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High-temperature heat pumps

Guidance for applications, integration, and assessment

ENERGY EFFICIENCY & CONSERVATION AUTHORITY
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Executive summary

This guide provides a structured and practical framework for using high-temperature heat pumps (HTHPs) within New Zealand industry. It explains the technical feasibility, economic viability and strategic value of HTHPs for industrial users, and is based on the latest international experience, technology developments and process integration methods.

Heat used during industrial processes (process heat) is a major source of energy consumption, efficiency gaps and greenhouse gas emissions in New Zealand.

Energy efficient, low emissions process heat is therefore a critical focus area for meeting national climate and energy productivity targets, and maintaining industrial competitiveness.

HTHPs have emerged as a key technology for achieving these purposes. HTHPs, including those not yet commercially available, are now capable of supplying process heat in the 100–250°C range and are significantly more efficient than direct electric heating or electrode boilers.

Advances in refrigerants, compressors and cycle technologies have expanded the operating window of HTHPs. Commercial and near-commercial systems are now available in both kilowatts and megawatts, and supply temperatures exceeding 160°C. There has been a strong shift towards natural refrigerants (driven by environmental regulation), safety-by-design approaches and improved performance at high temperatures.

It is vital to note that the success of HTHP projects depends mainly on the HTHP being effectively integrated into the broader industrial system, rather than on the heat pump unit alone. Efficient integration will require careful matching of heat sources and sinks, minimisation of temperature lift, and alignment with how the process operates over time. Pinch analysis is the most effective method for identifying viable opportunities for integrating HTHPs, thereby avoiding inefficient electrification outcomes.

This guide outlines four common heat pump integration patterns, discusses electrical supply and network constraints, and highlights the importance of operational flexibility, reliability and infrastructure reuse. Four case studies are included to show how HTHPs have been used by industries overseas. Simplified financial assessment tools are also provided to support screening and prioritisation.

Overall, when applied in appropriate temperature ranges and integrated using sound thermodynamic principles, HTHP technology is capable of playing a significant central role in improving the energy efficiency and decarbonising of industrial process heat in New Zealand.

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1 Introduction

This guide provides a structured and practical introduction to high-temperature heat pumps (HTHPs) for industry professionals, onsite-engineers and engineering consultants. It explains the underlying concepts behind HTHPs, outlines the current technology used for them and illustrates how HTHPs can be effectively integrated into industrial energy systems.

The guide emphasises the importance of understanding the technology readiness of HTHPs and their suitability for integration, including understanding cycle configurations, evaluating the impacts of refrigerant selection, identifying appropriate heat sources and sinks through pinch analysis, and recognising the potential for reusing existing infrastructure. Case studies and assessment tools are provided to support informed decision-making.

Further general information about HTHPs can be found in *SNZ PAS 5210 High-temperature heat pumps*,[1] which sets out general principles, terminology and background information for the technology.

1.1 Overview of high-temperature heat pumps

Within New Zealand, there is significant potential for HTHPs to improve energy efficiency, reduce fossil gas and coal consumption, and accelerate progress towards national emissions-reduction and energy productivity targets.

Like conventional heat pumps and refrigeration, HTHPs rely on a thermodynamic cycle. Normally, this cycle is either a vapour-compression cycle, a reverse Stirling cycle, a reverse Rankine cycle or a reverse Brayton cycle.[2] Each of these cycles works by upgrading low-temperature thermal energy to supply higher temperatures. To deliver heat at significantly elevated temperatures, HTHPs are engineered to handle the required pressures and can be scaled to suit a range of industrial applications.

Recent advances in refrigerants, compressor technologies and cycle configurations have extended the feasible operating ranges of HTHPs, making them increasingly viable for producing hot water and steam, and delivering direct process heating in the 100–250°C range. These advances have been well summarised and documented by the Technology Collaboration Programme's IEA HPT projects 58[3] and 68.[4]

At the core of every HTHP is the thermodynamic dependence between the temperature lift and coefficient of performance (COP). As the temperature difference between the heat source (i.e., the stream to be cooled) and the heat sink (i.e., the stream to be heated) increases, the maximum COP declines according to the Carnot and Lorenz models. As a result, efficient system design is critical for HTHPs.

Designing an efficient HTHP system requires consideration of four aspects.

- Refrigerant – the inherent thermodynamic properties and relations of the specific refrigerant fluid (see Section 3).

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[1] Standards New Zealand. (2026). *SNZ PAS 5210:2026 High-temperature heat pumps.* https://www.standards.govt.nz/shop/SNZ-PAS-52102026
[2] The reverse Brayton cycle is also known as a Joule cycle.
[3] Technology Collaboration Programme. (n.d.a). *Project 58: Task 1: Technologies – state of the art and ongoing developments for systems and components.* https://heatpumpingtechnologies.org/project58/task1/
[4] Technology Collaboration Programme. (n.d.b). *Project 68 – Industrial high-temperature heat pumps: Task 1: Technologies, 2025.* https://heatpumpingtechnologies.org/publications/project-68-industrial-high-temperature-heat-pumps-task-1-technologies-2025/

- Component technology – the individual performance characteristics of compression, expansion, heat exchange and ancillary components (not directly covered in this guide – speak with a heat pump supplier).
- Cycle architecture – the internal layout of components within the heat pump itself, including whether the heat pump operates as an open or closed cycle (see Section 4).
- System integration – how the heat pump connects to the process and its final heating demand through new and reused infrastructure (see Section 6).

Together, the first three aspects help to define how the HTHP performs for given cycle pressures, while the fourth aspect influences external efficiencies related to heat transfer and system-level performance.

2 Potential uses for New Zealand industry

Increasing and volatile non-renewable energy prices alongside supply uncertainties are increasingly motivating industrial energy users to consider more efficient and renewable alternatives.

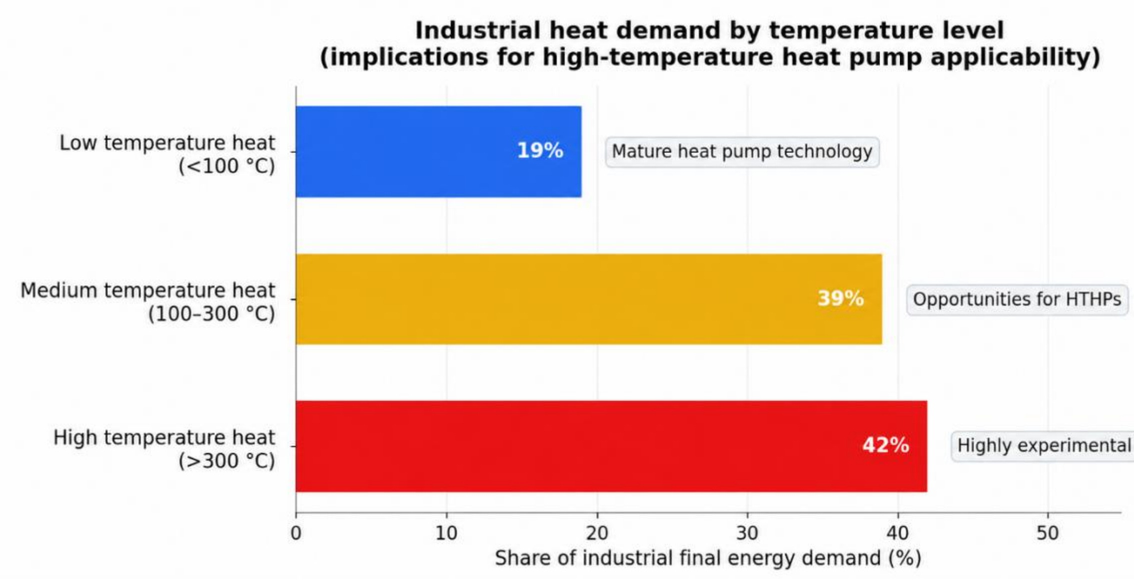
For example, New Zealand's declining domestic production continues to drive increased prices and a tight gas supply environment (domestic natural gas production fell 20.8% to 118 PJ in 2024 and is projected to continue to fall). New Zealand's gas use is highly concentrated to industrial energy users (60%) in the north island and 48% is consumed by industrial boilers alone.

In 2023, 60% (68.7 PJ) of all energy demand for industrial process heating was supplied by fossil fuels[5] and accounted for 21% of all energy-related greenhouse gas emissions in New Zealand.[6] The risk of higher carbon prices and customers increasingly demanding low emission products is also a motivating factor for many industrial energy users.[7]

Low-cost biomass (e.g., from forest residue) is predicted to only be able to supply 22% of the energy for process heat that is currently generated from fossil fuels,[8] while electrode boilers and hydrogen technologies are costly to operate.

HTHP technology offers a more energy efficient, low-emission option for generating process heat that is suitable for a range of industries.[9]

The 2023 profile for New Zealand's industrial process heat (see Figure 1) shows that about 58%, or 66.7 PJ, of the heat demand is in the low to intermediate range (< 300 °C) – which is the sweet spot for HTHPs. Approximately 39% of heat demand is for >300 °C, where HTHPs can still reduce use of other fuels by being used to preheat process streams (where applicable).



[5] EECA. (2025). *Energy end use database*. Retrieved on 8 January 2026. https://www.eeca.govt.nz/insights/data-tools/energy-end-use-database/
[6] Ministry for the Environment. (2025). *Te rārangi haurehu kati mahana a Aotearoa 1990–2023: New Zealand's greenhouse gas inventory 1990–2023*. Ministry for the Environment. https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-19902023/
[7] Ministry of Business, Innovation, and Employment. (2025). *Energy in New Zealand 25.* https://www.mbie.govt.nz/assets/energy_in_new_zealand_2025.pdf
[8] Hall, P. (2017). *Residual biomass fuel projections for New Zealand: Indicative availability by region and source.* Scion.
[9] Arpagaus, C., Bless, F., Schiffmann, J., & Bertsch, S. S. (2016). Multi-temperature heat pumps: A literature review. *International Journal of Refrigeration*, 69, 437–465. https://doi.org/10.1016/j.ijrefrig.2016.05.014

Figure 1. Industrial process heat use by temperature band in 2023
Source: EECA (2025); see footnote 6

By sector (see Figure 2), the largest electrification opportunities are in the dairy industry, where the total energy demand for process heat is approximately 27.7 PJ.[10] This is predominantly for low- and medium-temperature duties that would be well suited to HTHPs, such as clean-in-place, pasteurisation, evaporation and spray drying activities.

The wood products manufacturing (around 18.1 PJ) and pulp and paper (around 12.1 PJ) sectors both involve intensive medium-temperature duties.[11] HTHPs are ideal for drying and process-water preheating activities in these contexts, and are often complemented by existing biomass systems to enhance overall efficiency.

In the primary metal, and petrochemical and chemical manufacturing sectors, most final process duties require temperatures exceeding 300°C. However, HTHPs can still deliver significant value if integrated into the manufacturing process through preheating combustion air, feedwater and the process stream, and enabling waste-heat recovery from the cooling systems. As a result, fossil fuel input per tonne of product is reduced, even when direct-fired systems remain necessary for achieving the final temperature.

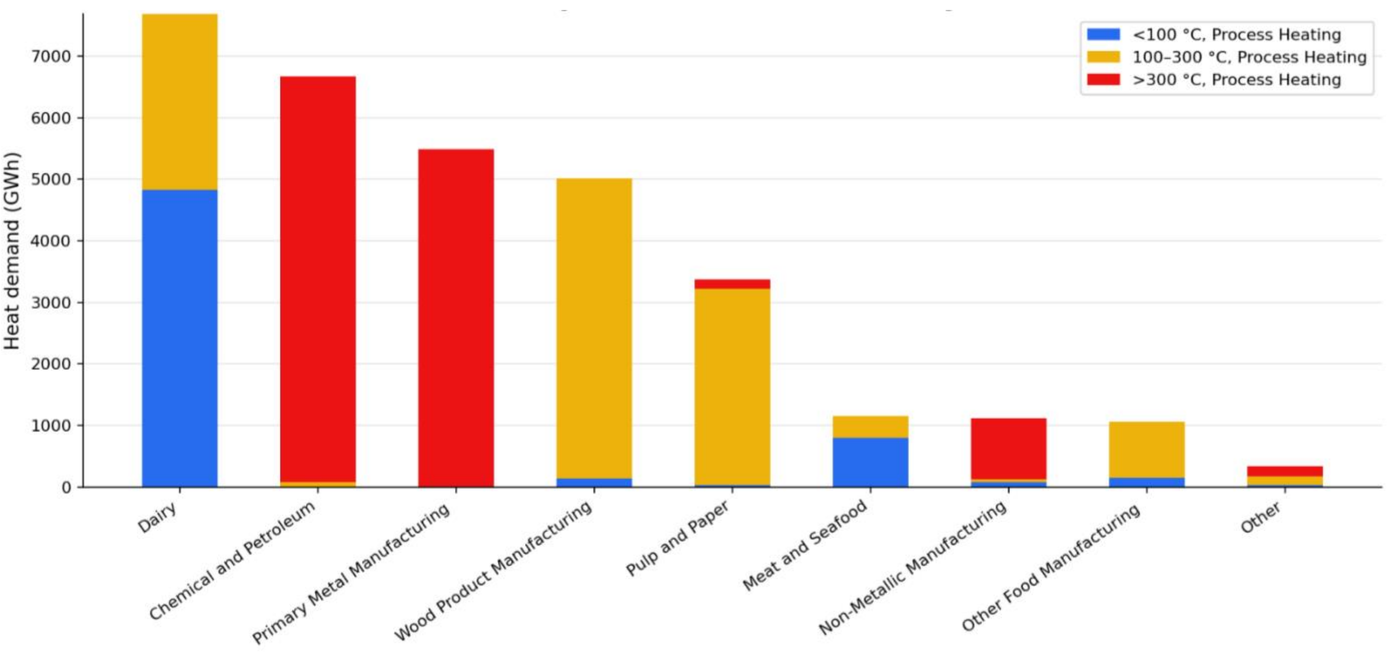


Figure 2. Industrial process heat energy demand by sector and temperature range in 2023
Source: EECA (2025); see footnote 6

A diverse range of industrial processes are suitable for HTHP integration. However, the feasibility of such integration depends on the temperature range required, the stability of the process, and the capacity and temperatures of both the source and the sink streams. Moreover, the type of process (batch, semi-continuous or continuous), the annual operating hours of the plant, and the existing energy infrastructure will all have a significant influence on techno-economic factors that affect feasibility.

[10] See footnote 5.
[11] See footnote 5.

An often-overlooked requirement for integrating a HTHP system into an industrial process is to have an adequate heat source for the pump to draw from that matches the timing of the heat sink (although this requirement can potentially be supported by thermal storage). Typical heat sources for HTHPs include waste heat from industrial processes (such as refrigeration systems), cooling water streams being directed to cooling towers, process and recirculation streams, exhaust air (particularly when moisture content is high) and other effluent streams. There are also low- or zero-cost renewable heat sources, including solar thermal, geothermal energy, sea or river water, and ambient air.[12]

On the heat sink side, HTHPs can deliver heating directly to process streams or indirectly through intermediate utility streams. Mechanical vapour recompression (MVR) systems are a special class of HTHPs, where the process stream itself acts as the working fluid (refrigerant) in an open-loop vapour-compression cycle. MVR systems have been successfully applied in a wide range of industries, including in distillation units and trains, reducing energy consumption up to 65%.[13]

Figure 3 shows some suitable uses for HTHPs across different industrial sectors. The temperature bands indicate how ready heat pump technology is to be used at various temperatures for each process, as of 2025.[14] The figure demonstrates there is significant potential for HTHPs to be used in the pulp and paper, food and beverage, chemicals, metals, plastics, automotive, wood and textiles sectors. Common uses for HTHPs within these sectors include drying, pasteurisation, sterilisation, evaporation and distillation.

