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Development and Application Potential of a Steam-Generating Ammonia-Water Absorption Heat Transformer (AHT) for Industrial Waste-Heat Recovery

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ABSTRACT

Absorption heat transformers (AHTs) are gaining attention for industrial waste-heat recovery, yet commercial systems remain largely limited to $LiBr–H_2O$ technology, constrained by crystallization, corrosion, and vacuum operation. This work presents a novel $NH_3–H_2O$ AHT concept developed within the EU-funded ZIMBA project, enabling thermally driven steam generation with enhanced robustness and flexibility. The system upgrades low-grade waste heat (70–80 °C) to 100–110 °C steam using two units of heat and minimal electricity (0.025), while rejecting one unit of usable low-temperature heat (10-35 °C). Ejector integration is investigated to enhance stability, performance, and operating range. A market review identifies substantial untapped potential for 70–80 °C waste heat, with distilleries as a key early application. A techno-economic case study for a French cognac distillery confirms feasibility and strong commercial potential, with payback periods of 5.0–6.5 years. The results demonstrate a strong potential for near-term industrial deployment.

Keywords: Absorption heat transformer, water-ammonia, refrigerant mixtures, waste heat, decarbonization industry

1. INTRODUCTION

1.1. Motivation

Global industrial final energy consumption for heat is nearly 112 exajoules (EJ), accounting for about 63% of total industrial energy use. Around 52% is required for process temperatures below 400 °C (SHIP Solar Heat for Industry, 2026). Industry contributes nearly 22% of direct and approximately 31% of total greenhouse gas (GHG) emissions, including indirect electricity-related emissions (UNIDO, 2024). Despite ongoing efforts, over 70% of industrial energy demand is still supplied by fossil fuels (IEA, 2023).

Decarbonizing industrial heat is therefore essential to achieve net-zero targets by 2050. Heat pumps (HP) that use natural refrigerants (e.g., water, ammonia) align with global climate policies, such as the Kigali Amendment, to phase down HFCs. In particular, steam-generating high-temperature heat pumps (HTHPs) provide efficient, low-carbon process heat (Arpagaus et al., 2026a, 2018). According to the IEA Net Zero Emissions Scenario, around 500 MW of HP capacity must be deployed each month over the next 30 years to supply 30% of industrial heat demand by 2050 (IEA, 2024, 2022, 2021).

However, large-scale electrification is expected to significantly increase electricity demand, potentially causing supply constraints as energy-intensive industries expand and low-carbon electricity generation grows slowly. This may lead to prioritization of industrial electricity use and limited power availability.

At the same time, industrial waste heat represents a major untapped resource. Marina et al. (2021) estimated 212.5 TWh/a (67.6%) of waste heat below 200 °C is available at 40–100 °C across European EU28 industries.

Similarly, Luberti et al. (2022) highlighted further potential, especially in power generation (40–59 °C, e.g., engine cooling) and the 60–79 °C range across food and other industrial sectors.

Thus, alongside electrically driven vapor-compression heat pumps (HPs), thermally driven absorption heat transformers (AHTs, also referred to as type II absorption heat pumps) (Ametta et al., 2026; Corrales Ciganda & Martinez-Urrutia, 2023) offer an alternative for upgrading waste heat. HPs enable full heat recovery but require electricity, whereas AHTs are primarily heat-driven systems that upgrade only part of the heat source (e.g., to hot water or steam), require minimal electricity, and reject the remaining heat to a lower-temperature sink (Gorlovsky, 2026). The choice between these two systems depends on the application (Villa et al., 2025).

As shown in Figure 1, AHTs operate across three temperature levels (ZIMBA, 2024). The same heat source drives both the evaporator and the generator (Best et al., 1987). Typically, waste heat at 70–80 °C is upgraded to 100–110 °C, converting two units of input heat into one unit of useful heat with 0.025 units of electricity input, while one unit is rejected at 10–35 °C. This highlights the key advantage of AHT: efficient waste heat upgrading with minimal electrical demand (Collignon et al., 2025, 2024).

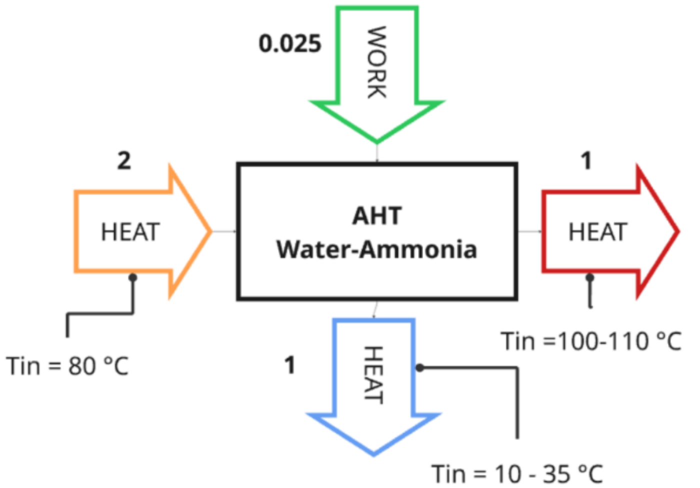

Figure 1: Energy flows of an ammonia/water AHT upgrading two units of waste heat (70–80 °C) to one unit of useful heat (100–110 °C), with 0.025 units of electricity input and one unit rejected at 10–35 °C (ZIMBA, 2024)

1.2. Objective of the work

This paper is structured as follows:

(i) review on the current state of the art of $LiBr–H_2O$ and $NH_3–H_2O$ AHT technology;

(ii) introduction to the $NH_3–H_2O$ AHT concept that will be realized in the EU Horizon ZIMBA project;

(iii) analysis of the market potential and a business case study;

(iv) outlook on future research, scale-up, and practical applications.

