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Implementation of High Temperature Heat Pumps for heat upgrade and supply of process steam in the industry

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High temperature heat pumps, compressor technology, heat transformer technology, process integration, heat upgrade, steam generation

Abstract

PUSH2HEAT is an EU-funded project aimed at scaling up heat upgrading technologies to overcome technical, economic, and regulatory barriers. The project focusses on four different technologies with supply temperatures ranging from 90 °C to 160 °C, integrating them into the paper and chemical industries. Demonstrations of the four technologies will take place at selected industrial sites. The project also aims to develop business models and exploitation roadmaps for increased market penetration of heat upgrading technologies.

The heat upgrade systems based on electrically and thermally driven heat pumps are located at three demonstration sites in Germany, Italy and Spain. A fourth heat upgrade system is based as an industrial scale system in Belgium aiming at demonstrating the application potential of the thermochemical heat pump technology. In all demonstration sites the surplus waste heat potentials and the heat demands have been analysed for assessing the optimal integration of the high temperature heat pumps into the energy supply systems of the three industrial partners. While in Germany and Italy electrically driven multi-stage heat pumps based on piston compressors and turbo compressors provide process steam for paper production facilities, in Spain an absorption heat pump (heat transformer) provides process steam for a chemical facility.

Waste heat potentials are given at a temperature level of 35 °C to 90 °C at the demonstration sites. The high temperature heat pumps are designed for the supply of process steam in the range 1.8 bara to 3.3 bara, thus upgrading unexploited waste heat to a temperature level of 117 °C to 137 °C. Depending on the required temperature lifts, COP values for the electrically driven heat pump systems in the range of 2.3-3.6 are expected. For the thermally driven absorption heat pump a thermal COP of 0.47 and a total electrical COP for the heat upgrade system in the range of 20 are expected for the nominal working conditions.

To provide process steam at higher pressure levels, in two of the demonstration sites the steam pressure will be further upgraded using thermocompressors (steam jet compressor technology). Using motive steam from the industrial sites, the produced steam from high temperature heat pumps is further pressurized to 4.5 bara- 6.2 bara (148 °C-160 °C).

The PUSH2HEAT project shows a variety of technological solutions for the process integration of high temperature heat pumps in the industry allowing thus a wide application of the technology in other industrial sectors with similar process heat demands in the temperature range of 90 °C-160 °C.

Introduction

With the continuous and rapid growing demand for energy, technological solutions to reduce dependencies from fossil fuels, tackle environmental problems and maintain competitiveness is a major challenge for the industry and its role within the energy transition to meet the targets of climate neutrality. Decarbonization of industrial processes can be achieved through increasing energy efficiency and the recovery and upgrade of unutilized waste heat. Within the industrial sector the demand for process heat accounts for approximately 66 % of the final energy demand (Boer et al. 2020) High temperature heat pumps (HTHP) providing process heat in the temperature range between 100 °C and 200 °C can cover about 25 % of this energy demand for process heat. A wide deployment of such systems can be accelerated by generating experience through successful integration, highlighting the industrial related technical challenges and demonstrating energy efficiency gains generated throughout the operation.

PUSH2HEAT is an EU-funded project focussing on four different HTHP technologies with supply temperatures ranging from 90 °C to 160 °C that will be integrated into industrial processes and demonstrate their potential for heat upgrade at selected industrial sites. Within this publication the Heat Upgrade Systems of two demonstration sites and another case study will be described and presented. A commissioning at the demonstration sites is expected to start in mid-2024. Detailed results from each demonstration site and its system design are given in (Paitazoglou 2023), (Abrami und Toppi 2023) and (Alonso und Corrales 2024).

Further information regarding the PUSH2HEAT project can be found online https://push2heat.eu/.

Heat Upgrade Technologies in PUSH2HEAT

In PUSH2HEAT the heat upgrade systems rely on electrically and thermally driven heat pumps for three sites. While two demonstration sites are in the process of implementing the HTHPs based on mechanical compression, for a third industrial site a case study is undertaken in order to highlight the integration potential of a heat upgrade system based on an Absorption Heat Transformer (AHT), see Figure 1. A fourth heat upgrade system is based as an industrial scale system and test site in Belgium aiming at demonstrating the application potential of the thermochemical heat pump technology.

