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Potential evaluation of integrated high temperature heat pumps: A review of recent advances

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ABSTRACT

Industrial and high temperature pumps are a well-established, sustainable, and low-emission technology for processing temperatures below 100 °C, especially when driven by renewable energy. The next frontier in heat pumping is to enhance the economic working envelope to serve the 100–200 °C range, where an estimated 27% of industrial process heat demand is required. High temperature heat pumps (HTHP) are an effective technology for delivering heat and recovering waste heat from various industrial processes, hence reducing primary energy consumption and the resulting CO_2 emissions. The integration of high temperature heat pumps into different industrial process networks provides significant environmental and performance improvements,an innovative and profitable solution for different decarbonizing sectors. Higher temperature heat pumps offer significant potential to enhance thermally demanding industrial processes due to their high temperature lift capability. This review looks at how future improvements in HTHP technology can take use of breakthroughs in high-temperature heat pump research to address important technical obstacles. This review primarily consolidates data from HTHPs integrated with various industrial processes applications such as thermal energy storage, low-grade waste heat recovery, membrane fuel cell, organic Rankine cycle, super-critical water desalination, co-generation and poly-generation, vapor injection, steam injected gas turbine, and solar absorption system. However, the widespread diffusion of HP technologies faces several challenges, including technological (limitation of the electrical network due to intensive electrification of the heating sector), economic (high investment and installation cost), regulatory (lack of standards and mandatory policies), policy (uncertainty in policy and lack of clear heat decarbonization pathways and technology uptake), and public acceptance issues (unwarranted fear, misperception, misinformation, and previous experiences on the reliability of heat pumps) are highlighted.

1. Introduction and State-of-the-Art

Global warming is among the enormously fundamental concerns of innovative society. Energy consumption and greenhouse gas (GHG) emissions from industrial processes are growing endlessly in the upcoming years [1–5]. The generation and consumption of energy constitute for a considerable portion of the world economy. Global primary energy extraction was 162,000- Terawatt hour (TWh) in 2019, of which fossil fuels provided 137,000 TWh, or 84.5% [6]. It’s critical to comprehend the world energy demand profile to develop efficient low-emission solutions for massive energy users as the need to decarbonize becomes more critical. Fig. 1 shows an estimate of the entire world energy consumption for 2019. Despite constituting merely 19% of the total energy demand, industrial process heat is accountable for 36.8%

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(12.3 Gt CO_2-e) of all emissions associated to energy. This is because a significant portion of the energy used for industrial process heat is generated by fossil fuel boilers. Industries will be required to migrate from fossil fuels to more sustainable and renewable sources to meet global benchmarks defined by The International Energy Agency (IEA) to achieve net-zero greenhouse gas emissions by 2050 [7]. Considering environmental benign, cost-effective, and sustainability concerns, hence, boosting the energy efficiency of industrial processes and reducing direct greenhouse gas (GHG) emissions, e.g., from burning fossil fuels [8], becomes a must-have option. Simultaneously, significant quantities of low-grade waste heat (<250 °C) [9,10 11] are accessible for potential surplus heat uses in many industrial processes, which are often not directly usable. In this regard, it is imperative to build more effective and ecologically acceptable approaches to upgrade thermal energy for utilization in association with industrial applications. High temperature heat pump deliver heat in a more appropriate way than the alternative.

A promising method for achieving different industrial applications and requirements, it has been increasingly investigated in recent years, is to integrate high temperature pumps in conjunction with various advanced technologies to facilitate industrial users in an applicable way [13 14 15]. For particular significance in consideration for environmental protection is the application of renewable sources with a low significant impact on global warming [16,17,18], whose impacts on the environment for the operation can be eased by the heat pump and refrigeration systems. The selection of fuel or heating technology used for a specific process depends on numerous criteria, such as the structure of a specific industrial sub-sector or in which region the process is situated. Multi-generation (heating, cooling, electricity, drying, steam generation, and desalination) integrated systems have expanded in demand over the years because they use significantly less energy coupled with thermodynamic approaches to provide a wide range of results. Multi-generation networks have the potential to provide better exergy and energy efficiency, as well as reduced emissions and operational costs [19].

A variety of applications have already been investigated. Urbanucci et al. [20] integrated an HTHP to recover heat from an absorption system and provide hot water at 90 °C. When compared to standard tri-generation, cogeneration, and separate production units, this method could save 10.3%, 10.6%, and 41.7%, respectively. For a commercial central heat pump and combined heat and power plant, as well as individual heat pumps installed in a district heating and cooling network, Bargo-Burgos et al. [21] computed an overall coefficient of performance (COP) between 3 and 4. Local heat pumps in fourth and fifth-generation district heating networks have a COP of 1.0 to 1.5. Sharan et al. [22] proposed integrating an HTHP to reduce the energy requirement for supercritical water desalination. For a 25% feed concentration, this combination was 20% more energy-efficient than commercial systems. Waste heat between 80 and 200 °C might reduce CO_2 emissions by 164 kilotons annually in the food and beverage sectors in the UK. Then, using projected grid electricity emissions factors for 2030, there is potential to save 2.6 Metric tons of carbon dioxide ($MtCO_2$) annually [23]. The simultaneous optimization of HTHP heating capacity and yearly net profits was discovered to be incompatible by Wu et al. [24], thus they suggested a decision-making process for the best outcome. The system had a heating capacity of 499 kW and a payback time of 3.9 years at the ideal heat source intake temperature of 71 °C and condensing temperature of 145 °C. Mazhar et al. [25], Mateu-royo et al.[26], Volkova et al. [27] examined four various kinds of district heating (DH) processes and how they might be combined to yield low temperature distributed renewable heat sources into centralized and decentralized configurations. Pieper et al. [28], Sommer et al. [29], and Roh et al.[30] compared the system effect of average daily changes in terms of the temperature of various source of heat on the seasonal coefficient of performance (SCOP) of heat pumps operated under district heating in distributed systems. Ommen et al. [31,32] examined the operational performance of five designs of heat pumps and their optimum integration into a district heating system. By integrating high-temperature heat pumps to integrate the process, the waste heat can be upgraded to meet the requirement. An illustration of such an integrated system, in which heat pumps at various temperature levels meet both cooling and heating requirements, is seen in Fig. 2.

Various configurations are applicable upon integrating novel heat pumps (HPs) [33]. Though enhancement in performance is achieved, more severe operational limits may occur on the heat pump unit. However, only very few efforts were discussed to address heat pumps' optimal and fundamental integration in different industrial application. For example, a detailed summary regarding the high- temperature heat pump integration techniques, sink temperature subject to various working fluids, and their application is listed in Table 1. Several authors have classified HPs based on the maximum sink temperature level. On this way heat pumps can be classified as follows: Conventional heat pump (HP) with temperature recovery $T_{source}[0^{\circ}C \le HP < 40^{\circ}C]$ and heat supply temperature $T_{sink}[0^{\circ}C \le HP < 80^{\circ}C]$ as applicable to integrate with district heating application. High temperature heat pump (HTHP) with the heat recovery temperature $T_{source}[40^{\circ}C \le HP < 60^{\circ}C]$ with heat supply temperature $T_{sink}[80^{\circ}C \le HP < 100^{\circ}C]$ is mostly suitable for different industrial applications. Finally, very high temperature heat pump (VHTHP) with heat recovery temperature $T_{source}[60^{\circ}C \le HP < 120^{\circ}C]$ and heat supply $T_{sink}[100^{\circ}C \le HP < 160^{\circ}C]$ which is mostly used in steam generation [34]. Nowadays, the manufacturers of HTHP can provide T_{sink} at temperatures of at least 90 °C. This review

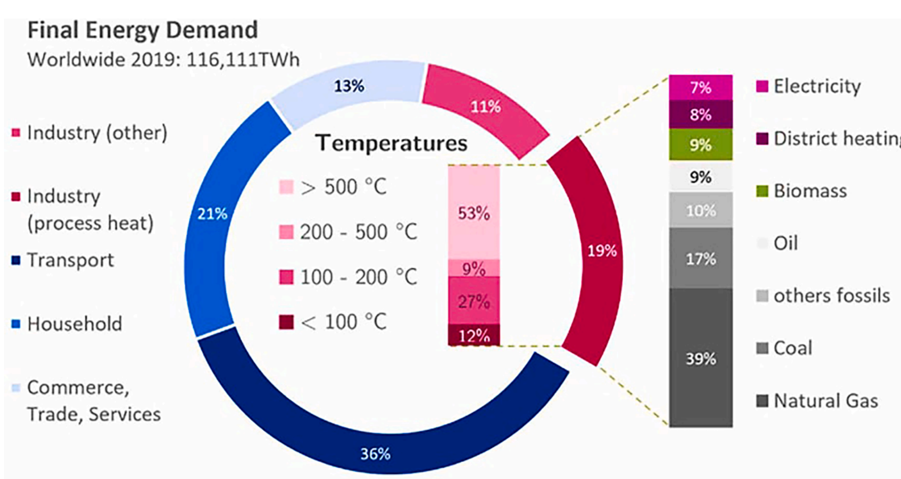


Fig. 1. The global final energy demand by sector in 2019, together with estimations for application temperatures and final energy sources [12].

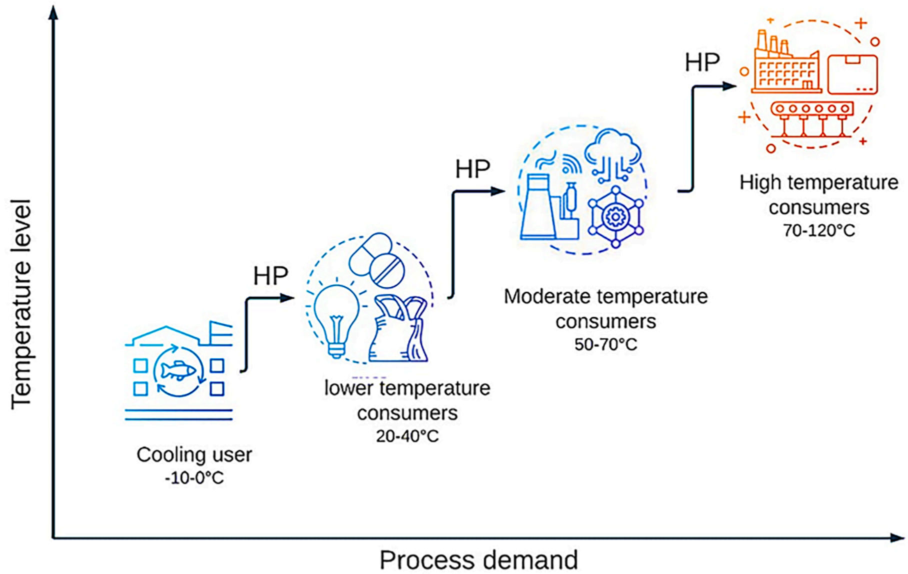


Fig. 2. Process integration of HTHP for the different consumers at various demand levels.

Table 1
Summary of different integrated high temperature pumps articles (between 2010 and 2021).

Ref.	HTHP Type	Study Type	Refrigerant	Sink Temperature	Application
[35]	Vapor compression	Experiment	R134a	80 °C	Water heating
[36]	Hybrid	Simulation	NH_3/H_2O	90 °C	Water heating
[37]	Vapor compression	Experiment	N/A	N/A	Regenerative for air condition domains
[38]	Hybrid	Experiment	NH_3 & H_2O	~90 °C	Hot water production
[39]	Hybrid	Simulation & experiment	H_2O –LiBr	90–120 °C	Solar Water heating
[40]	Hybrid	Simulation	NH_3 & H_2O	170–240 °C	R&D for HTHP for high sink temperature
[41]	Vapor compression	Simulation	R152a	92–102 °C	Cogeneration (heating & cooling)
[42]	Vapor compression	Simulation	R718	N/A	Space heating
[43]	Vapor compression	Experiment	R410A	80 °C	Energy storage & space heating
[44]	Hybrid	Simulation	NH_3 & H_2O	150 °C	Large scale steam generation
[45]	Hybrid	Simulation	NH_3/H_2O	80 °C	Hot water production
[46]	Vapor compression	Simulation	BY-5	120–130 °C	Vapor steam generation for industrial process
[20]	Vapor compression	Simulation	NH_3	90 °C	Tri generation.
[47]	Vapor compression	Simulation	R245fa R600 R600a & R1234ze(Z)	120 °C	Water heating
[48]	Vapor compression	Simulation	Butane, Pentane, HFO-1336mzz(Z)R-514A, HCFO-1233zd(E), HCFO-1224yd(Z) HFC-245fa	140 °C	Industrial waste recovery
[49]	Vapor compression	Simulation	N/A	125 °C	Waste heat recovery
[50]	Vapor compression	Simulation	HFC-245fa	140 °C	Hot water process
[51]	Vapor compression	Experiment	R245fa R410A	150 °C.	Hot water process
[52]	Vapor compression	Simulation	R-1233zd(E)R-1234ze (Z)	133 °C	Water heating for industrial use
[22]	Vapor compression	Simulation	N/A	~100° C	Water desalination treatment
[3]	Hybrid	Simulation	NH_3 NH_3-H_2O	95 °C	Cogeneration (heating & cooling)
[53]	Hybrid	Simulation	$NH_3/LiNO_3$	120–200 °C	Heating and cooling for domestic uses

article aims to explore and evaluate different innovative integrated systems, based on the real work conditions of an HTHP that provides>80 °C sink or delivery temperature. Table 1 suggests that high temperature heat pumps can provide heat or steam vapor for industrial application via integration methods.

