattoir is does not rendering facilities. Generally lower viability for heat pump installations in abattoirs with rendering facilities with surplus recoverable heat.
- As the heat pump is designed to utilise waste heat from freezers, changes in demand from frozen to chilled products impacts operation of the heat pump.



* Not actual cost of Lobethal heat pump – indicative cost supplied by heat pump installer Cold Logic

Information and image sources: http://www.ampc.com.au/2010/07/Heat-Recovery-From-Refrigeration-Plant & http://155.187.2.69/atmosphere/ozone/sgg/equivalentcarbonprice/case-studies/pubs/cs-mayekawa.pdf ; Nekta Nicolau, Thomas Foods International

Supplementary information regarding installation of a heat pump similar to that installed at Lobethal Abattoir

Courtesy of Brad Semmler, Director, Cold Logic

To supply and install a 630 kW high stage ammonia heat pump onto an existing ammonia refrigeration plant will cost approximately $900,000 plus GST. This would include:

- Multiple compressors on VSD with 50% redundancy
- Sound attenuated enclosure
- Ammonia detection and ventilation system
- Wiring and electrical control system with a SCADA PC
- Integration to existing refrigeration plant pipework and controls
- Commissioning and spare parts.

In addition to this the following costs would need to be considered:

- Power supply to the unit – 500 amps
- High efficiency Air purger on the ammonia plant $50,000 installed
- Hot water storage tank – size dependant on water demand, refrigeration loads etc as a guide a 50,000 litre insulated tank will be $55,000
- Hot water piping to connect to existing system – site dependant
- Plant area 9 m x 4.5 m, ideally located 3 to 4 m above existing liquid receiver, can engineer this requirement out but adds some cost
- Access to plant area.

In order to realise the full capacity of the heat pump, the base refrigeration load needs to be in excess of 500 kWR. The system can run off any ammonia system with a suitable base load.

6.2.2 Shene Estate Distillery, Tasmania

Context of heat pump installation

- Shene Estate is a historic property north of Hobart containing a distillery that produces gin and whisky using traditional distillation practices.
- The distillation process involves heating malted barley mash. Each day 6,000 litres of hot water is required, initially at 90°C, with the temperature then reduced to approximately 64°C to 65°C, the optimum temperature to dissolve sugars contained within the starch of malted barley. Finally the temperature is brought up again to 70°C at the end of the mashing in process to dissolve enzymes.
- The estate is not connected to the gas grid and has been subject to increasing electricity prices, providing the impetus to improve energy efficiency.
- Conventionally hot water used in the distillation process is heated using an instantaneous electric hot water heater.
- Heat pump installed in mid 2017 as an alternative method to heat water.

Information and image source: David Kernke, Owner, Shene Estate Distillery

Equipment installed

- 1 x 30kW Mitsubishi Heavy Industries Q-ton $C0_2$ air-to-water heat pump.
- COP: 2.8 – 4.3 (per specifications http://mhiae.com/products/heat-pumps/q-ton/specifications)

Costs and benefits of heat pump compared to electric instantaneous heater

- Heat pump is a more environmentally responsible method of producing hot water as it is less energy intensive than instantaneous heaters. Existing water heater has a COP of 1: 48 Kw input and 48 Kw output. The Q-ton has achieved COP of 4.2: 7 Kw input and 30 Kw output.
- Heat pump is cheaper to run due to lower energy use. Anticipate energy savings of 66.6% per year compared to instantaneous heater.
- Heat pump is able to heat water significantly faster than existing instantaneous hot water heater, improving plant efficiency.
- Capital cost: approximately $30,000 plus installation costs approximately $5,000.
- Shene Estate has good quality filtered water, therefore envisage minimal maintenance requirements into future.

Next steps

- Investigating installation of PV and battery system to further reduce energy consumption.

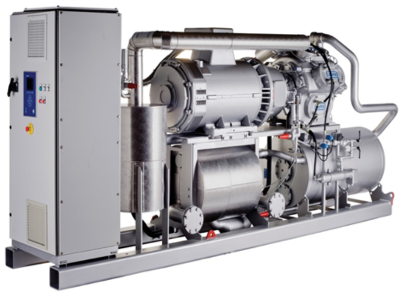
6.2.3 Food processing facility, Victoria

Context of proposed heat pump installation

- Heat pump proposed for food processing plant located in outer suburbs of Melbourne.
- Current plant equipment includes: 1 hot water boiler, 1 steam boiler, 5 Stal compressors, 2 BAC evaporative condensers.
- Hot water boiler: 15,700MJ/h and outlet temperature of 61°C for cleaning in place (CIP).
- Heat rejection of the refrigeration plant (5 Stal compressors): 1,210KW
- Water use in the evaporative condensers: 21,000 l/day.

Equipment proposed

- SABROE HeatPAC with reciprocating compressor and Ammonia as refrigerant.



- COP = 5.5 – 7.5
- In the proposed system, the heat pump will use the heat rejected by the refrigeration plant to generate hot water for CIP.

Initial estimates of costs and benefits of the proposed heat pump compared to current system

- Estimated equipment cost of SABROE HeatPAC heat pump of 1,500 kW of heating capacity is approximately $390,000 (excl GST).
- Savings due to reduced operating costs estimated to be approximately 57%.
- CO_2 footprint reductions estimated to be approximately 27%.
- Reduction in water use related to the evaporative condensers.
- Reduction of chemical cleaning of evaporative condensers.

Comments

- In food applications where both the cooling and heat capacity can be used the combined COP increases considerably.
- Recovering heat on the cooling water helps reduce chemical and water use.
- The hot water can be used for: sanitary hot water, space heating, process heating, cleaning, disinfecting and drying.
- There are many sources to recover the heat and sink combinations possible to use the hot water.
- When a heat pump is operating heat is kept within the plant and not rejected into the atmosphere.
- SABROE heat pumps use Ammonia as refrigerant, with zero ozone depletion potential and zero global warming potential.
- Refrigerant charge 50% smaller than conventional heat pumps, because of special condenser/ evaporator design.
- Factory-assembled, pre-tested packaged units based on SABROE reciprocating compressor.