In the following the AHT case study and the HTHP systems for the demonstration sites in Germany and Italy will be shortly described with respect to their optimal integration. For each heat upgrade system a detailed system analysis and an assessment of operational and technological characteristics has been undertaken among the involved partners. Hence, aspects like the utilization potential of the identified heat source, the heat sink requirements, operational constraints given by the system, the use of refrigerants, the selection of key components especially regarding the HTHP setup, etc. were taken into consideration within this phase of the project.

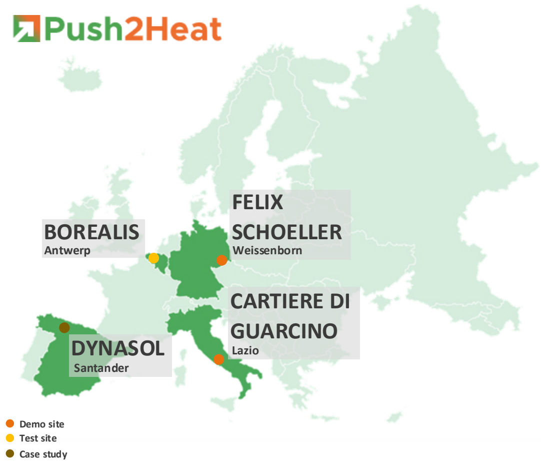

Figure 1: Heat upgrade systems in PUSH2HEAT

High Temperature Heat Pump for steam generation in Germany

Industrial partner for the integration of the heat upgrade system is a paper production factory of Felix Schoeller GmbH & Co KG located in Weissenborn Germany and is dedicated to the production of technical and specialty paper. The main energy demand for the production and processing of paper is process heat (steam at different pressure levels between 2 bara and 8 bara). A combined heat and power plant on site and based on natural gas is supplying the industrial complex with process heat and electricity.

The technology provider for the HTHP, SPH Sustainable Process Heat GmbH, is carrying out the full-scale development and manufacturing of a two-stage heat pump system for the upgrade of surplus waste heat and the supply of steam that will be integrated directly into the paper production process at Felix Schoeller. Figure 2 highlights the integration of the heat upgrade system into the heat source and the heat sink at the production facility.

Waste heat from the return air of the various production areas is recovered by using three air/water-heat recovery systems allowing a water-glycol circuit to be used as heat source of the high-temperature heat pump. The analysis of the given waste heat source has shown that the temperature and the available capacity of the waste heat strongly depend on factors such as the paper production type, ambient air conditions and setpoint requirements for the supply air in the production areas that are using the waste heat source primarily. An average waste heat temperature of 46 °C and an available heat source capacity of 700 kW are selected for the design of the heat upgrade system.

With the given heat sink requirements for the direct supply of process steam and integration into the low pressure paper production process the operation parameters for the HTHP supplying low-pressure steam at 2.2 bara have been identified. A possible re-compression of the low-temperature steam to the operating lower pressure supply line of the facility at 4.5 bara using mechanical vapor compression technology was assessed by the involved partners. Such a combined system is technologically possible, allows the supply of steam at higher pressure levels and a temperature lift increase to values >100 K, but for the given installation results in a reduced cost-effectiveness. As a result, the heat upgrade system for the demo site in Germany focusses primarily on the integration of a high temperature heat pump and the direct supply of process steam with a capacity of 1.2 MW_{th}. At its design point the heat upgrade system is expected to reach a COP of 2.3.

