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Heat Pumps for Industrial Drying Processes – An Overview of Realized Case Studies

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Abstract

This paper provides a comprehensive and current overview of the application of heat pumps (HPs) in industrial drying processes. The core of the paper presents recent, real-world case studies that demonstrate the successful implementation of HP technologies in various drying applications, including:

- High-temperature heat pumps (HTHPs) for brick and starch drying
- The electrified feed dryer
- A transcritical HTHP with R1234ze(E) applied in paper drying
- A transcritical CO_2-HP for spray drying systems

These case studies demonstrate the substantial energy-saving potential of electrifying industrial drying using heat pump technology. A key advantage is the ability to recover low-temperature waste heat and reuse it as dehumidified, heated air for drying, thereby enhancing process efficiency and sustainability. The examples underline the growing maturity and practical viability of heat pumps in industrial drying, reinforcing their role in decarbonizing thermal processes. Additionally, the paper provides a review of the recent literature on heat pumps in drying processes, categorized into books, reviews, and case-study papers.

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Keywords: drying; high-temperature heat pump; case studies

1. Introduction and goal

Drying is a crucial industrial technology for preserving a wide range of products. Drying processes are widely used across sectors such as food, paper, chemicals, and ceramics, as well as in commercial laundries and households (e.g., tumble dryers). The *Handbook of Industrial Drying* [1,2] describes more than 15 industrial dryer types and over 20 different drying processes. In industrialized countries, drying processes account for roughly 10% to 25% of industrial energy consumption [1–3], with most systems still relying on fossil fuels.

Industrialization has significantly improved the efficiency of drying technologies. Convective dryers remain the most common type of dryer. The moisture removed from the material is typically released to the environment either as vapor or in conjunction with a drying medium (e.g., air or steam). This moist exhaust air contains substantial energy that can be recovered through heat-recovery systems.

Heat pumps (HPs) can play a key role by cooling the moist exhaust air below its dew point, thereby recovering the latent heat of the water vapor [4]. HP technology enables the supply of dehumidified and reheated air for drying processes. Using electrically driven HPs can achieve energy savings of up to 80% compared with conventional fossil-fuel-based systems [5,6] (Figure 1).

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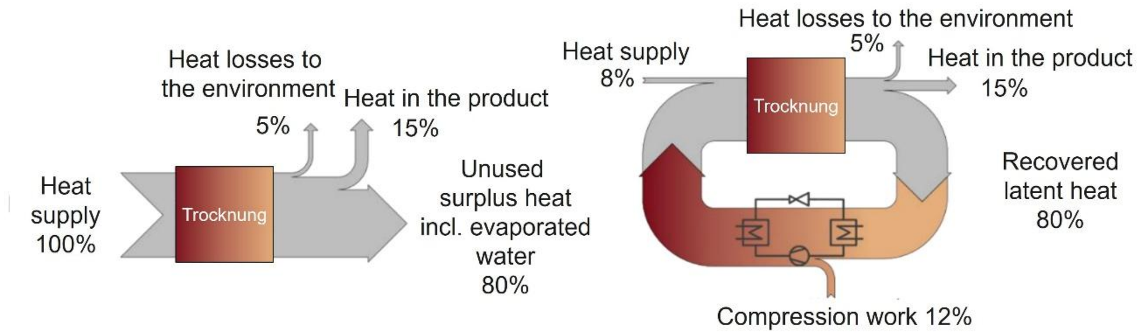

Figure 1. Comparison between conventional drying (open cycle) and heat-pump drying (closed cycle). The use of heat pumps enables energy savings of up to 80% through heat recovery (Source: Lauermann et al. (2023) [5] and IEA HPT TCP Annual Report (2025) [6]).

This paper presents an overview of case studies on High-Temperature Heat Pump (HTHP) drying in industrial applications. It synthesizes published cases and highlights key outcomes. The novelty lies in the clear presentation of integration concepts through schematics and visualizations, complemented by an overview of relevant literature for further reading. First, it compiles literature on HTHP applications in drying, followed by several realized case studies, including:

- HTHP for brick and starch drying,
- Drying of fish-feed pellets,
- Pulp drying using a transcritical R-1234ze(E) HTHP, and
- Spray drying of milk powder using a CO_2 heat pump.

Finally, conclusions and an outlook are provided.