2. LITERATURE REVIEW

2.1. Publications and patents on AHT technology

Figure 5 illustrates the evolution of scientific publications and patents with the keyword "absorption heat transformer", reflecting growing industrial interest in energy efficiency and CO_2 emissions reduction. Publications on ScienceDirect have increased exponentially from about 600 papers in 2020 to 1'700 today, corresponding to an average annual growth rate of 24% over the past five years.

Patent data from Espacenet (keyword "absorption heat transformer") reveals 73 patents filed between 1975 and 2025, with a notable increase since 2014 and a broad range of applicants and inventors (see Figure 5, right). In addition, several comprehensive review studies on AHT technology have been published (Ayou et al., 2025; Cudok et al., 2021; Donnellan et al., 2015; Parham et al., 2014; Rivera et al., 2015).

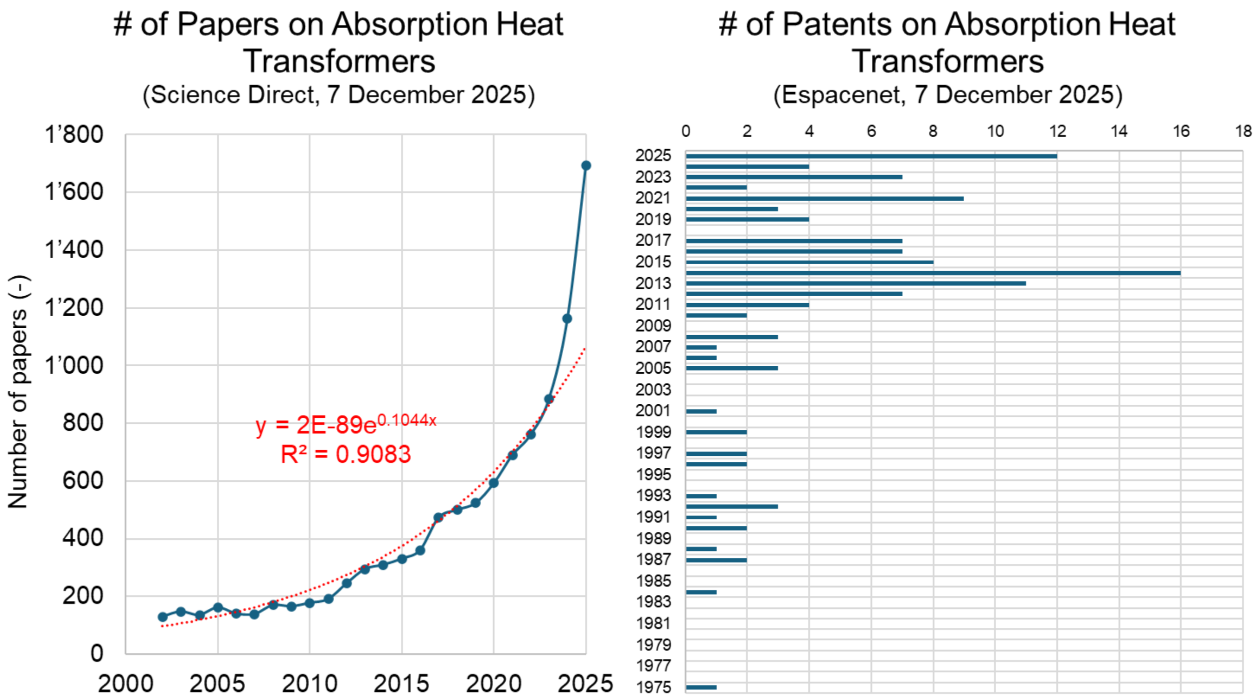

Figure 2: Number of papers (left) and patents (right) published based on a search in Science Direct (www.sciencedirect.com) and Espacenet (www.worldwide.espacenet.com) with the keyword "absorption heat transformer" (accessed on 7 December 2025).

2.2. AHT working fluids water–lithium bromide ($LiBr–H_2O$) and ammonia–water ($NH_3–H_2O$)

AHT systems typically use water–lithium bromide ($LiBr–H_2O$) or ammonia–water ($NH_3–H_2O$) as working pairs, with $LiBr–H_2O$ dominating commercial applications (Ayou et al., 2025; Cudok et al., 2021; Donnellan et al., 2015; Parham et al., 2014; Rivera et al., 2015; Su et al., 2024). In $LiBr–H_2O$, water acts as the refrigerant, while ammonia fulfills this role in $NH_3–H_2O$. Alternative mixtures exist but remain less established (Ametta et al., 2026; Ji et al., 2023; Su et al., 2024; Sun et al., 2012; Talpada and Ramana, 2022).

Table 1 summarizes the key advantages and limitations of both working pairs based on the literature. Despite their maturity, $LiBr–H_2O$ systems face key limitations, including high corrosivity, viscosity, and crystallization risk, especially at elevated absorber temperatures (Cudok et al., 2021; Kurem and Horuz, 2001). They operate under vacuum conditions, leading to low heat transfer coefficients, sensitivity to non-condensable gases, larger heat exchangers, and higher CAPEX and maintenance requirements (Cudok et al., 2021; Liu et al., 2023).

Crystallization can impair operation and reduce system lifetime, particularly at high solution concentration. Mitigation strategies include chemical inhibitors (e.g., salts), additives, and cycle modifications (Ametta et al., 2026; Parham et al., 2014; Sun et al., 2012).