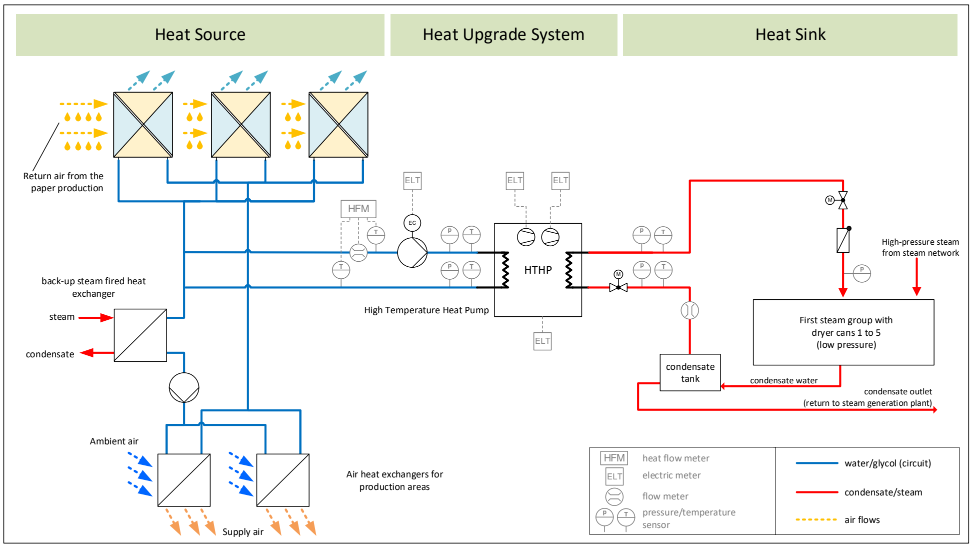

Figure 2: Heat Upgrade System based on a double-stage vapor compression heat pump for steam generation (Demo 1, Germany)

As highlighted in Table 1, the design parameters of the heat upgrade system including the selection of appropriate refrigerants have been assessed among all involved partners with respect to energy efficiency, environmental and safety aspects. Moreover, demo site specific requirements of the installation site, such as space availability, close proximity to heat source/sink circuits, safety-related issues, weight load, control integration etc. have been assessed during the planning phase.

According to the given work plan of the demo site, the finalization and implementation of the heat upgrade system including the monitoring is expected for the second quarter of 2024. Hence, a commissioning of the whole system is scheduled for an operational period with a high share of unutilized waste heat at the demo site. The main operation time of the high temperature heat pump at full capacity is expected to take place at summer months with an overall operation time of approx. 4000 h/a.

High Temperature Heat Pump for steam generation in Italy

The demo site for the integration the high temperature heat pump for steam generation is a paper production factory owned by Cartiere Di Guarcino S.P.A., located in Guarcino, Italy, and specialized in the production of paper for the furniture industry. The plant requires process heat in form of steam for the paper production, currently provided by two gas boilers and a cogeneration plant. The cogeneration plant, made of three engines fuelled with oils from the residuals of the food industry, generates electricity sold to the national grid, process steams at 6.5 bara from the exhaust gases and hot water at 90 °C used for combustion air preheaters and for space heating needs of the site. For practical reasons, the pressure of the steam produced by the boilers is 14.5 bara and is reduced to 6.5 bara while supplied to the main steam collector. The hot water loop from of the cogeneration plant has a capacity exceeding the needs for combustion air preheating and space heating by about 2 MW_{th} in the winter season and 6 MW_{th} during summer. Currently, this excess waste heat capacity is dissipated to the environment through an air cooler system.

The integration of the HTHP in the current system aims at recovering part of this capacity using it as the low-temperature source for the evaporator. The capacity of the heat pump has been chosen accordingly, to maximise the operational time. As a result, a 2.54 MW_{th} unit with a two-stage turbo-compressor using R1233zd(E) as refrigerant will be designed and manufactured by Enertime. As mentioned in Table 1, 1.91 MW_{th} will be delivered as steam at 3.3 bara produced in the condenser, while 0.63 MW_{th} will be derived from the subcooler of the refrigerant as steam at 1.8 bara.

With reference to Figure 3, the steam at 3.3 bara stream will be delivered to the main steam collector, after being further compressed to 6.5 bara by a thermo-compressor. Motive fluid of the thermo-compressor will be the high-pressure steam produced by the gas boilers at 14.5 bara. This choice is motivated by efficiency reasons and by the availability of high-pressure steam from the boilers, suitable for the activation of the thermo-compressor. The steam at 2.8 bara will be delivered to the deaerator of the feed water of the plant. The expected COP of the HP in the selected configuration is 3.6.

