D3.1

Demonstration site at STC – system design

V0.6

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ABBREVIATIONS

PUSH2HEAT: Pushing forward the market potential and business models of waste heat valorisation by full-scale demonstration of next-gen heat upgrade technologies in various industrial contexts.

BMS: Building Management System

CHP: Combined Heat and Power

D: Deliverable

DGSTR : Steam fired heat exchanger

HP: Heat Pump

HRS: Heat Recovery System

HUS: Heat Upgrade System

M: Month

MS: Milestone

MVR: Mechanical Vapor Compression

P&ID: Process and Instrumentation Diagram

PH: Production hall

T: Task

WP: Work Package

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PARTNERS

Partner short name	Legal name	Role
FRAUNHOFER	FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV	Local site coordinator WP3 Leader
SPH	SPH SUSTAINABLE PROCESS HEAT GMBH	Technology provider
STC	FELIX SCHOELLER GMBH & CO KG	Demo site

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1. Introduction

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 overall project duration of PUSH2HEAT is 48 months.

The recovery and upgrade of waste heat with high-temperature heat pumps in industrial processes plays a significant role for decarbonizing the industry and providing sustainable and environmental alternatives to the conventional energy supply systems based on fossil fuels. 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.

In PUSH2HEAT 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 and test site in Belgium aiming at demonstrating the application potential of the thermochemical heat pump technology (see Figure 1). For each demonstration site the main coordinator is given by the following research partners:

- Demo site in Germany: Fraunhofer Gesellschaft zur Förderung der Angewandten Forschung E.V.
- Demo site in Italy: Politecnico di Milano
- Demo site in Spain: Fundación Tecnalia Research & Innovation

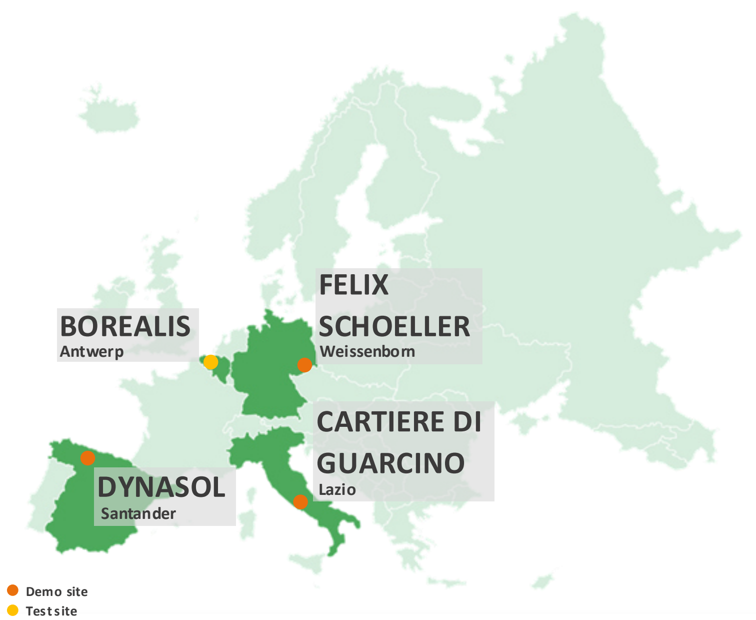

Figure 1: Heat upgrade systems in PUSH2HEAT

This report derives from the works undertaken in WP3 'Implementation of demonstration sites', which consists of four main tasks that last for the first 36 months of the project:

- T3.1 Demonstration site at Felix Schoeller (STC)
- T3.2 Demonstration site at Cartiere Di Guarcino (CDG)
- T3.3 Demonstration site at Dynasol
- T3.4 Assessment on commissioning of heat upgrade systems

The main objective of WP3 is to implement demonstration plants for heat upgrade technologies at three locations in Europe in cooperation with partners from the different industrial sectors. These case studies will be used to demonstrate the utilization potential of the mentioned technologies for heat upgrade in interaction with various industrial processes by using waste heat. Thus, for each implementation, that is an individual task, the following subtasks are given:

- Analysis and requirements for the demo site
- Planning and engineering
- Manufacturing of the heat upgrade technologies
- System integration
- Commissioning and first performance tests

This report (deliverable D3.1) will focus on the results gained from analyzing the requirements of the demo site in Germany (Weissenborn), planning the optimal integration of the heat upgrade technology into the industrial process (paper production) and providing a basic engineering for the installation. First engineering results undertaken among the involved partners will be presented and discussed.

2. Analysis and requirements

This chapter focusses on the analysis and definition of requirements of the demo site in Germany (Location Weißenborn), that will allow and initiate the full-scale development of the heat upgrade technology included in WP2 (Task 2.1 Full scale development of vapor compression heat pumps with piston compressors). This first phase, i.e. the system analysis and evaluation of the demo site will be undertaken also with respect to the optimal integration of the heat upgrade technologies and is taking place within T3.1.

Hence, missing and needed monitoring data around components, interfaces and circuits of the running facility must be collected. All in all, this will prove as the starting point for the planning and engineering around the demo site with a preliminary focus on analysing technical and infrastructural requirements in every operating system.

The partners involved in the Task 3.1 Demo site 1 (Germany) are as follows:

- Fraunhofer Gesellschaft zur Foerderung der Angewandten Forschung E.V. (FRAUNHOFER)
- Felix Schoeller GmbH & Co KG[1] (STC)
- SPH Sustainable Process Heat GmbH (SPH)

In addition, the VOITH company (J.M. Voith SE & Co. KG) is involved in the project as a subcontractor in the field of plant design and plant construction.

2.1 Demo site

Felix Schoeller GmbH & Co KG (STC) is one the of the biggest groups in Europe dedicated to the production of technical and specialty paper. Headquartered in Osnabrück, STC is a globally active family-owned company founded in 1895. With more than 3 703 employees at 19 locations in 11 countries, STC develops, produce and market specialty papers for photographic applications, for digital printing systems, for the packaging market, for self-adhesive applications and for the furniture, wood-based panel and wallpaper industries.

The specialty paper factory of the group in Weißenborn is located in the free state of Saxony in Germany. 700 employees on that site are producing around 100 000 t of paper a year.

Moreover, STC has a series of certifications[2] for the quality, safety and sustainable use of resources (see Figure 2). The project “Paper Mill of the Future” aims at producing paper climate neutral by 2050. Together with other partners this vision is followed with the “Model Factory of the Future” where a model factory will highlight a possible change from paper producing companies into companies in the bio economy.

[1] Formerly known as Schoeller Technocell GmbH &Co KG (STC)

[2] https://www.felix-schoeller.com/en/responsibility/nature-and-environment

Figure 2: Certification standards by Felix Schoeller GmbH & Co KG

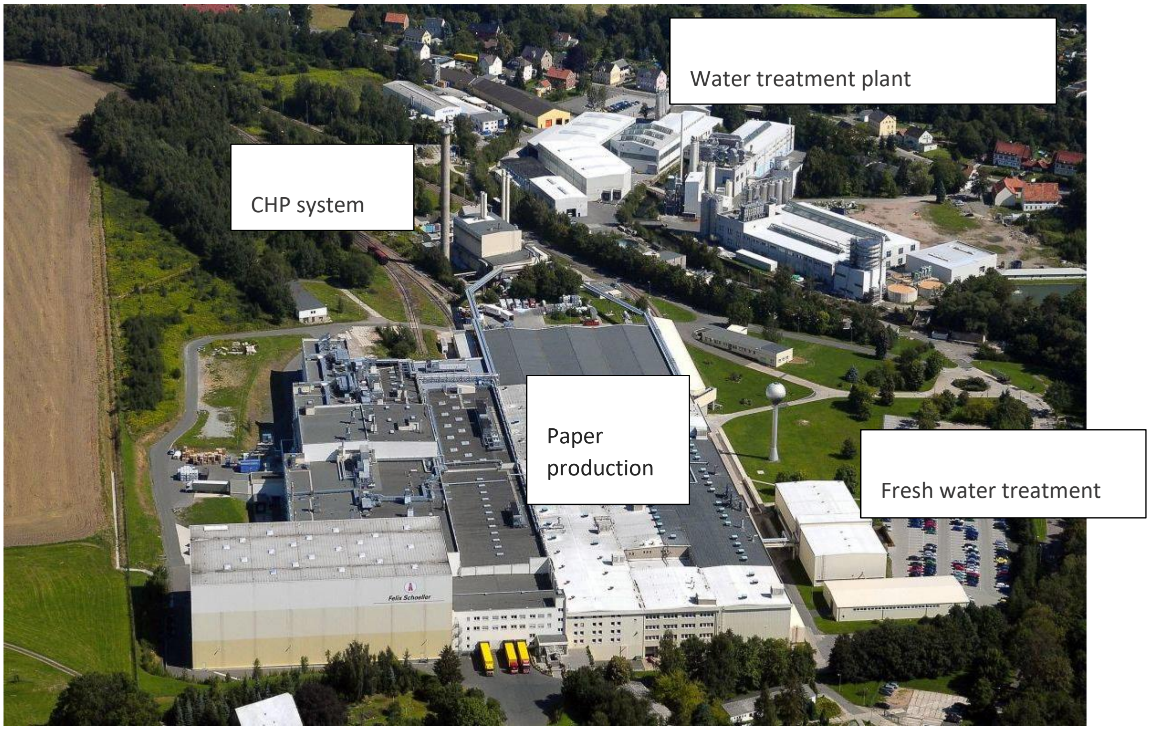

Figure 3: Aerial view of the paper factory in Weißenborn

2.2 Current energy consumption of fossil-based systems

The paper factory has a yearly demand for natural gas of 400 GWh (0,0382 Gm^3 NG) and is regarded as one of the biggest gas consumers in Saxony. The yearly demand for electricity and process heat accounts for 88 GWh_{el} and 230 GWh_{th} (steam). The CO_2-emissions for providing these process energies are 80 000 t_{CO2} per year. 100% of these process energies are provided by CHP units installed on site. Steam is currently produced by means of a central boiler that burns natural gas. With a consumption of nearly 140 000 MWh/a of steam the paper machine has the main energy demand in the mill. Most of that heat is used for the drying process.

The Combined Heat and Power supply system consists of three gas turbines and one steam turbine producing in total 17 MW_{el}. Steam is generated at three flue gas fired steam boilers with a maximal production capacity of 82 t/h. Figure 4 shows the simplified CHP system at the demo site. Steam is generated at the pressure levels of 4,5 bar(a) and 8 bar(a). An overall thermal efficiency of 0,8 can be assumed for the process steam production.

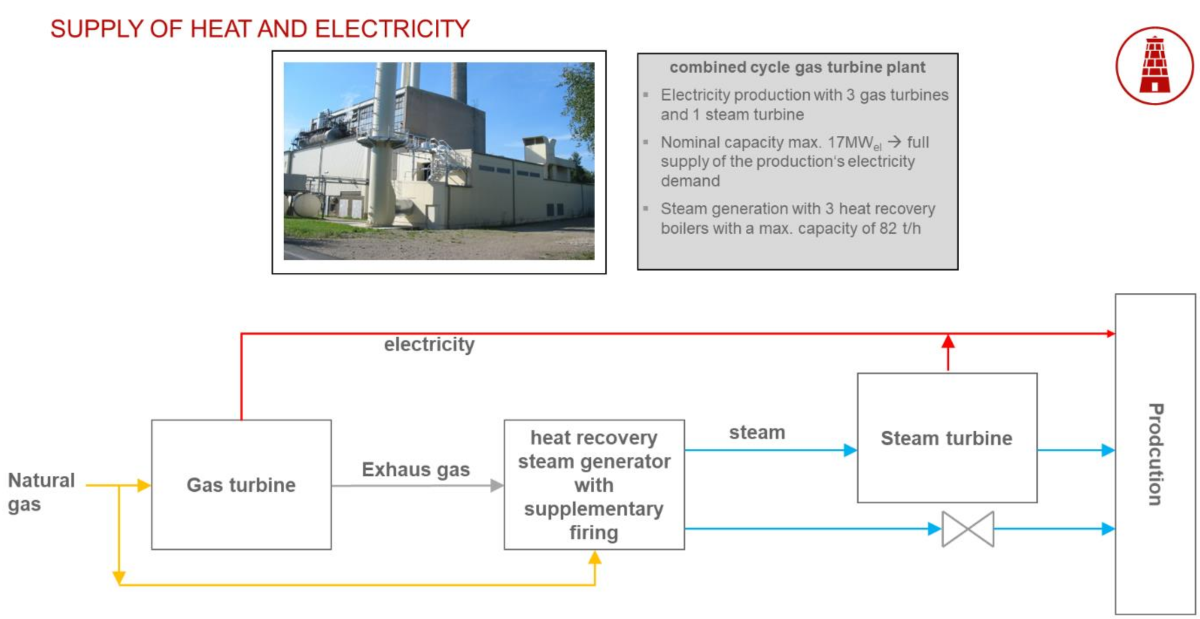

Figure 4: Combined Heat and Power (CHP) supply on site

Figure 5 shows the end energy demand for the various industrial applications at the paper production facility. Approximately 50 % of the energy demand is needed for the paper production of which approximately 80 % is the heat demand for process steam. In addition, a quarter of the end energy demand (23 %) is required for the extruder stages (ET9/ET10) and other processes related to the paper production. 27 % of the end energy usage is needed for other various remaining processes (space heating, fresh and sewage water treatment, etc.).

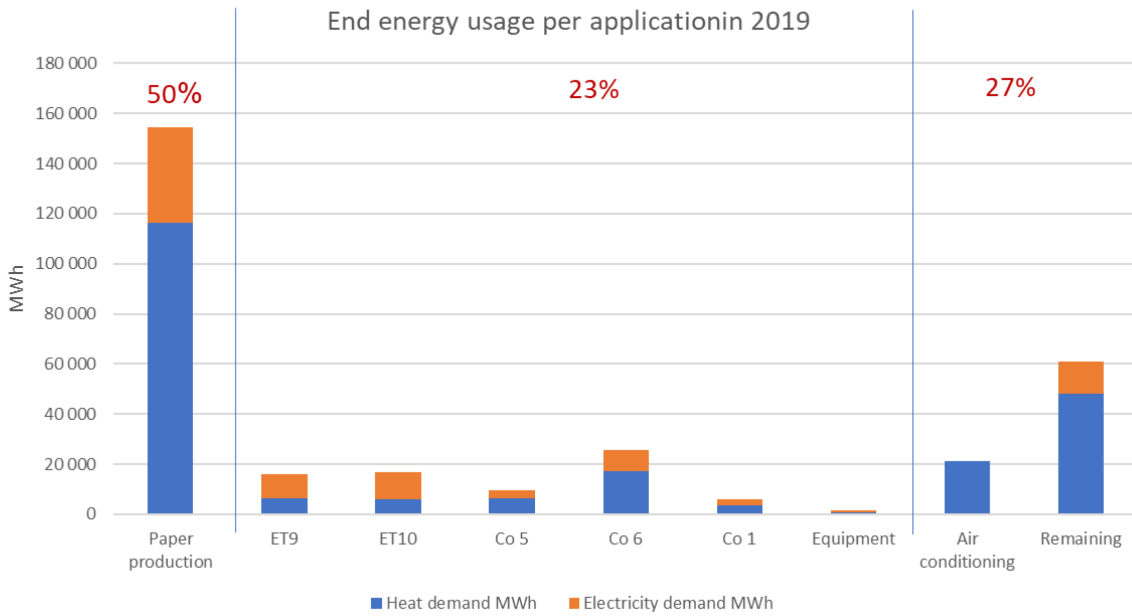

Figure 5: End energy usage per industrial application at the paper factory in 2019

Figure 6 highlights the carbon dioxide (CO_2) emissions for various balanced areas of operation for STC for the years 2018-2021. The highest CO_2-emissions are allocated to the Combined Heat and Power (CHP) supply of the industrial site. Reduced values in the year 2020 are due to a reduced production capacity in the beginning of the COVID pandemic in March 2020.

