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Integration of High-Temperature Heat Pumps in Swiss Industrial Processes (HTHP-CH)

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Abstract

High-temperature heat pumps (HTHP) with supply temperatures above 100 °C are becoming increasingly important for the electrification and decarbonization of industry. However, their adoption is slow because there is still a lack of knowledge about their capabilities, design, control, and optimal integration, resulting in few practical implementation examples. This study investigates the technical and economic feasibility of HTHP integration based on case studies from the Swiss industry. ELSA (Estavayer Lait SA), Cremo SA, and Gustav Spiess AG support the research and provide access to industrial process data. ELSA, Switzerland's largest industrial dairy on a single site, is interested in a HTHP supplying steam for cleaning-in-place processes. Cremo SA manufactures dairy products and sees opportunities to integrate a HTHP in a milk permeate drying plant that consumes a large amount of 3 bar steam. Gustav Spiess AG produces meat products and sees potential for integrating a HTHP into sausage cooking processes for steam generation at about 115 °C. In addition, other Swiss industrial companies in the food, biotech, and chemical sectors also show interest in HTHPs for applications such as distillation, sterilization, drying, and steam generation. This study presents suitable HTHP integration concepts based on case studies with quantified efficiency gains, energy savings, CO_2 reduction, and cost-efficiency results. It also includes an up-to-date review of HTHP suppliers derived from participation in the IEA HPT Annex 58 that shares results and knowledge with international experts on HTHPs.

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Keywords: industrial processes; high-temperature heat pumps; techno-economic analysis; payback period; case studies; CO_2 emissions

1. Introduction

1.1. Application potential of industrial HTHPs in Switzerland

Switzerland has been pioneering in developing and commercializing heat pumps (HP). The first European HPs were realized in Switzerland (e.g., in 1877 at the salt works at Bex) [1]. In 2021, HP sales increased to an all-time high of 33'704 units (20% growth compared to 2020) [2]. Especially in the small-capacity range for single- and multi-family houses, HPs are an established technology for space heating and domestic hot water, with a market share of over 90% in new buildings. Above 100 kW heating capacity, 169 HPs were sold (around 0.5% of all units) since, in larger heating capacity ranges, oil and gas boilers still dominate process heat generation [3]–[5]. Therefore, replacing fossil heating systems with electrically-driven industrial HPs is

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a possible scenario to reduce CO_2 emissions from industry. High-temperature heat pumps (HTHP) with supply temperatures above 100 °C are increasingly important to replace fossil fuels in industries [6]–[8]. The most relevant application areas for HTHPs are the food/beverage, chemicals, and pulp/paper industries for processes like drying, evaporation, sterilization, or similar thermal processes with available waste heat from about 30 °C to 70 °C and process heat demand from 80 °C to 150 °C [9]. Based on annual energy consumption of around 43 TWh in Switzerland [10], a 30% share of process heat and steam below 150 °C [11], and a moderate conversion rate of 40% to HPs and HTHPs [12], the addressable energy savings potential from the use of HTHPs in the Swiss industry can be roughly estimated at 2’893 GW/a which is approximately 6.7% of the total process heat demand [13] (Table 1).

Table 1. Potential energy savings through industrial HTHPs in Switzerland (top-down estimate) [13].

	Energy consumption	**Data source / Estimations**
Swiss industry	42’972 GWh	154,7 PJ as of 2018 [10]
Process heat demand	24’107 GWh	56,1% (>80 °C) [10]
Process heat and steam demand below 150 °C	7’232 GWh	30% (estimate based on Heat Roadmap Europe [11])
Energy savings potential through the use of HTHPs (= addressable process heat share)	2’893 GWh (6.7% of the process heat demand)	40% (moderate estimate of conversion rate to HPs and HTHPs based on technical analysis within SCCER EIP [12])

Compared to natural gas, which has an emission factor of 0.201 kg CO_2 per kWh_{th} of useful heat [14], the consumer electricity mix available in Switzerland is 0.128 kg CO_2/kWh_{el} [15]. On this basis and with an average COP of 3.0 to 4.0 for an industrial HTHP at about 40 K to 60 K temperature lift from heat source inlet to sink outlet (assuming 45% Carnot efficiency [6], [7], [16]), the generated CO_2 emissions per useful heat are about 0.032 to 0.043 kg CO_2/kWh, which is 5 to 7 times lower than for a gas boiler (assuming 90% boiler efficiency). Assuming that integrated HTHPs would run with 5’000 operating hours per year on average, this results in a total heating capacity of 579 MW and, with specific investment costs (incl. installation, without integration, valid for 500 kW_{th} HP size) of approx. 450 to 700 EUR per kW heating capacity [17], a potential market of 260 to 405 million EUR for Switzerland. Assuming an average heating capacity per HTHP unit of 1 MW_{th} is equivalent to installing around 579 HTHP units.

Thus, integrating industrial HTHPs will contribute to energy savings, CO_2 reduction, and a substantial new market. Furthermore, expanding renewable energy and increasing energy efficiency in industrial processes align with the federal government’s Energy Strategy 2050 [18]. Consequently, HTHP technology supports the efforts of Switzerland’s net carbon emissions to net zero by 2050 [19].

1.2. Existing challenges for the wider spread of HTHPs

However, HTHPs are just beginning to enter the market of industrial heat production. There is still a lack of knowledge about available HTHP technologies and products (>100 °C supply temperature), methods for optimal integration, proper sizing, control, dynamic behavior, and techno-economic feasibility, resulting in few realized references with operational experience. As highlighted in a white paper [20], demonstration projects with increased knowledge sharing at the international level are needed to drive further HTHP technology dissemination and achieve greater visibility, particularly in process electrification. In this context, the authors of this study participate as Swiss representatives in the IEA HPT Annex 58 on HTHPs to exchange results and knowledge with international experts. In recent studies, the techno-economic feasibility of integrating HTHPs for steam generation in distillation applications was investigated [21], [22], and an up-to-date overview of the latest HTHP developments and products for supply temperatures above 100 °C was presented at the China Heat Pump Conference 2022 [16]. The analysis of the integration of HTHPs into ammonia and pulp production was also presented at CPOTE 2022 [23] and ECOS 2022 [24].

1.3. Objectives of this study

This study investigates the technical and economic feasibility of HTHP integration based on case studies in Swiss industrial companies with heat source temperatures from 40 to 80 °C to provide process heat (e.g., steam) at 115 to 150 °C and about 0.5 to 3.5 MW heating capacity. First, a review of current HTHP products and the corresponding working domains (e.g., heating capacity, temperatures) is given. Next, a simple economic model is used at an early planning stage to assess whether a HTHP integration could be economically viable. Then, the investment and operating costs of HTHPs are analyzed for the case studies using a cost model with different input parameters. Finally, the payback period, the avoided CO_2 emissions, and the energy savings are calculated, and the main influencing factors are discussed in a sensitivity analysis.