Looking at the integration of the heat pump with the production lines, the heat pump delivers at nominal capacity about 3 t/h of steam at 3.3 bara. About 9 t/h of high-pressure motive steam at 14.5 bara is required from the boilers in order to upgrade the steam produced by the HTHP in the thermo-compressor. As a result, 12 t/h of steam at 6.5 bara are supplied to a steam header. This quantity is lower than the 23 t/h required by the two production lines and the 14 t/h required when one of the lines is in stand-by mode. Since very rarely both the lines are in standby mode or out of operation, it is estimated that the heat pump will operate for at least 7000 h/a.

According to the given work plan of the demo site, the finalization and implementation of the heat upgrade system including the monitoring is expected for the fourth quarter of 2024. The commissioning of HTHP is scheduled for the end of the 2024 / beginning of 2025.

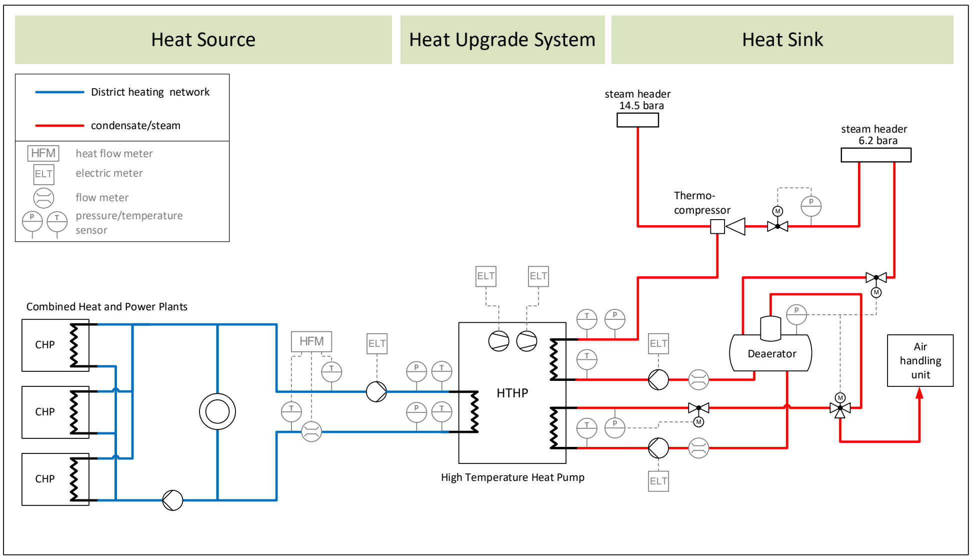

Figure 3: Heat Upgrade System based on a double-stage vapor compression Heat Pump for steam generation at two pressure levels and in combination with a thermo-compressor (Demo 2, Italy)

Case study Absorption Heat Pump for steam generation

The case study analyses the generation of steam upgrading waste heat inside a chemical plant. The case study is based on the analysis of potential waste heat sources and heat sinks within the polymers production plant of the company Dynasol near Santander, in the north of Spain. The plant produces synthetic rubber of types SBS (Solution styrene butadiene rubber) and SEBS (Styrene ethylene butylene styrene), based on solution polymerization.

The heart of the heat upgrade system is an Absorption Heat Transformer (AHT) built by the company BS-Nova that is an upscaled and optimized version of a smaller scale AHT system previously installed in the facilities of a petrochemical complex (Corrales Ciganda und Martinez-Urrutia E. 2023). The Absorption Heat Transformer works with the working pair Water/Lithium Bromide and upgrades approximately 50 % of the recovered waste heat to a higher temperature level. The AHT can boost the temperature level of the upgraded heat by 50 K, for supply temperatures above 150 °C.

The integration concept for the AHT within the chemical plant of Dynasol is presented in Figure 4. The AHT unit is combined with a flash tank (FT) for steam production. In the flash tank steam is produced from the pressurized water coming from the absorber (A) of the AHT. The low-pressure steam from the flash tank (1.5 bara) is recompressed using a thermo-compressor that uses motive steam available from the HP steam network of the plant (10 bara), and delivers steam which will be used in the strippers of the plant (required pressure: 2 bara).

