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High-Temperature Heat Pumps for Industrial Decarbonisation

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Summary

High-temperature heat pumps (HTHPs) can supply heat above 80°C. They play an important role in improving the efficiency of industrial thermal supply – a sector that constitutes a significant portion of global energy consumption.

Over the past decade, HTHPs have had significant advancements in system configurations, working fluids, key components, products, and applications. In addition, HTHPs being at an early stage of their market promotion, it is necessary to compare them to their alternatives. This technical brief reviews the current development of HTHP's system configurations, working fluids, and components to support R&D activities by technology developers; introduces the products, application scenarios, and innovative applications to improve industrial users' awareness and acceptance; analyses its current economic and environmental performance and targeted improvement strategies to inform decision-makers in developing relevant policies. A variety of configurations, working fluids and key components for compression and absorption systems are available to meet HTHPs' high-temperature operating conditions. Mature products have been available for temperature ranges of 100-300°C and capacities from 0 to 100 MW, which have been applied in food processing, chemical engineering, material processing and other industries. Innovative applications of HTHPs such as combined cooling and heating and integration with thermal energy storage can improve its utilization efficiency, application flexibility and economic performance. HTHPs still do not have sufficient economic and environmental benefits compared with conventional boilers, requiring joint efforts in technological R&D, environmental tax policies and the improvement of electricity cleanliness. This technical brief aims at offering insights that support the collaboration in scaling up HTHP deployment and at advancing deep decarbonization of industrial heating.

1

Introduction

Heat pumps are an efficient technology for thermal energy supply due to their high energy conversion efficiency compared to conventional heating systems. Heinrich Zoelly was the first to put forward an electrically driven ground source heat pump for low-temperature heat production and made in a Swiss patent in 1912. But the technology sector was not yet ready for his ideas.

Between 1919 and 1950, heat pumps for space heating and domestic hot water heating were developed, evolving from rare prototypes to a reliable heating. After 1990, cheaper, more efficient and reliable heat pumps became available. With the rise of environmental concerns and oil prices, the heat pump market has significantly expanded. Until the 2010s, heat pump applications were mainly used in the civil sector or in medium-temperature industrial processes such as distillation (60-80°C)[1].

Since the market for low- to medium- temperature heat pump has matured, the research and development (R&D) for high-temperature heat pumps (HTHPs) was launched to facilitate a deeper energy transition of heating. The industrial sector takes a large proportion of global energy consumption, accounted for 37% in 2022[2]. Within industrial energy use, two-thirds is dedicated to heat generation[3]. The industrial thermal process requires temperature from tens to thousands of degrees Celsius, from water heating to metal melting. The 100-200°C thermal range is the key target for HTHPs and is commonly found in the industrial processes illustrated in **Figure 1**.

For HTHPs supplying hot water at around 80-90°C, some European companies developed units since the 1980s for district heating applications[5]. As for steam generating heat pumps, a few Japanese companies are the forerunners. One of the earliest steam-generating HTHP was Kobelco's SGH series, developed around 2011. From 2009 to 2012, Mayekawa worked on a project to develop a 150°C steam supply HTHP[1]. After 2010, progress in HTHP technology has accelerated steadily. The number of annual publications in this field has grown significantly from 921 in 2010 to 5,480 in 2024[6], reflecting increased research interest and development activities. HTHPs are now located midway between research and industrial deployment, with a growing collaboration between academia and industry. Organisations such as HighEFF and IEA-HPT (IEA Heat Pumping Technologies) gathered participants from research & education institutes and industries to advance HTHP technologies. To date, dozens of suppliers have launched HTHP technologies[7]. According to the prediction from IRENA, the number of industrial heat pumps is expected to increase from less than 1 million units in 2020 to 35 million units by 2030 and then to 80 million units by 2050[8].

Unlike conventional medium-temperature heat pumps, configurations, working fluids, key components of HTHP must withstand high temperatures and potential high-pressure conditions. Moreover, the characteristics of thermal demands in industrial scenarios also have significant differences compared to civil applications. Therefore, the R&D of HTHP is not a straightforward extension of civil heat pumps. For this emerging technology, new schemes are required. This technical brief summarises the development, applications, and comprehensive performance assessment of HTHPs, providing an overview about HTHP for researchers, users, and policymakers to enhance their understanding of this technology and advance relative efforts.

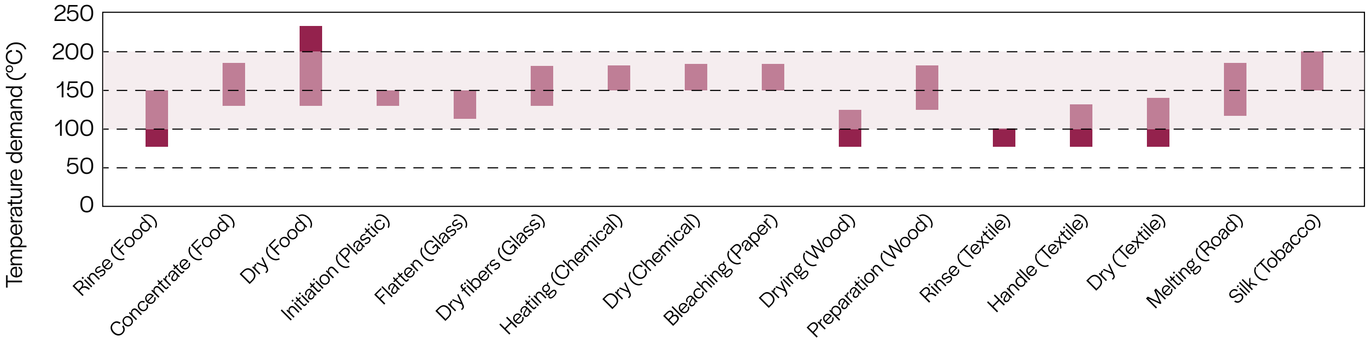


Figure 1 | Heating temperature ranges in different sectors[4].

2

System configurations of HTHP

The laboratory-scale HTHP systems with heat sink temperature over 80°C can be classified as compression, absorption and hybrid absorption-compression HTHPs according to different configurations.

2.1 Compression HTHP

The basic single-stage vapour compression heat pump (VCHP) includes four key components: compressor, condenser, throttling valve, and evaporator. The heating and cooling are achieved by the liquid-vapour phase change of working fluids. Different scenarios, including low heat source temperature, large temperature lift and complex heat source composition, often occurring in practical applications, prevent single-stage HTHPs to operate properly. In order to address these issues, optimised configurations have been proposed. All the compression HTHP configurations mentioned subsequently are displayed in **Figure 2**.

The compressor being the primary power consumption component in the HTHP cycle, it is important to improve its performance. Injection technique has been proven to be an effective solution, which achieves interstage cooling of the compressor to reduce discharging superheat, thereby reducing power consumption and ensuring system reliability. Flash tanks and economisers are commonly used devices in vapour and two-phase injection, as shown in **Figures 2 (b)** and **2 (c)**. As shown in **Figure 2 (d)**, replacing the throttling valve by ejector for expansion is another way to improve system performance by reducing throttling losses and irreversibility. Ejecting refrigerant with high pressure vapour flow can avoid heat exchange losses and increase the pressure of low-pressure stage.

As shown in **Figure 2 (e)**, the multi-stage vapour compression HTHP is developed by incorporating extra compressors into single-stage VCHPs. The increasing compressors resolve the temperature lifting capability constraint caused by the limited pressure ratio of the single-stage compression. However, increasing the overall compression ratio leads to a significantly rising superheat of the compressor discharging fluid. Injection is also generally employed between stages to reduce the discharging temperature.

As shown in **Figure 2 (f)**, the cascade configuration is divided into two independent cycles. Each cycle could employ a specific working fluid that is suitable for its corresponding temperature ranges. The cascade heat pump is advantageous in applications with large temperature lift[10]. Since each stage undergoes an independent evaporation process, injection is rarely required compared to multi-stage systems. The appropriate coupling of each stage requires consideration in cascade configuration.

The heat pumps in **Figures 2 (a)-(f)** are closed-cycle systems, supplying heat to users through an indirect heat exchange loop. Many industrial processes have direct steam demand. Hence the importance of the open-cycle configuration shown in **Figure 2 (g)**. In an open system, compressing low-temperature steam into high-temperature steam is considered a generalised form of heat pump. Some processes, such as flashing and injection, are required for phase separation and cooling. However, the open-cycle system requires steam at the inlet, thereby demanding a higher-grade heat source. The combination of closed- and open-cycle enables the use of low-temperature heat sources and the supply of high-temperature steam. Two combined steam-generating systems are illustrated in **Figure 2 (h)** and **(i)**. In **Figure 2 (h)**, the cascade HTHP can supply hot water up to 120°C[11], which can then be flashed into steam. If higher steam temperature is needed (150-180°C), the **Figure 2 (i)** [12] illustrates how an open-steam compression stage can be integrated with the cascade HTHP. The hot water produced by the cascade HTHP is initially flashed then compressed into steam. The liquid water is injected into the vapour compressor for cooling and lowering the discharge temperature.