Table 1 illustrates both mathematical and experimental studies. The simulation studies considered both the vapor compression and hybrid systems for the research. The water-ammonia absorption system is very commonly integrated with vapor compression systems in hybrid systems. In vapor compression system, both natural and synthetic refrigerants were investigated. The refrigerants used are R718, R-1234ze (Z), HFC-134a, R600, R600a, R601, R-514A, and HCFO-1224yd(Z), HFC-245fa, and R152. Most experimental studies consider the vapor compression HP system to explore the potential, and very few only found using the hybrid system. The number of experimental studies is minimal compared to simulation-based investigations. The system potential efficiency was investigated using R134a, R-245fa, and R-410A. The experimental results indicate that the Cascade systems are influential.

The main motivation for the present study comes from the existing gap in the field. Apparently, only a few reviews have been published on the HTHPs during the past decade. A short overview of the existing reviews on HTHPs is provided in the Table 2.

The aims of the review article are to identify research gaps and opportunities in the emerging field of HTHP technologies (heat sink ≥ 80 ∘C) and their integration to make the process efficient, environmentally friendly and cost effective. To achieve this aim, the fundamental concepts of HP cycles are presented to identify how each of the essential processes (expansion, heat exchange and compression) may be enhanced to achieve greater performance and higher temperatures. Subsequently, the review focuses on how these enhancement opportunities have been exploited in practice and finally the challenges and potential solutions to the advancement of HTHP cycles (which have not been comprehensively reviewed to-date) are covered. It mainly discusses the integration of HTHPs with different process such as thermal energy storage, different industrial waste heat recovery, fuel cell membrane, an organic Rankine cycle, super-critical water desalination, co-generation, and poly-generation desiccant wheel, vapor injection, steam injected gas turbine as well as solar absorption system. Also, this review highlights the single and multi-stage HTHPs, vapor compression, absorption, hybrid systems, and some novel configurations beside key challenges regarding integration. In addition, key challenges in HTHPs integration such as political ambiguity, public conscience, adverse market (industrial sectors), and technological challenge are discussed. Furthermore, performance indicators for the HTHPs are presented.

Table 2
A short overview of the existing reviews on HTHPs.

Ref.	Year of publication	Description
[34]	2018	• Provides market overview of HTHP • Reviews HTHP cycles • Analyses the selection of desirable working fluids • Compares various HTHPs • Reviews from the year 1988 to 2017
[54]	2022	• Highlights configurations • Reports refrigerants • Describes applications • Reviews from the year 1995 till now
[8]	2017	o Covers vapor compression HPs o Discusses natural working fluids o Presents components development o Reports Mixture proposals o Discusses Cycle variations o Reviews till the year 2017
-	Current	• Reviews single and multi-stages HTHPs • Presents vapor compression, absorption, and hybrid systems • Provides an overview of novel configurations • Mainly discusses the integration of HTHPs with other cycles such as thermal energy storage, waste heat recovery, fuel cell membrane, ORC, super-critical water desalination, co-generation and poly-generation, desiccant wheel, vapor injection, steam injected gas turbine as well as solar absorption system • Emphasizes on the recent advances • Discusses key challenges in HTHPs integration such as political ambiguity, public conscience, adverse market (industrial sector), and technological challenge • Presents performance indicator for the HTHPs

1.1. Performance indicators for HTHP integration

Several studies have investigated how to integrate high-temperature heat pumps into different applications to improve energy efficiency [55 56 57]. The absorption heat pump (AHP) and the vapor compression heat pump (VCHP) are the two most common heat pump technology solutions for recovering heat from exhaust gas. Zhu et al. [58] and Qu et al. [59] explored how absorption heat pumps may be operated either in contact or indirect contact along with the flue gas condensers, thereby improving efficiency for conventional boilers accordingly. In addition, Wei et al. [60] presented a method for recovering waste heat from a gas boiler using an open cycle absorption heat pump (AHP). Hou et al. [61] presented an absorption heat pump gas boiler system.

The outlet gas temperature could be reduced to 30 °C, and the boiler efficiency is increased by approximately 11.8% in the examined case. Li et al. [62] integrated vapor compression heat pump with swing distillation by using binary azeotropic to investigated the minimum cost of different processes.

Statistical evidence plays a growing role in heat decarbonization initiatives due to the evident connections between heating, cooling, and other industrial application systems and social concerns such as customer experience, transition difficulties, and fuel poverty. Several articles have been published on integrating heat pumps typically into district heating and cooling and other industrial networks. Despite this, none of the articles discussed a suitable configuration of integration of high-temperature heat pump (HTHP). To increase the system performance is to apply integrated techniques in the design of HTHPs. The intrinsic integration into a process might need minimal new process equipment and, at the same time to obtain the maximum COP as illustrated in Fig. 3. A heat pump's COP is generally governed by the temperature difference between the heat source and the heat sink. It can be defined as a first approximation by considering the efficiency in terms of the theoretical value. Equation (1) defines the COP of a heat pump, which can be estimated by using the Carnot factor. The typical value for η_{cop} is 55% [63].

$$COP = \frac{\dot{Q}_{th}}{\dot{E}_{hp}} = \eta_{COP}\frac{T_{sink}}{T_{sink} - T_{source}} \tag{1}$$

Equation (2) describes the economic assessment of a heat pump's interest.

$$I_{annual} + M + \dot{Q}_{th}.d.\left(\frac{C_{el}}{COP} - \frac{C_{fuel}}{\eta_{th}}\right) \leqslant 0 \tag{2}$$

$$I_{annual} + \dot{Q}_{th}.d.\frac{C_{fuel}}{\eta_{th}}\left(\frac{C_{el}}{C_{fuel}}.\frac{\eta_{th}}{\eta_{COP}}\cdot\frac{T_{\text{sink}}}{T_{\text{sink}} - T_{source}} - 1\right) \leqslant 0 \tag{3}$$

In this equation $\dot{Q}_{th}.d.\frac{C_{fuel}}{\eta_{th}}$ is the current energy bill, which corresponds to the boiler's annual operating cost. As a result, the profitability of the heat pump is described by equation (4). It is determined by the investment cost and how it is annualized (based on estimated lifetime and interest rate), the maintenance cost, the fuel to electricity price ratio, the system's COP, and the current heating system's efficiency η_{th} (boiler).

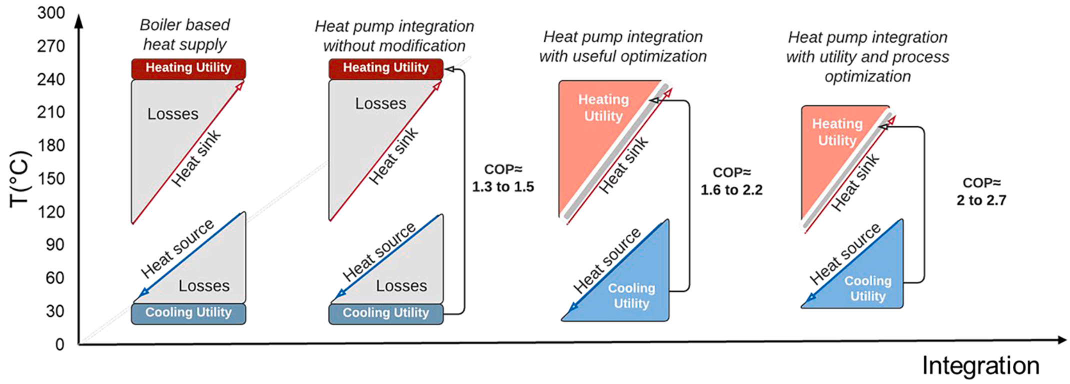


Fig. 3. Process integration of the heat sink and heat source for industrial application [64].

$$I_{annual} + \frac{M}{\left(1 - k_{kel} \cdot \frac{\eta_{th}}{\eta_{COP}} \cdot \frac{T_{sink}}{T_{sink} - T_{source}}\right)} \leqslant Energy - bill \tag{4}$$

• CO_2 value of the employed fuel ($CO_{2\text{-}LHV}$ in kilogram $_{CO2}$ /MJ_{LHV}); CO_2 content of fuel (natural gas): 0.057 kg/MJ

$$\Delta CO_2 = \left(\frac{CO_{2-LHV}}{\eta_{th}} - \frac{CO_{2-elec}}{COP}\right)\dot{Q}_{th}.d \tag{5}$$

$$\Delta CO_{2\ relative} = \left(1 - \frac{CO_{2-elec}}{CO_{2-LHV}} \cdot \frac{\eta_{th}}{COP}\right) \tag{6}$$

Equation (5) calculates the CO_2 savings from utilizing heat from a HTHP instead of heat from a boiler, and equation (6) calculates the relative CO_2 emission decrease. Therefore, interest in HTHP integration will grow if the electricity has a low CO_2 content, the substitute fuel has a high CO_2 content, the heat pump has a high coefficient of performance. With equation (1) equation (6)

$$CO_{2\ relative} = \left(1 - \frac{CO_{2-elec}}{CO_{2-LHV}} \cdot \frac{\eta_{th}}{COP} \cdot \frac{T_{sink}}{T_{sink} - T_{source}}\right) \tag{7}$$

The significant CO_2 savings that could be made as a function of the heat sink temperature for two alternate energy mixes with varying CO_2 contents and for different temperature elevations are shown in Fig. 4. The boiler uses natural gas (η_{th} = 0.9), and the Fig. 4(a) for France's electricity mix and the Fig. 4 (b) Europe's electricity mix are shown (UCTE). COP is considered as 0.67. (calculated value) [63]. The normal ambient temperature is 15 °C. The "ambiance UCTE" and "ambiance France" curves distinguish between the situations in which the heat source is below ambient temperature (on the left) and above ambient temperature (on the right); $\Delta T = (T_{sink} - T_{source})$. At constant heat source and sink temperatures, an ideal Carnot heat pump cycle reflects the best possible theoretical performance.

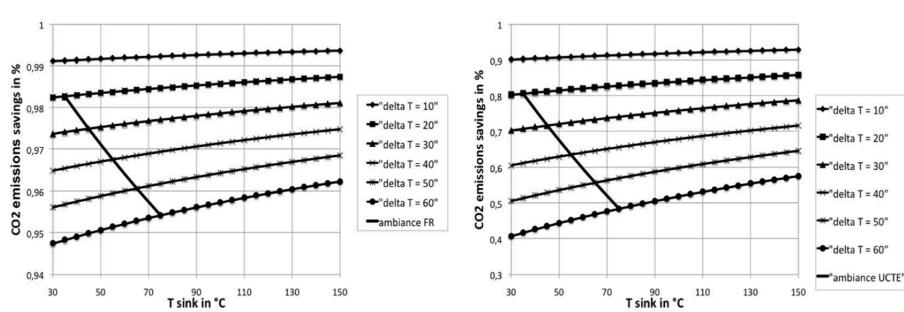
A Lorenz cycle, which is identical to an infinite multi-stage Carnot cycle, is the theoretical limit taking into consideration a temperature glide on the heat source and sink sides (logarithmic mean temperatures). Depending on the industrial application, the temperature glide of the heat source and the heat sink might change dramatically. Compared to other applications, such as high temperature networks, which have greater temperature glides and are more suitable for the Lorenz COP, drying and steam production operations, for instance, are closer to Carnot. The feasible Carnot COP and Lorenz COP values are compared as a function of the heat source and heat sink temperatures as shown in Fig. 5**.** The COP Lorenz calculation assumes a temperature glide of 30 K on the source and sink sides. A higher heat source temperature results in a greater heating COP for a constant heat sink temperature. When the temperature rise is constant (e.g., 70 K and 50 K), the temperature of the heat sink has only a minimal effect on the COP when compared to the temperature lift. The slight rise in COP is due to the heat source's increasing temperature and higher exergy. This nearly linear rise demonstrates the utility of employing industrial heat pumps for waste heat recovery.

