

Steam Compressors or Closed-Cycle High Temperature Heat Pump (HTHP)? – Efficiency and Market-Ready Solutions in Comparison

*Cordin Arpagaus, Frédéric Bless, Leon P.M. Brendel, Sidharth Paranjape,
Daniel Gstöhl, Stefan S. Bertsch*

OST – Eastern Switzerland University of Applied Sciences, Institute for Energy Systems,
Werdenbergstrasse 4, CH-9471 Buchs, Switzerland,
cordin.arpagaus@ost.ch

Keywords:

Industrial steam generation, steam compressor, high-temperature heat pump (HTHP), steam generating heat pump (SGHP), efficiency analysis, market readiness

Extended Abstract

Decarbonizing industrial steam generation is crucial to achieving climate goals and reducing reliance on volatile fossil-fuel markets. In industrial settings, there's a growing debate over whether process steam can be provided more efficiently by steam compression with small turbo compressors or closed-cycle high-temperature heat pumps (HTHPs).

This study compares the technical conditions of both approaches and analyzes available steam compressors and HTHP products, including their typical performance ranges, efficiency metrics, and current market offerings. Hybrid configurations that combine closed-cycle HTHPs with steam compressors, utilizing ammonia, hydrocarbons, HFOs, and water as refrigerants, are evaluated. Insights from the Steam-Generating Heat Pumps (SGHP) Webinars organized by OST in 2023, 2024, and 2025 are incorporated, capturing both recent theoretical developments and early implementation experience.

The results show that steam compression systems (e.g., MVR mechanical vapor recompression) are an efficient solution, especially in existing steam networks with high pressure levels up to about 11 bar(a), while HTHPs offer advantages primarily in hot-water and low-pressure steam networks with waste-heat utilization. The efficiency analysis reveals differences in COP values. MVR typically achieves COP values of 3 to 11 and HTHP COP values of 2 to 6, depending on the temperature lift. An OST survey (2025) identified the food and beverage sector as a key application area, with typical steam requirements of 100 °C to 200 °C and a large market potential for HTHP with heating capacities of 1 to 3 MW.

The number of market-ready HTHP products has nearly doubled between 2018 and 2024, and several manufacturers (including SPH, Enerin, Olvondo, Heaten, or Mayekawa) have field-proven systems. Combined HTHP+MVR concepts are considered particularly promising but are still in the demonstration phase. Economic incentives, standardization, and pilot projects with a willingness to invest are crucial for broad market introduction to drive the decarbonization of industrial steam networks.

Overall, the study provides practical decision-making aids for selecting suitable steam-generating heat pump technologies and identifies which systems are already market-ready and in which areas further development is still needed.

Introduction

Steam is the most important heat carrier in industry and is predominantly generated by fossil-fired boilers. The temperature ranges of 100–150 °C and 150–200 °C are particularly relevant for steam-based applications. In Europe, the annual process heat demand in these ranges amounts to approximately 192 TWh and 80 TWh, corresponding to 10.6 % and 4.4 % of total industrial heat consumption in the EU-28 (1,821 TWh; Eurostat 2015) [1], [2]. Germany has the highest consumption, followed by France, the United Kingdom, Italy, and Spain.

Electrically driven heat pump technologies offer a promising alternative. A survey conducted ahead of the OST webinar *Steam Generating Heat Pumps (SGHP) 2025* (21 October 2025; 218 respondents, 30 % response rate) [3], [4], identified the food and beverage sector as having the greatest potential for SGHPs (29 %), followed by chemicals (21 %), pharmaceuticals and pulp and paper (each 17 %), textiles (8 %), and other sectors (8 %) (Figure 1, A). The most frequently requested process temperatures were 100–160 °C for low-pressure steam (43 %) and 100–200 °C for medium-pressure steam (26 %) (Figure 1, B). This aligns with practical experience from the food industry, where approximately 73% of heat demand is below 150 °C [5]. The greatest application potential is for heat pumps with a heating capacity of 1–3 MW (Figure 1, C). The main alternatives considered are electric boilers and biomass.

Key challenges include system integration (35 %), high energy costs (26 %), limited availability of reliable suppliers and components (20 %), and regulatory and financial uncertainties (11 %) (Figure 1, D). These results align with a European market study [6], showing that most of the 4,174 identified heat pumps have heating capacities below 10 MW, with a median of 3.0 MW.