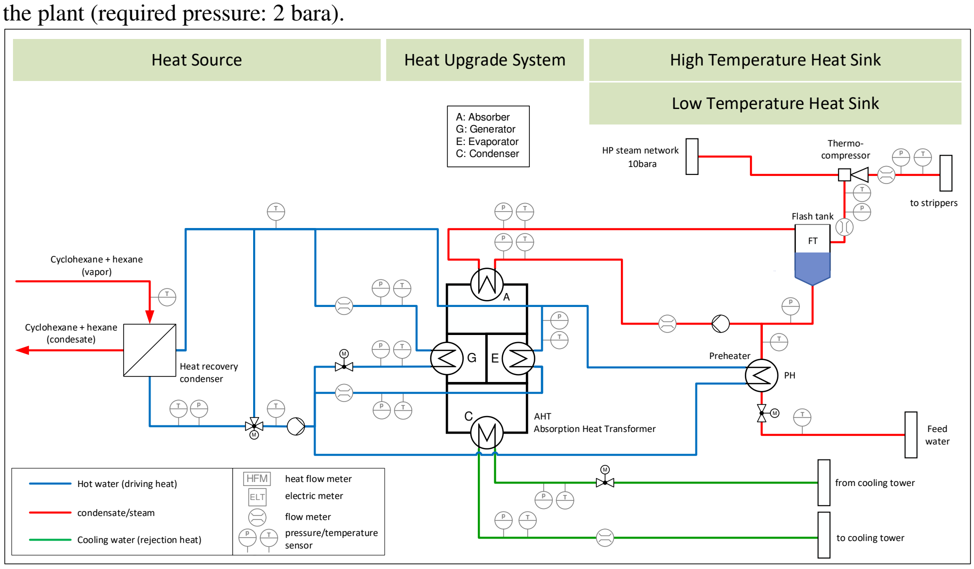

Figure 4: Case study for a Heat Upgrade System based on an Absorption Heat Transformer for steam generation and in combination with a thermo-compressor (Spain)

The waste heat source for the heat upgrade system is the condensation heat of a solvent used in a polymer production line, that is currently condensed using a cooling tower. A small portion of the waste heat is used to preheat the make-up water in the Heat Upgrade System, in the preheater (PH). In the AHT, the heat stream recovered from the condensation process (980 kW_{th}) is divided into a high-temperature heat stream (450 kW_{th}) and a low-temperature heat stream (530 kW_{th}). As presented in Table 1, the hot water in the driving heat circuit enters the evaporator and generator of the AHT with 85 °C and leaves it with 80 °C. In the high-temperature sink circuit the pressurized hot water enters the AHT with 111 °C and leaves it with 116 °C. At the same time, in the low-temperature heat sink circuit, cooling water from the cooling tower enters the condenser with 15 °C and leaves it with 20 °C.

The total electric consumption of the AHT for the heat upgrade process accounts for 5 kW needed to operate the internal pumps of the unit. The electrical coefficient of performance (COP) of the AHT unit is around 90. If the balance of plant for the calculation of the electrical COP is extended to include the electrical consumption of the pumps in the three external heat carrier circuits, the electrical COP value reaches a value between 15 and 25, as it is discussed in (Corrales und Alonso).

Based on the set up proposed for this case study, a thermo-economic analysis that evaluates the proposed concept operating under different boundary conditions is presented in (Corrales und Alonso). In this study, payback periods are analysed considering different constellations of CAPEX and OPEX that can arise for two different combinations of heat source and heat sink, constrained by different combinations of gas and electricity prices.

Table 1: Overview of design parameters for HTHP of Demo 1&2 and case study parameters for AHT

