Push2Heat

D3.3 Demonstration site at Dynasol - System Design

V0.1

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Push2Heat

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Push2Heat

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.

AHT: Absorption Heat Transformer

BREF: Best Available Techniques Reference Document

FT: Flash Tank

HUT: Heat Upgrade Technology

PH: Preheater

SBS: Solution Styrene Butadiene Rubber

SEBS: Styrene Ethylene Butylene Styrene

SGM: Steam Generation Module

TC: Thermocompressor

UH: Upgraded Heat

WH: Waste Heat

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BS NOV A	BS Nova Apparatebau GmbH	Technology provider
DYNASOL	DYNASOL ELASTOMEROS SAU	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

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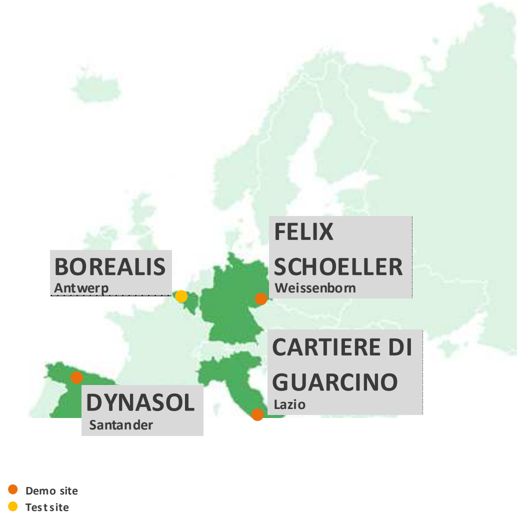

Figure 1: Heat upgrade systems in PUSH2HEAT

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

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

Section 2 describes the analysis and requirements of Dynasol demo site. Firstly, the current energy consumption of fossil-fuelled systems is described. The description of the energy produced and consumed in the plant as well as the different pressure levels of steam are provided. Two possible cases for the AHT integration in the plant have been proposed. For both cases the waste heat source and sink have been identified and described. After a comparison of the different scenarios, the most convenient for the plant was chosen as the final one.

Section 3 describes the preliminary planning and basic engineering of the selected case for the HUT (AHT) integration. The system configuration is described, with the corresponding functional P&ID, which includes all the components that are needed for the operation of the system. Furthermore, this section outlines the initial control scheme at system level, detailing the specifications for both AHT control and steam generation module control. Finally, an introductory overview of the monitoring scheme encompassing all sensors included in the installation is presented as an initial framework for the demonstrator. All this information is included in the first P&ID of the system revealing all the design parameters of the AHT for the nominal operation point of the selected case.

Section 4 includes a brief of the conclusions obtained after the analysis.

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2. Analysis and requirements

2.1. Demo site

Dynasol Group is considered one of the world leaders in the synthetic and chemical rubber markets, ranking among the 10 largest companies in this sector in the world. Founded in 1999, Dynasol is a joint venture between the spanish Repsol and the mexican Kuo Group. The core activity of the company is focused on the production of synthetic rubber, based on solution polymerization, and on the development of new products.

The Dynasol elastomeres plant in Santander has a capacity of 120 000 tons per year of SBS (Solution styrene butadiene rubber) and SEBS (Styrene ethylene butylene styrene). These products find application in various sector, such as asphalt modification, adhesive seals, polymer modification, thermoplastic compounds, shoe soles and industrial vulcanized articles.

Figure 2. Dynasol plant aerial view. Location: Santander, Spain.

The specific energy consumption per unit of product is around 15 GJ/ton (data of 2021) (Dynasol, 2021).

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The phases of production include:

- Purification of monomers and solvent
- Polymerisation
- Hydrogenation (if applicable)
- Blending section
- Solvent removal and product isolation
- Packaging

A basic flow scheme on how solvent, Styrene and other ingredients interact within the different phases of the polymerization production process is shown in Figure 3.

Different chemicals are used in the processes, principally the monomers, catalysts, solvents and other process additives.

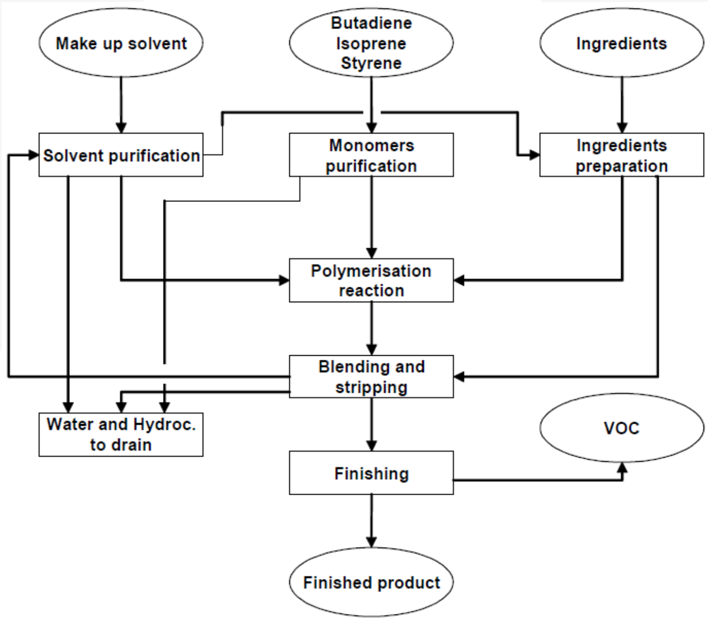

Figure 3. Basic flow scheme of solution polymerization process (**European Commission, 2007**)

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2.2. Current energy consumption of fossil-based systems

The Dynasol plant in Santander uses steam for their production processes, which is delivered from a neighbouring cogeneration plant at a pressure of 10 bar(a) (High pressure steam). A significant part of this heat is then reduced to a lower pressure level (4.5 bar(a)) for its use in different production lines. See Figure 4.

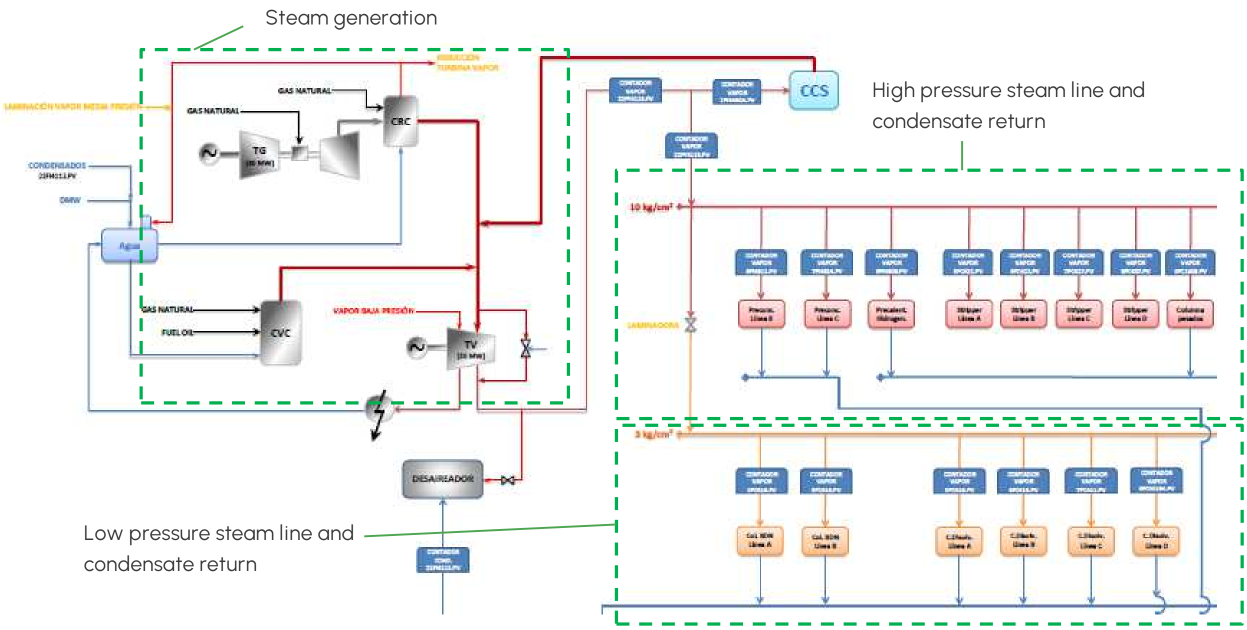

Figure 4. Steam production and use within the Dynasol plant.

The annual consumption of steam in the plant is 480 000-450 000 t/year. About 25 % of the steam consumed is low pressure steam and 63 % is high pressure steam.

Main consumers are solvent stripping units and solvent distillation columns.

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2.3. Analysis of potential heat source

Waste heat (WH) is available in different processes within the plant. A first screening of the possible waste heat sources for the HUT is show in Table 1. Among the preliminary identified waste heat sources, two have been selected for the HUT integration study. This selection results in two potential HUT integration scenarios, each pairing a specific waste heat source and heat sink. These are referred to as Case 1 and Case 2.

The potential integration scenario referred to as Case 0 makes use as the same waste heat source as Case 1, but with a different heat sink. For this reason, the heat sink for both cases is analyzed in the same subsection.

Table 1. Identified sources of Waste Heat (WH) for HUT integration in Dynasol plant.

Option	Description	Type of source (Liquid/Vapor)	Flow rate (kg/h)	Inlet T (°C)	Outlet T (°C)	Calculated heat (kW)	Comments
WH1	Solvent column head condensers.	V	7 400	85	85	688	
WH2	Condenser of venting from the crumbs tank.	V	2 000	100	100	1 163	Fluctuating waste heat source.
WH3	Condensers of solvents in lines B and C	V	17 500	85	67	1 628	

Among the different options, WH1 was discarded because the possible amount of upgraded heat is significantly smaller than for the other options.

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WH2 refers to a condenser which will be installed to comply with BREF (Best Available Techniques Reference Document) requirements. and its quantification is based on the operation conditions of the crumbs tank. The potential amount of heat that could be recovered from this source is based on the capacity estimations that have lead to the sizing of the new condenser. The condenser of the project to implemented is sized for a condensing capacity of 2 MW. The use of the waste heat stream WH2 s for its HUT integration corresponds to Case 2.

WH3 refers to the condensation of solvents in lines B and C. Line B is selected for the AHT integration, the denominated PreconB line. This scenario is identified with the name "Case 1".