2. Literature Review

Table 1 summarizes scientific literature on HTHPs in drying processes (extended from Arpagaus (2023) [7]). The list is organized into books, review articles, and case-study articles. The applications covered include, among others:

- Spray drying of fish feed or milk powder
- Drying of fish-feed pellets
- Starch and fruit drying
- Laundry drying
- Brick and tile drying
- Wood drying
- Laminate and sludge drying,
- and others.

Table 1 can serve as an entry point for readers interested in specific applications, guiding them to relevant references for more detailed information.

3. Realized Case Studies

3.1. High-temperature heat pumps for brick and starch drying

As part of the EU Horizon 2020 project Dryficiency (www.dryficiency.eu), coordinated by the Austrian Institute of Technology (AIT), two HTHP demonstrators for industrial applications were developed [8–11]:

- Brick drying at Wienerberger AG in Uttendorf, Austria (operating approximately 200 brick dryers worldwide), and
- Starch drying at AGRANA Stärke GmbH in Pischelsdorf, Austria (operating numerous dryers across 54 sugar and starch plants).

The HTHPs utilize waste heat from existing drying processes as a heat source, supplying hot water/air to the dryers and thereby reducing steam consumption. Both systems are designed for supply temperatures of up to 160 °C and a heating capacity of approximately 400 kW. By replacing conventional natural gas burners, they enable energy savings of up to 84% and CO_2 reductions of 60-80% compared to natural gas [8–10].

The systems employ semi-hermetic screw compressors from BITZER Kühlmaschinen GmbH, reciprocating compressors from Heaten AS (formerly Viking Heat Engines A/S), and novel lubricants from FUCHS Lubricants Germany GmbH. Both HPs are integrated into compact containers (8 m × 3 m × 3 m, L × W × H).

Table 1. Literature on heat pumps for drying processes. Some literature is in German (extended from Arpagaus (2023) [7]).

Titel (teilweise von Englisch auf Deutsch übersetzt)	Quelle
Books	
Advances in Heat Pump-Assisted Drying Technology	Minea (2016) [4]
Heat Pump Dryers: Theory, Design and Industrial Applications	Alves-Filho (2015) [12]
Heat Pump Drying Systems: Chapter 47	Kiang und Jon (2006) [13]
Review articles	
Optimal Designs of Air Source Heat Pump Dryers in Agro-food Processing Industry	Fernando und Rosentrater (2023) [14]
Integration of heat pumps in drying systems	Eikevik (2023, 2024) [15,16]
Heat pump heat recovery options for food industry dryers	Wang et al. (2018) [17]
A comprehensive review of heat pump wood drying technologies	Gao et al. (2024) [18]
Review of heat pump systems for drying application	Goh et al. (2011) [19]
Overview of Heat-Pump-Assisted Drying Systems, Part II: Data Provided vs. Results Reported	Minea (2015) [20]
Improvements in high-temperature drying heat pumps	Minea (2010) [21]
A review of heat pump drying: Part 1 – Systems, models and studies	Colak und Hepbasli (2009) [22]
A review of heat-pump drying: Part 2 – Applications and performance assessments	Colak und Hepbasli (2009) [23]
Heat pump drying: Recent developments and future trends	Chua et al. (2002) [24]
Heat pump-assisted continuous drying Part 1: Simulation model	Jolly et al. (1990) [25]
Heat pump-assisted continuous drying, Part 2: Simulation results	Jia et al. (1990) [26]
Articles with case studies	
Sprühtrocknungsverfahren mit HTWP, Rekuperator und elektrischer Heizung	Arpagaus et al. (2023) [27]
Sprühtrockner für die Herstellung von proteinreichem Fischfutter	Andersen et al. (2023) [28]
Integration einer Hochtemperatur-CO2-Wärmepumpe in einen Sprühtrocknungsprozess	Bellemo et al. (2022) [29]
Integration von CO2-HTWP und konventionellen Heizgeräten für Sprühtrockner	Bellemo und Bergamini (2022) [30]
Milchpulverherstellung mit Sprühtrocknung	Bühler et al. (2019) [31]
Integration von HTWP mit zeotropen Arbeitsflüssigkeiten für Sprühtrocknungsanlagen	Zühlsdorf et al. (2017) [32]
Tixotherm Process for drying milk permeate powder	Arpagaus et al. (2023a) [33]
Trocknung von Fischfutterpellets bei BioMar	Petersen und Zühlsdorf (2022) [34]
Industrietrockner	Holder und Schlehuber (2022) [35]
Ziegel- und Stärketrocknung	Wilk et al. (2021, 2022, 2023) [8,11,36]
Elektronische Spulentrocknung	Schlosser (2022) [37]
Analyse der Integration von WP in den Trocknungsprozess zur Dekarbonisierung in der Industrie	Kaida et al. (2020) [3]
Industrielle Wäscherei (Tunnelwaschmaschine, Wäschetrockner)	Bühler et al. (2020) [38]
DryFiciency: Großwärmepumpen in Europa - HTWP für die Ziegeltrocknung, Stärketrocknung, Tiernahrungstrocknung	Lauermann (2017) [39]
Laminattrocknung	Jakobs (2017) [40]
Schlammtrocknung	Warthmann (2006) [41]
Trocknung, Prozessintegration und Hochtemperatur-Wärmepumpen	Bertsch (2023) [42]
Kostengünstiger Wärmepumpen-Früchtetrockner für Entwicklungsländer: Technologie und Möglichkeiten	Bless et al. (2022) [43]
Wärmepumpen-Früchtetrockner für Afrika (Low-cost heat pump dryer for Burkina Faso)	Gschwend and Bertsch (2013) [44]