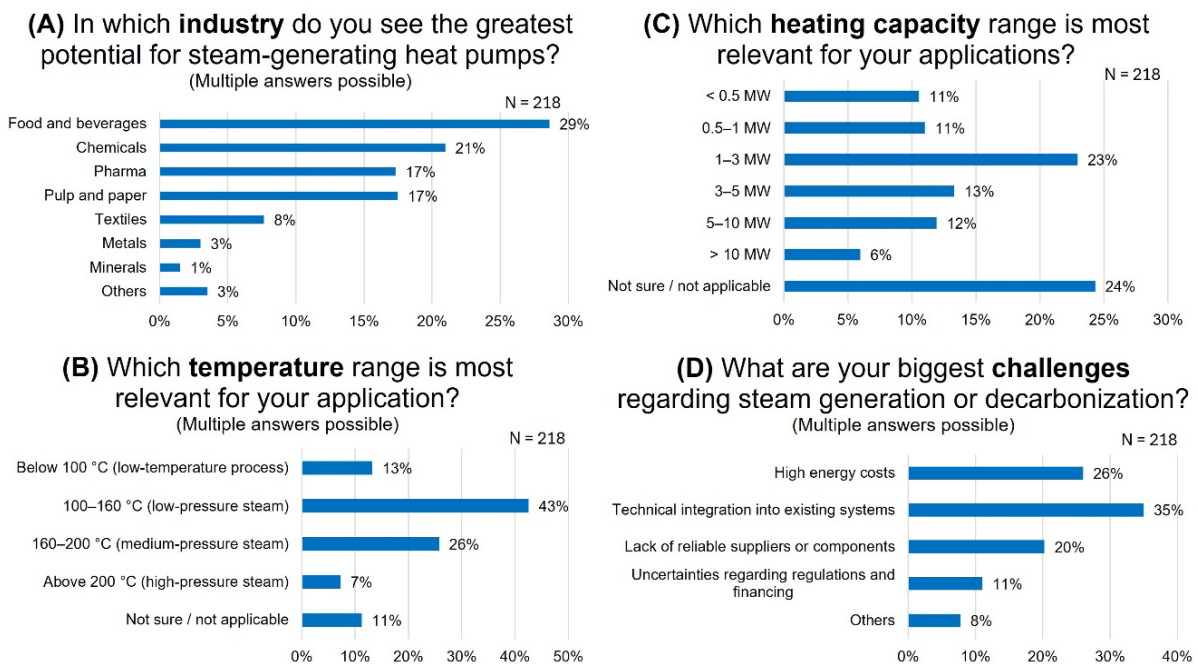


Figure 1: Survey results collected ahead of the OST webinar *Steam-Generating Heat Pumps (SGHP) 2025* on 21 October 2025, based on 218 respondents (30% response rate, multiple-choice format) [4].

Objective of the study

This study evaluates steam compressors and closed-cycle HTHPs, focusing on efficiency, practical deployment, and market-ready technologies in the 100 kW–10 MW range. It also reviews alternative SGHP concepts, including Stirling heat pumps and hybrid systems that combine closed-cycle HTHPs with direct steam generation, identifies remaining development gaps, and offers guidance on technology selection.

Methods and Concepts for SGHPs

After reviewing commercially available solutions and conducting a literature search focusing on steam compression and heat pump designs, various key concepts for steam generation are [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18] Figure 2 summarizes the most important concepts for steam generation, including HTHP cycles, evaporators, condensers, flash tanks, and mechanical vapor compression (MVR).

- (A) Open-loop MVR systems (suited when low-pressure steam is available)
- (B) Steam compression combined with evaporators (vacuum operation for waste heat < 100 °C)
- (C) Direct steam-generating closed-cycle HTHPs with different designs, refrigerants (e.g., hydrocarbons, hydrofluoroolefins, ammonia), compressor types, and staging, combined with direct heat exchangers
- (D) Direct steam-generating HTHPs with downstream MVR
- (E) HTHPs for hot water combined with flash tanks and MVR

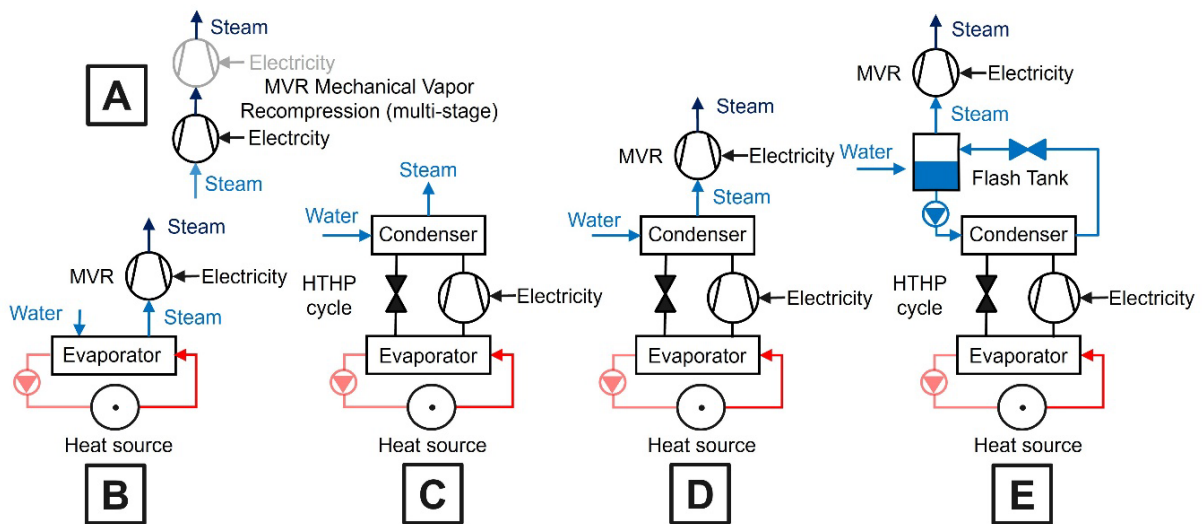


Figure 2: Concepts for steam-generating heat pumps (SGHP) [7].

There is a wide range of HTHP cycle designs, characterized by different cycle components (e.g., with a subcooler for heating water for steam generation in the condenser, cascade with intermediate heat exchanger, economizer, flash tank, parallel compression, ejector, etc.), refrigerants, compressor types, and number of compressor stages [19]. The optimal concept depends on the application, the required steam pressure/temperature, and the available waste heat.

MVR systems use electrically driven compressors to recompress low-pressure steam to higher pressure and temperature levels, enabling its reuse as process steam (Figure 2, Concepts A and B). Depending on the application, number of stages, and suction pressure, MVR systems cover power ranges from approximately 100 kW to more than 10 MW [7]. Of crucial relevance is the combination of steam compression and evaporator (Figure 2, Concept B), which requires operation under vacuum when the (waste or excess) heat sources are below 100 °C, which is often the case in industry.

Other concepts use TVR systems (thermal vapor compressors) with steam ejectors, auto-cascades with refrigerant mixtures, and the integration of pressurized hot water circuits to decouple the refrigerant from the steam [11], [15]. For steam-generating AHT systems (absorption heat transformers), the reader is referred to further literature [20].

Results and Discussion of Steam Compressor and Closed-Cycle HTHP Technologies

Depending on the applied steam compressor technology (e.g., integrally geared compressors, MVR blowers, rotary lobe compressors, direct-driven turbo compressors, reciprocating, screw, sliding vane, or spindle compressors), system performance, achievable temperature lift per stage, and maximum steam temperatures vary significantly [7], [8], [9], [11], [14], [21], [22], [23], [24], [25]. Table 1 provides an overview of commercially available steam compressors for SGHPs.

Table 1: Overview of steam compressor technologies for steam-generating heat pumps (SGHP) (*with water injection) [7].