2.3.1 Case 0 and Case 1

Case 0 and Case 1 incorporate the condensing heat of the solvent in the PreconB line as the waste heat source (identified as WH3 case in Table 1). Figure 5 and Figure 6 depict the annual profiles of solvent inlet temperature, outlet temperature and flow rate covering the period from 1st November 2021 to 31st October 2022 (hourly data). The recoverable waste heat has been calculated based on the properties of the solvent (considered to be 100 % cyclohexane) and its profile is shown in Figure 7. Considering a thermal efficiency of the AHT of 0.48 (Thermal efficiency corresponds to the thermal capacity of the upgraded heat divided by the thermal capacity of the waste heat) the corresponding upgraded heat is computed. The operating hours are calculated as the number of hours per year in which the upgraded heat exceeds 400 kW; this leads to 7 608 hours a year, with an average upgraded heat of 684 kW (recovered heat of 1 425 kW). This enables the production of an average of around 1 050 kg/h of steam with the AHT in combination with the Steam generation module (SGM), corresponding to a total of 8 050 ton/year.

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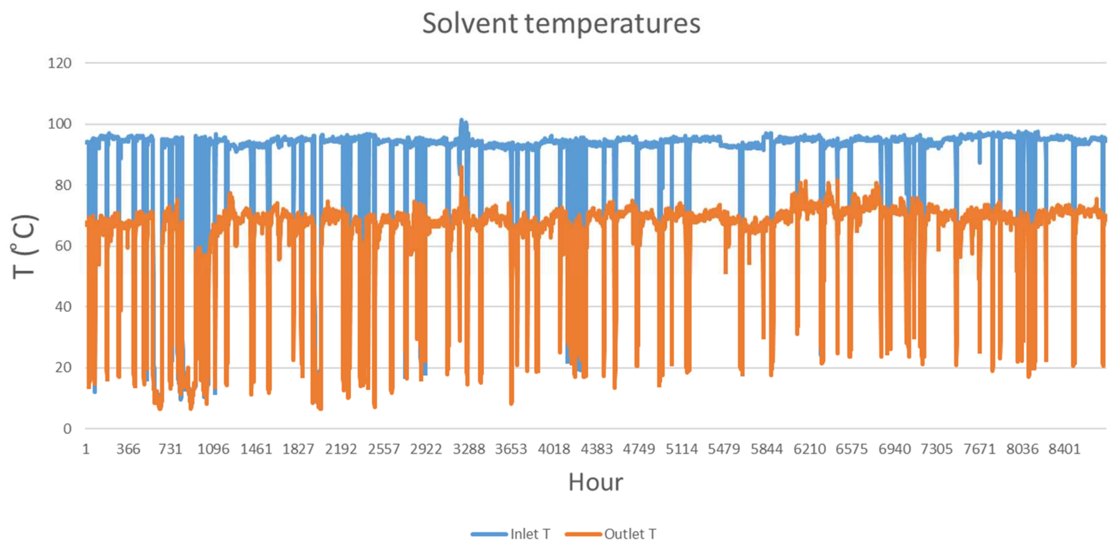

Figure 5. Solvent inlet and outlet temperatures in PreconB line.

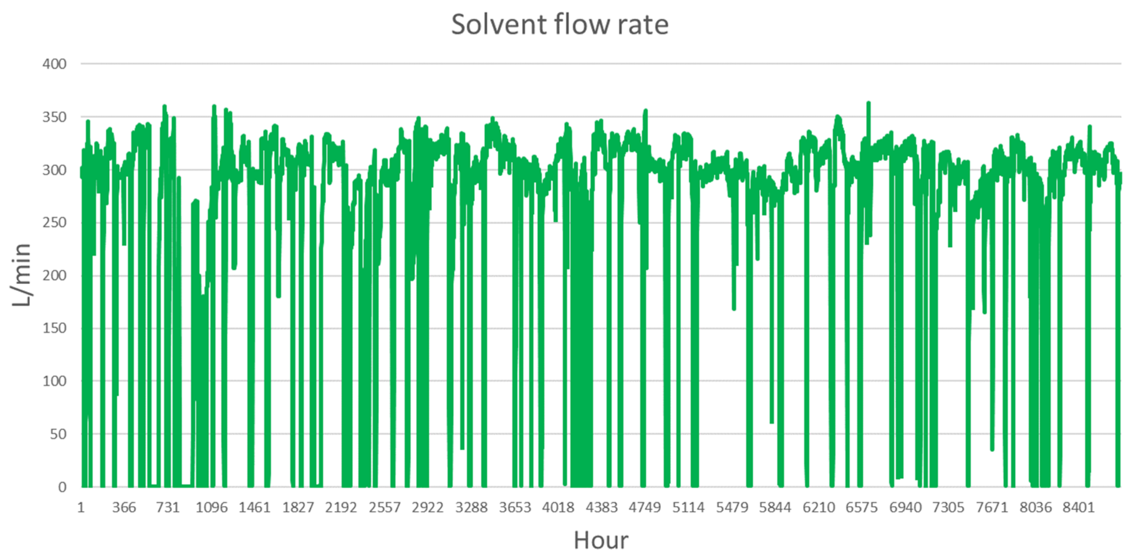

Figure 6. Solvent flow rate in PreconB line.

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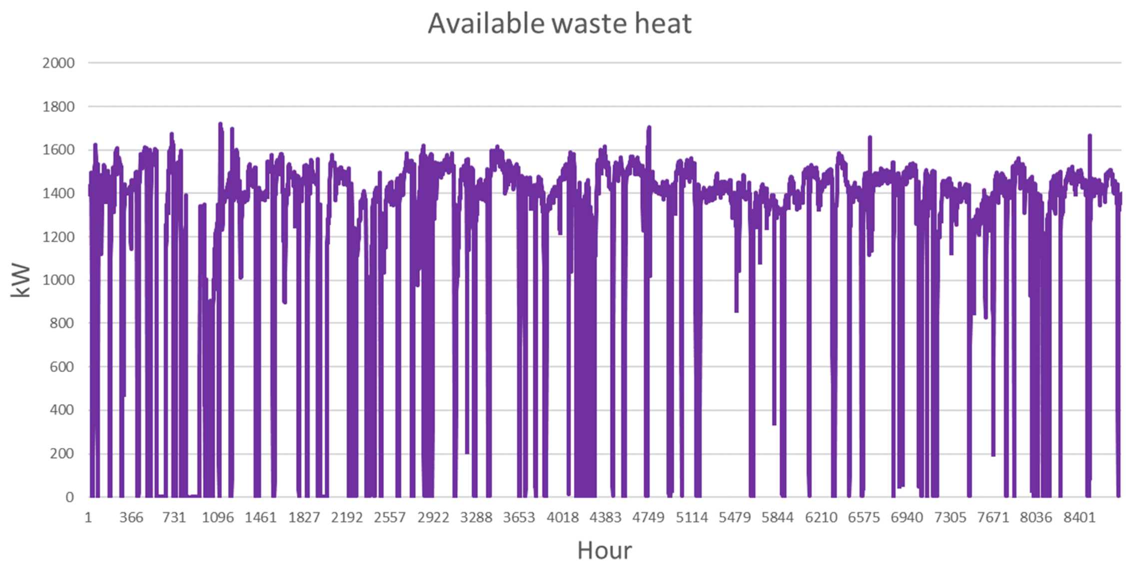

Figure 7. Available waste heat in PreconB line.

2.3.2 Case 2

Case 2 utilizes as a waste heat source the condensing of the vents from the crumbs tank (WH2 case in Table 1). In this case, actual measured values of waste heat profiles are not available, as the condenser of the vents from the crumbs tank is a forthcoming project to be implemented in the plant. Relying on other process parameters, the plant owners have offered an estimation of the waste heat available in different conditions. Taking into account this information, the maximum recoverable heat in this case would be 640 kW, resulting in 307 kW of upgraded heat and around 440 kg/h of steam. Extrapolating this information to a whole year poses a challenge, as only average values are available.

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Table 2. Data of waste heat available from the condensing of the crumbs tank in different conditions

	Venting flow rate (Nm3/h)	Venting flow rate (kg/h)	Condensing heat (kW)
Normal flow rate (New SBR line at 68 ton/day and 3 strippers)	1 370	1 101	640
Normal flow rate (New SBR line at 68 ton/day and 2 strippers)	1 143	918	534
Minimum flow rate in continuous operation	900	723	421

2.4. Heat sink requirements

Similar to the identification process for waste heat sources, potential heat sinks, or upgraded heat (UH) injection points, have been identified among the processes in the plant. The initial screening of potential cases for HUT integration involved the following upgraded heat sinks (see Table 3).

Table 3. Identified potential upgraded heat sinks for HUT integration in Dynasol plant.

Option	Description	Type of source (L/V)	Flow rate (kg/h)	Inlet T (°C)	Outlet T (°C)	Calculated heat (kW)	Comments
UH1	Solvent preheater for feeding the column.	L	37 000	75	85	215	Low temperature and capacity
UH2	Reboiler of solvent colum.	L	37 000	75	85	3 442	Low temperature
UH3	Preheating of the demi	L	15 000	15	80	1 134	

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	water with which the condensate tank is replenished.						
UH4	Stripping steam	V	8 000	120	120	4 652	
UH5	Solvent preheater for reactors.	L	60 000	28	40	419	Low temperature
UH6	Preheater in PreconB line	L	28 000	60	Up to 150	650	

Option UH1, UH2 and UH5 were discarded because of their low temperature requirements, presented in Table 3.

The selection of heat sinks has been narrowed down to prioritize steam generation, leading to the integration schemes Case 1 and Case 2. The initially considered Case 0 has been abandoned during the early stages of the project due to technical concerns.

- *Case 0*, correspond to the upgraded heat sink case UH6 in Table 3.
  In this case, the upgraded heat generated with the system will be used to preheat the PreconB, one of the Preconcentration liquid streams of the plant that needs to be preheated to a temperature up to 150°C, starting with a temperature of 60°C.
  In this case, the heat sources that have been identified near the PreconB line are the main candidates for heat recovery since this significantly reduces the integration effort.
- *Case 1*, low pressure steam for direct consumption in a process (UH4 in Table 3).
  In this case the heat sink is the low-pressure steam (2 bar(a)) consumed directly in the stripping process of the solvent from the polymers. The total amount of steam at 2 bara consumed by those strippers is around 8 000 kg/h and is much higher than the amount of steam that will be produced by the Push2heat system. Therefore, the heat recovery system will not disturb the strippers' operation.
- *Case 2*, steam for the medium pressure steam line, not appearing in Table 3.

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This case includes as heat sink medium pressure steam for injection in the medium pressure steam line in the plant, at 4.5 bara. The plant has medium pressure distribution lines in different places, where this upgraded heat can be injected.

These options will be described below in section 2.6.

2.5. Heat rejection circuit

The AHT needs for its operation a third fluid stream at lower temperature for heat rejection. The source available in Dynasol for this purpose is water from the cooling towers, with a variable temperature along the year according to external conditions. Figure 8 shows the profiles of the cooling water temperature along the year. The yearly average temperature is 20°C.