1.2. HTHP process integration

Numerous levels, including the process level, the unit level, or the energy level, can integrate high-temperature heat pumps. With respect to operational performance and investment costs, defining the level of integration is a fundamental choice that is influenced by several aspects. High temperature heat pumps can be integrated into industrial processes at numerous levels of integration, such as:

- Process level
- Unit level
- Utility level

The placement of the heat pump influences several important characteristics, and the optimal placement is thus essential to the sustainability of heat pump projects for industrial process and decarbonization



(a) **(b)**

Fig. 4. Relative CO_2 emission savings with different heat sinks of HTHP [63]

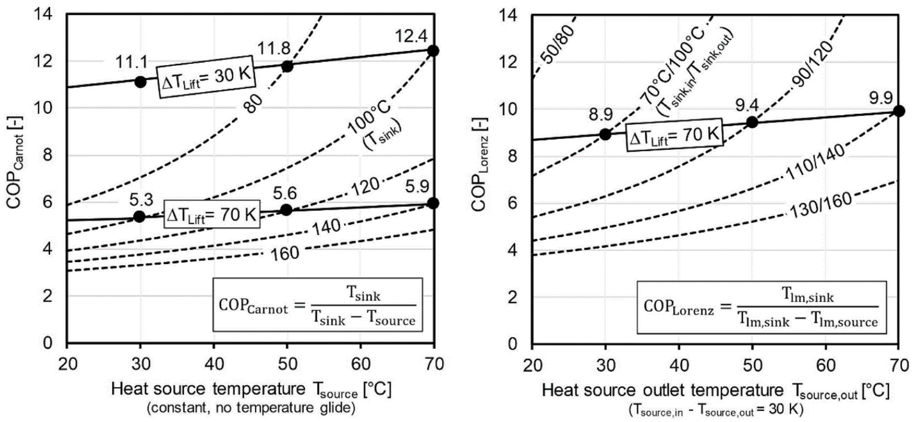


Fig. 5. Carnot's COP (left) and Lorenz's COP (right) as a function of heat source and heat sink temperatures [34].

of Co_2 emission. Overall, there is significant application opportunity for HTHPs in the food, paper, and chemical sectors, particularly in drying operations, as well as pasteurization, sterilization, evaporation, and distillation. Fig. 6 depicts an overview of industrial processes in several industrial sectors considered as potential for HTHP integration. Process temperatures ranging from 20 to 200 °C have been developed and substantiated using various literature data [65 66 67 68 69 70 71 72].

1.3. HTHP integration with thermal energy storage

HTHPs are crucial component in the decarbonizing the heating and power domains. Heat pumps combined with thermal energy storage offer electrical system operators better flexibility to adjust non-synchronous sources. There are three ways to store thermal energy, with the first two being the ones used in thermal energy storage (TES) systems the most commonly:

- Sensible heat storage.
- Latent heat storage.
- Thermochemical storage.

1.3.1. Sensible heat storage

Sensible heat storage (SHS) is the method for heating a material without going to cause it to change phase. The quantity of energy stored is dependent on the specific heat, the changes in temperature, and the amount of material [75], and may be expressed as follows:

$$Q = \int_{T_i}^{T_f} mC_p \Delta T = mC_{ap}(T_f - T_i) \tag{8}$$

1.3.2. Latent heat storage

Latent heat thermal energy storage (LHS) involves heating a material until it undergoes a phase change, which can be from solid to liquid or liquid to gas; when the material reaches its phase change temperature, it absorbs a large amount of heat to carry out the transformation, which is known as the latent heat of fusion or vaporization depending on the case, and the energy is thus stored. The following expression can be used to indicate the storage capacity of an LHS system.

$$Q = \int_{T_i}^{T_f} mC_p \Delta T + ma_m \Delta h + \int_{T_i}^{T_f} mC_p \Delta T \tag{9}$$

$$Q = m[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_i) \tag{10}$$

The first term of the equation represents the sensible heat stored by the temperature increase of the material from its initial temperature to the phase change temperature, while the second term represents the energy stored by the material's latent heat during the phase change; the energy stored depends on the amount of material, the specific latent heat, and the fraction of the material that has experienced a transformation. If the material is heated further after the phase shift, a third factor enters the equation to account for sensible heat storage once more.

In the most typical diagram Fig. 7 thermal energy storage systems are made up of four subsystems: high temperature heat pump, heat engine, high-temperature, and low-temperature. Most thermal energy storage systems include a separate storage module for each of the high- and low-temperature subsystems. Multiple storage module numbers are, nevertheless, feasible. Simple designs do not include a low-temperature; instead, the environment serves as a low-temperature heat sink and source.

The main barrier is the intermittent nature of managing the effective energy storage system associated with renewable energy. Hassan, A.H., et al [52] investigated various system configurations, refrigerants, and PCM melting temperatures (HTHP's heat sink) under the assumption of a 1 Megawatt electrical power input. The findings provide a complete description of the thermodynamics of a Pumped Thermal Energy Storage (PTES) system that comprises a high-temperature heat pump to drive an organic Rankine cycle through an interim high-temperature thermal energy storage system (HT-TES). The latter integrates sensible heat and latent storage of thermal energy sub-systems to optimize the benefit of refrigerant sub-cooling. Following the validation of the suggested model, multiple parametric experiments were conducted to evaluate system performance by utilizing various refrigerants and configurations, as well as a varied temperature ranges of the source and sink.

The findings reveal that R-1233zd(E) and R-1234ze(Z) provide the highest efficiency for a system that uses the same refrigerant in the HTHP and ORC, and for a storage system of latent heat thermal energy at 133 °C. The best system performance, including environmental effect, was attained with R-1233zd(E) in the HTHP and Butane in the ORC, among all the instances investigated using a storage system of latent heat thermal energy at 133 °C. A source of HTHP and ORC temperature of sink is 100 and 25 °C; correspondingly, such a system could achieve a power ratio of 1.3. The configuration of the CHEST system is seen in Fig. 8. The HTHP pumps heat (left cycle) from a low-temperature heat source and stores it in the HT-TES system during the charging cycle (left cycle). Initially, the thermal energy is stored as latent heat in the latent heat thermal energy storage (LH-TES) unit during refrigerant condensation (2 → 3). Second, the sensible heat thermal energy storage (SH-TES) unit recovers extra heat due to refrigerant subcooling (3 → 4). To complete the cycle, the refrigerant is increased (4 → 5). The CHEST system offers a significant degree of theoretical versatility, especially when combined with such a smart local distric heating (SDH) system [76].

Zauner et al. [49] investigated the integration of high temperature heat pump with energy efficiency extrusion (a generic industrial method

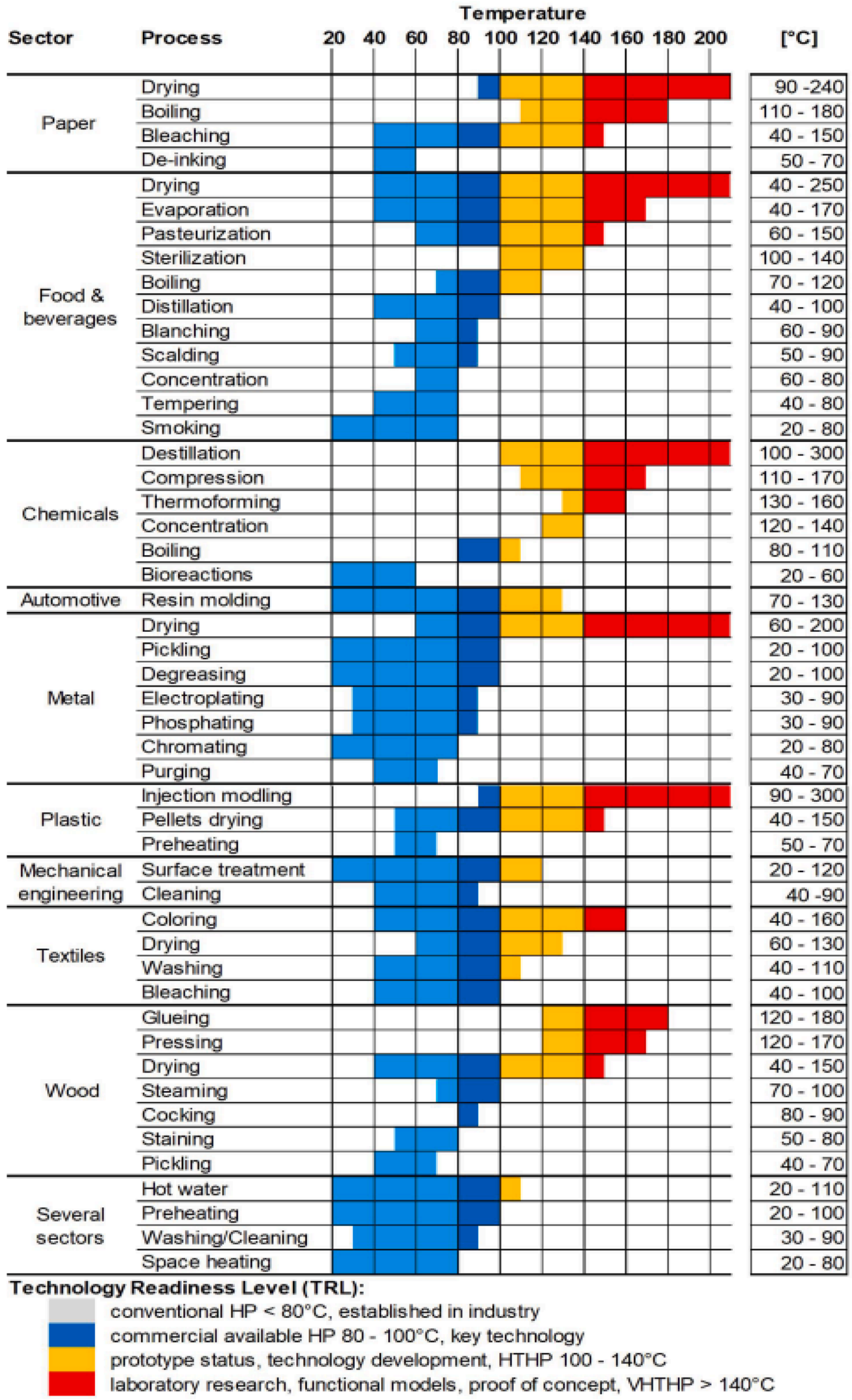


Fig. 6. Typical temperature ranges from different literature structured as an overview of processes in different industrial sectors [72 68 69 70 71 73 74].

for producing a variety of products, including food, chemicals, medicines, and consumer items) processes

As a result, they develop a brand-new concept based on hot water insulated bath, a high temperature heat pump for latent heat storage, allowing for substantial recovery of waste heat and use within a variety of heated processes as well as space heating. The results are based on experimental work of a demonstration factory at Geba Kunststofftechnik in St. Veit, Austria. The critical technological components include simulation work and the findings of a real experimentation factory at Geba Kunststofftechnik in St. Veit, Austria. Finally, they performed economic simulations for a hypothetical yet prototypical EEE Factory, demonstrating that the payback on investment maybe within three years. A comprehensive overview of the system, including hydraulics and temperature levels, is presented in Fig. 9. The system's maximum heating capacity and COP are 35 kW at 60 °C sources and 125 °C sink temperature and 2.5, respectively.

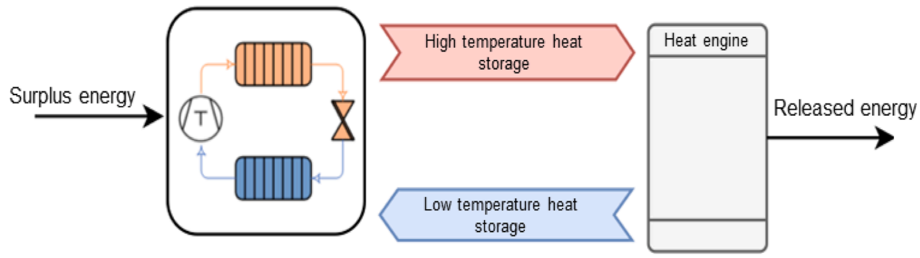


Fig. 7. HTHP with thermal energy storage.