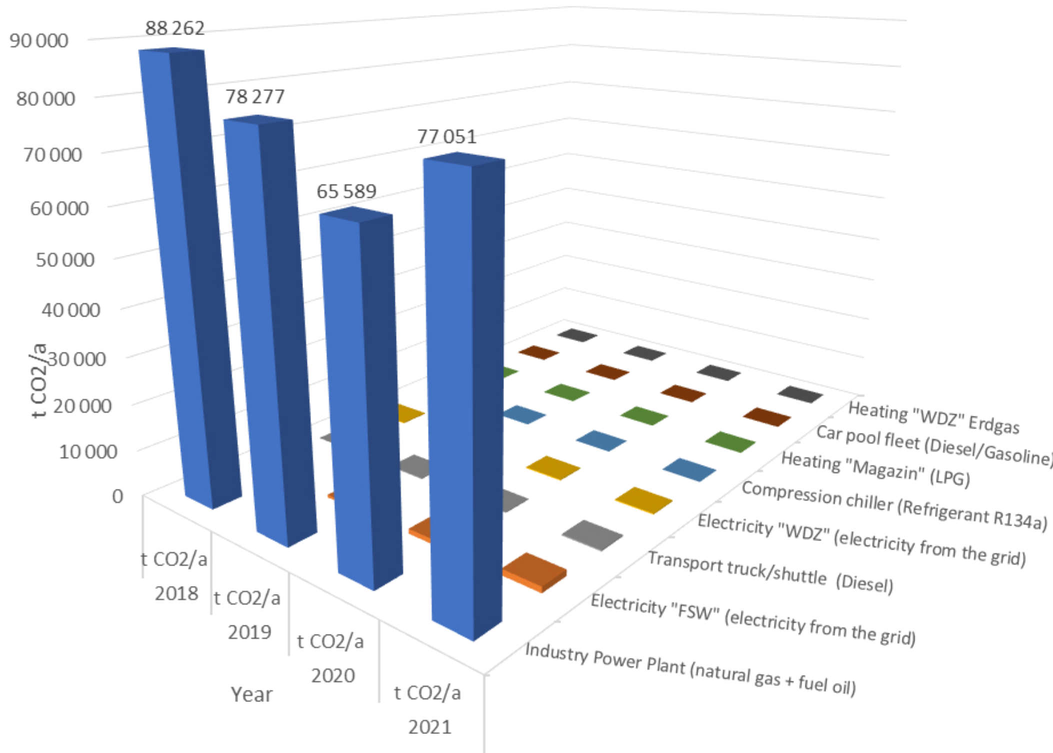

Figure 6: Annual CO2-emissions for the production site per sector (2018-2021)

From the yearly process heat demand of approx. 230 GWh/a approx. 60 % is needed for the paper production. The hot water demands on site are insignificantly low. The monthly energy demand for process heat (steam) and electricity is given Figure 7. Apart from the calendar month December, where a reduced, and holiday related, paper production is given, the average monthly demand for process heat and electricity is 12.2 MWh_{th} (+/- 11 %) and 4.0 MWh_{el} (+/- 13 %). Process heat (steam) is the main energy demand for the paper production process and accounts on average for 75 % of the total energy demand.

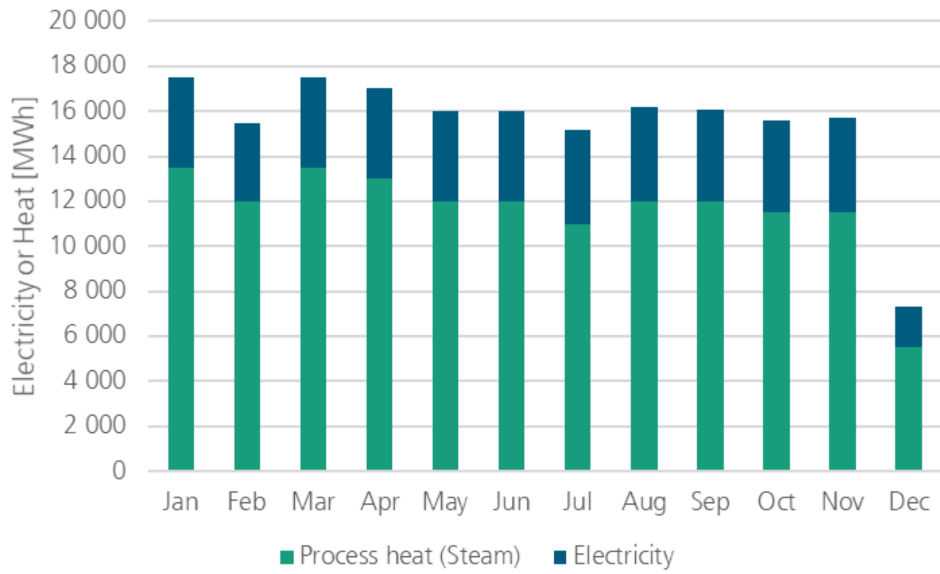

Figure 7: Monthly energy demand for process heat (steam) and electricity for the paper production in the year 2019

2.3 Initial concept for the Heat Upgrade System

Waste heat from the production process of the factory will be used for the production of upgraded heat. The waste heat that will be used in the project is part of the exhaust heat from the paper machine dryer air hood system. This exhaust heat is currently recovered by means of a heat recovery system developed by the company VOITH, as an integral part of the efficient papermaking technology used by the demo site. The heat recovery system recovers the excess heat of the air used for drying purposes of the paper by means of air to water-glycol heat exchangers.

The water-glycol circuit of the heat recovery system is used for heating the hall system of the paper factory whenever heat is demanded. The glycol water circuit will serve as a heat source for the vapor compression heat pump. However, the temperature of the water-glycol circuit is often much higher than the temperature required by the hall heating system. The amount of hours with an excess heat that can be used as a heat source for a heat pump and thus for the generation of upgraded heat account for at least 4800 hours per year.

The available temperature of the water-glycol circuit that will be used in the project for the heat pump varies throughout the year between 45 and 55 °C, but its average value can be estimated to be 50 °C. An average flow rate of 65 m^3/h is estimated. The temperature set point of the water-glycol heating system of the factory hall is around 40 °C allowing a temperature decrease in the water-glycol circuit of 10 K (see Figure 8). As a result, the available heat potential in the water-glycol circuit accounts for approx. 700 kW.

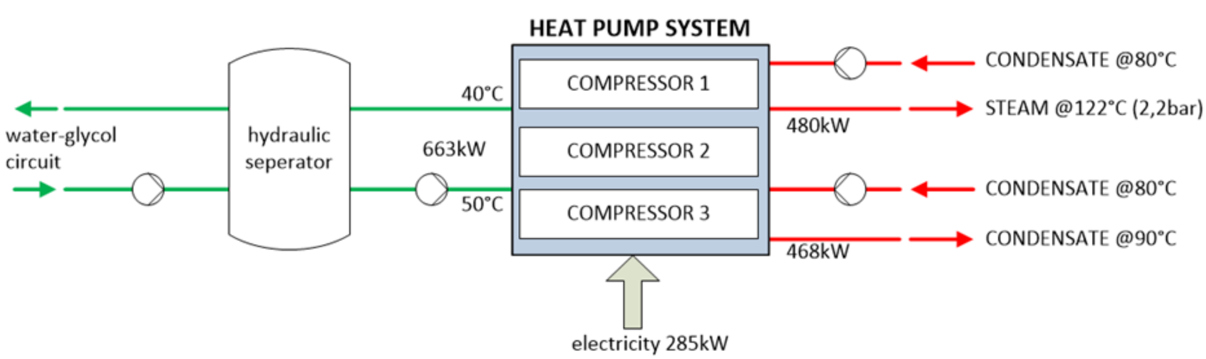

Figure 8: Initial heat upgrade system of the STC paper factory in demo site 1

The heat pump system from the HP manufacturer (SPH) was initially aiming at including three parallel piston compressors specially designed for high temperature operation. As shown in Figure 8 the total amount of upgraded heat was estimated at 948 kW and at an estimated COP of the compression heat pumps of approx. 3.3.

Upgraded waste heat from the water-glycol circuit should be delivered at two different temperature levels:

- 480 kW vapor steam at 122 °C and 2.2 bara
- 468 kW (hot) condensate at 90 °C

480 kW of the upgraded heat should be delivered as low-pressure steam in the condenser of the heat pump, whereas 468 kW should be used to preheat the feed water to the boilers of the energy central from 80 to 90 °C. The low-pressure steam will be injected in the low-pressure steam network of the paper factory.

The final concept for the Heat Upgrade System has been slightly adjusted with respect to the available temperature levels of the heat source and the heat sink. Throughout the first discussions taking place among the partners the demo site confirmed that the need for providing condensate (feed water) at a temperature level of 90 °C is not given anymore as the temperature of the condensate returning to the boilers of the energy central is already at this temperature level. As a result, the design temperature for condensate at the inlet of the condenser is also raised to 90 °C (see chapter 3.2). Furthermore, the demo site's interest lies mainly on providing process steam that can be used directly in the paper production process or the steam supply network. As has been described in chapter 2.2 process steam is the main energy demand for the paper production (see Figure 7).

2.4 Utilization potential of the heat source

In the paper mill waste heat from the return air of the various production areas is recovered by using three air/water-heat recovery systems. Return air from the paper production with a high relative humidity and high temperature is cooled down in the heat recovery system by a water-glycol circuit. Vaporous water in the return air condensates and allows a recovery of a fraction of the process heat used for the drying process of the paper production.

The water-glycol circuit and the heat recovery from return humid air has been defined as the heat source for the heat upgrade system. In this chapter the potential for utilizing this as a heat source will be addressed.

The water-glycol exits the heat recovery system with an increased temperature. The recovered heat is used for the heating of the supply air entering the production areas. This is needed to supply those areas with a dry, warm air flow and allow a removal of heat and humidity sources from the paper production. However, in case the temperature of the water-glycol at the outlet of the heat recovery system is below a given variable setpoint temperature value, an additional steam-fired heat exchanger (DGSTR) is used to raise the temperature of the water-glycol. As a result, the required supply air temperature can be reached for the given operating conditions and requirements in the production areas. Variable flow pumps (pressure difference control) are used to regulate the flow in the water-glycol-circuit. A simplified setup of the water-glycol-circuit is shown in Figure 9.

The operating conditions of the water-glycol circuit (temperature and flow rate) depend strongly on factors such as:

- Ambient air condition
- Set-point temperature for the supply air in the production areas
- Humidity and temperature level of the return air in the heat recovery system (which depends strongly on the paper production and type of paper being produced)

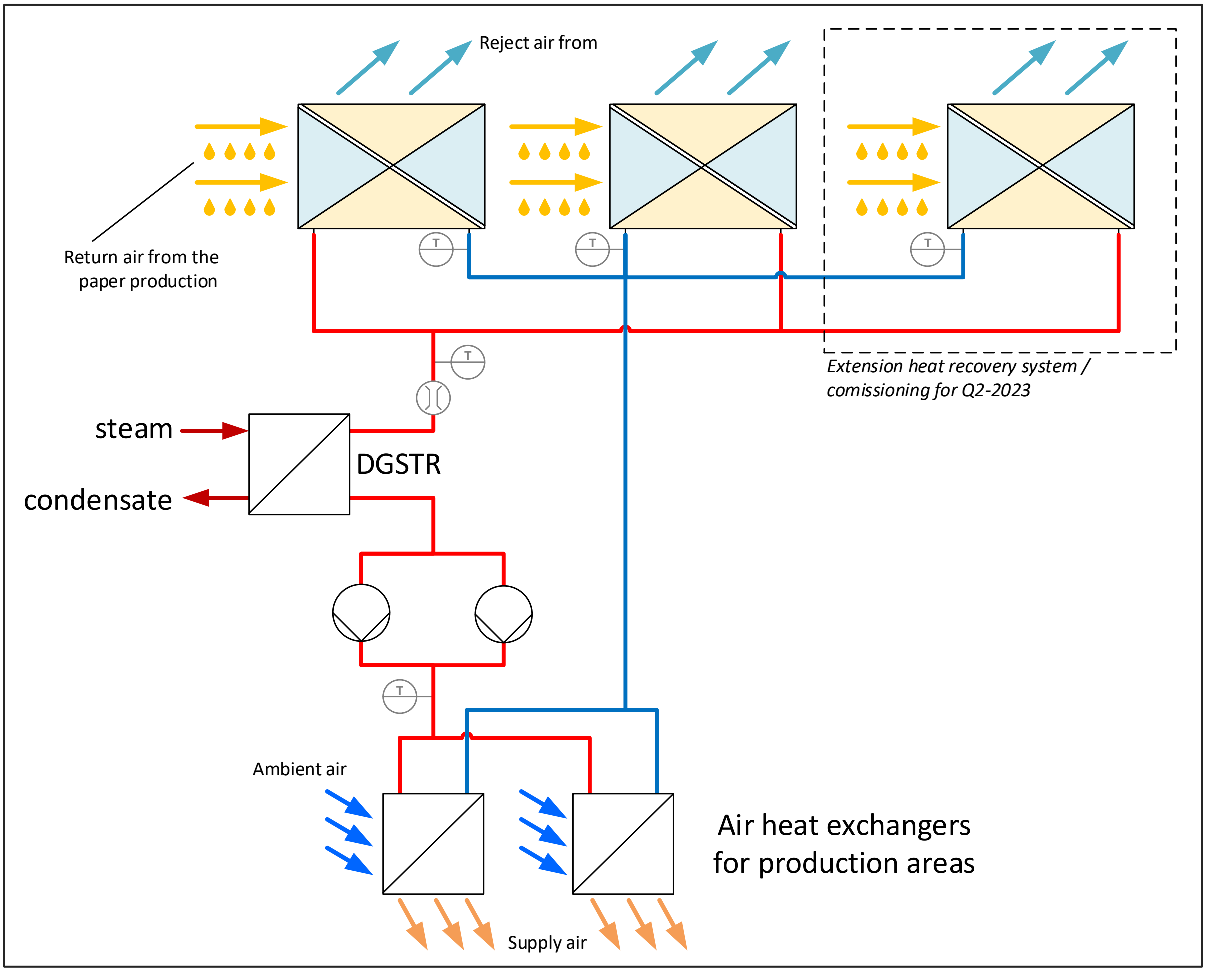

Figure 9: Simplified setup of the water-glycol-circuit and the heat recovery system

A new extension of the heat recovery system has been installed, which will allow an increase of the recovered heat from the return air and a higher potential for waste heat usage. Commissioning took place at the end of Q2/2023. Further shown in Figure 9 are some monitoring data points that are used for the evaluation of the heat source potential within Task 3.1.1.