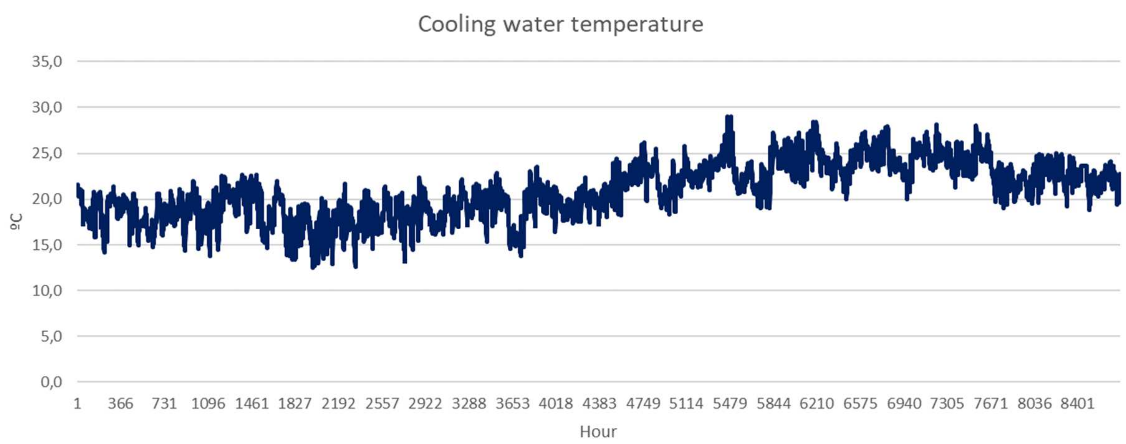

Figure 8. Cooling water temperature hourly profile in Dynasol plant (average values among the three cooling towers).

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2.6. Scenarios for the Heat Upgrade System and case selection

The combination of the possible waste heat sources and the heat sinks leads to three possible cases for the AHT integration. Table 4 shows an overview of these cases.

Table 4.Selected cases for analysis of AHT integration in Dynasol

<table>
<tr><td></td><td colspan="3">Heat source</td><td colspan="2">Heat sink</td><td colspan="2">Heat rejection</td></tr>
<tr><td></td><td>Form</td><td>Available waste heat (kW)</td><td>Temperature (inlet to AHT)</td><td>Form</td><td>Pressure and temperature</td><td>Form</td><td>Temperature</td></tr>
<tr><td>Case 0</td><td>Solvent condensation heat</td><td>Average of 1 425 kW)</td><td>85°C</td><td>Hot water for preconB Line prehating</td><td>-
120°C</td><td rowspan="4">Water from cooling tower</td><td rowspan="4">Between 15°C and 25 °C</td></tr>
<tr><td rowspan="2">Case 1</td><td rowspan="2">Solvent condensation heat</td><td rowspan="2">Average of 1 425 kW)</td><td rowspan="2">85°C</td><td rowspan="2">Low or medium pressure steam</td><td>2 bar(a)
120.2°C</td></tr>
<tr><td>4.5 bar(a)
147.9°C</td></tr>
<tr><td>Case 2</td><td>Condensation of vents from a crumbs tank</td><td>Variable (640 / 534 / 421 kW)</td><td>95°C</td><td>Medium pressure steam</td><td>4.5 bar(a)
147.9°C</td></tr>
</table>

In the following subsections, the three cases are described in terms of HUT integration scenarios and the obtained operational data.

The configuration for case 0 is a little bit different than the other two and it will be explained in section 2.6.1.

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The configuration for cases 1 and 2 is based on the same concept, which is depicted in Figure 9. An overview of these cases is given in this section, although they will be deeply described in section 2.6.2 and 2.6.3.

The Absorption Heat Transformer (AHT) has three circuits, the heat rejection circuit at low temperature, the waste heat (or driving heat) circuit at medium temperature, and the upgraded heat circuit at high temperature. The upgraded heat circuit provides hot water and is connected to the Steam Generation Module (SGM). The SGM is composed of a flash tank (FT), for the production of low-pressure steam, and a thermocompressor (TC), which upgrades the pressure level of the steam generated by the FT exploiting high pressure steam at 10 bar(a) derived from the plant. Included in the system is a preheater (PH) which captures part of the waste heat in order to preheat the make-up water, essential for replenishing the equivalent amount of water discharged as steam from the flash tank. This way, the energy balance improves, with a higher temperature make-up water.

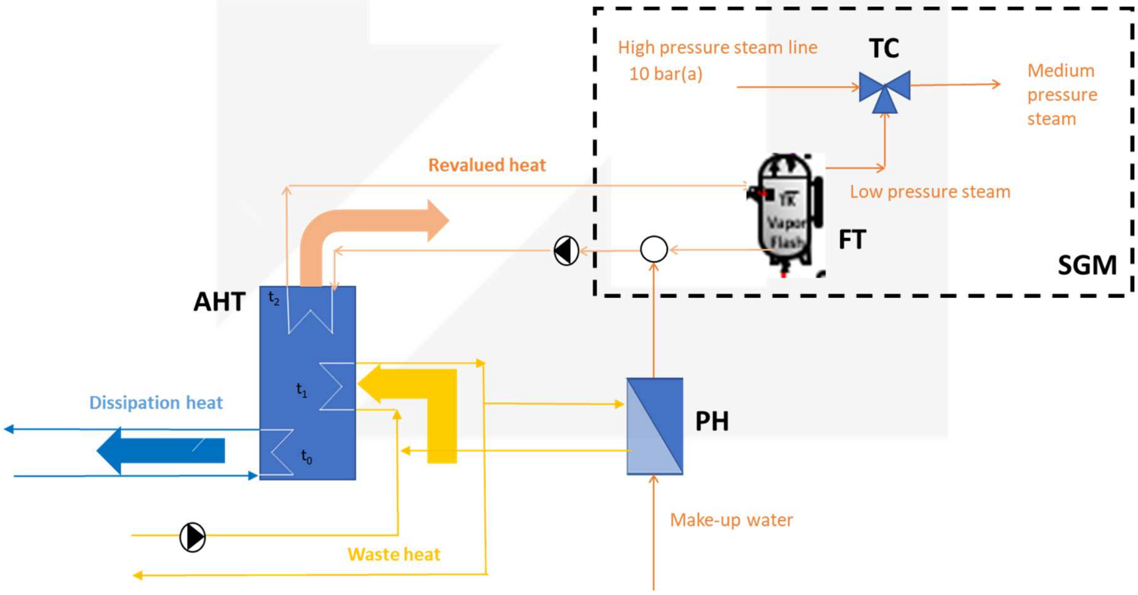

Figure 9. Basic scheme of AHT integration

In the following subsections, the different possibilities of integration base on the scheme above which have been studied are described, and the final case selection explained.

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2.6.1 Case 0 - HUT integration scenarios

In Case 0, the configuration is different than that of the basic scheme presented in Figure 9 in the previous section for steam production, The main difference is that the upgraded heat must be transferred to a liquid circuit of a polymer production line (PreconB line) in order to preheat it. Additionally, a certain amount of the recovered waste heat could be directly used for the preheating up to a temperature level of 85 °C, as presented in Figure 10.

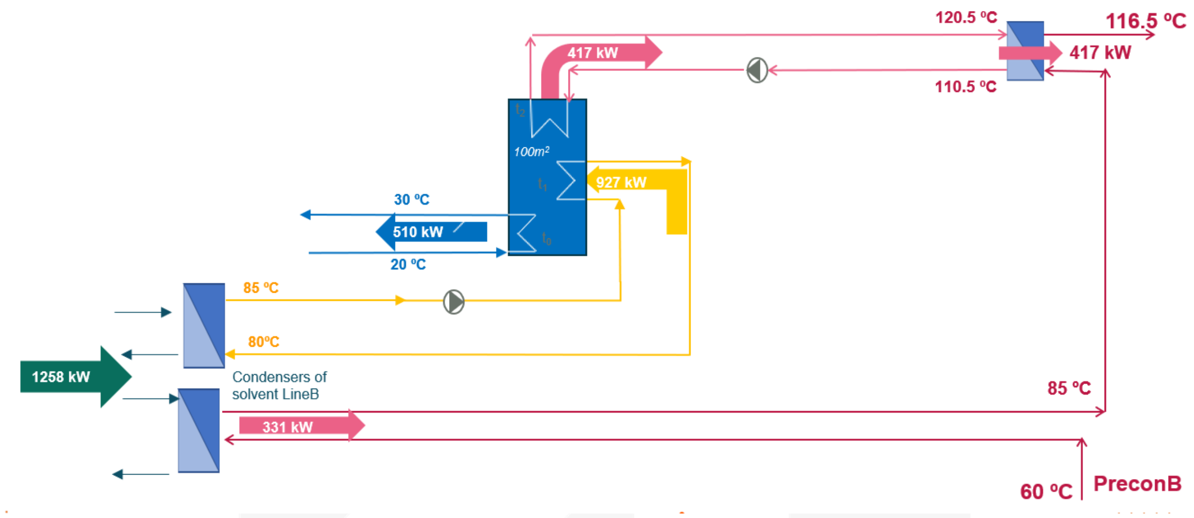

Figure 10. Integration scheme of the AHT for Case 0

The expected yearly energy savings with Case 0 are higher than those expected with Case 1 and Case 2, because of the possibility to include direct use of the waste heat for preheating the Precon B up to 85 °C. However, the expected investment costs for Case 0 are considerably higher than those of the other cases, because of the inclusion of an additional segment of Precon B piping line with two expensive heat exchangers (the condenser/Precon B preheater1 and the hot water/Precon B preheater 2). Additionally, the operation of the two preheaters on the preconcentration side is expected to be problematic, drawing insights from past operational experiences with steam-based preheating of Precon B. Because of that, Case 0 was not considered for a more detailed system analysis.

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2.6.2 Case 1 - HUT integration scenarios

Initially, two options for upgraded heat (heat sink) were considered in Case 1, either to produce medium pressure steam at 4.5 bar(a) and inject it into the medium pressure steam line in the plant (Case 1A), or to produce low pressure steam at 2 bar(a) and inject it directly in the process strippers (Case 1B).

As it has been presented in Table 4, the available heat source energy for Case 1 is more than 1 200 kW, which allows for the installation of an AHT with a capacity of 640 kW of upgraded heat. However, due to limitations in the manufacturer budget and the increase of material costs, the maximal size considered for the AHT is of 100 m^2 (equivalent absorber heat transfer area). This heat transfer area has been used for all the calculations of the analysis.