Table 1. Advantages and limitations of AHT working pairs ($LiBr–H_2O$ vs. $NH_3–H_2O$) based on literature (Ametta et al., 2026; Ayou et al., 2025; Cudok et al., 2021; Donnellan et al., 2015; Ji et al., 2023; Kurem and Horuz, 2001; Liu et al., 2023; Parham et al., 2014; Rivera et al., 2015; Su et al., 2024; Sun et al., 2012; Talpada and Ramana, 2022)

Working pair	Advantages	Limitations
$LiBr–H_2O$	+ Commercially mature and widely applied + Water as refrigerant: non-toxic, low cost + Relatively high COP in typical conditions	- High corrosivity and viscosity - Crystallization risk (especially at high concentration and temperature) - Operation under vacuum → low heat transfer coefficients - Sensitive to non-condensable gases - Larger heat exchangers, higher CAPEX and maintenance
$NH_3–H_2O$	+ No crystallization risk + Operation at moderate pressures (no vacuum) + Lower sensitivity to non-condensables + Smaller heat exchangers, more compact systems + Higher achievable temperature lift (supply temperature up to 150–160 °C) + Greater flexibility in heat-source utilization	- Typically lower COP - Higher operating pressures - Ammonia toxicity requires safety measures

In contrast, $NH_3–H_2O$ systems avoid crystallization (Ametta et al., 2026) and operate at moderate pressures, enabling smaller heat exchangers, lower sensitivity to non-condensables, and improved robustness. Although typically achieving lower COP (Ji et al., 2023), they offer higher temperature lifts and greater flexibility in heat-source utilization, making them attractive for industrial applications (Liu et al., 2023).

Recently, Collignon et al. (2025, 2024) developed a steady-state model of an $NH_3–H_2O$ AHT for upgrading low-temperature industrial waste heat. As shown in Figure 3, the operating range narrows with increasing heat-rejection temperature (T_{cold}) and depends on the waste-heat temperature (T_{waste}). For example, at T_{cold} = 15 °C, the feasible waste heat range is 61–98 °C.

As a rule of thumb, the maximum absorber solution temperature before saturation in a single-stage $NH_3–H_2O$ AHT follows approximately $T_{sol,max} \approx T_{waste} + 30$ °C (Collignon et al., 2025, 2024).

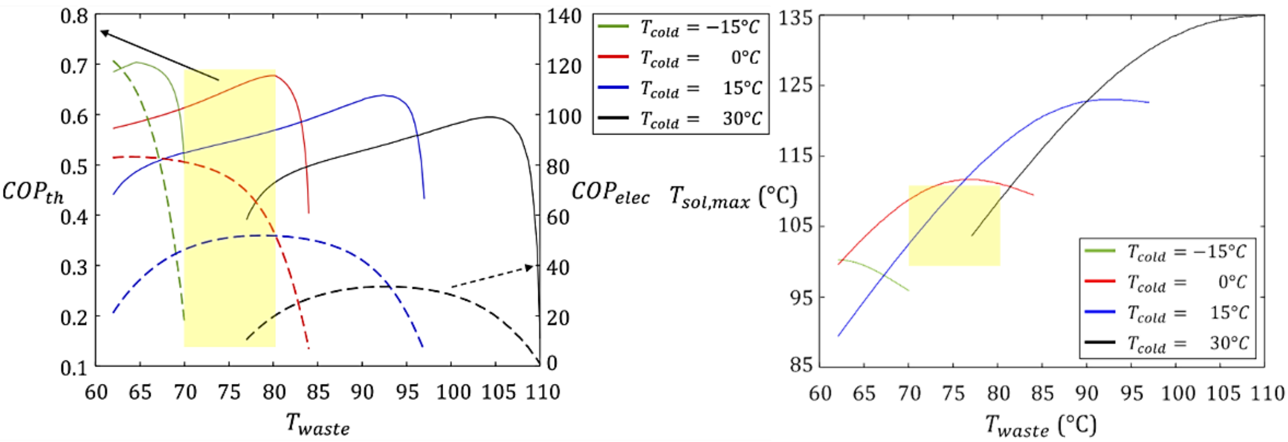

Figure 3: Operating range of an $NH_3–H_2O$ AHT: Estimated performance (left) and maximum absorber solution temperature at saturation (right) as a function of heat rejection temperature (*T_{cold}*) and the waste heat (*T_{waste}*) (Source: Collignon et al., 2025). The yellow region indicates the ZIMBA AHT operating window

However, NH_3–H_2O AHTs operating at heat-supply temperatures above 80 °C remain rare, and experimental data are limited. One example is the AGO Calforma system (AGO GmbH Energie + Anlagen, Germany), delivering 60–110 °C heat at 0.4–1.5 MW with COPs of 0.35–0.50 from 45–70 °C waste heat (Ayou et al., 2025), though no commercial deployment has been reported.

The EU Horizon Europe project ZIMBA project (Grant Agreement No. 101146932, 12/2024–11/2028) addresses these gaps by developing a single-stage NH_3–H_2O AHT that replaces electrical vapor compression with thermally driven absorption (ZIMBA, 2024). The system targets waste-heat temperatures of 80/72 °C (inlet/outlet) (see yellow-marked region in Figure 2) and a heat supply of 100–110 °C (about 1.3 bar(a) steam), with heat rejection <30 °C potentially usable in 5th-generation district heating.

The ZIMBA project aims to improve energy efficiency in high-temperature industrial applications and supports the EU net-zero 2050 goals. The consortium is coordinated by CEA, with partners POLMI, Clauger, AMIRES, and OST.

3. ZIMBA NH_3–H_2O AHT PROTOTYPE

The ZIMBA NH_3–H_2O AHT system targets 15 kW_{th} capacity, upgrading waste heat from 70–80 °C to 100–110 °C while rejecting heat below 30 °C. To extend the operating range, a two-phase ejector is integrated to decouple generator and condenser pressures.