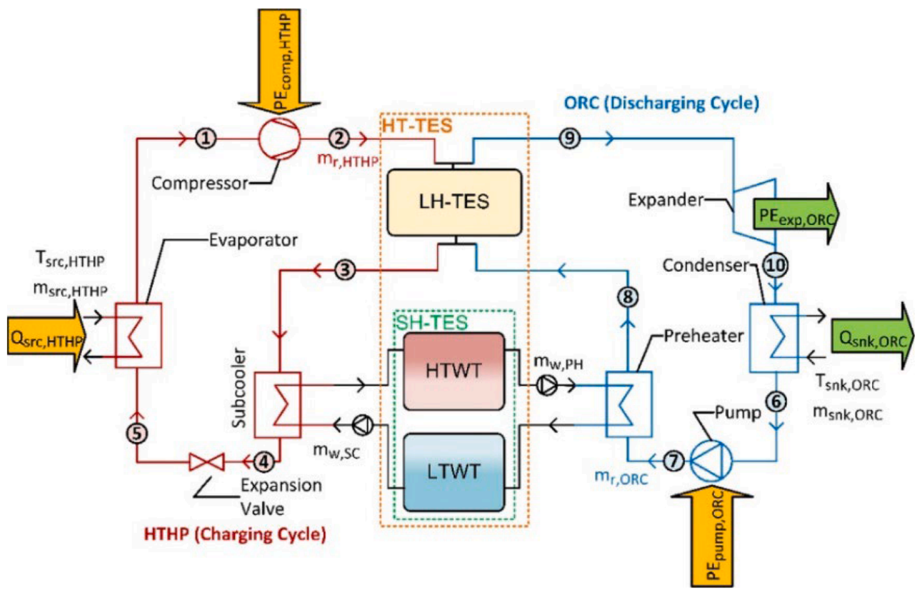


Fig. 8. Scheme of the compressed heat energy storage (CHEST) integrated with HTHP[52].

1.4. HTHP for waste-heat recovery

Key statistics for waste heat generation and temperature levels in the EU's power generating and main industrial sectors as shown in Fig. 10. In 2018, the power generating sector had a significantly larger waste heat potential of 8551.8•10^6 gigajoule (GJ) than the sum of industrial sectors (1808.0•10^6 GJ). The ultralow grade fraction (80 °C) was substantially larger in the electricity sector, accounting for 93.9% of total waste heat, compared to the industrial sectors, where it contributed only for 20.8% [77]. It should be mentioned, however, that the two major industrial contributors, the mining, and metals sectors, produced waste heat at temperatures much exceeding 100 °C.Fig. 11..

To enhance thermal matching in the heat sink, five variants of double-pressure condensation HTHP are suggested and investigated [78]. The models were evaluated from both perspectives of energy and exergy, and the efficiency of dual-pressure condensation HTHP systems is thoroughly evaluated and associated to that of standard single-stage, two-stage, and cascade HTHP systems. From the standpoint of energy efficiency and energetic performance, the dual-pressure condensation HTHP system outperforms the standard HTHP system.

At the ideal transitional water temperature, the highest COP is achieved. DWSAS (dual pressure condensation water-cooled saturated system) has the greatest COP of 4.16, which is 3.37–9.34 percent greater than standard HTHPs. For HTHP applications, R1234ze(Z) has a considerably better energy efficiency than the other working fluids, with a COP of 2.62–4.47% greater than R600a at an outlet heat source temperature of 15–35 °C. Due to improved thermal matching in the condensers, exergy destruction also decreases when dual-pressure condensation high temperature heat pumps (HTHPs) are used. DWSAS has the least amount of exergy degradation, which is 4.28–19.35 percent less than the standard HTHPs. Due to its exceptional energetic and energetic performance, DWSAS utilizing R1234ze(Z) was suggested.

Mateu-Royo et al. [50] provides an in-depth study of parallel compression configurations for the ejector and economizer including internal heat exchanger to improve the efficiency of the single-stage cycle in HTHP applications for waste heat recovery. To compare the suggested choices, a single stage cycle was utilized as a reference. Low-GWP refrigerants have also been investigated as a replacement for the standard working fluid HFC-245fa. Using HFC-245fa to produce the temperature up to 140 °C, the parallel compression via ejector and economizer with IHX raises the COP by 36% and 72.5%, respectively. The advanced configuration in Fig. 12 can be obtained by involving the ejector in a single-stage cycle along with IHX. There are several configurations available. However, the configuration with IHX could boost the discharge temperature.

Furthermore, with IHX, the ejector's volumetric heating capacity (VHC) and the economizer cycle improves by about 36% and 80%, respectively. When compared amid HFC-245fa, HC-601, HFO-1336mzz (Z), and R-514, the largest COP accompanies the lowest VHC loss. The single stage and design of ejector with internal heat exchanger (IHX) have the same results, but the parallel compression cycle having economizer and IHX yields a considerable COP and VHC improvement, according to multi-objective assessment. The correct trade-off between COP and VHC is represented by HCFO-1233zd(E) and HCFO-1224yd(Z).

Cao, X.-Q et al. [79] Studied of the performance of several high-temperature heat pumps for low-grade waste heat recovery having an average of 45 °C temperature and produce hot water of 95 °C of temperature, so several heat pump systems were integrated.

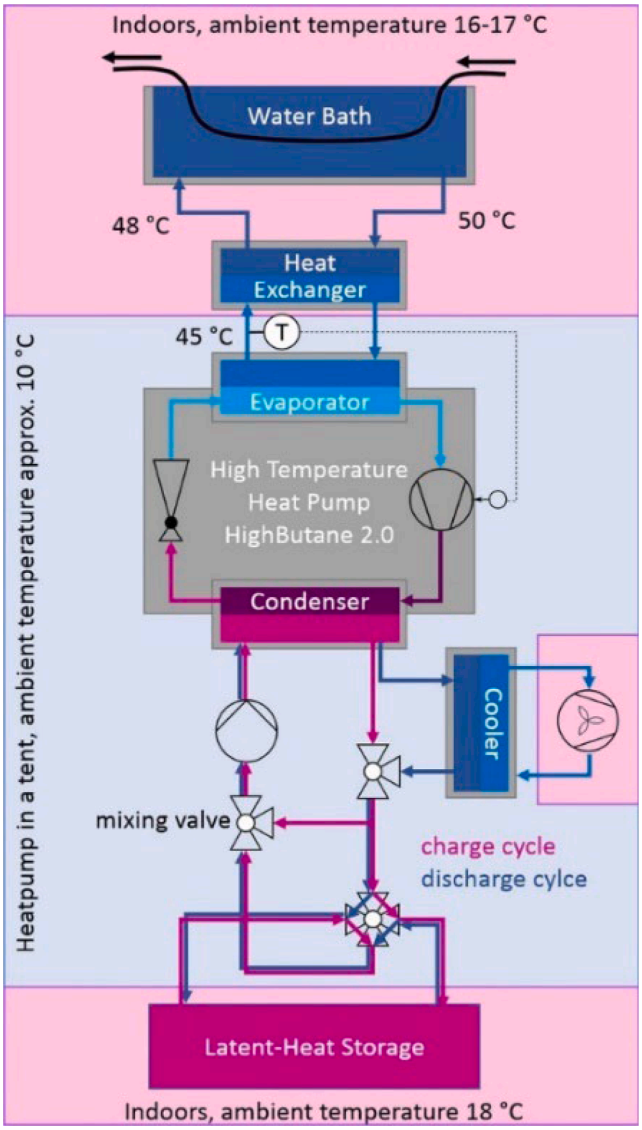


Fig. 9. Layout of HTHP integrated with latent heat storage[49].

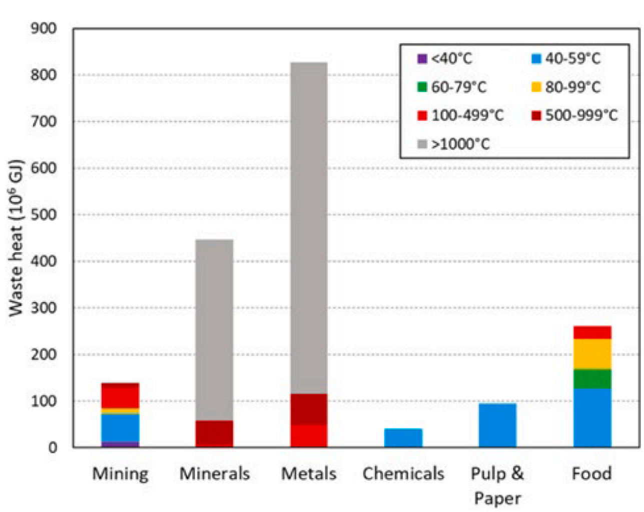


Fig. 10. Primary waste heat was generated in the EU's industrial sectors in 2018 [77].

A heat pump with single-stage vapor compression (system 1), a heat exchanger along with a heat pump works on two-stages (system 2), a refrigerant which is injected with heat pump works on two-stages (system 3) and internal heat exchanger (IHX) (system 4), flash tank with heat pump works on two-stage (system 5) and flash tank and intercooler with heat pump which works on two-stages (system 6) are some of the systems available. For the comparison of the performance of each system, thermodynamic and economic studies were performed. Fig. 13 shows various heat pump systems compared for their thermodynamic and economic performances. The reference is the single stage system (system 1), two stage with IHX (system 2), two-stage with injection (system 3), combination of second and third system (system 4), two-stage with flash tank (system 5), two-stage with flash tank and intercooler (system 6). According to the findings the approach 5 & 6 have very close results in COP and energy efficiency and are significantly greater than all other systems which were tested. Furthermore, in comparison to other designs, both System 5 and 6 have a shorter payback period. When performance through thermodynamic point of view and economic quality are considered, system 5 is ultimately selected since it requires less initial budget than system 6.Fig. 14. Fig. 15..

Zhao et al. [80] studied both theoretically and experimentally a novel system for recovering heat and delivering hot water is described and studied using twin screw compressors with higher temperature ammonia (NH_3). For twin screw compressors with high-pressure, a novel semi-empirical model was developed. The COP decreases with the increase of heating temperature and decreases more rapidly when the evaporating temperature is higher. The COP ranges from 3.0 to 7.0 according to the operating condition. The discharge temperature increases rapidly with the increase of heating temperature, whose difference is approximately 10 °C. When the evaporating temperature is higher, the discharge temperature will be higher but increase less significantly with the increase of condensing temperature.

To evaluate the performance of the compressor and system at various capacities, two sets of twin-screw compressors are mounted in parallel with each other. The two sets of compressors constitute part of the high-pressure ammonia twin screw compressor series.

Liu et al. [44] developed that could achieve a heat supply temperature of 180 °C for air or water. They also studied the use of ACHP at an Asian noodles plant in Hebei, China, which requires 0.410 MPa sustained steam (144.5 °C) for the drying process. The flue gas from internal combustion served as a heat source for the ACHP's reboiler and evaporator, as shown in the flow sheet in Fig. 15. . Meanwhile, the engine jacket water (99 °C) functioned as a heat source for the rectifier in ACHP. The absorber provided high-temperature heat to the user, resulting in a heating capacity of 432.03 kW and a COP of 5.23.

Wang et al. [35] investigated the heating cycle of a high temperature heat pump (HTHP). The results reveal that when the condensing temperature exceeds 75 °C, a heat pump (HP) that cycles with parallel heating and is operated in a parallel design performs quite well. For the cycle study, an HTHP model with parallel cycles on the water side and a heating capacity of 700 kW was developed. A screw compressor was also modified due to the high temperatures. The HTHP output water temperature could reach 85 °C, with a corresponding COP of 4.3.

Zhao et al. [51] demonstrate the design and development of an air source cascade heat pump with vapor injection for high-temperature heat supply. The performance of the designed heat pump's heating coefficient ranges from 1.16 to 1.58 when the supply temperature is 140 °C and the ambient temperature is between 10 and 20 °C. Under the conditions of 20 °C ambient temperature and 130 °C heating supply temperature, the COP of this optimized prototype increased by 18.71% as compared to the prior system. The actual findings are in good agreement with the conclusions of the numerical analysis, and they also show that the cascade heat pump with vapor injection has a strong application potential for raising temperatures.