[12] See footnote 3.
[13] Xu, Y., Li, J., Ye, Q., & Li, Y. (2021). Design and optimization for the separation of tetrahydrofuran/isopropanol/water using heat pump assisted heat-integrated extractive distillation. Separation and Purification Technology, 277, 119498. https://doi.org/10.1016/j.seppur.2021.119498
[14] Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., & Bertsch, S. S. (2018). High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy, 152, pp. 985–1010. https://doi.org/10.1016/j.energy.2018.03.166

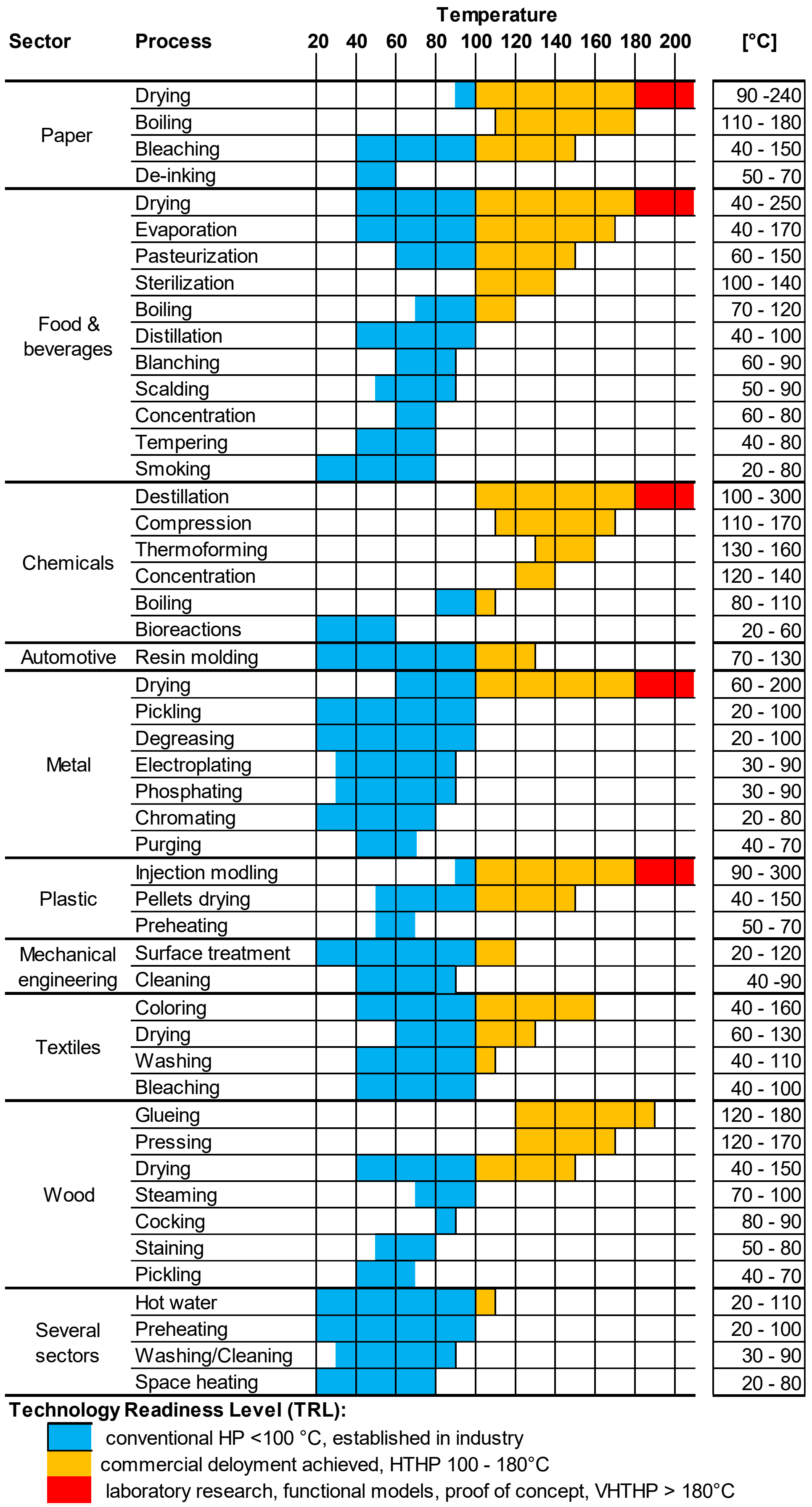


Figure 3. Potential processes and their respective sectors in which HTHPs could be implemented
Source: Updated from Arpagaus et al. (2018), p. 6; see footnote 14

3 High-temperature heat pump refrigerants

How well a HTHP performs for a given process, and its safety and complexity, depend heavily on selecting the most appropriate refrigerant (or managing constraints on the refrigerants able to be selected) and identifying which HTHP cycle configuration is most suitable for the process (see Section 4).

This section discusses the common refrigerants used in HTHPs and factors to consider in selecting a suitable refrigerant.

There is more information about the types of refrigerants suitable for specific HTHP cycle configurations in Section 4.

3.1 Types of refrigerants

The refrigerant used will directly influence the thermodynamic cycle, overall performance, safety and system design of a HTHP, and whether it complies with environmental regulations. Selecting an appropriate refrigerant requires balancing multiple criteria, often with competing priorities.

Key factors to consider include:

- safety – toxicity, flammability and operating pressures
- environmental impact and regulations – global warming potential and ozone depletion potential
- thermodynamic suitability – ability to achieve the required temperature lift and heating capacity efficiently
- economic and practical considerations – availability, cost and long-term regulatory viability.

No single refrigerant performs best across all these areas. The optimal choice will depend on the specific application, the operating temperature range and any integration constraints.

Refrigerants for HTHPs can be broadly grouped into synthetic refrigerants – hydrofluorocarbons (HFCs), hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs) – and natural refrigerants. In general, synthetic refrigerants have been manufactured for higher performance; however, there are uncertainties around their environmental impact. Conversely, natural refrigerants are considered to have lower environmental impact, but it can be challenging for them to meet performance and safety criteria.

Table 1 summarises the common refrigerants available for HTHPs, including their advantages, limitations and risks. Additional information is available in the New Zealand HTHP specification: SNZ PAS 5210.[15]

The suitability of the refrigerants for specific cycle configurations is discussed in Section 3.2.

[15] See footnote 1.

Table 1. Types of refrigerants available and key features

Category	Refrigerant type or family	Examples and application range	Main advantages	Main limitations and risks	Regulatory and application outlook
Synthetic	Hydrofluorocarbons (HFCs)	R410A, R134a, R404A Upper limit produced: ~130 °C Typical capacity: 0.03–1 MW	Good thermodynamic performance; low toxicity; often a fire retardant	High global warming potential	Being phased out globally under the Kigali Amendment; generally not considered future-proof for new heat pump or refrigeration projects
Synthetic	Hydrofluoroolefins (HFOs) and low global warming potential hydrochlorofluoroolefins (HCFOs)	R1234ze(E), R1233zd, R515B Upper limit produced: ~185 °C Typical capacity: 0.02–3 MW	Low global warming potential; attractive operating pressures; promoted as replacements for HFCs	Some degrade into trifluoroacetic acid, a persistent PFAS (forever chemical); environmental persistence and water-body accumulation are significant concerns; long-term acceptability is uncertain	Regulatory direction is evolving, especially in the EU, creating uncertainty despite current technical attractiveness
Natural	Ammonia (R717)	R717 Upper limit produced: ~95 °C Typical capacity: 0.5–10 MW	Excellent thermodynamic performance; high volumetric heating capacity; efficient operation up to approximately 95 °C; well established in industrial systems	Toxicity and moderate flammability require strict safety design and monitoring; large refrigerant charges in large-scale HTHPs increase containment and ventilation complexity	Strong candidate for industrial and large-scale HTHPs where safety measures can be robustly implemented
Natural	Hydrocarbons	Propane, butane, pentane Upper limit produced: ~180 °C Typical capacity: 0.01–3 MW	High critical temperatures; very low global warming potential; suitable for HTHPs above 100 °C; potentially high COPs	High flammability limits require safety considerations, especially in large systems with significant refrigerant charge; lower volumetric heating capacity than ammonia and CO_2 systems lead to larger compressors and heat exchangers	Growing adoption globally for low-charge systems, and likely to scale in the future as safety measures are proven in industrial settings
Natural	Carbon dioxide (R744)	R744 / CO_2 Upper limit produced: ~150 °C	Non-flammable; low toxicity; global warming potential of 1; very high volumetric heating capacity enables compact	Very high operating pressures, about 140 bar in transcritical operation; requires specialised components and rigorous safety systems, increasing capital cost	Effective for hot-water and air-heating duties with low return temperature; can outperform other natural refrigerants in

Category	Refrigerant type or family	Examples and application range	Main advantages	Main limitations and risks	Regulatory and application outlook
		Typical capacity: 0.1–50 MW	designs, useful in retrofit applications		large-scale applications with moderate temperature lifts
Natural	Water (R718)	R718 / water Upper limit produced: ~250°C Typical capacity: 0.4–50 MW	Abundant; low cost; excellent thermal stability; very high COPs possible in steam compression and MVR applications	High boiling point restricts use to processes with sufficiently hot waste-heat sources; at lower source temperatures, large volumetric flow rates and multi-stage compression increase system size and cost	Attractive for high-temperature applications where suitable waste-heat sources are available
Natural	Air	Air Upper limit produced: ~250°C Typical capacity: 0.5–5 MW	Environmentally benign; universally available; excellent safety profile	Low density and low specific heat capacity lead to poor COPs and large components	Mainly relevant for open-Brayton or reversed-Brayton cycle heat pumps, where expander-based work recovery can partially offset low performance
Natural	Helium (R704)	R704 / helium Upper limit produced: ~250°C Typical capacity: 0.5–5 MW	Inert; non-toxic; non-flammable; zero global warming potential and ozone depletion potential; suitable for very high-temperature vapour-only cycles; can exceed 200°C	Very low density leads to large volumetric flow rates, large compressors, and generally lower COPs than condensable-refrigerant vapour-compression systems; limited availability and high cost	Best suited to smaller sites, high-temperature applications where safety, chemical inertness, or extreme temperature capability outweigh efficiency and cost disadvantages

3.2 Key considerations for selecting a refrigerant

Each type of refrigerant presents distinct trade-offs between efficiency, environmental impact and operational safety. Refrigerant selection should therefore be informed by a whole-of-lifecycle perspective.

- Where halogenated synthetic refrigerants are considered, try to prioritise the lowest feasible global warming potential and also minimise the amount of refrigerant charge. Systems should be designed to achieve very low leakage rates and include appropriate provisions for refrigerant recovery and end-of-life management.

- HFOs and HCFOs may serve as transitional refrigerants, and offer moderate operating pressures and improved environmental performance compared with legacy HFCs. However, their long-term suitability depends on evolving regulatory settings. Where these refrigerants are selected, the technical rationale (including performance requirements and safety constraints) should be documented, compliance with local regulatory requirements confirmed, and plans established for monitoring or substituting the refrigerant if policy requirements tighten.
- In many applications, natural refrigerants such as ammonia (NH_3), carbon dioxide (CO_2), hydrocarbons, and water or steam may represent a more future-resilient option, provided site-specific safety and process constraints can be effectively managed. Ammonia and hydrocarbons offer high thermodynamic efficiency, but require careful management of toxicity and flammability risks; while CO_2 and water are environmentally benign, but necessitate specialised system design to accommodate high pressures or large volumetric flow rates.

Ongoing advances in component design, lubrication and materials compatibility will be important to expand the safe operating envelopes of natural refrigerants and support their greater use in industrial HTHP applications.

4 High-temperature heat pump cycle configurations

This section provides an overview of the HTHP cycle technologies and configurations relevant for industrial process heat applications.

Each subsection describes a distinct class of heat pump configuration, outlining its fundamental operating principle, typical system architecture and key performance characteristics. The intention is not to provide an exhaustive design review but instead highlight the configurations' suitability for different industrial uses.

Table 2 provides an overview of the different heat pump configurations discussed.

The different types of configuration introduced here provide a foundation for the subsequent discussion of integration strategies and performance trade-offs in Section 6.

Table 2. Overview of high-temperature heat pump cycle technologies

Cycles	Common refrigerants	Advantages	Limitations and challenges	Applications
Simple vapour compression heat pumps – Section 4.1	Ammonia, hydrocarbons, CO_2, HFCs/HFOs	Mature technology, simple design, high efficiency, wide range of capacities and temperatures	Limited temperature lift	Water heating, food processing, drying, low to medium pressure steam Typical range: 60–120 °C supply temperature, 50 kW–10 MW heating capacity
Vapour compression heat pumps with subcooling – Section 4.2	Same as simple vapour compression heat pumps (especially hydrocarbons)	Improves COP, enables integration in industrial systems with multiple heating demands at different temperature levels	More complex, requires extra heat exchanger, offers limited benefit without a usable heat recovery stream	Systems with multiple heat demands at different temperature levels
Vapour compression heat pumps with internal heat exchangers – Section 4.3	Same as simple vapour compression heat pumps (hydrocarbons benefit most)	Improved reliability and performance of vapour compression heat pumps	Increases compressor work	Systems needing stable suction conditions
Open-cycle vapour compression heat pumps – Section 4.4	Water vapour, steam, process vapours	Very high energy efficiency, well-established technology	Complex, higher capital cost	Industrial evaporation processes (food processing, dairy, pulp and paper, and chemical production) Typical range: ~0.1–10+ bar steam, 0.5–50+ MW heating capacity
Heat-booster heat pumps – Section 4.5	Ammonia (common), water vapour (mechanical vapour compression stage)	High efficiency at large temperature lifts, enables steam generation from low-temperature heat sources	Complex, costly integration	Steam-intensive industries (food processing, chemical production)
Customised advanced vapour	Same as simple vapour compression heat pumps;	Better temperature matching, higher overall temperature lift	Complex design, higher cost, sensitive to control	Multi-level heating demands

Cycles	Common refrigerants	Advantages	Limitations and challenges	Applications
compression cycles – Section 4.6	cascade systems use different refrigerants per cycle			
Transcritical vapour compression heat pumps – Section 4.7	CO_2	Good for processes with large temperature glide, not limited by critical temperature	High discharge pressures and temperatures, higher expansion losses	Large temperature rise processes (hot-water generation and drying) Typical range: 50 kW–6 MW heating capacity with supply temperature 60–130 °C; 10–50 MW heating capacity with supply temperature up to 150 °C
Stirling heat pumps – Section 4.8	Helium (most popular), nitrogen	Very high temperature lift, environmentally friendly refrigerant	Complex mechanics, lower COP, larger equipment	High-temperature industrial processes (>200 °C) Typical range: 0.3–10 MW with supply temperature 200–250 °C
Brayton heat pumps – Section 4.9	Air, nitrogen, argon and other gas mixtures	Very high supply temperatures, environmentally friendly refrigerants	Large heat exchangers, low COP at moderate lifts	High-temperature processes with large temperature glides (e.g., drying) Typical range: 50 kW–1 MW heating capacity, supply temperature up to ~300 °C

4.1 Simple vapour compression heat pumps

4.1.1 Cycle overview

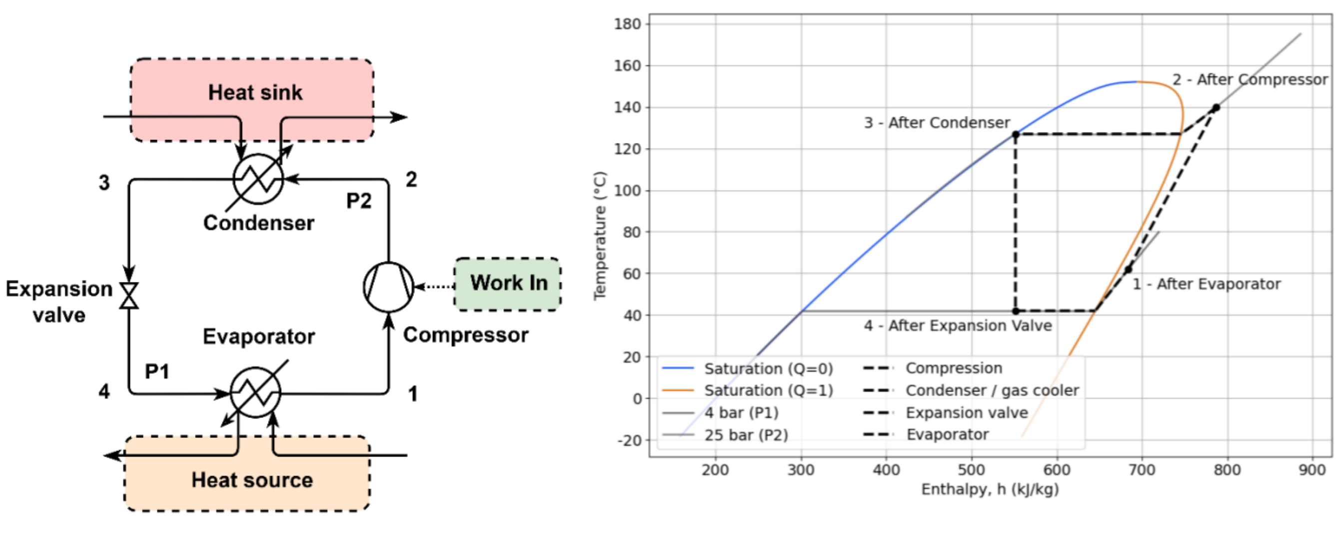
The simple vapour compression heat pump is the most fundamental and widely applied heat pump configuration. The cycle consists of four main thermodynamic processes:

- heat absorption (evaporation)
- compression (increasing pressure and temperature)
- heat rejection (condensation or gas cooling)
- expansion (pressure reduction before re-entering the evaporator).

Figure 4 shows the fundamental cycle architecture (a) and temperature–enthalpy diagram (b) for simple vapour compression heat pumps.

The cycle is a closed cycle, meaning the refrigerant remains contained within the system and transfers heat between a defined heat source and a heat sink via heat exchangers. Heat is absorbed from the source in the evaporator, as the refrigerant vaporises (process 4–1). The vapour is then compressed to a higher pressure and temperature (process 1–2), before rejecting heat at the higher temperature level in the condenser or gas cooler (process 2–3). The refrigerant is subsequently expanded through a throttling device to reduce its pressure before returning to the evaporator to repeat the cycle (process 3–4).

This simple cycle configuration forms the basis for many advanced heat pump architectures used in industrial HTHP systems.



a) b)

Figure 4. (a) Simple vapour compression heat pump; (b) Temperature-enthalpy plot for the cycle

4.1.2 Common refrigerants

Vapour compression heat pumps can operate with a wide range of refrigerants, allowing the cycle to be adapted to different operating conditions and temperature levels. Common refrigerants used include natural refrigerants (such as ammonia (R717)), hydrocarbons (such as propane (R290), isobutane (R600a) and pentane (R601)), and carbon dioxide (R744). Synthetic refrigerants are also used in some systems, including HFCs and HFOs (such as R134a, R1234ze(E) and R1233zd(E)). The refrigerant selected will strongly influence the achievable supply temperatures, pressure levels and overall system performance.