Type	Suppliers (examples in alphabetical order)	Heating Capacity (MW)	Minimum suction pressure (bara)	Temperature lift per stage (°C)	Steam temperature (°C)
Integrated gear compressors	Everllence, Howden, MHI, Siemens, Turboden	10 to 80	0.2 to 0.5	20 to 25	Up to 250*
MVR blowers and turbo fans	Atlas Copco, Continental Industrie, EPCON, Howden, Hoffman & Lamson, Piller, Shandong Zhangqiu, Shangu, Skyven	0.5 to 50	0.2 to 0.5	10 to 20	105 to 230
Direct-drive turbo compressors	Rotrex, Weel & Sandvig, CS Techcom, SPXFLOW, Johnson Controls	0.1 to 5	0.2 to 0.5	30 to 40	100 to 200* (superheated)
Sliding vane compressors	AERZEN, Kaeser, Kay, Kubicek, Shangu, Robushi	0.1 to 15	0.3 to 0.5	10 to 20	105 to 115
Piston compressors	Spilling	1 to 10	1.4 to 20	30 to 40	Up to 280*
Screw compressors (oil-free)	Atlas Copco, Howden	0.3 to 2	0.45 to 1.5	50 to 70	130 to 165*
Twin screw compressors	Kobelco	0.6	1.5 to 2	40	165 to 175*
Rotary lobe compressors	ToCircle	1 to 5	1	50 to 90	160 to 188*
Spindle compressors	Hamburg Vacuum	0.2 to 0.6	1	80 to 120	160 to 230 *

Integrated gear compressors offer high efficiency and a compact design. A central motor drives multiple compression stages via planetary or bevel gearing, allowing each stage to operate at an individually optimized speed. Variable inlet guide vanes and a configurable number of stages enable flexible operation and fast load changes. Key suppliers include Everllence (formerly MAN Energy Solutions), Turboden, Mitsubishi Heavy Industries (MHI), Siemens and Howden [7], [21], [26], [27], [28].

MVR blowers are high-speed centrifugal machines designed for large volumetric flow rates and small pressure or temperature lifts. They are primarily used in evaporators (e.g., dairy, wastewater, chemical, and pharmaceutical industries), drying processes, and industrial waste heat recovery systems. Typical suppliers include Atlas Copco, Continental Industrie, EPCON, Howden, Hoffman & Lamson, Piller, Shandong Zhangqiu, Shangu, and Skyven [7], [8], [9], [21], [22], [23].

Direct-drive turbo compressors are well-suited for small- to medium-scale steam applications. They feature compact axial or multistage radial designs, oil-free operation, and high rotational speeds (35,000–70,000 rpm) [5]. High efficiency is achieved at small to moderate temperature lifts (up to 20 K per stage) and suction pressures of 200–500 mbar. Key suppliers include Rotrex [29], Wheel & Sandvig [30], CS Techcom, SPX Flow, and Johnson Controls. For example, Wheel & Sandvig's WSE TURBO compressors achieve pressure ratios of 2.0–2.8 per stage, enabling up to 30 K per stage or 83 K across three stages [7], [21].

Figure 3 shows the COP of different steam compressor types as a function of the temperature lift between suction and discharge, based on literature data and reference cases [21], [30], [31], [32], [33], [34]. The data can be described by the fit $COP = 106.03 \cdot \Delta T_{Lift}^{-0.766}$. The compressors achieve Carnot efficiencies of 53–70% (average 64% at a fixed steam temperature of 165 °C and 20 K to 120 K temperature lifts). The COP decreases from ~6.3 to 3.1 when the temperature lift increases from 40 K

to 100 K. Isentropic efficiencies of various steam compressor types (i.e., screw, centrifugal, and turbo) typically range from 0.75 to 0.85, depending on design [11], [25].

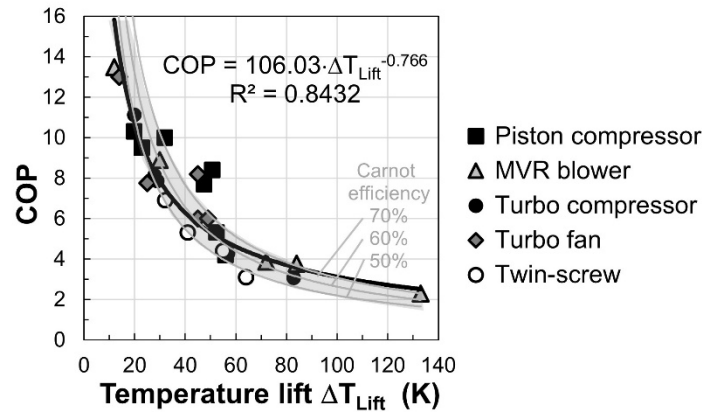


Figure 3: COP of various steam compressor types as a function of the temperature lift between suction and discharge for piston compressors, MVR blowers, turbo compressors, turbo fans, and twin screws [21], [30], [31], [32], [33], [34].

Figure 4 presents direct SGHPs with closed cycles (Figure 2, Concept C) from SPH, Enerin, Olvondo, Heaten, and Mayekawa [9], [35], [36], [37], [38]. The SGHPs differ in design, refrigerants (e.g., HFOs, hydrocarbons, helium), compressor types (piston, screw), and compression staging (e.g., cascades). All feature a direct steam heat exchanger, such as those supplied by Vahterus or GESMEX.