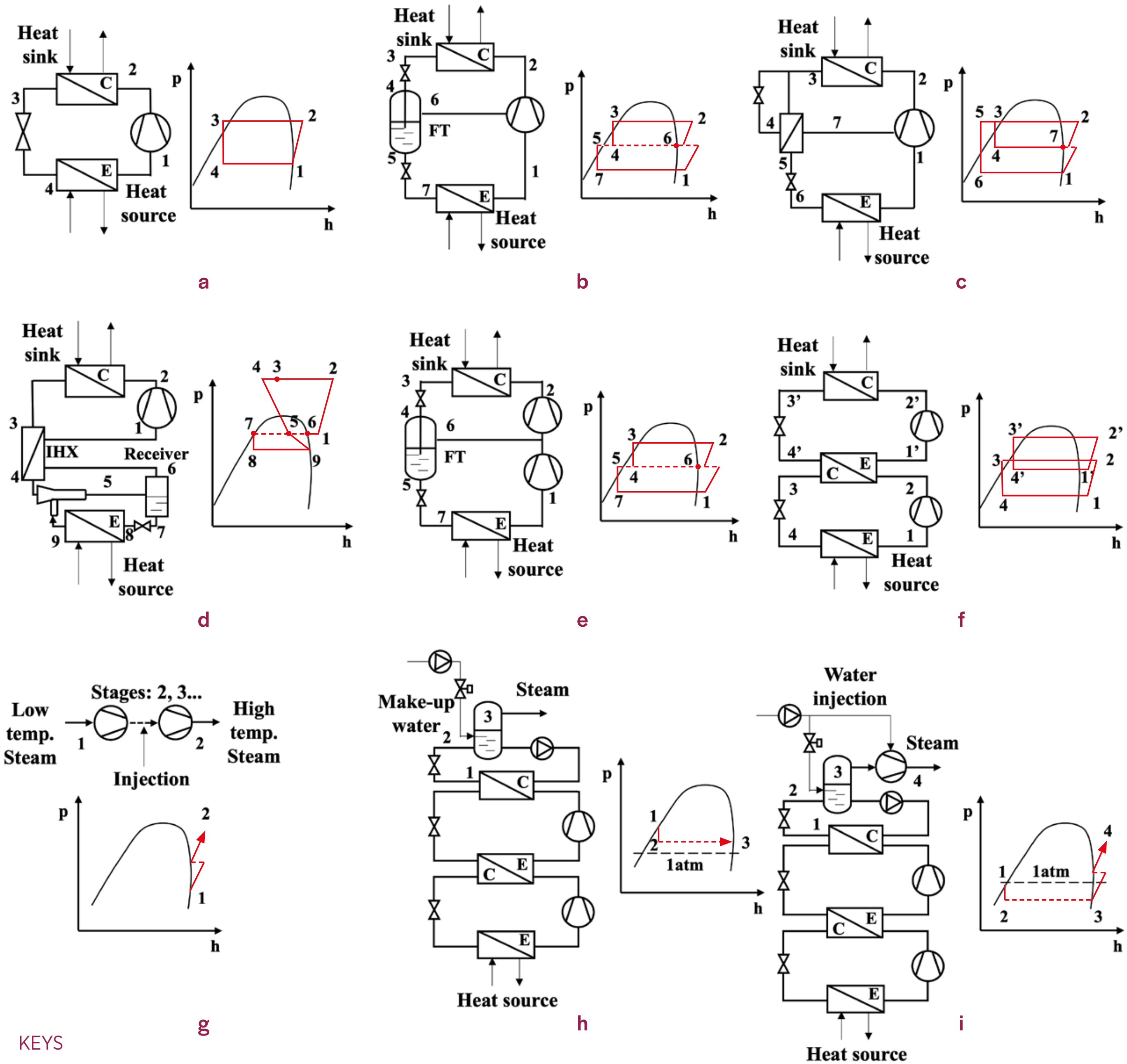
2.2 Absorption HTHP

Absorption heat pumps are thermally driven systems that can directly use industrial waste heat to conserve electricity consumption. The absorption heat transformer (AHT, Type II absorption heat pump) operates with a medium-temperature heat source to generate high-temperature energy, with the goal of enhancing quality (**Figure 3**).

Single-stage AHTs have limited temperature-raising capacity, while multi-stage AHTs can significantly enhance the overall temperature-raising capability of the system (**Figure 3 (a)**). Typical experimental results have demonstrated that the double-stage cascaded AHT achieved a temperature lift 30°C higher than the single-stage AHT[13] (**Figure 3 (b)**).

Besides multi-stage cycles, the multi-effect cycle is also a common approach to enhancing AHT performance.

Dual-effect absorption heat transformers feature two generators (**Figure 3 (c)**). Vapour produced by the high-temperature generator releases condensation heat and drives the low-temperature generation process. With two distinct generation processes, dual-effect absorption heat transformers achieve more efficient energy utilization. Zhao *et al.* compared double-effect and single-effect AHTs. The double-effect AHT shows improved performance when operating at large temperature lifts and high-temperature outputs. However, as the absorption temperature increases, the double-effect AHT's coefficient of performance (COP) decreases more rapidly than that of the single-stage AHT, ultimately reducing the achievable temperature lifting range. Therefore, the multi-effect strategy is only suitable for applications where the heat source temperature is high and the temperature rise is moderate[14].



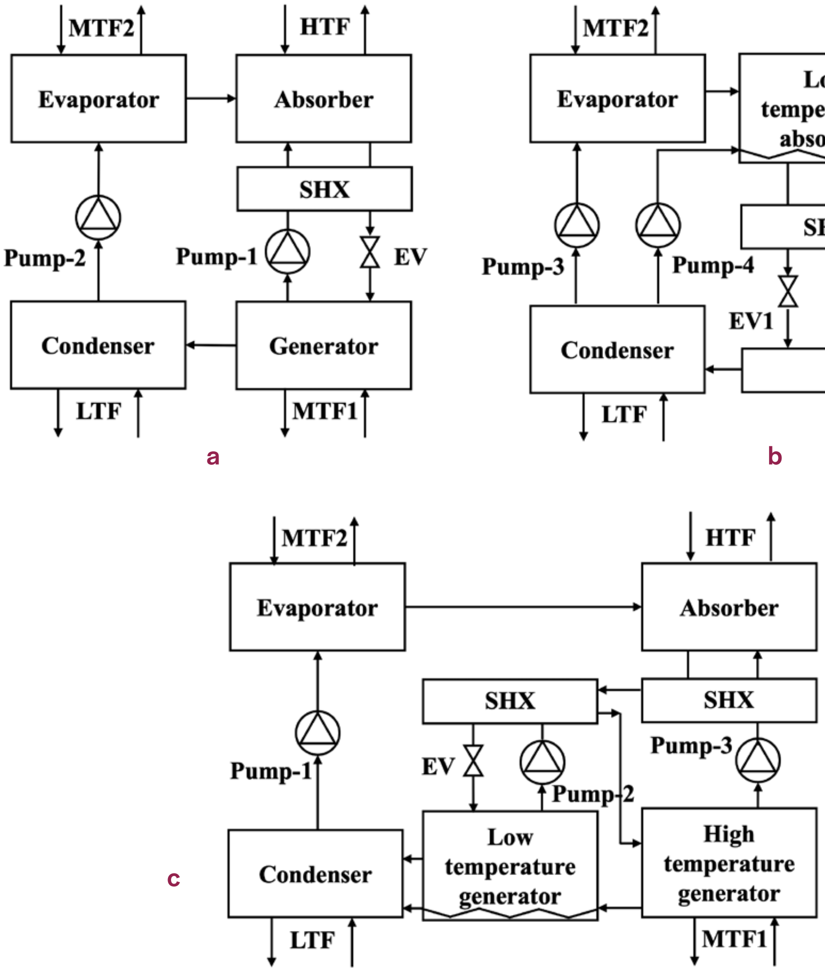
KEYS

E	evaporator
C	condenser
FT	flash tank
IHX	internal heat exchanger

Figure 2 | Configurations of compression HTHPs [12] **(a)** basic VCHP configuration; **(b)** VCHP with vapor injection; **(c)** VCHP with two-phase injection; **(d)** single stage VCHP with ejector; **(e)** two-stage VCHP; **(f)** cascade VCHP; **(g)** open-cycle steam compression; **(h)** cascade VCHP + direct flash; **(i)** cascade VCHP + open cycle steam compression.

2.3 Hybrid compression-absorption HTHP

By integrating compression and absorption cycles, the hybrid compression-absorption system combines the advantages of both types. **Table 1** shows the working conditions of several typical systems. These systems are efficient solutions to provide high output temperatures. Hybrid systems can be categorised as thermal-coupling and mass-coupling hybrid heat pumps according to different coupling strategies. Both strategies and improvement structures will be demonstrated below.



KEYS

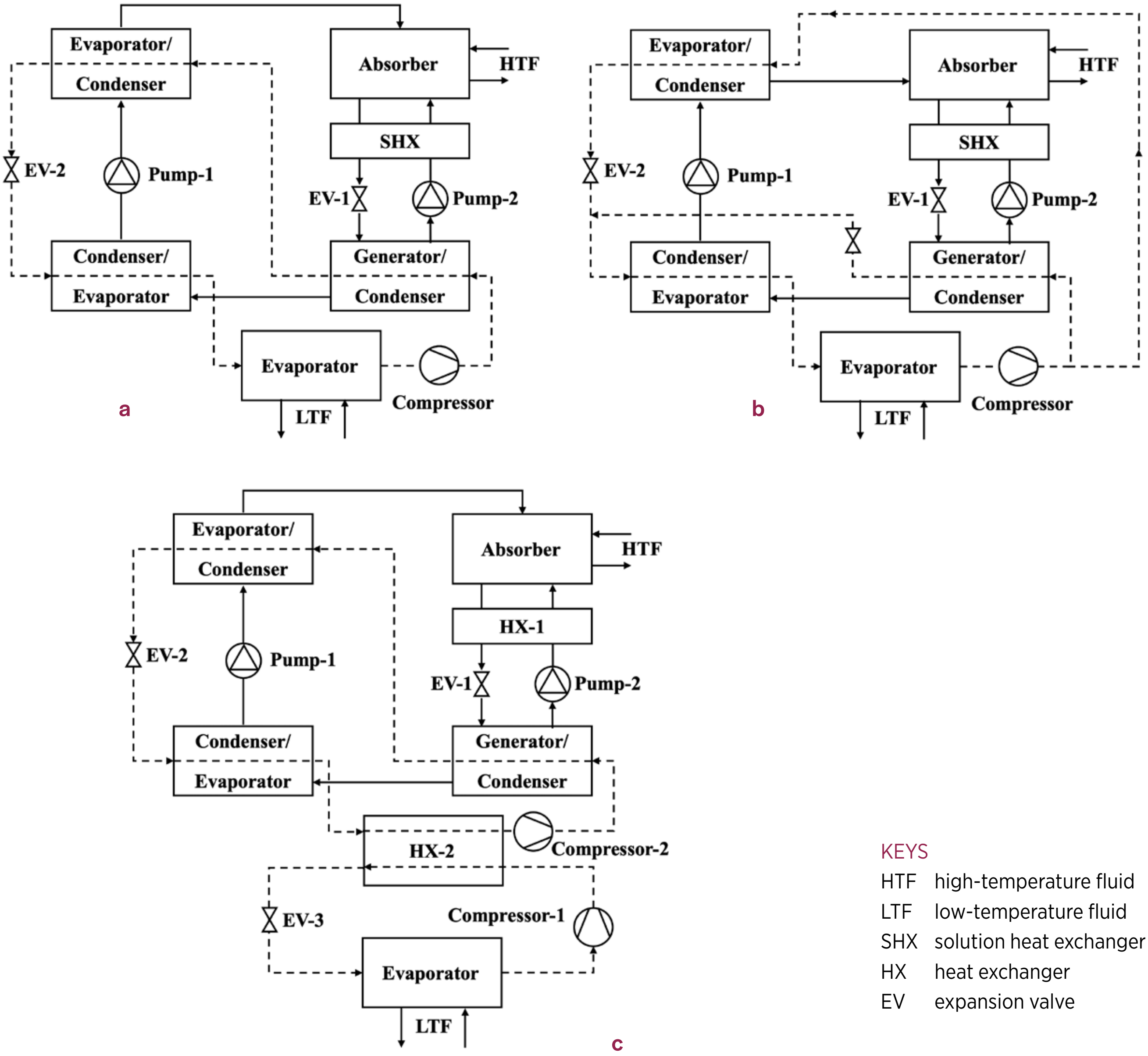
SHX	solution heat exchanger
LTF	low-temperature fluid
MTF	medium-temperature fluid
HTF	high-temperature fluid

Figure 3 | Configurations of absorption heat transformers **(a)** single-stage; **(b)** double-stage; **(c)** dual-effect.