2. Market review of industrial HTHPs and operating ranges

The range of industrial HTHP products on the market has grown steadily in recent years (especially since 2018 [6]). Table 2 presents an overview of 33 HTHP products with heat supply temperatures above 100 °C based on information collected in the IEA HPT Annex 58 project [25]. The list includes closed-cycle and open-cycle HPs for mechanical vapor recompression (MVR). It is structured by maximum supply temperature, HTHP supplier, country, compressor type, the working fluid (refrigerant), maximum heating capacity, and technology readiness level (TRL) [16]. The specific investment costs are also given in EUR/kW$_{th}$. It should be noted that the HTHP suppliers provided the information without third-party validation. Therefore, the data is indicative and may vary in the final installations depending on the application-specific parameters.

Table 2. Overview of HTHP technologies and suppliers structured by maximum supply temperature above 100 °C [16] (Data based on IEA HPT Annex 58 [25]) (Note: The HTHP suppliers provided all information without third-party validation. Therefore, the information is indicative and may vary in final installations depending on application-specific parameters).

HTHP supplier (High-Temperature Heat Pump)	Country	Product	Compressor type	Working fluid (Refrigerant)	Max. heating capacity (MW)	Max. supply temp. (°C)	TRL (Technology Readiness Level)	Spec. invest. cost (EUR/kW$_{th}$)
Spilling	DE	Steam Compressor	Piston (MVR)	R718 (water)	15	280	9	100 to 400
Enerin	NO	HoegTemp	Piston	R704 (helium)	10	250	6	600 to 800
Qpinch	BE	Heat Transformer	Chemical heat transformer	R718, H_3PO_4 and derivatives	2	230	9	1000 to 2000
Piller	DE	VapoFan	Turbo (MVR)	R718	70	212	8 to 9	850
Olvondo	NO	HighLift	Piston (double acting)	R704	5	200	9	1200
Turboden	IT	LHP	Turbo	Application specific	30	200	7 to 9	300 to 700
ToCircle	NO	TC-C920	Rotary vane	R717 (ammonia), R718	5	188	6 to 7	250 to 430
Kobelco MSRC160	JP	MSRC160	Twin -screw (MVR)	R718	0.8	175	9	n.a.
Kobelco SGH165	JP	SGH165	Twin-screw (MVR)	R245fa/R134a (mixture), R718	0.62	175	9	n.a.
Heaten	NO	HeatBooster	Reciprocating, custom design	HFOs (hydrofluorolefins)	6	165	7 to 9	250 to 350
SPH	DE	Thermbooster	Piston	HFOs (hydrofluorolefins)	5	165	6 to 8	150 to 1000
SRM	SE	Compressor for water vapor	Screw (MVR)	R718	2	165	5	n.a.
Siemens Energy	DE	Industrial Heat Pump	Turbo (geared or single-shaft)	R1233zd(E), R1234ze(E)	70	160	9 (to 90 °C)	250 to 800
Enertime	FR	HTHPs	1- or 2-stage centrifugal	R1336mzz(Z), R1224yd(Z), R1233zd(E)	10	160	4 to 8	300 to 400
Weel & Sandvig	DK	WS Turbo Steam	Turbo (MVR)	R718	5	160	4 to 9	150 to 250
Rank	ES	Rank® HP	Screw	R245fa, R1336mzz(Z), R1233zd(E)	2	160	7	200 to 400
MAN	DE	ETES CO_2 Heat Pump	Centrifugal turbo with expander	R744 (CO_2)	50	150	7 to 8	300 to 500
Epcon	NO	MVR-HP	Centrifugal fan / Blower	R718	30	150	9	200 to 400
Ohmia Industry	NO	SPHP	Piston, Centrifugal fan (MVR)	R717, R718	10	150	7 to 8	n.a.
ecop	AT	Rotation Heat Pump K7	Rotational heat pump	ecop fluid 1 (He, Kr, Ar)	0.7	150	6 to 7	700
Mayekawa FC Comp	BE	FC-compressor	Screw	R601 (n-pentane)	1	145	5	720
GEA Refrigeration	NL	CO_2 Heat Pump	Semi-hermetic piston	R744	1.2	130	8	200 to 300
Mitsubishi Heavy Ind.	JP	ETW-S	Two-stage centrifugal	R134a	0.6	130	9	n.a.
Hybrid Energy	NO	HyPAC-S	Piston/screw	R717/R718 mixture	5	120	9	200 to 600
Johnson Controls	DK	Cascade Heat Pump System	Reciprocating	R717, R600 (n-butane) (cascade)	5	120	7 to 8	n.a.
Fenagy	DK	H1800-AW/WW	Reciprocating	R744	1.8	120	5 to 6	250 to 425
Mayekawa HS Comp	BE	HS-compressor	Piston	R600 (n-butane)	0.75	120	7	450
Kobelco SGH120	JP	SGH120	2-stage twin-screw	R245fa	0.37	120	9	n.a.
Mayekawa EcoCircuit	JP	Eco Circuit 100	Reciprocating	R1234ze(Z)	0.1	120	9	n.a.
Fuji Electric	JP	Steam Generation Heat Pump	Reciprocating	R245fa	0.03	120	9	n.a.
Emerson	US	Cascade Solution	Scroll and EVI scroll	R245fa, R410a, R718	0.03	120	6	n.a.
Skala Fabrikk	NO	SkaleUP	Piston (semihermetic)	R290 (propane), R600 (cascade)	0.3	115	7	500 to 700
Mayekawa EcoSirocco	JP	Eco Sirocco	Reciprocating	R744 (CO2)	0.1	100	8 to 9	n.a.

Figure 1 shows the industrial HTHP products sorted by their maximum heat supply temperature and heating capacity. The heating capacities range from laboratory demonstrators of about 10 kW to larger 70 MW units. Illustrated in color are the compressor technologies, including screw, piston, turbo, and others like the rotary vane compressor from ToCircle, the heat transformer from QPinch, or the Rotational HP from Ecop using a noble gas in a Joule cycle. These last examples show various technologies emerging alongside more classical Carnot cycles.

In most cases, turbo compressors are used for large heating capacities. For HTHP applications and high temperature lifts, compressors must be able to handle high pressure ratios. Therefore, the compressor manufacturers offer optimized designs for special applications.