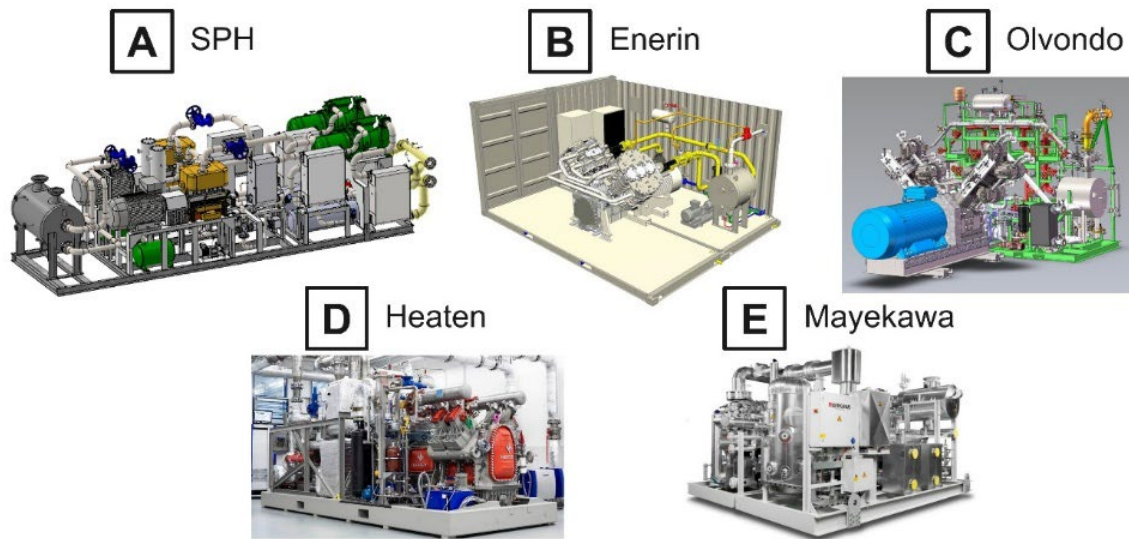


Figure 4: Steam-generating heat pumps (SGHP) from (A) SPH, (B) Enerin, (C) Olvondo, (D) Heaten, and (E) Mayekawa with plate and shell heat exchangers [9], [35], [36], [37], [38]. Images courtesy of the manufacturers.

SPH's ThermBooster systems (recently acquired by Copeland) with integrated steam generators (Figure 4, A) currently achieve 115 to ~160 °C (up to 6 bar), covering a large share of industrial applications. The systems offer high configurability, including heat exchanger design, tailored source and sink media, and large temperature lifts. Project examples in the Netherlands, Germany, Italy, Austria, Spain, and Switzerland demonstrate successful industrial steam heat pump deployments [39]. Reported steam applications show an average COP of 3.1 ± 1.1 , a mean heating capacity of $1,105 \pm 685$ kW, and an average sink temperature of 129 ± 16 °C [7].

Enerin and Olvondo offer the Stirling-cycle-based HTHPs HoegTemp [40] (Figure 4, B) and HighLift [35] (Figure 4, C), using helium (R704) and double-acting piston compressors. These systems enable large temperature lifts, flexible operation, and supply temperatures above 200 °C. Enerin delivers 0.3–10 MW of heating capacity at up to 250 °C [40] and achieves higher COPs than comparable technologies

above ~ 160 °C and temperature lifts >80 K. For steam generation, its 6-cylinder unit supplies pressurized hot water to a plate steam generator. Energin reports 30,000 prototype operating hours, series production since 2023, and a 12-cylinder (800 kW) version planned for 2025. Olvondo systems deliver steam at 100–183 °C from heat sources between -5 and 120 °C, with COPs of 1.4–2.5 [35]. Typical values are ~ 1.7 at 36/183 °C (147 K lift) and ~ 2.6 at 90/144 °C (54 K lift).

Heaten AS offers the HeatBooster with piston compressors [37] (Figure 4, D). The product portfolio includes the HBL4 (4 cylinders, 0.8–2.5 MW) and HBL16 (16 cylinders, 3.2–10 MW). The systems deliver 90–200 °C using water or steam. Single-stage configurations enable temperature lifts of up to 80 K, while two-stage systems achieve up to 140 K, with higher capacities achieved via cascading or parallel operation. Refrigerants include HFOs (e.g., R1234ze, R1233zd, R515b) and hydrocarbons (e.g., R600a). Reference applications for steam generation, including the HBL-4-S/S (steam/steam), can be found in sugar processing, paper manufacturing, and district heating, supported by partnerships with ADVENT and INNIO. For water–water applications, COPs of 3.6 (70/125 °C, 55 K lift, R1233zd) and 3.2 (25/95 °C, 70 K lift, R515b) are reported [37]. Compressor scaling is currently underway.

Mayekawa manufactures around 6,000 compressors per year [38], with MYCOM models widely used in the EU. The SGHPs M-HT (R600/R600a) and FC-HT (R601/R601a) systems employ ATEX-compliant components that deliver steam capacities of 0.5–3 MW and are scalable beyond 12 MW. M-HT systems deliver 110–125 °C from 35–70 °C sources, while FC-HT systems reach 155–160 °C (6 bar) from 55–90 °C sources (Figure 4, E). Typical food applications report COPs of 2.4 at 38/159 °C (water/steam) and 5.7 at 90/112 °C (1.5 bar), with ~ 2 MW heating capacity or 3 t/h of steam for seafood processing [38]. In the EU SPIRIT project, a two-stage ammonia/pentane cycle (R717/R601) produces 0.7 MW of steam (~ 1.2 t/h) at 145 °C and 4.1 bar(a), enabling simultaneous heating and cooling with an overall COP of 2.5. Commissioning is planned for Q1/2026.

An alternative technology is air-to-steam heat pumps [9], [41], [42], [43], [44], [45]. For example, since 2020, the Hongjitang Brewery in China's Shandong province has been operating three units with a total capacity of 180 kW (3×60 kW) [43], [45]. The air-to-steam heat pumps use an R410A/R245fa cascade cycle with a 3 m³ flash tank at 90 °C, producing about 0.2 t/h of steam at 120 °C and 1.2 bar [44]. Stable operation is reported at ambient temperatures of 5–35 °C, with COPs ranging from 1.5 to 2.1 [44]. At 18.9 °C, a COP of 1.85 is achieved [45].

In September 2025, US-based AtmosZero commissioned the first commercial Boiler 2.0 at New Belgium Brewing in Fort Collins, Colorado. The 650-kW system delivers 1 t/h of saturated steam at 150 °C and 4.7 bar(a), using a two-stage cascade cycle with an intermediate heat exchanger. It operates with R513A and R1233zd(E) refrigerants and Danfoss Turbocor compressors, achieving isentropic efficiencies of 77–81 % and pressure ratios of 1.6–2.3 [41]. Ambient air (-10 to $+40$ °C) serves as the primary heat source. Under local climatic conditions in Fort Collins (-3.6 to 22.7 °C), the air-to-steam heat pump achieves an annual COP of 1.81 for 150 °C steam [42].