TABLE 1 TYPICAL SYSTEM CONFIGURATIONS OF HYBRID ABSORPTION-COMPRESSION HTHP

CONFIGURATION TYPE	HEAT SOURCE TEMPERATURE (°C)	OUTPUT TEMPERATURE (°C)	WORKING FLUID	COP
Thermal-coupling hybrid HTHP[15]	10-36	80-120	R134a/LiBr-H_2O	1.2-1.7
Thermal-coupling hybrid HTHP[16]	10	150-186	R152a/H_2O-[EMIM][MPH]	1.7-2.3
Thermal-coupling hybrid HTHP[17]	160	200	R245fa/LiBr-H_2O	3.49
Thermal-coupling hybrid HTHP [18]	30	100-181	R134a/R245fa/LiBr-H_2O	2.10-3.12
Thermal-coupling hybrid HTHP [19]	40-60	50-200	NH_3-H_2O	-
Compression-assisted absorption cycle [20]	50	80	NH_3-H_2O	5.219
Absorption-assisted compression cycle [21]	150	200	LiBr-H_2O	3.01

The thermal-coupling hybrid strategy is a combination of a cascaded compression heat pump and a cascaded absorption heat transformer. Similar to the aforementioned multi-stage configurations, the strategy allows for larger temperature lifts and meets ultra-high temperature requirements when used with a low-temperature heat source. Within the hybrid cycle, compression sub-cycles usually handle the low-temperature process of upgrading the heat to an applicable generation temperature, while absorption sub-cycles provide further heat upgrading and deliver the heat to the user side. Generally, thermal coupling refers to various heat transfer relationships between the heating and cooling demand of sub-cycles. Heating demands include the generation process of the absorption sub-cycle and evaporation processes of both sub-cycles. Cooling demands include condensation processes of both sub-cycles and the absorption process of the absorption sub-cycle. Configuration design of thermal-coupling HTHPs revolves around these internal thermal demands and external working conditions, as summarised in **Figure 4**. Some researchers satisfied the heat demand of the absorption sub-cycle by using the condensation heat of the compression sub-cycle. As shown in **Figure 4 (a)** and **Figure 4 (b)**, these heat demands for generation and evaporation process of absorption sub-cycle can be supplied by condensation heat flow in series[22] or independently[16]. The double-stage compression sub-cycle was used to extend the hybrid system to a three-stage configuration[18] with the goal of raising the temperature lift, as shown in **Figure 4 (c)**. Besides, downstream of the EV-2, the condensation heat of the absorption sub-cycle can be recovered by the compression sub-cycle for higher efficiency.



KEYS

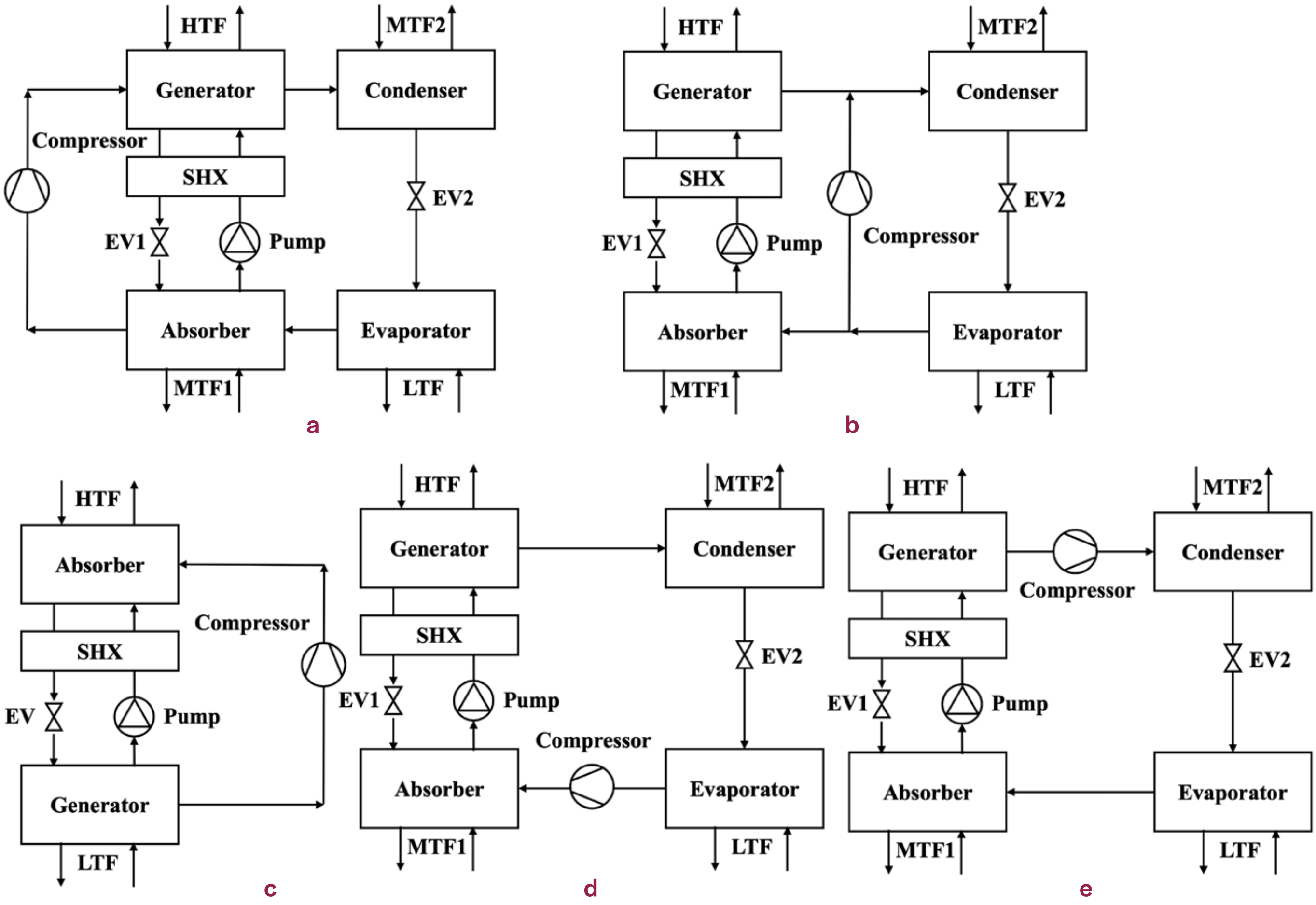
HTF	high-temperature fluid
LTF	low-temperature fluid
SHX	solution heat exchanger
HX	heat exchanger
EV	expansion valve

Figure 4 | Thermal-coupling hybrid absorption-compression heat pump[23] : heat exchange through generator and evaporator **(a)** in series or **(b)** independently; **(c)** used double-stage compression sub-cycle.

Mass-coupling hybrid absorption-compression heat pumps combine the two sub-cycles using the compressibility of gaseous absorbate state. Gao *et al.* reviewed and classified the mass-coupled hybrid cycles depending on different compressor positions[23], as shown in **Figure 5**. In this review, the absorption heat pump cycle, with the compressor placed between the absorber and the generator as shown in **Figure 5 (c)**, was identified as an efficient approach for high-temperature output of above 100°C. Among the five combination types, **Figure 5 (a)**, **(b)**, **(d)** and **(e)** are type-I absorption heat pump sub-cycles and compression heat pump sub-cycles. In **Figures 5 (a)** and **5 (b)**, flexible heating load can be achieved by adjusting the proportion of refrigerant entering compressor. The design of **Figure 5 (e)** is intended to reach the generation process with a lower pressure and temperature. **Figures 5 (c)** and **(d)** have been widely studied and named as 'compression-assisted absorption cycle' and 'absorption-assisted compression cycle' depending on the sub-cycle in dominance[24].

Based on the absorption-assisted compression cycle, the use of multi-stage compression[25], double-stage rectifier and sub-cooler [26] has been suggested as an efficiency enhancing strategy. The cascaded hybrid cycle has smaller compression ratio, maximum pressure and compressor discharging temperature[19]. The cycles all use ammonia-water as working pair. Other working pairs such as LiBr-H_2O[21] have also been employed for higher output temperature.

In order to recover sensible heat of flue gas of 150°C to generate saturated steam of similar temperature, Liu *et al.* placed the compressor between the generator and the condenser of a basic AHT. The application of a compressor and an ammonia pump allows the absorbate compression process to combine gas compression with liquid pressurization process, thereby reducing energy consumption[27]. Both theoretical and experimental research on optimal solution concentration range has been conducted.



KEYS

HTF	high-temperature fluid
MTF	middle temperature fluid
LTF	low-temperature fluid
SHX	solution heat exchanger
EV	expansion valve

Figure 5 | Mass-coupling hybrid absorption-compression heat pump[23]: **(a)** & **(b)** with compressor between high and low stages; **(c)** with compressor between absorber and generator; **(d)** with compressor between evaporator and absorber; **(e)** with compressor between generator and condenser.

2.4 Comparison among configurations

Due to their high efficiency and easy installation, VCHPs have already been widely adopted. However, as core component of VCHPs, compressors are restricted with regards to high discharging temperature and pressure ratio. Configurations including cascaded cycles, multi-stage compressions and inter-stage refrigerant injections can help lowering the discharging temperature and the single-stage pressure ratio, thus enhancing the system's temperature elevation capacity.

Absorption-compression heat pumps (ACHPs) have lower working pressure[28], less electricity consumption, less noise and larger heating capacity. ACHPs are a kind of good alternative when medium waste heat (above 60°C), mainly from industrial processes, is available. In contrast, VCHPs are more flexible when using any waste heat temperature. As for working fluids, ACHP systems use environmentally friendly options such as ammonia-water, LiBr-H_2O, and ionic liquids. However, these working pairs may face issues like crystallization and high viscosity at low solution temperatures. VCHPs also offer many choices for natural working fluids. However, they pose risks such as flammability, high operating pressure or temperature.

Hybrid absorption-compression HTHPs combine the benefits of both VCHPs and ACHPs. Among the two coupling strategies, the thermal-coupling strategy ensures large temperature lift and high temperature output with low-temperature heat source. A mass coupling strategy lowers the working pressure and the discharging temperature while raising the temperature lift to VCHPs[20]. This new technology incorporates additional settings that increase the system's complexity. As a result, in-depth research and analysis of the system's configuration, component selection, and thermodynamic properties need to be conducted while considering specific operating conditions, component characteristics, and thermal capacity.

3

Working fluids of HTHPs

The primary screening criterion for working fluids in compression heat pumps is that they must include phase-change behaviour and thermophysical properties suited to the operating temperature range. In subcritical cycles, Devotta *et al.* suggested that: 1) the normal boiling point of the working fluid should be lower than ambient temperature to maintain positive pressure when the unit is shut down; 2) the critical temperature should provide a safety margin — for instance, when the condensation temperature is around 120°C, the critical temperature of the working fluid should fall within 130–150°C[29]. Except thermodynamic properties, other factors such as environmental impact, safety, compatibility, cost, and efficiency also need to be considered (**Figure 6**).