Information and image sources: Ricardo Hoffmann, Johnson Controls; http://www.sabroe.com/en/products/chillers-and-heat-pumps/

6.2.4 Salt processing facility, Victoria

Context of proposed heat pump installation

- Heat pump proposed for salt processing plant located in regional Victoria.
- Hot air at 70°C is required to evaporate water from saturated brine to create salt flakes and other salt products.
- Air is currently heated using conventional electric resistance heaters.
- At present 17 dryers are in operation. It is proposed 8 of these dryers are replaced with heat pump technology coupled with PV as a pilot.
- Heat sources -
    - Salt pond:

      50°C in summer for 12 hours

      35°C in winter for 8 hours.
    - Ground water:

      16°C to 20°C.

Initial estimates of costs and benefits of the proposed heat pump compared to current system:

- Heat pump equipment cost estimated at approximately $75,000 + approximately $30,000 for installation.
- Initial proposal also includes installation of 100kW of PV at an estimated cost of $150,000.
- Energy cost savings related to reduced energy consumption estimated to be up to $160,000 per year (assumes plant running 24 hours per day).
    - Equates to an estimated reduction in energy consumption of 45%.
- Payback: 2-3 years.

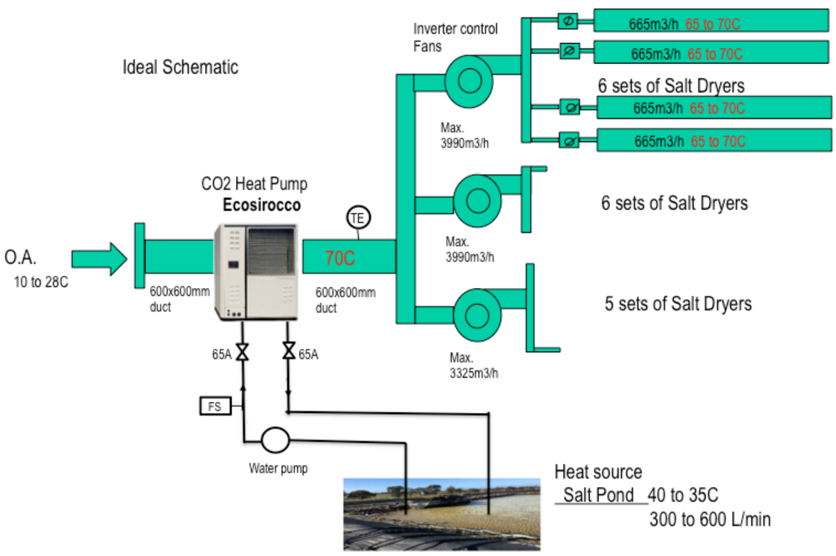
Next steps

- Detailed feasibility assessment to be undertaken prior to final decision on conducting pilot being taken.

Equipment proposed

- Mayekawa CO_2 Heat Pump Eco Sirocco
- Salt pond heat source COP: 4.7-5.2
- Ground water heat source COP: 3.9-4.6

Existing hot air system to be retained as a back up.



Information and image sources: Mike Ono/Peter O'Neill, Mayekawa Australia Pty Ltd and Abhijit Date, RMIT

7 Scale of opportunity

The rapidly rising price of natural gas and potentially limited availability in the next five years has made heat pumps more immediately interesting to the food industry than they have been in the past.

It is very difficult to put a meaningful number or even range on the potential total economical scale of application of HT heat pumps in the Australian food industry for the following reasons:

- The economics of HT heat pumps are dependent on the specifics of the application, as discussed earlier in this report, including: the temperature of the application; the size of the temperature lift required (related to availability of waste heat as a heat source); the potential for replacing all or part of steam systems which may deliver much greater savings; and, the specific business benefits of the heat pump in an application.
- There is very poor information available to model many of these aspects. Ideally, we would be able to at least source data on the temperature of thermal needs in each sector of the food industry, the availability of waste heat streams and their temperature. This would provide a starting point for further analysis but this data is not available.
- As a result, we took a very simplistic approach to at least see the outer limits of the potential as follows:
    - Scale of possible impact:
        - Food processing consumes 165PJ/year of energy (up 7% in 2016 – only industry sector to grow). 41PJ is liquid and gas fossil fuel (37PJ natural gas, 1PJ LPG, 3PG oil), potentially replaceable using heat pumps (see the table on energy consumption in the industry below).

Energy use in the Australian food, beverage and tobacco industry 2014-15

11-12 Food, beverages and tobacco	
Fuels consumed	PJ
Black coal	8.3
Brown Coal	0.0
Crude Oil and Other Refinery Feedstock	0.2
Coal byproducts	
Brown coal briquettes	0.2
Wood, woodwaste	2.8
Bagasse	88.4
LPG	0.8
Auto gasoline	0.3
Lighting kerosene	0.2
ADO	1.4
IDF	
Fuel oil	0.5
Petroleum products nec	2.4
Bitumen	
Natural gas	36.7
Town gas	
Electricity	22.1
Liquid/gas - Biofuels	0.6
Derived fuels produced	
Thermal electricity	
Synthetics – biofuels	
Energy consumption	164.9

Extracted from: Office of the Chief Economist 2016, *Table F Australian energy consumption, by state, by industry, by fuel, energy units*. Retrieved from https://industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Australian-energy-statistics.aspx#

- A recent report prepared by IT Power[2] for ARENA indicates that of the 35PJ of fuel used in 2012-2013 in the food industry outside the sugar industry, some 15PJ is produced in the temperature range up to 150°C, and the remaining 20PJ above this temperature. This seems a surprisingly low proportion, but it appears that the report bases its estimates on the temperature at which heat is generated rather than the temperature requirement of the process. For now, let's assume that this is the outer limit of potential heat pump applications (escalated to today's usage – so say 18PJ).
  - Use of central steam systems is typically relatively inefficient, so replacement with distributed heat pumps would reduce energy demand.
  - Most of the above heat load could be provided by heat pumps (though we aim to replace a lot of thermal processes with non-fossil/non-thermal processes).

[2] IT Power 2015*, Renewable energy options for Australian industrial gas users*, Australian Government, Canberra

- The economics of heat pumps is significantly improved where waste heat is available at temperature below process temperature – the efficiency is improved by about 3% for each degree reduction in lift. But there is no information available on the availability of waste heat in each food industry, so we cannot use this to narrow the potential market. Where waste heat is not available, or is limited, it may be feasible to use relatively low cost solar collectors and storage to provide heat at 60°C or higher.
- If you could displace say 20-25% of the 18PJ of fuel displacement this would reduce liquid/gas use by 4PJ, (using 0.5-0.8PJ of electricity), saving about 1/3 of carbon emissions or 200KT C02 (up to 600Kt if powered by renewables, depending on the proportion of time and energy the renewable energy system could provide).