Combined HTHP+MVR cycles (Figure 2, D) and SGHP systems with flash tanks and downstream MVR (Figure 2, E) have been investigated and partially implemented by several manufacturers, thereby expanding the range of SGHP demonstration plants [9], [16], [46], [47].

Table 2 summarizes case studies from Kobelco [48], ANEO [49], Johnson Controls [50], Nestlé [5], and the EU Horizon projects AHEAD [39] and Push2Heat [20]. The overall performance of a combined-cycle system is largely determined by the refrigerant used in the closed-cycle HTHP, the compressor types, and the intermediate (transfer) temperature of water evaporation from the HTHP to the first MVR vapor compression (i.e., suction pressure).

In 2011, Kobelco introduced the SGH165 steam heat pump in Japan. It features an HTHP unit with R245fa, a flash tank, and a single-stage screw steam compressor. Using heat sources at 35–70 °C, it produces saturated steam at 135–175 °C, with a heating capacity of 624 kW (~ 0.9 t/h steam). Hot water at 115 °C is expanded in the flash tank and further compressed in an oil-free, water-injected screw

compressor. COP ranges from 1.9 (50/165 °C source/sink) to 3.0 (70/135 °C), with 2.5 at 70/165 °C. Drop-in alternatives R1224yd(Z) and R1336mzz(E) were tested [48]. Optimal flash tank temperatures are 98–114 °C. Hydrocarbons have not been tested due to poor oil compatibility, and ammonia is incompatible with the seals and materials used.

Table 2: Case studies with combined cycle of HTHP, flash tank (separator), and MVR (*in operation, ** planned for 2026).

Firma, Projekt	Refrigerant in HTHP	Heating capacity (kW) (t/h steam)	Heat source (°C)	Intermediate temp. (°C)	Steam temp. (°C)	COP (-)	Compressor type HTHP / MVR	Ref.
Kobelco*	R1224yd(Z), R1336mzz(E)	624 (0,84 t/h)	70/65	110	165	2,5	Screw / screw	[48], [51], [52]
ANEO*	R717	1,600 (2 t/h)	29/24	85	120	3,1	Screw+piston / turbo fans	[49]
Johnson Controls**	R717	1,075 (1,7 t/h)	39/34	120	139	2,4	Piston / screw	[50]
Nestlé**	R717	1,100 (1,8 t/h)	-	-	135	-	- / turbo	[5]
AHEAD*	R600	1,561 (2,5 t/h)	70/65	115	184	2,3	Piston / piston	[39]
Push2Heat**	R1233zd(E)	855 (1,31 t/h)	90/80	115	162	3,0	Screw / screw	[20], [53]

ANEO [21], [49] implemented a combined-cycle steam heat pump at Felleskjøpet Agri in Trondheim, recovering heat from the pet food pelletizing process and from moist exhaust air. The HTHP uses ammonia (R717) and a two-stage configuration with screw and reciprocating compressors from GEA. Steam is recompressed using four Piller VapoFans with water injection and a water/steam separator at 85 °C. The pilot system (1.6 MW heating capacity) supplies 2 t/h of steam at 120 °C and 1.5 bar(a), achieving a COP of 3.1 with a heat source at 29/24 °C.

Johnson Controls developed a combined ammonia heat pump (HeatPac 712) and MVR system [50]. The HTHP uses a 39/34 °C heat source and supplies hot water at 80/89 °C with 800 kW heating capacity and a COP of 4.0. Steam generated at 80 °C (0.455 bar) is compressed in a three-stage MVR system from 0.455 to 3.5 bar, producing saturated steam at 139 °C with a mass flow rate of 1.7 t/h. The combined HTHP+MVR system delivers 1.075 MW with an overall COP of 2.36 (~61 % Carnot efficiency). A broader commercialization requires additional customer projects [50].

A similar system is planned for the Nestlé France Petfood Retorting Decarbonisation project starting in 2026 [5]. It combines an 85 °C ammonia heat pump with three turbo MVR units to produce steam at 135 °C with a heating capacity of 1.1 MW. The project is close to financial approval. In addition, it is foreseen to use a Copeland VILTER unit (single-screw compressor, 80 bar system pressure) to increase the heat pump hot-water supply temperature to 110 °C, with Nestlé acting as the industrial partner [5].

The AHEAD (Advanced Heat Pump Demonstrator) project demonstrates a combined HTHP using butane (R600, 180 kg refrigerant charge) from SPH and a reciprocating steam compressor from Spilling at Takeda's pharmaceutical site in Vienna, Austria [54]. The HTHP uses 70/65 °C hot water and generates steam at 115 °C (1.67 bar) with a COP of 4.3, which is then recompressed to 184 °C and 11 bar(a). The piston steam compressors from Spilling operate at suction pressures above 1.4 bar(a) (110 °C) and achieve temperature increases of up to 100 K using a two-stage compression design within a single unit. The overall system delivers 1.56 MW and 2.5 t/h of steam, with a total COP of 2.3 [39]. The SGHP plant has been successfully commissioned but is not yet in continuous operation.

One of the Push2Heat demonstration projects is being implemented at Cartiere di Guarcino in Fuggi, Italy [20], [53]. The HTHP developed by Cannon Bono uses R1233zd(E) and 600 kW of waste heat from a biomass CHP cooling circuit (90–80 °C) to produce steam at 115 °C (1.7 bar(a), 740 kW, COP 5.3). The steam is then recompressed via MVR to 6.5 bar(a) and 162 °C (855 kW, 1.31 t/h) for injection into the medium-pressure steam network on site. The combined HTHP+MVR system achieves a total COP of ~3.0. Commissioning is planned for 2026 [53]. The screw compressor is supplied by Palladio Compressors, recently acquired by Danfoss.

Conclusions

Steam compressors and steam-generating heat pumps (SGHP) are key technologies for decarbonizing industrial steam networks. An OST survey conducted ahead of the Steam-Generating Heat Pumps Webinar 2025 highlighted strong potential in the food and beverage sector, where process steam between 100–200 °C is common, with the largest market for 1–3 MW heat pump systems.