For brick drying, a two-circuit HP configuration with four reciprocating compressors per circuit is used. Condensers are connected in series, while evaporators are arranged in parallel. The refrigerant is the hydrofluorolefin (HFO) R1336mzz(Z) (Opteon™ MZ from Chemours), featuring a Global Warming Potential (GWP) of 2, critical temperature of 171 °C, non-flammability, and non-toxicity.

Figure 2 illustrates the integration concepts of both HTHP demonstrators. In brick production, drying occurs in a continuous tunnel kiln, reducing moisture content from ~28% to 2%. For starch drying, a waste heat recovery loop (intermediate water circuit at ~70 °C) serves as the evaporator's heat source, while the humid exhaust air at the outlet of the flash dryer (52 °C, 48% relative humidity) is not utilized. The heat generated in the condenser is transferred to the drying air via a water intermediate circuit and a water-to-air heat exchanger.

Figure 3 shows the COP values under various steady-state operating conditions (at least 10 hours) at constant temperatures and fixed compressor speeds. For the Wienerberger demonstrator, the COP ranges from 5.0 (84°C heat source outlet/120 °C heat sink outlet) to 2.2 (89 °C/160 °C). For the AGRANA demonstrator, the COP ranges from 3.1 (62 °C/121 °C) to 2.7 (73 °C/153 °C) [8,10]. The measured COP values are consistent with other published data for industrial heat pumps [45]. The solid line indicates the theoretical COP of a heat pump at 120 °C utilization temperature, based on 50% of the ideal Carnot COP. The demonstrators achieved efficiencies up to 50%, representing a satisfactory demonstration performance.

Overall, the Dryficiency project enabled the successful development of key HTHP components, including compressors, lubricants, and refrigerants, and their verification through more than 8,000 operating hours on both demonstrators [8,10].