8 Conclusions and next steps

Conclusions

The Australian Alliance for Energy Productivity has reached the following conclusions as a result of conducting this project:

- High temperature (over 65°C) industrial heat pump technology has developed rapidly in the past decade. There are now many commercial products for industrial processes, including the food processing industry. Thousands of units are now in service, in Japan, South Korea and Europe to supply heat at up to 95°C. The technology has also extended to development of heat pumps delivering steam at up to 150°C.
- There are barely a handful of high temperature industrial installations in Australia. This means that there are very few local case examples of the technology being successfully deployed, and this needs to be overcome to assist in the accelerating deployment of this technology.
- The local suppliers of heat pumps are branches of global companies, are quite motivated and have access to international technology, though there is not much local practical expertise and experience on the ground given the potential market. This could be turned around rapidly however, as the refrigeration industry has the skills to rapidly learn about heat pumps for heating duties.
- High temperature heat pumps could play an important role in the Australian food industry to recover heat and displace steam currently supplied from natural gas and LPG. With the rapid escalation in gas prices and potential gas supply constraints, and the need to move to low carbon energy solutions (as the electricity used in heat pumps could be supplied from renewable sources), high temperature heat pump technology could be a significant contributor, providing some of the many barriers to implementation can be overcome.

Recommended next steps

There is enough potential identified through this project to justify further actions to promote the application of HT heat pumps in the Australian food industry, including:

- Part fund and conduct at least five case implementations in a range of ideal applications (and in a variety of industries) with significant replication potential to demonstrate the benefits of heat pumps in local practice. This would both have the benefit of demonstration for others in the same industry, but also build local capacity and experience with implementing HT heat pumps in Australia. ARENA and/or NSW/Victoria State government agencies may be a suitable source for this funding.
- Part-fund at least two additional larger projects demonstrating the complete replacement of boilers and steam systems with point of end use heating applications, including heat pumps. Fully document the business benefits and disseminate this information.
- Associated with these case studies, run a series of training courses on heat pumps and steam system replacement opportunities for manufacturers, and involve business associations and a range of stakeholder that could benefit from exposure to this knowledge.

- Design and run a training course on pinch analysis, specifically designed to cater to identifying optimal heat pumps applications.
- Build a formal relationship with the IEA Heat Pump Centre and the Japanese Heat Pump Association, and consider the benefits of establishing a Centre in Australia (ideally at one of the State government's existing activities e.g. NSW OEH or Sustainability Victoria), to promote the benefits of heat pumps and provide support for suppliers and users, and transfer international best practice technology.
- Consider funding the development and application of a computer model to simulate applications of HT heat pumps. This could be used to screen potential sites for demonstration projects, potentially be done in partnership with commercial suppliers or the IEA Heat Pump Centre.

Appendix A: Heat pump stakeholder contributors

The list below contains the names of organisations and individuals that provided input to this report. We thank them for their contribution.

AIRAH – Phil Wilkinson

Borgcraft – James Papadopolous

CA Group Services – Ian Tuena

Craft Beer Industry Association – Chris McNamara

Cold Logic – Brad Semmler

CSIRO – Stephen White

Dairy Industry Association – Ian Olmstead

ECO2 Technologies/Minus 40 – Michael Bellstedt

Emerson – John Thorne

Fonterra Australia – Jack Holden

Goodman Fielder – Mick Anderson

Johnson Control – Ricardo Hoffmann

KDR Compressors - Tony Kitchener

Mayekawa – Peter O'Neill

Meat and Livestock Australia – Doug McNicholl

Mitsubishi Heavy Industries – Trent Miller and Oscar Xu

NSW Office of Environment and Heritage – David Malicki

Oak Ridge National Laboratory – Van Baxter

Parmalat – Michael Robinson

Pyramid Salt – Gavin Privett

RMIT University – Aliakbar Akbarzedeh, Abhijit Date and Cameron Stanley

Simplot – Graham Bryant and Scott Hall

Shene Estate Distillery – David Kernke

Sustainability Victoria – Warren Overton, Katrina Woolfe, Yolanda Sztarr and Nick Katsanevakis

Teys Australia – Carl Duncan

Thomas Foods International – Nekta Nicolaou

Appendix B: International technology review

B.1 Food industry case studies

Thomas Foods International, Australia: Heat recovery from refrigeration plant

In 2012 a heat pump was installed at the Lobethal Abattoir in South Australia to offset gas-fired boiler use. The two stage Ammonia heat pump takes waste heat from refrigeration plant to heat water to 75°C. The incoming water temperature is 11°C. Once heated, the hot water is delivered to a thermal storage tank. Most of the water is used at night for cleaning and sterilising processes. The tank is refilled during the day when there is little demand for hot water.

http://www.ampc.com.au/uploads/cgblog/id28/Heat-Recovery-From-Refrigeration-Plant.pdf

Mohrenbrauerei, Austria: Compression heat pump reducing gas usage in brewery

To reduce gas usage associated with its steam plant and boiler, the brewery installed a high temperature heat pump with a heating capacity of 370 kW, using an ammonia refrigerant. The heat pump utilises waste heat from chillers for space and process heating and heating of process water to 77°C. The heat pump cost 365,000 EUR.

Case study 8.3.2: http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/

Agrana, Austria: Drying starch from potato, wheat and corn

Austrian food producer Agrana is participating in a European Union funded project, DryFiciency. As part of the project a demonstrator heat pump system will be installed for drying of starch from potato, wheat and corn. Starch is dried using hot air. The air is heated in three consecutive steps: preheating by a heat recovery cycle (HRC), heated by waste heat from another dryer; heating by steam condensate; and heating by steam. To gain more energy from the HRC, the demonstrator heat pump unit will be installed. The useful supply temperature of the heat pump system will be from 130 to 160 °C and the heating capacity will be approximately 600 kW.

http://dry-f.eu/Demonstrations/Agrana-Food-industry

McCain Foods, The Netherlands: Drying French fries before they are baked

A belt dryer that operates at a maximum temperature of 70°C is used to dry French fries before they are baked. The heat pump uses Ammonia as its refrigerant and is designed to condensate 1,500 kg of water per hour. Two reciprocating compressors are used; a Grasso 45 HP and a Grasso 65 HP. These compressors have a continuous capacity control. Their COP in this process depends on the drying conditions and varies between 5 to 8. Savings up to 70% on the dryer's energy consumption are achievable.

http://www.industrialheatpumps.nl/en/practices/heat_pump_for_drying_of_fries/

Nortura, Norway: Hybrid heat pump to heat water for cleaning in slaughterhouse

The heat pump installation uses water and ammonia. The source of waste heat has a temperature of 49°C which is upgraded by the hybrid heat pump to 88 - 90°C. It is used to heat water for cleaning and sterilization. The installation has a COP of 5.2. Annual energy savings of 13.700 GJ or

500,000 litres of fuel oil are realized.