With growing awareness of environmental protection, the use of chlorofluorocarbons (CFCs) such as R114, which have a high ozone depletion potential (ODP), in new and retrofit systems was completely phased out by 2010. Hydrochlorofluorocarbons (HCFCs) including R142b, R123 and R124, which served as transitional replacements for CFCs, are also scheduled to be phased out by 2040. Following the Kigali Amendment, 18 types of hydrofluorocarbons (HFCs) with high global warming potential (GWP) — such as R245fa, R236fa and R365mfc — have been added to the list of controlled substances. Some working fluids complying with current environmental regulations and suitable for HTHPs are listed in **Table 2**. It is notable that PFAS (Per- and Polyfluoroalkyl Substances) gases such as HFOs and HCFOs may raise another concern in the future due to their potential for accumulation and persistent toxicity to human health and ecosystems. European Union's restrictions on PFAS are expected to be fully assessed by the end of 2026[30]. If PFAS-based refrigerants face usage limitations, the range of available working fluids may be reduced primarily to natural refrigerants and a limited number of synthetic alternatives.

The working fluid must not pose harm to users. In terms of safety indicators, working fluids are classified as follows: toxicity is categorised into A (lower toxicity) and B (higher toxicity), while flammability is identified numerically (1-3), with higher numbers representing greater flammability. A1 refrigerants are considered as safe working fluids. HCs (A3 safety level as shown in **Table 2**) deserve special attention, as they are likely to become the most used HTHP working fluids in the future due to environmental concerns. Their charge mass requires further regulation, and heat pump machine rooms must be designed with fire and explosion prevention measures.

Working fluid compatibility with materials is essential for ensuring the long-term stable operation of the unit. For example, the working fluid must be miscible with lubricating oil and must not cause corrosion to component materials.

After meeting usability, environmental friendliness and safety requirements, working fluids can be further evaluated and optimally selected. Fluids with high volumetric heating capacity (VHC) and high coefficient of performance could enhance the overall system efficiency, which are optimal choices.

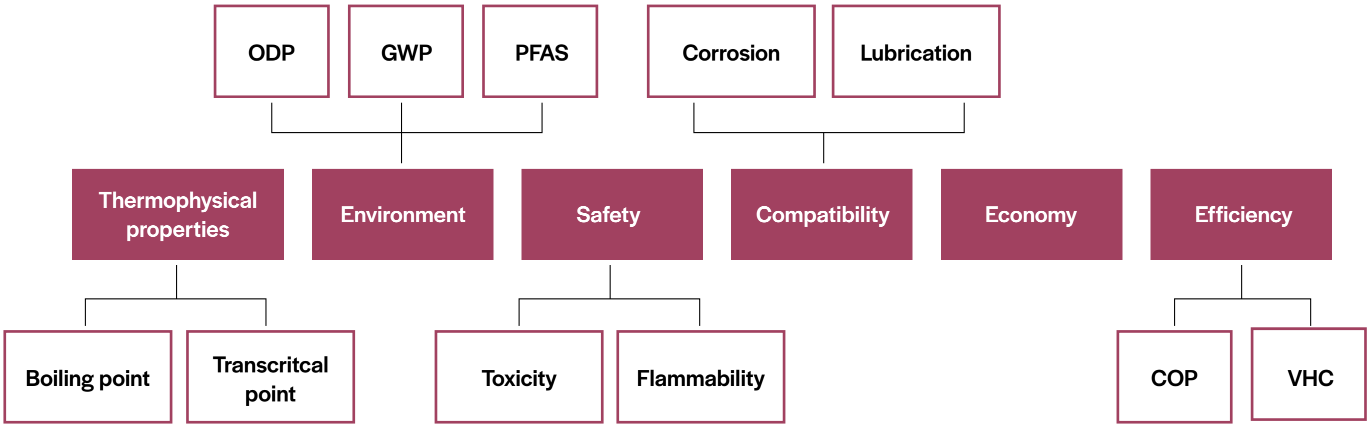


Figure 6 | Requirements for working fluids in HTHPs.

TABLE 2 PROPERTIES OF A FEW APPLICABLE WORKING FLUIDS IN HTHPS

TYPE	REFRIGERANT	t_{cr} (°C)	p_{cr} (MPa)	NBP	ODP	GWP	SAFETY
HFC	R161	102.2	5.09	-37.5	0	5[a]	A3
HFC	R152a	113.3	4.52	-24.0	0	164[a]	A2
HFO	R1234yf	94.7	3.38	-29.0	0	<1	A2L
HFO	R1132(E)	97.4	5.09	-35.7	0[b]	1	A1[b]
HFO	R1243zf	103.8	3.52	-25.5	0[c]	0.8	A2L[c]
HFO	R1234ze(E)	109.4	3.64	-19.0	0	<1	A2L
HFO	R1336mzz(E)	137.7	3.15	7.5	0	18	A1
HFO	R1234ze(Z)	150.1	3.53	9.8	0	<1	A2L
HFO	R1336mzz(Z)	171.3	2.90	33.4	0	2	A1
HCFO	R1224yd(Z)	155.5	3.33	14.0	0.00012	<1	A1
HCFO	R1233zd(E)	166.5	3.62	18.0	0.00034	4[a]	A1
HCO	R1130(E)[b]	234.1	5.51[d]	47.7	0.00024	5	B2
HC	R1270[e]	91.1	4.55	-42.1	0	<1	A3
HC	R290	96.7	4.25	-42.0	0	<1[a]	A3
HC	R600a	134.7	3.66	-11.0	0	<1[a]	A3
HC	R600	152.0	3.80	-0.5	0	<1[a]	A3
HC	R601a	187.8	3.38	27.7	0	4	A3
HC	R601	196.6	3.37	36.1	0	5	A3
Others	R717	132.3	11.33	-33.0	0	0	B2L
Others	R718	373.9	22.06	100.0	0	0	A1
Others	R744	31.0	7.38	-78.5	0	1	A1

Note: The data was gathered from [31] and [32], unless otherwise specified. a: [33], b: [34], c: [35], d: [36], e: [37].

Good economic performance is another advantage of a working fluid. Natural refrigerants are inexpensive and show economic benefits in medium- and large-scale heat pump systems.

The properties of pure working fluids are limited. Mixtures could balance the strengths and weaknesses of various fluids. Spale *et al.* evaluated the comprehensive performance of fluid mixtures for the 200°C heat pump in terms of safety, environmental concerns, material and lubrication oil compatibility. A blend of cyclopentane and R1336mzz(Z) in a mole fraction of 0.68 and 0.32, respectively, emerged as the most promising candidate[38]. Ganesan *et al.* investigated the thermodynamic performance of CO_2 and HC mixtures. These mixtures are promising because they leverage CO_2's temperature glide while offsetting CO_2's high discharge pressure and HC's flammability[39]. HFOs have slight flammability. One commercial fluid mixture, HP-1, uses R1336mzz(E) as flame retardant to suppress the flammability of R1234ze(Z)[40]. In summary, blending working fluids may create product with superior performance. However, the solubility and compatibility among components and the composition changes during operation need to be carefully examined.

The above discussions are targeted to working fluids in compression heat pumps. In absorption heat pumps, the refrigerant's boiling point needs to be low enough to ensure its release from the absorbent during the generation phase. NH_3/H_2O and $H_2O/LiBr$ are the most used working pairs in absorption heat pump. NH_3 is toxic and flammable, while the $H_2O/LiBr$ pair is prone to crystallization issues, and LiBr exhibits strong corrosivity to equipment above 150°C. Alcohols and ionic liquids have been used as refrigerants and absorbents, respectively in the development of new working pairs, demonstrating excellent properties such as non-toxicity, non-corrosiveness, and non-crystallization[41, 42]. The use of natural working fluid pair provides great economic advantage, whereas employing salt solutions or ionic liquids rises the cost of absorption heat pumps.

4

Key components of HTHPs

4.1 Heat exchangers

The heat exchanger can be used as condensers, evaporators, generators and absorbers in compression and absorption systems. Its performance has significant impact on the overall system. Heat exchanger types include shell and tube, plate, fin and tube, double pipe and microchannel. Schematic diagrams of heat exchangers commonly used in HTHPs are shown in **Figure 7**.

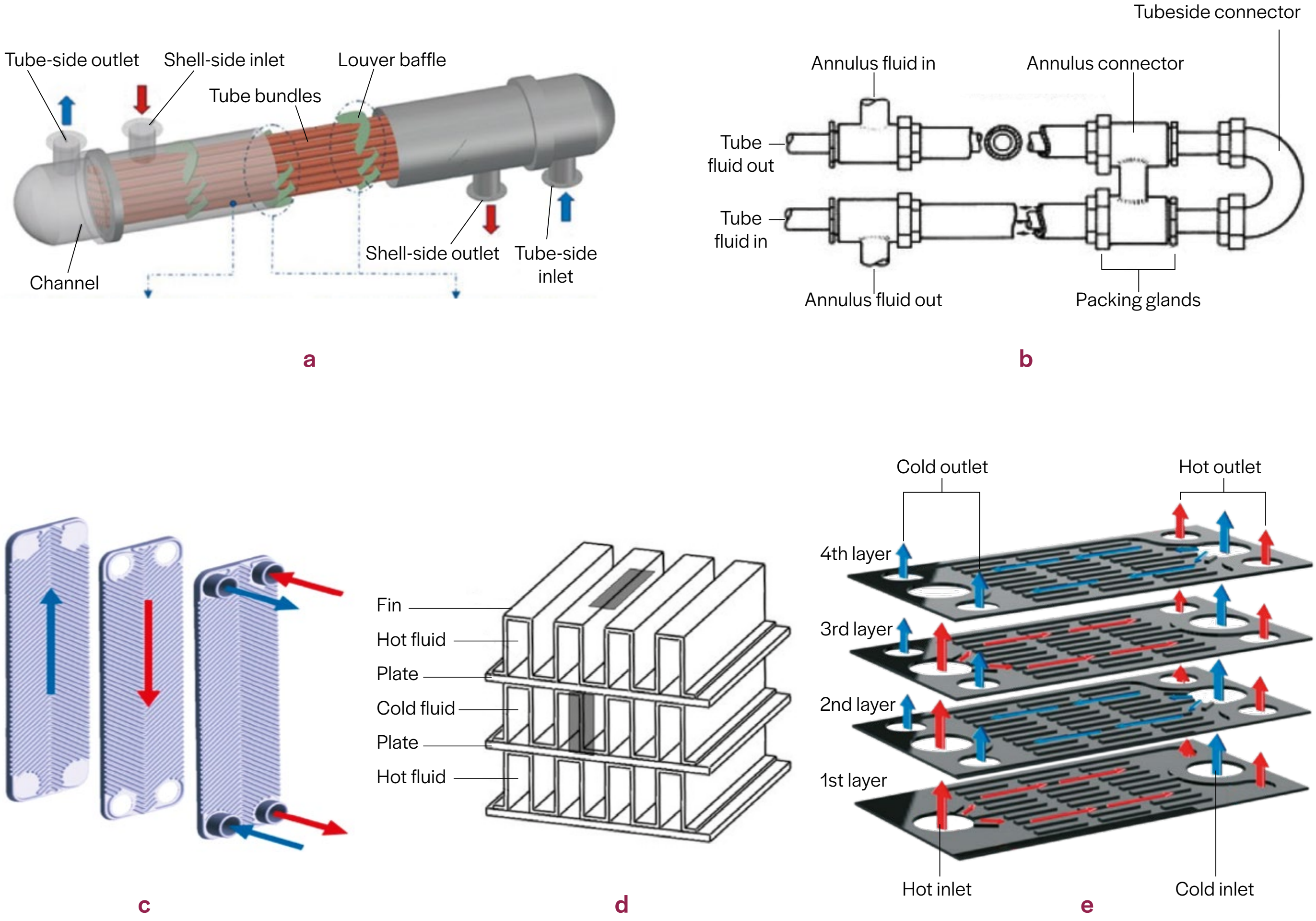


Figure 7 | Heat exchanger constructures commonly used in heat pump system[43] **(a)** shell-and-tube heat exchanger; **(b)** double-pipe heat exchanger; **(c)** plate heat exchanger; **(d)** plate-fin heat exchanger; **(e)** multi-layer microchannel-plate type heat exchanger.