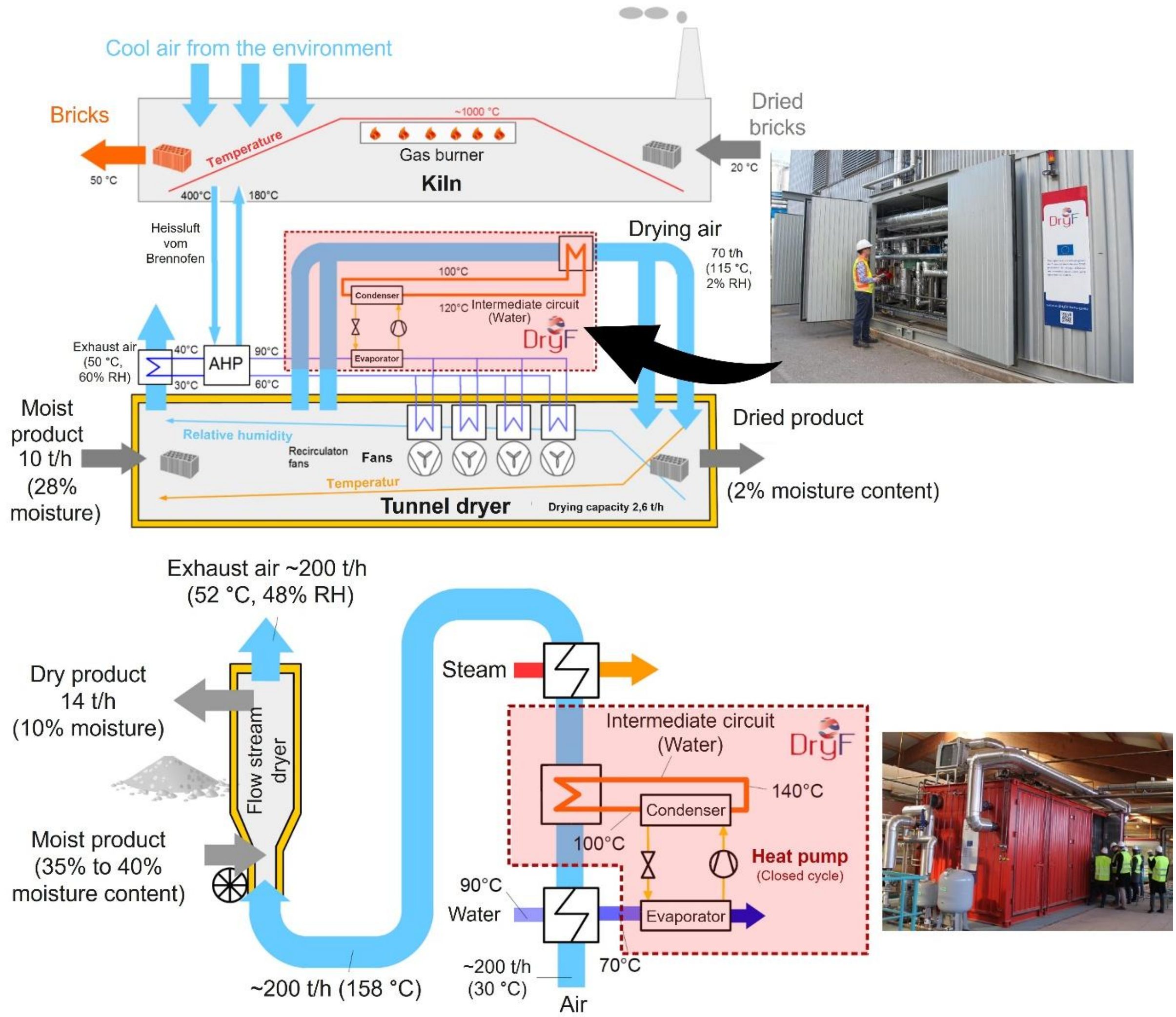

Figure 2. Schematics of HTHP integration for brick drying at Wienerberger AG in Uttendorf and starch drying at AGRANA Stärke GmbH in Pischelsdorf (Sources: Wilk et al. (2021, 2023) [8,10,11]).

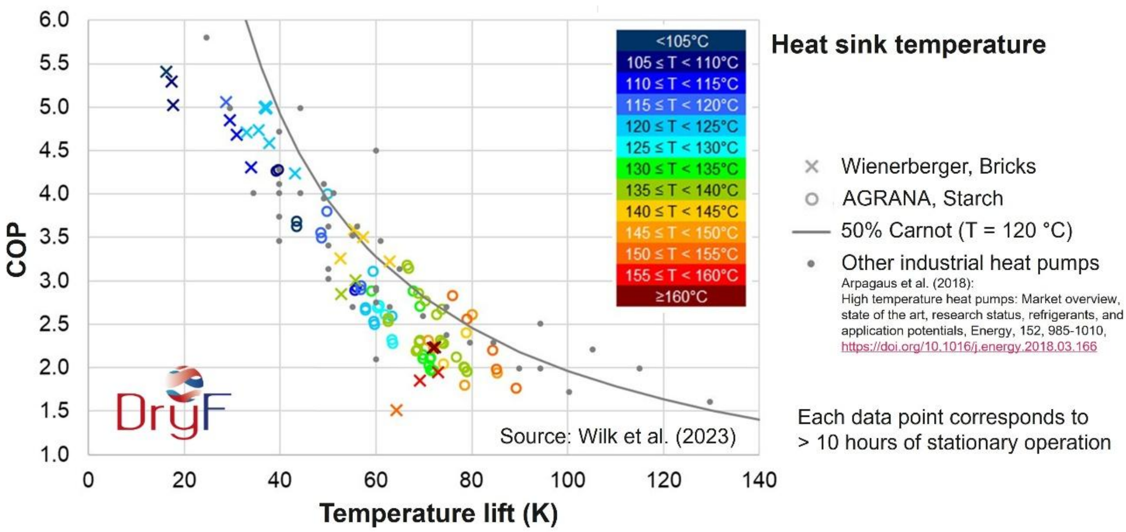

Figure 3. COP data from the operation of the HTHP demonstrators at Wienerberger AG (brick drying) and AGRANA Stärke GmbH (starch drying) (Source: Wilk et al. (2023) [10]).