A hybrid heat pump uses the principles of operation of both a mechanical and an absorption heat pump. Temperatures as high as 130 °C can be reached with relatively low system pressure. Therefore, standard components can be used. The Norwegian Institute for Energy Technology developed the hybrid heat pump technology.

http://www.industrialheatpumps.nl/en/practices/hybrid_heat_pump_at_slaughterhouse/

Dairy Cooperative Tine, Norway: Heat recovery for hot water generation

The heat recovery system utilises waste heat from the dairy's refrigeration system to fulfil the dairy's demand for CIP water at 73°C (COP 5.8). The system is also connected to a local heating network which supplies heat to nearby greenhouses at 58°C (COP 9.0). The system uses an Ammonia refrigerant.

Case study 7.5: http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/

Slaughterhouse, Switzerland: 800kW heat pump system for hot water generation and heating

The 800kW system is made up of 3 carbon dioxide refrigerant heat pumps that deliver water up to 90°C. The heated water is used for slaughtering and cleaning purposes and for feed water for a steam generator and the heating system. The heat pump system uses waste heat from an existing Ammonia refrigeration machine, an oilcooled air compressor plant and fan-coil units. The COP of the heat pump is 3.4.

Case study 7.2: http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/

Nestle, UK: Heating and cooling in chocolate manufacturing process

Nestle installed a combined heating and cooling system using ammonia heat pumps in its Halifax chocolate manufacturing facility. Heating capacity of the system is provided by 2 x 600kW units and cooling capacity by 2 x 1600 kW units. Heat is sourced from the glycol cooling process and results in process water being heated from 10°C to 60°C in one step. The plant requires a small amount of water at 90°C. The incremental heat is supplied by a small gas boiler heating the water from 60°C to 90°C. The combined heating and cooling COP is 6.25. In addition to reducing energy costs and carbon emissions, installation of the heat pump system has also resulted in a significant reduction in water consumption.

Case study 7.6: http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/

Hakutsuru Sake Brewing Company, Japan: heat recovery to produce hot and cold water

In 2012 the Nadauozaki factory of Hakutsuru Sake Brewing Co was constructed with energy efficiency and environmental sustainability in mind. The sake production process requires both heating and cooling energy. The heating and cooling loads sit side by side, allowing the very efficient utilisation of a CO_2 heat recovery heat pump that simultaneously produces hot and cold water. The exhaust heat generated when producing cold water is used produce hot water. The

heat pump system has achieved a COP of 5.7. http://www.hptcj.or.jp/e/publication/tabid/790/Default.aspx
Frozen noodle production, Japan: Simultaneous hot and cold water production Production of frozen noodles requires hot water at 80°C or higher in the noodle boiling process then cold water at around 5°C in the cooling process before freezing. The noodle company installed a heat pump to produce both hot and cold water. The heat pump produces hot water at 90°C, which is stored in a hot water tank until required. Most of the hot water is used to fill boiling pools at the start of production in the morning to reduce the peak load of the steam boilers. Cold water at 5°C is supplied by the heat pump and used to cool the water in the raw water tank (17°C) to reduce the refrigeration load. The heat pump has a total COP for simultaneous supply of 5.1 (3.0 for heating and 2.1 for cooling). Case study 8.3.1: http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/
Sungrain Ltd, Japan: Combined vapour re-compression system for alcohol distillation A combined thermal vapour re-compression (TVR) and mechanical vapour re-compression (MVR) system was developed to reduce the re-compression power required for low-pressure steam recycled for heating of the ethanol rectifying tower. The TVR compresses vapour at a compression ratio of 1.7, then the MVR compresses vapour at 2.1. Installation of the combined vapour re-compression system resulted in a 43% reduction in primary energy consumption for the rectifying and methyl towers. Case study 8.3.2: http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/
Poultry processing, US: Scalding and feather removal To remove feathers and scald chicken carcass skin, water at 60°C is required in a continuous process at a Texan poultry processing facility. The same process also requires significant cooling which provides the source of heat for the heat pump. Entering water temperature is approximately 20°C. A simple single stage heat pump achieves a COP of 7.0 (compared to gas boiler system COP of 0.83). The system delivers 56,603 MMBTU of heat annually and cost US$750,000. http://www.emersonclimate.com/Documents/Vilter/Product_Brochures/White_Paper_2011ECT-27_C.pdf
Beef processing, US: Hot water for equipment sanitation A beef processing facility in Tennessee has significant cold storage and freezing loads that provide a source of heat for its heat pump system that produces hot water for sanitation purposes. However, sanitation takes place between processing shifts when refrigeration demand is at a minimum or diminishing so a storage tank is used to build up the hot water supply throughout the day. The entering water temperature is 15°C and the leaving water temperature is 70°C. The capital investment was US$800,000 for a heat pump system that delivers 64,287 MMBTU of heat per year. The heat pump system COP is 5.9 (compared to gas boiler system COP of 0.96).

http://www.emersonclimate.com/Documents/Vilter/Product_Brochures/White_Paper_2011ECT-27_C.pdf

Dairy processing, US: High temperature short time (HTST) pasteurisation

The HTST pasteurisation process in this Wisconsin dairy factory utilises an efficient two stage heat pump to deliver the 90°C water temperature required. Entering water temperature is 10°C and refrigeration is the heat source. The two stage heat pump system cost US$1,250,000 and delivers 60,507 MMBTU of heat per year. The heat pump system has a COP of 4.2 (compared to gas boiler system COP of 0.85).

http://www.emersonclimate.com/Documents/Vilter/Product_Brochures/White_Paper_2011ECT-27_C.pdf

Poultry processing, Canada: Cascaded heat pump system

The first stage of the cascaded heat pump system used in this poultry processing plant recovers waste heat from an industrial ice machine. Cold water enters the system at 12°C and is heated to 25°C in the pre-heating heat exchanger, then heated up to 63°C with the cascade heat pump prior to being stored in a storage tank and/or supplied to industrial processes. The total investment cost of this heat recovery system was US$165,000 and the system overall COP has been estimated at 10.7.