Figure 4 shows a schematic of the upgraded NH_3–H_2O AHT system with an ejector. A portion of the high-pressure vapor (primary flow) entrains and compresses the low-pressure vapor from the generator (secondary flow), thereby enabling thermal compression. This reduces performance losses, improves performance stability and expands operating flexibility, particularly at high ambient temperatures (>35 °C).

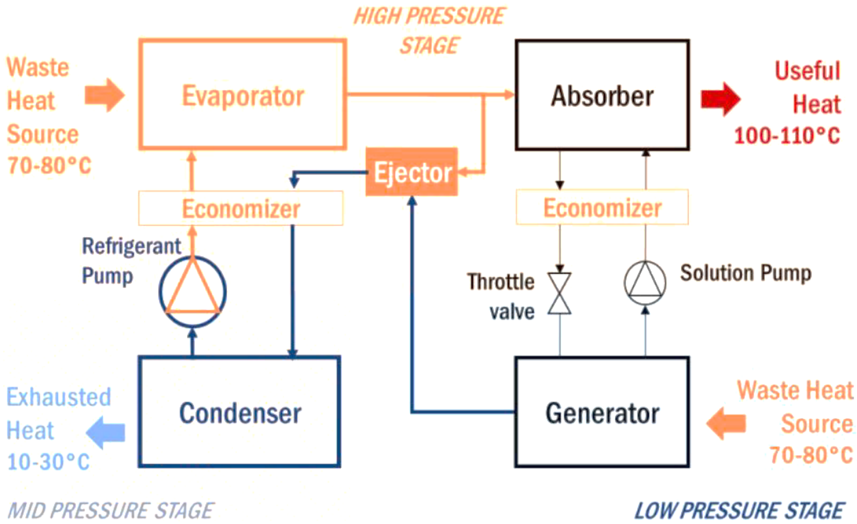

Figure 4: Scheme of the upgraded AHT system in the ZIMBA project with ejector integration.

Vaghini et al. (2026) evaluated ejector integration via numerical simulations at varying condenser water inlet temperatures. At the design point (20 °C condenser water inlet), the baseline system (i.e., without the ejector) delivers 15.1 kW_{th} with a thermal COP_{th} = 0.46 and COP_{el} = 37.9. As the condenser water inlet temperature increases, performance deteriorates. At 35 °C (cut-off condition), the baseline system yields 4.19 kW_{th} (COP_{th} = 0.30, COP_{el} = 11.85). With ejector integration, thanks to decoupling of generator and condenser pressures, the system reaches 9.37 kW_{th} (COP_{th} = 0.45, COP_{el} = 21.08), demonstrating improved robustness.

In parallel, Mazzelli et al. (2026) developed a CFD-based ejector design and optimization framework that uses a coupled optimization loop and high-fidelity 2D CFD simulations to refine the mixing chamber geometry, thereby achieving a unique optimal configuration for the targeted entrainment ratio.

Figure 5 shows the baseline 3D prototype designed by POLIMI (status April 2026).

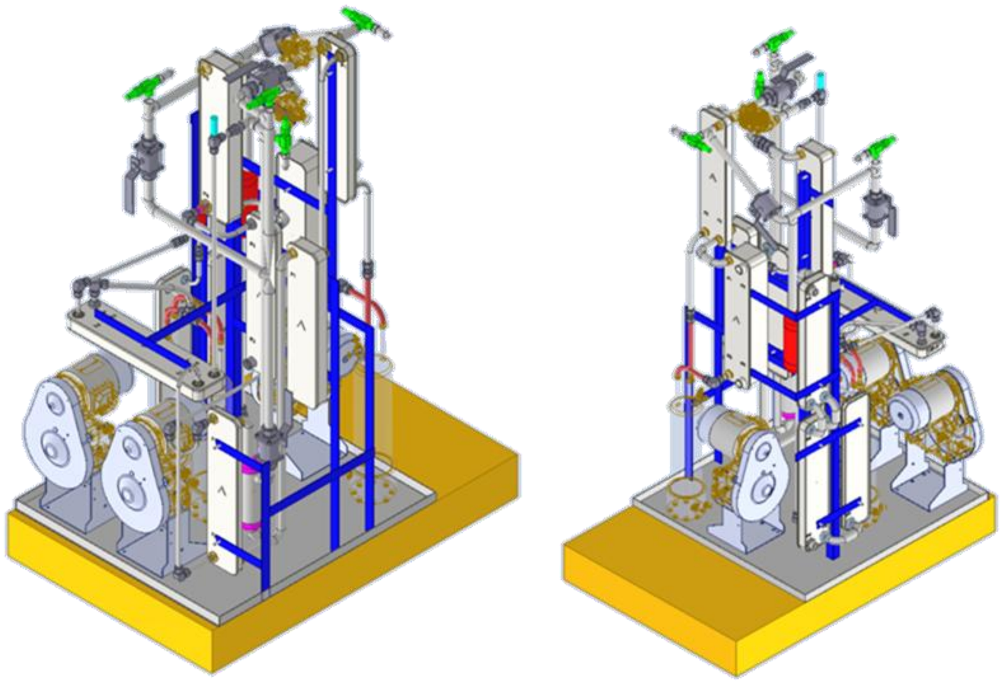

Figure 5: 3D drawings of the ZIMBA AHT baseline prototype design by POLIMI (Status: April 2026)

Next steps in the ZIMBA project include finalizing the ZIMBA AHT baseline design and conducting performance tests at OST laboratories in 2026. Subsequently, an upgraded system with ejector integration will be developed.

4. MARKET ANALYSIS

The market analysis is based on a comprehensive review of AHT technologies, including scientific literature, patents, research and demonstration projects, and commercially available AHT products.