3.2. Electrified feed dryer

The electrified feed dryers from Geelen Counterflow, equipped with integrated HTHP, represent a significant step toward sustainable and energy-efficient drying. Since 2018, these dryers have been designed for HTHP integration. Electrification can be implemented in a modular manner, offering advantages as gas and CO_2 prices rise. When higher temperatures are required, electric heating coils or gas burners can be used.

Warm, humid exhaust air from the drying process first passes through a counterflow heat recovery unit, where a heat exchanger transfers its heat to cold water in the HTHP circuit. Due to the temperature difference, water vapor in the exhaust condenses, releasing heat that warms the water, which then returns to the HTHP as a heat source.

In collaboration with project partner Combitherm GmbH, Geelen Counterflow implemented an electrified feed dryer for extruded aquafeed (e.g., salmon feed) at Cargill-EWOS in Bergneset, Norway [46–48]. Electrically driven HTHPs of type HWW 2/9583I R1233zd(E) generate hot water up to 120 °C in a secondary water circuit. This heat is transferred via heat exchangers to produce hot air for drying the wet product. The system utilizes BITZER CSH2T screw compressors, which enable condensation temperatures of up to 125°C, with R1233zd(E) as the working fluid (GWP < 1, non-flammable, low toxicity).

The average COP across the dryer is about 2.8. Approximately two-thirds of the heating power comes from zones operating with a temperature lift from 40 °C (source) to 120 °C (sink), yielding a COP of ~2.4. The remaining third operates with a temperature lift from 40 to 90 K, achieving a COP of ~4.0.

The Cargill-EWOS facility has been operational since April 2022 and consists of 15 drying decks and 4 HTHPs, providing a total heating capacity of 3,3 MW. The installation enables annual energy and CO_2 savings of 15,000 MWh (a 66–75% reduction compared to conventional systems) and 3,000 t CO_2.

Figure 4 shows the electrified feed dryer. Explanatory videos on the dryer's operation are available on YouTube [49,50]. The photo depicts the facility at Cargill-EWOS in Norway, featuring four HTHPs [46].

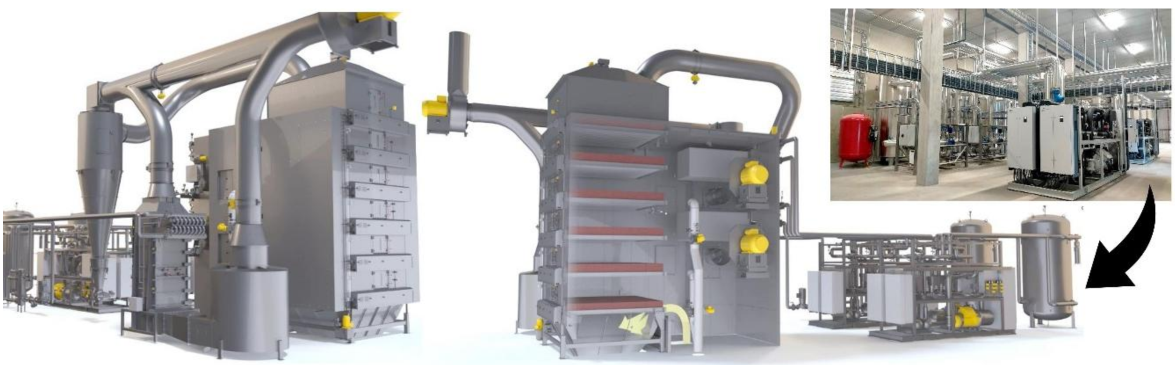

Figure 4. Electrified feed dryer from Geelen Counterflow with two Combitherm HWW 2/9583I R1233zd(E) heat pumps (1.2 MW each) (see animated YouTube videos) [49,50], Photo: 4 HTHPs at Cargill-EWOS in Norway [46]).