Mateu-Royo et al. [48] propose an advanced technology that relies

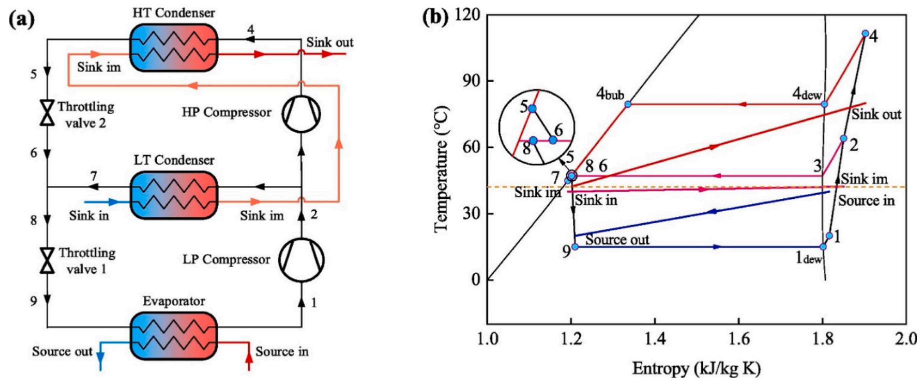


Fig. 11. Schematic diagram of baseline dual-pressure condensation HTHP (a) layout and (b) T-s diagram [78].

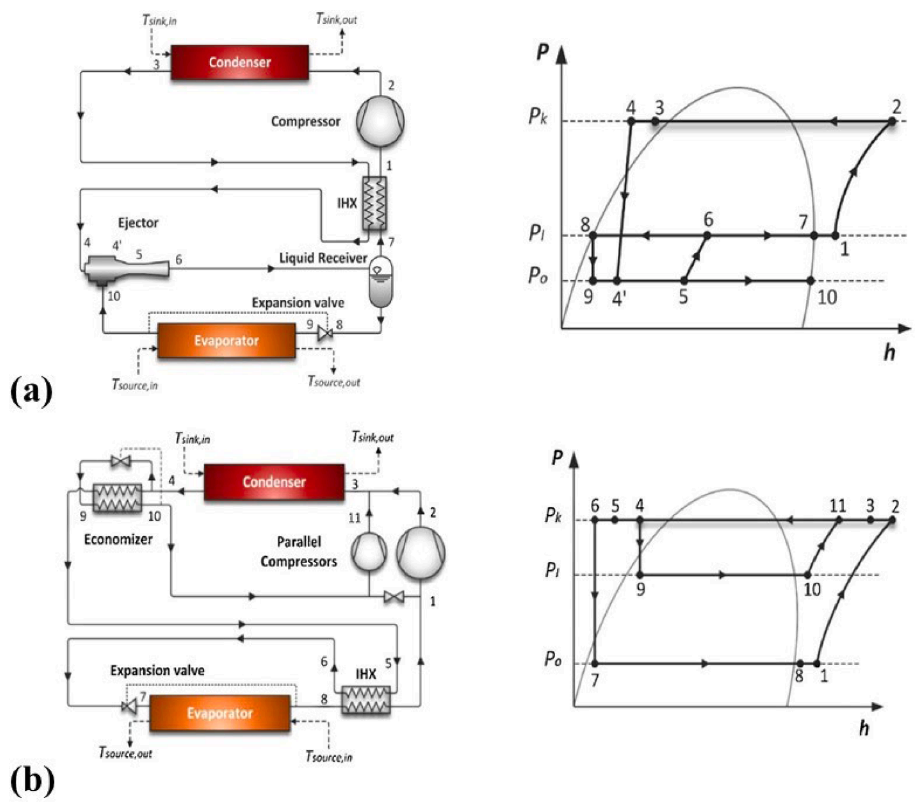


Fig. 12. (a) Ejector arrangement with IHX and P-h diagram (b) Economizer parallel with IHX P-h diagram [50].

on a reversible HTHP and an organic Rankine cycle (ORC) for recovering low-grade heat. The suggested system reuses low-quality surplus heat to create power or usable heat according to consumer demand. They adopted computational simulation for the reversible system, expander, and semi-empirical compressor models with refrigerant HFC-245fa. To achieve optimum energy efficiency, the built-in volume ratio, and efficacy of the embedded heat exchanger have been adjusted. Notice that HFC-245fa shows energy efficient but it has significant impact on global warming potential (GWP) that may pose a problem in terms of climate change.

Fig. 16 (a) shows the operation of the reversible system in HTHP mode. It includes a IHX in the basic Vapor compression cycle. The combination of ORC and HTHP increases the waste heat recovery to a great extent. Fig. 16 (b) the system can be operated in any of the modes, either in ORC or HTHP by changing the valve position. As a result, multi-objective optimization of the ecologically acceptable operational fluids like), R-514A, HCFO-1233zd(E), and HCFO-1224yd(Z) and many others was examined. The results revealed that the suggested system could reach a COP of 2.44 at a condensing temperature of 140 °C while running in HTHP mode.Fig. 17.Fig. 18..

Vandersickel et al. [81] proposed integrating of absorption HTHP reinjecting steam from the next gas turbine's heat recovery steam generator offers enhanced energy and efficiency at a low specific cost, as well as an assessment of the absorption system's potential and limits gas turbine for a steam injection. The "High Temperature Condensation Boiler Technology" (HT-CBT) contains a vapor condenser that outperforms the standard flue gas cooler across the full Steam injected gas turbines (STIG) working range from the perspective of efficiency of fuel consumption and recovery of water for a return temperature of 60 °C. Fuel efficiency stays stable at around 95–102% upon steam injection rates up to 1.16 kg/s (60 °C) and 0.96 kg/s (40 °C), respectively. In this range, complete water recovery relieves the significant water use, making it a suitable technology for flexible cogeneration in dry locations as well. The additional advantage of the HT-CBT was discovered to be

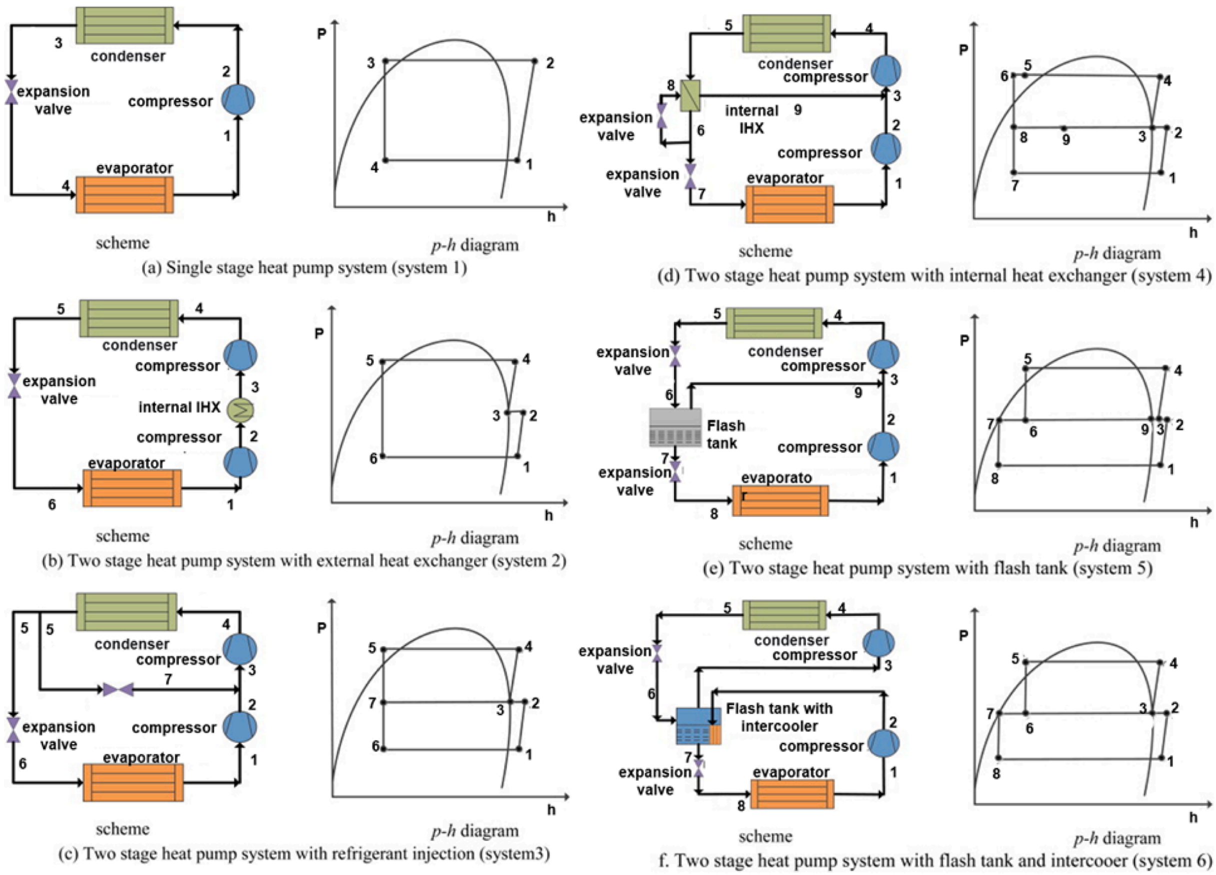


Fig. 13. Arrangements and P-h diagrams for several heat pump systems[79].

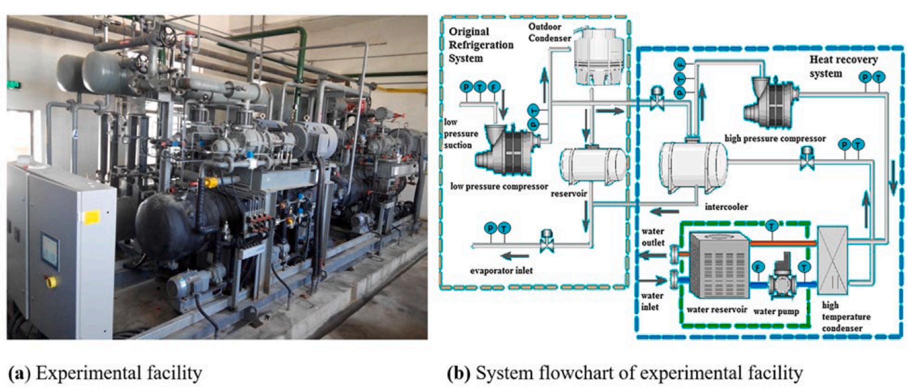


Fig. 14. Schematic combined HTHP integrated with waste heat recovery refrigeration system [80].

limited by higher steam injection rates due to the limited accessibility of desorber heating from the HRSG, denoting the combination of external desorber heating.

Chaiyat et al. [39] conducted both simulation and experimental tests on water-lithium bromide absorption heat transformer with a 10-kW solar system which is integrated with two stage vapor compression. The VCHP was utilized at the AHT condenser for the recovery of waste heat, which was then transferred to the absorption heat transfer evaporator at a higher temperature. The AHT device received solar heat from a series of flat-plate solar collectors with serial connections.

In the VCHP cycle, R123 and R134a were used as refrigerants. The total cycle coefficient (COP) was 0.71 in the simulation of solar-CAHT, compared to 0.49 for the normal solar-AHT. As a result of the test, the solar-CAHT and solar-AHT of complete cycle COPs were 0.62 and 0.39, respectively. Due to the experimental compressor's oversize, the findings from the experimental work were giving inferior results value than those models used in simulation work.

1.5. Summary of different cycles configuration and challenges

As previously stated, a simple vapor compression cycle is insufficient for multi-temperature applications. To address numerous heats sinks and sources and increase performance, more complex systems are necessary. Several ideas for multi-temperature cycles employing methodological approaches have been developed and examined. The main difficulties for the analyzed cycles are presented in Table 3.

