Push2Heat

D3.2

Demonstration site at CDG - system design

V1.1

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Prepared by: Gianluca Abrami, Tommaso Toppi, Mehdi Aminyavari

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Push2Heat

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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.

CDG: Cartiera di Guarcino

BEG: Bio Energia Guarcino

DH: District Heating

CHP: Combined heat and power

M: Motor (biomass engine)

DC: Dry cooler

HE: Heat exchanger

A-M1, A-M2, A-M3: Air preheater of engine 1, 2 and 3.

PM: Paper Machine

HRSG: Heat recovery steam generator

COP: Coefficient of performance

OH: Operational hours

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PARTNERS

Partner short name	Legal name	Role
POLIMI	POLITECNICO DI MILANO	Local site coordinator
BONO	CANNON BONO ENERGIA	System integration, Technology provider
CDG	CARTIERA DI GUARCINO	Demo site

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1. Introduction

1.1 Overview of WP3 structure

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 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 and Italy. 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 1 (Germany): Fraunhofer Gesellschaft zur Förderung der Angewandten Forschung E.V.
- Demo site 2 (Italy): Politecnico di Milano
- Demo site 3 (Italy): Fundación Tecnalia Research & Innovation

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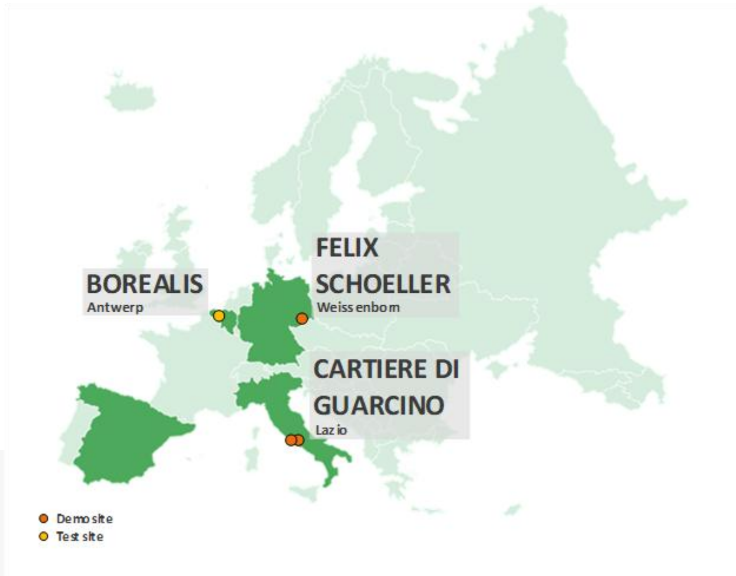

Figure 1: Heat upgrade systems in PUSH2HEAT.

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) for HTHP
- T3.2 Demonstration site at Cartiera Di Guarcino (CDG) for HTHP coupled with MVR
- T3.3 Demonstration site at Cartiera Di Guarcino (CDG) for AHT
- T3.4 Assessment on commissioning of heat upgrade systems

The main objective of WP3 is to implement demonstration plants for heat upgrade technologies at two locations in Europe in cooperation with partners from 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

1.2 Contents of the report

This report (deliverable D3.2) will focus on the results gained from analyzing the requirements of the demo site in Italy (Guarcino, Lazio), planning the optimal integration of the heat upgrade technology into the industrial process (paper production) and providing a basic engineering for the

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installation. First engineering results undertaken among the partners involved will be presented and discussed.

Section 2 describes the analysis and requirements for the heat upgrade system of the demo site in CDG. Firstly, the current energy consumption of fossil-fueled systems is described. The description of energy produced and consumed in the plant and the different pressure levels of steam is provided. The waste heat source available in plants is described as well as the most suitable upgraded heat sink for the HTHP.

Section 3 describes the preliminary planning and basic engineering for the HUT (HTHP coupled with MVR) integration in the chosen configuration, including the functional P&ID with all auxiliary components and the specifications for HTHP control and MVR control. Moreover, an overview of the monitoring concept is presented.