For the configuration analysis and operational data in this case, different considerations have been made:

- Temperature difference inlet/outlet in the AHT absorber (UH circuit): 5 K.
- Temperature difference inlet/outlet in the AHT evaporator/generator (WH circuit): 5 K or 10 K.
- Temperature difference inlet/outlet in the AHT condenser (Heat rejection circuit): 10 K.

To try to reduce the electrical consumption of the external circuit pump, alternative options with different temperature differences between inlet and outlet of the AHT at the intermediate temperature level (WH circuit) have been studied. The analysis have been performed also considering different temperatures for the heat rejection circuit: 15 °C inlet temperature to the AHT for sizing of the system, and 20°C for the calculation of the average operation conditions.

Case 1A - Medium pressure steam production

Table 5 shows an overview of the analyzed options in the case of intermediate-pressure steam production at 4.5 bar(a). Intermediate options have been calculated as well, but here only the ones corresponding to a temperature difference of 5 K and 10 K in the WH circuit are shown. Figure 11 shows the calculation made with the software EES (Klein, 2022) of the selected option (for a

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temperature difference of 10 K in the WH circuit) and with the average operating conditions (heat rejection water at 20 °C). The system is able to produce between 303 kW (263 kg/h steam) and 450 kW (473 kg/h steam) depending on the temperature difference at the WH circuit and the heat rejection water temperature. The steam flow rate is referred to low pressure steam from the flash tank. The final amount of steam will be higher after thermal recompression with high pressure steam from the plant.

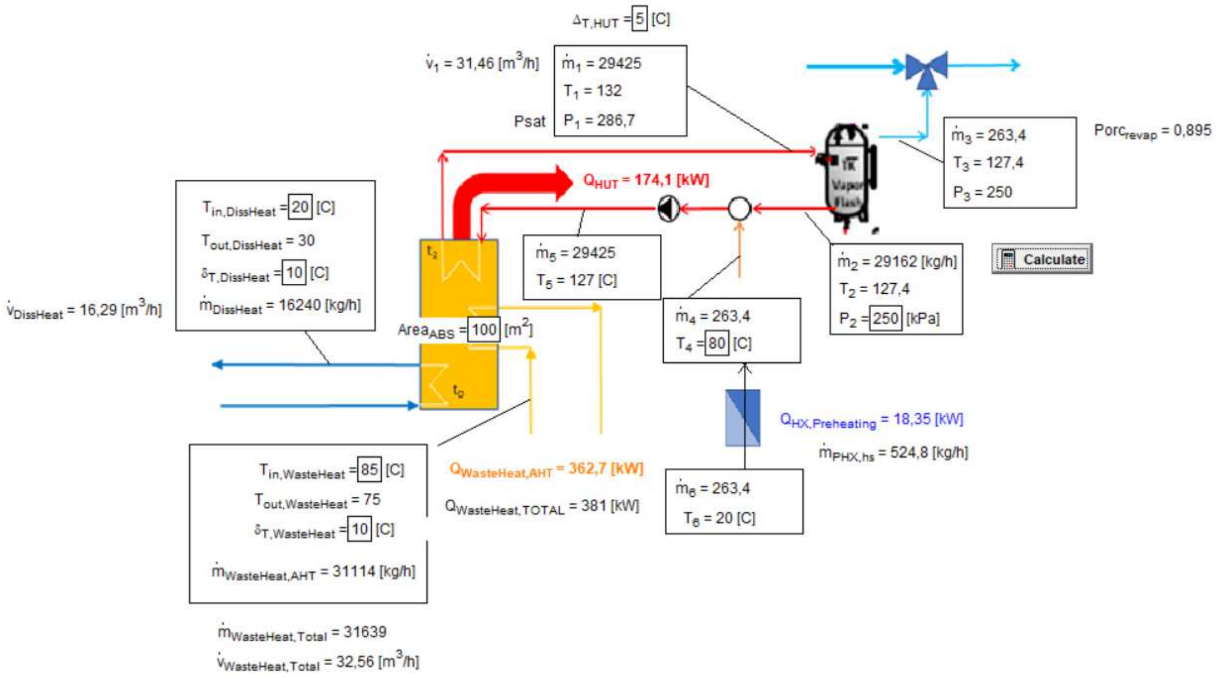

Figure 11. Case 1A - Operation conditions with heat rejection water at 20 °C

Case 1B - Low pressure steam production

Table 6 shows an overview of the analyzed options in the case of low-pressure steam production. at 2 bar(a) for the strippers. Intermediate options have been calculated as well, but here only the ones corresponding to a temperature difference of 5 K and 10 K in the WH circuit are shown. Figure 12 shows the calculation in EES of the selected option (for a temperature difference of 10 K in the WH circuit) in the average operating conditions (heat rejection water at 20 °C). The system is able to produce between 174 kW (574 kg/h steam) and 315 kW (789 kg/h steam) depending on the temperature difference at the WH circuit and the heat rejection water temperature.

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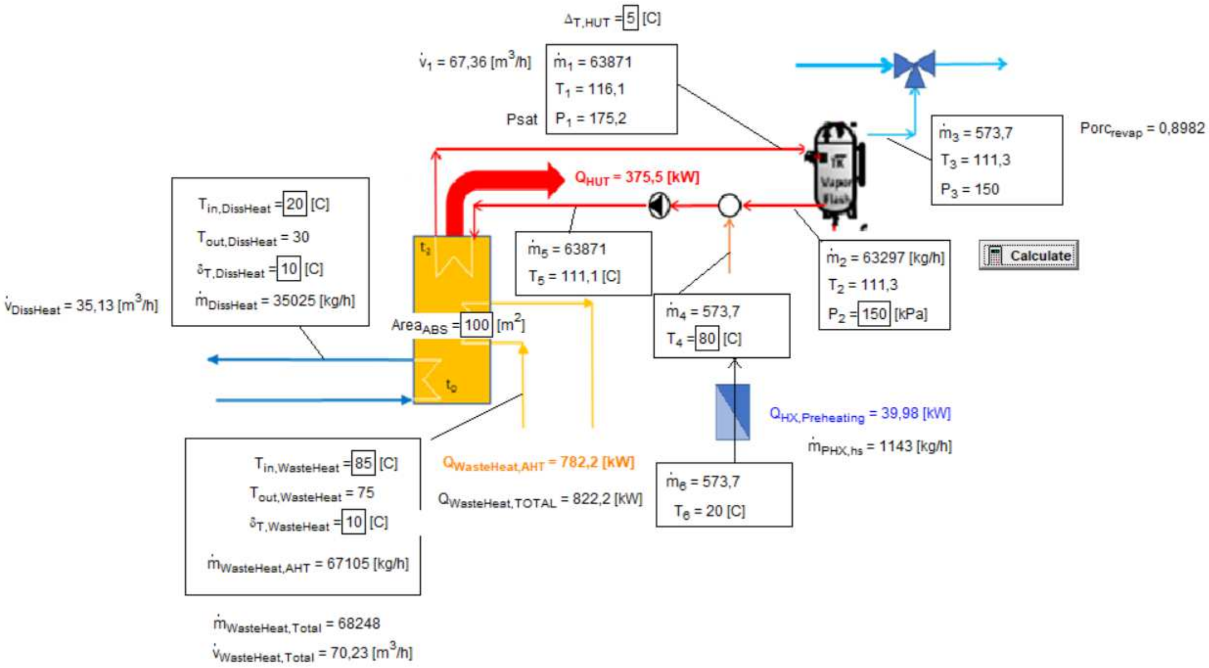

Figure 12. Case 1B - Operation conditions with heat rejection water at 20 °C

Case 1B has been selected among both options for upgraded heat, as the amount of steam produced is higher and the amount of high-pressure steam needed for the thermocompressor is lower, being the cost effectiveness of this option higher.

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Table 5. Screening of sizing and operational conditions in Case 1A with different temperature differences in the waste heat circuit.

	Heat rejection circuit		Waste heat circuit						Upgraded heat circuit					
Data	Temperature (°C)	Flow rate (m³/h)	Temperature difference (K)	Flow rate (m³/h)	Capacity (kW) To AHT	Capacity (kW) To water preheating	Capacity (kW) Total	Temperature to AHT (°C)	Temperature from AHT (°C)	Capacity (kW)	Flow rate (m³/h)	Steam produced in FT at 2.5 bar(a) (kg/h)	Motive steam at 10 bar(a) to TC (kg/h)	Steam at 4.5 bar(a) from TC (kg/h)
Operation (avg)	20	22.5	5	86.5	504	26	530	85	132	242.0	40.9	366	1 296	1 662
Sizing (max)	15	29.3		112.5	656	33	689	85	132	314.8	53.2	476	1 686	2 162
Operation (avg)	20	16.2	10	31.1	363	18	381	85	132	174.0	29.4	263	931	1 194
Sizing (max)	15	23.0		44.1	514	26	540	85	132	246.8	41.7	373	1 321	1 694

Table 6. Screening of sizing and operational conditions in Case 1B with different temperature differences in the waste heat circuit.

	Heat rejection circuit		Waste heat circuit						Upgraded heat circuit					
Data	Temperature (°C)	Flow rate (m³/h)	Temperature difference (K)	Flow rate (m³/h)	Capacity (kW) To AHT	Capacity (kW) To water preheating	Capacity (kW) Total	Temperature to AHT (°C)	Temperature from AHT (°C)	Capacity (kW)	Flow rate (m³/h)	Steam produced in FT at 1.5 bar(a) (kg/h)	Motive steam at 10 bar(a) to TC (kg/h)	Steam at 2.0 bar(a) from TC (kg/h)
Operation (avg)	20	41.5	5	164.7	923.9	47.2	971.1	85	116.1	443.5	79.6	677.6	476	1 153.6
Sizing (max)	15	48.2		191.7	1 075	55.0	1 130.0	85	116.1	516.2	92.6	788.7	554.0	1 342.7
Operation (avg)	20	35.1	10	70.2	782.2	40.0	822.2	85	116.1	375.5	67.4	573.7	403.0	976.7
Sizing (max)	15	41.9		83.8	933.8	47.7	981.5	85	116.1	448.2	80.4	684.8	481.1	1 165.9

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2.6.3 Case 2 - HUT integration scenario

In Case 2 integrates, the AHT exploits waste heat derived from the condenser of the steam vented from the crumbs tank. The upgraded heat is steam at 4.5 bar(a), to be injected in the medium pressure line of the plant. The operational conditions set from the SGM is to produce steam at 2.5 bar(a) in the flash tank, and thermally recompress it to 4.5 bar(a) using high pressure steam at 10 bar(a), available in the plant.