For HTHP application, the steam compressors must preferably offer high flow rates at low suction pressure, high pressure ratios to reduce the number of compression stages, temperature resistance (e.g., need for liquid injection), and long-term corrosion resistance. In particular, a development perspective is small steam compressors for integrating HTHPs in industrial processes with an open cycle or combined in a two-stage cycle with MVR [26].

For example, Spilling's piston steam compressors operate at suction pressures above 1.4 bar(a) (110 °C) and achieve temperature lifts of up to 100 K with a 3-stage compression design in one unit. Piller's VapoFans are used in multi-stage MVR applications with suction pressures down to about 100 mbar(a) (45 °C). Enerin and Olvondo provide HTHPs with helium (R704) as working fluid and double-acting piston compressors in a Stirling cycle, which allow flexible operation conditions, high lifts, and supply temperatures above 200 °C.

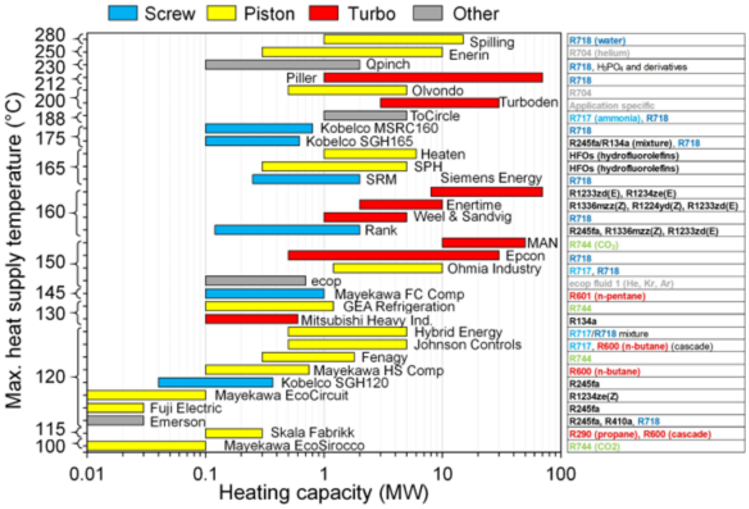

Fig. 1. Industrial HTHPs products sorted by maximum heat supply temperature (>100 °C) and heating capacity. The implemented compressor technology is color-coded (blue: screw, yellow: piston, red: turbo, grey: others). The table indicates the refrigerant [16].

Some HTHP suppliers provide closed-cycle HTHPs with up to 165 °C supply temperature using HFO refrigerants, e.g., the HeatBooster from Heaten or the ThermBooster from SPH. Other suppliers realize steam-generating HP using natural refrigerants, e.g., Ohmia Industry with ammonia (R717) in a bottom cycle and water (R718) in an open top cycle with MVR, Mayekawa with n-butane (R600), or Johnson Controls (Sabroe) with an R717/R600 cascade system using piston compressors.

Hybrid Energy uses ammonia/water (R717/R718) as the working medium in an absorption/compression cycle. As a result, temperatures up to 120 °C are achieved with high efficiency, and potentially high temperature glides on the heat source and sink. Recently, Fenagy commercialized CO_2 HPs for hot water heating from 30 to 120 °C with heating capacities up to about 1,800 kW.

Other manufacturers of HTHP products not listed in Table 2 and Figure 1 are Ago Calora (absorption-compression cycle, R717/R718, up to 150 °C), Ochsner (HFO refrigerants, up to 130 °C), Oilon (R1233zd(E), up to 120 °C), PureThermal (Pure PLUS, up to 120 °C), ThermoDraft (R1233zd(E), up to 120 °C), or Combitherm (HFO refrigerants, up to 120 °C). Finally, several large-scale HTHPs with > 10 MW heating capacity for industrial applications are supplied, for example, by Friotherm, MAN Energy Solutions, Turboden, Mitsubishi MHPS, or Siemens Energy.

Figure 2 shows the operating maps of some industrial HTHPs as a function of the heat source and sink temperature. In particular, there is a higher share around 50 °C heat source and 120 °C sink temperature. The operating limits are determined by the permissible condensation pressure, evaporation pressure, compression ratios, differential pressure across pistons, compressor speed, discharge gas temperatures, lubrication (e.g., oil temperature issues), and lowest allowable suction pressure.

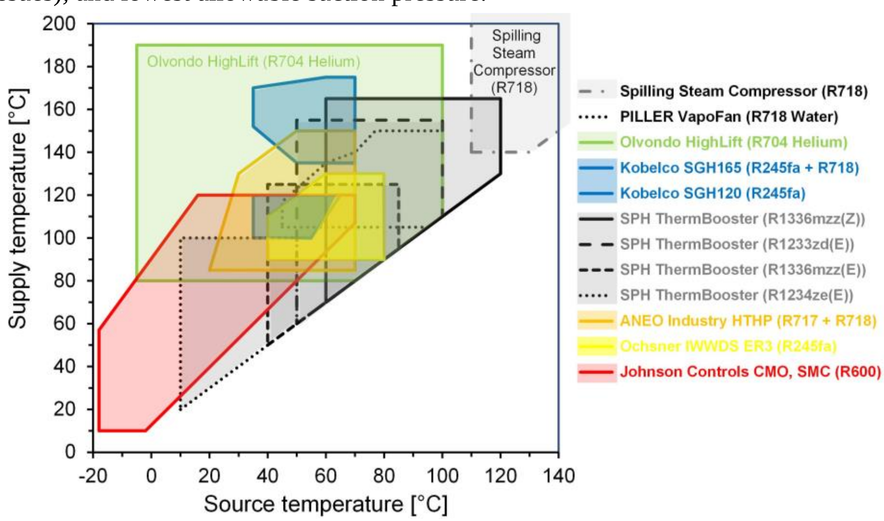

Fig. 2. Operating maps of some industrial HTHPs as a function of heat source and supply temperature.

Overall, Table 1 and Figures 2 and 3 demonstrate the availability of HTHP products and steam compressors and can be used as decision-support data for selecting appropriate HTHP suppliers. A preliminary technical feasibility check for HTHP integration consists of verifying the availability of a HTHP compatible with the temperature levels of the heat source and sink and heating capacity for a given project. In addition, industrial site constraints may further limit the HTHP integration options, such as the choice of refrigerant used (e.g., natural or synthetic), cycle concept (e.g., open, closed, or combinations), and space limitations.

Finally, a Pinch analysis can determine the optimal HTHP integration in an industrial context, which also identifies heat recovery options to increase efficiency and reduce energy consumption. Depending on the application, tailor-made HTHP designs are required (i.e., concepts for large temperature glides in the heat sink versus steam generation with no temperature glide).