Within task 3.1.1 the potential for using the water-glycol circuit as a heat source for the heat upgrade system will be analyzed and discussed. Monitoring data is provided by demo site for the time period November 2020 to September 2022. A key for assessing the integration of a Heat Upgrade System (HUS) is the quantification of the available heat that can be extracted along its temperature level throughout the year. Further, the interaction of the HUS with the running heat recovery system and its requirements need to be taken into account as well.

Figure 10 (top) highlights the monitoring values for the temperatures of the water-/glycol circuit at the outlet of the current heat recovery system for the given time period (November 2020 to September 2022). The monitoring values have a time resolution of 15 min. Depending on the operating conditions the available inlet temperature for a HUS can reach values in the range of 30 °C to 60 °C. Figure 10 (bottom) shows the monitoring values for the flow rate in water-/glycol circuit in the same period. With the given pump control flow rate values in the range of 55 m^3/h to 160 m^3/h are reached.

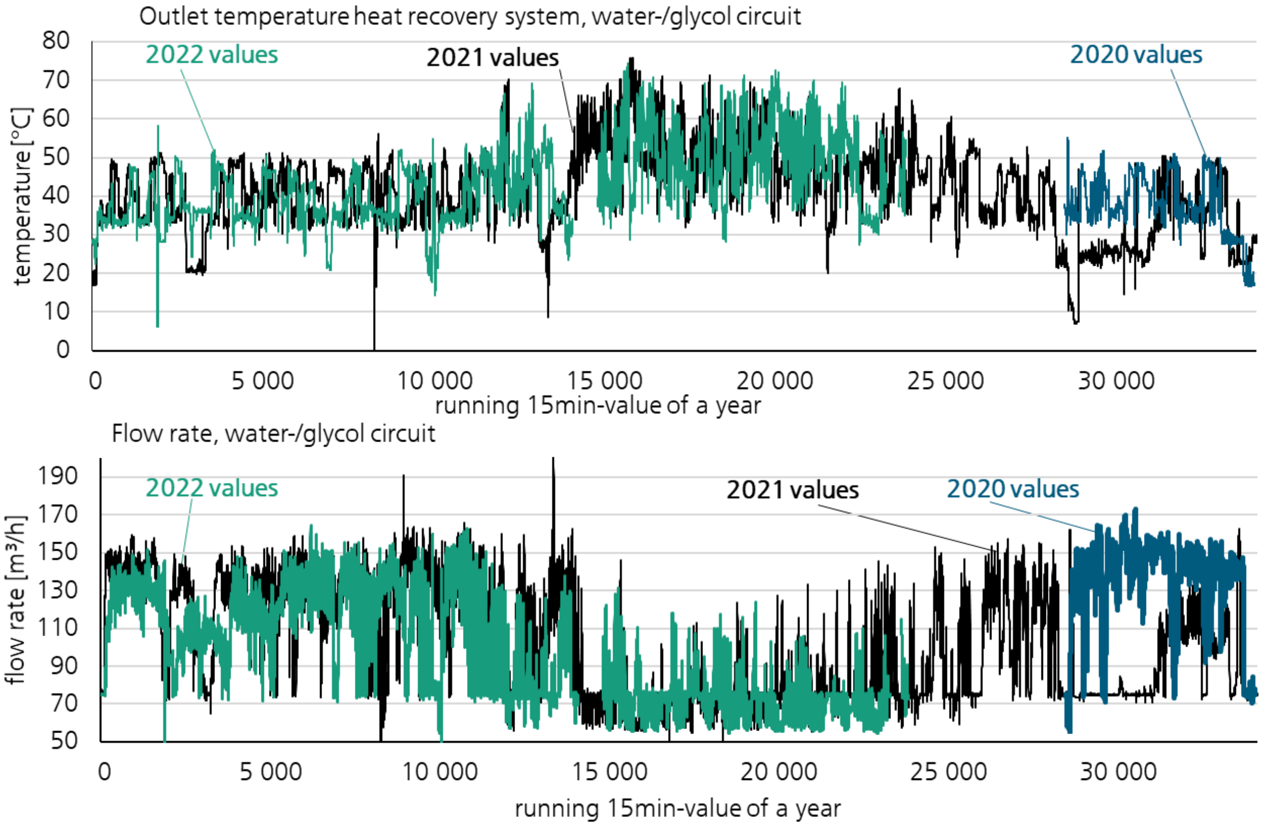

Figure 10: Outlet temperature of the heat recovery system (top) and flow rate in the water-/glycol circuit (bottom) for the years 2020, 2021, 2022

As previously described, the heat recovery system is extended with a third heat recovery unit (see Figure 9). The commissioning of this system took place at the end of Q2/2023. Table 1 highlights the design conditions for an ambient air temperature of 0 °C. The glycol type used is Glykosol N with a mass fraction of 25 % in the water-/glycol mixture. A density of the mixture of 1 025 kg/m³ and a heat capacity of 3.99 kJ/(kg·K) is given at a temperature of 50 °C.

		HRS new	HRS
Inlet temperature	°C	25	25
Outlet temperature	°C	46	43
Flow rate	m³/h	220	220
Heat recovered	kW	5 250	4 500

Table 1: Design conditions for heat recovery system (HRS) before and after extension

Figure 11 highlights the calculated heat capacity (power in kW) of the heat recovery system for the given time period. The thermal capacity $\dot{Q}_{HRS}$ is calculated as follows:

$$\dot{Q}_{HRS}(t) = \dot{V}_{wg}(t) \cdot \bar{\rho}_{wg} \cdot \bar{c}_{wg} \cdot \left(T_{out,HRS}(t) - T_{in,HRS}(t)\right)$$

With

$\dot{V}_{wg}$ measured flow rate of the water glycol (in m³/s),’

$\bar{\rho}_{wg}$ volumetric density of water/glycol used (constant value, in kg/m³)

$\bar{c}_{wg}$ heat capacity of water/glycol used (constant value, in kJ/(kg·K))

$T_{out,HRS}$ HRS outlet temperature (in °C)

$T_{in,HRS}$ HRS inlet temperature (in °C)

Available heat is within a range of 500 kW to 3 000 kW with a high fluctuation of the recovered heat in the HRS. This is most likely due to operation-related reasons of the paper production, i.e. high fractions of latent heat can be recovered when process heat (steam) is required for the drying process (see chapter 2.5). An indicator to evaluate this effect would be the monitoring values for consumption of process heat in that part of the production process, which are not available.

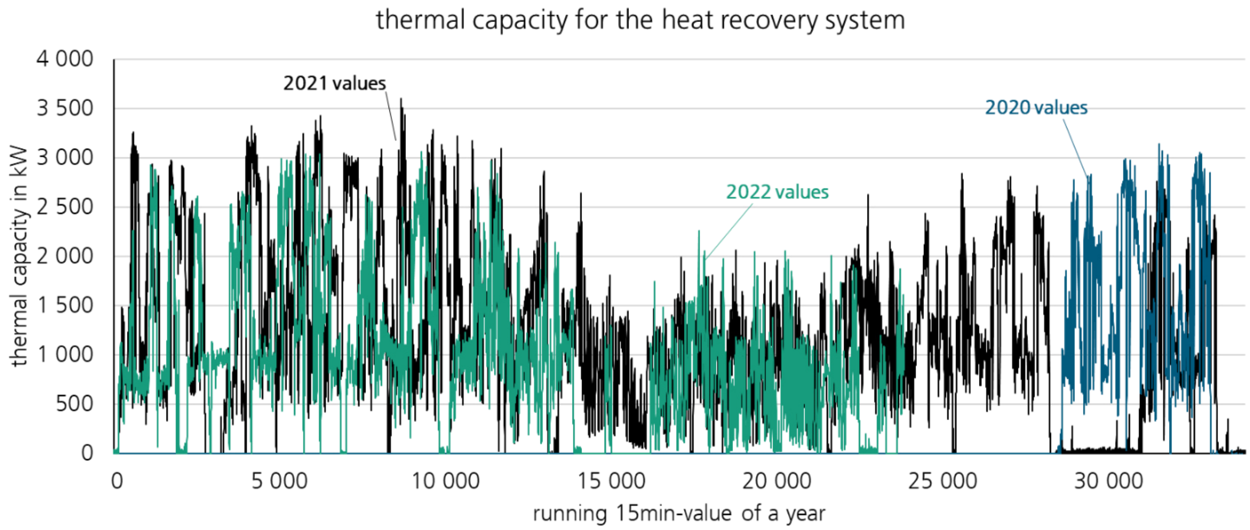

Figure 11: Calculated thermal capacity of the heat recovery system for the years 2020, 2021, 2022

Figure 12 shows the relative distribution of the calculated heat capacity values for each year (2020-2022). In general, 50 % to 60 % of the recovered heat is within the range of 500 kW to 1 500 kW. For the year 2022 higher values than 1 500 kW are not as common as for the years 2020 and 2021. However, since the values of 2020 are only representing two months of the year, the heat capacity values of 2021 and 2022 can be regarded as more reliable for the assessment of the heat extraction potential.

Nevertheless, a high fraction of the recovered heat is needed for heating the supply air of the production areas. If this heat is not sufficient, process heat (steam) is used in a heat exchanger (DGSTR, see Figure 9) to provide the necessary heat for reaching the required air supply temperature for the production areas. During this operation period with a high heat demand the heat source potential is limited and a heat extraction (e.g. by a heat upgrade system) is not possible and would lead to an additional supply of steam in the DGSTR heat exchanger.

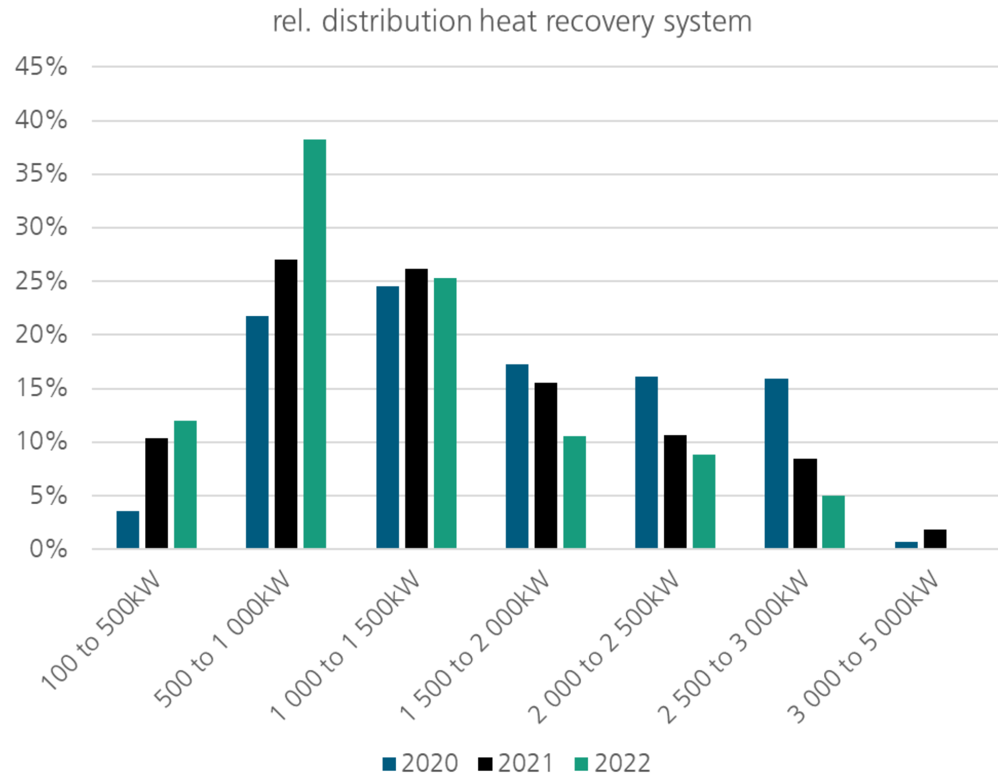

Figure 12: Relative distribution of recovered heat in the HRS (per year 2020, 2021, 2022)

Moreover, with the given monitoring data the heat supply by the steam fired heat exchanger ($\dot{Q}_{DGSTR}(t)$) and the total heat supply for the production hall ($\dot{Q}_{PH}(t)$) can be calculated. For a given time period Δt the total supplied heat values can be calculated as follows:

$$Q_b^{\Delta t} = \int_{t_o}^{t_o+\Delta t} \dot{Q}_b(t)$$

With

$\dot{Q}_b$ heat capacity for the corresponding boundary b (in kW),

{b = DGSTR or b = HRS or b = Production Hall PH}

As a result, the annual heat values for the HRS, DGSTR and PH are given for the years 2018, 2021 and 2022 in Figure 13. The fraction of additionally needed heat in the DGSTR accounts for approximately 21 % (2018), 42 % (2021) and 38 % (2022). Apart from the fact that approx. 40 % of the heat required for heating the production areas is needed by process heat (steam), this fraction has increased in comparison to values from 2018.

The monitoring data for the time period 2018 is shown in order to highlight the altered heat source conditions in comparison to the data from 2018, on which the initial concept for the Heat Upgrade System was defined. In the following, the information analyzed and provided with regard to these altered heat source conditions will be discussed.