4.1. Applications for AHTs

Cudok et al. (2021) reviewed 43 AHT installations (approximately 134 MW total heating capacity), of which 17 were still operational in 2021. Most systems are in East Asia (74%), particularly China (12 units), followed by Europe (23%). Applications are dominated by the chemical industry (26 of 43, 61%), followed by food (9%), and sectors such as paper and heavy industry (16%). Most systems (40 out of 43, 93%) use LiBr–H_2O working pairs. Typical operating ranges are:

- Waste heat (inlet / outlet) = 56 to 130 °C / 75 to 105 °C
- Heat supply (inlet / outlet) = 25 to 152 °C / 80 to 165 °C
- Heat rejection (inlet/outlet) = 15 to 46 °C / 20 to 46 °C

Notably, 37 LiBr–H_2O AHTs operate at waste heat driving temperatures of 75–110 °C, aligning well with ZIMBA NH_3–H_2O AHT targets (see Figure 1, Figure 3, and Figure 6). Several cases upgrade waste heat from 70–80 °C to 100–110 °C, particularly in alcohol distillation. Low-temperature heat is typically rejected via cooling towers, seawater, or groundwater (Cudok et al., 2021).

Additional applications include drying and food processing (e.g., pasta drying at 135 °C, vegetable cooking at 105 °C) (Ayou et al., 2019; Gorlovsky, 2026). Broader reviews highlight applications in distillation, seawater desalination, evaporation, and cogeneration (Donnellan et al., 2015; Parham et al., 2014; Rivera et al., 2015).

Overall, significant untapped potential exists for waste heat at 70–80 °C across various sectors, such as power generation, chemicals, refining, paper, and food. Alcohol distilleries are particularly promising due to continuous demand and well-matched temperature levels.

As illustrated in Figure 6, AHTs can be integrated into energy cascades, enabling the circular use of heat by upgrading waste heat with minimal electricity and rejecting low-temperature heat (<30 °C) to systems such as 5th-generation district heating.

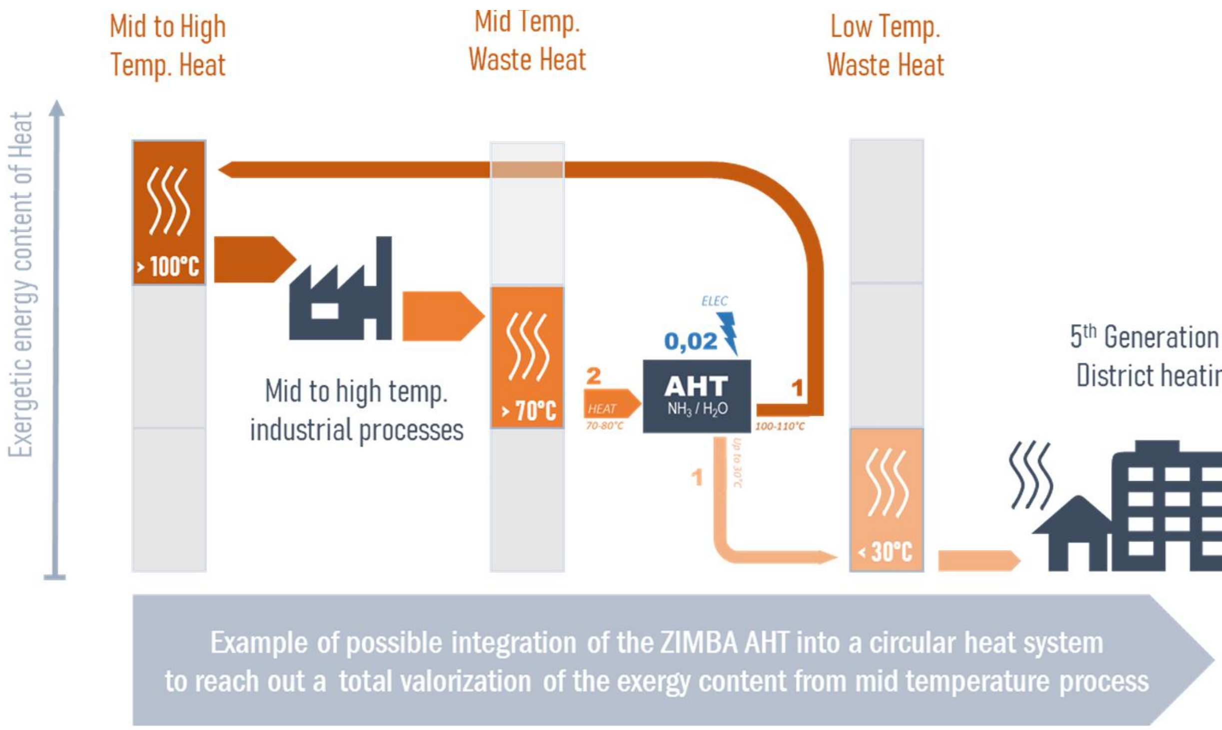

Figure 6: Integration of the ZIMBA AHT system into a circular heat system.

4.2. Commercial AHT products

A comprehensive review of projects, publications and patents identified the main suppliers of commercial LiBr–H_2O AHTs as Ebara Refrigeration Equipment & Systems Co., Ltd. (China), Johnson Controls-Hitachi Air Conditioning (Japan), Jiangsu Shuangliang Eco-Energy Co., Ltd. (China), LG Electronics (Japan), Thermax Ltd. (India), World Energy (Republic of Korea), and BS Nova Apparatebau GmbH (Germany) (Alonso et al., 2025; Ayou et al., 2025, 2019; Cudok et al., 2021; Gorlovsky, 2026).

Some former suppliers have exited the market (e.g., Hitachi Zosen and Tokyo Sanyo Electric, Japan). Other manufacturers are Steps Ahead (Austria), York (England, USA), and TRANE ROGGENKAMP (Germany).