In this case, three scenarios have been identified, depending on the available waste, as shown in Table 2:

- Waste heat (condition 1): 640 kW
- Waste heat (condition 2): 534 kW
- Waste heat (condition 3): 421 kW

¡Error! No se encuentra el origen de la referencia. shows the operational conditions of the system taking into account the maximum recoverable waste heat capacity (640 kW). Part of the waste heat is dedicated to the preheating of make-up water (31 kW) and the rest (609 kW) for the AHT, producing 292 kW of upgraded heat, corresponding to 442 kg/h of steam at 2.5 bar(a). The necessary amount of high-pressure steam at 10 bar(a) to produce 4.5 bar(a) steam is 1 362 kg/h. Thus, 1 804 kg/h of steam at 4.5 bar(a) are produced.

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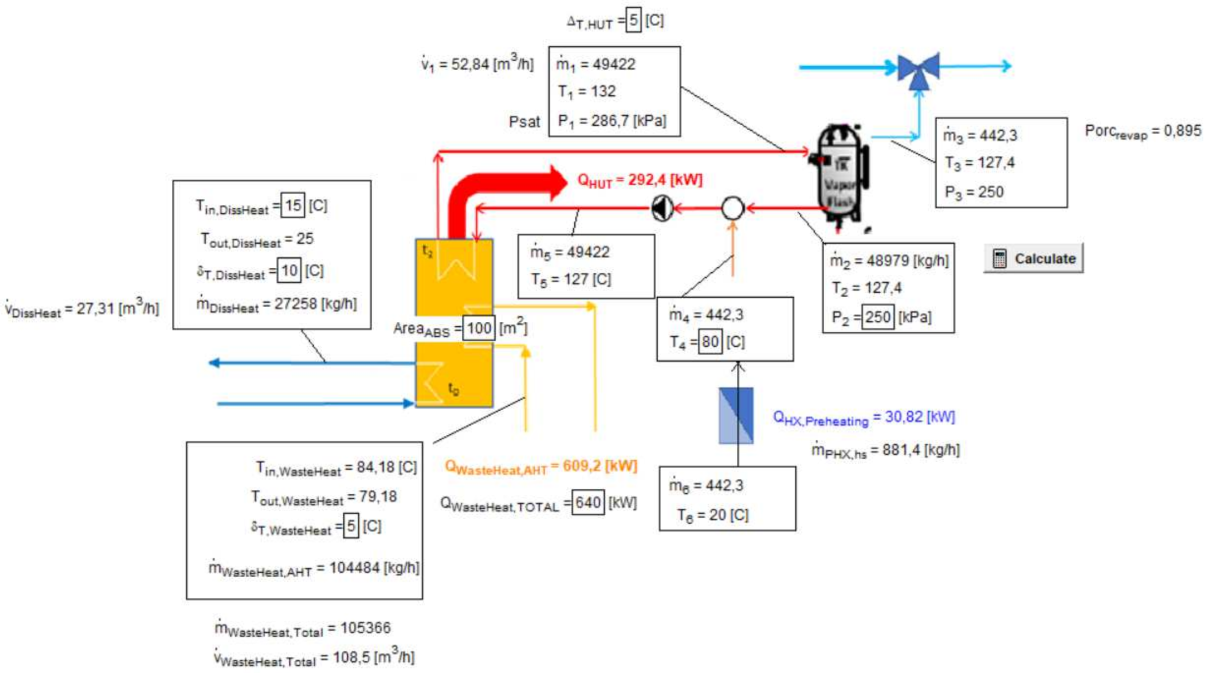

Figure 13. Case 2 - Operation conditions with the maximum waste heat capacity available (640 kW).

2.6.4 Final case selection

For the final case selection, the economical performance figures of Case 1B and Case 2 have been compared by Dynasol considering both the yearly savings in operational cost (calculated with the steam production values shown in Figure 11 and Figure 12 and in Table 5 and Table 6) and the investment cost for the integration of the HUT system. Although the integration cost for Case 2 is smaller than for Case 1B, the amount of steam that can be produced is considerably smaller with Case 2.

The calculation of the investment cost for the integration of the HUT unit has been made based on the equipment sizing and operating conditions defined in the basic engineering design phase that is explained in section 3.1.

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As mentioned in section 2.6.2, two different options have been considered for the operating conditions of Case 1B, depending on the considered temperature difference in the cold side of the heat recovery heat exchanger of the WH circuit, either 5 K or 10 K. As it is presented in the following tables, although the heat upgrade capacity and steam production is higher with 5 K temperature difference, the total electrical consumption is higher and electrical COP of the system is lower (defined as $COP_{EL} = Q_{upgrade}/P_{el,total}$) for this option. Thus, the case with temperature difference of 10 K was eventually chosen.

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Table 7. Electrical consumption for Case 1B with different temperature differences in the waste heat circuit.

	Heat rejection circuit			Waste heat circuit				Heat upgrade circuit			TOTAL			
Data	Temperature (°C)	Flow rate (m^3/h)	Pel,pump* (kW)	Temperature difference (K)	Flow rate (m^3/h)	DP*** (bar)	Pel,pump (kW)	Flow rate (m^3/h)	DP*** (bar)	Pel,pump (kW)	Qupgrade (kW)	Pel,pumps (kW)	Pel,AHT** (kW)	COP_{EL} (-)
Operation (avg)	20	41.5	0	5	164.7	2.5	15.8	79.6	1.5	5.7	443.5	20.8	4.3	19.6
Sizing (max)	15	48.2	0		191.7	2.5	18.7	92.6	1.5	5.0	516.2	24.0	5.5	19.4
Operation (avg)	20	35.1	0	10	70.2	2.5	7.0	67.4	1.5	5.5	375.5	12.5	4.6	25.5
Sizing (max)	15	41.9	0		83.8	2.5	8.4	80.4	1.5	6.5	448.2	14.9	5.5	25.3

*In the heat rejection circuit there is no need for a pump, because the water from the cooling network has enough pressure to overcome pressure drops

**Conservative approach, normally a smaller value is expected

*** Pressure Losses in the circuits have been estimated in agreement with Dynasol (conservative values) considering expected pressure and piping circuit lengths)

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3. Preliminary planning and basic engineering

3.1. Process integration of the Heat Upgrade System

The basic integration scheme of the AHT into the plant has already been depicted in Figure 9 as presented in Section 2.6.

A detailed description of the hydraulic circuits and other individual components necessary for the process integration is provided in this section, with reference to Figure 14, which depicts the configuration that corresponds to the application case finally selected (Case 1B, see 2.6.2 Case 1 - HUT integration scenarios). Although only the design process for the Case 1B is explained in detailed, an analogue design has been made for the Case 1A and Case 2.

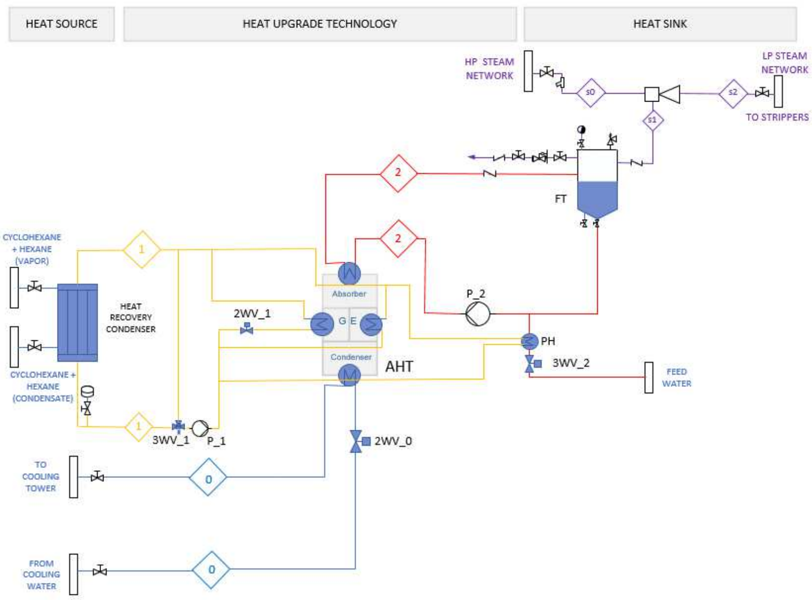

Figure 14. AHT process integration scheme in Dynasol plant with main components

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In Table 8 the main components needed for the Integration of the HUT are listed. Each component in the table is part of one of the three water circuits within the system, distinguished by ascending temperature levels: circuit 0 (heat rejection, represented in blue in Figure 14), circuit 1 (driving heat, represented in yellow in Figure 14) and circuit 2 (upgraded heat, represented in red in Figure 14). The Absorption Heat Transformer Unit (AHT) is connected to all three water circuits. Additionally, the steam circuits (illustrated in purple in Figure 14) incorporate the produced steam into the plant system.

The components included in the following table are those that have been considered for the economic analysis that eventually lead to the selection of Case 1b as the most favorable one.

Table 8. Main necessary components for the process integration

Water circuit 0 (heat rejection circuit / Heat source integration)		
Component	TAG	Operation range and notes
2-way flow control valve	2WV_0	Flow rate range: 0-50 m^3/h
Water circuit 1 (driving heat circuit)		
Heat recovery condenser	HX_1	Hot side: cyclohexane + hexane
3-way mixing valve	3WV_1	Outlet flow rate range: 0 - 100 m^3/h.
Driving heat Hot water circulation pump	P_1	Flow rate range: 0 - 100 m^3/h. H circa 35 m. Temperature < 85 °C
2-way flow control valve	2WV_1	Flow rate range: 0 - 100 m^3/h
Expansion tank	EV_1	Big expansion valve for large circuit.
Water circuit 2 (upgraded heat circuit)		
2-way flow control valve	2WV_2	Flow rate range: 0 - 100 m^3/h.
Preheating heat exchanger	HX_2 (PH)	Hot side: circuit 2 / Cold side: cold water
Upgraded heat hot water circulation pump	P_2	Flow rate range: 0 - 100 m^3/h. H circa 15 m. Temperature < 125 °C
Flash Tank	FT	Inlet hot water flow: 100 m^3/h Outlet steam flow: kg/h
Steam circuit s (upgraded heat circuit / Heat sink integration)		
Flash Tank	FT	Inlet hot water flow: 100 m^3/h Outlet steam flow: kg/h
Thermocompressor	TC	Pressure ratio: 2/1.5 = 1.3

The main function and boundary conditions for the operation of each of the components can be described as follows:

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- In the heat rejection circuit (Heat Rejection circuit or circuit 0) the pipes are connected on one end to the cooling water network of the plant and on the other one to the condenser of the AHT. Due to sufficiently high pressure (>2 bar) there is no need to include an additional pump. A 2-way flow control valve 2WV_0 is the only relevant active component within this circuit. The flow rate must be controlled below 50 m^3/h, that is the maximum flow rate that can be extracted for the heat rejection of the P2H HUT system.
- The driving heat circuit (WH circuit or circuit 1) is a closed one and connects the heat source heat exchanger HX_1 and the generator and evaporator of the AHT. The heat recovered from the industrial process is the condensation of the solvent in the preconB line, that consists mainly of cyclohexane and hexane. The condensation takes place at the component HX_1.