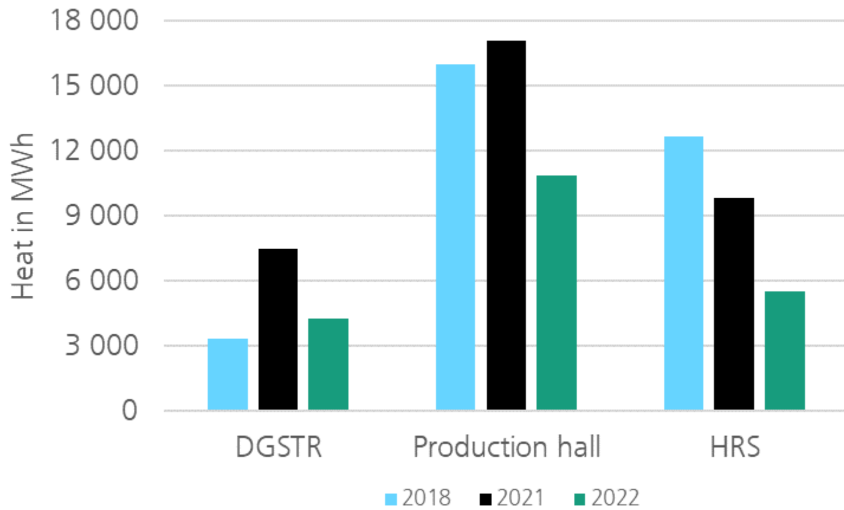

Figure 13: Annual heat demands for Back-up heat exchanger (DGSTR), heat consumers (Production hall) and Heat Recovery System (HRS)

Based on internal discussions among the involved partners during Task 3.1.1 the following information concerning the increase of the heat demand after 2018 by the DGSTR has been noted:

- Change of the production paper type with reduced water content, thus reducing the latent heat in the exhaust air streams entering the HRS[3]
- A reduced heat transfer in the HRS due to possible accumulation of solid material; influencing negatively the heat transfer between the water/glycol circuit and the hot exhaust air streams can be ruled out (maintenance)

Further, since the building management system and the control of the set point temperature for the supply air streams is a complex and internal control system, an evaluation with regards to changed set point temperature values for the outlet temperature of the DGSTR was not undertaken. However, the relative distribution of $T_{out,HRS}$ and $\dot{V}_{wg}$ for the time period 2018 and 2020-2022 is given in Figure 14.

[3] According to the site owners, the amount of heat that can be recovered depends strongly on the production process and parameters like paper thickness, water content of the paper produced.

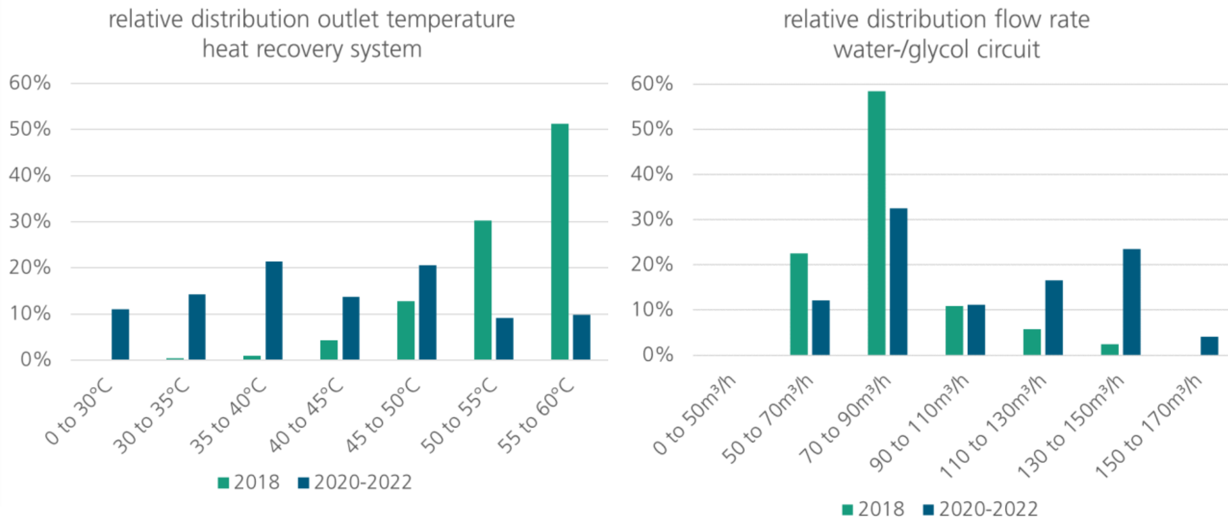

Figure 14: Relative distribution of the outlet temperature heat recovery system (left) and relative distribution of the flow rate in the water-/glycol circuit (right) for the time periods 2018 and 2020-2022

As shown in Figure 15, the time period 2020-2022 shows overall an increased heat demand from process heat supplied by the steam in the DGSTR. In the time period 2018, these operating points[4] account for approx. 30 % in comparison to 70 % of operating points with no heat demand from the DGSTR heat exchanger. In the time period 2020-2022 operating points with DGSTR account for 60 % in comparison to 40 % of operating points with no heat delivery by the DGSTR.

[4] Operating points with DGSTR are given when $\dot{Q}_{DGSTR}(t) > 100kW$

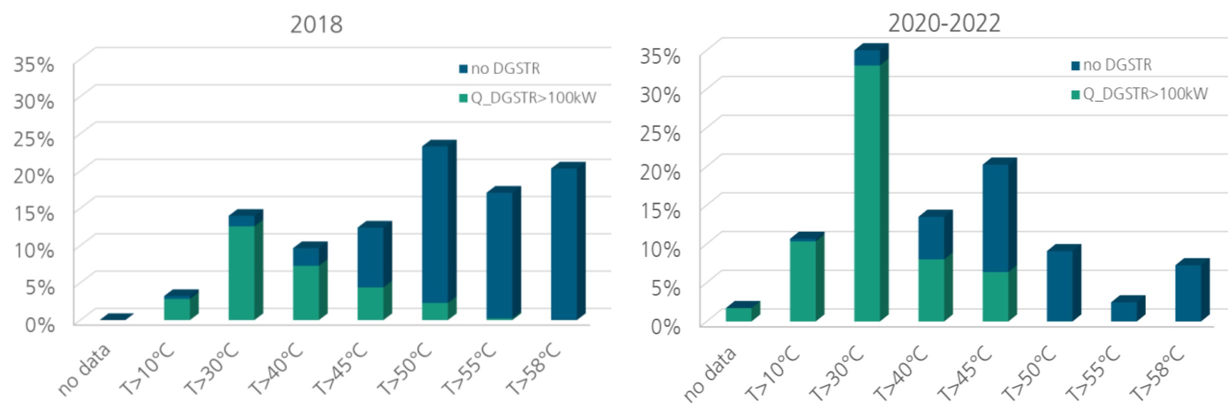

Figure 15: Relative distribution of operating points with heat supply from DGSTR and without any additional heat demand for the time periods 2018 (left) and 2020-2022 (right) according to different water/glycol outlet temperatures of the HRS system

Figure 16 shows the distribution[5] of possible heat extraction capacities for various ranges of $T_{out,HRS}$ assuming a 5 K temperature decrease after the water-/glycol exits the HRS. For the given time period 2021-2022 the resulting operation hours with no heat from the DGSTR heat exchanger account for approx. 6.200 h in total as already shown in Figure 16. As a result, this corresponds to 42 % of the given time period. Further, as has been already shown in Figure 15 (right), 83 % of the potential operation time ('no DGSTR') takes place for $T_{out,HRS}$>45 °C. According to Figure 16 possible heat extraction capacity values between 300 kW and 700 kW are given.

The distribution of potential heat extraction capacities for each temperature range is similar to a boxplot, ie. the rectangle distribution box corresponds to 50 % of the values given within the first and third quartile. Within the whiskers all values apart from outliers can be found.

[5] Distribution shown in a ‚box-and-whisker plot'

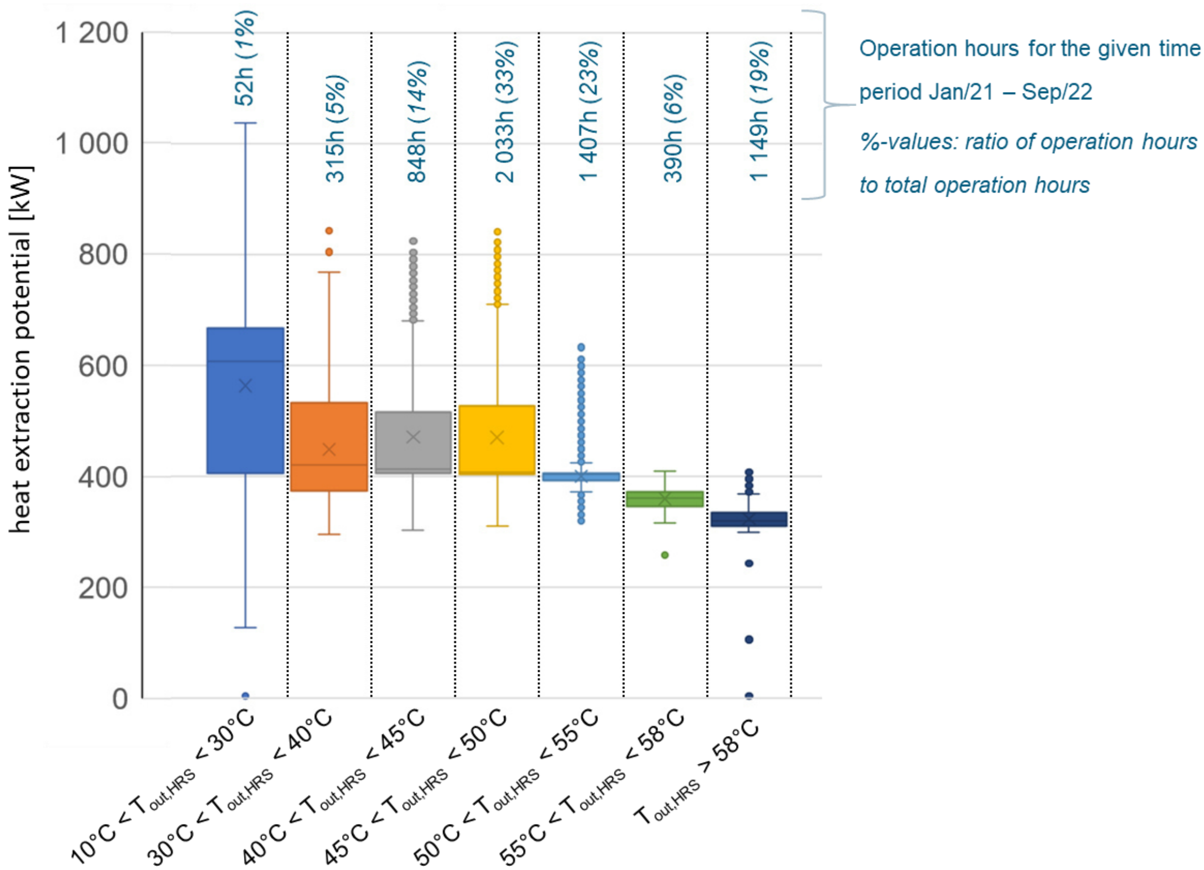

Figure 16: 'Boxplot' and distribution of the heat extraction potential for the time period 2021-2022

Together with the company responsible for the development and implementation of the heat recovery system, the project partners assessed the available heat extraction potential and thereby taking the new extension of the heat recovery system into consideration (see Figure 9). As a result, for ambient air temperatures ≥ 8 – 9 °C the total accumulated operation hours without any additional heat supply from the DGSTR is estimated to account for approx. 4 000 h/a. Below this a part-load operation a Heat Upgrade System is necessary in order not to indirectly force a heat supply from the DGSTR due to reduced water-glycol temperatures (more information will be provided in chapters 3.1 and 3.4).

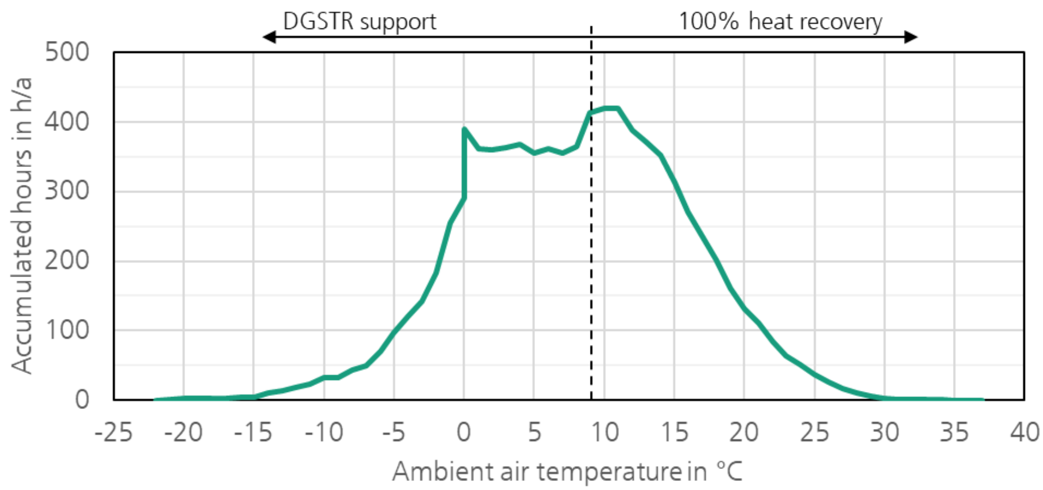

Figure 17: Distribution of accumulated hours for ambient air temperatures at demo site 1

Further, with an overall increase nominal flow rate in the water-glycol circuit and an increased outlet temperature of the HRS (see values in Table 1) an available heat extraction potential of 700 kW at a flow rate of 130 m^3/h and a temperature decrease of 5 K (46 C → 41 °C) in the primary circuit of the Heat Upgrade System has been identified and agreed upon as a design condition for the heat source circuit of the HP.

2.5 Heat sink requirements

The process of drying paper in the paper industry is responsible for most of the energy demand. Thus, it is very important to find a solution to recover waste heat from this process. At the paper machine the evaporation of water in the paper is driven by steam. This steam is condensed in so-called dryer cans (see Figure 18).