Case study 4.7: http://heatpumpingtechnologies.org/publications/application-of-industrial-heat-pumps-part-2/

B.2 Research and development

Tocircle Industries, Norway: Development of high temperature heat pump for the European food and beverage market

Tocircle Industries of Norway and Duynie Holdings of the Netherlands have established a joint venture for production and sales of industrial heat pump systems, with first deliveries scheduled for Q3 2018. The heat pumps include a two stage compressor assembly, each consisting of four compressors. The heat pumps will be used for upgrading residual heat recovered in heat intensive food manufacturing.

http://www.tocircle.com/commercial-breakthrough-tocircle-industries/

De Kleijn Energy Consultants, The Netherlands: Pasteurisation with an add on heat pump

For pasteurization a product needs to be heated above 70°C. Afterwards the product is cooled down. The product temperature thus varies from cold before pasteurization to hot during pasteurization and back to cold again after pasteurization. Application of an add-on heat pump enables reuse of the waste heat from the mechanical cooling system in the pasteurization process. If the add-on heat pump is applied, no additional steam is needed for the pasteurization process.

http://www.industrialheatpumps.nl/en/applications/

ECN, The Netherlands: Development of heat pump that uses waste heat or geothermal heat to generate steam up to 200°C

The STEPS project will develop and test two advanced heat pump concepts: a multistage reverse Rankine system and a single stage thermoacoustic system. Thermoacoustics refers to the physical phenomenon that a temperature difference can create and amplify a sound wave and vice versa, hence a sound wave is able to create a temperature difference. This enables the development of a system with no moving parts that can operate under a wide range of temperatures. https://www.ecn.nl/news/item/high-temperature-heat-pump-technology-for-sustainable-steam-production-in-industry/
Kobe Steel, Japan: Air-sourced 90°C hot water supplying heat pump This heat pump is capable of supplying hot water at 65-90°C to the heating process of factories making products such as food, beverages, automobiles and chemicals. The newly developed heat pump has achieved very high energy efficiency for supplying hot water by circulation heating. This was made possible by using a two-stage twin-screw compressor modified for high temperature operation by selecting an adequate refrigerant and optimising an air-sourced evaporator unit. http://www.kobelco.co.jp/english/ktr/pdf/ktr_32/070-074.pdf
IEA Heat Pump Centre, International: Industrial heat pump projects Heat Pump Centre projects “Annex 35” and “Annex 48” looked at heat pumps with the ability to produced heat at up to 200°C which can be used for heat recovery and heat upgrading in industrial processes, and also for heating, cooling and air-conditioning in commercial and industrial buildings. http://heatpumpingtechnologies.org/
IEA Heat Pump Centre, International: Heat pumps in smart grids Heat Pump Centre project “Annex 42” examined use of heat pumps as a tool for demand management in smart grids. Smart heat pumps, with the ability to communicate with the grid, can be used as a bridge between power and heating, converting renewable power to heat, which can be stored. HPT Magazine, p.19 https://issuu.com/hptmagazine/docs/hpt_magazine_no1_2017?e=24860023/46502186 Other references: Fischer D., Madani H. On heat pumps in smart grids: A review, Renewable and Sustainable Energy Reviews 70, 342 (2017). Dallmer-Zerbe, K., Fischer, D., Biener, W., Wille-Haussmann, B., & Wittwer, C. Droop, Controlled Operation of Heat Pumps on Clustered Distribution Grids with High PV Penetration. In IEEE Energycon. inproceedings, Leuven (2016).
Heat Pump & Thermal Storage Technology Centre of Japan: Survey of availability of heat pumps in the food and beverage fields Report examining replacing steam boilers (end use temperature below 100°C) with heat pumps In the food and beverage industries of 11 counties. The report found significant energy consumption and CO_2 reductions were achievable by deploying heat pump technologies in the food and

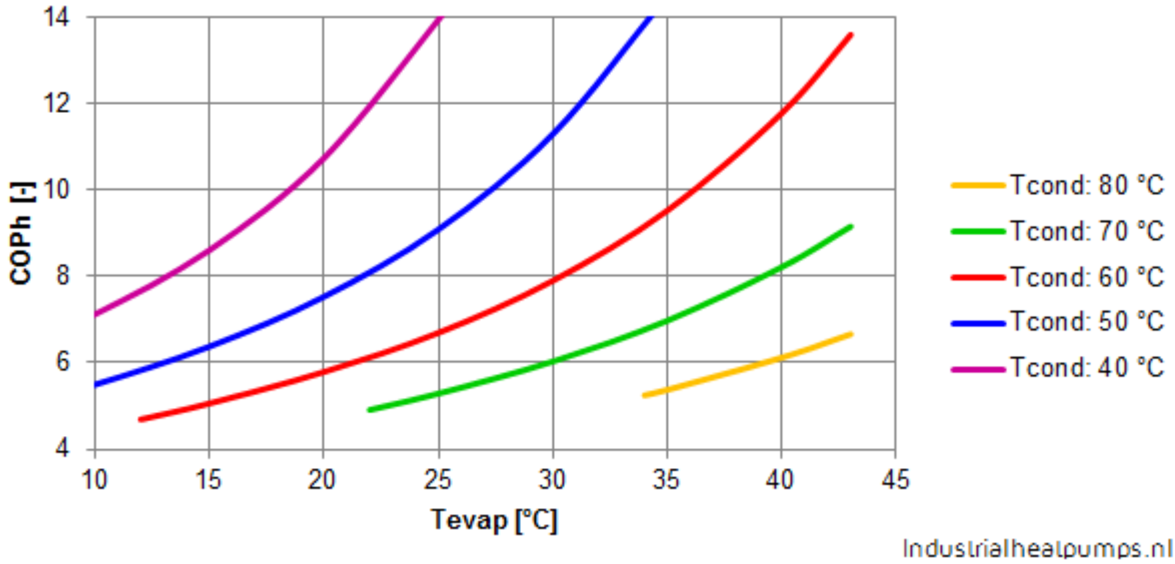
beverage industry. In most cases electric drive compression heat pumps were utilised, with the exception of mechanical vapour recompression used in the beer brewing industry. http://www.hptcj.or.jp/Portals/0/data0/e/publication/pdf/survey.pdf
Centre of Applied Mathematics Mines ParisTech, France: Heat recovery with heat pumps in the food and drink industry A detailed bottom up energy model was used to analyse the impact of heat recovery with heat pumps on industrial processes up to 2020 on energy savings and CO_2 emission reductions in the French food and drink industry. The results showed heat pumps could be an excellent energy recovery technology. http://www.sciencedirect.com/science/article/pii/S0306261913004364