R718 could be used to supply high-temperature heat (120 °C), and once again, the heat is utilized for manufacturing processes like furnaces

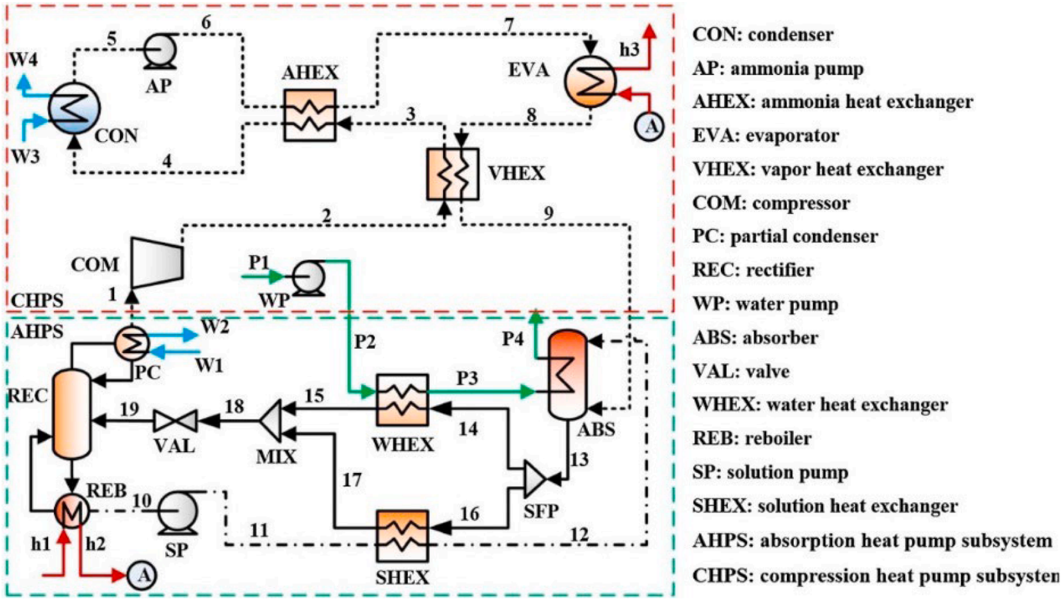


Fig. 15. Layout for absorption compression heat pump integrated with waste heat recovery for noddle drying application [44].

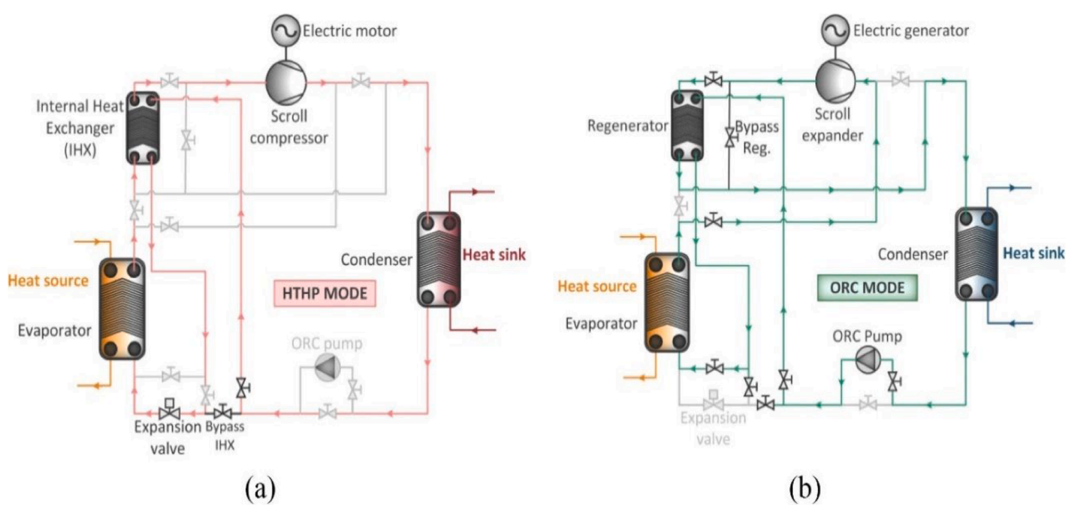


Fig. 16. Reversible HTHP with ORC system, operating in a) HTHP mode and b) ORC mode [48].

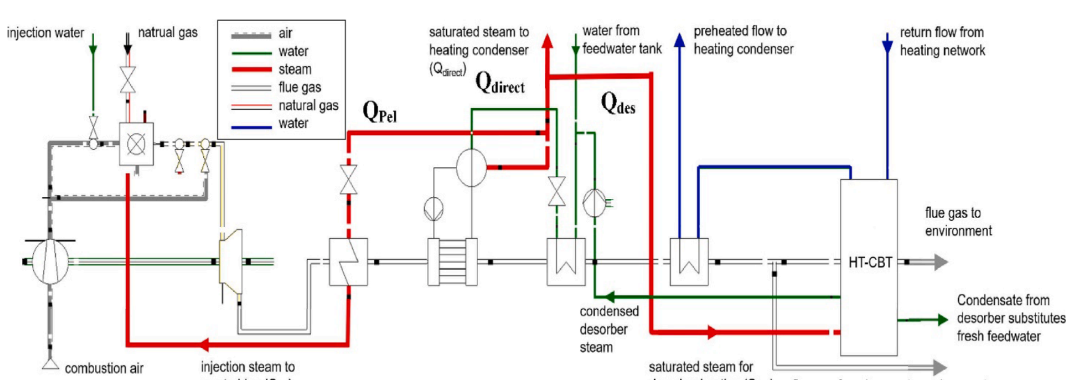


Fig. 17. Schematic of HRSG and integrated HT-CBT component [81].

drying and industrial heating. Fig. 19 provides a summary of the preferable refrigerant and cycle options for waste heat recovery. The sources of industrial waste heat are listed according to their temperature range, from high to low. The most prominent refrigerants currently in use and their matching low GWP alternatives are examined. R744 and R717, which are natural refrigerants, are widely used in typical heating

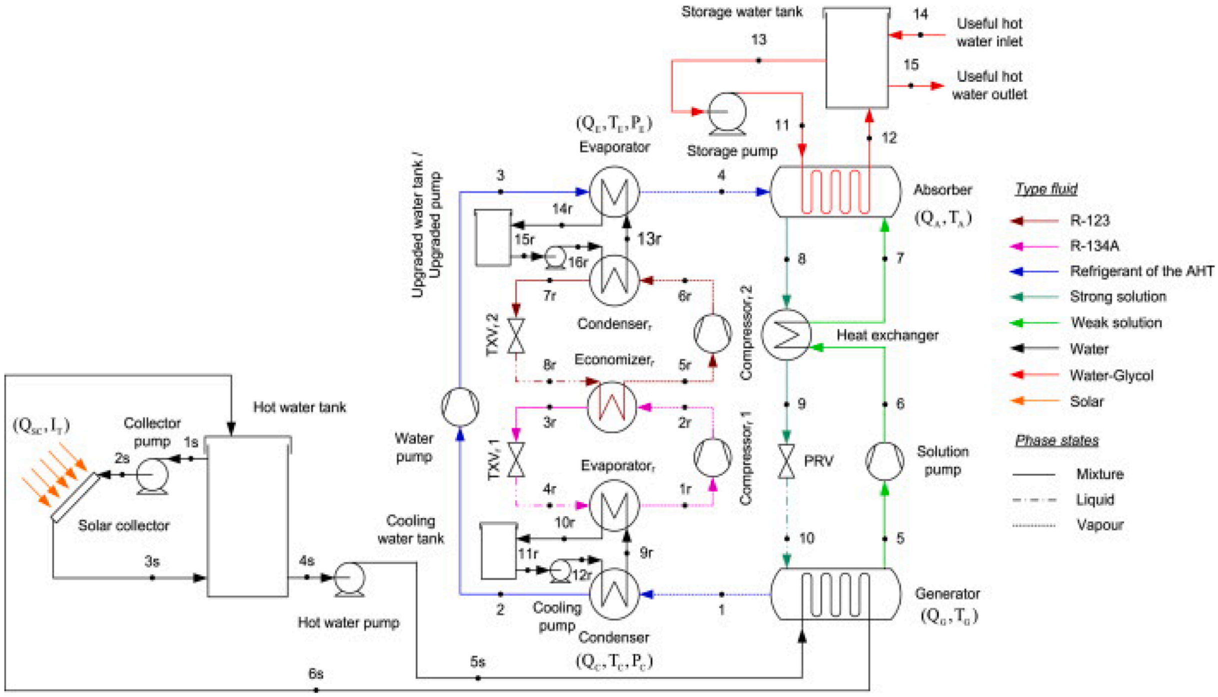


Fig. 18. Solar-CAHT integrated with two stage vapor compression heat pump [39].

Table 3
Potential challenges regarding high temperature heat pump cycles.

System	Major R&D challenges
Multistage compressor	• Compressor configuration and high initial cost • Compressor lubrication
Cascade	• A large temperature gap between heat source and sink
Secondary loop	• limits energy performance due to temperature gap • viscous secondary fluid pump losses
Throttle valves	• Energy losses during multi-stage compressor
Ejector	• Capacity management • Flexible ejector design
Multiple ejectors	• Control system especially in CO_2 system • Configuration and variable designs for different cycles
Separated gas cooler	• High performance only for certain heat source and sink flow rates
Absorption compression single stage	• Compressor discharge temperature • Oil-free compression • Absorber design • Liquid–vapor mixing and distribution process • Solution pump
Transcritical cycles	• There is a lack of understanding regarding the heat exchange and pressure drop correlations for super-critical working fluids.

applications. Due to their excellent thermodynamic characteristics, R245fa and R718 are competitive refrigerants for R1234ze (Z) and R1233zd (E), which are extremely motivating in high heat transfer temperature applications [82].Fig. 20..

1.6. HTHP integration with multi-generation energy system

For heating and cooling cogeneration, a high temperature heat pump system working at high temperature with transcritical cycle CO_2 and subcritical of R152a was developed [41]. The focus was on assessing and comparing the thermodynamic performance of a separate heat pump and a single CO_2 refrigeration system operating alone. Match behavior of temperature of the heating process of the supply water is also illustrated by using entrants' dissipation rate and T-Q diagram. Fig. 20. represents the HTHP combined system made up of a CO_2 transcritical cycle, a sub-critical cycle with R152 refrigerant, and an intermediate heat exchanger. Analysis of the supply water temperature, COP and heating and cooling capacity of the system, exergy efficiency, and energy utilization were performed.Fig. 22..

In addition, a comparison of performances was made between systems including and without an intermediate heat exchanger and systems using various refrigerants. According to the research, there are acceptable CO_2 discharge pressure ranges for the CO_2 transcritical cycle that facilitate the criteria of pinch point temperatures for heat transfer operations. The heating and cooling capabilities of the system are both enhanced when the CO_2 discharge pressure is increased. The overall system power usage, on the other hand, drops initially before increasing substantially. With increasing discharge pressure of CO_2, both COP and exergy efficiency improve accordingly. Compared to a heat pump with refrigerant of R152a and working alone single CO_2 transcritical cycle, the combined system's exergy efficiency and COP are enhanced by roughly 54.7% and 175%, respectively, under identical operating conditions circumstances.

According to the testing results, the parallel cycles that have a heating in serial along the side of water and the redesigned compressor, may considerably enhance the typical heating capacity of HTHP and COP, which is a performance indicator in high-temperature circumstances. All the data show that in industrial heating usage, the HTHP having cycles in parallel configuration and a redesigned compressor having heating which is in serial along the water side is highly competitive.

Ahrens et al. [3] investigate the existing energy system of an existing dairy to evaluate the system performance and energy consumption related to the production processes. The dairy has a unique and creative energy system that uses hybrid heat pump with natural working fluids to meet both heating and cooling demands. . Fig. 21 shows three various heat pump systems and six different temperature levels delivered for various users. The findings demonstrate that the integrated system can meet the needs that arise. On an annual basis, however, it is predicted that energy usage would be decreased much further. When compared to conventional dairy systems, energy use was decreased by 37.90%, and greenhouse gas (GHG) discharge by up to 91.70 %. The method

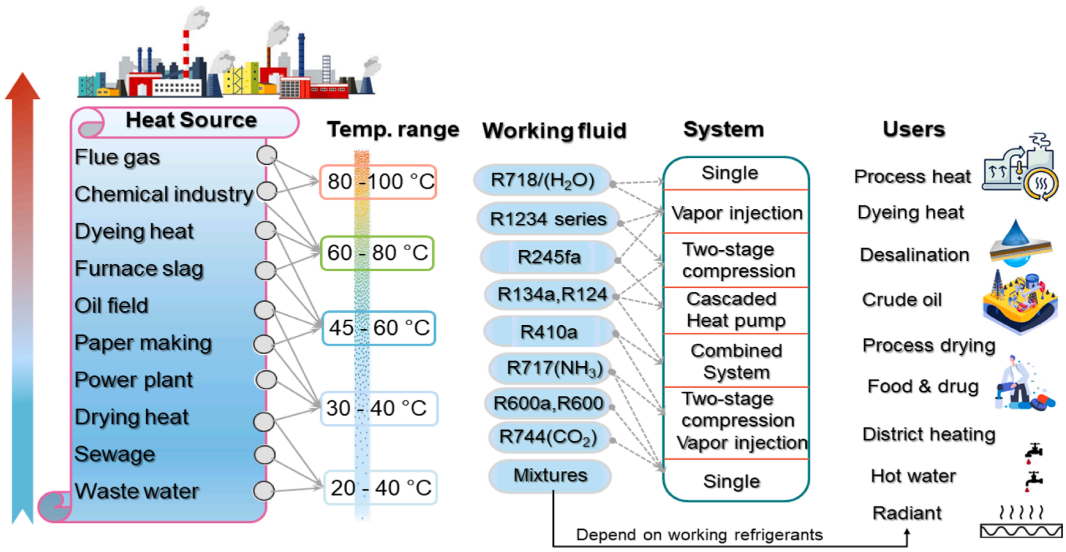


Fig. 19. VPC HTHP integration for waste recovery and their industrial applications.

simultaneously achieves a recovery rate of waste heat was above 95%. Peaks of demand were also adjusted, and a system COP of 4.1 was obtained and the identification of possibilities for future enhancements.