The electrified feed dryer currently employs two configurations for electrification:

- Full electrification using 120 °C HFO heat pumps (R1233zd(E)) with screw compressors
- Partial electrification using 90 °C NH_3 heat pumps (R717) with reciprocating compressors

Additional variants using natural refrigerants are feasible, including multi-stage steam compression (MVR), isobutane (R600a), and butane (R600). Projects currently in the implementation phase include [46,51]:

- South Korea – Royal Canin (MARS Petcare): Drying extruded pet food, 1.2 MW heating capacity. One line has been in operation since May 2022 with a COP of 2.9. Repeat orders for two additional lines are scheduled for delivery in 2025.
- Thailand – Nestlé Purina Amata: Drying extruded pet food, 2,4 MW heating capacity, 7-deck counterflow dryer. Commissioning planned for Q2/2025.

Several further projects are currently being planned in China, Germany, France, Belgium, Spain, the Netherlands, Turkey, and the USA.

3.3. Transcritical HTHP in pulp drying

TRANSPAC is the first transcritical HTHP using an HFO refrigerant to be deployed industrially for drying applications [52]. The HTHP demonstrator, providing around 580 kW of heating capacity, was installed at WEPA Greenfield in Château-Thierry, France, a pulp production facility [53,54].

The project was led by EDF R&D and Dalkia, with financial support of EUR 400,000 from the French environmental agency ADEME (Agence de la transition écologique) [52]. Additional partners included Armines, Dalkia Froid Solutions, a compressor manufacturer, and the paper producer WEPA Greenfield. The demonstrator was developed over a 4-year project (2017–2023) and has been in operation since April 2023 for waste-heat recovery [52,53]. A video presentation by Dalkia provides further insights into the project and the technology [55].

The system uses the HFO refrigerant R1234ze(E), which has a critical temperature of 109.4 °C (see the T-s diagram in Figure 5). Initial operating results confirm the expected industrial-scale performance [52]. With a waste-heat source of 70–80 °C and heating of the pulp dryer inlet air from 97 °C to 138 °C, the COP ranges from 3.6 to 4.2, with an average of 4.0 [53].

The transcritical HTHP replaces approximately 5 GWh of heat previously supplied by a gas boiler, resulting in annual reductions of around 1,000 t CO_2 (assuming a COP of 4) [53,55]. This corresponds to a 75% reduction in energy consumption and CO_2 emissions, which are 16–20 times lower than those from steam generation using natural gas [52].

Figure 5 illustrates the integration concept of the transcritical HTHP for waste heat recovery and drying air heating. The photos show the container housing and the piston compressor used in the system [52,54,56].

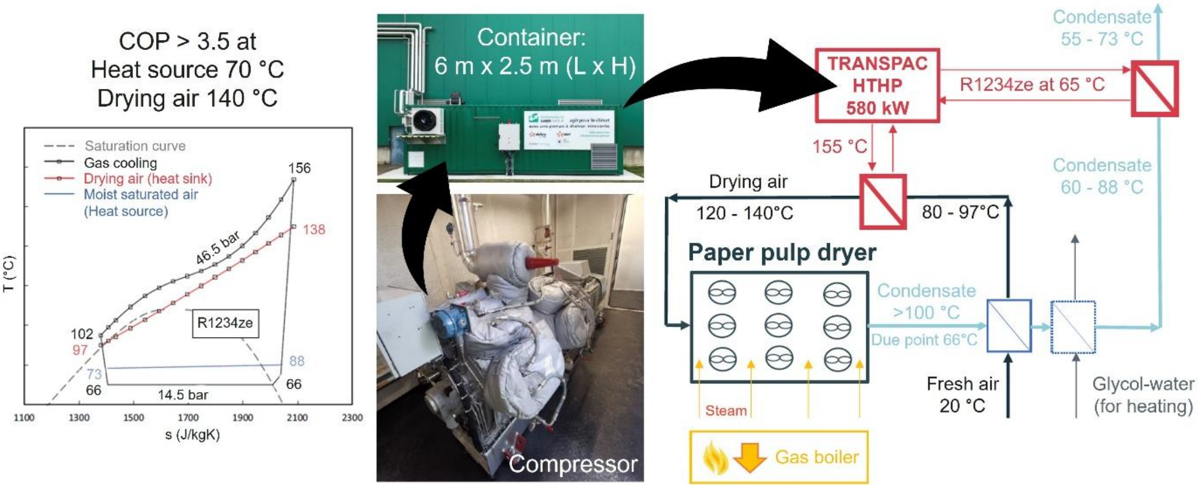

Figure 5. Concept for integrating the transcritical HTHP (TRANSPAC) at Wepa Greenfield into the pulp drying process for waste heat recovery and drying air heating (heating capacity: 580 kW, 120 to 140 °C, HFO refrigerant R1234ze). The photos show the container housing (6 m x 2.5 m, L x H) and the piston compressor used (Sources: Dalika Groupe EDF (2024) [52,54], EDF R&D (2024) [56].