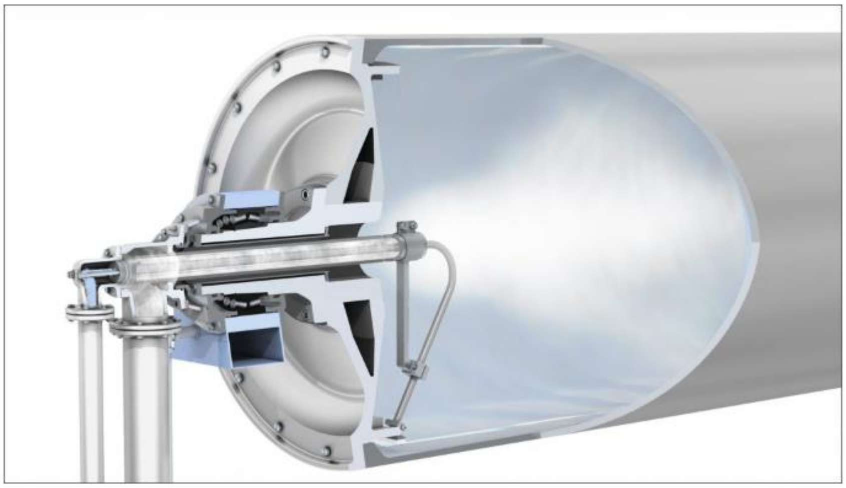

Figure 18: Dryer can showing steam inlet and outlet through a stationary syphone

The saturated steam pressure level inside the cans provides the temperature as the driving force for the drying process. Figure 19 shows the heat flux and temperature profile at the cylinder shell. Heat from condensated steam inside the dryer can is used to evaporate the water in the paper.

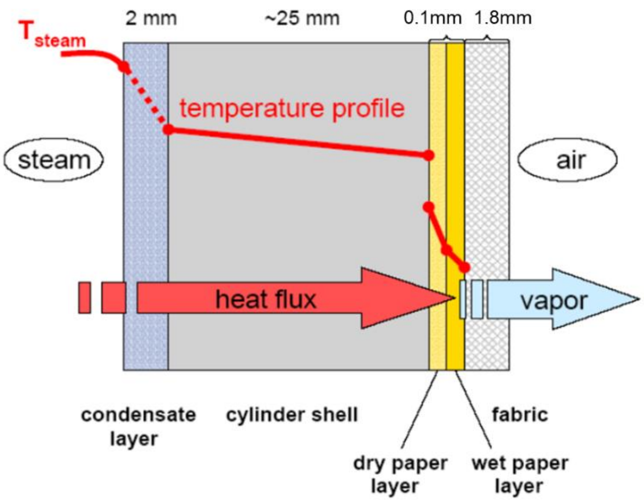

Figure 19: heat flux from steam through the shell of the dyer can to the paper

Dryer cans are grouped together to be supplied by a specific steam pressure level and steam temperature level starting by low temperature at the very beginning to the highest temperature at the end of the drying section.

The main stream supply pressure levels in Felix Schoeller Weißenborn mill are

- 4.5 bar(a) – 148 °C
- 8.0 bar(a) – 170.5 °C

The steam pressure that is produced by the heat pump will be on a lower level (2.2 bar(a)). In this way the temperature lift of heat pump is kept as low as possible in order to increase the efficiency (COP) of the heat pump. Saturated steam at 2.2 bar(a) will be sufficient to feed the first steam group in the dry section (cans 1 to 5, see Figure 20).

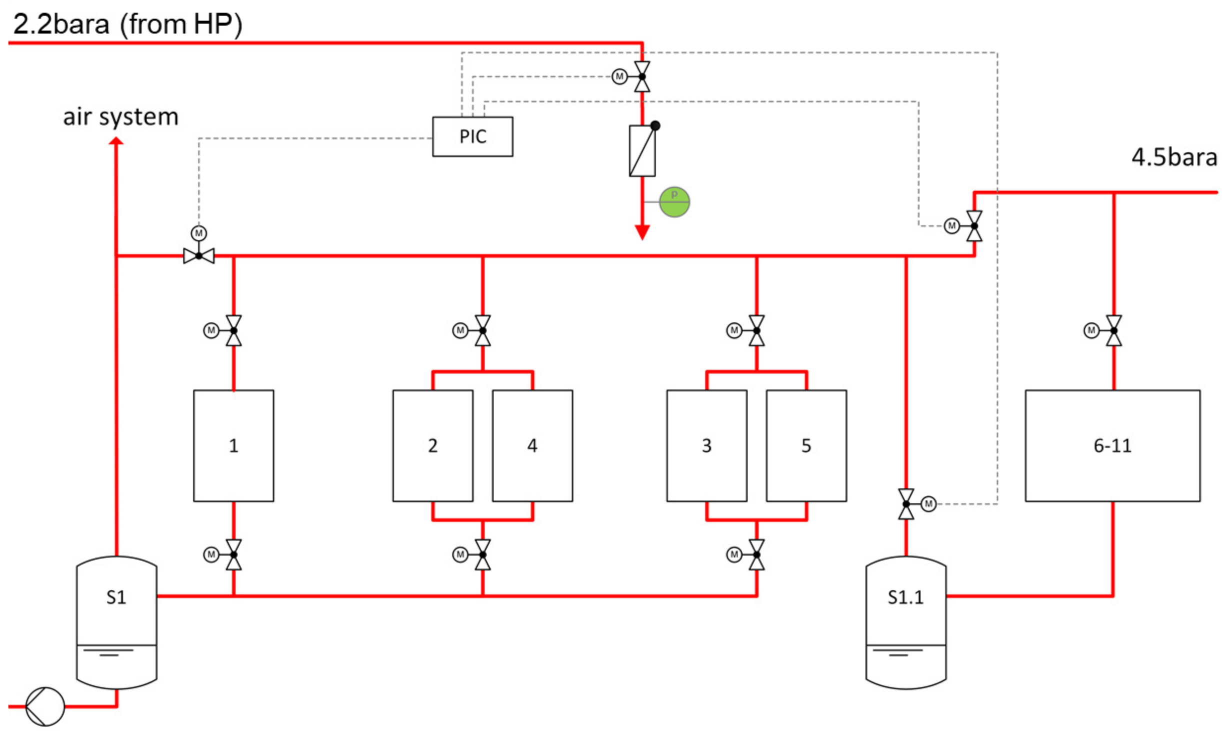

Figure 20: First dry section (can 1 to 5) and supply line from Heat-Pump

The steam pressure in can 3 and can 5 are on the highest pressure steam consumers in this first group and give the setpoint for supply pressure of the heat pump. According to different operation phases the pressure set points can vary throughout the year (see Table 2). The analysis of the production shows three set points for this. In 2 640 h the paper machine is in shutdown/standby/startup mode where pressure setpoint values <2.2 bara is given. In approx. 600 h/a (Product C) the pressure setpoint is higher than 2.2 bara due to product specification requiring a higher pressure level. The cans 1, 2 and 4 are always driven on a lower steam pressure.

Phase	Fraction	Time period	Pressure level

	%	h/a	bar(a)
startup/stand-	31	2 640	<2.2
Product A	50	4 320	1.5
Product B	13	1 080	2.1
Product C	7	600	2.4
Total year	100	8 640	

Table 2: Setpoints and frequency of pressure setpoints (can 3 and 5), year 2020

The pressure levels and the pressure control valves are monitored continuously during production. Condensed steam from the dyer cans is collected in the main condensate tank at the paper machine around 90 °C. The condensate is then pumped to the boiler house within the CHP system to be used as feed water for the boilers again. The condensate for the heat pump is pumped from the main condensate tank in a separate line to the heat pump.

2.6 Scenarios for the Heat Upgrade System

For the development of Heat Upgrade System several aspects were assessed and discussed among the involved partners in the planning process. The goal was to identify and select the most optimal boundary and operating conditions for a Heat Upgrade System based on Heat Pump technology.

For Felix Schoeller it is important to conduct a comprehensive cost-benefit analysis and evaluate specific operational requirements before investing in a heat pump system. Factors such as availability of waste heat, load requirements, installation costs, maintenance needs, and available incentives have been checked to acquire the best feasibility and potential return on investment. In addition, the current integration shows a typical waste heat case that is often found in the production facilities of Felix Schoeller.

These aspects will be shortly described below.

2.6.1 Interconnection of heat source and heat pump

For the integration of the heat source circuit of a heat pump into the existing water-/glycol circuit several options based on the existing hydraulic configuration on site were discussed among the involved partners:

a) Serial configuration on the general outlet of the old HRS

b) Serial configuration on the outlet of the new extension of the HRS

c) Serial configuration on the general outlet of the HRS

d) Parallel configuration on the main supply/return of the water-/glycol circuit

One integration criteria is to avoid any influence on the current control regime of the main supply pumps in the given water-/glycol circuit and simultaneously have an independent heat extraction concept. With respect to a high efficiency of the Heat Upgrade System, high values of the flow rate in the external evaporator circuit of the Heat Pump are favorable. As a result, the integration options b) and d) are causing a reduced HP efficiency and a reduced capacity for the supply of process heat. Integration option c) shows the highest advantages with regards to HP efficiency and performance and is shown simplified in Figure 21.

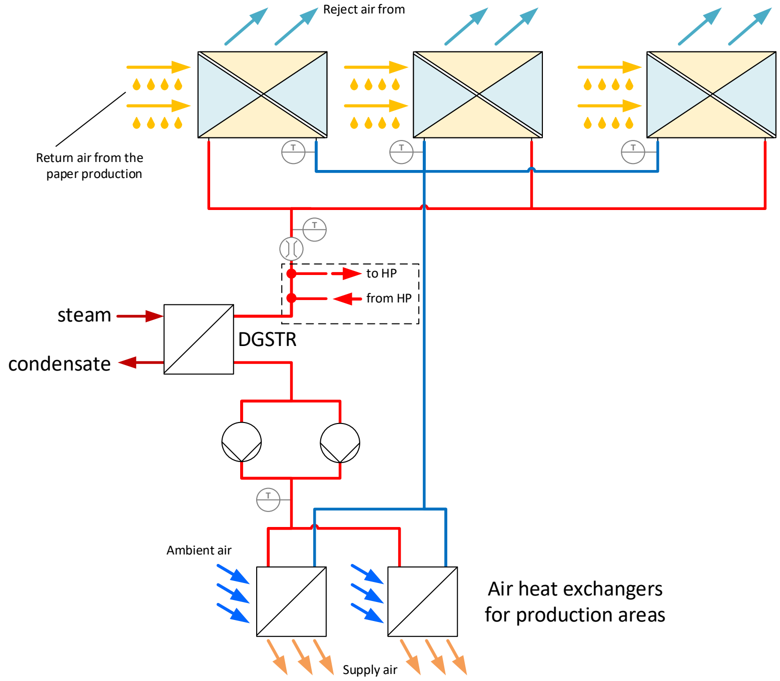

Figure 21: Selected hydraulic integration for the HUS into existing HRS (see dotted box)

2.6.2 Energy efficiency and cost-effectiveness of steam supply concepts

Felix Schoeller has several incentives for investing into a heat pump system. These can be summarized as follows:

- Energy Efficiency:
  Heat pumps are known for their high energy efficiency. By using a heat pump, FSG expects to significantly reduce its energy consumption compared to traditional heating and cooling systems in the future.

- Cost Savings:
  Heat pump systems can lead to substantial cost savings for the paper industry. As mentioned earlier, heat pumps are energy-efficient, which means they require less electricity or fuel to operate than electrical or fuel-fired boiler. This can result in lower utility bills and decreased dependence on fossil fuels. Further cost savings can be achieved through a reduced expenditure on CO2-certificates.

- Environmental Benefits:

The paper industry, like many other sectors, is increasingly concerned about its environmental impact. Heat pumps contribute to sustainability efforts by reducing carbon dioxide emissions and reliance on non-renewable energy sources.arized as follows:

2.6.3 Re-compression of low-pressure steam

The paper plant has different steam supply lines. The lowest pressure supply line works at a steam pressure of 4,5 bara, which corresponds to a steam temperature of 148 °C. With that temperature target, having a heat source temperature in the range of 45 °C, a temperature lift of 100 K is required by a heat pump for which a multiple stage system is needed. A combination of a steam producing heat pump and a steam compression system can serve as a good alternative to a singular multi-stage heat pump. With this combination the heat pump will upgrade the waste heat from the source temperatures to the temperature level of low pressure steam (at approx. 2.2 bara) and the steam compressor will increase further the pressure level up to the required steam pressure (at 4.5 bara).

In principle there are two different technologies to compress the steam, with thermal energy or with mechanical energy. Thermal steam compressors use high pressure steam to bring the low pressure steam up to the required medium pressure level which is needed. The various technological options will be addressed and described in the deliverable D2.5 ('Process integration and steam production in industrial processes') from WP2 that is due in M15 of the project timeline.

The technology of thermal steam compressors was not analysed for this application in detail due to the fact that a high amount of high pressure steam is required. Data from a technology provider is given in

Data supply steam (high pressure):				
m_T	Mass flow	:	5 692	kg/h
p_T	Pressure level	:	8.0	bara
t_T	Temperature	:	170.4	°C (saturated)
Data low pressure steam:				
m_S	Mass flow	:	1 015	kg/h
p_S	Pressure level	:	2.2	bara
t_S	Temperature	:	123.3	°C (saturated)
Data supply steam (intermediate pressure):				
p_D	Pressure level	:	4.5	bara