2. Analysis and requirements

This chapter focusses on the analysis and definition of requirements of the demo sites, that will allow and initiate the full-scale development of the heat upgrade technologies included in WP2 (Task 2.2 Full scale development of vapor compression heat pumps coupled with MVR). This first phase, i.e. the system analysis and evaluation on each demo site will be undertaken also with respect to the optimal integration of the heat upgrade technologies and is mainly taking place within T3.2.

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 each demo site with a preliminary focus on analyzing technical and infrastructural requirements in every operating system.

The involved partners and their role in Task 3.2 are as follows:

- Cartiera di Guarcino (CDG): plant operator, support system integration.
- Cannon Bono (BONO): demo site analysis and system integration for Demo 2 and Demo 3.
- Cannon Bono (BONO): heat pump manufacturer.
- Politecnico di Milano (POLIMI): demo site coordinator.

2.1 CDG site layout

Cartiera di Guarcino is an industrial group located in Guarcino in Lazio (Italy). The company heritage lies in the production of decor paper for high- and low-pressure lamination and flooring paper. Their

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products include Unicolor, Backer paper, Print base paper and Underlay. The plant occupies an area of 144 000 square meters, and it has a production capacity of 50 000 t of paper per year, thanks to the commitment of 170 employees. Paper production is an energy intensive process, requiring considerable amounts of steam. Since the foundation of the plant in 2003 the steam was entirely produced by gas boilers on site. However, in 2006 the team behind CDG invested in a dedicated energy company named Bio Energia Guarcino (BEG), a specialized facility equipped with a technologically advanced cogeneration plant that uses animal fats and vegetable oil residues as fuel. Such a plant produces both electrical and thermal energy, allowing CDG to decrease the production of the on-site gas boilers. The company is also committed to avoiding any unnecessary use of water from the river flowing near the plant and to maximizing production efficiency, to reduce the production cost as well as any paper waste. Figure 2 shows an aerial view of CDG. The plant could be divided into three main areas: production site, generation site and offices/other buildings (canteen, etc.).

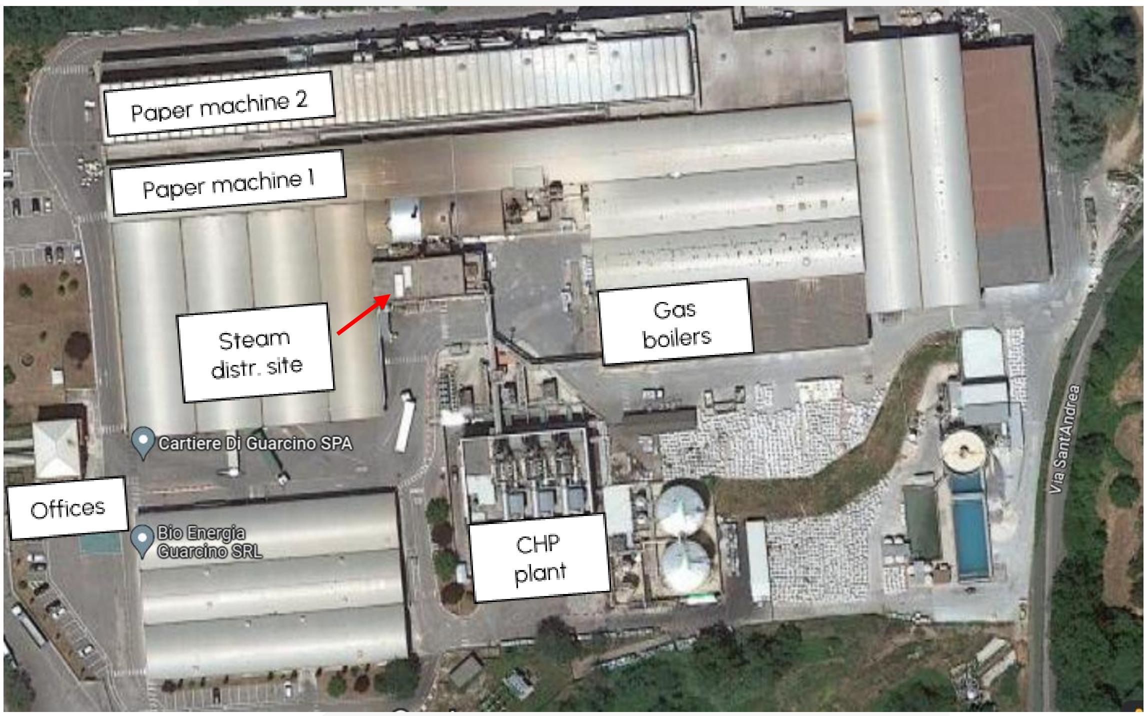

Figure 2: CDG and BEG aerial view.