Appendix C: Coefficient of performance background Information

The efficiency of refrigeration systems and heat pumps is denoted by its coefficient of performance (COP). The COP is the ratio between energy usage of the compressor and the amount of useful cooling at the evaporator (for a refrigeration installation) or useful heat extracted from the condenser (for a heat pump). Most of the electric energy needed to drive the compressor is released to the refrigerant as heat, so more heat is available at the condenser than is extracted at the evaporator of the heat pump. For a heat pump a COP value of 4 means that the addition of 1 kW of electric energy is used to achieve a release of 4 kW of heat at the condenser. At the evaporator side 3.0-3.5 kW of heat is extracted and additional heat from the electricity input to run the motor/compressor is added, so that a total of 4 units of heat is delivered when only 1 unit of electricity (or mechanical energy) is used. For a refrigeration system a COP of 4 indicates that 1 kW of electricity is needed for a evaporator to extract 4 kW of heat. Due to this important difference in COP definition, for a heat pump one often speaks of COPh.

Figure 28 – Coefficient of performance for heating for ammonia refrigerant

$$\mathrm{COP_h} = \frac{Q_{\text{useful heat}}}{Q_{\text{electric}}} \approx \frac{Q_{\text{waste heat}}}{Q_{\text{electric}}} + 1$$



The efficiency of a heat pump, COPh, depends on several factors, especially the temperature difference between waste heat source and potential heat requirement (?). The temperature difference between condensation and evaporation temperature largely determines the efficiency: the smaller the difference, the higher the COPh. The figure above shows the influence of this temperature difference on the COPh value. These values are based on figures from a compressor using Ammonia refrigerant.

Appendix D: High temperature heat pumps with natural refrigerants

Andy Pearson, UK

Introduction

The economic, commercial and technical conditions now seem to be interacting in such a way as to make the recovery of heat from buildings and process outputs, or even from their surroundings, compellingly attractive, like never before.

Some of the technical requirements are quite demanding. Refrigerants which do not interact with the ozone layer or other aspects of the global climate, yet offer a high efficiency from compact and relatively inexpensive plant, are now highly desirable. In many cases requiring major investments, the environmental aspects of the specification are a prerequisite for getting the project funded. In others, particularly for private "blue-chip" clients, there may be corporate social responsibility guidelines to meet, which preclude the use of fluorinated refrigerants unless strictly necessary. This perception is particularly important in large systems. For example a system with a 10 000 kg charge of R-134a which leaks 2% of the charge per year has a climate effect that is equivalent to driving a family saloon more than 50 000 km per week.

With these constraints the list of possible refrigerants and systems is very short. Five substances offer the most promise as working fluids in industrial heating applications: water, air, hydrocarbon, ammonia and carbon dioxide. The optimal configuration of operating system varies widely depending on the class of fluid, but they all fall within the general description of thermodynamic systems in which heat is added to a fluid by cooling the surroundings and then work is performed on the fluid to raise it to a higher pressure, at which point the heat input and the work input can jointly be extracted and usefully applied to a process, product or situation which requires to be heated. In some of these systems, notably with water, hydrocarbon and ammonia, the working fluid is evaporated and recondensed in a Perkins cycle. The air system, however, works by heating and cooling the gas without any change of phase. In the special case of carbon dioxide the heat extraction is accomplished by phase change but the heat delivery is at a pressure above the critical point and therefore there is no change of phase as the gas is cooled.

Water

Systems using water as a working fluid operate at very low pressures – the boiling point of water at atmospheric pressure at sea level is 100°C, so for most industrial heat pumps the entire circuit would be at sub-atmospheric pressure. The latent heat of water is also very high, about fifteen times that of R-134a at 50°C. These properties raise the prospect of delivering high temperatures, say 150°C, at modest pressures compared to all other working fluid choices, but some of the other properties of water make this a challenging proposition. The swept volume required is extremely high, due to the low density of water vapour, and the pressure ratio required is also quite high, due to the low inlet pressure. For example to raise heat from 50°C to 150°C would require the discharge of the water vapour system to be between 4 and 5 bar gauge but the inlet would be at about 0.1 bar absolute, so the pressure ratio is between 50 and 60. Since water is a relatively simple molecule the isentropic index is quite high, at approximately 1.3 at these conditions. This makes water quite similar to ammonia in this respect, but an ammonia system operating at these pressures would evaporate at –71°C and condense at 4°C. Therefore, in order to keep the discharge temperature down to a tolerable level, many stages of compression are required, with inter-stage cooling between them.

Air

The original concept of the heat pump proposed by Lord Kelvin in 1852 was of an air cycle machine (IEA Heat Pump Centre Newsletter Volume 30 - No. 1/2012 www.heatpumpcentre.org) with compression and expansion cylinders on a common drive shaft burning coal to raise ambient air temperatures sufficiently to heat houses with the discharge air from the compressor. Kelvin calculated that the coefficient of performance of such a system would be 35:1 based on the shaft power when operating between temperatures of 10°C and 27°C, and since a "very good steam engine" converted about 10% of the heat of combustion of the coal in its furnace to shaft power, he concluded that such a device would deliver 3.5 times more heat than could be achieved by burning the same amount of coal in a direct process. He added that if a water wheel were used to drive the compressor and expander the economy would be even more attractive. In Kelvin's preferred arrangement of this apparatus the system could be used for heating or cooling. The system had two cylinders of equal size, one passing air from the outdoor ambient to a large, thin-walled receiver and the second drawing air from the receiver and delivering it to the occupied space. A third, smaller, auxiliary cylinder was used to determine whether the system acted as a heating or cooling device. If it pressurised the air in the receiver, causing the main inlet cylinder to do work on the inlet air, then the receiver would be heated and would lose heat to the surroundings. In this case the outlet cylinder would act as an expander, cooling the air as it brought it back down to atmospheric pressure. If the auxiliary cylinder drew air from the receiver and delivered it to the destination space then the receiver would be below atmospheric pressure and would draw heat from its surroundings. The inlet cylinder would be an expander and the outlet would be the compressor, bringing the air back up to normal pressure but at higher temperature. Kelvin calculated that to deliver air at 27°C when the outside temperature was 10°C would require the receiver to be held at 0.82 bar absolute. In a modern version of Kelvin's system the receiver would be replaced by a finned heat exchanger and the compressor/expander device would probably be a turbocharger with a small screw or reciprocating compressor replacing the auxiliary cylinder.