Table 6 (Annex 2: Data Point List

Datapoint	measurand	sensor type	zone	sensor mounting	medium	unit	decimal places	data aquisition system	interface / protocol	measuring interval [in s]	respo for pu
T_FL_evap_HME	temperature	Pt100	HP source	immersion sleeve for DN ???	water / glycol ? %	°C	2	heat meter evap (HME)	Mbus	60	tbd
T_RL_evap_HME	temperature	Pt100	HP source	immersion sleeve for DN ???	water / glycol ? %	°C	2	heat meter evap (HME)	Mbus	60	tbd
V_dot_evap_HME	volume flow	MID	HP source	flange for DN	water / glycol ? %	m³/h	3	heat meter evap (HME)	Mbus	60	tbd
Q_dot_evap_HME	thermal power	-	HP source	-	water / glycol ? %	kW	1	heat meter evap (HME)	Mbus	60	tbd
Q_evap_HME	thermal energy	-	HP source	-	water / glycol ? %	kWh	0	heat meter evap (HME)	Mbus	60	tbd
sp_mv_evap	position	setpoint mixing valve	HP source	-	water / glycol ? %	-	1	tbd	tbd	60	tbd
T_FL_VTP_in	temperature	Pt100	HP source	immersion sleeve for DN ???	water / glycol ? %	°C	2	felix schöller group	tbd	60	tbd
T_FL_evap_HP	temperature	?	HP	?	water / glycol ? %	°C	1	controller HP	modbus TCP	60	SPH
T_RL_evap_HP	temperature	?	HP	?	water / glycol ? %	°C	1	controller HP	modbus TCP	60	SPH
p_FL_evap_HP	pressure	?	HP	?	water / glycol ? %	bar	1	controller HP	modbus TCP	60	SPH
T_FL_cond_HP	temperature	?	HP	?	water / steam	°C	1	controller HP	modbus TCP	60	SPH
T_RL_cond_HP	temperature	?	HP	?	water / steam	°C	1	controller HP	modbus TCP	60	SPH
p_FL_cond_HP	pressure	?	HP	?	water / steam	bar	1	controller HP	modbus TCP	60	SPH
P_pu_evap	electrical power	electricity meter	HP source	-	-	kW	1	felix schöller group	tbd	60	tbd
E_pu_evap	electrical energy	electricity meter	HP source	-	-	kWh	1	felix schöller group	tbd	60	tbd
P_comp_ST_1	electrical power	electricity meter	HP	-	-	kW	1	controller HP	modbus TCP	60	tbd
E_comp_ST_1	electrical energy	electricity meter	HP	-	-	kWh	1	controller HP	modbus TCP	60	tbd
P_comp_ST_2	electrical power	electricity meter	HP	-	-	kW	1	controller HP	modbus TCP	60	tbd
E_comp_ST_2	electrical energy	electricity meter	HP	-	-	kWh	1	controller HP	modbus TCP	60	tbd
T_amb	temperature	Pt100	ambient	tbd	air	°C	1	felix schöller group	tbd	60	felix s group
T_RL_VTP_2	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	alread prese
T_RL_VTP_0	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	alread prese
T_FL_VTP	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	alread prese
T_FL_VTP_b_HEX	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	60	felix s group
T_FL_VTP_a_HEX	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	alread prese
T_RL_VTP	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	alread prese
status_blowdown	operating signal	digital value	feed water heat sink HP	?	water	-	1	controller HP	modbus TCP	tbd	tbd
V_dot_RL_VTP	volume flow	?	feed water heat sink HP	?	water	°C	1	felix schöller group	tbd	tbd	alread prese
p_cond_feed	pressure	?	feed water heat sink HP	?	water	bar	1	felix schöller group	tbd	60	tbd
V_dot_cond_feed	volume flow	?	feed water heat sink HP		water		1	felix schöller group	tbd	60	tbd
T_cond_group	temperature	?	feed water heat sink HP	?	water	°C	1	felix schöller group	tbd	tbd	tbd
V_dot_cond_group	volume flow	?	feed water heat sink HP	?	water	m³/h	1	felix schöller group	tbd	tbd	tbd
P_HP_total	electrical power	electricity meter	HP	-	-	kW	1	felix schöller group	tbd	60	tbd
E_HP_total	electrical energy	electricity meter	HP	-	-	kWh	1	felix schöller group	tbd	60	tbd
sp_valve_HS_1	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd
sp_valve_HS_2.1	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd
sp_valve_HS_2.2	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd
sp_valve_HS_3.1	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd
p_HS_1	pressure	?	heat sink	tbd	water / steam	bar	1	felix schöller group	tbd	60	tbd
p_HS_2	pressure	?	heat sink	tbd	water / steam	bar	1	felix schöller group	tbd	60	tbd

Annex 3: Thermocompressor data), where an Entrainment Ratio[6] for this specific case of 5.6 is reached. As this value is significantly high for typical values considered in thermo-compressor applications (see further details in D2.5), this technological solution was not further discussed within task 3.1.2.

Mechanical vapor recompression (MVR) uses a steam compressor, normally driven by an electric motor to compress the steam directly. Three types of compressors are dominating:

- Piston compressor
- Screw compressor
- Radial fans/ turbo compressors

Radial fans and turbo compressors are only available for large steam flows above 5 t/h. For this application, with approximately 1.8 t/h steam production, they prove inappropriate. The other two types of systems are available for the planned steam mass flow and are very similar in the achievable full load efficiencies. The differences are a better part-load efficiency of the piston compressor but with higher investment costs and an overall larger size.

After analysis of different combinations of heat pump working fluids and the transfer pressure between heat pump and MVR, the combination of HP and MVR resulted in an overall COP[7] of about 2 – 2.1. The alternative for such a system is to directly connect the 2-stage steam producing heat pump with a low-pressure steam part of the paper machine. This means higher integration and control effort, but better energetical efficiency of a heat upgrade system because the steam pressure level can be lower and so the lift of the heat pump is significant lower and an overall COP of about 2,3 can be reached. A short analysis showed the additional effort for the direct integration in the paper machine is compensated very fast with the increase in COP for such a solution. As a result, a combined system (i.e. HP and MVR) was no longer investigated.

2.6.4 Selection of refrigerants and HP process setup

The selection of the heat pump process setup and the used refrigerant depends mainly on the temperature level in the heat source and heat sink. Additional criteria are related to environmental and safety impact of the working fluid.

The first step is to select possible refrigerants according to their critical point compared to the required steam temperature. With direct steam production in the condenser of the heat pump the condensing temperature of the refrigerant is always higher than the required steam temperature. The resulting condensing pressure of the refrigerant must be lower than the design pressure of the heat pump system components (like compressor discharge pressure or heat exchanger maximum pressure). For good

[6] The Entrainment Ration of a thermo-compressor describes the ration of Motive steam flow rate to suction steam flow rate. Typical values can be found in the range of 1.5 to 3 and depend on expansion as well as compression ratio.
[7] Considering all electricity demands for the supply of steam in a combined system consisting of HP and MVR.

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performance, a sufficient distance between critical pressure and condensing pressure should be maintained.

The next step is to check the resulting pressure at the designed evaporation temperature. First, the pressure ratio between the condensing pressure and evaporation pressure must fit to the compressor type and design. For example, a piston compressor can work with pressure ratios of up to 10 or more, but with increasing pressure ratio the volumetric efficiency of the compressor decreases, which reduces the volumetric refrigerant flow. The thermal power output of the heat pump is proportional to the mass flow of the refrigerant, which is the product from volumetric mass flow, defined by the compressor size, and the density of the refrigerant at the compressor inlet. This density is mainly dependent on the evaporation pressure. If the evaporation pressure is too low, the thermal power output of the system is reduced in a way that an economical operation of the heat pump is no longer possible. In this case a 2-stage system can be a better economic and technical solution. In a 2-stage system, two heat pump systems are cascaded and coupled by a common heat exchanger which works as a condenser for the first stage and as an evaporator for the second stage. Figure 22 shows the principal arrangement of a 2-stage heat pump system.

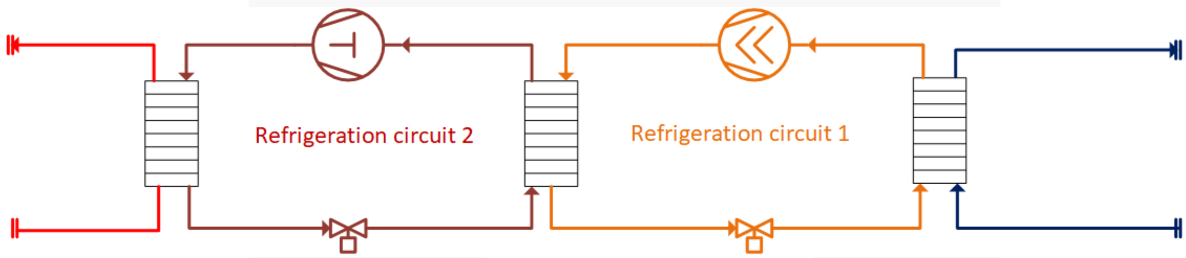

Figure 22: Simplified setup of 2-stage heat pump system

With a 2-stage system it is possible to choose a refrigerant which fits very well to the requirements on the steam producing heat sink side and in parallel to choose a refrigerant which gives optimal performance at the evaporator conditions of the first stage. The cascade temperature level can be used to optimize the system further on, also during operation by shifting it up and down by the control of the two stages.

In principle two groups of refrigerants exist and are used for heat pump systems, natural and synthetic refrigerants.

Natural refrigerants are for example hydrocarbons, ammonia or CO_2. Synthetic refrigerants are groups like HFO, HCFO, HFC with the well-known and widely used refrigerants like R134a, R1234ze, R1233zd or any blends of those.

Environmental and safety factors are further criteria for the selection of the refrigerants. Environmental factors are:

- Global Warming Potential (GWP)
- Ozone Depletion Potential (ODP)
- Decomposition products (e.g. TFA)

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Natural refrigerants have a lot of advantages. Their ODP value is 0, most have a very low GWP (<5) and the decompositions products are non-harmful or the refrigerant itself is stable. Modern synthetic refrigerants also have a low GWP (<20), none or nearly no ODP. But the decomposition products are not 100% clear, and it is not sure if they are not harmful and their long-term impact on the environment and human health is unknown. From an environmental point of view natural refrigerants are preferable. However, if safety issues are taken into account and the fact that during normal heat pump operation none, or nearly no working fluid, is emitted to the environment, there are also good arguments for using synthetic refrigerants. Most modern synthetic refrigerants are so called A1 safety fluids which classifies them as not flammable and non-toxic. Natural refrigerants for high temperature heat pumps on the other hand, are easily flammable with some of them being classified also toxic. Consequently, the integration of a high temperature heat pump with natural refrigerants into a facility can pose a high challenge in certain applications.

The design conditions for the heat pump are:

- 1. stage
    - Heat Source 46 °C/41 °C
    - Evaporation temperature 38 °C
    - Condensing temperature 85 °C
    - Lift = 47 K
- 2. stage
    - Evaporation temperature 75 °C
    - Condensing temperature 128 °C
    - Lift=53 K
    - Heat Sink: saturated steam at 123 °C

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Name	type	pressure @ 128°C	critical pressure	critical temperature	GWP-value	ODP-value	toxicity	Flammability	Safety class
		[bar]	[bar]	[°C]					
R1233zd	synthetic	18.38	35.71	165.6	1; <5	0.0003	low	none	A1
R1224yd	synthetic	20.33	33.32	155.54	0.88	0.00023	low	none	A1
R1336mzz-E	synthetic	26.86	27.66	130.22	1.2; 7; 18	0	low	none	A1
R1336mzz-Z	synthetic	12.99	29.01	171.27	2; 4.1	0	low	none	A1
Butane (R600)	natural	25.45	37.96	151.98	4	0	low	extremely	A3
Iso-Butane (R600a)	natural	32.48	36.29	134.66	3	0	low	extremely	A3
Ammonia (R717)	natural	105.18	113.33	132.25	0	0	high	slightly	B2L
n-Pentane (R601)	natural	10.62	33.7	196.55	5	0	low	highly	A3

Table 4 shows an overview of potential refrigerants to produce steam at a temperature level of 123 °C (saturated steam). Table 3 shows potential refrigerants for the first stage in a two-stage system with 85 °C as a condensing temperature for the first stage. This is chosen as a reference value because it is about the middle temperature between evaporating (38 °C) and condensing (128 °C) temperature levels in this application.

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Name	type	pressure @ 85°C	critical pressure	critical temperature	GWP-value	ODP-value	toxicity	flammability	Safety class
		[bar]	[bar]	[°C]					
R1234ze(E)	synthetic	22.32	36.35	109.36	6	0	low	slightly	A2L
R515B	synthetic	22.34	35.78	108.50	299	0	low	none	A1
Ammonia	natural	46.10	113.33	132.25	0	0	high	slightly	B2L
Propane (R290)	natural	34.36	42.50	96.74	3	0	low	extremely	A3
Iso-Butane (R600a)	natural	14.87	36.29	134.66	3	0	low	extremely	A3

Table 3: Possible refrigerants for 1. stage

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Name	type	pressure @ 128°C	critical pressure	critical temperature	GWP-value	ODP-value	toxicity	Flammability	Safety class
		[bar]	[bar]	[°C]					
R1233zd	synthetic	18.38	35.71	165.6	1; <5	0.0003	low	none	A1
R1224yd	synthetic	20.33	33.32	155.54	0.88	0.00023	low	none	A1
R1336mzz-E	synthetic	26.86	27.66	130.22	1.2; 7; 18	0	low	none	A1
R1336mzz-Z	synthetic	12.99	29.01	171.27	2; 4.1	0	low	none	A1
Butane (R600)	natural	25.45	37.96	151.98	4	0	low	extremely	A3
Iso-Butane (R600a)	natural	32.48	36.29	134.66	3	0	low	extremely	A3
Ammonia (R717)	natural	105.18	113.33	132.25	0	0	high	slightly	B2L
n-Pentane (R601)	natural	10.62	33.7	196.55	5	0	low	highly	A3

Table 4: Possible refrigerants for steam production in 2. stage

Two refrigerants (R600a, R717) of this table show discharge pressures that are too high (>30 bar) for the use in the planned system, R1336-mzz-E is too near at its critical point to operate in a good and safe way. R601 and R1336mzz-Z have very low volumetric heating capacity at the planned 75 °C evaporation in a 2-stage system and would require much large compressors to reach the needed thermal output, so only three refrigerants matched the thermodynamic criteria for steam production at about 123 °C: Butane, R1224yd and R1233zd. Only the refrigerant Butane has the theoretical potential to the complete temperature lift from 46 °C/41 °C heat source temperature to the required steam temperature of 123 °C

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in a single stage. For Butane a pressure ratio of about 7.1 with an evaporation pressure of about 3.5 bar is usable. The other two refrigerants necessitate a 2-stage system to produce steam at the given heat source boundary conditions. For the first stage R1234ze, R515B or Iso-Butane fit to the criteria to use as a fluid in this stage. Ammonia and Propane show discharge pressures above 30 bar at 85 °C, which is too high for the planned system. R515B is a blend of R1234ze and R229ea and has the same thermodynamical properties as R1234ze, but the advantage of no flammability.

Due to safety issues with electrical transformation systems in close proximity of the installation site, the use of non-flammable fluids is required. In this case a combination of R515B with either R1224yd or R1233zd is the preferable solution. R1224yd and R1233zd have very similar thermodynamic properties so the differences in the performance are quite small. The Python based simulation model of the technology provider (SPH) for R1233zd shows a slightly higher efficiency, while R1224yd shows a bit higher thermal output. Due to the limitations in the available heat source power and the slightly higher efficiency R1233zd in the second stage in combination with R515B in the first stage was chosen. The COP on maximum power output will be around 2.3. During part load an optimization of the temperature in the cascading heat exchanger can be used to increase the COP to 2.4 – 2.5.

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3. Preliminary planning and basic engineering

3.1 Process integration of the Heat Upgrade System

Figure 23 shows a functional, simplified process and instrumentation diagram (P&ID) for the integration of the heat upgrade system into the heat source system (heat recovery system) and the heat sink system (paper production). The P&ID can also be found in the Annex 1 on page 55. The final concept of the heat upgrade system is based on a double stage heat pump as described in chapter 2.6. The monitoring points shown in Figure 23 will be introduced and described in chapter 3.5.