The number of commercial high-temperature heat pump (HTHP) products nearly doubled between 2018 and 2024. Many manufacturers now offer ready-to-use closed-cycle HTHP systems and steam compressors, with successful industrial applications demonstrated by SPH, Enerin, Olvondo, Heaten, and Mayekawa.

Steam compressors are available in various types, including integral-gear, mechanical vapor recompression (MVR) blowers, rotary, screw, turbo, reciprocating, vane, and spindle compressors, differing in capacity, temperature lift, and achievable steam pressure/temperature. Combining one- or two-stage closed-cycle HTHPs with steam compressors significantly extends the performance range, enabling applications at higher temperatures and pressures.

Various system concepts are used for steam generation:

- open steam compressor (MVR) loops,
- steam compressors combined with an evaporator,
- direct steam-generating HTHPs (closed or combined with steam compression), and
- hybrid (combined) HTHP systems with hot-water, flash tank, and steam compressors.

The choice depends on the required steam pressure and temperature. Steam compressors are suitable for pressures up to ~11–12 bar(a) (183–188 °C saturated steam), while closed-cycle HTHPs efficiently utilize waste heat (or air sources) to supply hot-water or low-pressure steam networks. Efficiency analyses show clear differences in COP values between these approaches.

Steam compressors typically achieve COPs of 3–11 (53–70 % Carnot efficiency, average 64 % at 165 °C steam pressure), while closed-cycle HTHPs reach COPs of 2–6 (35–50 % Carnot efficiency, average 43 % at 120 °C) [55]. Open MVR systems are generally more efficient, whereas closed-cycle HTHPs enable higher temperature lifts. Temperature lifts of up to ~100 K appear technically feasible. Air-to-steam heat pumps can achieve annual COPs of around 2 under local climatic conditions.

Combined HTHP+MVR cycles offer additional potential but are still in the demonstration phase, as shown by projects from Kobelco, ANEO, Johnson Controls, Nestlé, and EU Horizon projects AHEAD and Push2Heat. Key to system efficiency is the intermediate temperature between the HTHP and the first MVR stage, which depends on the refrigerant, compressor efficiency, and steam pressure.

Future developments target compact, high-efficiency turbo compressors and optimized HTHP+MVR concepts. Broader commercialization requires favorable economics (electricity cost, investment), standardized interfaces, and robust safety and integration designs to accelerate planning and implementation, alongside pilot and customer projects willing to adopt innovative solutions.

Acknowledgments

The authors gratefully acknowledge the Swiss Federal Office of Energy (SFOE) for the financial support of the SWEET project DeCarbCH (DeCarbonisation of Cooling and Heating in Switzerland) (Contract number SI/502260, www.sweet-decarb.ch) and the EU-funded Horizon 2020 projects Push2Heat (Grant agreement No. 101069689, www.push2heat.eu) and ZIMBA (GA 101146932, www.zimba-project.eu).