Poly-generation energy systems have been shown to be a dependable, cost-effective, and efficient source of energy. Luca et al. [20] integrated high temperature heat pump (HTHP) within a trigeneration (heating, cooling, and steam production) system. The heat pump employs low-temperature heat from the absorption chiller's condenser as a heat source to make hot water. To analyze the technical feasibility of existing heat pump technology for this scenario and to examine the performance of alternative working fluids, a theoretical model of the heat pump cycle is constructed. An exergy study is conducted to demonstrate the gains of the innovative trigeneration system over standard energy production methods. Furthermore, the proposed energy system is subjected to a leveled cost of electricity analysis to demonstrate its general economic viability.

The high-temperature heat pump integration into a trigeneration system delivers a space to cover flexible energy demands and attain valuable financial and energy performance, with around 40% global cost savings compared to discrete production and around 10% compared to conventional cogeneration and trigeneration systems, according to the findings.

1.7. HTHP integrated with water desalination process

Super-critical water desalination (SCWD) is a zero-liquid-displacement technique that can regulate various electrolytes' solubility. SCWD, on the other hand, is a high energy consumption process that requires high-grade thermal energy (>450 °C). Sharan et al. [22] proposed HTTP to minimize the energy consumption of SCWD. The energy consumption of their proposed system dropped by 36% for a 3.50% feed concentration and 14% for a 20% feed concentration, while distillate costs dropped by 15% and 10%, respectively. Another advantage of the suggested integration is that, contrasting frequently desalination technology applied for thermal recovery, the system may be run only with electricity as a heat source. When a commercially existing brine concentrator is used as the crystallizer equipment, the performance of the combined SCWD-heat pump is improved. For a feed concentration of 25%, it is roughly 20% more energy efficient and 8% less costly. The integration of water desalination system is illustrated in Fig. 23.

The supercritical hot water coming from the separator gets cooled partially in the heat exchanger to heat the heat transfer working fluid. The temperature of the heat transfer fluid increases while the pressure is kept constant. The heat transfer fluid is compressed and acts as a heat source for the feed water. As a result, the SCWD-heat pump combination could surpass current high-recovery desalination technologies.

1.8. HTHP integrated with fuel cell membrane

Proton exchange membrane fuel cell (PEMFC)-based distributed energy systems provide a viable technical path to carbon neutrality. PEMFC waste heat may be recovered successfully for cooling/heating. However, if the waste heat from the gas is insufficient to achieve the cooling or heating needs of the building, additional systems are necessary. Hence, a new PEMFC system used for distributing energy is combined with a hybrid-energy heat pump to create a dynamic supply–demand match effectively and flexibly (HEHP) [53]. It showed that it could convert to a single absorption heat pump when the waste heat is abundant. By contrast, it can switch to a hybrid absorption-compression heat pump upon the shortage of waste heat. Fig. 24 indicates the proposed PEMFC-HEHP system. The photovoltaic array and the electrolyze do solar power energy and hydrogen productions, respectively. For a high-temperature PEMFC, the operating temperature is generally in the range of 120–200 °C. A substantial amount of waste heat recovery is possible with this system. It has great flexibility in switching between vapor compression and absorption systems.

A validated model characterizes and optimizes the combined PEMFC-HEHP system under various operating circumstances and hybrid configurations. With a temperature of supply 10–10 °C for cooling, the corresponding power density and efficiency from the fuel cell may be enhanced by 18.51% & 7.90 %, respectively, while with provide temperatures of 40–60 °C for heating, they can be improved by 54.80 % and 20.30 %. In cooling mode, the highest equivalent power density is 4.341 kW/m^2, and in heating mode, it is 5.3570 kW/m^2, compared to 3.290 kW/m^2 for the individual system of PEMFC. The hybrid design must consider the needs of cooling/heating loads as well as the available waste heat. A greater absorption percentage increases the PEMFC equivalent power, while a fraction of higher compression enhances the HEHP cooling and heating capability. The findings may aid in developing a PEMFC- system based on energy distribution.

2. Key challenges for HTHP integration

Regarding high temperature heat pumps' ability to reduce GHG emissions and overall contribution to the sustainable development of the energy efficient heating and cooling industries, there is almost universal

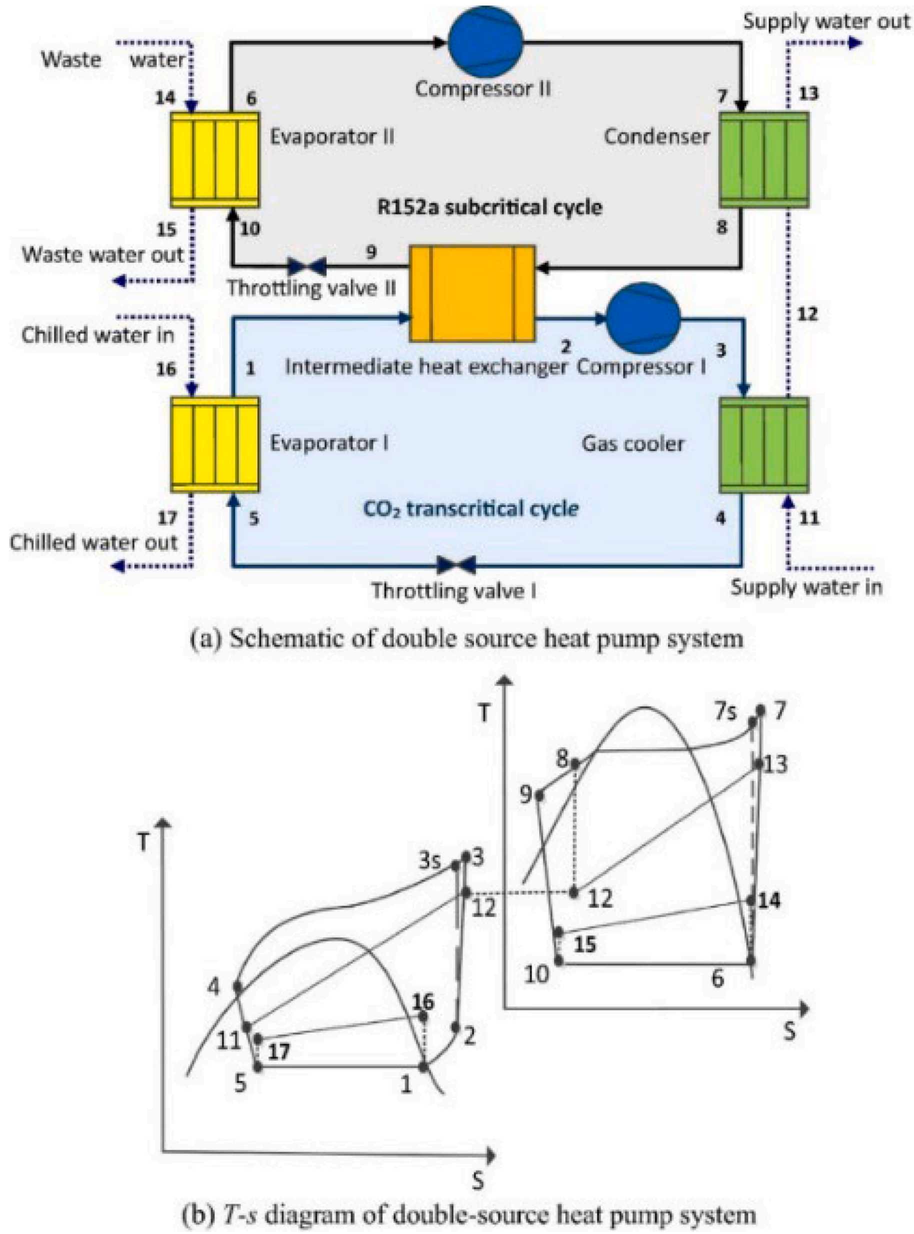


Fig. 20. Schematic and T-s diagram of a double source cogeneration HTHP [41].

agreement [83,84]. Heat pumps have a large market potential, which can have positive socioeconomic effects [85]. Despite the broad use of HTHP technologies, there are several obstacles, including problems with technology, the economy, regulations, policies, and public acceptance. The primary constraints influencing the implementation rate of heat pumps are shown in Fig. 25.

2.1. Political ambiguity

One of the key reasons for the dearth of unambiguous heat decarbonization paths and technology adoption is policy uncertainty [86,87]. Most countries either have a specialized high temperature heat pump policy instrument or be inclined to have a single policy for all types of heating system. Such a "one fits all" policy might not be successful in reducing carbon emissions. For instance, a cross-country analysis in the EU shows that a lack of legal and regulatory rules hinders the advancement of technology [88]. The kind of end-use and the heating technology have a significant impact on the economic and fiscal concerns design for low carbon heating [89]. Another economic constraint that influences the economic benefit of such technologies, and hence their acceptance, is inadequate financing for heat pump research and development.

2.2. Public conscience

Adopting the innovation of HTHP is also significantly hampered by concerns with public acceptance and understanding. These are the result of unfounded concern, false impression, factual inaccuracies, and/or negative experiences with the reliability of HTHP integration, i.e., lack of technologies from HP. Even in highly developed societies, there is sometimes a lack of public awareness of the financial and environmental advantages of HTHP integration [90]. For example, HTHPs may produce noise pollution, which may raise public concerns and reduce their levels of adoption. However, to prevent noise-related annoyances in a neighborhood, the noise levels are frequently maintained in check using noise barriers [91,92]. While HTHP have a net positive influence on the environment. Several research investigate at environmental challenges associated to the use of HTHP, notably problems with land subsidence

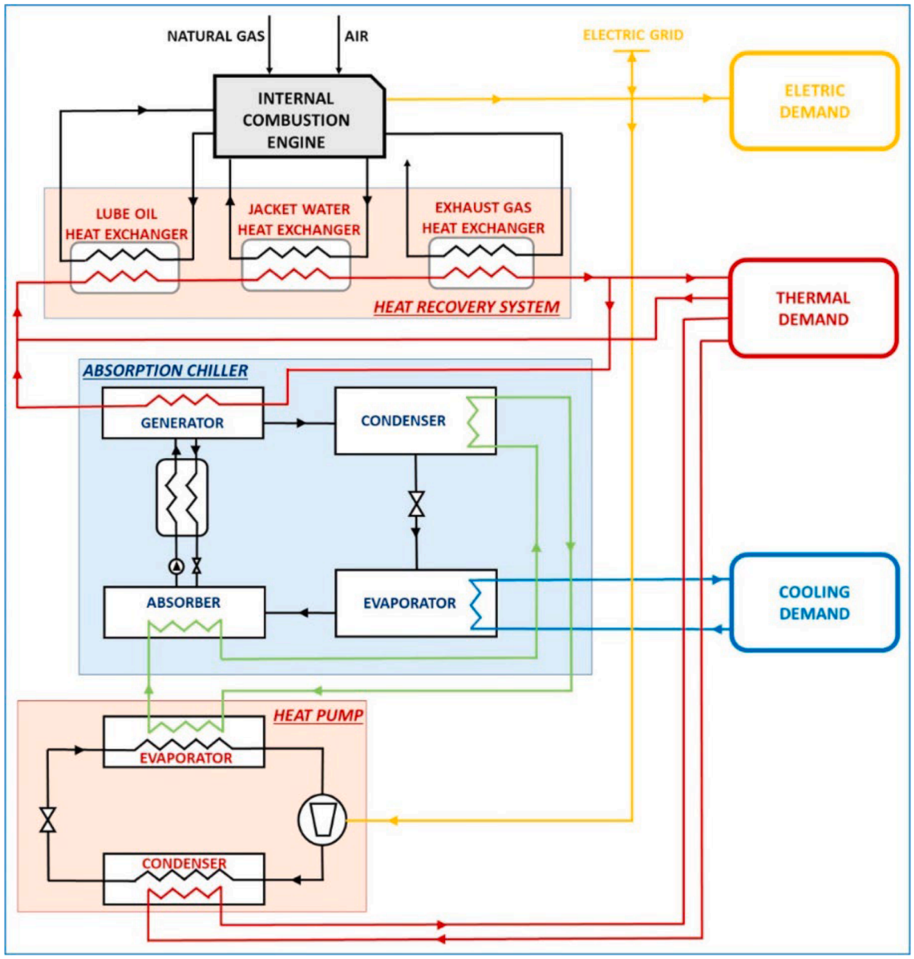


Fig. 22. Diagram of the integrated HTHP-trigeneration system [20].