3. Case studies and economic model

The following section describes case studies of potential HTHP integrations from the industrial companies ELSA, Cremo SA, and Gustav Spiess AG that support the Swiss project Annex 58 HTHP-CH by giving access to industrial process data. Furthermore, various other Swiss industrial companies (e.g., food, biotech, chemical) and HP suppliers are in contact with the project team showing interest in HTHP integration.

3.1. Case Study at ELSA (Estavayer Lait SA)

ELSA (Estavayer Lait SA) is Switzerland's largest dairy on a single site, processing around 260,000 t/a of milk into a wide range of fresh dairy products, such as UP/UHT milk, yogurt, quark, and cream. The main heat treatments are pasteurization and sterilization in the temperature range of 65 to 155 °C. In addition to the production processes, CIP processes (Cleaning in Place) require large amounts of water and are an important steam consumer (e.g., 4.5 bar(a), 148 °C) (Figure 3). Today, process steam is generated by a wood chip steam boiler and several natural gas boilers (71.6 GWh/a or 275 kWh/t milk processed).

The process requirement for CIP is keeping the circulating basic and acidic solutions at 75 °C and 60 °C respectively, while the"sterilization" step of processing equipment, taking place after cleaning and, if needed, before the next operation, requires circulating hot water at 90 °C. These requirements could, in principle, be fulfilled with a hot utility below 100 °C; however, retrofitting the CIP stations (comprising 65 heat exchangers in total) for a hot water utility at 95 to 100 °C instead of steam at 4.5 bar(a) would be both expensive and difficult to implement because of the lack of space.

Therefore, to save energy and water, ELSA is interested in integrating steam-generating HTHPs that use waste heat from the NH_3 chillers (about 23.7 GWh/a at 40 °C, currently discharged through cooling towers) or drain water (about 490,000 m^3/a at 50 °C) as a heat source to replace some of the steam required for the CIP processes (about 22.7 GWh/a steam in 7,200 h of operation corresponding to 3.15 MW). Although the heat sources and sinks have yet to be confirmed, Figure 3 shows potential HTHP integration points for the CIP plants. Measurements are ongoing to determine the mass and heat balance of CIP operations and to check whether a significant share of the consumed 4.5 bar(a) steam could, in practice, be supplied at a significantly lower temperature and affordable costs.

The electricity price for 2023 is around 0.18 CHF/kWh [27] in Estavayer for a large industrial company (Category C7), and the gas price (Type X) is about 0.13 CHF/kWh, including CO_2 tax of 0.02 CHF/kWh [28]. These conditions result in a favorable electricity-to-gas price ratio of around 1.4. Compared with natural gas, which has a CO_2 emission factor of 0.201 kg CO_2 per kWh_{th} [14], an average Swiss consumer electricity mix of 0.128 kg CO_2/kWh_{el} is considered [29]. The cost multiplication factor for planning and integration is assumed to be 3.0 because the installation environment is quite complex, and space is tight.

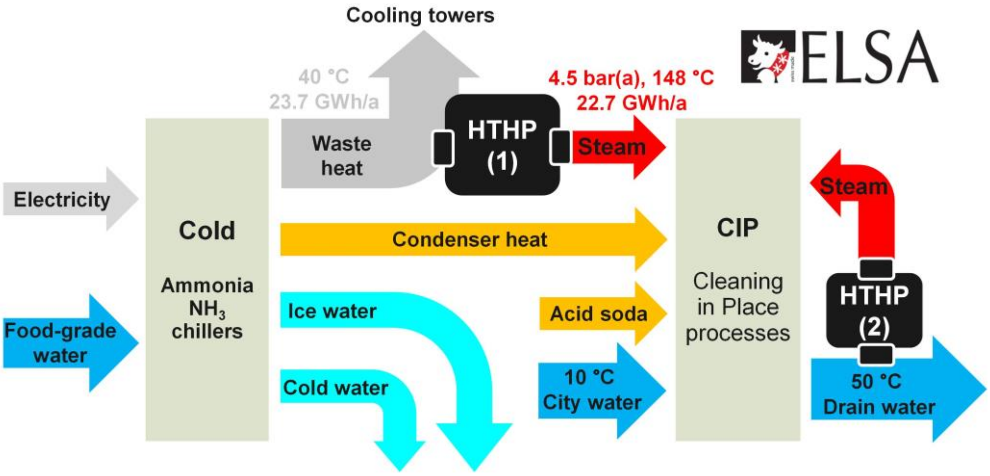

Fig. 3. Potential integration points for a steam-generating HTHP at ELSA using waste heat from the ammonia chillers at 40 °C as a heat source (1) or heat from drain water at 50 °C (2).

3.2. Case Study at Cremo SA

Cremo SA in Villars-sur-Glâne processes around 240,000 t/a of milk into various dairy products, including cheese (Gruyère, Vacherin fribourgeois, Raclette), butter, skim milk, milk proteins, and milk permeate powder. Today, the heat is supplied by two 5 MW gas-fired steam boilers (12 t/h steam, baseline consumption). In addition, a district heating network (105 °C/80 °C supply/return) from the nearby waste incineration plant provides heat to an internal hot water loop at 105 °C/60 °C that is connected to spray dryers (for preheating air), a TIXOTHERM™ drying process [30], evaporators, pasteurizers, CIP stations, building HVAC, and tap hot water. In case of a future reduction of the district heating temperature to 80 °C / 60 °C, the possibility of a large-scale HTHP is considered (around 5 to 10 MW_{th}) to adapt to the changing heat transfer rate (Figure 4).

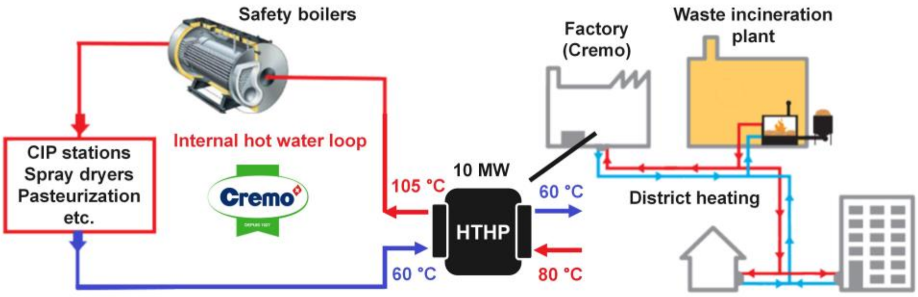

Fig. 4. Potential HTHP integration point at Cremo using district heat as a source and upgrading the heat to the internal hot water loop.