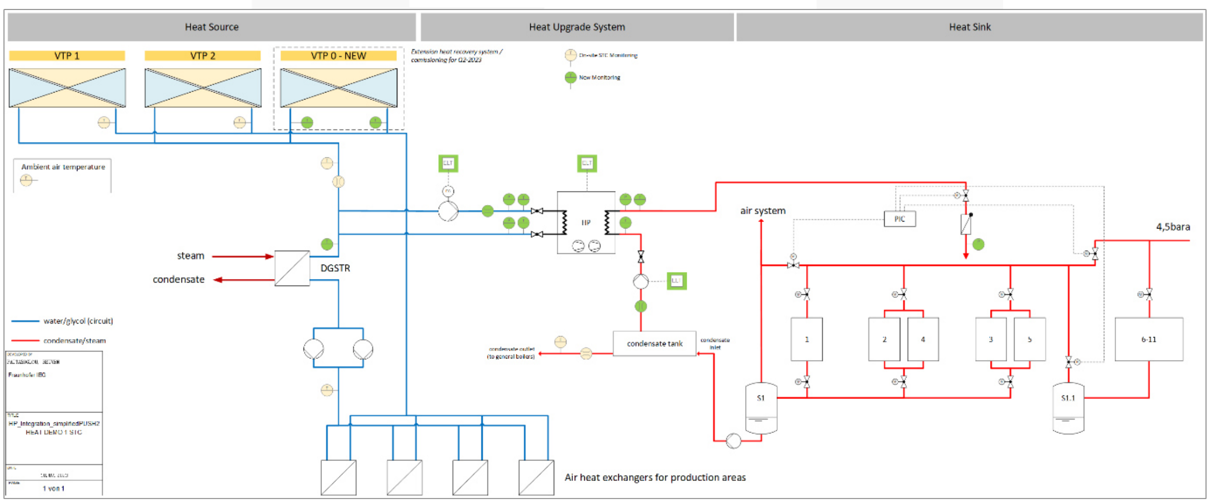

Figure 23: Functional P&ID Scheme for the heat upgrade system in the demo site 1 in Weißenborn

The heat recovery system recovers the excess heat of the air used for drying purposes of the paper by means of air to water-glycol heat exchangers. The water-glycol circuit of the heat recovery system is used for heating the hall of the paper factory whenever heat is demanded. The DGSTR is a heat exchanger used for supplying the water-glycol circuit with additional heat (process steam) whenever the inlet temperature for air heat exchanger is too low. As this additional (process heat) demand increases with reduced values of the ambient air temperature, the operation of the heat upgrade system is limited to operating times with an ambient air temperature not lower than 8 °C (see chapter 2.4, Figure 17). Regarding the heat

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source circuit, the heat upgrade system must be operated in such a way that the water/glycol inlet temperature to the DGSTR heat exchanger is not lower than a setpoint value provided by the building management system (BMS). In the external evaporator circuit of the HP (water/glycol) a variable flow circulation pump is foreseen in order to undertake adjustments with regard to the required flow rate.

On the heat sink side condensate (water) collected from the paper production process in a condensate tank is used to supply the heat upgrade system at a pressure level of approx. 2.2 bara. Condensate form the paper production process will serve as feedwater for the steam production. The double stage heat pump (see chapter 2.6) will provide slightly overheated steam that will be used directly in the paper production. As described in chapter 2.5 the process steam provided by the HUS will be directly integrated into the existing pressure-controlled production process and utilized in the low-pressure dryer cans 1, 2 and 4. A valve will be used to control the steam utilization into the existing system according to the required and given pressure level.

A detailed P&ID scheme will be provided by the engineering company VOITH responsible for the implementation of the HUS.

3.2 Design parameters for the Heat Upgrade System

This chapter highlights shortly the operating conditions at the design point and heat pump parameters for the heat upgrade system. The values are given in Table 5.

The electricity consumption of the heat pump by SPH does not include the electricity consumption of the external pumps for the evaporator circuit of the HP and the external pump supplying the steam heat sink circuit of the HP with condensate.

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Heat Source design parameters		
parameter	unit	value/information
Thermal capacity	kW_{th}	690
Flow rate	m^3/h	130
Inlet temperature evaporator	°C	46
Outlet temperature evaporator	°C	41
Pressure drop evaporator	hPa	800[8]
Fluid	-	Glykosol N with a mass fraction of 25%
Heat Sink design parameters		
parameter	unit	value/information
Thermal capacity	kW_{th}	1 180
Flow rate	kg/h	1 800
Inlet temperature condenser	°C	90
Outlet temperature condenser	°C	123
Outlet pressure	bara	2.2 (saturated steam)
Fluid	-	condensate water[9] 90°C
Heat Pump		
parameter	unit	value/information
Electricity consumption	kW_{el}	517
Coefficient of Performance (COP)	kW_{th}/ kW_{el}	2.3
Stages	-	2
Refrigerant type used	-	1st stage: R515B 2nd stage: R1233zd
Charge of Refrigerant	kg	200 (R515B) 350 (R1233zd)
Compressors per stage (configuration)	-	2 (parallel)
Compressor type used	-	1st stage: screw compressor 2nd stage: piston compressor
Noise emission levels	dB	<95 db(A) in 1m
Weight (operation)	kg	13 000

Table 5: Design parameters for the heat upgrade system based on vapor compression heat pump by SPH

As described in chapter 2.2, the energy demand for process heat (steam) in the paper production accounts for 140 GWh/a. In the initial HUS concept proposal, a process heat supply of 480 kW and an operation time for the HUS of 4 800 h per year were assumed (see chapter 2.3, Figure 8). With the given design parameters in Table 5 and a full capacity operation for at least 4 000 h/a the contribution of the HUS to

[8] 800 hPa = 0.8 bar
[9] Condensate used in the heat pump is degasified

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the process heat demand of the paper production accounts for 3.3 % (in comparison to a contribution of 1.7 % as per initial concept).

3.3 Layout of installation site

When considering the installation of a heat pump, there are several important factors to consider ensuring optimal performance, efficiency and safety. Some of the main requirements for the installation of a HP can be summarized as follows:

- Sufficient space:
  Placement of the HP container unit outside the machine building in order to ensure an easy installing and accessibility. 1 m distance to the machine wall will be foreseen to increase fire protection (see Figure 24).

- Avoid unnecessary long piping:
  The water/glycol circuit as the heat source is in very close proximity. Steam injection for the produced low-pressure steam at 2.2bar(a) into the heat sink (see Figure 25) is done in such a way that the first steam groups in the dry section (cans 1 to 5) are supplied directly.

- Container:
  The entire heat pump system together with its electrical cabinets are installed within a container. The HP manufacturer is given the opportunity to prefabricate everything on company's premises. The container will be designed to keep noise emission levels low.

- Piping & wiring:
  All the necessary installation works (like hydraulic and electrical installation) on site need to be done in an existing environment. At the planed installation point the installation of the piping and the electrical wiring is most optimal.

- Minor impact on the paper production process:
  Since the main installation of the heat pump is outside of the main building, only short paper machine stops are necessary to install the connection and integration points (condensate tank and steam supply lines of the paper machine).

- Weight load:
  The container will be placed on its own fundament in order to minimize noise emission, vibrations or any impact on the paper production and the surrounding infrastructure.

- Safety-related issues:

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A steam safety relief valve (in case the produced steam pressure level exceeds the tolerance values) will be installed outside the building and outside the container solution.

- <u>EN378</u>
  The European Norm EN378 for heat pumps describes in a detailed way the requirements for the installation depending on the used refrigerant, the required ventilation system and the required safety devices. It also describes the required safety device at the heat pump itself, like safety pressure relief valves on the high and low pressure parts for the refrigeration circuits. Such safety valves will be piped and installed in such a way that releasing refrigerant can safely flow into the environment in case of an emergency.

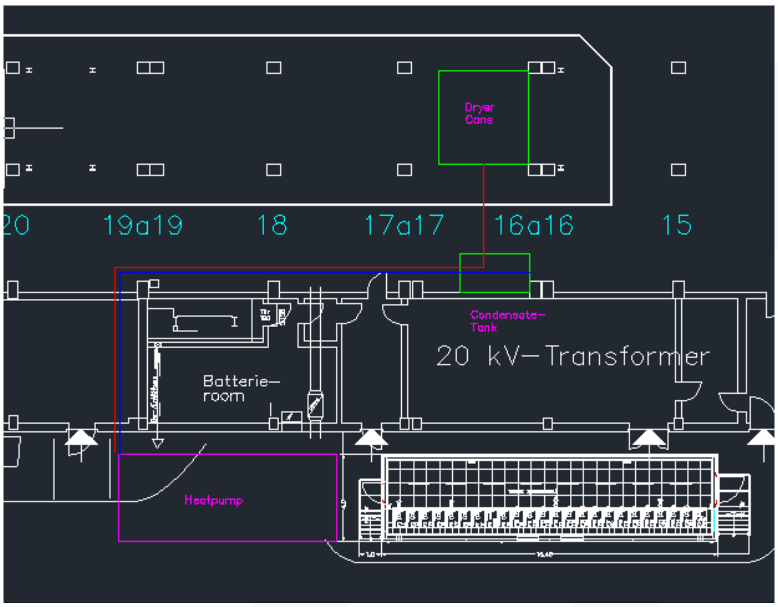

Figure 24: Layout of heat pump installation in Weißenborn (Container = 3 m x 10,5 m) and foreseen integration points into the heat sink (blue line: condensate, red line: produced steam)

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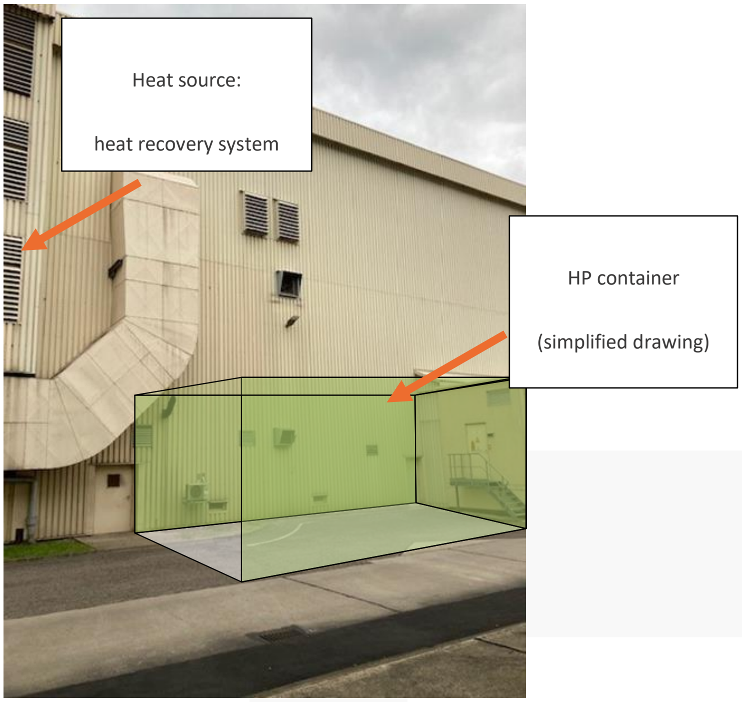

Figure 25: Installation site for HP container solution

3.4 Control concept and control integration

Within this chapter important aspects for the developing a first concept for an operation strategy and its boundary conditions are addressed.

Important Parameters

The following parameters and measurement datapoints are to be taken into account within the overall functional control of the Heat Upgrade System.

- Paper on the machine: [yes/no]
- Flow rate main water-/glycol circuit [m^3/h]
- Flow rate water-/glycol of external evaporator circuit of HP [m^3/h]
- Inlet temperature water-/glycol supplying the HP [°C]
- Outlet temperature water-/glycol circuit of HP [°C]
- Temperature water-/glycol circuit at the outlet of heat recovery system [°C]
- Inlet temperature steam heat exchanger (DGSTR) water-/glycol circuit [°C]
- Outlet temperature steam heat exchanger (DGSTR) water-/glycol circuit [°C]

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- Ambient air temperature [°C]
- Steam pressure of first group of dryers (cans 1, 2+4, 3+5) [bar]

Existing monitoring system

A detailed and extensive monitoring system is available at the paper mill. On the paper machine a process automation system is installed ('Siemens PCS7'). The visualisation is done with 'WINCC'. For long term data monitoring and analysis a second system called 'KRIKO Engineering GmbH – KRIS' is used. Both systems store values from all kind of measurement devices, actuators, production data in one system. The sampling rate depends on the measuring devices and can go up to values per second.

Heat source side

In general heat extraction from the water-/glycol circuit is possible when:

a) the paper production process is running,
b) sufficient heat in the circuit,
c) heat is not needed for the ventilator system of the production halls .

The necessary flow will be controlled by a separate circulation pump (see Figure 23) in the external evaporator circuit of the HP. This can be done when the inlet temperature of the steam fired heat exchanger (DGSTR) exceeds a setpoint value (e.g. >43 °C). Part load operation by the heat upgrade system can be done by adjusting the speed of the circulation pump. A part load control is necessary in order to provide enough energy for the heating of the production hall which serves as the primary goal of HRS.

Heat sink side:

On the heat sink side, the steam produced by the HP is used to feed the dryer cans in the first group (dryer 1 to 5, as described in chapter 2.5). This is mainly a steam pressure control loop. If the paper machine is running and the maximal setpoint for the steam pressure in this first section is below the steam pressure produced by the HP, steam from the HP can be used for this group (dryer 1 to 5) and thus used for the drying process (see integration point in Figure 20 or Figure 23).

Control concept of the heat pump

The heat pump system has two main control actuators in every stage. On the one hand, the expansion valve is used to control the superheat in the evaporator to run with the best efficiency while protecting the compressor of liquid in the suction gas. And on the other hand, the speed of the compressor is controlled, which has a direct influence on the thermal power produced by the heat pump.

The heat pump will have two controllers for the speed control of the compressor. The first one will control the steam pressure at the heat sink. With decreasing consumption of steam at the paper machine, the steam pressure will increase. If the steam pressure exceeds the setpoint, the system will reduce the compressor speed to keep the steam pressure constant by decreasing the steam production. The second controller will control the heat source outlet temperature in order to avoid reaching a value below a specified setpoint and thus extracting more heat from the heat source than available. This controller will decrease the compressor speed if the outlet temperature falls below the setpoint. With decreasing

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compressor speed the produced thermal energy, as well as the consumed thermal energy from the source will drop.

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3.5 Monitoring concept

General

The aim of the monitoring is to conduct a comprehensive evaluation of the performance and operational behavior of the heat pump installed in the facility of Felix Schoeller. To achieve this, the focus is on measuring the energy flows surrounding the heat pump. Specifically, data on the thermal energy supplied by the heat source and the thermal energy provided to the heat sink will be gathered.