  The hot water coming from HX_1 is pumped by the pump P_1, that is controlled by means of a variable frequency driver. A motor-driven 2-way control valve 2WV_2 limits the flow rate that flows through the generator of the AHT and fixes the flow rate distribution between generator and evaporator of the AHT, that are hydraulically connected in parallel (the total flow rate to be pumped by P_1 is the combination of both flow rates and the flow rate of hot water used for preheating the feed water to the steam generation module by means of the heat exchanger HX_2 (PH)). The position of valve 2WV_2 also determines the flow rate through HX_2, which is connected in parallel to the generator and evaporator of the AHT. The return lines from the generator and evaporator of the AHT and that of the preheater HX_2 (PH) come together into a common return line to HX_1. Under certain operating conditions, a certain fraction of the flow rate of this common return line will be recirculated using the mixing valve 3WV_1 in order to keep the feed temperature of the driving heat to the AHT and to the preheater at a certain temperature value.
- In the upgraded heat circuit (circuit 2) pressurized hot water at a temperature level included in the range 111-116 °C circulates between the absorber of the AHT and the flash tank of the steam generation module. In the flash tank (FT) a small amount of the large pressurized hot water flow rate evaporates. The amount of water that evaporates depends on the difference between the temperature of the hot water entering the flash tank and the steam pressure inside it in steady state. This temperature difference is the

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same as the temperature difference between absorber inlet and outlet. The ratio of evaporated steam in the tank increases with this temperature difference, while the heat upgrade capacity of the AHT decreases.

A design compromise has been found by fixing the temperature difference at the absorber at 5 K, prioritizing in this way the AHT heat capacity per heat transfer area over the ratio of evaporated steam. Consequently, for the operating design conditions for the flash tank at around 1.5 bar(a), the percentage of flash steam formed in the tank is around 0.87 % resulting in a water flow rate of 80.4 m^3/h and a steam flow rate of 0.7 m^3/h.

The former is equal to the the flow rate pumped by the circulation pump P_2, which is similar to the flow rate to be pumped in the driving heat circuit (1) by the pump P_1 (83.8 m3/h). The flow rates through either the generator or the evaporator of the AHT (that are hydraulically connected in parallel) are approximately half as large as the flow rate through the absorber of the AHT because, although the heat flow rates are similar for all three heat exchanger, the nominal temperature glides in the evaporator and generator are around 10 K and the nominal temperature glide in the absorber is around 5K.

- In the steam integration circuit (circuit s) the steam produced at a pressure around 0.5 bar(a) in the flash tank FT is increased to a pressure level of 1 bar(a) by means of the thermocompressor TC. In the thermocompressor or steam ejector, motive steam at a higher pressure level of 10 bar(a) is used to perform this pressure upgrade. The calculation of the flow rate of motive steam that is necessary for the pressure increase has been calculated by means of the selection software of the thermocompressor manufacturer company Baelz. (Sugein) and has been used to select the size of the corresponding ejector. The resulting flow rates and characteristics of the ejector are included in Table 9.

As Figure 15 shows, for the relatively moderate pressure increase of 0.5 bar, the mass flow rate ratios between the motive and suction stream are not dramatic. The Figure marks the expected operation point for the selected ejector.

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Table 9. Main characteristics of the selected thermocompressor

Termocompressor selection for Case 1B		
Manufacturer / Model		Baelz /Steam Jet Pump 590
Nominal ejector diameter	DN	80
Nozzle diameter	mm	11.7
Suction stream (lowest pressure)		
pressure	bar(a)	1.5
Mass flow rate	Kg/h	789
Motive stream (highest pressure)		
pressure	bar(a)	10.0
Mass flow rate	Kg/h	535
Discharge stream (intermediate pressure)		
pressure	bar(a)	2.0
Mass flow rate	Kg/h	1324

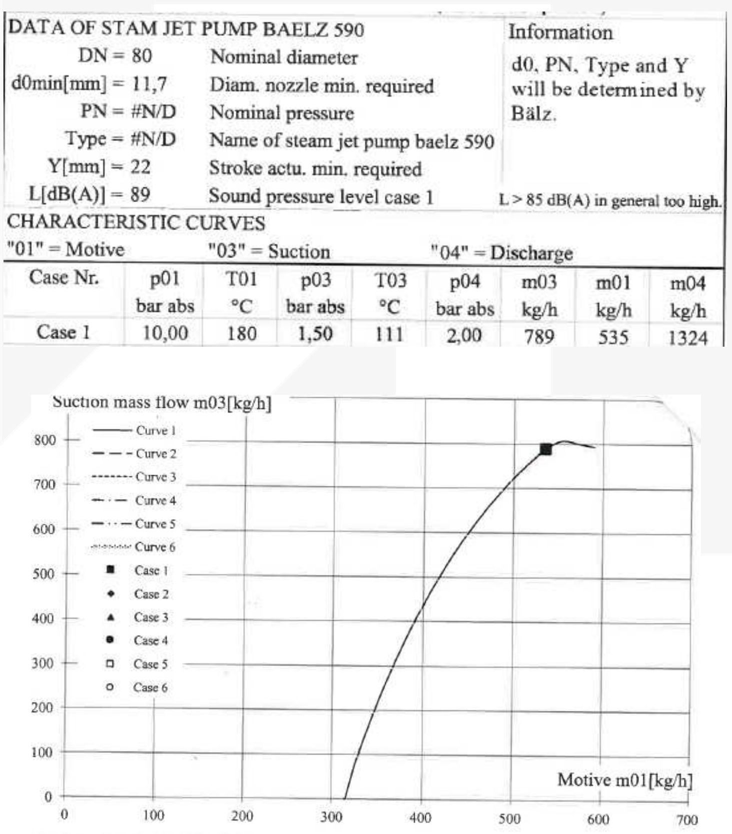

Figure 15. Thermocompresssor characteristics (from manufacturer calculation)

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3.2. Design parameters of the Heat Upgrade System

Table 10 summarizes the main characteristics of the heat upgrade system for the design conditions (maximal expected heat upgrade).

Table 10. Main nominal characteristics of the heat upgrade system

Heat Source design parameters		
parameter	unit	value/information
Total thermal capacity	kW_{th}	982
Thermal capacity for driving AHT	kW_{th}	934
Thermal capacity for preheating	kW_{th}	48
Flow rate	m³/h	81.8
Inlet temperature evaporator	°C	85
Outlet temperature evaporator	°C	80
Heat transfer fluid	-	water
High Temperature Heat Sink design parameters (useful heat)		
Thermal capacity	kW_{th}	448
Mass flow rate hot water circuit 2	m³/h	80.3
Inlet temperature absorber AHT	°C	111.1
Outlet temperature absorber AHT	°C	116.1
Fluid circuit 2	-	pressurized water
Mass flow rate Flash Tank steam (s1)	Kg/h	685
pressure Flash Tank Steam (s1)	bar(a)	1.5
Flow rate TC motive steam (s0)	kg/h	480
pressure TC motive Steam (s0)	bar(a)	10
Flow rate TC discharge steam (s2)	kg/h	1 185
pressure TC discharge steam (s2)	bar(a)	2.0
Low Temperature Heat Sink design parameters (heat rejection)		
Flow rate	kg/h	41.9
Inlet temperature condenser	°C	15
Outlet temperature condenser	°C	20
Fluid circuit 0	-	cooling water from plant network
Absorption Heat Transformer unit (single effect)		
Electricity consumption*	kW_{el}	5
Coefficient of Performance (COP_{el})*	kW_{th}/ kW_{el}	448 / 5 = 90
Coefficient of Performance (COP_{th})	kW_{th}/ kW_{th}	0.48
Refrigerant / solution	-	H_2O / LiBr aqueous solution

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* Considering only internal pumps and control of the AHT unit

3.4. Control concept and control integration

The initial basic control concept has been defined within the basic engineering phase. This initial control integration scheme determines the main active components that are necessary for the operation and part-load regulation of the HUT system. These are shown in Figure 16.

The so called "DDt-control" module, integrated in the HUT control unit and developed within the frame of this project by TU Berlin assisted by Tecnalia will control the pumps and valves of the system in order to have the best combination of external heat carrier flow rates and inlet temperatures to the AHT at each of the three external circuits. Its purpose is to provide the minimal possible electrical consumption of the external pumps when generating steam at the required pressure level.

- In the heat rejection circuit, the flow rate of cooling water will be controlled by means of the control flow rate 2WV_0. There will be no possibility for inlet temperature control at the heat rejection circuit.
- In the driving heat circuit, the total flow rate of hot water circulating through the generator and evaporator of the AHT, and through the preheater PH connected in parallel, will be controlled by the pump P_1. This will also be affected by the positions of the valves 2WV_1 and 3WV_ 1. The valve 2WV_1 will be used to limit the flow rate through the generator of the AHT, and indirectly to control the flow rate ratio between the generator and the evaporator. The valve 3WV_1 will be used to recirculate hot water leaving the AHT and thus to limit the inlet temperature to both the generator and evaporator. The temperature of the hot water leaving the heat recovery condenser/heat exchanger HX_1 will be affected by the return temperature from the AHT and by the flow rate of hot water that enters HX_1. Thus, the temperature inlet control implies a coupled system depending

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on AHT performance, the recirculation flow through valve 3WV_1 and the total flow rate of the pump P_1. Thus, the control system of this driving heat circuit must be designed thoroughly.

- In the upgraded heat hot water circuit 2 the flow rate of hot water will be controlled by the pump P_2. The temperature of the hot water entering the absorber of the AHT will be determined by the governing pressure at the flash Tank FT. The pressure at the flash tank is coupled with the operation of the thermocompressor TC as it will be described below. Additionally, the maximal pressure within the flash tank is controlled by means of relieve valves that will open if the pressure at FT arises over a certain boundary. This will only happen if the TC is not on operation.