4.1.3 Advantages

Vapour compression heat pumps are widely applied due to their technological maturity, relatively simple system architecture and high thermodynamic efficiency. The cycle can be implemented across a wide range of capacities and operating temperatures by selecting appropriate refrigerants and compressor technologies. The closed-cycle configuration also enables heat to be recovered from many different heat sources and upgraded for use in industrial heating applications.

4.1.4 Limitations and challenges

Despite their widespread use, vapour compression heat pumps are subject to several limitations. The achievable temperature lift is constrained by the refrigerant's thermophysical properties, and compressor discharge temperatures (which are themselves limited by the lubricants' operating temperatures and pressure ratio limits). At higher supply temperatures, the required condensing pressure and discharge temperature increase, which can make compressor operation challenging due to lubricant limitations and elevated mechanical stresses. As a result, it may be necessary to make additional cycle modifications or use alternative heat pump technologies for very high-temperature applications.

4.1.5 Applications

In industrial settings, simple vapour compression heat pumps are commonly used to recover waste heat from process streams, cooling systems or wastewater, and upgrade the heat to temperatures suitable for process heating.

Typical applications include water heating, process heating in the food and beverage industry, drying processes, and low- to medium-pressure steam generation.

Vapour compression systems commonly supply heat in the range of 60 °C to 120 °C, although some systems can reach higher temperatures depending on the refrigerant and system configuration. Industrial installations typically have thermal capacities ranging from approximately 50 kW to 10 MW. These systems are particularly suited to applications with moderate temperature lifts, where stable heat sources such as process cooling water, refrigeration systems or wastewater are available.

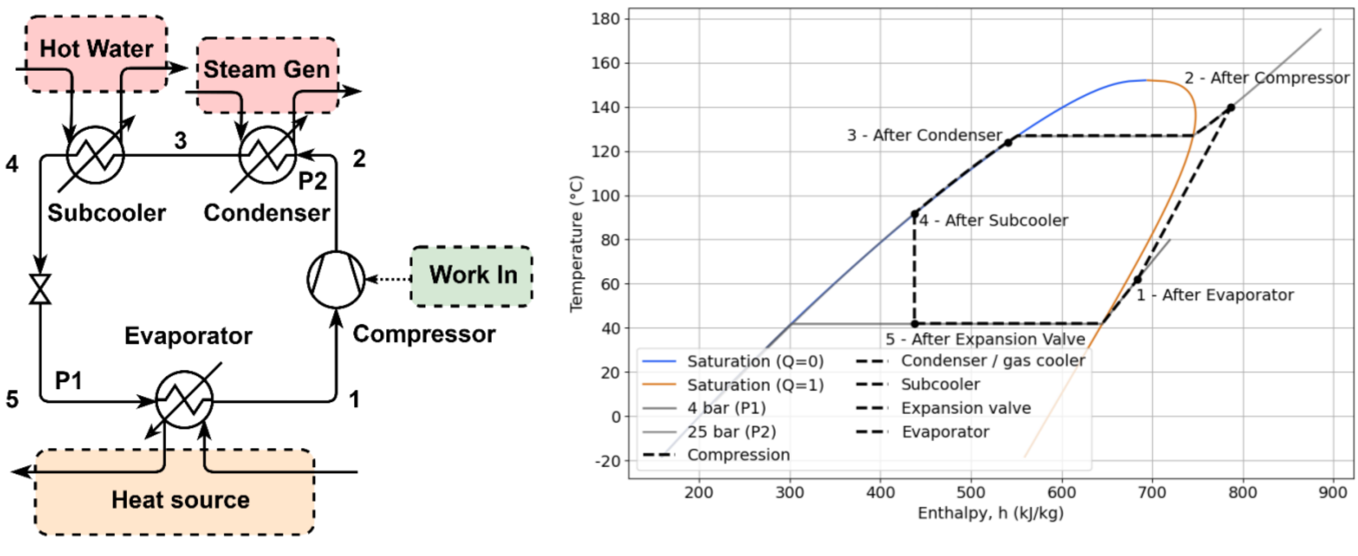
4.2 Vapour compression heat pumps with subcooling

4.2.1 Cycle overview

Subcooling refers to the process whereby the condensed liquid refrigerant is cooled to below its saturation temperature before it is expanded. In vapour compression heat pumps, this is typically achieved using a dedicated subcooler located downstream of the condenser.

Figure 5 shows a schematic diagram (a) and the temperature–enthalpy plot (b) for a subcritical single-stage vapour compression system with a subcooler.

After the condenser (point 3), the liquid refrigerant is further cooled before entering the expansion device (point 4). Lowering the refrigerant's temperature before throttling reduces the amount of flash vapour that is generated during expansion, increasing the useful heating or refrigeration effect of the cycle.



a) b)

Figure 5. (a) Subcritical single-stage vapour compression system with subcooler; (b) Temperature-enthalpy plot for the cycle

4.2.2 Common refrigerants

The refrigerants used in subcooled vapour compression systems are generally similar to those used for simple vapour compression cycle systems. How much the system's performance improves from subcooling will depend on the thermophysical properties of the refrigerant. In general, refrigerants with higher flash gas fractions after expansion, such as hydrocarbons, tend to benefit more from being subcooled, while refrigerants such as ammonia typically experience smaller efficiency gains.

4.2.3 Advantages

Subcooling can improve the performance of vapour compression heat pumps by reducing the amount of flash vapour formed during the expansion process. By lowering the temperature of the liquid refrigerant before it is expanded, more of the refrigerant is available to contribute to useful heat transfer, which increases the effective heating or cooling capacity of the system. This can result in an improvement in COP.

Using a separate subcooler can also provide added flexibility for heat integration. The heat removed during subcooling can be recovered and used to heat another process stream. This can be useful in industrial systems that have multiple heating demands at different temperature levels.

4.2.4 Limitations and challenges

The benefits of subcooling can be modest and will depend on the operating conditions of the heat pump.

Adding a separate subcooler also increases system complexity and requires additional heat exchanger area. If there is no suitable process stream to use the recovered heat, the practical benefit of installing a dedicated subcooler may be limited.

4.2.5 Applications

An example of where it may be beneficial to use a subcooler is in an industrial hot-water heating system that supplies water at 90 °C. The return water may enter the heat pump at around 30 °C. The water can first pass through the subcooler, where it is preheated using the subcooling heat from the refrigerant. The partially heated water then enters the condenser, where it is heated to the final supply temperature.

4.3 Vapour compression heat pumps with internal heat exchangers

4.3.1 Cycle overview

An internal heat exchanger transfers heat within the refrigerant loop of a vapour compression heat pump. Heat is generally exchanged between the high-pressure liquid refrigerant leaving the condenser (or gas cooler) and the low-pressure vapour exiting the evaporator.

This internal heat transfer simultaneously subcools the liquid refrigerant before it reaches the expansion valve and superheats the suction vapour entering the compressor. On the one hand, subcooling can improve system performance by increasing the useful refrigeration or heating effect, while superheating prevents wet compression. On the other hand, superheating also increases the work of the compressor, due to higher vapour-specific volume and enthalpy. The overall benefit therefore depends on the balance between these opposing effects. The heat exchange occurs entirely within the cycle and does not interact with external heat sources or sinks.

4.3.2 Common refrigerants

Internal heat exchangers can be used with the same refrigerants as are used in the simple vapour compression cycle. Refrigerants that benefit most from internal heat exchange are typically those for which the performance gains from liquid subcooling outweigh the additional compressor work caused by suction superheating. Hydrocarbon refrigerants often benefit from internal heat exchangers because they tolerate higher suction superheating and require dry compression. The performance benefit for refrigerants such as ammonia can be smaller, depending on the operating conditions.

4.3.3 Advantages

Internal heat exchangers can improve the reliability and performance of vapour compression heat pumps by recovering heat within the refrigerant cycle. By transferring heat from the high-pressure liquid stream to the low-pressure vapour stream, the liquid refrigerant is subcooled before it is expanded and the suction vapour is superheated before entering the compressor.

In some systems, the reduced throttling losses and improved evaporator use associated with an internal heat exchanger can lead to a small improvement in the COP (typically less than about 5%), depending on the refrigerant and operating conditions.

4.3.4 Limitations and challenges

The overall benefit of an internal heat exchanger depends on whether the reduced throttling losses and improved evaporator use that the exchanger enables will outweigh the increase in compressor work required. In some systems, the net efficiency improvement will be limited, and in certain cases the impact on performance may be negligible.

4.3.5 Applications

Internal heat exchangers are commonly implemented in vapour compression heat pumps where stable suction conditions are required, particularly in systems using hydrocarbon refrigerants.

4.4 Open-cycle vapour compression heat pumps

4.4.1 Cycle overview

Mechanical vapour compression (MVC), including MVR, is an open-cycle heat pump technology in which the process vapour itself acts as the working fluid. Unlike closed-vapour compression systems, the vapour is not contained within a refrigerant loop, but is instead directly compressed and reused within the process.

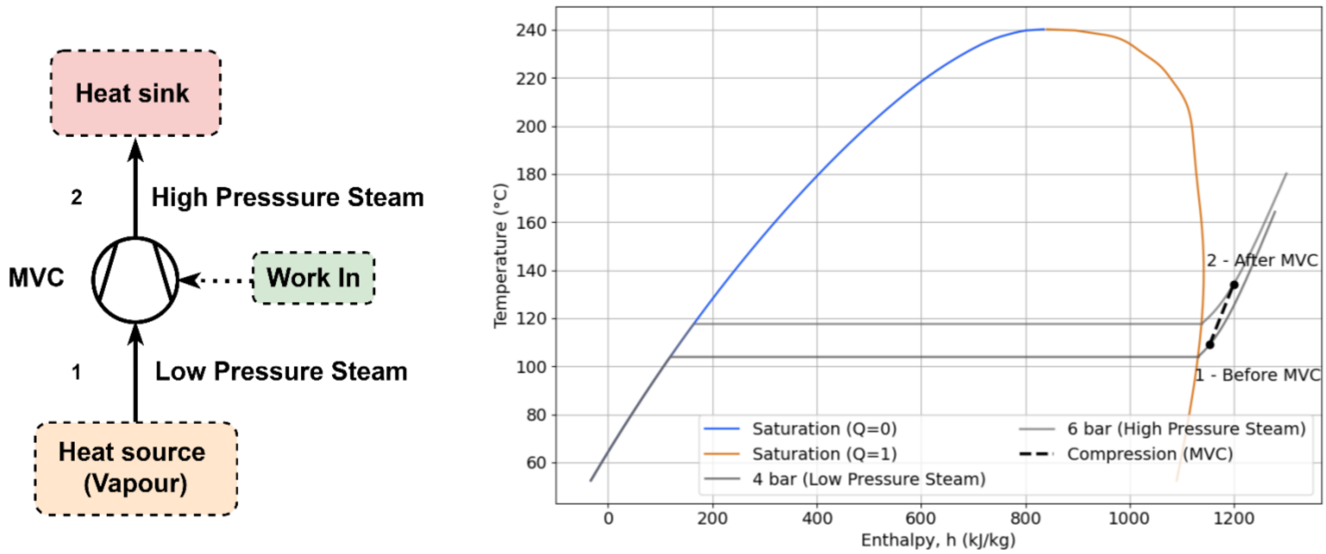
Figure 6 shows a schematic diagram (a), and a temperature-enthalpy plot (b) for an open-cycle compression heat pump.

In operation, low-pressure vapour is mechanically compressed using a blower or compressor, increasing both the vapour's pressure and saturation temperature. The upgraded vapour can then condense at a higher temperature and release its latent heat to the process. This allows the recovered energy to be reused as useful heating.

The distinction between compressors and MVR fans is mainly the achievable pressure ratio. Compressors typically operate at pressure ratios greater than about 3, while MVR fans generally operate at lower pressure ratios, typically in the range of 1.1 to 1.3. In MVR fans, the achievable shaft speed sets this limit, whereas in compressors, the compression mechanism itself determines the pressure ratio.

4.4.2 Common refrigerants

MVC systems do not use a separate refrigerant. Instead, the process vapour itself acts as the working fluid. In many industrial applications this vapour is water vapour or steam, although other process vapours may also be compressed.



a) b)

Figure 6. (a) Open-cycle heat pump using the mechanical vapour compression principle; (b) Temperature-enthalpy plot for the cycle

4.4.3 Advantages

MVC systems can achieve very high energy efficiency because they recover and reuse the latent heat of the process vapour. Only a relatively small amount of mechanical energy is required to compress the vapour compared with the large amount of heat that can be recovered during condensation.

The technology is already well established in several industrial processes, and can be integrated directly into existing evaporation, distillation and flashing systems where suitable vapour streams are available.

4.4.4 Limitations and challenges

MVC systems rely on the availability of a suitable vapour stream within the process. As a result, their application is generally limited to processes where vapour is already generated, such as evaporation, distillation or flashing systems.

The achievable temperature lift in a single stage is also typically small, particularly when using MVR fans. Larger temperature lifts may require multiple compression stages, which increases system complexity and equipment cost.

4.4.5 Applications

MVC is widely used in evaporation processes where vapour generated within the process can be recompressed and reused as a heating medium.

Single-stage systems are typically used where the required temperature lift is relatively small, often 2–10 °C; multi-stage systems can achieve significantly larger lifts.

A common example of MVC's use is in dairy evaporation plants, where the required temperature lift can be very small. In these cases, temperature lifts of around 4 °C have been reported with typical COP values in the range of 40–60.

Where larger temperature lifts are required, multiple blowers or compression stages can be connected in series while still maintaining comparatively high efficiency. For example, waste vapour at around 60 °C can be recompressed to approximately 130 °C (a temperature lift of about 70 °C) with a COP of roughly 4.5.[16]

MVC systems are widely used in industrial evaporation processes, particularly in industries such as food processing, dairy, pulp and paper, and chemical production where large quantities of vapour are generated and can be recompressed for heat recovery.

In these systems, the working fluid is typically water vapour. MVC systems commonly operate with steam pressures ranging from approximately 0.1 bar to above 10 bar, corresponding to saturation temperatures of roughly 45 °C to 200 °C.

Commercial MVC installations typically range from 0.5 MW to over 50 MW of thermal capacity depending on the process scale.

4.5 Heat-booster heat pumps

4.5.1 Cycle overview

Heat-booster heat pumps are hybrid systems that combine a closed-cycle vapour compression heat pump with MVC to achieve larger overall temperature lifts. In this configuration, the closed-cycle heat pump is first used to produce pressurised hot water, typically at temperatures around 80–90 °C. This hot water is then flashed in a flash tank to generate low-pressure steam.

The low-pressure steam is subsequently compressed using one or more MVC stages to reach the required pressure and temperature for the process, as shown in Figure 7.

By combining these two technologies, the system can efficiently span a larger temperature range than either technology could achieve alone.

[16] Schumm, G. (n.d.). Optimizing EPDM plants: Waste heat recovery in thermal separation processes through steam generation using MVR Blower Technology, Annex 58.
https://heatpumpingtechnologies.org/content/uploads/sites/81/2025/12/a58demo10pillerepdm20251104.pdf

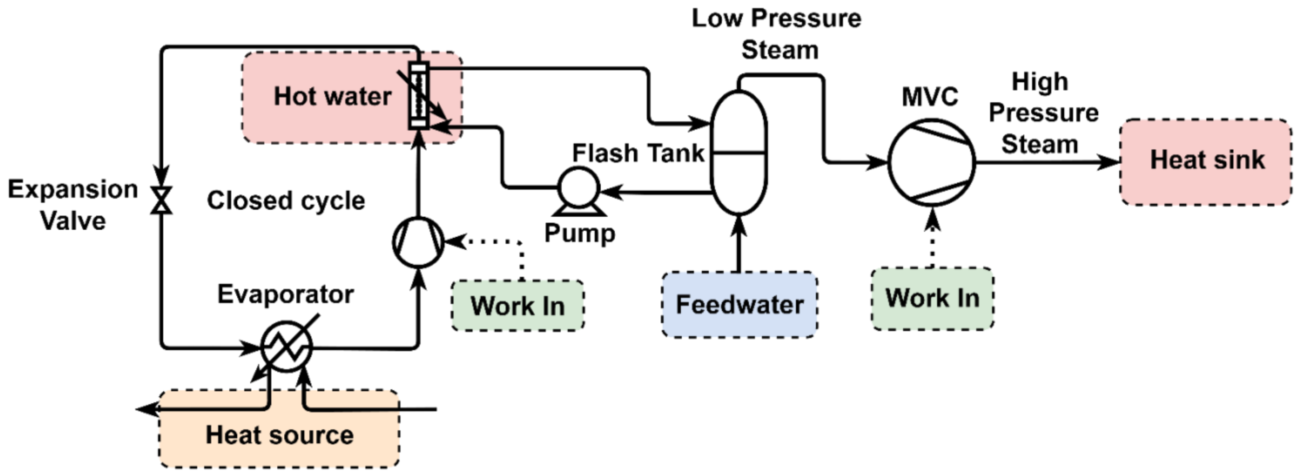


Figure 7. Hybrid closed-cycle heat pump with flash tank and mechanical vapour compression configuration providing multi-temperature capability

4.5.2 Common refrigerants

The closed-cycle heat pump in a heat-booster system typically uses the same refrigerants as conventional vapour compression heat pumps. Ammonia (R717) is commonly used in industrial applications, due to its favourable thermodynamic properties and widespread use in large-scale refrigeration systems.