Another potential integration point for a HTHP has been identified in the TIXOTHERM™ drying plant (Figure 5), which produces milk permeate powder (containing milk sugars) and currently consumes about 10% to 15% of the total steam demand for heating a Rosinaire™ paddle dryer [30]. Presently, there is only limited heat recovery on the humid exhaust air. Therefore, this case study is *a priori* suitable for a HTHP integration to supply low-pressure steam at around 1.4 bar(a) (110 °C) to the paddle dryer using humid exhaust air as a heat source (65 °C) and substitute steam generation from the steam boilers.

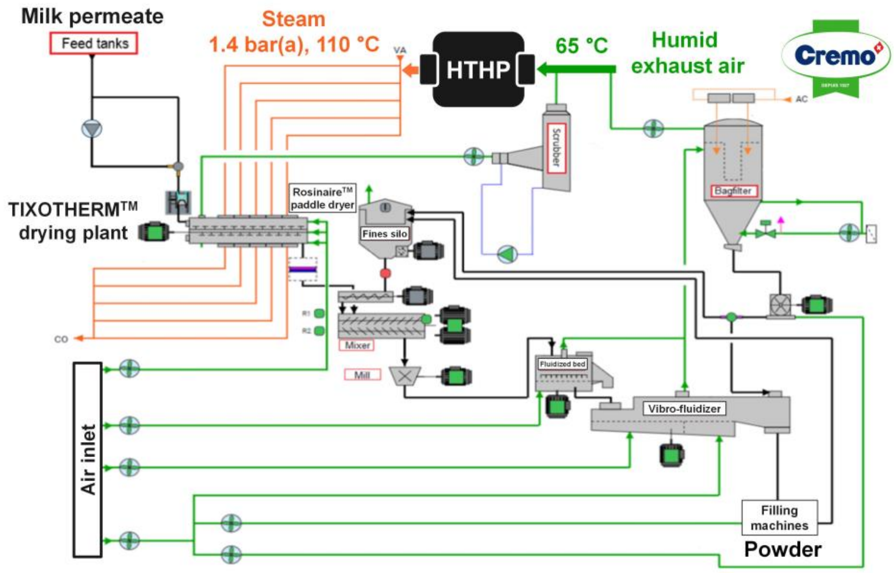

Fig. 5. Potential HTHP integration point at Cremo in the TIXOTHERMTM drying process with a RosinaireTM paddle dryer, where humid exhaust air could be used as a heat source to generate steam.

Figure 6 (left) shows the calculated Composite Curves (CCs) as the initial situation before the integration of a HTHP, indicating a Heat Recovery (HR) potential through direct heat transfer of about 600 kW between air flows and a Pinch temperature at around 70 °C. Furthermore, Figure 6 (middle) shows the corresponding Grand Composite Curve (GCC) with an integrated HTHP, providing a 940 kW condensation capacity at 120 °C and 570 kW evaporation capacity at 38 °C, from which a COP of 2.3 can be derived (see COP-fit formula in Figure 8). Finally, Figure 6 (right) shows the CCs after integrating the HTHP. The example demonstrates a potential reduction of the Hot Utility (HU) by 100% (from 940 to 0 kW) and the unused waste heat by 47% (from 1,204 to 634 kW), and an increase of the HR potential by 249% (from 605 to 2,113 kW).

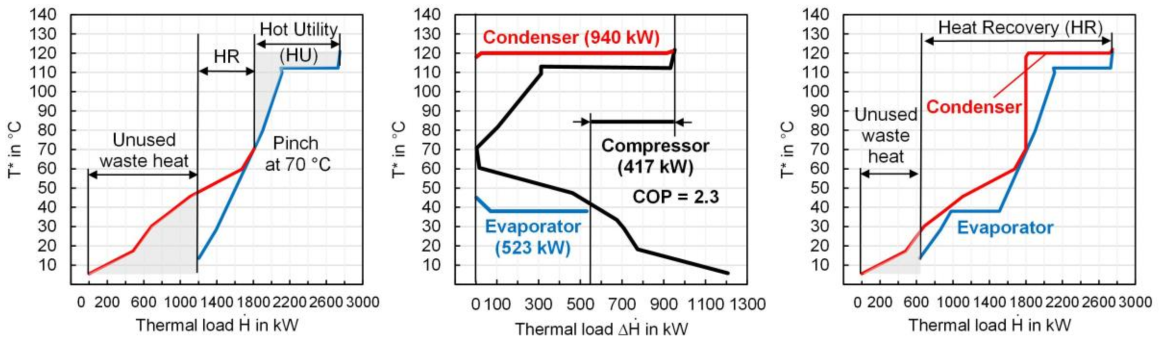

Fig. 6. Composite curves (CC, left) and grand composite curve (GCC, right) of the TIXOTHERM™ process with paddle dryer at Cremo showing the potential HTHP integration providing low-pressure steam at 110 °C and using humid exhaust air as a heat source (Pinch at 70 °C, evaporation temperature at 38 °C, condensation temperature at 120 °C, COP of 2.3).

A challenge is the low evaporation temperature (and thus the large temperature lift of 80 K) and the probably insufficient evaporation capacity if the waste heat is to be recovered exclusively from the drying process. Therefore, additional waste heat sources must be identified at about 35 to 40 °C. The estimated annual operating time of the potential HTHP is about 6,400 hours, which is within the range of various techno-economic studies presented in a literature review [21], [22]. The electricity price for a customer of the size of Cremo is 0.2 CHF/kWh$_{el}$, and the gas price is 0.11 CHF/kWh$_{th}$, corresponding to an electricity-to-gas price ratio of about 1.8. The CO_2 emission factor of electricity at Cremo is around the average Swiss consumer electricity mix of 0.128 kg CO_2/kWh$_{el}$ [29], as the mix contains renewables, just not purely renewables. Furthermore, a discount rate of 2% is used to estimate the discounted payback period of the HTHP investment. The cost multiplication factor for calculating planning and integration costs is assumed to be 2.0.

3.3. Case Study at Gustav Spiess AG

Gustav Spiess AG in Berneck (SG) produces meat products such as sausage, ham, and bacon. Today, a gas boiler provides steam (6 to 8 bar(a)) to heat the pasteurization and cooking/smoking cabinets (Figure 7). The steam pressure is reduced to 1.5 bar(a) (115 °C) to achieve cabinet temperatures of 85 to 90 °C and a sausage core temperature of about 72 °C. Here, integrating a 550 kW_{th} steam-generating HTHP is under consideration, using the waste heat from the NH_3 chillers as a possible heat source at 40 to 50 °C. Typical operation is 12 hours per day, 250 days per year, resulting in an annual operating time of about 3,000 hours. The expected payback period for new energy-related infrastructure investments is about 8 to 10 years. The electricity price for medium-sized customers in the given area is 0.25 CHF/kWh, and the gas price is 0.17 CHF/kWh resulting in an electricity-to-gas price ratio of 1.5, which appears favorable for electricity-powered heating and cooling technologies. The purchased electricity mix is nuclear energy with a low CO_2 emission factor of about 0.012 kg CO_2/kWh_{el}. The cost multiplication factor accounting for planning and integration is assumed to be 2.0.