Fin heat exchangers are characterised by their technological maturity, broad application, stable performance, and corrosion resistance.

The shell-and-tube heat exchanger is designed to improve the performance through the tube shape optimization and surface treatment to enhance the heat transfer coefficient. However, its relatively low heat transfer efficiency and large physical size limit its applications.

Plate heat exchangers are constructed by stacking multiple metal plates featuring with distinct compression patterns. A space is created between each pair of consecutive plates, allowing hot and cold fluids to flow along the plate surfaces without mixing. Compared to shell-and-tube heat exchangers, plate heat exchangers offer larger heat exchange surface and higher heat transfer coefficient[44]. It is the most commonly used heat exchanger in HTHPs and performs well for both single-phase and phase-changing applications.

The microchannel heat exchanger was developed for high heat transfer rates, compactness and reduced weight, that is primarily applications with limited space. However, microchannel heat exchangers exhibit very low corrosion resistance and require low refrigerant charge. As a result, they are more suitable for refrigeration and HVAC systems rather than industrial HTHPs.

4.2 Compressors

When designing heat pump systems, the design and selection of compressors is a critical aspect. HTHPs are generally applied in industrial scenarios where they are required to withstand high supply temperatures, large capacities, and high temperature lifts (when there is no high-grade waste heat source). The features of some mainstream compressors are summarised in Table 3.

The volumetric compressors such as piston, scroll, screw face issue of lubrication. Oil selection based on specific operating temperature and corresponding working fluid can guarantee the stability of the heat pump system. However, as temperatures rise, oil compatibility diminishes due to changes in solubility, viscosity and thermal stability, leading to separation and coking issues. Conventional lubricants undergo thermal degradation when compressor temperatures become excessively high. There has been extensive research for improving the performance of polyester oils at temperatures higher than 180°C[45]. Oil-free compressors present advantages for high-temperature applications, which removes the oil degradation risks, avoids heat transfer deterioration and extends the operating temperature range. Research shows that oil-free twin-screw compressors can achieve operating temperatures up to 221°C, which is significantly higher than their oil-lubricated counterparts limited to approximately 200°C. However, oil-free screw compressors face performance constraints including lower achievable pressure ratios compared to oil-injected ones, and deteriorated performance due to thermal expansion and increased clearance gaps[46].

The key approach to achieving breakthroughs towards higher heating temperatures and larger capacities involves centrifugal compressors. Their long service life and high reliability are attributed to few moving parts and frictionless rotation. For future centrifugal compressor designs, the high-efficient and high-strengthen impellers are important. Generally, the centrifugal configuration has lower compression pressure ratio, thus requiring the multi-stage compression with internal vapour injection. The direct drive permanent magnet synchronous motor and oil-free bearings (such as magnetic or air foil bearings) are crucial for the high efficiency of centrifugal compressors.

4.3 Others

Ejectors can be used to capture expansion work. The entrainment capability of ejector reduces irreversible losses caused by lower temperature differentials[47]. Although the ejector is capable of both transcritical and subcritical cycle, it is not widely used in HTHPs. The ejector performance is strongly dependent on flow rates and pressures; it can be easily influenced by slightly varying heat load or working status. Simple solutions for the challenge of variable discharge pressure still lack research[48].

Expanders are mainly suitable for single-phase expansion, while two-phase expansion requires rigorous design and precise control. So, it is mainly used in transcritical cycles instead of expansion valves to recover expansion work. The configurations of expanders include scroll-type, reciprocation, double rolling piston, turbo and van-type[48].

Absorbers and generators are critical components in absorption heat pumps. As two types of heat exchangers,

TABLE 3 FEATURES OF DIFFERENT COMPRESSORS

HEATING CAPACITY	COMPRESSOR TYPES
<100 kW	Piston, Scroll
0.1-1 MW	Piston, Screw, Centrifugal
1-10 MW	Screw, Centrifugal
>10 MW	Centrifugal

their performance strongly affects overall efficiency. Research on absorbers since 2010 has focused on intensifying heat and mass transfer. Key strategies involve increasing liquid–vapour contact area, enhancing solution mixing, and rapidly removing absorption heat[49]. Various absorber designs (falling-film, spray, bubble, membrane) incorporate these enhancements. Generators use relative high-grade heat to drive refrigerant desorption. Enhanced generator heat exchangers (e.g. finned tubes and microchannels) improve boiling heat transfer and reduce required heat input. Advanced cycle configurations (e.g. multi-effect or multi-stage generation) further boost COP by thermal energy gradient utilization. Combining multiple generator stages as a subcooler in ammonia–water systems has also shown performance gains[26]. Overall, the optimised absorber and generator designs, including improved surfaces and cycle innovations, has significantly enhanced absorption heat pump’s performance in recent years[50].

5

⁄ HTHP products and applications

5.1 HTHP Products from the suppliers

The major manufacturing companies in air conditioning, refrigeration, and compressors have expanded their commercial offering into the field of HTHP products. Products are varied in terms of compressor type, working fluid, heating capacity, supply temperature, and technology readiness level (TRL). The IEA-HPT-TCP (IEA's Technology Collaboration Programme on Heating Pumping Technologies) launched a project called *Annex 58-High-Temperature Heat Pump*, which includes a task to survey the HTHP technologies from suppliers as summarised in **Table 4**, which includes some products from Chinese suppliers. HTHP systems are now commercially available at a high maturity level (TRL=9), covering a temperature range of 100-300°C and capacities from 0 to 100 MW. Units supplying heat above 200°C with capacities exceeding 10 MW are typically open-cycle water vapour compression systems.

TABLE 4 HTHP TECHNOLOGIES FROM SUPPLIERS (EDITED FROM [7]).

SUPPLIER	COMPRESSOR TYPE	WORKING FLUID	CAPACITY	$T_{MAX, SUPPLY}$	TRL
Fuji Electric	Reciprocating	R245fa	0.03 MW	120°C	9
Emerson	Scroll and EVI Scroll	R245fa, R410a, R718	0.03 MW	120°C	6
Mayekawa (EcoSirocco)	Reciprocating	R744	0.1 MW	120°C	9
Skala Fabrikk	Piston	R290, R600	0.3 MW	115°C	7
Pars Makina	Rolling piston	R1233zd(E)	0.5 MW	150°C	6
GEA	Semi-hermetic piston	R744	0.1-1.2 MW	130°C	8
Fenagy	Reciprocating	R744	0.3-1.8 MW	120°C	5-6
SRM	Screw	R718	0.25-2.0 MW	165°C	5
Combitherm	Semi-hermetic screw	R1233zd(E)	0.3-3.3 MW	120°C	9
Johnson Controls	Reciprocating	R717, R600	0.5-5.0 MW	120°C	7-8
ToCircle	Rolling piston	R718	0.3-5.0 MW	188°C	7-8
Weel & Sandvig	Turbo	R718	1.0-5.0 MW	160°C	4-9
Olvondo	Piston	R704	0.5 MW	200°C	9
AGO Energie	Piston	R717, R718	0.7-10.0 MW	140°C	8-9
Spilling	Piston	R718	1.0-15.0 MW	280°C	9
Everllence	Turbo	Natural and synthetic	10-100 MW	300°C	6-9
Piller	Turbo	R718	1.0-70.0 MW	212°C	8-9
Skyven	Turbo	R718	<73 MW	215°C	7
Midea [51]	Centrifugal	R718	3.5MW	200°C	8
Gree [52]	Centrifugal	R1233zd(E)	<10MW	140°C	8-9

5.2 Cases on application

Being not limited to domestic heating, HTHPs broaden the application scenarios of heat pump technology. These new applications require higher output temperatures, greater capacity, and broader heat source compatibility. District heating is a large market where HTHPs have been introduced early. In the Sörnäinen of Helsinki, the HTHP is generating hot water of 88°C, recovering heat from sewage. The scale of this district heating application is 90 MW in total[53]. Industrial applications of HTHPs have been deployed across many sectors, such as food processing, papermaking, and chemical industry, with heating capacities ranging from kilowatt to megawatt. Some examples are as follows.

SGH120 and SGH165[7] are two high-temperature steam generators developed by Kobe Stell, Japan. In SGH120, pressurised feed water is heated by a HTHP and then throttled and flashed to the required saturation pressure. Saturated steam is further compressed for higher output temperature and pressure in SGH165. These two HTHPs are in different configurations while both use twin-screw compressor. The equipment is widely used in steam-requiring industrial projects such as bioethanol production plants.

The brewing industry is a demand-intensive industrial sector. Its processing extensively requires hot water, hot air, and steam. To promote energy saving in this sector, Shanghai Nuotong New Energy Technology Co., Ltd. designed air-source HTHP systems for brewery steam supply. A cascade compression HTHP and twin-screw steam compressor are used to supply steam with mass flow up to 300 kg/h. The system achieves COP of 1.85 when supplying steam at 120°C and evaporating at 20°C, saving 46% electricity consumption compared to electric boilers. The payback period of project is only 2.4 years.

In the food industry, Arpagaus[54] provided a heating supplying solution for a Swiss cheese factory, as shown in Figure 8 (a). The factory uses an HTHP to recover and upgrade waste heat from a nearby data centre for dairy processing, achieving annual natural gas savings of 1.5 million kWh.

The heat generated by the HTHP can be directly used in industrial processes or combined with energy storage systems. Zauner *et al.*[55] suggested a novel energy-saving extrusion plant concept based on HTHPs and has demonstrated it in an actual factory in Austria. The energy flow is illustrated in Figure 8 (b). The heat released by extruded polymer chains in a cooling water tank serves as the heat source. When using a HTHP, this heat is elevated to up to 125°C and stored in phase change material (PCM). This heat can be used for processes such as drying and preheating. This scheme achieves waste heat recovery for industrial processes through an HTHP.

In addition, according to the investigation of China Heat Pump Alliance[56], HTHPs have had many applications in various industrial sectors. Due to space constraints, an extensive list cannot be provided here, however typical cases are presented in Table 5.