The MVC stage typically compresses water vapour generated within the system, which then acts as the working fluid for the steam upgrading stage.

4.5.3 Advantages

Heat-booster heat pumps allow larger temperature lifts to be achieved while maintaining relatively high efficiency. By combining a closed-cycle heat pump with MVC, the system can efficiently upgrade heat across multiple temperature levels.

This configuration also enables process steam to be generated from lower-temperature heat sources, which can be difficult to achieve efficiently with a single heat pump cycle.

4.5.4 Limitations and challenges

Heat-booster systems are more complex than conventional vapour compression or MVC systems because they combine multiple technologies, additional equipment, such as flash tanks, and multiple compression stages. This increased complexity can result in higher capital costs and more challenging system integration and control.

4.5.5 Applications

Heat-booster heat pumps are used in industrial processes where steam is required at higher temperatures or pressures than can be efficiently produced by a single heat pump stage. They are particularly suited to sites where low- or medium-temperature heat can first be upgraded to hot water and then converted to steam for process use. Typical applications include food processing, chemical production, and other industries where steam is a primary heating utility.

The operating ranges of heat-booster systems are largely determined by the limits of their component technologies. The closed-cycle vapour compression stage typically operates within the temperature and capacity ranges of conventional industrial heat pumps; while the MVC stage follows the operating limits typical of MVC systems. As a result, the overall system performance and capacity depend on the combined design and operating conditions of both subsystems.

4.6 Customised advanced vapour compression cycles

4.6.1 Cycle overview

There are a wide range of advanced vapour compression cycle configurations that can be used to improve the performance of heat pumps or better match them to specific industrial applications. The most suitable configuration will often depend on the temperature levels, temperature glide and integration requirements of the process.

Among these advanced cycle configurations, multi-temperature and cascade heat pump systems are two of the most commonly applied approaches.

Multi-temperature heat pumps are bespoke designs and deliver useful heating at two or more distinct temperature levels within the same cycle. This is typically achieved by extracting heat at different points in the cycle, for example through using de-superheaters together with condensers or multiple condensers operating at different pressure levels.

Cascade heat pumps are another advanced cycle configuration. These use two or more separate vapour compression cycles connected through an intermediate heat exchanger. Each cycle operates with a refrigerant suited to a particular temperature range. The low-temperature cycle absorbs heat from the source and transfers it to the intermediate heat exchanger, where the high-temperature cycle upgrades the heat to the final process temperature. A cascade heat pump can also include multi-temperature heat pumping.

4.6.2 Common refrigerants

The refrigerants used in multi-temperature and cascade heat pump systems are generally similar to those used in conventional vapour compression heat pumps.

In cascade systems, different refrigerants may be selected for each cycle so that their thermodynamic properties match the temperature range in which they operate. This allows each stage of the system to operate more efficiently across the overall temperature lift.

4.6.3 Advantages

Multi-temperature and cascade heat pump configurations allow better matching between the heat pump and industrial heat demand. By delivering heat at multiple temperature levels or splitting the temperature lift across multiple cycles, these systems can reduce thermodynamic losses during heat transfer.

Cascade systems can also enable higher overall temperature lifts by allowing each cycle to operate within a more suitable temperature range for the selected refrigerant. This can improve system efficiency and expand the range of achievable supply temperatures for industrial heat pump applications.

4.6.4 Limitations and challenges

Multi-temperature and cascade heat pump systems are more complex than simple vapour compression cycles because they require additional compressors, heat exchangers and control systems. This increased complexity can lead to higher capital costs and more challenging system design and integration.

In cascade systems, the performance of the overall system also depends on the effective operation of the intermediate heat exchanger that connects the cycles. Poor temperature matching or control between the cycles can reduce the performance. As a result, careful system design and process integration are required to achieve the expected performance benefits.

4.6.5 Application

A common use of advanced vapour compression cycles is the efficient co-generation of multiple utility levels. For instance, a heat pump may supply high-temperature heat for a primary process while simultaneously providing lower-temperature heat for duties such as preheating process streams or hot-water generation. By matching the heat pump outputs to different process temperature requirements, the overall system efficiency can be improved.

4.7 Transcritical vapour compression heat pumps

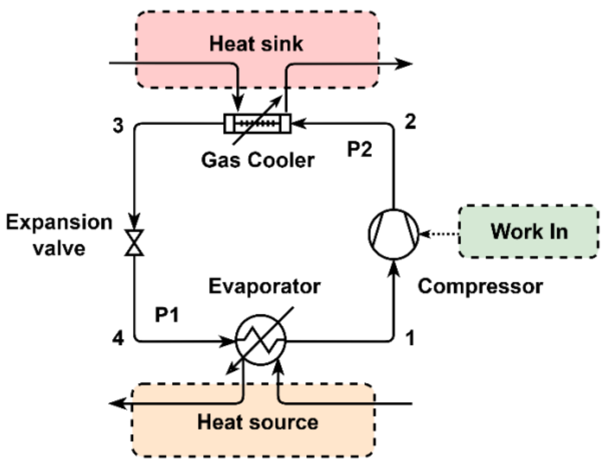
4.7.1 Cycle overview

Transcritical vapour compression heat pumps operate similarly to conventional vapour compression systems, but the refrigerant is compressed to a pressure above its critical point. As a result, the heat rejection process differs from subcritical cycles, because the refrigerant does not condense but instead cools as a supercritical fluid in a gas cooler.

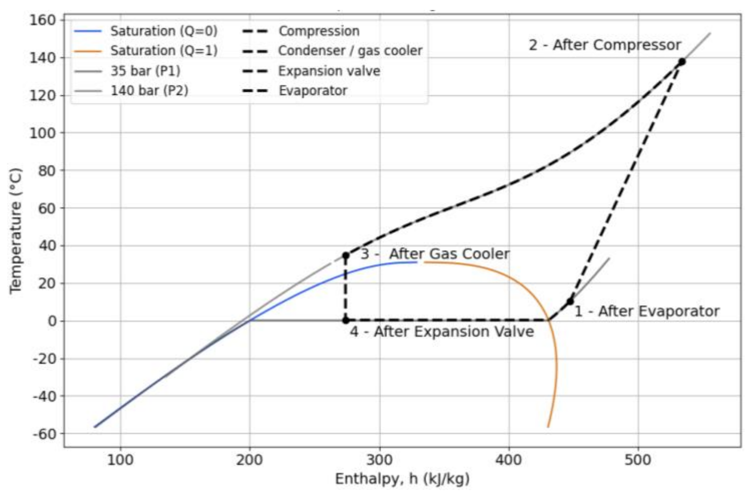
Figure 8 shows a schematic diagram (a) and temperature–enthalpy plot (b) for a transcritical vapour compression heat pump.

In transcritical vapour compression heat pumps, during the heat rejection stage, the refrigerant releases heat over a wide temperature range, producing a temperature glide – rather than the near-constant temperature heat rejection observed during condensation in subcritical systems. This characteristic can allow the heat pump to better match heating processes that require heating across a large temperature range (for example, compare the temperature-enthalpy plots for Figure 4 and Figure 8).

The performance of transcritical heat pumps depends strongly on the temperature of the heat sink and the outlet temperature of the gas cooler. Lower return temperatures allow greater cooling of the supercritical refrigerant and can improve overall cycle performance.



a)



b)

Figure 8. (a) Simple transcritical heat pump; (b) Temperature-enthalpy plot for the cycle

4.7.2 Common refrigerants

Transcritical vapour compression heat pumps most commonly use carbon dioxide (CO_2, R744) as the working fluid. Carbon dioxide has a relatively low critical temperature of approximately 31°C, which allows the cycle to operate in the transcritical region while still producing high heat sink temperatures.

Other refrigerants can also operate in transcritical cycles under certain conditions, but CO_2 is the most widely applied.

4.7.3 Advantages

Transcritical heat pumps can perform well in applications where heat must be supplied across a wide temperature range. The temperature glide during gas cooling matches well with heating processes that require continuous temperature increases, such as water or air heating (see Figure 9).

Another advantage is that the achievable heat sink temperature is not limited by the refrigerant's critical temperature because condensation does not occur. For example, CO_2 systems can produce supply temperatures well above 100°C despite having a critical temperature of only about 31°C.

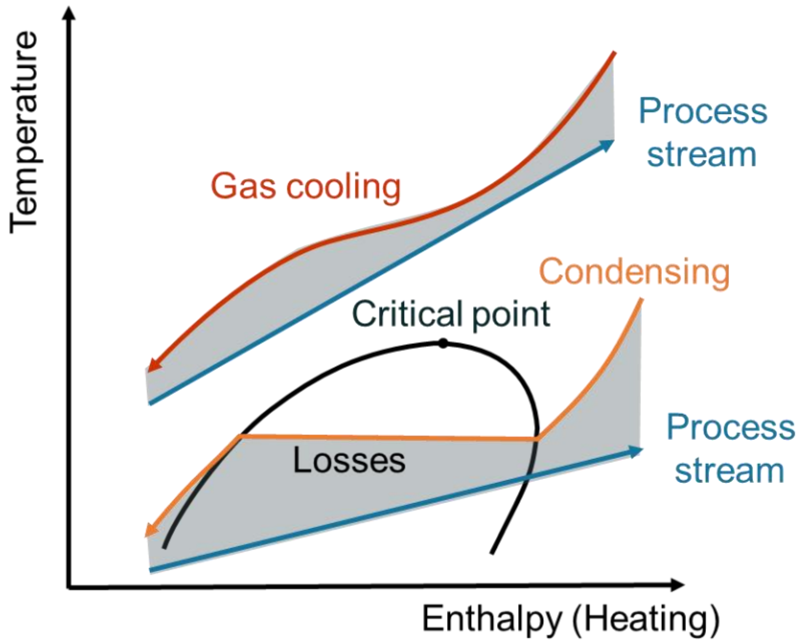


Figure 9. Comparison of the gas cooling process in transcritical cycles and the condensing process in subcritical cycles, illustrating how transcritical cycles are better suited to processes requiring a steep temperature rise

4.7.4 Limitations and challenges

Transcritical heat pumps can tolerate higher compressor discharge temperatures and operating pressures than subcritical vapour compression systems. This can increase equipment requirements and place greater demands on system design.

Expansion losses can also be higher, because the refrigerant expands from supercritical conditions, which can lead to increased vapour formation during throttling.

In addition, transcritical systems are less suitable for processes with small temperature glides, as efficient operation relies on a sufficient temperature difference between the refrigerant and the heat sink during gas cooling.

4.7.5 Applications

Transcritical heat pumps are well suited to applications where the heating process involves a large temperature rise, such as water or air heating across a wide temperature range. In these cases, the temperature glide of the refrigerant during gas cooling can better match the process heating profile, improving heat transfer performance.

Typical applications include industrial hot-water generation, air heating processes such as drying, and systems where relatively low return temperatures allow the supercritical refrigerant to be cooled effectively in the gas cooler.

The capacity of transcritical heat pump systems varies according to the supply temperature and system scale. Systems supplying heat from approximately 60°C to 130°C are commercially established and routinely achieve capacities ranging from about 50 kW to around 6 MW. Larger systems in the range of 10 MW to 50 MW, supplying heat up to about 150°C, have also entered commercial operation in recent years. Across these applications, the maximum temperature lift is typically around 165°C.

4.8 Stirling heat pumps

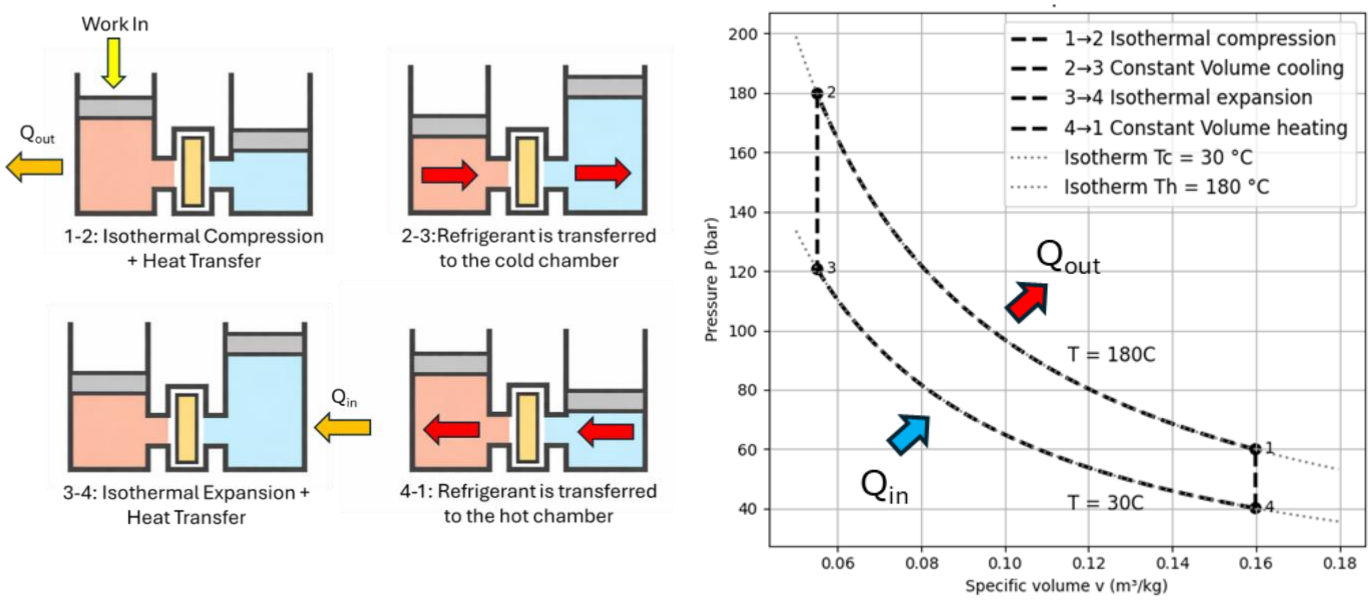
4.8.1 Cycle overview

The Stirling heat pump, which uses a reverse Stirling cycle, is a gas-phase heat pump that operates without any phase change. The working fluid remains in the gaseous state throughout the cycle and is typically helium.

In these heat pumps, the refrigerant undergoes four thermodynamic processes, as shown in Figure 10a (numbering reflects the state points in the pressure–volume plot of the Stirling cycle in Figure 10b).

- 1–2: the refrigerant is compressed isothermally at the heat sink temperature in the hot chamber in which the work is done, and heat is transferred to the heat sink (i.e., the process water) to keep the refrigerant at a constant temperature during the volume change.
- 2–3: the refrigerant is the transferred to the cold chamber through an internal regenerator at a constant volume. The regenerator is heated and the refrigerant is cooled. To achieve a constant volume, the movement of the two pistons is mechanically synchronised.
- 3–4: the refrigerant is expanded isothermally in the cold chamber. During the expansion process heat is transferred from the source (i.e., the waste heat or cooling tower) to the refrigerant to keep temperature constant.
- 4–1: finally, the refrigerant is returned to the hot chamber at constant volume, and the refrigerant is heated by the regenerator.

Mechanical work is supplied to drive the cycle, enabling heat to be absorbed at the low temperature level and rejected at the higher temperature level.



a) b)

Figure 10. (a) Thermodynamic processes for Stirling heat pump; (b) Pressure–volume plot for the cycle

4.8.2 Common refrigerants

Stirling heat pumps typically use helium as the working fluid. Helium remains in the gaseous state throughout the cycle and is well suited to Stirling machines due to its low molecular weight, high thermal conductivity and chemical stability.

Other gases, such as nitrogen, can also be used in some designs, although helium is generally preferred in industrial systems.

4.8.3 Advantages

Stirling heat pumps can operate across very large temperature lifts because the working fluid remains in the gaseous phase throughout the cycle. This avoids limitations associated with phase change, such as critical temperature constraints or wet compression.

The use of helium as the working fluid also offers environmental advantages, as it is inert and has zero global warming potential. These characteristics make Stirling systems attractive for high-temperature applications where conventional refrigerants may face stability, safety or operating limits.

4.8.4 Limitations and challenges

Stirling heat pumps rely on complex mechanical components, including pistons, displacers and high-performance regenerators. This increases system complexity and can result in higher capital costs compared with simpler vapour compression heat pumps. Stirling systems also typically achieve lower COPs at comparable temperature lifts.

In addition, Stirling machines generally have lower power density, meaning larger equipment sizes are required to deliver the same thermal capacity. This can make large-scale industrial deployment more challenging.

4.8.5 Applications

Stirling heat pumps are primarily used for applications that require very high supply temperatures or large temperature lifts, where conventional vapour compression systems may face limitations. Potential applications include high-temperature process heating in the chemical, food drying and other sectors where temperatures above the typical range of conventional heat pumps may be required.

One example application is for raising process steam from low-temperature waste heat. For instance, a Stirling heat pump could upgrade waste heat of around 40°C to produce steam at approximately 200°C (around 10 bar), providing a potential pathway for electrified steam generation in industrial processes.