The TRANSPAC technology originated from a 30 kW prototype developed in the laboratories of EDF R&D and MINES ParisTech in France, with financial support from ADEME [57–60]. The technology was patented by EDF (EP 2880 379 B1, WO 2014/020255).

The first version used the HFC refrigerant R32 [60]. A second-generation system using the HFO refrigerant R1234ze(E) [57,58] was later developed to preheat air up to 150 °C, for example, for tunnel-drying processes using waste heat at around 82 °C as a source. Experimental testing confirmed the technical feasibility.

For the prototype, commercially available CO_2 components were adapted, including a semi-hermetic reciprocating compressor (Bock HGX2/90), an electronic expansion valve (Danfoss CCM10), stainless steel/aluminum finned heat exchangers as the gas cooler and evaporator, and synthetic POE lubricant. Efficiency enhancements were analyzed using an internal heat exchanger (+6% COP), parallel compression (+9% COP), and a combination of both (+12% COP) [58].

The transcritical R1234ze(E) HTHP, with supply temperatures ranging from 105 °C to 140 °C, is suitable for most industrial facilities with waste-heat sources between 60 °C and 90 °C [55]. Typical sectors include the paper, food, chemical, metallurgy, and textile industries.

Applications include spray drying, evaporation, and distillation [54]. Additional potential exists in starch production, wood pellets, tiles and bricks, technical nonwovens, pulp, and pet food [52,54,55,57].

3.4. Transcritical CO_2 heat pump for spray drying plants

Since 2016, GEA has been conducting R&D on integrating heat pumps into spray-drying systems. Pinch analyses of several milk-powder spray dryers show that the pinch point typically lies close to the dryer exhaust temperature, usually between 58 °C and 70 °C [61], and thus represents the largest usable waste-heat stream.

Single-stage transcritical CO_2 HP technology has been identified as the most promising solution for spray-drying applications. Key advantages include the ability to reach CO_2 temperatures of up to 150 °C with semi-hermetic reciprocating compressors, simultaneous production of hot air and chilled water in a single compression stage, high heating COP at large temperature lifts, and the environmental friendliness and ease of handling of CO_2.

GEA's CO_2 heat pumps [62] (marketed as GEA AddCool® [63]) can simultaneously produce hot water at 90–130 °C and chilled water at about 2 °C. Specific investment costs without integration range from 200 to 300 EUR/kW, with heating capacities of 0.1–1.2 MW. The systems achieve heating COPs of up to 4.07 at 12 °C/8 °C (source in/out) and 11 °C/90 °C (sink in/out), and 3.13 at 6 °C/4 °C to 20 °C/130 °C [62].

GEA has patented a dedicated CO_2 HP integration concept (EP 3542114 B1, WO 2018/091049) designed to deliver high energy savings and increase dryer productivity while ensuring stable, year-round operation of the CO_2 heat pump [64].

A CO_2 HP prototype has been installed at GEA's drying test center in Søborg, Denmark. Figure 6 shows a simplified process flow diagram and photos of the prototype installation.

The prototype is connected to the main air stream of a GEA MSD® 20 spray dryer [65], typically operated at 1,800 kg/h, as well as to separate air streams for the Static Fluid Bed (SFB) and Vibro-Fluidizer® (VF), with a total water evaporation capacity of around 80 kg/h. The dryer is also equipped with electric heaters sized for full-air heating, ensuring a fast start-up for testing.

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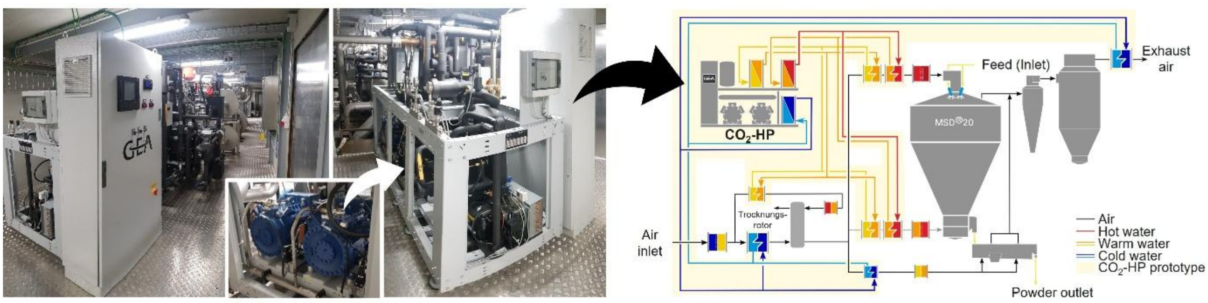