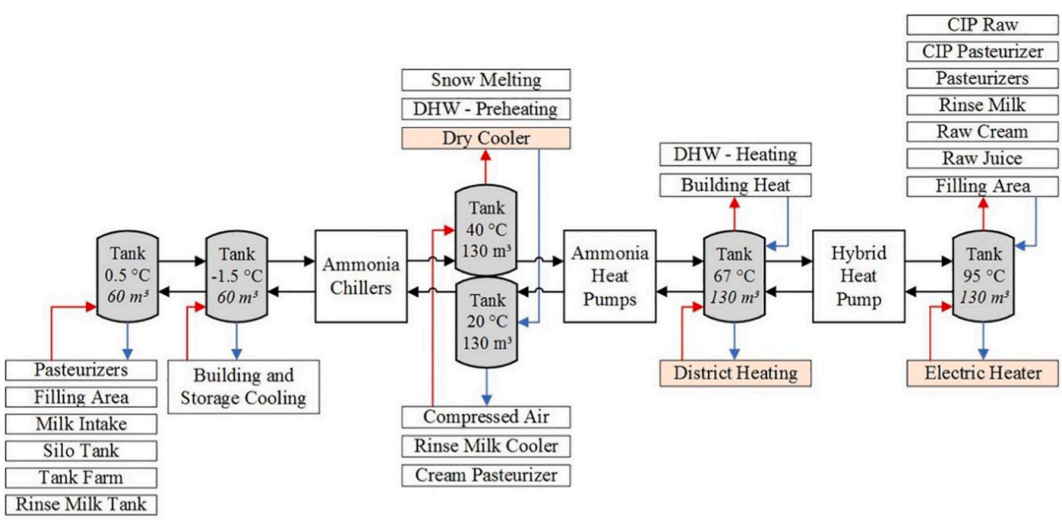


Fig. 21. Integrated hybrid absorption-compression heat pump energy system.[3]

and water pollution that have an influence on the dispersion of HTHP integration to the industrial process [93,94,95]. However, there are some government initiatives that aim to raise public awareness and promote larger deployment:

- Energy Efficiency 2016–2017 is a 4-year Innovation Action project called DryFiciency that is financed by the European Union's Horizon 2020 Research & Innovation Framework Program [96].

2.3. Adverse market especially industrial sectors

Financial constraints have been identified as one of the most

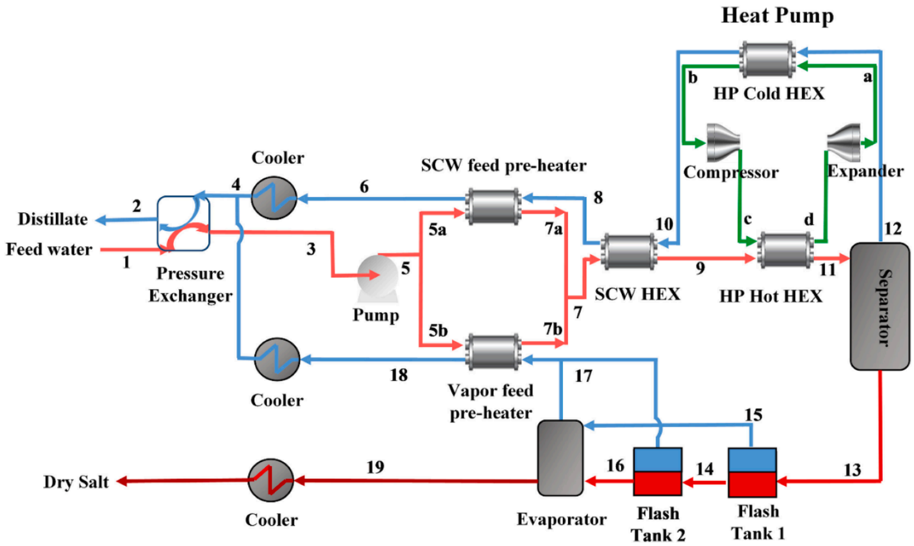


Fig. 23. Super-critical water desalination integrated with the HTHP system [22].

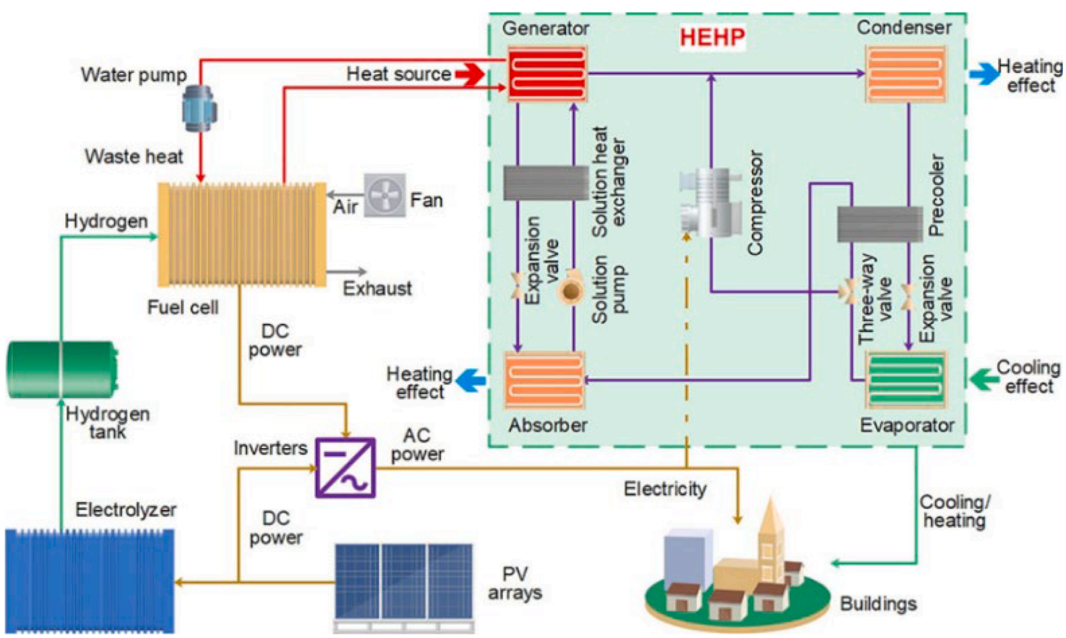


Fig. 24. Layout for PEMFC-HEHP system [53].

significant barriers to the HTHP integration [97]. According to EU studies, the price ratio between alternative sources of energy and electricity, as well as investment and installation expenses, are the biggest hurdles in the European heat pump industry [98,99]. Overcoming constraints such as cost and access to financial, as well as low consumer understanding and trust in HTHT integration, are feasible paths to achieving high uptake of heat pumps [100]. The public's impression of heat pumps associated with current market mechanisms might potentially be a barrier. According to research conducted in the UK, the major obstacles to the widespread use of HPs are a large market share for gas boilers and low-cost natural gas [101]. Heat pumps may be installed in well-insulated buildings with minimal energy demands since they perform best at low temperature [92]. Among the structural and economic obstacles to the widespread use of heat pumps are their high upfront costs as well as the requirement for extensive renovation of old and thermally inefficient properties [102].

2.4. Technological barrier

The power network's limitations, which is not widely recognized, is a significant barrier to growing application of high temperature heat pumps. HTHPs may enhance peak-period power demand, requiring more investment in electrical grid infrastructure to meet the demand [103]. The intensive electrification of the heating industry will have the greatest impact on electrical distribution systems, which have historically been designed to manage lower electrical demands. Increasing peak winter load might have serious economic and environmental consequences [103]. Heat pump adoption, for example, has the potential to raise peak power consumption by up to 14% in the United Kingdom [104]. Such an upsurge in peak demand may require network strengthening, which would have an unfavorable impact on the economic sustainability of HP integration. A larger heat pump penetration might result in overloading and problems with voltage stability[105]. Further study is required to understand the link between heat pump

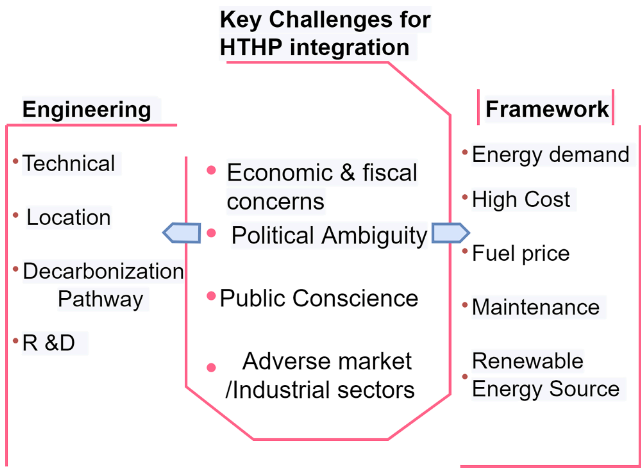


Fig. 25. Key challenges for implementation to HTHP deployment.

penetration of renewable energy sources and peak electricity demand, and it may be necessary to look at new strategies for lowering the ratio of peak to average demand.

2.5. Research and development opportunity

The development of new High temperature heat pump technology has the capacity to significantly reduce exergy destruction through additional cycle improvements and heat exchange procedures that better match heat source and sink characteristics. To understand the full potential of this technology, the research community must overcome various challenges related to HTTHP technology, most of them revolve on the **compressor** before integration to any process.

- Compressor discharge temperature restrict the ability to achieve larger sink temperatures because they may induce issues such as the degradation of used lubrication oils and material issues in the compressor.
- When oil is often used to lubricate or cold down the compressor, additional components are necessary for segregation and cooling, enhancing the complexity and costs. In furthermore, the oil tends to penetrate its complete circuit, which require a recirculation system and might have a detrimental influence on the heat pump performance.
- Compression the refrigerant to excessive pressures (e.g., >15 MPa for CO2) makes use of existing compressor technology challenging. Possible solutions include selecting or developing cycle designs that consciously limit high-pressure requirements by superheating vapor before compression or using refrigerants with relatively low critical pressures.
- For tighter mean temperature differences, substantial heat transfer surfaces are essential. Investigate the trade-off between cycle temperature lift and process flow rate, which influences heat transfer coefficient, pressure drop, and required pumping power as well as the desired pressure ratio and compressor power.
- Oil-free compressors or solutions that lubricate themselves are often linked with increased equipment costs owing to required modifications or are unsuitable for commercial usage.

3. Conclusions

Process integration is a holistic approach for increasing the efficiency of energy systems. In this study, the state-of-the-art regarding large-scale heat pumps has been systematically summarized, with an emphasis on prospective industrial applications, economics, and integration. Current information has been synthesized into new, user-friendly tools for integration, assessment, and decision-support to remove major obstacles preventing larger market penetration at the moment. Depending on the Grand Composite Curve form and where the pinch temperature is, the sophisticated integration approach enables the selection of several integration levels (process or utility level) and compatible HP technologies. The integration of HTHPs with other cycles—including thermal energy storage, waste heat recovery, proton exchange membrane fuel cells, organic Rankine cycles, super-critical water desalination, co-generation, and poly-generation—as well as desiccant wheels, vapor injection, steam injected gas turbines, and solar absorption systems—is the main topic of this paper. This review emphasizes the single-stage and multi-stage HTHPs, vapor compression, absorption, hybrid systems, and various novel combinations. This paper also emphasizes identifying problems such compressor discharge temperature, compressor lubrication, oil-free operation system, new developments for HTHPs, and workable remedies. Based on the literature evaluation, several future research directions are explored. The refrigerant charge management technique and flash tank cycle control approach require more research.

Some of the challenges are as follows.

- Low level of understanding among customers, consultants, investors, plant designers, manufacturers, and installers about the technical potentials and the economically viable application potentials of HTHPs.
- Lack of understanding of HTHP integration in industrial processes. Arrangements require costly integration into existing system.
- Alternative heating technologies utilizing fossil fuels to generate high temperatures at low energy costs (depends on the respective electricity to gas price ratio).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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