Figure 7 illustrates some products, and Table 2 summarizes the main technical features.

Figure 7: Commercial LiBr–H_2O AHT products for industrial applications.

Table 2. Commercially available single-stage LiBr–H_2O AHT systems. Data compiled from Alonso et al. (2025); Ayou et al. (2025, 2019); and Gorlovsky (2026).

Manufacturer	Heat Source	Heat Rejection	Delivered Heat	Heating capacity (kW)	COP_{th} (-)
Ebara Refrigeration Equipment & Systems Co., Ltd.	Waste hot water, exhaust steam (>80 °C)	Cooling water	Hot water or steam (up to 175 °C) 0.3–15 t/h steam	169–8’460	0.33–0.48
Johnson Controls-Hitachi Air Conditioning	Waste heat (<100 °C) from engine jacket water, industrial processes, or distillation heat	Cooling water, Underground water, recovery cooling water (24–32 °C)	Hot water or steam (70–145 °C) Temperature lift (34–52 K)	143–2’496, 400 (new model)	0.42–0.48
LG Electronics	Hot water (70 °C)	Cooling water (12 °C)	Hot water (up to 120 °C)	>300	0.45
Shuangliang Eco-Energy Systems Co., Ltd	Waste hot water (≥ 60 °C), Exhaust steam, Gas, Liquid (≥ 90 °C)	Cooling water (18 –34 °C)	Hot water (130–169 °C) Steam (1–6 bar) with a separate flash tank	1’000–9’300 (single unit up to 8’000)	0.44 –0.48
Thermax Ltd.	Hot water/process condensate, geothermal water, steam condensate from the steam turbine (80–150 °C)	Not reported	Hot water (110 –185 °C) Dry saturated steam (2–12 bar) with a separate flash tank	500–15’000	0.40–0.47
World Energy Co., Ltd.	Hot or drain water (88 °C)	Cooling water (26/32 °C)	Hot water (127–133 °C)	349–2’442	0.48
BS Nova Apparatebau GmbH	Industrial waste heat (85/75 °C)	Cooling water (15/25 °C)	Hot water (111–116 °C)	448	0.48

Overall, commercially available single-stage LiBr–H_2O AHTs are technically proven but remain a niche technology, with deployment concentrated in specific industrial applications (Gorlovsky, 2026). These systems typically deliver 100–185 °C hot water or steam, with heating capacities of 150 kW to 15 MW and COPs of 0.33–0.48. Typical waste heat sources are >60–90 °C (e.g., hot water, exhaust steam, CHP engine cooling water). Johnson Controls–Hitachi reports specific capital expenditures (CAPEX) in the range of 193–417 EUR/kW of installed heating capacity (Gorlovsky, 2026).

In addition, commercial hybrid absorption–compression heat pumps are available from AGO GmbH Energie (Germany) and Johnson Controls (Sabroe, Denmark) (Hamid et al., 2025; Johnson Controls, 2026; Ramming and Zengerle, 2026). Using NH_3/H_2O (R-717/R-718) mixtures, they deliver process heat up to about 120 °C at lower system pressures (<25 bar) and are well adaptable to temperature glides.

The Sabroe product families HyePAC (single-stage) and HyePAC-D (two-stage) offer 500–2’150 kW capacity, enable waste-heat recovery up to 90 °C and achieve COPs of 3.4–7.3 for 25–60 K temperature lifts (Johnson Controls, 2026).

Driven by rising industrial energy costs and tightening climate policies, such systems provide an efficient, low-pressure, and environmentally friendly solution based on natural refrigerants, supporting the transition toward a net-zero industry.

4.3. Demonstration projects of high-temperature AHT technology

Key demonstration projects on high-temperature process heat using LiBr–H_2O AHTs were analyzed, including EU Horizon Indus3Es (distillation for oil refining), Push2Heat (steam in the paper industry), and a South Korean–Swiss AHT+MVR project (distillation/desalination) (Table 3, Figure 8).

The EU Horizon 2020 project Indus3Es (2015–2020) developed a 200 kW LiBr–H_2O AHT that upgrades waste heat from 95 °C to 135–138 °C (Corrales Ciganda and Martinez-Urrutia, 2023) (Figure 8A). The BS Nova unit installed at the Tüpraş oil refinery (Turkey) achieved a 45 K temperature lift, a COP of around 0.50, and heat rejection <30 °C, with a payback <10 years (estimated at 6 years for mature systems, assuming 420 kEUR CAPEX for 600 kW). The project also developed sizing tools, advanced control strategies, and an online techno-economic assessment tool (Indus3Es, 2018).

The EU Horizon Push2Heat project (2022–2026) demonstrates a BS Nova LiBr–H_2O AHT at Cartiere di Guarcino paper mill (Italy) (Figure 8, B), upgrading 715 kW of waste heat (85–90 °C, cooling water from biomass CHP) to 340 kW of steam at 3.3 bar(a), 126 °C (0.6 t/h) with a COP of 0.48 (Alonso et al., 2025). Coupled with a flash tank and thermocompressor, steam is further upgraded to 6.5 bar(a), 162 °C (2.4 t/h) using 14.5 bar(a) motive steam (1.8 t/h) (Alonso et al., 2025; Push2Heat, 2025, 2022).

The South Korea–Switzerland R&D project *"Steam Production Using Waste Heat–Driven AHT and Mechanical Vapor Recompression (MVR)"* combines a LiBr–H_2O AHT (upgrading temperatures from <90 °C to around 120 °C, COP 0.45) with MVR to produce steam at around 160 °C for industrial use. Demonstration sites target distillation processes. Initial tests with the AHT unit show a capacity of approximately 260 kW, absorber temperatures of 118–124 °C, a heat-source temperature of 89–82 °C, and a heat-rejection temperature of 24–32 °C (Arpagaus et al., 2026b).