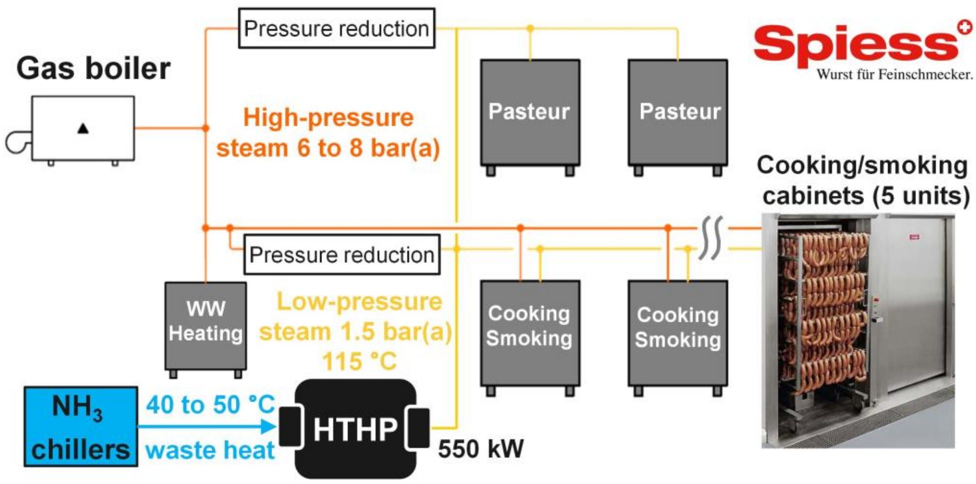

Fig. 7. Possible integration point of a steam-generating HTHP at Gustav Spiess AG for sausage cooking/smoking processes.

3.4. Economic evaluation and COP estimation

The economic evaluation of the case studies is based on a calculation tool developed in MS Excel, illustrated in Figure 8 [21], [22]. It assumes that the investment of the gas boilers is depreciated and that the gas boilers remain for production safety, redundancy, start-up operation, and peak load coverage. Input parameters to the evaluation tool are electricity price (c_{el}), gas price (c_{fuel}), operating hours (t), heating capacity ($\dot{Q}_h$), temperature lift between the heat source and sink (ΔT_{lift}), specific investment costs ($c_{inv,HP}$), maintenance cost factor ($f_{maintain}$), interest rate (i), the emissions factors of electricity and fuel (f_{CO2}), and CO_2 tax refund (subsidies). The output results are the COP, CO_2 emissions reduction ($\dot{m}_{CO2,reduction}$), annual cost savings ($C_{savings}$), and the payback periods (PP). The calculation tool helps to quickly evaluate the economic feasibility as a "go/no-go" decision.

1. First, the efficiency of the HTHP is estimated using the temperature lift (ΔT_{lift}) and a COP fit-curve ($COP = 52.94 \cdot \Delta T_{lift}{}^{-0.716}$) derived from quotes from various heat pump suppliers [21], [22].
2. Next, the investment costs ($C_{inv,HP}$) of the industrial HTHPs are evaluated based on the specific investment costs ($c_{inv,HP} = 3'157 \cdot \dot{Q}_h{}^{-0.322}$) according to price information from heat pump suppliers, the heating capacity ($\dot{Q}_h$), and a cost multiplication factor ($f_{inv,HP}$) accounting for planning and integration (typically between 1.5 to 4.0 depending on the complexity of integration, e.g., including heat storage, site's electrical installation, piping, hydraulics, etc.) [21], [22].
3. Then, the annual cost savings are calculated considering the following:
    - electricity cost (C_{el}) to operate the HTHP,
    - maintenance costs ($C_{maintain}$) of the HTHP using a multiplication factor ($f_{maintain}$) on capital cost (typically between 1.5% to 6%, in the case studies, 4% is used) [21], [22],
    - saved fuel costs (C_{fuel}) (assuming 90% boiler efficiency η_{fuel}), and
    - possible refunds of CO_2 reduction (C_{CO2}) (e.g., carbon taxes or subsidies).
4. After that, the payback period of the HTHP investment is evaluated as a trade-off between the investment costs versus the expected annual cost savings resulting from the heat pump investment.

5. Finally, the discount rates (i) are considered to calculate the discounted payback periods (DPP) [31], depending on the investor's risk tolerance (e.g., sector, company size, energy intensity, funding source, new technology, etc.) [32]. Typical discount rates for HP investments range from 5% to 15%, according to reviewed literature [21], [22]. The DPP (discounted payback period) is the period after which the cumulative discounted cash inflows cover the initial investment [31]. The DPP can therefore be interpreted as a period beyond which a project generates economic profit. In contrast, the static PP gives a period beyond which a project generates accounting profit.

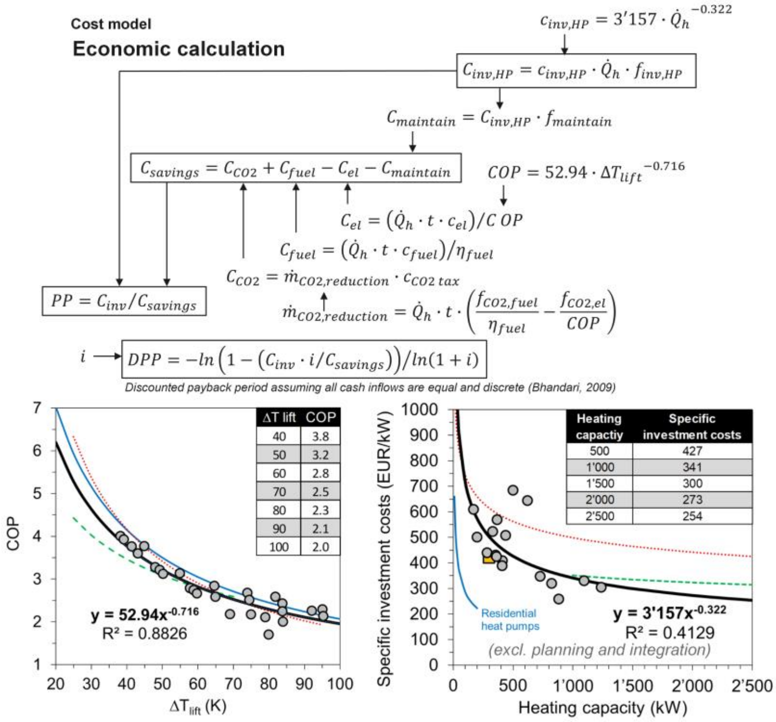

Fig. 8. Economic calculation, COP, and specific investment costs to derive the payback period for HTHP integration [21], [22].