5.3 Innovations on HTHP applications

5.3.1 Dual-use HTHPs in cooling and heating

The COP of HTHPs is generally lower than that of civil heat pump due to the larger temperature lift, especially in the absence of high-grade waste heat. As illustrated in Figure 9, if both heating (condensing) and cooling (evaporating) sides of a heat pump can be used, the overall COP is largely improved. Unlike building sector, the industrial cooling and heating

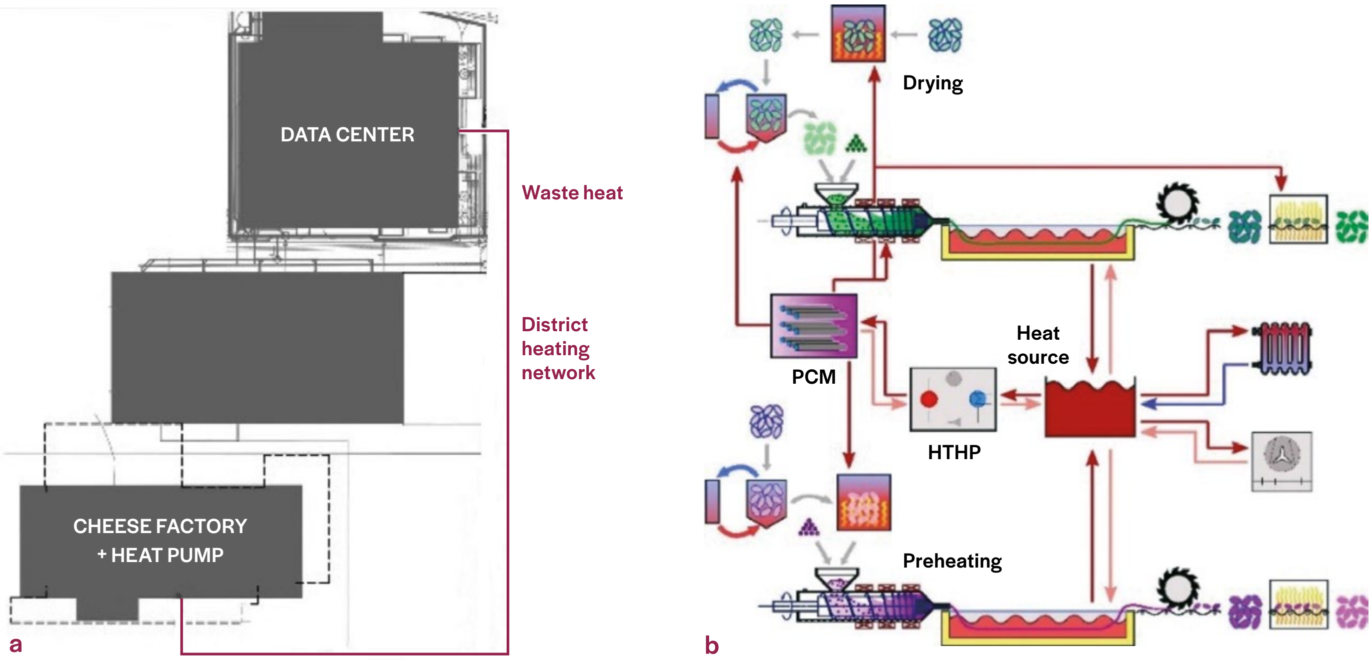


Figure 8 | Engineering applications of HTHPs in the **(a)** dairy industry[54] and the **(b)** plastic industry[55].

TABLE 5 HTHP APPLICATIONS

INDUSTRY FIELD	MANUFACTURER	HEATING CAPACITY (KW)	MEDIUM	HEAT SINK (°C)
Agricultural products processing	Snowman group	308	Hot water	80
Spray Coating Process	McQuay	–	Hot water	80
Chemical engineering	Invo Tech	2,200	Hot water	83
Textile industry	Hybrid Energy	1,200	Hot water	85
Automobile manufacture	Aspiration Energy	2×136	Hot water	85
Chemical engineering	Kobe Steel	2×400	Hot water	90
Wood processing	GEA	2×4,510	Hot air	90
Agricultural products processing	Olion	1,090	Hot water	95
Non-metallic mining	Viking Heat Engines	400	Hot air	110
Equipment manufacturing	Emerson/Cryotek	2×56	Hot water	120
Equipment manufacturing	Nuotong	480	Steam	120
Chemical engineering	Dongfang Electric Machinery	900	Steam	150

demands are less seasonal-dependent, thereby improving their suitability for simultaneous generation, which are suitable for the dual use of HTHPs. Some industrial processes with simultaneous cooling and high-temperature heating demands are presented in Table 6. Cascade configurations usually deliver better overall performance when facing large temperature gap between evaporating and condensing sides, which is a promising option for dual-use HTHP systems[10].

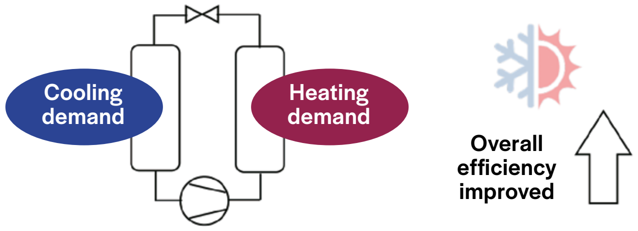


Figure 9 | Scheme of dual-use HTHPs in cooling and heating.

The utilization efficiency (η) and the combined COP of HTHPs are determined by:

$$\eta = \frac{Q_{c,demand} + Q_{h,demand}}{W} \qquad COP = \frac{Q_{c,produce} + Q_{h,produce}}{W}$$

in which, $Q_{c,demand}$, $Q_{h,demand}$, $Q_{c,produce}$, and $Q_{h,produce}$ are the demanded and the produced cooling and heating, respectively. W is the electricity consumption. $\eta \le COP$, depending on whether the heating and cooling produced by heat pump are totally or partially used by the industrial thermal processes. To avoid energy waste, it is essential to match the industrial thermal demands with the heat pump's supply capacity. Appropriate thermal process design or the optimal operating strategy of heat pump unit could help.

5.3.2 HTHPs combined with thermal energy storage

As mentioned above, the dual use of heat pump may face difficulties related to the supply–demand mismatch. Integrating thermal energy storage (TES) system with heat pump could essentially avoid this issue. TES enables the heat pump to balance the heat and cold demands within specific durations (in kWh) rather than at instant (in kW), coordinating the proportions of heat and cold production and supply.

The schematic diagram of the HTHP-TES system is shown in Figure 10. The condenser and evaporator of the heat pump are integrated with heat & cold users and latent heat & cold storage units. The storage units, the heat pump, and the user's loads are interconnected in a series–parallel configuration, enabling both storage units and the heat pump to function as potential energy suppliers. When $Q_{c(h),produce} > Q_{c(h),demand}$, the excess heat and cold are stored in TES. When $Q_{c(h),produce} \le Q_{c(h),demand}$, energy are supplied directly to users with any shortfall supplemented by TES.

It is should be stressed that an additional complexity arises regarding the capacity matching and heating–cooling strategies among heat and cold demands, heat and cold storage units, and simultaneous heat and cold production heat pumps. The specific system design and operating strategies need to be tailored to different applications.

Coupling TES also enables the system to take advantage of off-peak electricity price, improving the economic performance of thermal energy supply.

TABLE 6 INDUSTRIAL PROCESSES WITH BOTH COOLING AND HIGH-TEMPERATURE HEATING DEMANDS

INDUSTRY	HEATING PROCESS	HEATING TEMPERATURE	COOLING PROCESS	COOLING TEMPERATURE
Dairy [57]	Pasteurization	72-75°C, >80°C	Cold storage	4°C
	CIP cleaning	25-90°C		
Liquor [57]	Distillation	>78°C	Condensation	8°C
Battery [57]	Drying	90-120°C	Dehumidification	7°C
Poultry meat [58]	Scalding	50-60°C	Washing	4°C
	Evisceration	82°C	Cold storage	≤7°C
Frozen fried potato [58]	Washing	60-88°C	Cold storage	4-15°C
	Blanching	90-100°C	Cooling	5-10°C
			Freezing	-18°C
Beer [58]	Mashing	60-64°C, 70-80°C	Cooling	6-12°C
	Pasteurization	70°C	Maturation	-1°C
	Bottle washing	38-85°C		

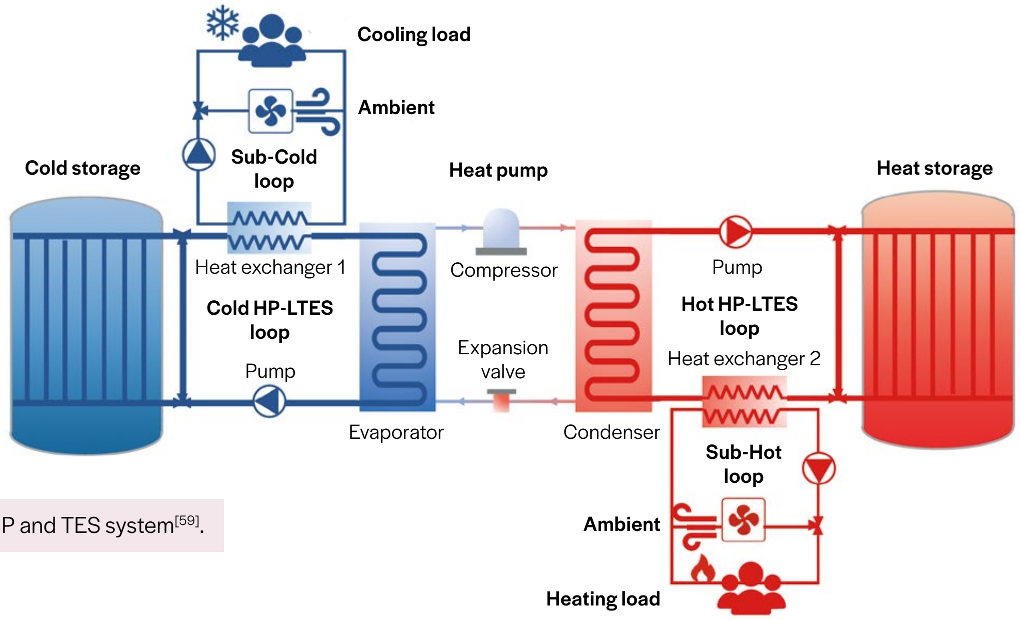


Figure 10 | Scheme of the HTHP and TES system[59].

Another HTHP-TES system is shown in **Figure 11**, in which the TES is placed between two heat pump units. This configuration enhances the flexibility of the high-temperature heating supply. The TES can be charged during off-peak hours, and the stored medium-temperature heat can be further pumped to high temperature when required. It is also feasible to extract medium-temperature heat from the TES module to fulfil corresponding heating demands.