Figure 6. Simplified process flow diagram and photos of the GEA CO_2-WP prototype integrated into the GEA spray drying test center in Søborg (DK). The image shows the two semi-hermetic GEA Bock reciprocating compressors (Source: GEA R&D Center for Drying Technology, Søborg (DK), Bellemo et al. (2020) [29]).

The prototype system includes a CO_2 HTHP connected via CO_2/water heat exchangers to three water circuits, which transfer heat to and from the process air streams through water–air heat exchangers:

- Hot-water circuit (135 °C to 75 °C): Connected to the main and SFB air streams to heat the air to about 120 °C.
- Warm-water circuit (75 °C to 25 °C): Connected to the main, SFB, and desorption air streams to heat the air to about 65 °C.

- Chilled-water circuit (2 °C to 15 °C): Used for dehumidifying the inlet air, cooling the Vibro-Fluidizer® (VF) air, and recovering heat from the dryer exhaust.

The CO_2 heat pump is equipped with two semi-hermetic GEA Bock reciprocating compressors capable of compressing CO_2 up to 115 bar and 150 °C. The supercritical CO_2 is cooled in two serial brazed-plate heat exchangers, the first connected to the hot-water circuit and the second to the warm-water circuit. The CO_2 then expands into the wet-steam region, where liquid CO_2 evaporates to generate chilled water. Afterward, the CO_2 is superheated to achieve the required discharge temperature. The heat pump is designed for a maximum heating capacity of 90 kW and is controlled via GEA's proprietary Omni controller [66]. All components are commercially available.

Testing demonstrated stable operation, with the CO_2 heat pump producing hot water at around 130 °C, warm water at about 75 °C, and chilled water between 2 °C and 10 °C [67]. The CO_2 compressors, operating with suction temperatures of up to 50 °C and discharge conditions of up to 110 bar and 150 °C, performed smoothly within the manufacturer's specifications and the tolerances defined in EN 12900 [68]. Under these conditions, the drying air could be heated to up to 115 °C, achieving a heating COP of 2.8 [29].

In March 2023, GEA received an order from Arla Foods AKAFA to integrate the new GEA AddCool system [63] into a GEA MSD® 315 spray dryer at their Svenstrup (DK) facility [69]. At this site, the global dairy producer aims to manufacture milk powder using a more sustainable process. Since 2024, the system has been in operation and delivering the expected performance. The GEA technology is projected to reduce fossil-fuel consumption by half, significantly lowering the plant's CO_2 footprint.

4. Conclusions and Outlook

The realized case studies demonstrate the successful integration of high-temperature heat pump (HTHP) technology into industrial drying processes, with significant potential for further deployment and eliminating substantial amounts of fossil fuels. Electrically driven HTHPs can reduce energy consumption by 60% to 80% compared with conventional fossil-based systems (e.g., electrified feed dryer). Utilizing moist exhaust air and recovering latent heat is becoming an increasingly energy-efficient heat recovery strategy in dryers.

HTHP technology is gaining importance and opens new application areas in drying. The transcritical CO_2 heat-pump cycle is particularly suitable for heating air in food applications (e.g., spray drying), offering flexibility in temperature lift of up to about 130 °C on the heat sink side. The transcritical R1234ze HTHP represents a novel, innovative case with growth potential. The use of natural refrigerants such as CO_2 (R744) and synthetic low-GWP HFOs like R1336mzz(Z), R1233zd(E), and R1234ze(E) (used in a transcritical cycle) is also considered promising. Literature references are provided to substantiate the summarized facts and figures and to support further reading by interested readers.

Further research is needed to optimize HTHP integration at higher supply temperatures, as COP decreases with increasing temperature lift. Future developments are expected to focus on superheated-steam drying, multi-stage vapor compression, natural refrigerants such as isobutane (R600a), butane (R600) [70] or pentane (R601), and refrigerant blends [71,72] to better match temperature profiles on both the heat-source and heat-sink sides. New case studies and research insights will help accelerate knowledge sharing and technology adoption of heat-pump solutions in drying applications.

Acknowledgements

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