		Germany Demo 1	**Italy Demo 2**		**Spain Case Study**
Heat Source Parameters					
parameter	unit	value/information	value/information		value/information
Thermal capacity	kW_{th}	690	2 100		980
Flow rate	m³/h	130	87		82
Inlet/Outlet temperature evaporator*	°C	46/41	90/69		85/80
Heat transfer fluid	-	Glykosol N with a mass fraction of 25%	water		water
Heat Sink Parameters					
parameter	unit	value/information	value/information		value/information
Thermal capacity	kW_{th}	1 180	630 (low pressure)	1 910 (high pressure)	450
Steam generation	-	Direct steam generation			Flash tank steam generation
Flow rate generated steam	kg/h	1 800	1 000	3 000	685
Inlet/Outlet temperature	°C	90/123 (condenser)	105/117 (subcooler)	105/137 (condenser)	111/116 (absorber)
Outlet pressure of saturated steam	bara	2.2	1.8	3.3	1.5
Fluid	-	Inlet: Liquid water / Outlet: Saturated steam			
Thermocompressor					
Flow rate pressure motive steam		n.a.	n.a.	9 000 kg/h 14.5 bara	480 kg/h 10 bara
Flow rate pressure discharge steam		n.a.	n.a.	12 000kg/h 6.5 bara	1 185 kg/h 2 bara
Heat rejection					
Thermal capacity	kW_{th}	n.a.	n.a.	n.a.	530
Inlet/Outlet temperature	°C	n.a.	n.a.	n.a.	15/20 (condenser)
Heat Upgrade System					
parameter	unit	value/information	value/information		value/information
Electricity consumption	kW_{el}	517	704		5
Coefficient of Performance (COP)	-	2.3 kW_{th}/kW_{el}	3.6 kW_{th}/kW_{el}		90 kW_{th}/kW_{el} 0.48 kW_{th}/kW_{th}
Stages	-	2	2		1
Refrigerant type used	-	1st stage: R515B 2nd stage: R1233zd	R1233zd(E)		H20 / LiBr aqueous solution
Compressor type used	-	screw and piston compressor	centrifugal		n.a.

*Evaporator and generator for the AHT in the Case Study (Spain)

Conclusion and next steps

The basic engineering for the process integration of two Heat Upgrade Systems based on electrically driven high temperature heat pumps is completed. The full-scale development and optimal integration of these Heat Upgrade Technologies has been carried out closely with the technology providers and the demo sites. Moreover, a detailed system analysis and an assessment of operational and technological characteristics has been undertaken in order to maximize the potential of waste heat recovery and integrate the High Temperature Heat Pumps into the industrial steam networks. Direct steam generation, indirect steam generation with the use of flash tanks and the use of thermo-compressors to further upgrade the generated steam aim together at demonstrating the integration potential of High Temperature Heat Pumps in the industrial sector.

For two demonstration sites the Heat Upgrade System based on mechanical vapour compression are designed for a steam supply of 1.2 MW_{th} at 2.2 bara (Demo Germany) and 2.5 MW_{th} at 1.8 bara and 3.3 bara (Demo Italy). Latter, allows through the use of a thermo-compressor a further increase of the high-pressure steam of the heat pump to 6.5 bara. In a case study for an Absorption Heat Transformer 0.5 MW_{th} of steam can supplied at 1.5 bara that can be further upgraded with a thermo-compressor to 2 bara.

Further, PUSH2HEAT puts an emphasis on the exploitation of unused waste heat sources at temperature levels between 40 °C and 90 °C. As the utilization potential of such waste heat sources is case specific and dependent on various site-related factors like production processes, ambient air temperatures, etc. a somewhat flexible operation of the Heat Upgrade System is required that can ensure at the same time a continuation of the industrial processes that are in close interaction not only with the heat sink but with the heat source of the High Temperature Heat Pump as well. Consequently, a special focus on the integration of the heat pump control system into the complex and operational control systems of an industrial complex is placed in the next phase of each demonstration site.

For all heat upgrade applications within PUSH2HEAT thorough assessments have been undertaken on utilization potential of the identified heat sources, the heat sink requirements, the operational constraints given by the industrial facilities, the use of refrigerants, the application of safety standards and measures as well as the selection of components aligned with the requirements of the industrial sites, the technology providers and the monitoring of the Heat Upgrade Systems.

For the HTHP in Germany implementation works are scheduled to be completed in second quarter 2024. The finalization and commissioning of the Heat Upgrade System is thus scheduled for the next summer period when on site high unutilized waste heat potentials are given. This will allow a first evaluation of the system performance. For the HTHP in Italy implementation works are scheduled to be completed in by the fourth quarter 2024. The commissioning of the Heat Upgrade System is expected to take place at the end of 2024 or early 2025.