References

- [1] G. Kosmadakis, "Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries," *Appl. Therm. Eng.*, vol. 156, no. December 2018, pp. 287–298, Jun. 2019, doi: 10.1016/j.applthermaleng.2019.04.082.
- [2] G. Kosmadakis, "Industrial waste heat potential and heat exploitation solutions," *Appl. Therm. Eng.*, vol. 246, no. March, p. 122957, Jun. 2024, doi: 10.1016/j.applthermaleng.2024.122957.
- [3] OST IES, "Steam-Generating Heat Pumps - OST Webinar 2025, 21 October 2025, 13:30 – 17:00 (GMT+2)." [Online]. Available: <https://www.sweet-decarb.ch/events/event/steam-generating-heat-pumps-ost-webinar-2025>
- [4] C. Arpagaus, "Webinar wrap-up, Steam generating heat pumps, OST Webinar, 21 October 2025." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/OST_Webinar_SGHP_2025_Wrap-up_Cordin_Arpagaus.pdf
- [5] G. Sutter, "High Temperature Heatpumps in Food Industry, Nestlé, OST Webinar Steam Generating Heat Pumps, 21 October 2025," pp. 1–29, 2025, [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Nestle_HT_Heatpumps_in_Food_Industry_-_Guido_Sutter.pdf
- [6] A. Marina, S. Spoelstra, H. A. Zondag, and A. K. Wemmers, "An estimation of the European industrial heat pump market potential," *Renew. Sustain. Energy Rev.*, vol. 139, p. 110545, Apr. 2021, doi: 10.1016/j.rser.2020.110545.
- [7] C. Arpagaus, F. Bless, L. P. M. Brendel, D. Gstöhl, and S. S. Bertsch, "Dampfverdichtung oder Hochtemperatur-Wärmepumpe (HTWP)? Effizienz im Vergleich," DKV-Tagung 2025, Magdeburg, 20. November 2025. [Online]. Available: https://www.researchgate.net/publication/398107249_Dampfverdichtung_oder_Hochtemperatur-Warmepumpe_HTWP_Effizienz_im_Vergleich
- [8] IEA HPT, "Annex 58 High-Temperature heat Pumps, Task 1 - Technologies, Final Report, August 2023, Report no. HPT-AN58-2." [Online]. Available: <https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2023/09/annex-58-task-1-technologies-task-report.pdf>
- [9] C. Arpagaus, F. Bless, L. P. M. Brendel, M. Uhlmann, and B. Stefan, "High-Temperature Heat Pumps. Market Overview, State of the Art, and Application Potentials," in *China Heat Pump Conference (CHPC2024), ShenZhen, China, August 27-30, 2024*, 2024, pp. 1–58.
- [10] IEA HPT, "Annex 58 High-Temperature heat Pumps, Task 2 - Integration Concepts, Task Report, April 2024, Report no. HPT-AN58-3." [Online]. Available: <https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2024/04/annex-58-task-2-integration-concepts-report.pdf>
- [11] S. Klute, M. Budt, M. van Beek, and C. Doetsch, "Steam generating heat pumps – Overview, classification, economics, and basic modeling principles," *Energy Convers. Manag.*, vol. 299, no. November 2023, p. 117882, Jan. 2024, doi: 10.1016/j.enconman.2023.117882.
- [12] C. Arpagaus, "Perspectives on the Technical (T) and Economic (E) Factors of Industrial Heat Pumps through the PESTEL lens, The Road to Sustainable Industrial Heat: A Roundtable on the Future of Industrial Heat Pumps, 22 May 2025, Online Teams Webinar." [Online]. Available: https://www.youtube.com/watch?v=9C_JWsyx7Qk&t=1795s
- [13] C. Arpagaus, "High-Temperature Heat Pumps: Market Overview, State of the Art, and Application Potential," in *International Congress on Sustainability Science & Engineering (ICOSSE '25), 20 February 2025, University of Auckland, Auckland, New Zealand, 2025*. [Online]. Available: <https://icosse.org/2025/technical-program>
- [14] F. Bless, C. Arpagaus, and S. Bertsch, "IntSGHP - Integration of steam-generating heat pumps in industrial sites (retrofit), Final Report, June 2024." [Online]. Available: <https://www.aramis.admin.ch/Default?DocumentID=72022>
- [15] G. D'Alessandro, M. Iezzi, and F. de Monte, "Steam Generating High Temperature Heat Pumps: Best Practices, Optimization Strategies and Refrigerant Selection for Performance Improvement," *Energies*, vol. 18, no. 22, p. 5879, Nov. 2025, doi: 10.3390/en18225879.
- [16] W. Jouni, Y. Beucher, and A. Zoughaib, "Thermodynamic architecture for steam generation using heat pumps system valorizing industrial waste heat," *Int. J. Refrig.*, vol. 172, no. November 2024, pp. 295–308, Apr. 2025, doi: 10.1016/j.ijrefrig.2024.12.010.
- [17] F. Bless, C. Arpagaus, I. Gummin, A. Keller, and S. Bertsch, "A detailed concept for a 2.3 MW steam-generating heat pump in a Swiss nutrition company," in *DKV-Tagung 2023, Hannover, 10 November 2023*, 2023, pp. 1–9.
- [18] F. Bless, C. Arpagaus, and S. Bertsch, "Theoretical investigation of high-temperature heat pump cycles for steam generation," 13th IEA Heat Pump Conference, May 11-14, 2020, Jeju, Korea, postponed to 26-29 April 2021. [Online]. Available: <https://heatpumpingtechnologies.org/publications/paper-no-062-theoretical-investigation-of-high-temperature-heat-pump-cyclesfor-steam-generation-13th-iea-heat-pump-conference-jeju-korea/>
- [19] C. Mateu-Royo, C. Arpagaus, A. Mota-Babiloni, J. Navarro-Esbrí, and S. S. Bertsch, "Advanced high temperature heat pump configurations using low GWP refrigerants for industrial waste heat recovery: A comprehensive study," *Energy Convers. Manag.*, vol. 229, no. December 2020, p. 113752, Feb. 2021, doi: 10.1016/j.enconman.2020.113752.
- [20] J. L. Corrales Ciganda, "Tecnalia: R&D activities on Steam-Generating Heat Pumps, OST Webinar on Steam Generating Heat Pumps, 21 October 2025." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Tecnalia_20251021_WebinarSGHM.pdf
- [21] C. Arpagaus, "Verdichtertechnologien für Großwärmepumpen, 2. VDI-Fachkonferenz Einsatz von Großwärmepumpen in der Industrie, 17. September 2025, Berlin," 2025.
- [22] H. Madsbøll, "Steam compressor technology and development: A general overview, OST Webinar on Steam Generating Heat Pumps, 18 March 2024." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Hans_Madsboell_DTI_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf
- [23] F. Bless, C. Arpagaus, M. Speich, and S. Bertsch, "Electrification of Heat Generation in Industry: State of Technologies, Integration Examples, and Integration Barriers," in *Young Energy Researchers Conference 2022 Electrification, 5. April 2022, Wels, Austria, 2022*, pp. 1–14.
- [24] T. W. Moesch, M. Enge, K. Klotsche, and C. Thomas, "Analyse des Wärmepumpeneinsatzes am Beispiel der industriellen Papiertrocknung," *KI Kälte Luft Klimatechnik, 08-09/2025*, www.ki-portal.de, pp. 35–41, 2025.
- [25] X. Ma, Y. Du, T. Zhao, T. Zhu, B. Lei, and Y. Wu, "A comprehensive review of compression high-temperature heat pump steam system: Status and trend," *Int. J. Refrig.*, vol. 164, no. 100, pp. 218–242, Aug. 2024, doi: 10.1016/j.ijrefrig.2024.04.024.
- [26] D. Rizzi, "Turboden S.p.A, Boosting Efficiency with Steam Generating Heat Pump and MVR, OST Webinar Steam Generating Heat Pumps, 21 October 2025." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Turboden_for_OST_Webinar.pdf
- [27] W. Van Den Mosselaer, C. Hüttl, N. Wenn, J. Voss, and F. Reissner, "Siemens Energy AG: Making the most of waste heat with high-temperature industrial heat pumps." [Online]. Available: https://flux50.com/media/8577/20231115_6_Siemens_Energy.pdf