Figure 8 (C) illustrates the experimental AHT system developed by World E&C.

Table 3. Demonstrators of LiBr–H_2O AHT systems providing high heat sink temperatures.

Institution, company, project	Reference	Application	Working pair	Heat Source	Heat Sink	Heat Rejection	Heating capacity	COP_{th} (-)
EU Horizon Indus3Es (BS Nova)	Corrales Ciganda and Martinez-Urrutia (2023), Indus3Es (2018)	Distillation for oil refining	LiBr–H_2O	88–95 °C	115–138 °C	20 °C	220 kW	0.50
EU Horizon Push2Heat (BS Nova)	Alonso et al. (2025), Push2Heat (2025, 2022)	Steam for paper factory	LiBr–H_2O	85–90 °C (cooling water from biomass cogeneration plant)	3.3 bar(a) steam (126 °C)	15–20 °C	340 kW	0.48
South Korean–Swiss AHT+MVR project (World E&C)	(Arpagaus et al., 2026b)	Distillation and desalination	LiBr–H_2O	82–89 °C (waste hot water)	124 °C/118 °C	24–32 °C	260 kW	0.45

Figure 8: (A) This BS Nova H2O/LiBr AHT demonstrator at Tüpraş (Turkey), developed in the EU Horizon 2020 Indus3Es project (200 kW; heat upgrade 95 → 135 °C; COP 0.50) (Indus3Es, 2018). (B) BS Nova H_2O/LiBr AHT demonstrator at paper mill in Cuartiere di Guarcino (Italy) developed in the EU Horizon Push2Heat project (715 kW waste heat at 85–90 °C upgraded to 340 kW steam at 3.3 bar(a), 126 °C, 0.6 t/h; COP 0.48), coupled with a thermocompressor to produce 6.5 bar(a), 162 °C steam (2.4 t/h) using 14.5 bar motive steam (1.8 t/h) (Alonso et al., 2025; Push2Heat, 2025, 2022) (C) H_2O/LiBr AHT system developed by World E&C (260 kW; absorber temperatures 118–124 °C; heat source 89–82 °C; heat rejection 24–32 °C (Arpagaus et al., 2026b).

4.4. Experimental research studies on NH_3–H_2O AHT

Experimental research on NH_3–H_2O AHTs remains limited, with only four laboratory-scale systems reported in the open literature and a limited understanding of dynamic behavior, highlighting the need for further work toward industrial scale-up.

At Politecnico di Milano, Garone et al. (2017, 2018) demonstrated a 4.5 kW single-stage NH_3–H_2O AHT operating with 60–64 °C waste heat and 8–16 °C condenser temperatures (suitable for dry cooling in winter), achieving 15–25 K temperature lifts and thermal COPs of 0.35–0.47 with less than 100 W electrical input.

At the Chinese Academy of Sciences, Liu et al. (2023) increased the heating capacity to 400 kW by extending the heat-source temperature span and improving the generator design. The prototype upgraded waste heat from 85 °C to 102 °C (COP 0.33), with a predicted output of up to 120 °C at a larger scale.

At the University of Stuttgart, a 10 kW laboratory system (9.8 kg charge, 67% NH_3, 40 bar limit) achieved 8.3 kW at 115 °C, COP 0.38–0.41, and 20–30 K lifts, highlighting sensitivity to low-pressure-side fluctuations and the importance of pump control for stable operation (Haak, 2025; Haak et al., 2024; Hönig et al., 2026). The unit is built with plate heat exchangers, speed-controlled piston diaphragm pumps, and a proportional expansion valve.

More recently, CEA developed a 10 kW prototype upgrading 80 °C waste heat to >100 °C with COP of 0.44 (Desage et al., 2026). The system uses plate heat exchangers (scalable design), stainless-steel piping, and EPDM diaphragm pumps, with 6.26 kg charge (56% NH_3). Optimal performance was achieved at a specific solution-to-refrigerant flow rate ratio. The design builds on prior modeling work (Collignon et al., 2025, 2024).

Table 4. Performance comparison of experimental research studies on NH_3–H_2O AHT prototypes.

Institution (country)	Reference	Heating capacity	Heat Source	Heat Sink	Heat Rejection	COP_{th} (-)
Politecnico di Milano (Italy)	Garone (2018), Garone et al. (2017)	4.5 kW	60–64 °C	70–80 °C	8–16 °C	0.35–0.47
Chinese Academy of Sciences (China)	Liu et al. (2023)	400 kW	85 °C	95–102 °C	20–35 °C	0.33
University of Stuttgart (Germany)	Haak (2025), Haak et al. (2024), Hönig et al. (2026)	8.4 kW	80–90°C	100–120 °C	25 °C	0.38–0.41
University Grenoble Alpes, CEA (France)	Desage et al. (2026)	10 kW	80 °C	90–103 °C	15 °C	0.44

5. DISTILLERY BUSINESS CASE STUDY

Distilleries were identified as a key target segment for the ZIMBA AHT because of their strong potential to reduce natural gas consumption by adopting alternative heat sources. In current distillery operations, a significant amount of low-temperature waste heat is lost after each batch. By integrating an AHT with thermal storage, some of this waste heat can be recovered, reducing natural gas use for still heating.

A techno-economic assessment was conducted for a representative French cognac distillery operating 9 stills (7 x 100 hL capacity, 2 x 25 hL; total 750 hL) operating in 10 h batches (2 per day). The analysis, based on operational data and close collaboration with ZIMBA partners, evaluates CAPEX, OPEX, and payback.