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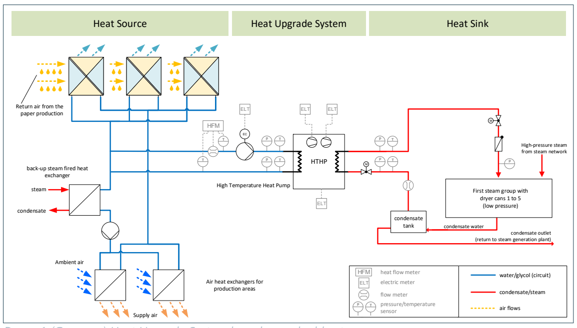
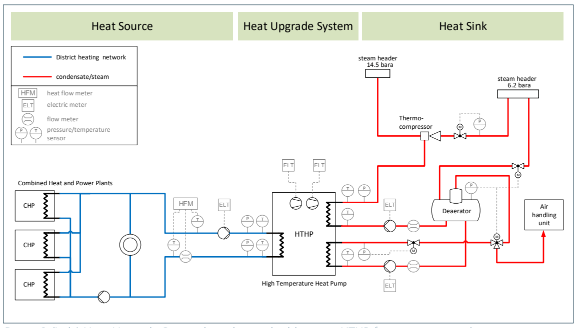
High-Temperature Heat Pump Symposium

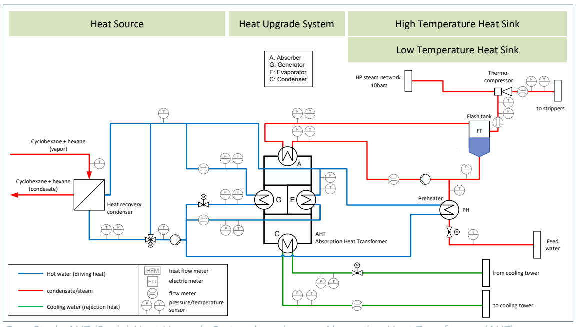
Overview of the Heat Upgrade Systems in Germany, Italy and Spain



Demo 1 (Germany) Heat Upgrade System based on a double-stage HTHP for steam generation and direct integration



Demo 2 (Italy) Heat Upgrade System based on a double-stage HTHP for steam generation at two pressure levels and in combination with a thermo-compressor



Case Study AHT (Spain) Heat Upgrade System based on an Absorption Heat Transformer (AHT) for steam generation and in combination with a thermo-compressor

Overview of design parameters for HTHP of Demo 1, Demo 2 and case study parameters for Absorption Heat Transformer (AHT)

		Germany Demo 1	Italy Demo 2		Spain Case Study
Heat Source Parameters					
Thermal capacity	kW_{th}	690	2 100		980
In-/Outlet temperature evaporator	°C	46 / 41	90 / 69		85 /80 (evaporator +generator)
Fluid	-	water/glycol	water		water
Heat Sink Parameters					
Thermal capacity	kW_{th}	1 180	630	1 910	450 (HT) 530 (LT)
In-/Outlet temperature	°C	90/123 (condenser)	105/117 (subcooler)	105/137 (condenser)	111/116 (HT:absorber) 15/20 (LT: condenser)
Steam generation	-	direct			flash tank
Steam outlet pressure	bara	2.2	1.8	3.3	1.5
Fluid	-	inlet: liquid water, outlet: saturated steam			
Thermo-compressor					
Flow rate Pressure motive steam	-	-	-	9.0 t/h 14.5 bara	0.5 t/h 10.0 bara
Flow rate Pressure discharge steam	-	-	-	12.0 t/h 6.5 bara	1.2 t/h 2bara
Heat Upgrade System					
Electricity consumption	kW_{el}	517	704		5
Coefficient of Performance (COP)	-	2.3 (kW_{th} / kW_{el})	3.6 (kW_{th} / kW_{el})		90 (kW_{th} / kW_{el}) 0.48 (kW_{th} / kW_{th})

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In all demonstration sites the waste heat potentials and the heat demands have been analysed for assessing the optimal integration of the HTHP into the energy supply systems of the three industrial partners.

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