4. Results and discussion

Table 3 summarizes the results of the three case studies. The calculations lead to payback periods of 2.0, 3.7, and 3.3 years, which means that HTHP integration would be cost-effective under current assumptions. Overall, the case study examples show significant annual energy savings of 55%, 60%, and 66%, and CO_2 emission reductions of 71%, 75%, and 98%, respectively. The COP varies between 2.0 and 2.7 according to the COP-fit function shown in Figure 8.

Table 3. Results of the case studies, with COP, energy savings, investment costs, reduction of CO_2 emissions, and payback periods.

Heat pump conditions	Symbol	Unit	ELSA CIP process	Cremo Milk drying	Gustav Spiess Sausage cooking	Reference 2023 (Ref)
Heat sink (outlet) temperature	$T_{h,out}$	°C	148	120	115	120
Heat source (inlet) temperature	$T_{c,in}$	°C	50	38	50	50
Temperature lift	ΔT_{lift}	K	98	82	65	70
Heating capacity	$\dot{Q}_h$	kW	3,150	940	550	1,000
Fuel (gas, oil) price	c_{fuel}	EUR/kWh	0.13	0.11	0.17	0.15
Electricity price	c_{el}	EUR/kWh	0.18	0.20	0.25	0.35
Electricity-to-fuel price ratio	$p_{el/fuel}$	-	1.38	1.82	1.47	2.33
CO_2 tax (or subsidies)	$c_{CO2\,tax}$	EUR/tCO_2	0	0	0	92.5
Electricity CO_2 emissions factor	$f_{CO2\,el}$	kgCO_2/kWh	0.128	0.128	0.012	0.128
Fuel CO_2 emissions factor	$f_{CO2\,fuel}$	kgCO_2/kWh	0.201	0.201	0.201	0.201
Annual operating time	t	h/a	7,200	6,400	3,000	6,400
The efficiency of fuel boiler	η_{fuel}	-	0.90	0.90	0.90	0.90

Maintenance factor (on capital costs)	$f_{maintain}$	-	0.04	0.04	0.04	0.04
Cost factor for planning & integration	$f_{inv,hp}$	-	3.0	2.0	2.0	3.0
COP ($COP = 52.94 \cdot \Delta T_{lift}{}^{-0.716}$)	COP	-	2.0	2.3	2.7	2.5
Specific investment costs ($c_{inv,HP} = 3'157 \cdot \dot{Q}_h{}^{-0.322}$)	$c_{inv,hp}$	EUR/kW	236	348	414	341
Annual CO_2 emissions reduction	$\dot{m}_{CO2,reduction}$	tCO_2/a	3,604	1,002	361	1,105
Annual CO_2 emissions reduction	-	-	71%	75%	98%	77%
Annual energy savings	$E_{savings}$	MWh/a	13,782	4,019	1,214	4,579
Annual energy savings	-	-	55%	60%	66%	64%
Investment costs	$C_{inv,hp}$	kEUR	2,230	655	455	1,024
Annual fuel cost savings	C_{fuel}	kEUR/a	3,276	735	312	1,067
Annual electricity costs	C_{el}	kEUR/a	2,055	533	155	886
Annual heat pump maintenance costs	$C_{maintain}$	kEUR/a	89	26	18	41
Annual CO_2 tax compensation	C_{CO2}	kEUR/a	0	0	0	102
Annual cost savings	$C_{savings}$	kEUR/a	1132	176	139	242
Discount rate	i	-	0.10	0.02	0.05	0.10
Payback period	PP	years	2.0	3.7	3.3	4.2
Discounted payback period	DPP	years	2.3	3.9	3.7	5.8

The case study ELSA has the highest temperature lift of 98 K and consequently the lowest COP as well as a cost multiplication factor for planning and integration of 3.0, but benefits from favorable electricity-to-gas price ratio and low specific investment costs due to the large HTHP (economies of scale).

In the Cremo case study, the electricity-to-gas price ratio is higher, and the integration factor is 2.0, but the discount rate is low, leading to a DPP of 3.9 years. The pinch analysis is a powerful tool to determine the optimal placement of a HTHP, its size, and adequate evaporation and condensation temperatures.

The case study of Gustav Spiess AG shows a high CO_2 emission reduction of 98% because the company benefits from low CO_2 emissions by purchasing nuclear power. Using waste heat from the NH_3 chillers as a heat source shows great multiplication potential in other case studies in the Swiss food industry, where refrigeration machines for cooling foods are state of the art.

In addition to the three case studies, Table 3 also shows the results of the payback period for a possible Reference Case 2023 (Ref) with a heat source of 50 °C, a heat sink of 120 °C (COP of 2.5), and 1 MW heating capacity, and specific investment costs of 341 EUR/kW_{th}. This scenario uses a discount rate of 10%, an average Swiss consumer electricity mix with a CO_2 emission factor of 0.128 $kgCO_2/kWh_{el}$ [29], and a possible carbon tax refund of EUR 92.5/tCO_2 due to the reduction of CO_2 emissions. Electricity and gas prices are based on market data for 2023 [33] (0.15 EUR/kWh PEGAS NCG Year Future and 0.35 EUR/kWh Phelix Year Future, price ratio 2.33, as of December 11, 2022).

Figure 9 shows a sensitivity analysis of the payback period for the Reference Case 2023 (abbreviated as Ref). All input factors of the model were individually varied from -25% to +25% (factor 0.75 to 1.25), while the other parameters were kept constant. The sensitivity analysis reveals that the payback period is strongly sensitive to a change in electricity and fuel prices as well as the temperature lift of the heat pump.

Favorable conditions for HTHPs are higher values of fuel prices, operating time, fuel CO_2 emission factor, CO_2 tax, heating capacity, and lower electricity prices. In addition, an increasing CO_2 tax, along with subsidies and possible CO_2 compensation through the European emission trading system increase the financial incentives for HTHPs.