In the current process, wine is heated to 95 °C in the stills using gas burners. Alcohol vapors are then condensed to 17 °C distillate using cooling water supplied at 8 °C and heated to 80 °C during the process. After distillation, residual vinasse (95 °C) is discharged after each batch. The heated condenser water is subsequently cooled via a cooling tower (25/30 °C) and a chiller (7/12 °C).

For the ZIMBA AHT integration, a minimum unit size of 400 kW was assumed. Due to a temporal mismatch between the available and required heat (70/82 °C), a 70 m³ thermal storage tank is included. Table 5 summarizes CAPEX, energy consumption, and resulting payback periods.

Suitable heat sources at 80/72 °C in the distillation process are: (i) latent heat from alcohol condensation and (ii) sensible heat from vinasse. The recoverable waste heat capacity in the distillation plant over 24 h is 935 kW, sufficient to supply a 400 kW AHT that requires 909 kW of heat input (assuming a COP of 0.44).

Table 5. CAPEX estimation for the ZIMBA NH_3–H_2O AHT integration.

Component	Costs (EUR)
AHT system (400 kW, incl. pumps)	300'000
Heat exchangers (water/wine + heat recovery)	142'000
Pumps (wine + heat recovery + process)	46'500
Storage tank (70 m^3)	70'000
Installation and commissioning	100'000
Civil works	20'000
Engineering and studies	30'000
Total CAPEX (excl. subsidy)	**708'500**
Total CAPEX (incl. 30% subsidy)	**495'950**

Table 6 summarizes current and future OPEX for a 750 hL distillery, including assumptions on energy consumption, CO_2 factors, and energy prices, and provides payback estimates.

Table 6. OPEX savings, CO_2 emissions reduction, and payback period estimation for the ZIMBA NH_3–H_2O AHT integration (Assumptions: 750 hL distillery, 5 months of operation, 2 x 10-hour batch operations per day, gas price 0.06 EUR/kWh, electricity price 0.20 EUR/kWh, CO_2 emission factor gas 0.243 kg CO_2/kWh, CO_2 emission factor electricity 0.052 kg CO_2/kWh, carbon price 80 EUR/tCO_2).

Parameter	Current operation with gas boiler	Future operation with ZIMBA integration (150 hL) and gas boiler (600 hL)	Savings	
Gas consumption	*5'981'740 kWh*	*4'785'392 kWh*	*1'196'348 kWh*	*20%*
Gas carbon footprint	*1'453'563 kg CO_2*	*1'162'850 kg CO_2*	*290'713 kg CO_2*	*20%*
Electricity consumption	*312'208 kWh*	*230'380 kWh*	*81'829 kWh*	*26%*
Electricity carbon footprint	*16'204 kg CO_2*	*11'957 kg CO_2*	*4'247 kg CO_2*	*26%*
Gas costs	344'073 EUR	275'258 EUR	**68'815 EUR**	**20%**
Electricity costs	63'385 EUR	46'772 EUR	**16'613 EUR**	**26%**
Maintenance costs	12'500 EUR	22'000 EUR	**-9'500 EUR**	**-76%**
Gas carbon tax	116'285 EUR	93'028 EUR	**23'257 EUR**	**20%**
Electricity carbon tax	1'296 EUR	957 EUR	**339 EUR**	**26%**
		Total OPEX savings (excl. carbon tax)	**75'928 EUR**	
		Total OPEX savings (incl. carbon tax)	**99'524 EUR**	
		Payback period (incl. 30% subsidy, excl. carbon tax)	**6.5 years**	
		Payback period (incl. 30% subsidy, incl. carbon tax)	**5.0 years**	

The ZIMBA AHT integration reduces gas-based heating and significantly lowers cooling demand (cooling from 18 °C to 8 °C instead of 80 °C to 8 °C), thereby lowering electricity consumption. Although additional pumps increase CAPEX and auxiliary consumption, overall OPEX decreases due to reduced gas and cooling energy demand.

Overall, the results indicate favorable economics, with payback periods of 6.5 years (incl. 30% subsidy, excl. carbon tax) and 5.0 years (incl. subsidy and carbon tax), confirming distilleries as a promising market for ZIMBA AHT.

6. CONCLUSIONS

This work provides a consolidated assessment of AHT technologies, identifying a clear gap between mature LiBr–H_2O systems and emerging NH_3–H_2O concepts, particularly for higher-temperature and more flexible industrial applications.

A central contribution is the development and system-level analysis of an NH_3–H_2O AHT within the EU-funded ZIMBA project, demonstrating thermally driven steam generation (100–110 °C) from low-grade waste heat (70–80 °C). Two-phase ejector integration improves stability, extends the operating range, and enhances performance.

NH_3–H_2O AHTs offer key advantages (no crystallization, moderate pressures, higher temperature lifts), but remain in the early stages, with limited experimental data and only a few laboratory-scale demonstrations.

The market and application analysis identifies distilleries as a high-impact early segment and confirms the feasibility of LiBr–H_2O AHTs and hybrid AHT+MVR systems (up to ~160 °C), while highlighting challenges in scale-up, integration, and cost.

A techno-economic case study for a French cognac distillery demonstrates strong commercial viability (payback 5.0–6.5 years), providing a concrete pathway toward near-term deployment.

Overall, NH_3–H_2O AHTs show strong potential for scalable industrial waste-heat upgrading but require further validation, dynamic analysis, and industrial-scale demonstration.

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USE OF ARTIFICIAL INTELLIGENCE

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NOMENCLATURE

AHT	Absorption heat transformer	GHG	Greenhouse gas
CAPEX	Capital expenditure	OPEX	Operating expenditures
COP	Coefficient of performance (-)	ΔT	Temperature lift
CHP	Combined heat and power		

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