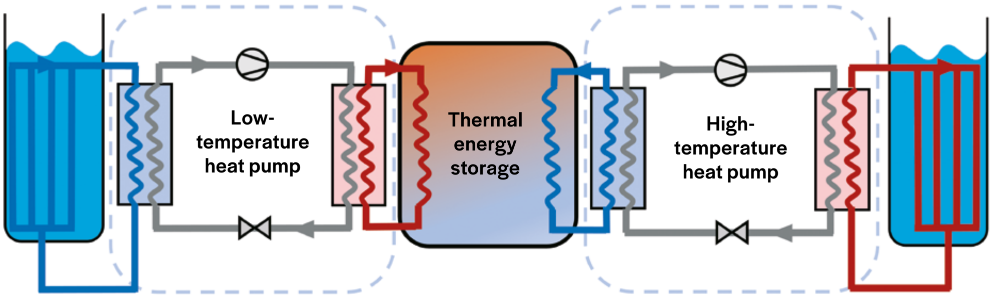


Figure 11 | Scheme of HTHP and intermediate TES system.

6 / Comparison between HTHPs and their alternatives

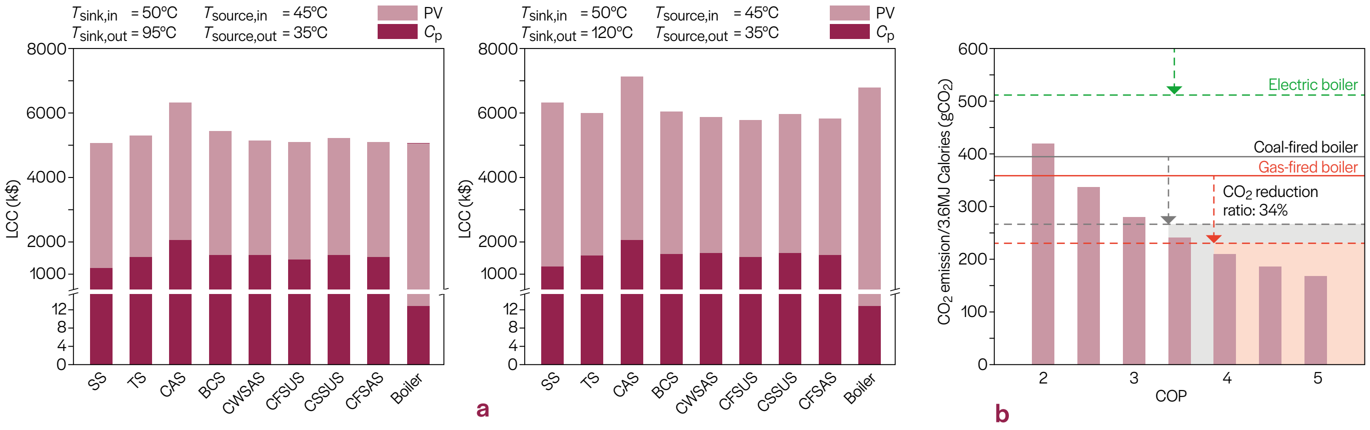
6.1 Economic and environmental performance comparison

For industrial heating, conventional boilers and HTHPs are competing alternatives. In terms of energy efficiency, the HTHP has inherent advantage over all types of heating boilers, with electricity-to-heat conversion efficiency exceeding 100%. Several studies have compared their economic and environmental performance, as summarised in **Table 7**. Results show that the economic and environmental advantages of HTHPs are still inconsistent, depending on multiple factors, including the system's COP, the price ratio between electricity and conventional fuels, and the carbon intensity of grid electricity.

6.2 Enhancing the benefits of HTHP

COP determines the electricity consumption of HTHPs and fundamentally influences both economic and environmental performance. As shown in **Figure 12 (a)**[65] and **Figure 12 (b)**[9], the life cycle cost of HTHPs rises with increasing $T_{sink,out}$, which corresponds to a lower COP, while the CO_2 emitted by HTHP reduces as COP improves. Using waste heat to improve Carnot efficiency, maximizing the use of HTHPs (such as dual use of heating and cooling as mentioned above) to increase the energy utilization efficiency, and upgrading equipment to reduce energy loss are three approaches to achieve higher COP.

The economic competitiveness of HTHPs varies among countries, mainly due to differences in electricity-to-fuel price ratios. As indicated in **Table 8**[67], countries with low electricity-to-natural gas price ratios already favour heat pump adoption, such as Finland and Sweden, while HTHPs remain economically difficult in countries with unfavourable price conditions such as Germany and the United Kingdom. Since fossil fuels generally have more CO_2 emissions than electricity, introducing the carbon tax will increase the total cost of fossil fuel boilers, as shown in **Figure 13 (a)**[64], which is an effective method to enhance the economic attractiveness of HTHPs. The environmental performance of HTHPs is closely tied to the carbon intensity of the electricity mix. As represented in **Figure 13 (b)**[63], the HTHP's CO_2 emission is lower than diesel and liquefied petroleum gas (LPG) boilers in Norway, Germany, and the EU, while HTHPs produce higher emissions in India due to the high electricity emission factor (790 $gCO_2\ kWh_{elec}^{-1}$) there. However, as national power systems continue to transition toward renewable energy, the carbon footprint of HTHPs is expected to decrease significantly. This trend is illustrated in **Figure 13 (c)**[68]. The HTHP shows a significant reduction in CO_2 emission intensity in future scenarios with low electricity emission.



KEYS LCC life cycle cost PV present value C_p project cost

Figure 12 | **(a)** Economic performance comparison between HTHP and boiler changing with COP (x-axis: HTHP in different configurations); **(b)** the changes of environmental performance of HTHP with varying COP.

TABLE 7 ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF HTHPS[60]

COMPETITORS	REGIONS	COP	ECONOMIC PERFORMANCE	ENVIRONMENTAL PERFORMANCE
HP NGB[61]	Sweden Finland Spain Italy Netherlands Poland	1.8		▪ Using HTHPs in Sweden, Finland, Spain, and Italy results in lower annual carbon footprint than using NGB, while NGB remains the cleaner option in Netherlands and Poland
HP NGB[62]	Germany Italy	1.37	The cost saving of replacing NGB with HTHPs does not offset the investment cost of HTHPs	
HP NGB OB EB[63]	Norway Germany EU India	1.6 (Eco.), 1.9-2.3 (Env.)	The steam cost generated by HTHPs is the lowest with India's energy prices	▪ The CO$_2$ emission from HTHPs is the lowest in Norway, German, EU, but not in India
HP CB NGB EB[64]	China US EU Japan	2.0-2.5	The steam cost generated by HTHPs is higher than CB or NGB	▪ The CO$_2$ emission generated by HTHPs is lower than CB in China
HP NGB OB CB EB[65]	China	3.5-4.1 ($t_{sink,out}$ = 95°C)	HTHPs have lower life cycle cost than boilers	▪ The CO$_2$, NOx emissions from HTHPs are lower than boilers ▪ The SO$_2$ emission from HTHPs are higher than NGB ▪ The CO, PM$_{10}$, and PM$_{2.5}$ emissions from HTHPs are higher than OB and NGB
HP EB NGB CB[66]	China	≈1.9 (VAHP)	The energy cost of HTHPs is higher than CB	▪ The CO$_2$, SO$_2$, NO$_x$ emissions from HTHPs are higher than NGB

KEYS CB coal boiler NGB natural gas boiler EB electric boiler OB oil boiler

TABLE 8 PAYBACK PERIOD OF HTHP COMPARED TO NATURAL GAS BOILER IN DIFFERENT COUNTRIES

COUNTRY	ENERGY PRICE (€/KWh) ELECTRICITY /NG	MEAN ANNUAL OCS	SPB
Finland	0.098/0.159	€1,212,000/yr	1.5 yrs
Sweden	0.132/0.155	€991,000/yr	1.8 yrs
Denmark	0.194/0.122	€387,000/yr	4.6 yrs
Portugal	0.128/0.085	€348,000/yr	5.1 yrs
France	0.127/0.067	€185,000/yr	9.6 yrs
Spain	0.204/0.089	€18,000/yr	>20 yrs
The Netherlands	0.176/0.073	€5,000/yr	>20 yrs
Croatia	0.197/0.069	€–139,000/yr	Unprofitable
Germany	0.202/0.057	€–277,000/yr	Unprofitable
United Kingdom	0.245/0.062	€–433,000/yr	Unprofitable

KEYS OCS operating cost savings SPB simple payback period

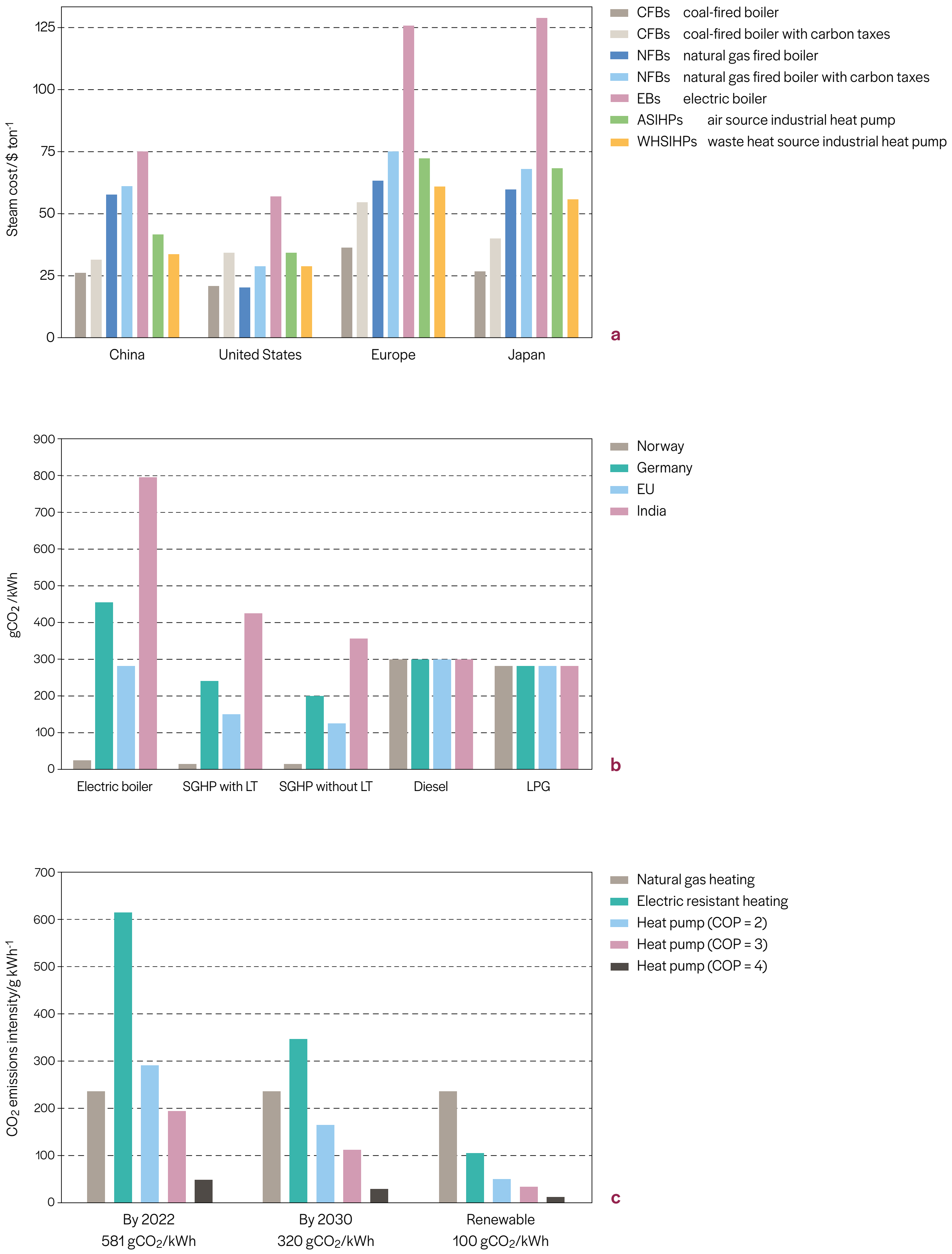


Figure 13 | **(a)** The economic performance of HTHP and boilers affected by carbon tax; **(b)** the CO_2 emission from HTHP and boilers in different countries (SGHP with/without LT are the different configurations of HTHP); **(c)** CO_2 emission from HTHP and boilers with varying electricity emission factor.