- [28] O. Sipilinen, "Howden Turbo Fans, MVR Process in general and Howden vapor compressor portfolio, A2EP Webiar (Australian Alliance for Energy Productivity) on High temperature heat pump solutions, 10 November 2021." [Online]. Available: <https://www.a2ep.org.au/post/event-high-temperature-heating-solutions-wednesday-10-november>
- [29] S. Schmidt, "Rotrex Subchargers, DryF Webinar on High temperature heat pumps in energy intensive industries: core components, 7 April 2021." [Online]. Available: <https://www.youtube.com/watch?v=v6RbDJhCB0U>
- [30] M. Weel, "Weel & Sandvig: High temperature heat pump test result and further development of high speed centrifugal compressors for steam generation, OST Webinar Steam Generating Heat Pumps, 18 March 2024." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Mogens_Weel_Weel_Sandvig_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf
- [31] EPCON Evaporation Technology AS, "EPCON Evaporation Technology AS, Integration of MVR-HP systems in industrial thermal processes, OST Webinar Steam Generating Heat Pumps, 1 March 2023." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/OST-Webinar_on_Steam_Generating_Heat_Pumps_1st_March_2023_-_EPCON.pdf
- [32] C. Fleischmann, "Spilling: Piston Steam Compressors to reach Process Heat up to 250 °C / 40 bar, OST Webinar on Steam Generating Heat Pumps, 1 March 2023." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/OST-Webinar_on_Steam_Generating_Heat_Pumps_1st_March_2023_-_Spilling.pdf
- [33] G. Schumm, "SGHP with Piller Blowers & Compressors, Verdichtertechnologien für Großwärmepumpen, 2. VDI-Fachkonferenz Einsatz von Großwärmepumpen in der Industrie, 17. September 2025, Berlin," 2025.
- [34] KOBELCO, "Micro Steam Recovery Compressor/MSRC160L." [Online]. Available: <https://heatpumpingtechnologies.org/content/uploads/sites/70/2022/07/technologykobelcomsrc160l-1.pdf>
- [35] T.-M. Tveit, "The reverse Stirling cycle applied to SGHPs, OST Webinar on Steam Generating Heat Pumps, 21 October 2025." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Olvondo_The_reverse_Stirling_cycle_applied_to_SGHPs_2025-09-05.pdf
- [36] A. Hoeg, "Enerin: Decarbonizing industry with stirling-cycle steam generating heat pumps, OST Webinar on Steam Generating Heat Pumps, 18 March 2024." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Arne_Hoeg_Enerin_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf
- [37] A. Bechem, "HEATEN & HeatBooster Technology, OST Webinar Steam Generating Heat Pumps, 21 October 2025."
- [38] A. Bahri and P. Kaden, "MAYEKAWA: Steam compressors and steam-generating heat pumps, OST Webinar on Steam Generating Heat Pumps, 21 October 2025." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Mayekawa_HochschuleOst_Steam_Heat_Pump_-_Produktpraesentation.pdf
- [39] C. Rau, "SPH ThermBooster: Dampf-Wärmepumpe im industriellen Einsatz, VDI Spezialtag Dampf-Wärmepumpen, 15.9.2025, Berlin," 2025.
- [40] A. Høeg, "Decarbonizing industry with Stirling-cycle steam generating heat pumps," Steam generating heat pumps, OST Webinar, 18 March 2024. [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Arne_Hoeg_Enerin_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf
- [41] K. P. Ryan *et al.*, "Transient modeling of an ambient-temperature-source centrifugal-compressor steam-generating heat pump," *Appl. Therm. Eng.*, vol. 274, no. PC, p. 126812, Sep. 2025, doi: 10.1016/j.applthermaleng.2025.126812.
- [42] A. Salvi *et al.*, "Technoeconomic analysis of electrified boiler technologies to decarbonize industrial steam," in *High-Temperature Heat Pump Symposium, 23-24 January 2024, Copenhagen, Denmark*, 2024, pp. 1–13.
- [43] R. Wang, "Research of water used as refrigerant in heat pump, OST Webinar on Steam Generating Heat Pumps, 21 October." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Ruzhu_WANG-Steam_generating_heat_pump.pdf
- [44] H. Yan, B. Hu, and R. Wang, "Air-Source Heat Pump for Distributed Steam Generation: A New and Sustainable Solution to Replace Coal-Fired Boilers in China," *Adv. Sustain. Syst.*, vol. 4, no. 11, Nov. 2020, doi: 10.1002/adsu.202000118.
- [45] IEA, "The Future of Heat Pumps in China," IEA Publications. [Online]. Available: <https://www.iea.org/reports/the-future-of-heat-pumps-in-china>
- [46] S. Li, Y. Song, T. Chang, Q. Yu, Y. Zhang, and F. Cao, "Revolutionizing 300 °C industrial steam with a novel transcritical carbon dioxide heat pump system: Thermodynamic and configuration analyses," *Energy Convers. Manag.*, vol. 346, no. June, p. 120556, Dec. 2025, doi: 10.1016/j.enconman.2025.120556.
- [47] C. Gauchot, "Steam generating heat pumps - market overview and BAMBOO HP DEMO results," Online Webinar: High-temperature heat pumps and steam generation, 23 November 2022. [Online]. Available: <https://www.youtube.com/watch?v=7pN4gV6ZK4&t=2387s>
- [48] M. Andersen, "Testing and modelling a Steam-generating heat pump at up to 175 °C, Steam-Generating Heat Pumps - OST Webinar 2024, 18 March 2024." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Martin_Pihl_Andersen_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf
- [49] Aneo Industry, C. Schlemminger, and M. Bantle, "Integration of a 1.6 MW steam supplying heat pump into the feed production process, OST Webinar Steam Generating Heat Pumps, 18 March 2024." [Online]. Available: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Presentation_Christian_Schlemminger_Michael_Bantle_ANEO_Steam-Generating_Heat_Pumps_Webinar_2024_OST.pdf
- [50] S. Henninger, "Johnson Controls: Industrielle Wärmepumpen für Fern- und Prozesswärme – Übersicht, Integration, Ökonomie, Swis cleantech, Treffen der Arbeitsgruppe HTWP, 14. August 2025, Online," 2025, pp. 1–33.
- [51] T. Kaida, "A Steam Supply Heat Pump System - Technology overview, energy performance and operating characteristics," in *IEA HPT Annex 58, Deep Dive about Steam Generation and MVR, 30 August, 2021*, 2021.
- [52] T. Kaida, "High-temperature heat pumps in Japan - Potential, development trends and case studies," in *2nd Conference on High Temperature Heat Pumps, September 9, 2019, Copenhagen*, 2019, pp. 92–107.
- [53] M. Aminyavary, "Cannon Bono: Heat upgrade technologies integration in paper production facility, MIAC 2025 Energy Conference, 8 October 2025, Lucca, Italy." [Online]. Available: <https://www.miacatalog.com/en/conference/energy/>
- [54] C. Rau, "Large Temperature Lifts: A Major Challenge? The Future of Industrial Process Heat," *Heat Pumping Technologies MAGAZINE*, Vol.43 No.3/2025.
- [55] C. Arpagaus, F. Bless, and S. Bertsch, "Techno-economic analysis of steam generating heat pumps for integration into distillation processes," *15th IIR-Gustav Lorentzen Conf. Nat. Refrig. June 13-15, Trondheim, Norw.*, 2022, doi: 10.18462/iir.gl2022.0029.