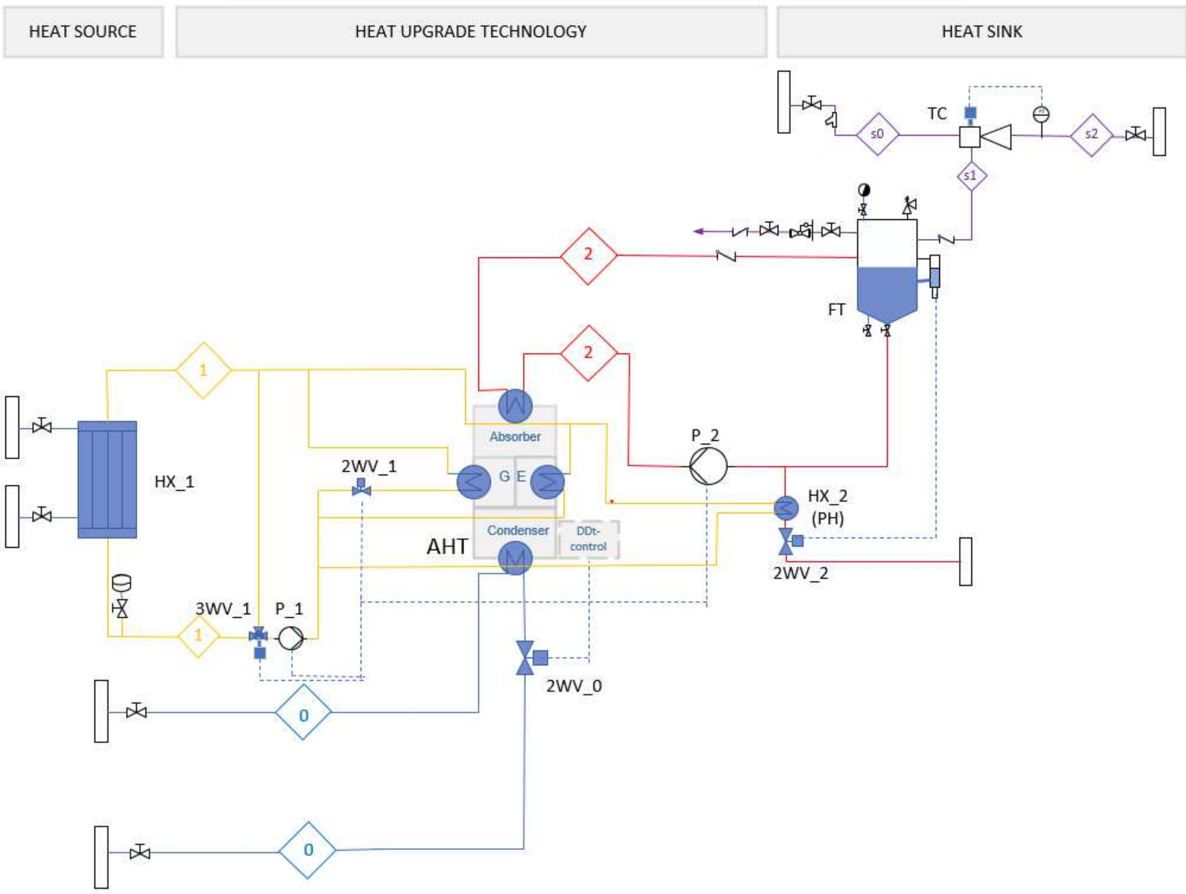

Figure 16. AHT control scheme for the HUT system

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Additionally, Figure 16 includes the control loop of the so-called "steam production module", that comprises the flash tank FT and the thermocompressor TC and controls the steam production by the HUT. When the thermocompressor is on operation, it will let steam at the higher-pressure level s0 to flow through, reducing its pressure to a lower pressure level s2 and sweeping along steam at the lowest pressure level s1.

During start up of the HUT or in case of malfunction of the AHT unit, the pressure level at the flash tank will be below its nominal value. Below a certain pressure level, no steam at the lowest pressure level will be dragged, and the thermocompressor will act as a reduction valve if it is open. For the start-up, however, the thermocompressor will be kept closed until the pressure level at the flash tank reaches its nominal value. At this point, the thermocompressor will start its operation. In normal operation, an electrically driven motor within the termocompressor keeps the discharge pressure at a certain level by changing the nozzle opening and its effective diameter.

The control loop will be integrated within the HUT control unit, together with the DDt-control of the AHT.

3.5. Monitoring concept

A first preliminary selection of the necessary measurement equipment that will be included with the HUT system have been made, taking into consideration the initial control concept presented in the previous section and the performance analysis that will follow within the project.

For the monitoring concept, a distinction is made between the sensors and instruments that will be part of the integration circuits of the HUT and those that will be supplied alongside the AHT by the technology provider. Additionally, the instrumentation equipment necessary for the steam production module is considered separately. The pressure and temperature sensors and flow meters that needs to be integrated in the circuits 0, 1 and 2 are summed up in Table 11 and visually represented in Figure 17.

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Table 11. Sensors defined for the HUT integration within the plant

Water circuit 0 (heat rejection circuit / Heat source integration)		
Component	TAG	Operation range and notes
Cooling water flow meter	FT_0	Flow rate range: 0-50 m3/h Temperature range: 5 - 40 °C
Water circuit 1 (driving heat circuit)		
Driving heat hot water flow meter	FT_1	Flow rate range: 0-50 m3/h Temperature range: 60 - 90 °C
Pressure driving heat hot water circuit	PT_1	Temperature range: 60 - 90 °C Lowest expected pressure in the circuit
Temperature hot water HX_1 outlet	TT_1_1	Temperature range: 60 - 90 °C Mixing temperature (used for control)
Temperature hot after 3MW_1	TT_1_2	Temperature range: 60 - 90 °C Mixing temperature (used for control)
Temperature hot water HX_1 outlet	TT_1_1	Temperature range: 60 - 90 °C Heat source temperature
Temperature hot after 3MW_1	TT_1_2	Temperature range: 60 - 90 °C Return temperature (used for control)
Temperature hot after 3MW_1	TT_1_3	Temperature range: 60 - 90 °C Temperature after mixing
Water circuit 2 (upgraded heat circuit)		
Upgraded heat hot water flow meter	FT_2	Flow rate range: 0-100 m^3/h Temperature range: 110 - 130 °C
Pressure upgrade heat hot water circuit	PT_2	Temperature range: 110 - 130 °C Lowest expected pressure in the circuit
Temperature hot water HX_1 outlet	TT_2_1	Temperature range: 20 - 80 °C Treated water feed temperature
Temperature hot water HX_1 outlet	TT_2_2	Temperature range: 110 - 130 °C Feed temperature after preheating
Temperature hot water HX_1 outlet	TT_2_3	Temperature range: 110 - 130 °C FT outlet liquid water temperature

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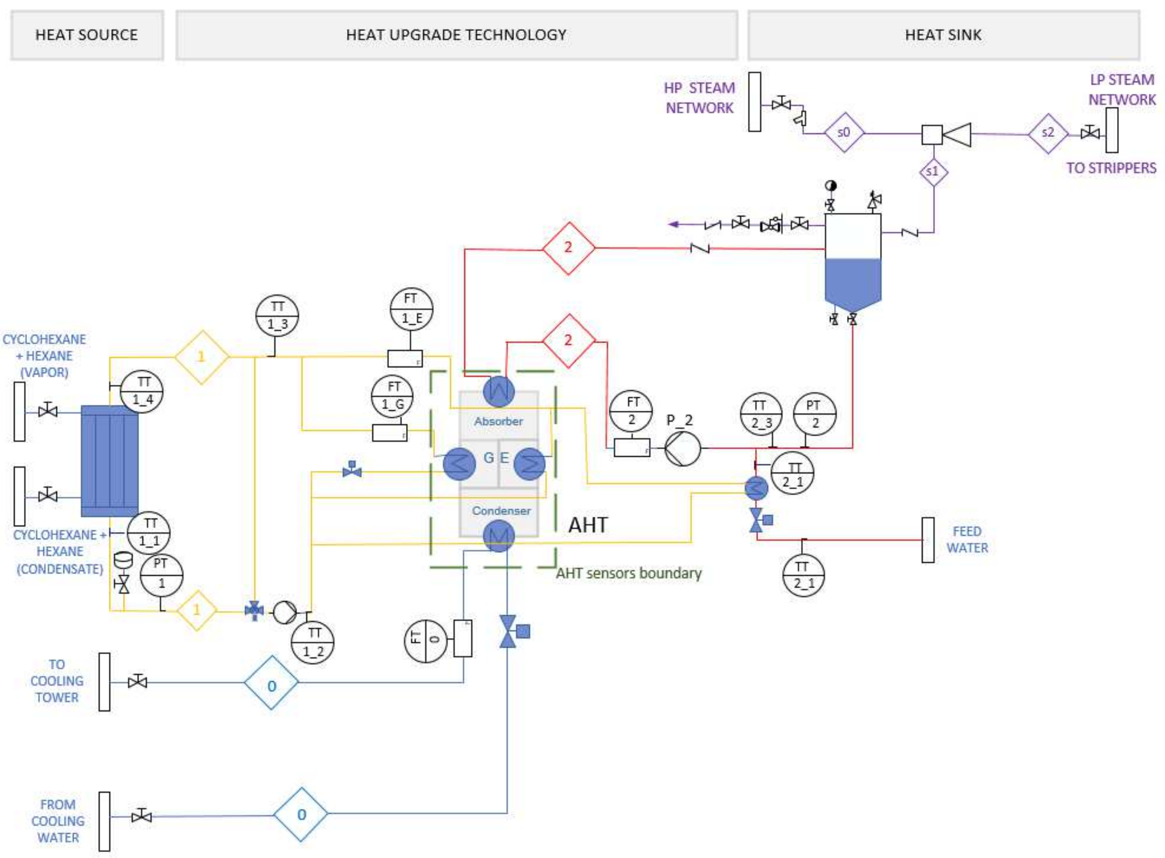

Figure 17. monitoring scheme for the HUT integration system

Figure 18 presents the sensors placed at circuits 0, 1 and 2, that will be delivered by the AHT manufacturer (BS Nova). All these sensors are listed in Table 12..