The production site consists of two paper machines, enclosed in two warehouses located in the upper part of Figure 2. The generation site includes two gas boilers and the CHP plant (combined heat and power), as shown in Figure 2. The steam produced by the engines and the boilers is collected at the "steam distribution site" (see Figure 2), tuned to the appropriate pressure level and distributed in the plant. The offices are located on the left side of Figure 2.

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2.2 Current energy consumption of fossil-based systems

2.2.1 Energy demand

CDG has a yearly demand for electricity and process heat equal to 42.12 GWh_{el} and 101 GWh_{th} respectively. The heat demand is in the form of steam and hot water. The hot water is mainly destined for space heating while a small portion is used for other domestic needs. Figure 3 below illustrates the daily tons of hot water transferred from the cogeneration plant of Bio Energy Guarcino (BEG) to CDG for the period between 01/01/2022 and 25/06/2023.

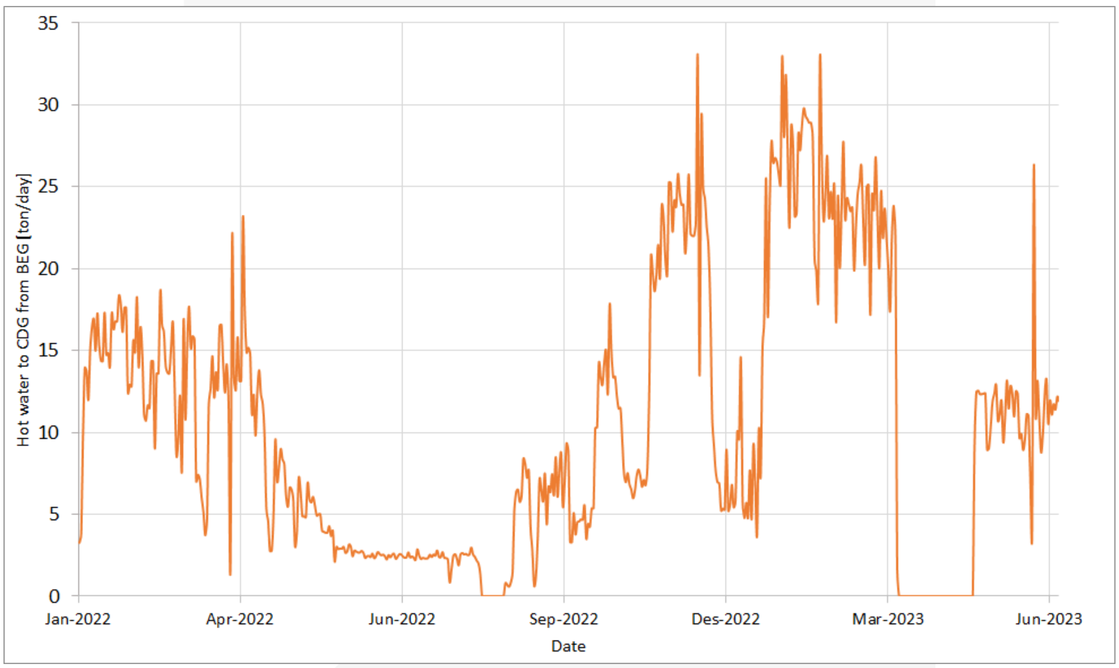

Figure 3: Hot water transferred from BEG to CDG for the period 01/01/2022 – 25/06/2023.

As for CDG's electricity consumption, the plant typically consumes approximately 140 MWh_{el} per day, with nearly 100 % of this power being supplied by BEG, except for days when all the three engines of BEG are simultaneously out of operation. Figure 4 illustrates the daily electrical energy exported from BEG to CDG for the period of 01/01/2022 to 30/06/2023.