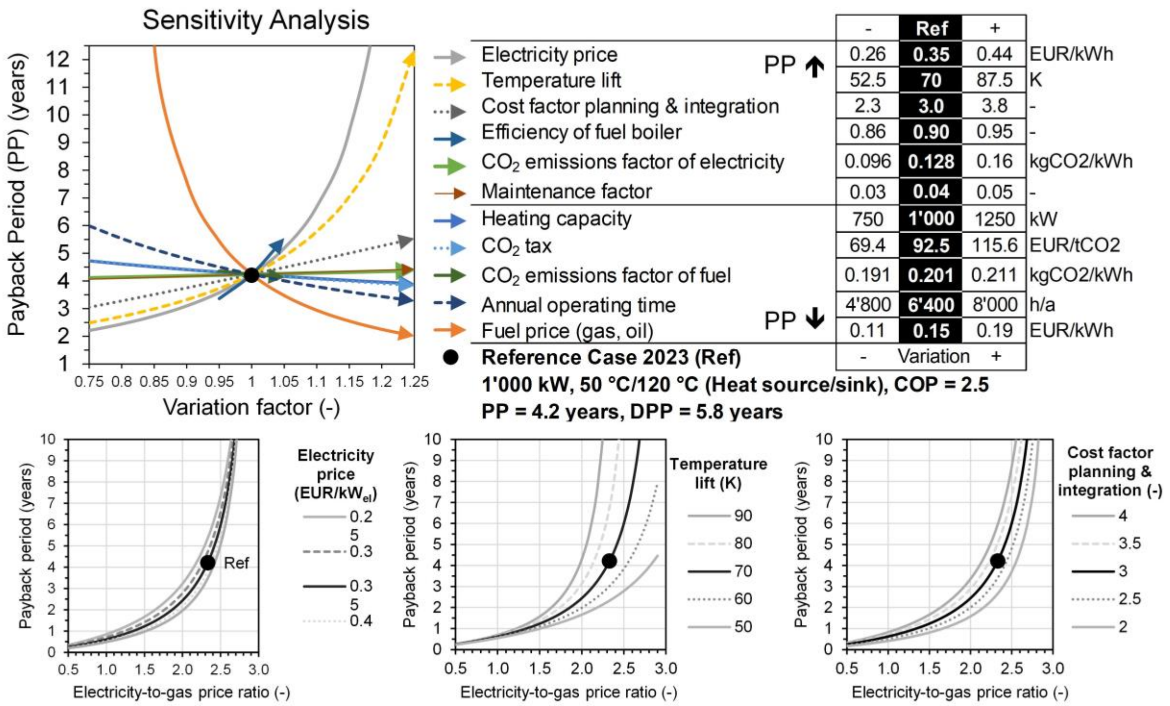

Fig. 9. Sensitivity analysis of the payback period for a Reference Case 2023 (Ref) at 50 °C/120 °C heat source/sink, 1'000 kW heating capacity, and an electricity-to-gas price ratio of 2.33. The graphs below show the impact of electricity price, temperature lift, and cost factor for planning & integration on the payback period as a function of the electricity-to-gas price ratio.

On the other hand, low gas and high electricity prices lead to unfavorable conditions and are significant barriers to the investment of industrial HTHPs. As seen in the lower diagrams of Figure 9, the payback period is strongly determined by the electricity-to-gas price ratio. Above a price ratio of 2.7, the payback period is more than 10 years. In addition, the payback period is strongly influenced by the temperature lift, which determines the COP and, thus, the operating cost of the HTHP and the avoided fuel consumption.

For given energy prices and temperature lift, the cost multiplication factor for planning & implementation leads to significant uncertainty in quantifying the payback period. The cost multiplication factor depends on the complexity of the HTHP integration and can only be properly determined after a thorough analysis of the project and indicative price quotations for the entire heating system implementation.

5. Conclusions

A simple cost model was developed to pre-assess the economic feasibility of integrating HTHPs into actual industrial processes based on investment costs and annual cost savings. The analyzed HTHP integrations at ELSA, Cremo, and Gustav Spiess show significant annual energy savings of 55%, 60%, and 66%, and CO_2 emission reductions of 71%, 75%, and 98%, respectively. The calculations lead to payback periods of 2.0, 3.7, and 3.3 years, which means that the integration of HTHP would be cost-effective under the current assumptions. However, it should be noted that the financial evaluation strongly depends on the individual case. A sensitivity analysis has shown that higher fuel prices mainly shorten the payback period. An electricity-to-gas price ratio below 2.7 leads to payback periods below 10 years. Temperature lifts below 70 K appear to be profitable. Economic challenges arise with high temperature lifts, low gas prices, and high discount rates. Overall, the availability of closed-cycle HTHP products and steam compressors shows that the case studies are technically feasible with the integration concepts presented. A wide range of HTHP products is available up to 120 to 160 °C supply temperature. Individual HTHP products achieve temperature lifts of up to 125 K. HTHPs are also available in the large heating capacity range >10 MW. More detailed discussions with HTHP manufacturers are required in the next step to clarify the end-user-specific integration conditions. In addition, the cost model can be applied to other Swiss case studies for initial cost estimation. Future work could include integrating an advanced heat pump model that considers the effects of refrigerant, compressor efficiency, and cycle design.

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Nomenclature

$\dot{Q}_h$	Heating capacity	kW	$C_{inv,HP}$	Investment costs of HP	EUR
ΔT_{lift}	Temperature lift	K	$\dot{m}_{CO2,reduction}$	Annual CO_2 emissions reduction	tCO_2/a
$c_{inv,HP}$	Specific investment costs of HP	EUR/kW	$E_{savings}$	Annual energy savings	kWh/a
$f_{inv,HP}$	Cost factor for planning & HP integration	-	C_{fuel}	Annual fuel cost savings	EUR/a
t	Annual operating time	h/a	C_{el}	Annual electricity costs	EUR/a
$f_{maintain}$	Maintenance factor (on capital costs)	-	$C_{maintain}$	Annual HP maintenance costs	EUR/a
η_{fuel}	Efficiency of gas boiler	-	C_{CO2}	Annual CO_2 tax compensation	EUR/a
i	Discount rate	-	$C_{savings}$	Annual cost savings	EUR/a
c_{fuel}	Fuel price (gas, oil)	EUR/kWh	PP	Payback period	a
c_{el}	Electricity price	EUR/kWh	DPP	Discounted payback period	a
$c_{CO2\ tax}$	CO_2 tax	EUR/tCO_2			
$f_{CO2,el}$	CO_2 emissions factor electricity	$kgCO_2/kWh$			
$f_{CO2,fuel}$	CO_2 emissions factor fuel	$kgCO_2/kWh$			

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