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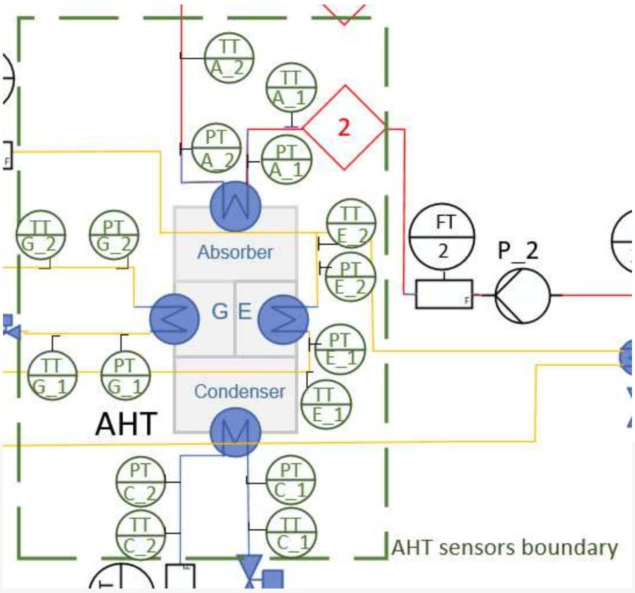

Figure 18. monitoring scheme for the AHT

Table 12. Sensors to be delivered with the AHT

Water circuit 0 (heat rejection circuit / Heat source integration)		
Component	TAG	Operation range and notes
Pressure cooling water condenser in	PT_C_1	Temperature range: 5 - 40 °C
Temp. cooling water condenser in	TT_C_1	Temperature range: 5 - 40 °C
Pressure cooling water condenser out	PT_C_2	Temperature range: 5 - 40 °C
Temp. cooling water condenser out	TT_C_2	Temperature range: 5 - 40 °C
Water circuit 1 (driving heat circuit)		
Pressure hot water generator in	PT_G_1	Temperature range: 60 - 100 °C
Temp. hot water generator in	TT_G_1	Temperature range: 60 - 100 °C
Pressure hot water generator out	PT_G_2	Temperature range: 60 - 100 °C
Temp. hot water generator out	TT_G_2	Temperature range: 60 - 100 °C
Pressure hot water evaporator in	PT_E_1	Temperature range: 60 - 100 °C
Temp. hot water evaporator in	TT_E_1	Temperature range: 60 - 100 °C
Pressure hot water evaporator out	PT_E_2	Temperature range: 60 - 100 °C
Temp. cooling water evaporator out	TT_E_2	Temperature range: 60 - 100 °C
Water circuit 2 (upgraded heat circuit)		
Temp. hot water absorber out	PT_A_1	Temperature range: 100 - 130 °C
Pressure hot water absorber in	TT_A_1	Temperature range: 100 - 130 °C
Temp. hot water absorber in	PT_A_2	Temperature range: 100 - 130 °C
Pressure hot water absorber out	TT_G_"	Temperature range: 100 - 130 °C

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Figure 19 is focused on the Steam Generation Module encompassing all sensors that will be used for monitoring the steam production. This includes sensors for monitoring the pressure and the temperature of the produced steam, as well as the mass flow rate of the motive steam required for thermocompression.

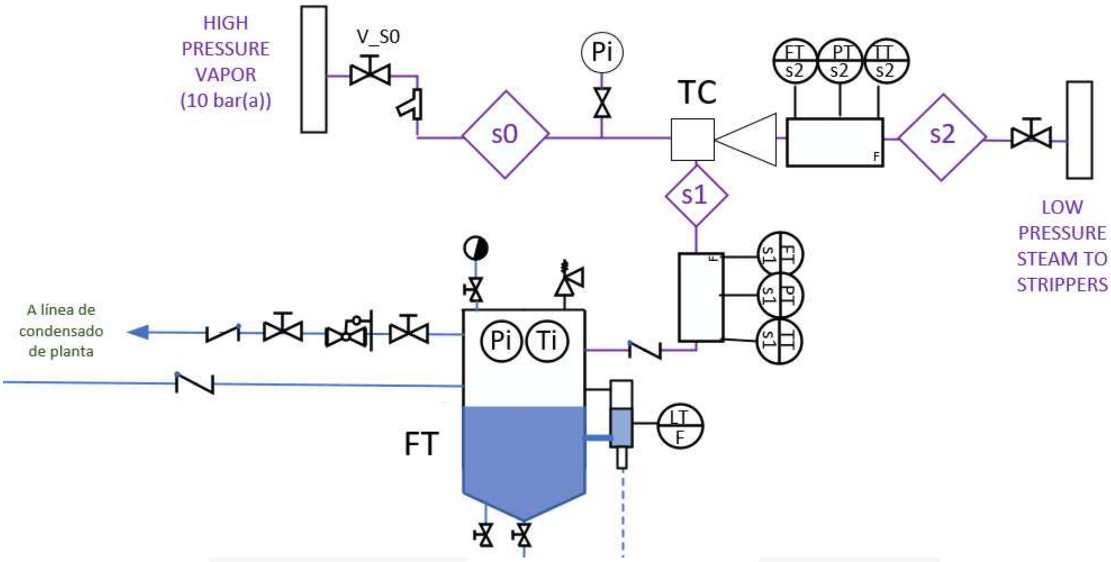

Figure 19. monitoring scheme steam generation module

Table 13. Sensors defined for the Steam Generation Module

Steam circuit s1 (steam produced at 1.5 bar(a) / Flash Tank Steam)		
Measured variable	TAG	Operation range and notes
Flow rate FT produced steam	FT_s1	0 to 1 000 kg/h
Temp. TT produced steam	TT_s1	100 to 130 °C
Pressure PT produced steam	PT_s1	1.0 to 2.0 bar(a)
Steam circuit s2 (TC discharge steam / to strippers at 2.0 bar(a))		
Flow rate FT produced steam	FT_s2	0 to 1 500 kg/h
Temp. TT produced steam	TT_s2	120 to 160 °C
Pressure PT upgraded steam	PT_s2	2.0 to 5.0 bar(a)

This list of sensors can be slightly adapted or updated following the decisions and recommendation that will be made in WP4, the work package of PUSH2HEAT project related to monitoring and data analysis of the heat upgrade technologies of the different demo sites

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3.6. First P&ID diagram

A first preliminary P&ID diagram has been elaborated incorporating all the relevant information, along with preliminary sizing and selection of equipment and instrumentation, detailed in section 3.1 to 3.5.

This preliminary P&ID has been the basis for the economic estimation of the integration cost for the HUT into the Dynasol facilities. This first P&ID is presented in Figure 20 .

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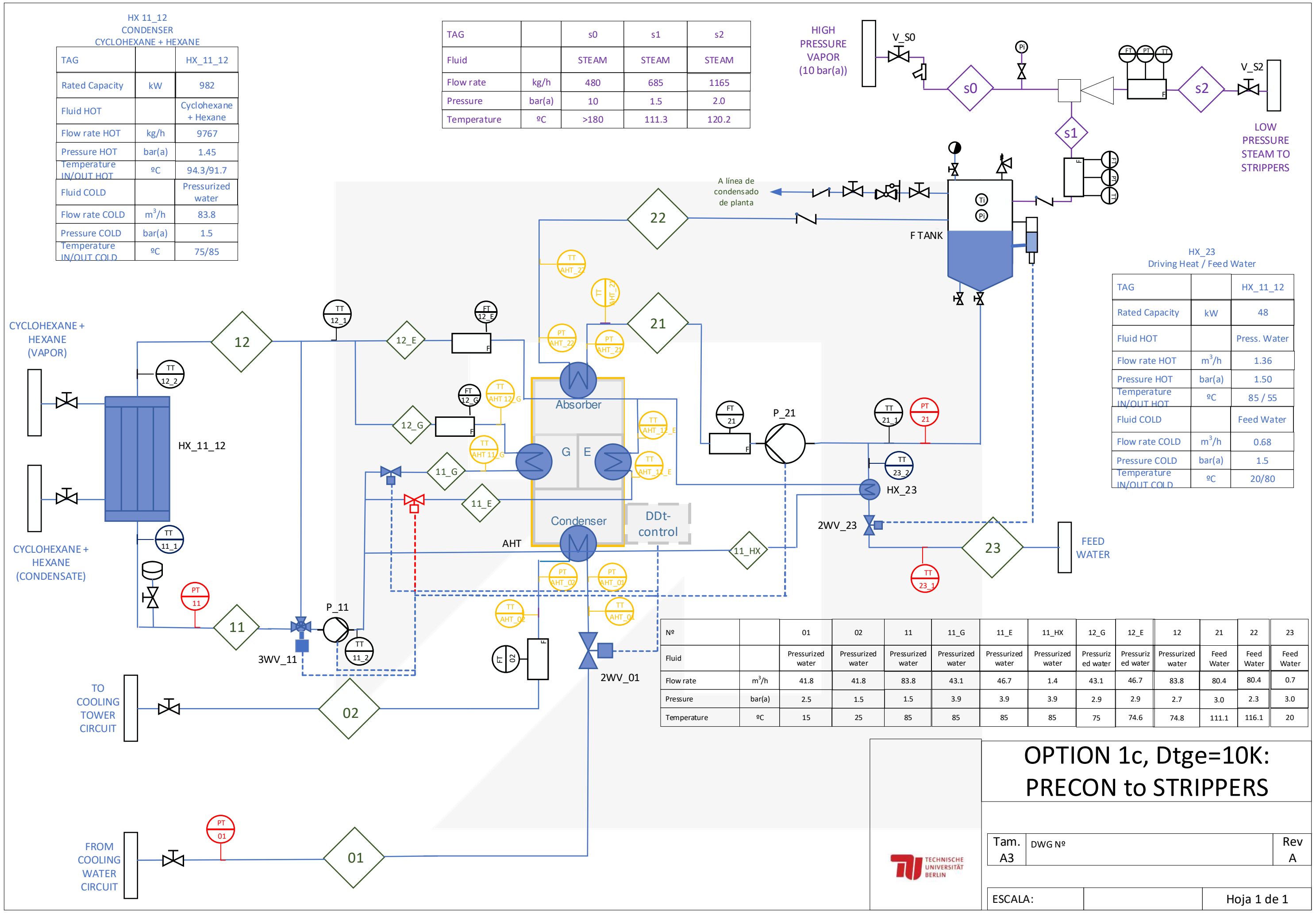

Figure 20. P&ID of AHT integration in Dynasol plant

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4. Conclusions

This document describes the application Case selected for the integration of the Push2Heat project absorption heat upgrade technology within the elastomers plant of the company Dynasol, located near Santander, Spain.

After having discussed all possibles heat source and sinks within the plant, 3 different cases for the integration of the AHT have been studied.

The production of low-pressure steam for its use in the strippers in the plant has been selected as the most attractive option, even if the other analyzed options could have led to larger energy and emission savings. The selected case uses waste heat from the condensation of the solvent used in the Precon B production line within the plant to drive an absorption heat transformer that heats up hot water at around 116 °C, providing an upgraded heat sink capacity of 448 kW. The latter enters a flash tank in which 685 kg/h steam at 1.5 bar(a) is produced. The steam leaving the flash tank enters the thermocompressor, that uses 10 bar(a) steam as motive steam to increase its pressure up to 2 bar(a), providing the final amount of 1 185 kg/h steam, that is used in the strippers.

Furthermore, the document has presented the components necessary for the integration of the heat upgrade system within the plant and illustrated the preliminary control scheme. Additionally, the sensors of the monitoring system necessary at each system level have been presented. All the information has been included in the P&ID diagram that has been used as the basis for the estimation of the initial costs of the integration system of the heat upgrade solution.

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