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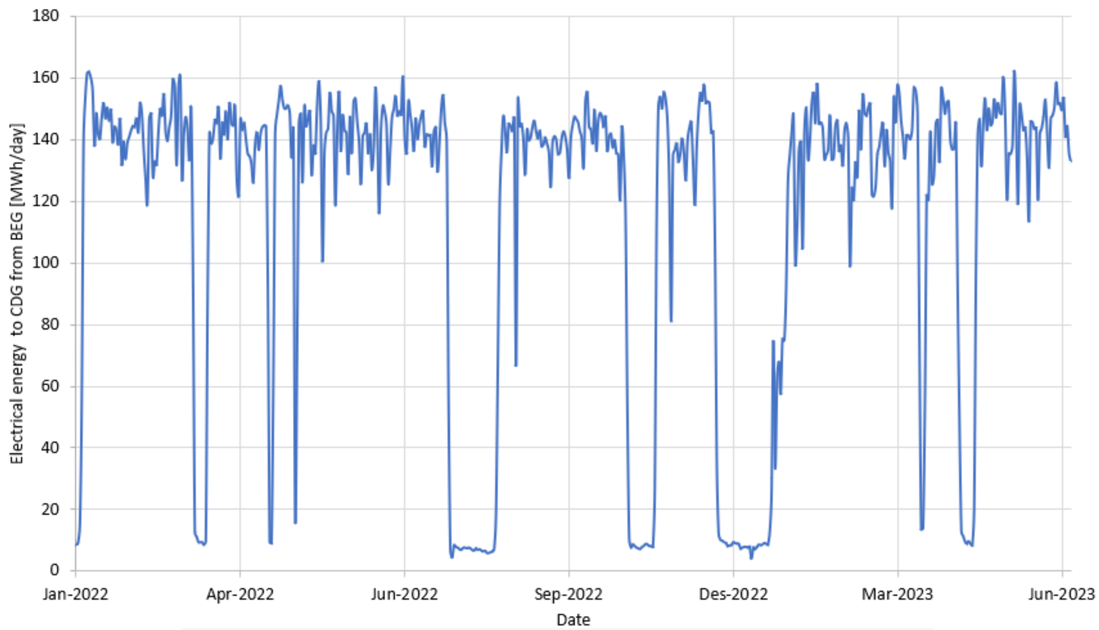

Figure 4: Electrical energy sold to CDG by BEG.

The energy consumption of CDG production site is in the form of saturated vapor. The two paper machines (PM1 and PM2) of CDG consume 10 t/h and 13t/h of saturated 6.5 bar(a) steam, respectively. Of the overall 23 t/h, about 7-8 t/h is supplied by BEG, while the rest is covered by the two gas boilers that produce saturated steam at 14.5 bar(a). Figure 5 shows the daily amount of steam transferred to CDG from BEG for the period of 01/01/2022 to 30/06/2023.