A few Stirling heat pump systems have been installed commercially, with reported capacities ranging from approximately 0.3 MW to 10 MW. These systems are capable of supplying heat at sink temperatures of approximately 200°C to 250°C, with maximum temperature lifts of up to around 200°C.

4.9 Brayton heat pumps

4.9.1 Cycle overview

The Brayton heat pump, also referred to as a Joule cycle heat pump, is also a gas-phase heat pump that operates entirely with a gaseous refrigerant and does not involve phase change.

In a Brayton heat pump, the cycle operates very similarly to a conventional vapour compression cycle, as show in Figure 11:

1–2: the working gas is first compressed in one or more compressors to a higher temperature and higher pressure
2–3: the high-temperature gas subsequently passes through a gas cooler, where heat is transferred to the process heat sink under constant pressure and elevated temperature
3-4: following heat rejection, the gas undergoes expansion, commonly in a turbine, where mechanical work is recovered and the gas temperature is significantly reduced
4-1: finally, heat is absorbed from the heat source before returning to the compressor, closing the cycle.

Unlike in vapour compression systems, all heat transfer in the Brayton heat pump occurs through sensible heat exchange, resulting in a continuous temperature glide on both the heat source and heat sink sides of the cycle. Internal heat recovery can be enhanced by a recuperator (i.e., an internal heat exchanger), which transfers heat from the hot exhaust gas leaving the sink-side heat exchanger to the colder gas upstream of compression, thereby reducing external heating and cooling requirements and improving the overall efficiency.

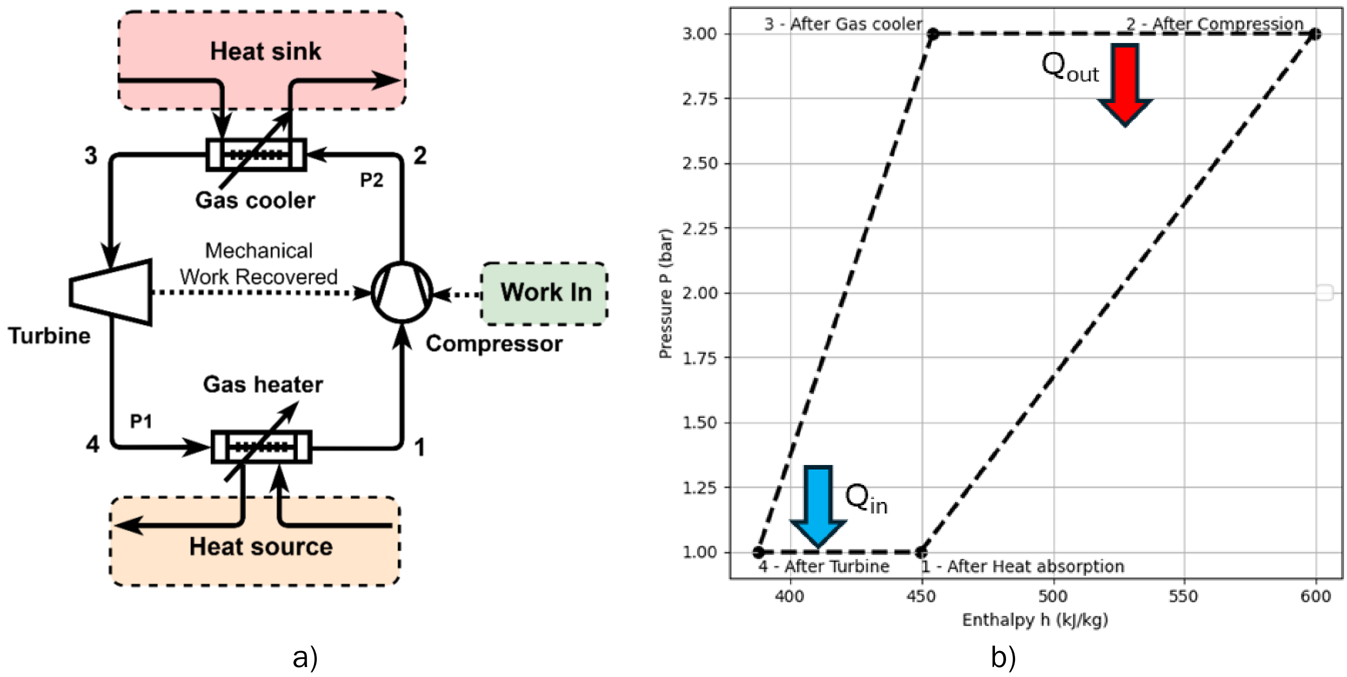


Figure 11. (a) Simple Brayton heat pump; (b) Pressure-enthalpy plot for the cycle

4.9.2 Common refrigerants

Brayton heat pumps operate with gaseous working fluids that remain in the gas phase throughout the cycle. Common working fluids include air, nitrogen, argon and other gas mixtures. These gases are widely available, stable at high temperatures, and do not require phase change to operate the cycle.

In many designs, air is used as the working fluid because it is readily available, non-flammable and has no global warming potential.

4.9.3 Advantages

Brayton heat pumps offer high temperature flexibility because the working fluid remains in the gaseous phase throughout the cycle. This avoids limitations related to refrigerant phase changes, such as critical temperature constraints or thermal stability limits.

As a result, Brayton systems can potentially operate at very high supply temperatures, in some cases exceeding 200–300°C. Using gases, such as air, also avoids the environmental and safety concerns associated with many synthetic refrigerants, as these working fluids are non-flammable and have zero global warming potential.

4.9.4 Limitations and challenges

Because Brayton heat pumps rely entirely on sensible heat transfer, the heat transfer coefficients are generally lower than those for phase-change systems. As a result, larger heat exchangers are often required to achieve the necessary heat transfer rates.

In addition, Brayton heat pumps typically achieve lower COPs compared with vapour compression heat pumps at moderate temperature lifts. This is because sensible heating and cooling are thermodynamically less efficient than the latent heat transfer processes used in phase-change cycles.

4.9.5 Applications

Brayton heat pumps are currently only at the pilot or demonstration stage for industrial heat pump applications.

Reported system heating capacities generally range from about 50 kW to around 1 MW. Demonstration systems have indicated the potential to supply heat at temperatures exceeding 200°C, and in some cases approaching 300°C, depending on the system configuration and working fluid.

These systems are therefore being explored for high-temperature industrial processes where large temperature glides occur on both the heat source and heat sink sides of the cycle. Because Brayton heat pumps rely on sensible heat transfer rather than phase change, the working fluid naturally experiences a continuous temperature change during heat exchange. This can provide good thermodynamic matching with processes that heat or cool across a wide temperature range.

An example application where Brayton heat pumps could be used is for spray drying. Spray drying requires large volumes of air to be heated from near ambient conditions to temperatures typically between 180°C and 200°C before entering the dryer. At the same time, the exhaust air leaves the dryer at warm temperatures and cools over a wide temperature range. A Brayton heat pump can recover heat from the exhaust air and upgrade it to supply the dryer inlet air, making use of the large temperature glide on both sides of the process.

5 High-temperature heat pump availability and development

The International Energy Agency's (IEA) Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) is "an international information, communication and dialogue platform for heat pumping technologies, applications and markets".[17]

IEA HPT Project 68[18] investigates the current state, development progress and future prospects of industrial HTHPs. This section summarises the project's key findings.

According to IEA HPT projects 58 and 68,[19] HTHPs with heating capacities ranging from 30 kW to 70 MW have been demonstrated worldwide, with the maximum supply temperatures of these HTHPS ranging between 100°C and 280°C.

Compared with earlier assessments under Project 58 (which concluded in 2023), Project 68 documents a sustained maturing of the supplier landscape, with 55 distinct HTHP technology platforms identified across a wide range of capacities and temperature levels.

Four major developments are highlighted by IEA HPT Project 68.

- **A shift toward natural refrigerants** – natural refrigerants are now used in approximately 85% of the identified technologies. This may be due to the tightening regulation of fluorinated gases (F-gases), improved safety-by-design approaches for hydrocarbons and ammonia, and the strong thermodynamic performance of water and steam-based systems at higher temperatures.
- **Technological maturity at higher temperatures** – credible technology platforms can now reach temperatures well beyond 160°C, with several suppliers reporting systems approaching or exceeding 200°C, and some reference installations moving toward 300°C. Multi-stage steam compression, large centrifugal compressors and hybrid cycle concepts have all progressed in terms of their technology readiness, particularly in the 1–10 MW range.
- **Rapid growth in demonstrations** – demonstrations for HTHP technology platforms have increased sharply, especially for systems supplying heat between 120°C and 200°C. Project 68 has identified many new or updated industrial reference projects that directly address the validation gaps previously noted in Project 58. Single installations of up to 40 MW now provide critical operational evidence for large-scale deployment of technologies.
- **Capacity scaling and consolidation** – small and medium systems are increasingly being modularised for replication, while large-scale platforms (>10 MW) based on steam and process-gas compression are consolidating. Large-scale systems benefit from economies of scale, improving specific capital costs and positioning HTHPs as viable central heat supply technologies for industrial clusters.

Table 3 shows the technology readiness levels used by the IEA HPT projects.[20]

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[17] Technology Collaboration Programme. (n.d.). *About HPT TCP*. https://heatpumpingtechnologies.org/about-hpt-tcp/
[18] See footnote 4.
[19] See footnote 4.
[20] European Commission. (2014). *Technology readiness levels (TRL): Extract from part 19-commission decision C(2014)4995.* https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Table 3. Definitions of technology readiness levels

Technology readiness level	Definition
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstrated in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies, or in space)

Source: European Commission (2014); see footnote 20.

Based on the first Project 68 report, the current technology readiness levels for the HTHP technology landscape show that at:

- **<120°C and up to 10 MW** – systems are fully commercial (TRL 9) and cost competitive in many European nations, and have low technological risk due to mature components; early adopters of these systems are often able to seek co-funding from government investment schemes
- **120–160°C** – systems are moving from pilot to routine demonstration (TRL 6–8), and entering the early stages of commercial availability; given the rapid advancements being made in these systems, they are expected to be at TRL 9 within the next 3 years
- **>160°C** – demonstration-led systems, with early commercial reference plants, are emerging; these rely heavily on government research and development investment.

Project 68 reports that industrial HTHPs are entering a decisive phase in terms of market formation. As demonstration plants continue to publish independently verified performance data, perceptions of risks associated with HTHPs are expected to fall among industrial end-users, enabling greater replication and scale-up.

Cost reductions are also anticipated through learnings from demonstrations, standardised components and integrated system designs, particularly for modular systems in the 120–160°C range. Continued progress in this area will depend on favourable boundary conditions, such as stable electricity prices, effective carbon pricing and targeted policy support for first-of-a-kind installations.

Figure 12 presents the HTHP technologies commercially available as of 2024.[21]

[21] Arpagaus, C. (2024). *Steam generating heat pumps webinar* [Webinar presentation]. Eastern Switzerland University of Applied Sciences and Institute for Energy Systems. https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Cordin_Arpagaus_Introduction_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf

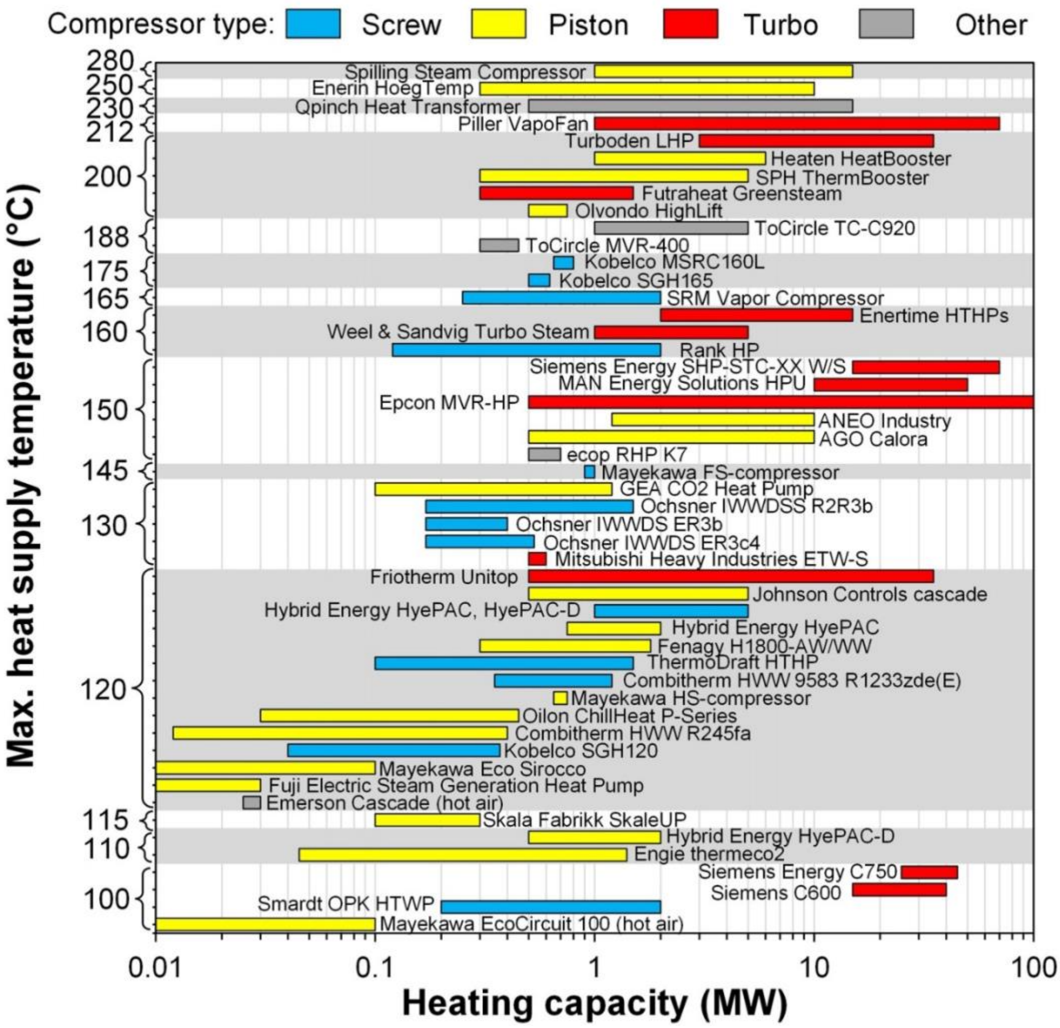

Figure 12. Market available high-temperature heat pumps, 2024

Source: Arpagaus (2024), p. 17; see footnote 21.

6 Integrating high-temperature heat pumps in industrial systems

Holistic integration of HTHPs into industrial thermal systems requires an approach that extends well beyond just selecting the appropriate technology, components or cycle architecture.

The impact a HTHP has on system performance and value will ultimately be determined by how effectively the heat pump interfaces with process heat demands, existing utility systems and the broader site-wide energy infrastructure.

As a result, a holistic analysis is required that coordinates inputs from multiple engineering disciplines in order to evaluate the energetic performance of the HTHP, its capacity and placement within the site, and the operational, spatial and electrical supply and transformation constraints that may influence feasible designs.

In this section, we describe the critical aspects of heat pump integration from a thermal, electrical, operations, space and existing infrastructure perspective. The costs of these combined aspects are commonly as much as, or even more than, the cost of the heat pump itself.

6.1 Thermal integration

In any HTHP integration project, the first step is to decide if a HTHP suits the process by determining what its heat sources and sinks should be, and how it could be designed efficiently.

These questions are best answered using pinch analysis.

To develop a thermal integration scheme for a HTHP, an engineer will need at least a conceptual-level understand of pinch analysis. There are many free guides online and in standard textbooks that will walk users through the pinch analysis method; section 6.1.1 Provides a high-level overview of the method.

6.1.1 Pinch analysis

Pinch analysis (or pinch technology) can help to unlock essential insights into the thermodynamic design of industrial heat recovery systems and the thermal integration of heat pumps.[22]

The crux of the method is in determining and understanding the pinch temperature (or pinch temperature range), as shown in Table 4. When a heat pump absorbs heat at temperatures below the pinch temperature, and releases heat at temperatures above the pinch temperature, it will reduce the process heat demand for external heating and cooling utilities.

[22] Linnhoff, B., & Flower, J. R. (1978). Synthesis of heat exchanger networks: I: Systematic generation of energy optimal networks. *AIChE Journal, 24*(4), 633–642. https://doi.org/10.1002/aic.690240411

Table 4. Significance of the pinch temperature

Process temperatures relative to the pinch temperature	Load balance	Do	Don't	Heat pump implications
At temperatures below the pinch temperature	Heat sink is less than the heat source	Maximise heat recovery, minimise cooling utility requirement	Avoid any heating utility	Use evaporator cooling
At temperatures above the pinch temperature	Heat sink is greater than the heat source	Maximise heat recovery, minimise heating utility requirement	Avoid any cooling utility	Use condenser heat

See section 6.1.4 for more detail on how pinch analysis is used to inform HTHP integration in practice.

6.1.2 Key thermal integration and design principles

There are three key principles for heat pump thermal integration and design, as shown in Table 5. The principles are grounded in thermodynamics and driven by the latest heat pump technologies.