In addition, electrical measurements of various components will be conducted, including the compressor, control system, heat source pump, and heat sink pump. These measurements will provide essential data to calculate key performance indicators (KPIs) such as COP (Coefficient of Performance), SPF (Seasonal Performance Factor), PER (Performance Efficiency Ratio), and more. These KPIs will help assess the efficiency and effectiveness of the Heat Upgrade System.

Moreover, the potential impacts of the heat pump operation on the production facility will be investigated. By doing so, any possible interactions or dependencies that may influence the overall efficiency of the facility's operations can be identified.

Furthermore, a detailed examination of the condition of the heat source will be conducted. This analysis will allow a better understanding of the heat pump's reliance on this energy source and its long-term sustainability.

Lastly, the presence of other heat generators within the facility will be taken into consideration. This includes analyzing their heat generation capabilities and fuel consumption patterns. Understanding the interplay between various heat sources will help optimize the overall energy usage and efficiency of the facility.

By undertaking this thorough evaluation, valuable insights into the heat pump's performance, uncover areas for improvement are gained, and strategies to enhance the overall energy efficiency of the facility can be developed.

Sensor set up

This project involves the installation of heat meters to measure the heat generated by the heat source and the heat consumed by the heat sink. Additionally, temperature and pressure sensors are installed to monitor the condition of the relevant thermal circuits.

Electrical energy meters will be installed to monitor the relevant electrical components like compressors, fluid pumps, additional heaters and the controller of the heat upgrade system.

The heat pump which will be installed at this demo site is equipped with a comprehensive control system. These internal sensors within the heat pump will be integrated in the Push2Heat monitoring system, allowing an assessment of the heat pump's performance.

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To facilitate seamless operation, a dedicated interface will be established to regulate and control the heat pump's functions. Furthermore, sensors from the production facility will be connected to the system to gather relevant data for analysis and optimization. To ensure smooth communication and data exchange, a designated interface will be set up, linking the system to the process control technology. This integration will enable effective process monitoring and management, ensuring optimal performance and energy efficiency.

Figure 26 highlights the transfer of information and measurement data within the monitoring concept.

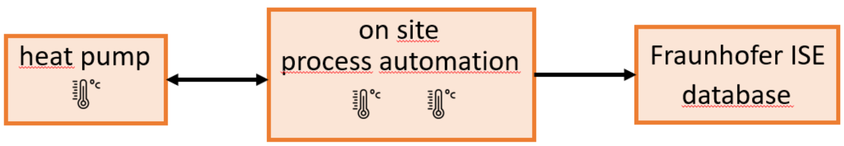

Figure 26 Applied principle of data handling

The controller of the heat pump is connected to the process automation of the demo site. The data of the sensors within the heat pump is transmitted to the process automation. There the sensor data is stored in a database.

Further sensors which are necessary for the monitoring are connected directly to the process automation. This sensor data is also stored in a database.

All the sensor data which is relevant for the Push2Heat monitoring is sent from the process automation to the Fraunhofer ISE data server. On this server the data is stored in a database. At this point the sensor data is available for post processing, evaluation and visualization.

The monitoring data points identified so far are shown in the PID of the Heat Upgrade System (see Figure 23 or Annex 1: Functional P&ID Scheme for the Heat Upgrade System)

All Datapoints which are gathered within the Push2Heat monitoring are listed in the data point list.

Current work and up-coming next steps

1. Determination of measuring points based on the plant layout:

   The PID with sensor positions and the Data point list is updated according to the planning proces of the system. The PID and the data point list will be finalized in a as build version.

2. Selection of communication protocols to the SCADA system and process control technology:

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Specific communication protocols to ensure seamless communication between the sensors, the process control system, and the Supervisory Control and Data Acquisition (SCADA) system are selected. Available options such as Modbus, Profibus, Ethernet/IP, or MQTT is evaluated and the most suitable protocol that ensures reliable and secure data transmission is selected.

3. Commissioning of the sensors and data acquisition:

   After determining the measuring points and selecting the communication protocols, the required sensors in the plant are installed and configurated. The sensors undergo careful calibration and testing to ensure accurate measurements. Subsequently, continuous data acquisition to obtain real-time data from the sensors will be initiated.

4. Commissioning of data transmission and evaluation:

   The collected data is transmitted to the process control system and SCADA platform using the designated communication protocols. Smooth data transmission is ensured and data integrity during this step is verified. Additionally, initial data evaluations are performed to ensure the data's accuracy and relevance.

5. Visualization of KPIs and plant parameters:

   To facilitate user-friendly, meaningful monitoring of the plant, clear and comprehensive data visualization is implemented. Specific dashboards, charts, and graphs that present essential Key Performance Indicators (KPIs) and relevant plant parameters in an easily understandable format are created. This visualization aids operators and maintenance technicians in better understanding the plant's condition and identifying potential issues proactively.

With these steps, efficient monitoring and control of the specific plant is given, enabling optimal performance and seamless operations. The precise technical details and implementations will be tailored to meet the specific requirements and conditions of the plant.

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4. Conclusion

For the demo site in Germany (Location Weissenborn) the basic engineering for the process integration of a high-temperature heat pump is completed. An electrical driven two-stage heat pump is designed for the upgrade of surplus waste heat and the supply of steam that will integrated directly into the paper production process of the paper mill.

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 paper production process the operation parameters for the high-temperature heat pump supplying low-pressure steam at 2,2 bara have been identified. A possible re-compression of the low-temperature steam to the operating the 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.

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. are currently being assessed further and need to be taken into account 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 can take place in a time with high unutilized waste heat potentials of the demo site. The main operation time of the high temperature heat pump at full capacity is expected to take place at summer months.

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ANNEXES

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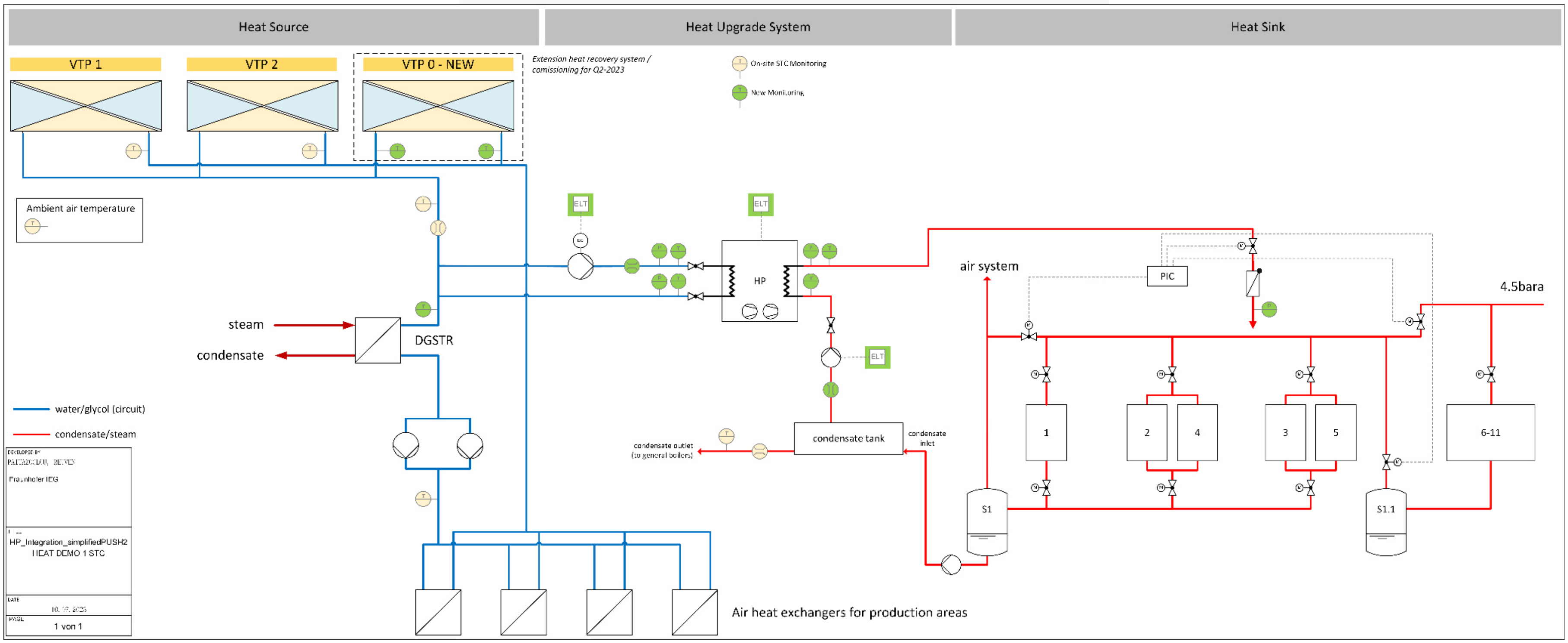
Annex 1: Functional P&ID Scheme for the Heat Upgrade System



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Push2Heat

Annex 2: Data Point List

Datapoint	measurand	sensor type	zone	sensor mounting	medium	unit	decimal places	data aquisition system	interface / protocol	measuring interval [in s]	responsible for purchase	responsible for mounting
T_FL_evap_HME	temperature	Pt100	HP source	immersion sleeve for DN ???	water / glycol ? %	°C	2	heat meter evap (HME)	Mbus	60	tbd	tbd
T_RL_evap_HME	temperature	Pt100	HP source	immersion sleeve for DN ???	water / glycol ? %	°C	2	heat meter evap (HME)	Mbus	60	tbd	tbd
V_dot_evap_HME	volume flow	MID	HP source	flange for DN	water / glycol ? %	m³/h	3	heat meter evap (HME)	Mbus	60	tbd	tbd
Q_dot_evap_HME	thermal power	-	HP source	-	water / glycol ? %	kW	1	heat meter evap (HME)	Mbus	60	tbd	tbd
Q_evap_HME	thermal energy	-	HP source	-	water / glycol ? %	kWh	0	heat meter evap (HME)	Mbus	60	tbd	tbd
sp_mv_evap	position	setpoint mixing valve	HP source	-	water / glycol ? %	-	1	tbd	tbd	60	tbd	tbd
T_FL_VTP_in	temperature	Pt100	HP source	immersion sleeve for DN ???	water / glycol ? %	°C	2	felix schöller group	tbd	60	tbd	tbd
T_FL_evap_HP	temperature	?	HP	?	water / glycol ? %	°C	1	controller HP	modbus TCP	60	SPH	SPH
T_RL_evap_HP	temperature	?	HP	?	water / glycol ? %	°C	1	controller HP	modbus TCP	60	SPH	SPH
p_FL_evap_HP	pressure	?	HP	?	water / glycol ? %	bar	1	controller HP	modbus TCP	60	SPH	SPH
T_FL_cond_HP	temperature	?	HP	?	water / steam	°C	1	controller HP	modbus TCP	60	SPH	SPH
T_RL_cond_HP	temperature	?	HP	?	water / steam	°C	1	controller HP	modbus TCP	60	SPH	SPH
p_FL_cond_HP	pressure	?	HP	?	water / steam	bar	1	controller HP	modbus TCP	60	SPH	SPH
P_pu_evap	electrical power	electricity meter	HP source	-	-	kW	1	felix schöller group	tbd	60	tbd	felix schöller group
E_pu_evap	electrical energy	electricity meter	HP source	-	-	kWh	1	felix schöller group	tbd	60	tbd	felix schöller group
P_comp_ST_1	electrical power	electricity meter	HP	-	-	kW	1	controller HP	modbus TCP	60	tbd	tbd
E_comp_ST_1	electrical energy	electricity meter	HP	-	-	kWh	1	controller HP	modbus TCP	60	tbd	tbd
P_comp_ST_2	electrical power	electricity meter	HP	-	-	kW	1	controller HP	modbus TCP	60	tbd	tbd
E_comp_ST_2	electrical energy	electricity meter	HP	-	-	kWh	1	controller HP	modbus TCP	60	tbd	tbd
T_amb	temperature	Pt100	ambient	tbd	air	°C	1	felix schöller group	tbd	60	felix schöller group	felix schöller group
T_RL_VTP_2	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	already present	already present
T_RL_VTP_0	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	already present	already present
T_FL_VTP	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	already present	already present
T_FL_VTP_b_HEX	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	60	felix schöller group	felix schöller group
T_FL_VTP_a_HEX	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	already present	already present
T_RL_VTP	temperature	?	heat source	?	water / glycol ? %	°C	1	felix schöller group	tbd	tbd	already present	already present
status_blowdown	operating signal	digital value	feed water heat sink HP	?	water	-	1	controller HP	modbus TCP	tbd	tbd	tbd
V_dot_RL_VTP	volume flow	?	feed water heat sink HP	?	water	°C	1	felix schöller group	tbd	tbd	already present	already present
p_cond_feed	pressure	?	feed water heat sink HP	?	water	bar	1	felix schöller group	tbd	60	tbd	tbd
V_dot_cond_feed	volume flow	?	feed water heat sink HP		water		1	felix schöller group	tbd	60	tbd	tbd
T_cond_group	temperature	?	feed water heat sink HP	?	water	°C	1	felix schöller group	tbd	tbd	tbd	tbd
V_dot_cond_group	volume flow	?	feed water heat sink HP	?	water	m³/h	1	felix schöller group	tbd	tbd	tbd	tbd
P_HP_total	electrical power	electricity meter	HP	-	-	kW	1	felix schöller group	tbd	60	tbd	tbd
E_HP_total	electrical energy	electricity meter	HP	-	-	kWh	1	felix schöller group	tbd	60	tbd	tbd
sp_valve_HS_1	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd	tbd
sp_valve_HS_2.1	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd	tbd
sp_valve_HS_2.2	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd	tbd
sp_valve_HS_3.1	position	setpoint valve	heat sink	-	water / steam	-	1	tbd	tbd	60	tbd	tbd
p_HS_1	pressure	?	heat sink	tbd	water / steam	bar	1	felix schöller group	tbd	60	tbd	tbd
p_HS_2	pressure	?	heat sink	tbd	water / steam	bar	1	felix schöller group	tbd	60	tbd	tbd

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Annex 3: Thermocompressor data

Data supply steam (high pressure):				
m_T	Mass flow	:	5 692	kg/h
p_T	Pressure level	:	8.0	bara
t_T	Temperature	:	170.4	°C (saturated)
Data low pressure steam:				
m_S	Mass flow	:	1 015	kg/h
p_S	Pressure level	:	2.2	bara
t_S	Temperature	:	123.3	°C (saturated)
Data supply steam (intermediate pressure):				
p_D	Pressure level	:	4.5	bara

Table 6: Operation data for thermal compressor by company Körting Hannover GmbH

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