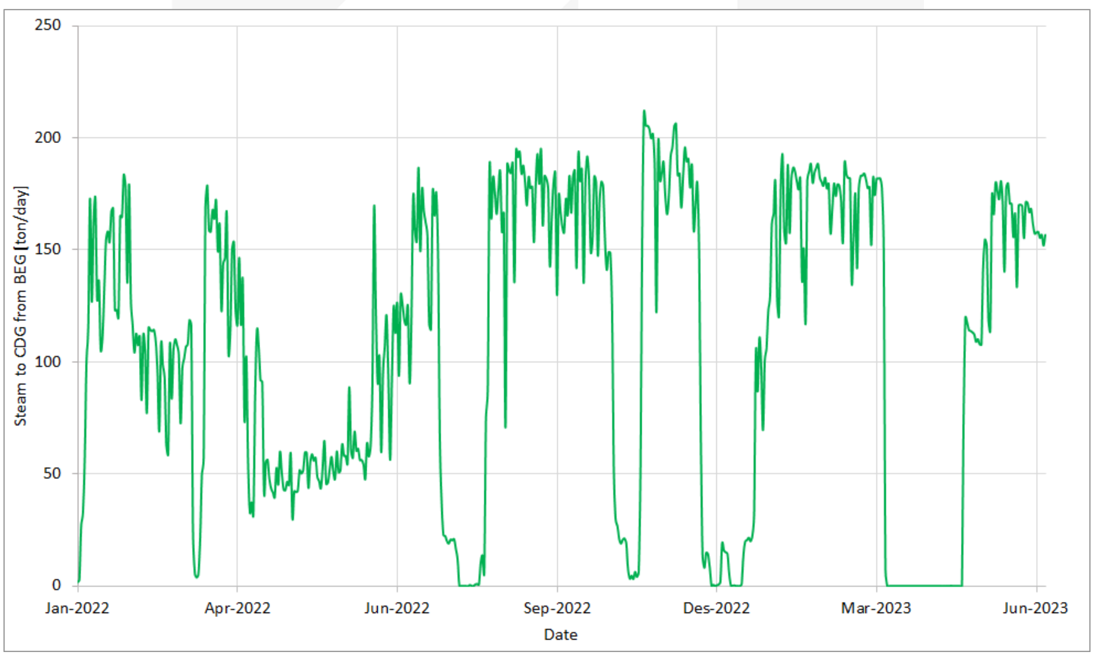

Figure 5: Steam transferred from BEG to CDG.

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2.2.2 Steam, hot water and electricity production

The energy requirements of CDG are partially satisfied by the cogeneration plant of BEG, which generates energy in three forms: steam, hot water and electricity. CDG is also facilitated with two fire tube boilers that cover the remaining steam demand of the plant. The boilers require a yearly supply of 7 544 633 Nm^3 of natural gas. Eventually, CDG is connected to the national grid for the supply/sale of electricity.

BOILERS

The two gas boilers are manufactured by Cannon Bono, and they generate steam at a pressure of 14.5 bar(a), corresponding to a saturated steam temperature of 197 °C. The main characteristics of each gas boiler are reported in Table 1.

Parameter	Unit	Value
Nominal capacity	t/h	15
Efficiency	%	90
Pressure	bar(a)	14.5
NO_x emissions at 3 % O_2	mg/Nm^3	100

Table 1: Main characteristic of the boilers installed at CDG.

The duty of the two boilers is almost constant throughout the year, with a capacity of 15 to 16 t/h of the generated steam, which corresponds to most of the steam that is used in the paper production processes of CDG. The steam produced by the boilers is collected in the high-pressure collector: around 2 t/h is used in some thermocompressors that are exploited to upgrade low-pressure steam from different processes to an intermediate useful pressure level for other processes. The remaining amount of 13 to 14 t/h is expanded in a valve to 6.5 bar(a) and united with the steam coming from the CHP plant. A deaerator is present in the plant to remove dissolved gases from feedwater before it enters the boilers.

CHP PLANT

The CHP plant owned by BEG is constituted of three bio-fuel engines, each of which is devoted to the production of electrical energy, steam and hot water used for district heating (DH). The rated nominal electrical capacity of each engine is 6.8 MW_{el}. The generated electricity is partially used inside of CDG facilities, while the excess production is exported to the national electricity grid. The following table reports the main characteristics of the engines.

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Parameter	Unit	Value
Nominal electrical capacity (per engine)	MW_{el}	6.87
Cooling water nominal inlet temperature	°C	72
Cooling water nominal outlet temperature	°C	92-94
Cooling water flowrate	m^3/h	135
Flue gas temperature	°C	90
Flue gas flowrate*	kg/h	1564
Fuel consumption**	g/kWh	0.23
NO_x emissions at 11.5 % of O_2***	mg/Nm^3	120

Table 2: Main characteristic of the engines of BEG plant (values refers to the individual engine).

* At full load (6.865MW_{el})

** Average value related to fuel quality and engine maintenance status

*** Average value related to fuel quality and SCR lifecycle time

Figure 6 demonstrates the running time of each engine during 2022. The maximum working minutes in a day is 1440 minutes (i.e. 24 hours) and the aim is to make the engine work at full load 24 hours a day. However, as one may note from the graph, there are days on which the engines do not exploit the maximum working time available. Data reveals that during 2022, engines 1, 2 and 3 ran for 69 %, 82 % and 80 % of maximum time available.