Kelvin's system could be described as "closed-open". In other words the heat extraction is through a heat exchanger (the thin-walled receiver) and the heat delivery is by direct passage of the air from the system to the occupied space. This is similar to the concept used for train air-conditioners, where the system draws outside air through an expander and a heat exchanger, then compresses it to return it to atmosphere. These systems need to operate below atmospheric pressure in order to achieve the cooling and heating effects. Most modern air cycle systems, in contrast, are "open-closed" or in some cases "closed-closed". When the heat delivery process is through a heat exchanger, or "closed", then the air will be cooled during the delivery of heat. Such a system is best suited to heating through a wide temperature range because there is no phase change in the working fluid. To maximise efficiency the heat exchanger must be designed for counter-current flow, with the inlet (hot) air in contact with the outlet (heated) process fluid and the outlet (cooled) air in contact with the inlet (cold) process fluid. If a crossflow or co-current heat exchanger is used then the operating temperatures need to be much further apart than for the counter-current system and so the temperature lift is higher and the efficiency is far poorer. If high process temperatures are required then the key design challenge is to make a cost-effective counter-current heat exchanger.

Hydrocarbon

The family of short-chain hydrocarbons offers several fluids with favourable properties for high temperature heat pump systems. Butane and isobutane (methyl propane) are particularly attractive because they have high critical temperatures of 136°C and 151°C respectively and so can heat to extremely high temperatures if required. However the operating pressures are moderate, even at high temperatures, and therefore equipment is readily available. For example to condense at 110°C the discharge from the compressor for butane and isobutane would be 17.3 bar g and 23.1 bar g respectively; not significantly different from the discharge pressures of R-22 and R-404A systems. However system application is constrained by safety requirements due to flammability. The quantity of working fluid in the system, also called the refrigerant charge, is used to determine permissible locations. If the system is designed under the jurisdiction of EN 378, the European Standard on refrigeration safety, then the charge of the system is limited to 150 g if it is installed in a location accessible to the general public, such as a school, a supermarket or a hospital, with some relaxation for large spaces where the charge could dissipate safely in the event of a leak. However there is an absolute upper limit of 1.5 kg charge. In supervised occupancies, such as offices and laboratories, the upper limit of charge is 2.5 kg. It is worth noting that the low molecular weight of hydrocarbons means that their liquid density is also comparatively low. It is therefore possible, on a like-for-like basis, to achieve a higher heating capacity from a given weight of refrigerant charge. For example methyl propane is only 60 % of the molecular weight of R-134a and its liquid density at 20°C is only 46% of that of R-134a. With propane the ratios are even lower, at 44% and 41% respectively.

For industrial systems it would be feasible to use much larger hydrocarbon systems with no restriction on charge but the equipment must be installed in a machinery room or outside the building in the open air, and strict precautions against explosions in the event of a leak are required. The charge in these systems can be minimised by using plate-type or plate and shell heat exchangers, but will probably still be larger than the practical limit for a typical sized machinery room due to the low value of the lower flammable limit of the hydrocarbons. The safety precautions include gas detection, ventilation and emergency lighting which must all be rated for operation in a flammable atmosphere, for example as flameproof (Exd) or increased safety (Exe). It is not normally necessary for the heat pump to be certified in this way unless it is intended to operate within a flammable atmosphere, although it will always be subject to a hazard assessment in line with the ATEX directive.

Components are generally widely available for use with hydrocarbons, although in some cases special certification is required. Compatibility of seals and O-rings should be checked, and the lubrication system may require special care because hydrocarbons are highly soluble in most lubricants. Apart from these minor considerations the hydrocarbons, especially butane and methyl propane, are relatively easy to work with, and have low discharge temperatures even over high pressure ratios.

Ammonia

Heat pumps with ammonia operate at relatively high pressures compared to almost all other options. However, as a result of ammonia's high critical temperature, it is possible to achieve excellent efficiency in high-temperature systems. Water can be heated to 90°C taking heat from an ambient source at 8°C with a coefficient of performance of 3.2 and if the source is from waste heat at higher temperatures then the efficiency is of course also much higher. At high temperature and pressure there are some significant challenges to overcome. Refrigerant solubility in lubricant increases, so that the viscosity of the lubricant fed to the compressor is extremely low. Seal materials which are acceptable at lower temperatures and pressures tend to shrink and harden, so alternative materials are required. The resins used in oil filters and coalescers are also affected by the high pressure and temperature which can shorten the filter life and possibly lead to failure of the filter element. Although the operating pressures are high the ratio of discharge to suction pressure is actually very low, so there are some additional challenges with screw compressors in getting the right volume ratio and keeping the compressor at optimal efficiency. Internal forces within the compressor are high due to the high pressure difference between discharge and suction. Vibration levels also tend to be high because of the high density of the discharge gas.

All of these challenges have been overcome, in some cases by selection of alternative materials and in others by redesign of the system components to ensure that the equipment is efficient and reliable. Compressors rated for 75 bar on the discharge side are now available, which in principle will allow heating to about 100°C with allowances for high-pressure safety switch and relief valve settings.

Small to medium-sized heat pumps have also been developed for heat recovery applications, combining the benefits of ammonia and water. These systems use an ammonia/water mixture like an absorption chiller, but with a compressor to raise the gas to high pressure. They give good efficiency at lower operating pressures than the ammonia systems, and can heat to 115°C, but it should be noted that both the heat extract and the heat delivery exchangers operate with a very wide temperature glide on the refrigerant side, as the composition of the ammonia/water mixture changes. This requires a special design of heat exchanger to ensure counterflow heat exchange. It also makes the machines unsuitable for use in water chilling applications due to the risk of freezing. These systems are therefore best suited to applications with high heat source temperatures operating across a wide temperature range, and applications heating fluid through a wide range.