7 / Conclusion and prospects

7.1 Summary of HTHP technologies, applications, and performance

By extending the heating temperature of heat pumps from medium to high level, HTHPs are a promising solution for the decarbonization in industrial sectors. This technical brief reviews the technologies, applications and performance of HTHPs and a summary is provided as follows:

- Various compression and absorption heat pumps could be used to meet the high-temperature heating demands. Based on their fundamental layout, some optimal configurations, such as injection, ejector, sub-cooler, multi-stage, cascade, multi-effect, hybrid absorption-compression, could better adapt to low heat source temperature, high-temperature lift, or complex heat source conditions. In general, compression HTHP has higher COP than the absorption one and has no strict requirement for heat source temperature. Absorption systems offer the unique advantage of requiring no compressor when waste heat approximately above 60°C is available. Compared to the absorption HTHP, the compression HTHP faces greater challenges when scaling to larger capacities. This is primarily due to the greater technical difficulty in scaling up high-temperature compressors. Combining compression and absorption cycles can leverage their respective strengths and mitigate their weaknesses. For example, using a compression unit at lower temperature and integrating an absorption stage to generate high temperature could improve the overall efficiency while avoiding the challenges to the compressor under high temperature and pressure conditions.
- The primary requirement for HTHPs' working fluids is to have the appropriate thermodynamic properties such as high critical temperature. The environmental impact of synthetic refrigerants is a major concern in recent years, but a few natural fluids are available in modern HTHPs. Safety and compatibility with materials are essential for their long-term stable operation, especially due to accelerated chemical reactions at high temperature and pressure. Moreover, the economic and efficiency performance of working fluids should also be considered in the optimization stage. In summary, numerous substances are available for use as working fluids in HTHPs; it is unlikely for a working fluid to outperform in all aspects.
- The types of HTHP's heat exchangers are similar to those in conventional heat pumps, yet they need to offer higher tolerance and reliability. High temperature, pressure and pressure ratio raise stricter requirements on compressor's materials, while also decreasing the solubility and viscosity of lubricants and accelerating their degradation and oxidation. Oil-free centrifugal compressors are the ideal solution. Regarding the transcritical cycle, ejectors and expanders deserve attention. In absorption heat pumps, additional attention should be given to absorbers and generators.
- HTHPs are at the early stage of their promotion. Many suppliers already developed HTHP units covering the heating temperature from 90 to 300°C with capacity reaching up to 100 MW (the unit supplying high temperature at large capacity is usually the direct compression of steam). Some products with high technology readiness level are ready to launch to the market. HTHPs have some demonstration applications in chemical, food industries. Apart from providing heating alone, HTHPs demonstrate their unique application in combined cooling and heating, increasing the overall efficiency of a heat pump unit. In addition, integrating them with thermal energy storage decouples users' demands and the heat pump's instantaneous production capacity, thereby improving the HTHP system's adaptability and flexibility.
- HTHPs are the alternative to conventional boilers. Their economic and environmental performance determines its market competitiveness. Currently, HTHPs do not always exhibit decisive advantage over traditional boilers, as their viability heavily depends on local energy prices and the electricity mix. Improving COP, introducing carbon price to increase the fossil fuel-to-electricity price ratio, and reducing electricity emission are effective ways to enhance the competitiveness of HTHPs.

7.2 Future R&D directions

In the future, efforts to promote HTHPs could be strengthened in the following aspects:

- As a replacement of fossil-fuel boilers, HTHPs are capable and will be an essential equipment for steam supply in the future. As a result, the cycle or system innovations about steam generation as well as the performance of water as both working fluid and process medium, deserve attention.
- The promotion of HTHPs using natural working fluids is increasingly important, as PFAS restriction may phase out most synthetic working fluids. Critical technical challenges include very high-temperature water vapour compression, transcritical and supercritical CO_2 systems, and safe flammability management of hydrocarbons.
- Compression HTHPs are expected to take a large proportion in the future HTHP market. The challenging problems such as high temperature and high pressure, transcritical cycle, and large capacity ultimately place high demands on compressor technology. Thus, developing high-tolerance, oil-free (such as Maglev) compressors is a crucial direction.
- HTHPs' COP is limited by thermodynamics. To maximise system efficiency, efforts should focus on finding waste heat as heat source to increase Carnot efficiency or fully using the energy output of the heat pump and minimizing waste. Using both cooling and heating sides of the heat pump unit is an effective method. Additionally, coupling TES with heat pump could solve the mismatch between heat production and heat demand, improving the overall utilization efficiency and enabling HTHPs to maximise use of renewable low carbon electricity. The future design of HTHP systems should be co-designed with application scenarios.
- With the global transition to renewable energy, HTHPs will ultimately play a key role in industrial heating electrification. However, its higher capital cost and unfavourable electricity price hinder its short-term promotion. Economy strategies such as carbon pricing or subsidies are suggested to facilitate the early deployment of HTHPs. Since the penetration of renewable energy and the implementation of economy policies cannot occur instantly, integrating HTHPs in sustainable industrial parks might be a more immediate solution, as illustrated in **Figure 14**. This park integrates electricity, cooling, and heating demand and supply through energy equipment including heat pumps, refrigerators, power boilers, Organic Rankine generators, and electricity/thermal storage systems. In this park, the renewable power is consumed locally, improving the cleanliness of electricity use without influencing the stability of the national grid. The waste heat is transformed and used across different energy equipment, maximizing the energy utilization. Compared with nationwide reforms in the electricity mix and energy policy, the construction of such industrial park is more feasible and thus deserves official support and pilot exploration.
- Currently, the wide deployment of HTHPs still requires policy support. Decision-makers could consider actions in the following aspects: 1) establishing subsides for HTHPs linked to energy efficiency performance; 2) promoting and supporting enterprises to develop demonstration projects; 3) introducing carbon pricing mechanism in places where it has not yet been implemented; 4) training professionals in development, manufacturing, and operation.

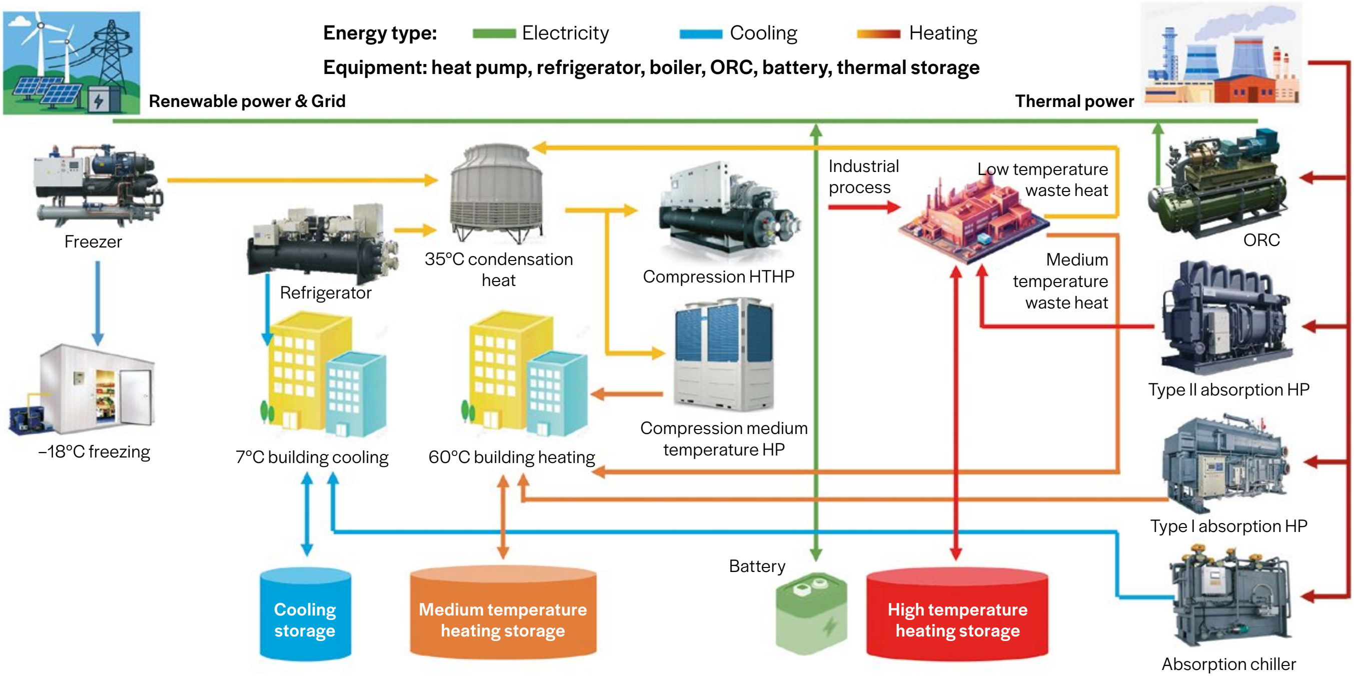


Figure 14 | Scheme of sustainable industrial park.

⁄ Abbreviation and nomenclature

ABBREVIATION	
t	temperature
p	pressure
η	utilization efficiency
Q	heating capacity
W	electricity consumption
C	cost
SUBSCRIPT	
cr	critical point
c	cooling
h	heating
p	project

NOMENCLATURE	
ACHP	Absorption-compression heat pumps
AHT	Absorption heat transformer
ASIHP	Air source industrial heat pump
CFB	Coal fired boiler
COP	Coefficient of performance
EB	Electric boiler
GWP	Global warming potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HTHP	High-temperature heat pump
LCC	Life cycle cost
LPG	Liquefied petroleum gas
NBP	Normal boiling point
NFB	Natural gas fired boiler
OCS	Operating cost savings
ODP	Ozone depletion potential
PFAS	Per- and Polyfluoroalkyl Substances
SGHP	Steam generating heat pump
SPB	Simple payback period
TES	Thermal energy storage
TRL	Technology readiness level
VCHP	Vapour compression heat pump
VHC	Volumetric heating capacity
WHSIHP	Waste heat source industrial heat pump

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