Following these principles can help ensure that a project is energy efficient and reduces utility costs. The principles assume that a site already recovers all the heat it economically can. A site pinch analysis can confirm if this is the case.

The first principle is an application of the first law of thermodynamics, and provides the basis for selecting heat sources and sinks.

The other two principles apply a second law of thermodynamics perspective to help optimise the architectural design and operation of the heat pump.

Table 5. Principles for the thermal integration and design of heat pumps

Principle	Description
1. **Effective heat pumping** upgrades heat at temperatures below the pinch temperature to temperatures above the pinch temperature.	The appropriate placement of heat pumps is across the pinch; that is, heat pumps aim to absorb heat at temperatures below the pinch temperature and release heat at temperatures above the pinch temperature.
2. **Efficient heat pump integration** minimises the mean temperature lift for a given heat load target.	Close temperature matching between the heat pump condenser and evaporator and the process sink and source will lower the pressure difference between the condenser and evaporator sides of the heat pump. This in turn reduces the compressor loading and entropy generation in the heat transfer.
3. **Efficient heat pump units** minimise internal entropy generation.	Once the heating and cooling loads and their temperatures are defined, the heat pump internals come into focus. Key decisions include the choice of refrigerant, compressor type and configuration. Many manufacturers offer standard HTHP designs for a range of loads and temperatures, including performance data.

6.1.3 Common patterns of heat pump integration

Every industrial site will require a detailed assessment to determine the most effective way to integrate a HTHP.

This assessment can be guided by a set of common thermal integration patterns, as detailed in Table 6.

The patterns reflect the trade-offs that typically take place between capital investment and energy efficiency. Their descriptions in the table are supported by example case studies of industries that have integrated HTHP following each pattern.

The selection of the integration pattern can also impact how a pinch analysis is carried out. For example, pattern 1 requires data for a detailed process stream, whereas pattern 4 (at its simplest), only needs the utility temperature and flow data.

Table 6. Heat pump integration patterns

Pattern	Description	Example case studies
1. Direct process gas compression	If process gas cooling is needed below the pinch temperature, the process gas may be considered as the working fluid for an open-cycle heat pump. MVC and MVR technology, for example, can be applied to upgrade the gas temperature to above the pinch, providing useful heating to the process.	In ethylene propylene diene terpolymer (EPDM) production, waste heat from solvent stripping is recovered using a multi-stage MVR heat pump that recompresses condensed process vapours to regenerate stripping steam. See case study 1 in Appendix A on standardised petrochemical installations.
2. Direct process heat supply	A suitably selected heat pump supplies heating and cooling directly to process streams. It is normally localised to a specific plant within a site where sources and sinks operate synchronously. As a result, significant heat storage can be avoided.	At a specialty paper mill in Germany, a double-stage HTHP upgrades low-temperature waste heat produced from paper drying to produce process steam for the paper drier. See case study 2 in Appendix A on Weißenborn speciality paper plant.
3. Localised hot water or steam loops	Local utility loops carry the heating and cooling duty from the heat pump to specific process streams, thereby physically separating the heat pump from the process. This avoids the need to transport heat over long distances, avoids issues with refrigerant leakage into sensitive projects, and minimises or eliminates the requirement for heat storage.	At a distillery in Ahascragh, Ireland, HTHPs replaced fossil-fuel boilers by using local utility loops for process heat, and space heating and cooling, thereby significantly reducing energy use and emissions. See case study 3 in Appendix A on the Ahascragh distillery.
4. General site utility supply	Integrating a HTHP into general utility systems reuses the existing pipe distribution network to supply hot water and steam to the site. Site cooling water, hot refrigerant gas (e.g., from chillers), air, geothermal (ground) and river water are common heat source options to supply the heat pump evaporator. Many sites prefer this approach because it maximises the use of existing piping and auxiliary infrastructure.	At AstraZeneca's Gothenburg research and development site, high-lift heat pumps using rejected cooling energy have replaced fossil-fuel steam generation. The HTHPs produce high-pressure process steam with a helium-based working fluid. See case study 4 in Appendix A on the AstraZeneca Plant.

6.1.4 Establishing heat pump potential using pinch analysis

With a clear understanding of the principles and patterns of heat pump integration, advanced pinch analysis can provide a rigorous method for exploring the key HTHP integration choices, namely:

- selecting streams to act as a heat source and heat sink for the heat pump
- calculating the required heat pump temperatures
- calculating the required load at each temperature.

Figure 13 illustrates the advanced pinch analysis workflow.

- As an abstract principle (a), heat pumps aim to absorb heat at temperatures below the pinch temperature and release heat at temperatures above the pinch temperature.
- Next (b), net load profiles, such as those demonstrated by the process grand composite curve and the site utility grand composite curve, will provide insights into the temperatures and duties of the condensers and evaporators, as well as their subcooling potential.
- Finally (c), these insights can be used to design concrete HTHP placement and system architectures.

A balance between complexity and performance must be struck when deciding on the number of condensers (including gas coolers and subcoolers) and evaporators to be used for a system.

Figure 13 shows an example using two condensers and one subcooler for providing hot utility, and one evaporator for providing the cooling. Several different heat pump system architectures could provide the required utility, including two independent heat pumps (as shown), a cascade heat pump or a single multi-temperature heat pump.

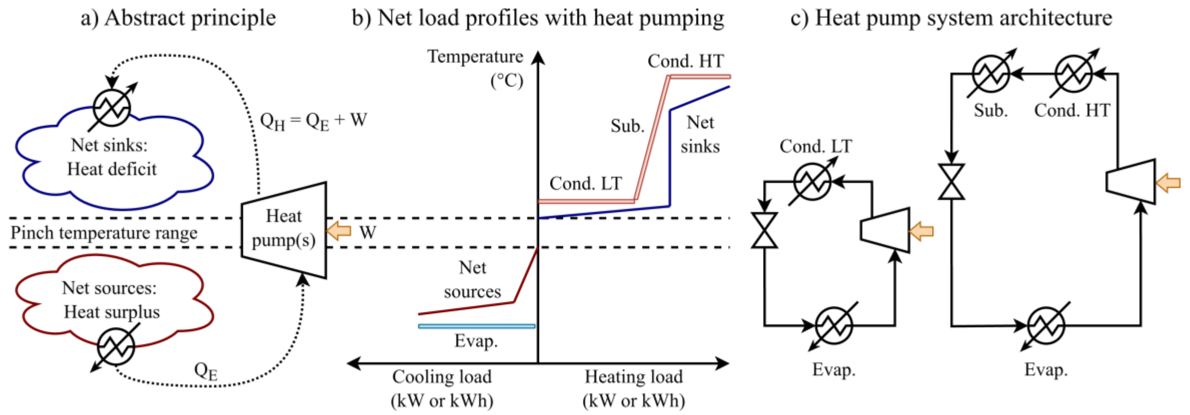

Figure 13. Advanced pinch analysis workflow showing relationship between the heat pump integration principle, net load profile and heat pump system architecture

Each of the heat pump integration patterns detailed in Table 6 requires specific data input to determine the appropriate pinch-based net load profile, as shown in Table 7.

These patterns reflect the classic capital investment to energy efficiency trade-off. The pattern selected can also impact how the pinch analysis is carried out and the stream data formulated.

For example, pattern 1 requires detailed process stream data, whereas pattern 4, at its simplest, only needs the utility temperature and flow data. Likewise, pattern 1 is likely to achieve the minimum mean temperature lift and lowest electrical load, whereas pattern 4 needs the greatest temperature lift and electrical load. In contrast, pattern 1 solutions may require a raft of process infrastructure changes and high investment cost, whereas pattern 4 could reuse the existing steam and hot water infrastructure, minimising integration costs.

Table 7. Data requirements for calculating the net load profiles of different heat pump integration patterns

Pattern	Minimum stream data requirement	Net load profile (pinch curve)	Description
1. Direct process gas compression	Temperatures, flow rates and heat capacities of all streams within a specified processing zone	Grand composite curve (detailed)	This pattern requires comprehensive information about the unit operation and process context surrounding the candidate for direct compression. Often this pattern focuses on integration of the HTHP within a unit operation.
2. Direct process heat supply	Process stream temperatures and duties currently supplied by utility, within a specified processing zone	Grand composite curve (simplified)	At a minimum, this pattern requires process stream data of those streams that are heated or cooled by existing utility. This simplified analysis assumes heat recovery is already maximised.
3. Dedicated hot water or steam loops	Process stream temperatures and duties currently supplied by utility, within a specified area of the site	Grand composite curve (simplified)	This pattern requires the same type of data as pattern 2, expect for a defined local area of the site. Dedicated, closed water or steam loops are designed with appropriate temperatures to match the process, rather than using the same temperatures as the central utility system.
4. General site utility supply	Site utility loads and temperatures	Site utility grand composite curve	As this pattern seeks like-for-like utility replacement, knowing the existing site utility use is a sufficient minimum basis for the analysis.

6.1.5 Measuring thermal system performance

The overall COP of a heat pump system is typically defined as the ratio of the heating delivered to the electrical power absorbed (Equation 1). However, if the heat pump displaces costly hot and cold utilities, the system (COP_{sys}) should also include the refrigeration duty (Equation 2).

$$COP_{sys} = COP_h = \frac{Q_h}{W} \quad \text{(Equation 1)}$$

$$COP_{sys} = COP_h + COP_r = \frac{Q_h + Q_r}{W} \quad \text{(Equation 2)}$$

Where:

- Q_h is the useful heating delivered
- Q_r is the useful refrigeration
- W is the work input to the heat pump
- COP_h and COP_r are the heating and refrigeration COPs
- COP_{sys} is the COP of a heat pump system.

6.2 Electrical supply and network connection

Electrifying industrial process heat with heat pumps can materially increase a site’s electricity demand where the previous heat source was thermal fuels, such as coal or gas. As a result, the availability, capacity and cost of electricity supply are often critical determinants of a project’s feasibility, cost and delivery timeframes.

Electrical supply and network capacity considerations should be assessed early and in parallel with thermal and process design.

Electricity supply to industrial sites is governed by a layered system comprising:

- the national wholesale electricity market, which determines generation availability and wholesale prices
- the high-voltage transmission network, operated by Transpower, which transports electricity across regions (the national grid)
- local distribution networks, owned and operated by electricity distribution businesses, which connect individual sites to the transmission network at grid exit points.

While generation adequacy is largely determined at a national level, the ability to supply new industrial heat pump loads is often constrained by local transmission or distribution capacity, particularly at times of peak demand.

6.2.1 Peak demand and network capacity

Recent work by EECA (the Energy Efficiency and Conservation Authority) through the Regional Energy Transition Accelerator (RETA) programme [23] has shown that in some cases the electrification of process heat may lead to increases in local peak demand, which can either be:

- accommodated through network upgrades
- mitigated through operational flexibility, storage or staged capacity increases.

The timing of growth in demand can be critical to the success of a HTHP integration project; rapid or clustered electrification projects in the same area can compound network constraints and increase both costs and lead times.

If the electrification of process heat requires a network upgrade, then the required connection capacity and security of supply may also become key factors influencing both the cost and delivery timeframe of the required electricity supply. Electricity networks are planned around peak demand and fault tolerance, and upgrades are sized not simply to meet average operating loads, but to meet specified security standards under contingency conditions. As a result, the technical definition of the electrical connection often has a greater impact on project feasibility than the heat pump technology itself.

In particular, the distinction between N-level supply, where a single network fault may result in a short interruption, and N-1 supply, where the connection remains secure following the loss of a major network component, has a disproportionate effect on upgrade cost. Achieving higher security of supply may typically require duplicated feeders, additional transformers or upstream reinforcement of distribution or transmission assets, thereby significantly increasing the capital cost and extending delivery timeframes. However, some industrial processes can tolerate short, infrequent interruptions, or can manage them through thermal inertia, staged operation or backup systems; in which case the less secure N-level supply may be acceptable.

An example of the potential price differentials between different connection upgrades can be seen in the data from the Waikato RETA.[24] Figure 14 illustrates the highly variable nature of connection upgrade costs across sites. Sites located in more constrained parts of the network may face

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[23] EECA. (n.d.). *Regional Energy Transition Accelerator*. https://www.eeca.govt.nz/co-funding-and-support/products/about-reta/

[24] EECA. (2025). *Government leadership: Regional Energy Transition Accelerator (RETA): Waikato – phase one report*. https://www.eeca.govt.nz/assets/EECA-Resources/Co-funding/RETA-Waikato-Phase-One-Report.pdf

substantially higher upgrade costs, while sites with little or no local constraints have comparatively low costs. However, almost across the board, adopting N-level security rather than N-1 security significantly reduces the connection costs.

Due to the highly variable costs across different locations, RETA recommends consulting the local electricity distribution business to obtain an indicative range of costs.

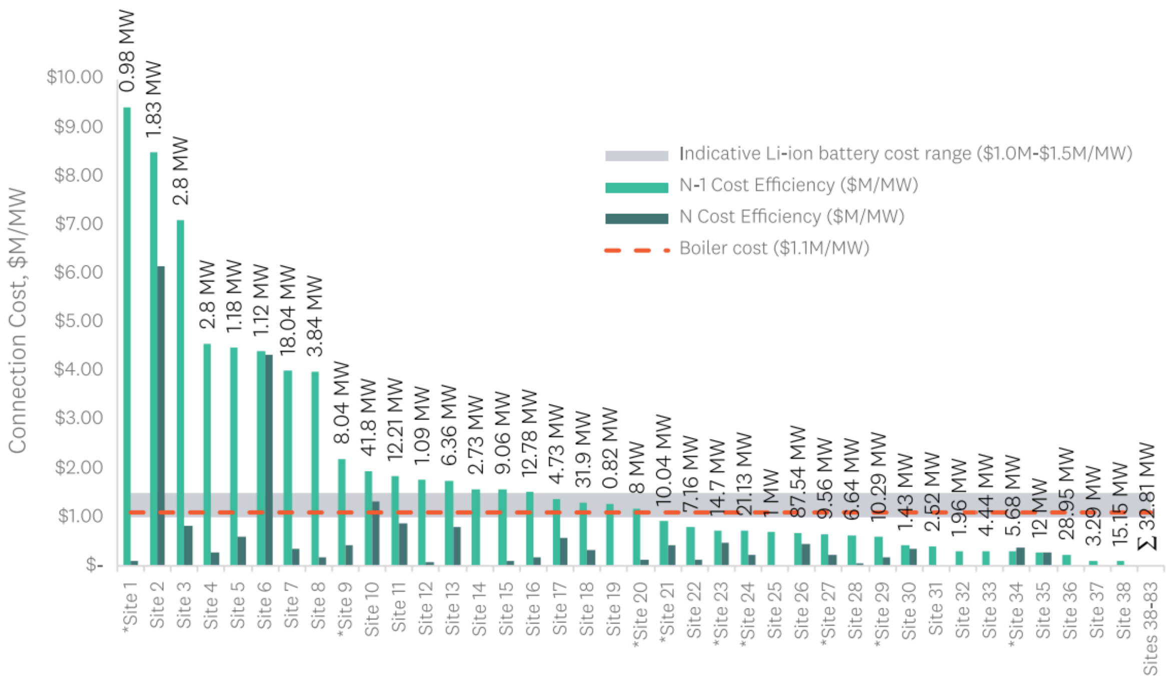

Figure 14. Estimated connection upgrade costs for sites across the Waikato region
Source: EECA (2025), p. 26; see footnote 24.

6.2.2 Electricity pricing and flexibility

For large industrial electricity users, including sites that are considering or already using HTHPs for process heat, electricity is typically procured through bespoke retail contracts, rather than at simple flat-rate tariffs.

A common pricing structure is a fixed-price, time-of-use contract, where electricity prices are agreed in advance, but may vary by season, the type of day (business vs non-business days) and time of day. These contracts can provide price certainty while reflecting the underlying wholesale market patterns, such as higher prices during winter and peak daytime periods, and are widely used to avoid direct exposure to half-hourly wholesale price volatility.

However, some larger sites, particularly those with sophisticated energy management capabilities, may choose to use indexed or partially indexed contracts, where prices are linked to wholesale market outcomes with an agreed retailer margin. These contracts may offer lower average energy costs, but can expose the site to price volatility, especially during periods of tight supply or high demand.

Across all electricity contract structures, load shifting and operational flexibility are key methods for reducing electricity costs for industrial HTHP projects. Because energy prices and network charges are strongly influenced by time of use and peak demand, the ability to move a heat pump's operation away from high-price or high-demand periods can materially lower both unit costs and network-related charges.

The RETA analysis[25] highlighted that the electricity costs faced by industrial users are often driven as much by when electricity is consumed as by how much is consumed, particularly once time-of-use pricing and demand-based charges are applied. Typical savings can be as much as 20–30% across a day, but a site or business should talk with its electricity provider about the various options on offer in order to maximise these savings.

Flexibility can be enabled through several mechanisms, including integrating thermal storage with the HTHP system, adopting staged or modular heat pump operation, and deliberately decoupling heat production from instantaneous process demand. Even modest levels of flexibility can reduce exposure to peak pricing periods and limit coincident demand with broader network peaks, which in turn can reduce both retail electricity costs and ongoing transmission and distribution charges.

6.3 Reliability and maintenance

Reliability and maintenance are critical considerations for industrial heat pump systems, as they directly influence the availability, operating costs and long-term economic performance of HTHPs.