Carbon dioxide

Carbon dioxide heat pumps are very common in smaller sizes, but have not been commercialised in the larger range due to the lack (to date) of a suitable compressor. Like the ammonia/water hybrid, they operate with a wide temperature glide on the high pressure side, but the low pressure side is like a traditional evaporator with phase change at a constant temperature. Operating pressures of 90 to 100 bar are required, so compressors need to be rated for about 120 bar. In the smaller sizes this has been the fastest growing segment of the market and units up to 100 kW heating capacity are now available. There have been no major technical barriers to the implementation of these systems, and no particular issues with availability of materials or components. Small systems are available for both air-source and water-source heat pumps.

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Appendix E: Pinch analysis

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http://www.industrialheatpumps.nl/en/applications/pinch_analysis/

Pinch analysis is a tool that can be used to analyse a set of heat flows and to determine whether it is possible to interchange these heat flows. When application of a heat pump is considered in a complex application, it is useful to carry out a pinch analysis. The goal is to map all heat flows and then connect hot and cold flows that can exchange heat. Furthermore, the analysis shows the amount of cooling and heating needed. A heat pump can be used to couple these needs for cooling and heating.

Procedure

The pinch analysis is a structured method that involves the following steps:

1. Map all process streams inside and in the vicinity of the plant and compose a mass and energy balance.
2. Put the different process streams in a table that shows their supply temperature, desired temperature and heat capacity.
3. Determine the power of the different process streams for different temperature steps and make a graphical representation of these data points.
4. Find out whether or not it is possible to interchange heat between different process flows with the use of heat exchangers.
5. Determine the location of the pinch point and find out if more exchange of heat is needed after direct heat exchange is performed.
6. Depending on the temperature levels and powers a decision can be made on which installation is most suitable to apply.

Example

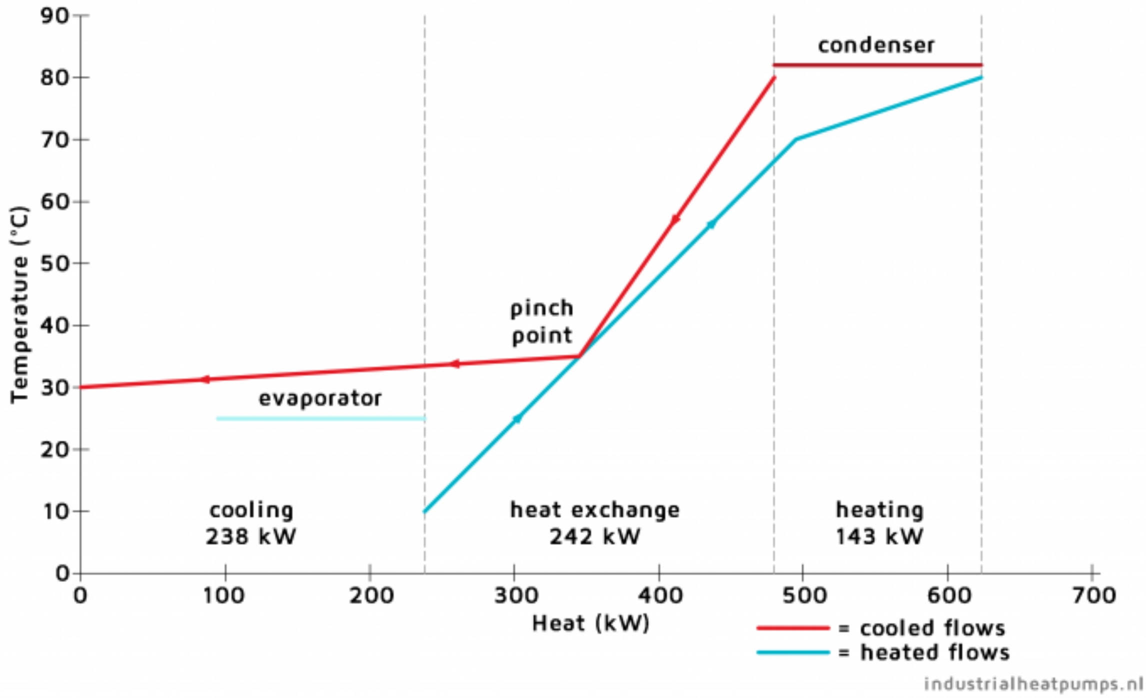
The different steps of a pinch analyses are explained in more detail in the example that is stated below.

1. Map all process streams inside and in the vicinity of the industrial plant and compose a mass and energy balance:
   The example is based on four process streams. Two streams that need to be cooled down and two streams that need to be heated.

2. Put the different process streams in a table that shows their supply temperature, desired temperature and heat capacity:

Flow ID	Flow type	Supply temperature °C	Target temperature °C	Heat capacity kW/°C	Heat kW
1	cooled	35	30	66,0	330
2	cooled	80	30	3,0	150
3	heated	10	80	4,3	-300
4	heated	70	80	8,5	-85

3. Determine the power of the different process streams for different temperature steps and make a graphical representation of these data points. On the x-axis the power (either heating or cooling) is shown and the y-axis shows temperature. Two graphs, one cold stream and one hot stream, are combined in to one graph:



4. By interchanging energy from the cold and hot stream with the use of a heat exchanger, 241 kW of heat can be recovered. Ideally above the pinch point as much a 186 kW of heat is needed while below the pinch point 238 kW of cooling is needed.

5. The pinch point is determined by the location where temperature differences (delta T) between process streams are the smallest. At this point heat exchangers can operate at minimal delta T. For an increase in delta T at the pinch point due to a change in process temperatures, specifications for heat exchangers change. Through combining the graphs of the two product flows, a joint curve is created that gives insight in process streams and temperature variations. At the pinch point a temperature difference of 0°C is kept. In practice a temperature difference is needed to be able to have heat exchange.

6. Depending on the temperature levels and powers a decision can be made on which installation is most suitable to apply: For small temperature difference and a need for heating and cooling that is comparable, a heat pump might be interesting to apply. With the use of a heat pump the cold and hot process streams can be coupled. In this case a heat pump can be

installed that has an evaporation temperature of 25°C and a condensation temperature of 82°C. The remainder is an additional cooling capacity of 50 kW. For a temperature difference that is too big, efficiency of the heat pump will drop to a non-feasible level in which case alternative heating and cooling system have to be installed. Examples of these alternative installations are cooling towers, refrigeration installations and hot water or steam systems.

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