This section outlines the expected equipment lifetimes, highlights how reliability varies with system scale, and summarises key maintenance considerations for both vapour compression heat pumps and open-cycle MVC heat pumps.

6.3.1 Maintenance and reliability for vapour compression heat pumps

Figure 15 illustrates the expected average equipment lifetime of HTHPs across different capacity ranges, showing that, irrespective of size, the reported average lifetimes cluster around 20 years. All vapour compression HTHP technologies indicate an average lifetime of between 10 and 30+ years. This provides a degree of confidence that industrial heat pumps, when correctly specified and maintained, can achieve service lives comparable to conventional boiler and refrigeration assets.

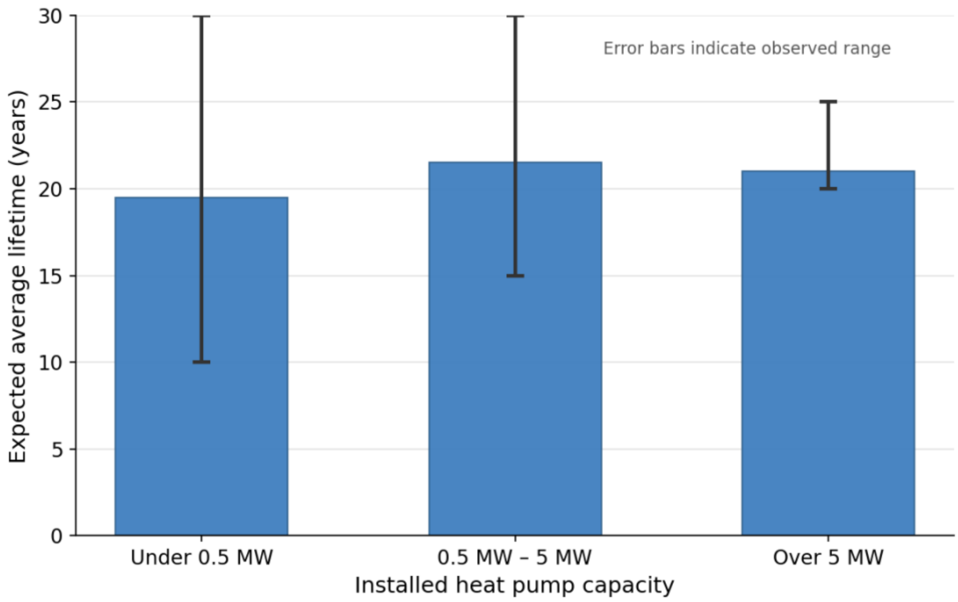

Figure 15. Average expected lifetime of high-temperature heat pumps, by capacity
Source: Technology Collaboration Programme (n.d.a); see footnote 3.

There is a clear trend in HTHP lifetimes with respect to capacity.

- Smaller systems (below ~0.5 MW) exhibit a much wider spread in their expected lifetime, reflecting a greater variability in their application, operating conditions and the robustness of their design.

[25] See footnote 24.

These units are often deployed across a diverse range of environments and duty cycles, from lightly loaded applications to highly cyclical operations, which can significantly affect their rates of wear and tear and maintenance requirements.

- In contrast, larger systems in the multi-megawatt range, show tighter convergence around the 20–25-year lifetime range. This aligns with field experience, where larger platforms typically incorporate heavier-duty compressors, heat exchangers and auxiliaries, which benefit from more conservative design margins, and are generally supported by well-established service and maintenance regimes.

From a maintenance perspective, this capacity effect has important implications for system design and an integration strategy. While a decentralised approach may rely on a larger number of smaller units, potentially increasing the number of components requiring inspection and servicing, larger centralised units tend to concentrate their maintenance activity but also demand higher levels of specialist support and planned downtime.

In both cases, predictable maintenance schedules, access to skilled service providers, and appropriate redundancy and operational flexibility are critical for achieving the lifetimes indicated.

6.3.2 Maintenance and reliability of mechanical vapour recompression fans

A key advantage of modern MVR fan systems is their robust mechanical and operational design, which enhances reliability and reduces maintenance requirements for HTHPs that incorporate them. One of the principal design considerations is the management of entrainment (the carryover of liquid droplets from the upstream process). Most industrial MVR fans are designed to handle vapour streams containing droplet sizes up to 1 mm without adverse effects on their performance or equipment integrity.

In terms of maintenance, most MVR fan units are characterised by low service demand and predictable maintenance intervals.

Manufacturer guidelines typically categorise maintenance activities into four levels.

1) Routine inspection (e.g., weekly) – visual inspection of the unit, combined with continuous monitoring of operational parameters and instrumentation, is recommended to identify any early signs of wear or imbalance.
2) Annual service – replacement of minor consumables, such as lubricating oil, grease cartridges and filters. These activities can generally be performed without interrupting operation.
3) Intermediate maintenance (e.g., every 3 years) – replacement of selected wear components, typically those in contact with moving parts, such as shaft seal rings. These tasks involve short shutdowns.
4) Major maintenance (e.g., every 6 years) – overhaul of key rotating components, including bearings and gearboxes. This corresponds to an operating lifetime of approximately 40,000 hours before bearing replacement is required.

6.4 Additional technical considerations

In addition to thermal integration, electrical supply and maintenance, several other technical considerations will strongly influence the feasibility, cost and operational robustness of HTHP projects. These factors are highly dependent on the selected integration pattern and often determine whether a technically viable concept can be implemented with acceptable risk.

Three aspects are particularly important:

- operation, control and dynamics, including part-load behaviour and interaction with process variability

- space constraints, which affect equipment selection and retrofit complexity
- re-use of existing infrastructure, which can significantly reduce capital cost and delivery risk.

While these considerations rarely present absolute barriers to the progression of a project, failure to address them early can lead to conservative oversizing, late-stage redesign and sub-optimal integration choices.

6.4.1 Operation, control and dynamics

HTHPs are inherently dynamic systems whose performance depends on both internal cycle control and external process interaction; with the degree of coupling between the heat pump and the process varying strongly depending on the chosen integration pattern.

Direct process integration (patterns 1 and 2) places the highest demands on control systems. In these configurations, the heat pump is closely linked to the process temperatures, flow rates and phase behaviour, resulting in limited tolerance for disturbances. Load fluctuations, fouling or batch operation must therefore be managed through advanced control strategies, thermal inertia or thermal storage. As a result, these configurations require high-quality instrumentation and close coordination between the process control and the heat pump vendor.

Utility-based integrations (patterns 3 and 4) provide greater decoupling between the heat generation and the process demand. Intermediate hot-water or steam loops act as thermal buffers, allowing for steadier operation and reducing compressor cycling. This improves controllability, simplifies integration with existing control systems, and generally lowers operational risk.

Across all patterns, the part-load performance of the HTHP is critical; many HTHPs experience a declining COP at low-loads, particularly when the temperature lift is fixed. Modularisation, variable-speed compression and staged operation can help to mitigate these effects but should be assessed explicitly during the concept selection and system design stages.

6.4.2 Space constraints

The availability of space frequently constrains HTHP deployment, particularly in retrofit projects. Requirements for space may extend beyond the heat pump unit itself, to include heat exchangers, pipework, electrical infrastructure, safety clearances and maintenance access.

Direct integration patterns benefit from the heat pump being located close to the process, but often face congestion issues within existing plant areas.

Utility-based patterns offer greater flexibility in terms of their placement, enabling the heat pump to be installed in service yards or energy centres, albeit with additional distribution losses.

Refrigerant choice can also affect the spatial requirements of a HTHP installation. For example, systems that use CO_2 and ammonia refrigerants are often relatively compact, whereas hydrocarbon and gas-cycle systems may be much larger. These trade-offs should be assessed alongside safety zoning and access requirements.

6.4.3 Re-use of existing infrastructure

The ability to re-use existing infrastructure is one of the strongest factors influencing project economics and delivery risk. Reusable assets may include pipework, heat exchangers, pumps, electrical connections, buildings and control systems.

Direct integration patterns (patterns 1 and 2) offer fewer thermal reuse opportunities, but may still make use of existing electrical infrastructure, foundations and control platforms. A structured audit of reusable assets should therefore form part of the early-stage concept development for any HTHP project.

Utility-level integration (patterns 3 and 4) offers the greatest reuse potential, particularly where hot-water or steam networks already exist. In such cases, the heat pump can replace or supplement existing heat generation systems with minimal disruption, provided pressure ratings, temperature limits and control philosophies are compatible.

7 Financial assessment

Assessing the financial viability of industrial HTHPs requires the balancing of capital investment, operating costs, energy prices and utilisation over time. While detailed techno-economic modelling is essential at later project stages, decision-makers often need early-stage tools with which to rapidly evaluate whether a HTHP system is likely to be economically attractive under the circumstances.

The comparison between heat-pump-based heat supply and conventional boiler-based heat generation can be visualised using a nomogram as a decision aid; with the nomogram expressing the ratio of the levelised cost of heat between the two options as a function of key technical and economic parameters – see, for example, the nomogram in Figure 16

In its simplest form, the nomogram shows how the relative cost of heat from a heat pump varies with temperature lift, and with the relative price of electricity to the reference fuel, using a consistent annuity-based costing approach. This enables rapid screening of the operating conditions and energy price combinations under which a heat pump is likely to be economically competitive.

The nomogram is based on a consistent set of technical and economic assumptions intended to represent a typical industrial process heat application, rather than a specific site. For example, the nomogram:

- assumes a project lifetime of 20 years
- applies a discount rate of 12%, which is consistent with rates commonly applied to industrial decarbonisation investments
- sets annual operating hours to 6,000 hours, reflecting high-use applications where capital-intensive technologies such as heat pumps are most likely to be viable
- represents maintenance costs using a fixed annual factor of 3% of capital cost.

If the project is not an efficiency project, and is instead being compared to a reference heat generation system, a uniform investment cost of 1,000 NZD/kW_{th}, a boiler efficiency of 0.87, and a reference fuel price of 63 NZD/MWh are assumed. This fuel price is intended as a neutral benchmark broadly representative of solid fuel or biomass-based process heat costs, rather than a forecast of future prices.

The nomogram shown in Figure 16[26] is used to find the range of temperature lifts for which a heat pump is financially viable as a function of the electricity-to-reference-fuel price ratio.

For example, when comparing the levelised cost of heat for a HTHP with that of a combustion boiler, an appropriate energy price ratio is first selected. An indicative value of 2.5 can be used, which assumes electricity costs are 2.5 times higher than the reference fuel used.

Indicative capital costs assumptions are then applied, for example, 2,000 NZD/kW_{th} for a HTHP and 1,000 NZD/kW_{th} for a combustion boiler.

Under these assumptions, the nomogram indicates that a HTHP supplying a temperature lift of up to approximately 50 K could be economically viable for the site.

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[26] Schlosser, F., Jesper, M., Vogelsang, J., Walmsley, T. G., Arpagaus, C., & Hesselbach, J. (2020). Large-scale heat pumps: *Applications, performance, economic feasibility and industrial integration. Renewable and Sustainable Energy Reviews, 133*, p. 110219. https://doi.org/10.1016/j.rser.2020.110219

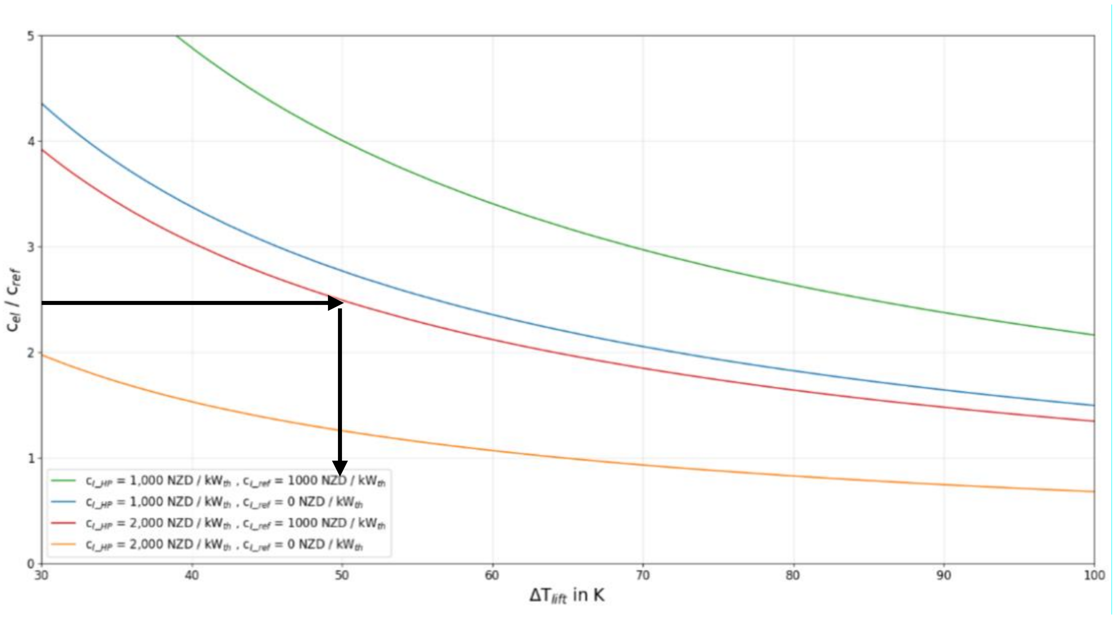

Figure 16. 2D-feasibility nomogram with levelised cost of heat parity curves (levelised cost of heat for heat pump = levelised cost of heat for reference boiler), with example

Source: Updated from Schlosser et al. (2020); see footnote 26.

Another method for calculating whether a HTHP project is financially viable is through the calculation of a simple metric such as the payback period and internal rate of return. An example calculation for this approach is given in Appendix B.

8 Questions to ask when planning and assessing a project

Table 8 provides a list of questions to consider during the feasibility planning and preliminary assessment stage of any industrial HTHP project.

The questions have been formulated to promote discussion and investigation among site engineers and consultants, and to help them apply this guide in practice. Each category of questions relates to a section of the guide.

Table 8. Questions to consider during the preliminary assessment of an industrial high-temperature heat pump project

Stage of assessment and questions
Section 5 of guide: Technology maturity
• *Are the required temperature and capacity within the ranges of proven heat pump technology?* • *What credible manufacturers with reference installations are willing to supply the target heat pump?*
Section 6 of guide: Preliminary questions for holistic integration
• *What are the site-specific drivers and co-benefits for the heat pump project?* • *What site-specific issues might limit the selection of heat pump technologies and their integration?*
Section 6.1 of guide: Thermal integration (results of pinch analysis)
• *Does the site require substantial heat below 250 °C?* • *Has a pinch analysis study been previously conducted for the site? Does the study need updating?* • *What significant heat recovery opportunities could be implemented to reduce demand prior to considering a heat pump?* • *To what extent are existing site utility lines appropriately used for process heating and supplied at their lowest feasible temperature?* • *Which pinch analysis integration patterns are of greatest interest to the site? What, therefore, are the minimum data requirements* from specific process streams? • *For direct process gas compression (heat pump integration pattern 1) specifically, what gas streams in the process sit below the pinch temperature? These will be candidates for mechanical vapour compression application.* • *According to the calculated net load profile (or grand composite curve), what number of heat pump units and associated temperature levels fit the case?* • *What acceptable refrigerants and cycle combinations would minimise the mean temperature lift of the heat pump?*
Section 6.2 of guide: Electrical supply and network connection
• *What is the current electrical spare capacity on the site?* • *What would be the network upgrade costs and lead times?* • *Could flexibility (load shifting, storage) reduce peak demand pricing or enable the site to act as a demand-response agent for the grid operator?*
Section 6.4.1 of guide: Operation, control and dynamics
• *How often does the process or site operate each year?* • *Does the process follow a regular operating schedule? If so, what is the pattern?* • *How regularly do the anticipated heat sources and sinks operate simultaneously?* • *Are thermal buffers or storage needed to allow the heat pump to operate stably near its design load?* • *If required, what is the part-load performance curve and is it acceptable?* • *Are the control requirements for the heat pump compatible with the site control strategy?*
Section 6.4.2 of guide: Space
• *What space is available for the heat pump system and where is it?*

- *How does the space meet regulations and operation guidelines* for safe refrigerant use *(access, clearances and maintenance requirements)?*

Section 6.4.3 of guide: Infrastructure reuse
• *Can existing pipework, utility loops or heat exchangers be directly used or reused as part of the heat pump system?* • *To what extent is the process operation infrastructure affected by the heat pump system?*
Section 7 of guide: Financial assessment
• *Is this project replacing a retiring boiler? Or is it viewed primarily as a means to increase energy efficiency (for example, supplementing an existing boiler)?* • *How does the expected COP compare to the site's electricity-to-fuel price ratio?*

Appendix A: Case studies

A.1 Case study 1: Standardised petrochemical installations – mechanical vapour recompression by Pillar

This project concerned over a dozen South Korean ethylene propylene diene terpolymer (EPDM) production facilities, where steam is used in stripping units to separate solvents from the reaction product.[27]

When steam is introduced into the stripper, it forms an overhead vapor mixture of steam and solvent vapours, which is subsequently condensed to recover the solvent.

Traditionally, the heat released during condensation would be rejected via cooling towers. In this retrofit project, however, that waste heat was recovered and reused to generate low-pressure steam in an evaporator. A multi-stage MVR system then compressed the steam back to the pressure required for the stripping process. The heat pump design also allowed for integration of additional heat sources between compression stages; for example, flash vapor was introduced mid-cycle to enhance overall efficiency.

A process flow diagram of the system is shown in Figure 17.

The HTHP system reduced energy consumption by more than 80% and reduced CO_2 emissions by 62%. Beyond lowering steam use, the system also decreased cooling water demand, further improving site-wide energy efficiency.

Overall, the retrofit achieved annual savings exceeding €4 million, with a payback period of just 1.7 years.

Key metrics

- Duty delivered: 1 MW.
- Temperature range: 40–230°C (212°C saturated steam).
- Working fluid: water and other process vapours (ethanol, methanol, IPA, other compounds).
- Investment cost for installed system without integration: approximately 850 €/kWth (1,719.79 NZD/ kWth – note the project was completed in South Korea and prices may vary by location).
- Payback: 1.7 years.
- Expected lifetime: 20+ years.

27 See footnote 16.

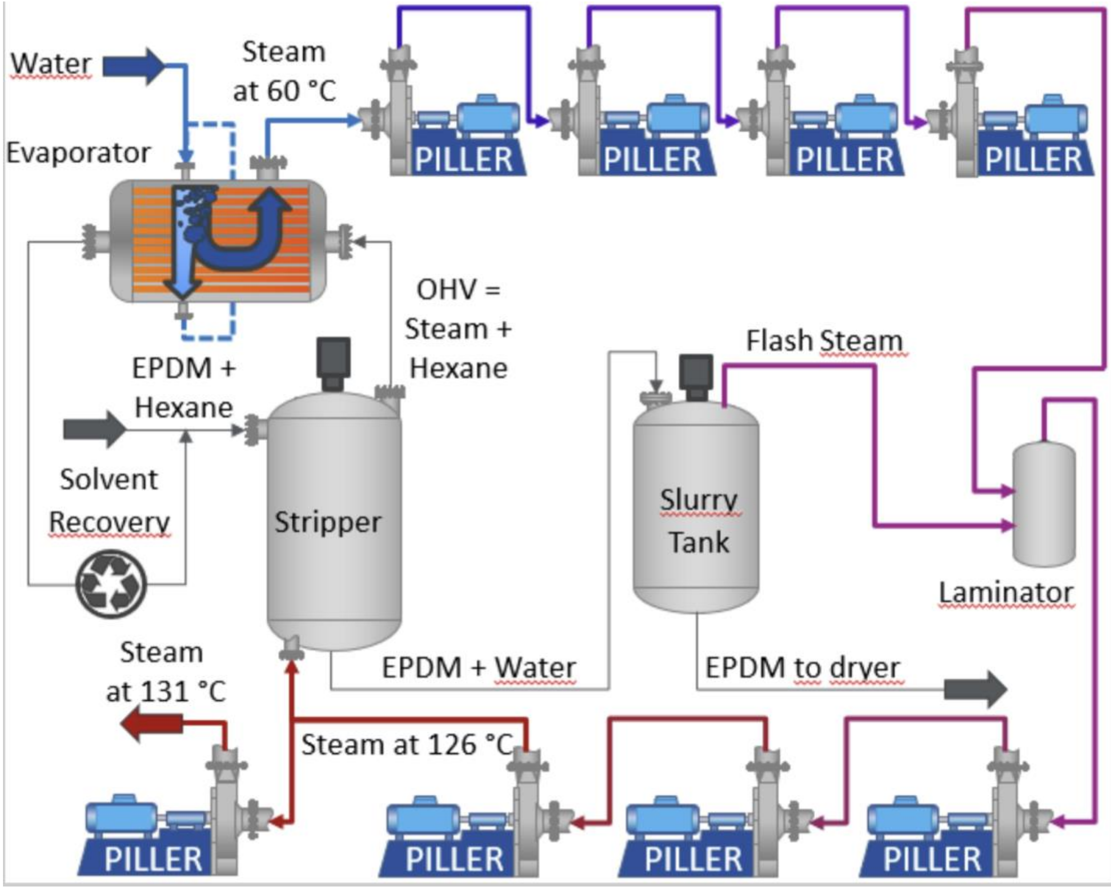

Figure 17. Process flow diagram of the multistage mechanical vapour recompression integration
Source: Schumm (n.d.), p. 1; see footnote 16.

A.2 Case study 2: Ahascragh Distillery – vapour compression high-temperature heat pump by Oilon

Located in the village of Ahascragh, Ireland, this project, led by Astatine Ltd, showcases the integration of HTHPs as a replacement for fossil-fuel boilers in the whiskey distilling process.[28]

Three Oilon heat pumps (two P450 units and one smaller P150 unit) supply all the heating and cooling needs of the process, delivering up to 1 MW of thermal energy at 115 °C with a COP of around 5.

The single-stage system, designed with integrated thermal storage, provides high-temperature process heat, medium-temperature heating and process cooling from the same installation.

This innovative configuration reduces energy use by 40% compared with conventional systems, saving approximately €330,000 and 736 tonnes of CO_2 annually.

Beyond energy efficiency, the system's use of low global warming potential refrigerants and 100% renewable power supports Ireland's broader decarbonisation goals.

Figure 18 shows the system being installed.

[28] Marren, T., & Smyth, A. (2026). Ahascragh Distillery revolutionizes whiskey production with 100% renewable energy using high temperature heat pumps installed by Astatine. *Annex 58*.
https://heatpumpingtechnologies.org/content/uploads/sites/70/2023/10/hthp-annex-58-demo-case-astatine.pdf

Figure 18. High-temperature heat pump being craned into services yard
Source: Marren & Smyth (2026), p. 1; see footnote 28.

Key metrics

- Duty delivered: 1 MW.
- Temperature range: 60 °C source (cooling system return); 115 °C pressured hot-water sink.
- Working fluids: R1234ze, R1233zd, R515B.
- Turnkey investment cost (total project cost): €1M which is approximately 1000 €/kWth (~2,000 NZD/ kWth – note the project was completed in Ireland and prices may vary by location).
- Savings: €330,000 pa (~$66,7000 NZD pa).
- Payback: 3 years.
- Operational hours: 6,200+ hours pa.

A.3 Case study 3: Weißenborn speciality paper plant – cascade high-temperature heat pump by SPH

This specialty paper plant in Weißenborn, Saxony, Germany, employs around 700 people and produces approximately 100,000 tonnes of paper annually.[29] The facility operates across the full paper value chain (pulp to paper), supported by on-site combined heat and power generation using three gas turbines and a steam turbine. Steam is currently supplied at 4.5 bar(a) and 8 bar(a), with the paper machine representing the main thermal load of the mill.

As part of the Push2Heat project, the site is now demonstrating an advanced double-stage cascade HTHP system designed to decarbonise steam production, as show in Figure 19.

Waste heat from the drying process, available at around 50 °C, is recovered via three air-to-water heat recovery systems and upgraded to produce 1.2 MW (1.8 t/h) of slightly superheated steam at 2.2 bar(a).

This integration reduces natural gas consumption and associated emissions, with estimated annual gas savings of 453,000 m³ and CO_2 reductions of roughly 231 tonnes, alongside operational expenditure savings of around €108,000 per year at a COP of 2.3.

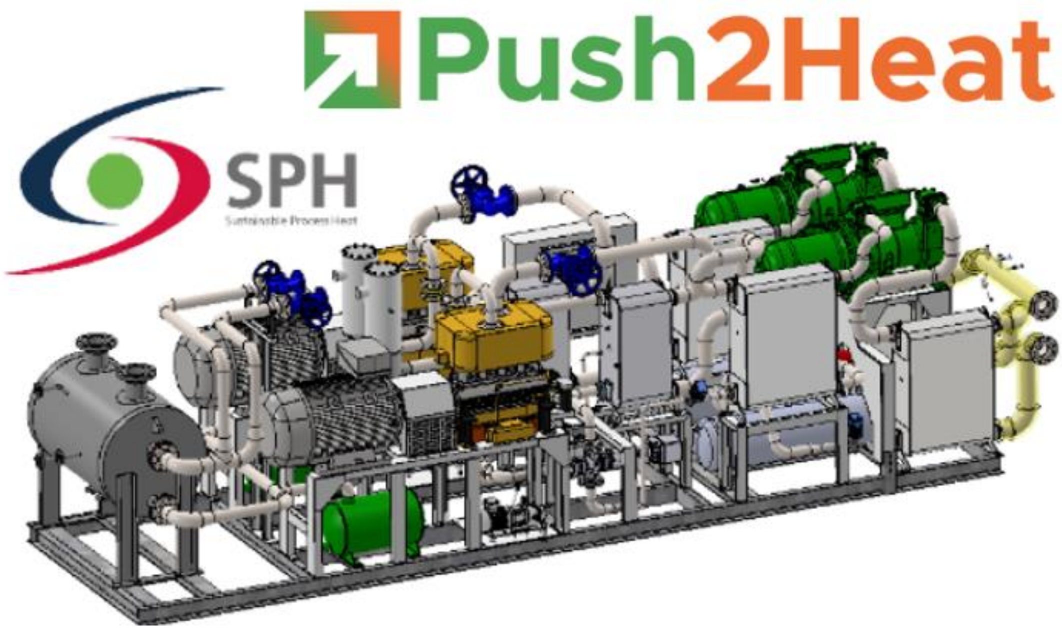

Figure 19. SPH high-temperature heat pump 3D Model
Source: Push2Heat. (n.d.); see *footnote 29*.

Key metrics

- Duty delivered: ~1.2 MW.
- Temperature range: ~45 °C source (exhaust humid air); ~120 °C pressured hot-water sink.
- Working fluid: R515B on low temperature side; R1233zd on high temperature side.
- Savings: €108000 pa (~$220,000 NZD pa).
- Operational hours: 4,800+ hours pa.

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[29] Push2Heat. (n.d.). *Process waste heat upgrading by vapor compression heat pump with piston compressors in the paper industry*. https://push2heat.eu/demo-sites/weissenborn-germany/

A.4 Case study 4: AstraZeneca Plant – Stirling high-temperature heat pump by Olvondo

The AstraZeneca's research and development site in Gothenburg, Sweden, historically relied on fossil fuels for steam production, transitioning from oil to natural gas in 1997 and later to biogas in 2018.[30]

The installation consists of three HighLift units, each delivering 500 kW of thermal output at a steam system pressure of 10 bar, supplied by rejected cooling energy from the site's air-conditioning chillers.

A fourth unit rated at 750 kW is scheduled, further expanding the site's low-carbon heat capacity.

Using helium (R-704) as the working fluid, the system enables high-temperature lifts and sink temperatures up to 200°C, while maintaining high robustness and flexibility.

Figure 20 shows Olvondo heat pumps under production.

Figure 20. Production of the Olvondo heat pumps
Source: Olvondo Technology AS. (n.d.), p. 1; see footnote 30.

Key metrics

- Duty delivered: 500 / 750 kWth unit.
- Temperature range: heat source 0–100°C; heat output 100–200°C steam.
- Working fluid: helium (R-704).
- Compressor technology: double-acting piston (reversed Stirling cycle).
- Technology performance: COP heating between ~1.7 and 2.6 depending on operating point.
- Specific investment cost: ~€1,200 per kW (equipment only, excluding integration).

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[30] Olvondo Technology AS. (n.d.). *Reversed Stirling cycle Olvondo Technology AS*. https://heatpumpingtechnologies.org/content/uploads/sites/70/2022/07/olvondo-highlift.pdf

- Expected lifetime: 20 years.
- Unit size: ~13 tonnes and ~20 m^2 footprint per HighLift unit.

Appendix B: Example calculation for simple payback and internal rate of return metric

Another method for determining whether a HTHP project is financial viability is through the calculation of a simple metric, such as payback and internal rate of return.

This section provides a structured calculation method for estimating the economic performance of a HTHP using a limited set of readily available inputs. The approach is intended to support rapid financial screening and sensitivity analysis, without requiring detailed process or system-level modelling.

The calculation sequence begins with an estimation of the heat pump COP as a function of the required temperature lift, ΔT_{lift}, and the heat delivery temperature, $T_{h,out}$. Equation 3 provides a COP regression for the HTHP derived from published performance data, valid for sink temperatures from 80°C up to 160°C.[31]

$$COP = 1.9118 \cdot \left(\Delta T_{lift} + 2 \cdot 0.044189\right)^{-0.89094} \cdot \left(T_{h,out} + 0.044189\right)^{0.67895} \qquad \text{(Equation 3)}$$

The estimated COP is then combined with the relative price of electricity to the reference fuel (price ratio) and an assumed reference fuel (C_{ref}) cost to determine the effective cost of supplying heat with the heat pump, as shown in Equation 4.[32] This step yields the demand-related cost of heat supplied by the HTHP (Note: $C_{dem,HP}$ denotes the demand-related cost for the heat pump and C_{ref} the cost of the reference fuel).

$$C_{dem,HP} = C_{ref} \cdot price\ ratio \cdot \frac{1}{COP} \qquad \text{(Equation 4)}$$

To evaluate the operating cost impact, the calculated heat cost is multiplied by the annual operating hours (t_{oh}) and compared against the cost of supplying the same heat demand using the reference technology, as shown in Equation 5.[33] The reference case accounts for the efficiency of the existing or alternative boiler (η_{ref}). The result of this calculation is the difference in annual heat supply costs between the heat pump and the reference technology ($\Delta_{dem,a}$).

$$\Delta_{dem,a} = C_{dem,HP} \cdot t_{oh} - C_{ref} \cdot \frac{1}{\eta_{ref}} \cdot t_{oh} \qquad \text{(Equation 5)}$$

This annual cost difference represents the net operating cost benefit and forms the basis for the economic assessment. By combining this value with estimated capital costs for both the heat pump ($C_{I,HP}$) and the reference technology ($C_{I,ref}$), and including maintenance cost factors (f_m), a simple payback period is calculated, as shown in Equation 6.[34]

$$Simple\ Pay\ Back = \frac{C_{I,ref} - C_{I,HP}}{f_{m,HP} \cdot C_{I,HP} - f_{m,ref}\ C_{I,ref} + \Delta_{dem,a}} \qquad \text{(Equation 6)}$$

[31] Schlosser et al. (2020); see footnote 26.
[32] Ibid.
[33] Ibid.
[34] Ibid.

Finally, the simple payback result can be combined with an assumed depreciation period (N) to estimate the internal rate of return. The internal rate of return is calculated by relating the annual economic benefit to the total investment and iteratively solving for the interest rate that satisfies the corresponding relationship, as shown in Equation 7.[35] This allows the project to be compared against typical industrial investment criteria.

$$IRR = solve(i)\left[\frac{(1+i)^N \cdot i}{(1+i)^N - 1} - Simple\ Pay\ Back\right] \qquad \text{(Equation 7)}$$

The same calculation framework can also be applied in reverse to determine the maximum allowable heat pump investment cost required to meet a specified payback period or internal rate of return target.

To illustrate how this equation and metrics can be used to inform quick decisions, two examples are shown below. Assumptions and inputs used in the examples are:

- maintenance (f_m). = 3% of capital cost
- efficiency reference boiler (η_{ref}) = 0.87
- investment cost for reference technology, either boiler 1,000 NZD/kWth or efficiency measure 0 NZD/kWth
- reference energy price = 63 NZD/MWh
- the plant under consideration is assumed to require a temperature lift of 30°C.

Before using these financial metrics, first define the integration strategy (is the project an efficiency project or utility replacement) and the type of heat pump to be assessed. Also, when constructing a more rigorous business case, it is important to consult an experienced professional.

Example 1 – determining internal simple payback and internal rate of return

In this example, the objective is to determine the internal rate of return for a heat pump implemented as an efficiency project (capital investment for the reference = 0).

- A representative electricity-to-reference-energy price ratio (price ratio) of 3 is assumed, which is consistent with average values for energy-intensive industrial users in New Zealand.
- At a temperature lift of 30 K, this corresponds to a COP of approximately 5.0 (calculated using Equation 3).
- The process operates 4,500 hours per year, and the heat pump investment cost is estimated at 1,500 NZD/kW_{th}.
- With a depreciation period (N) of 20 years, the equations indicate an internal rate of return slightly above 4%, corresponding to a payback period of approximately 13.4 years.

In practice, many energy decarbonisation projects in New Zealand are not efficiency upgrades, but rather direct substitutions of existing or planned heat supply assets, such as when the decision is made to use a biomass boiler or a heat pump. In this case, the project should be assessed as a utility replacement.

Therefore, instead of the capital investment for the reference technology being set to 0, a value of 1,000 NZD/kW_{th} is selected to represent a typical biomass boiler price. Under otherwise identical

[35] Ibid.

assumptions, this approach improves the payback period to just over 3.5 years and an internal rate of return of 28%.

Example 2 – determining the maximum allowable investment cost

The second example illustrates how the financial equations can be used to determine the maximum allowable heat pump investment cost that meets a company's economic criteria.

Many organisations require payback periods of less than 3 years, with large industrial sites often applying even stricter thresholds of 1–2 years. In this example, a payback target of 3 years is specified, while all other assumptions remain unchanged from example 1. A rearrangement of Equation 6 indicates a maximum allowable investment cost of approximately 430 NZD/kW_{th} for an efficiency project, or 1,430 NZD/kW_{th} when assessed as a utility replacement project.