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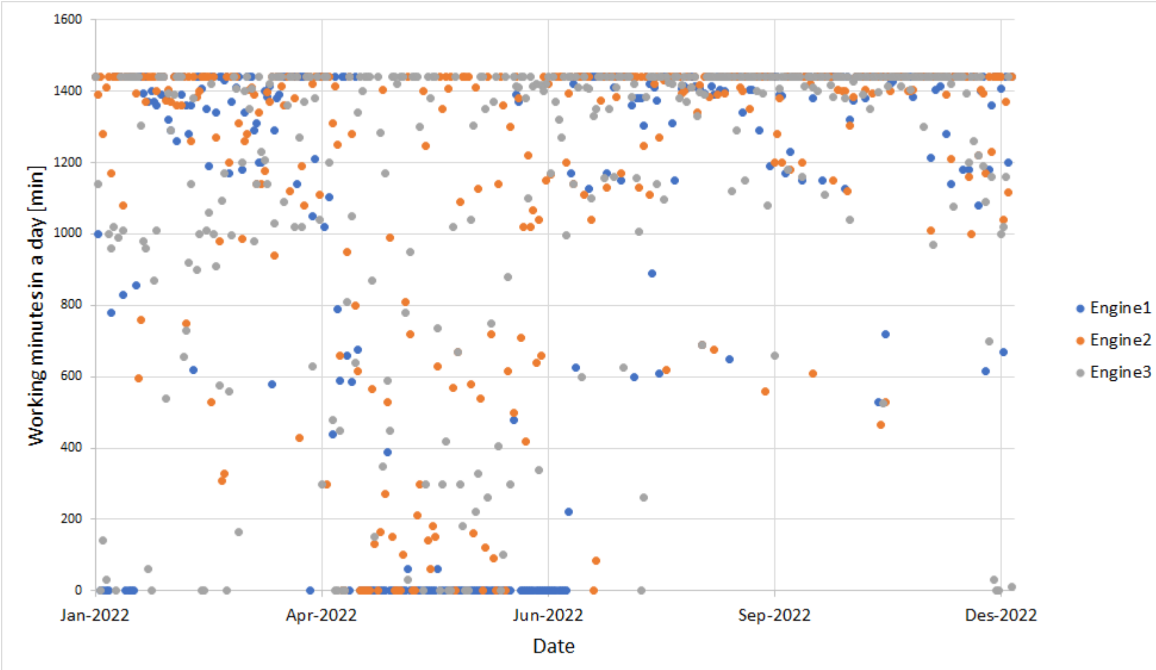

Figure 6: Daily working minutes of the three engines of the CHP plant in 2022.

The hot exhaust gases of the engines pass through a heat recovery steam generator (HRSG) which is designed to produce 7-8 t/h of saturated steam at 6.5 bar(a) (162 °C) for three engines together.

Water is used as coolant for the engine's body. After the cooling of the motor, hot water needs to be cooled down to its supply temperature. Heat derived from the cooling of the water is partially exploited by the district heating network, while part of it is discarded to the ambient through dry coolers. This amount of heat is identified as the waste heat source for the PUSH2HEAT project and the Heat Upgrade System. Figure 7 provides a clearer depiction of the cooling water circuit's schematic and its integration with the overall process. Considering engine 1 (M1) as an example, the cooling water gets out of engine at point 1 with a temperature of about 92-94 °C. After getting cooled down in Heat Exchanger 1 (HE1) to point 4, it passes partially through Dry Cooler 1 (DC1) where additional heat is dissipated to the ambient to guarantee an inlet temperature at the engine of 72 °C (point 10). The heat transferred from this primary circuit through HE1, HE2 and HE3 to the secondary water circuit preheats the combustion air of each engine in A-M1, A-M2 and A-M3 (point 21, 22 and 23) and additionally it also supplies hot water at around 90 °C for heating purposes at CDG (point 19). It is noteworthy that the three HEs are designed for 2 MW each, while the three A-Ms are dimensioned for 1.5 MW each.

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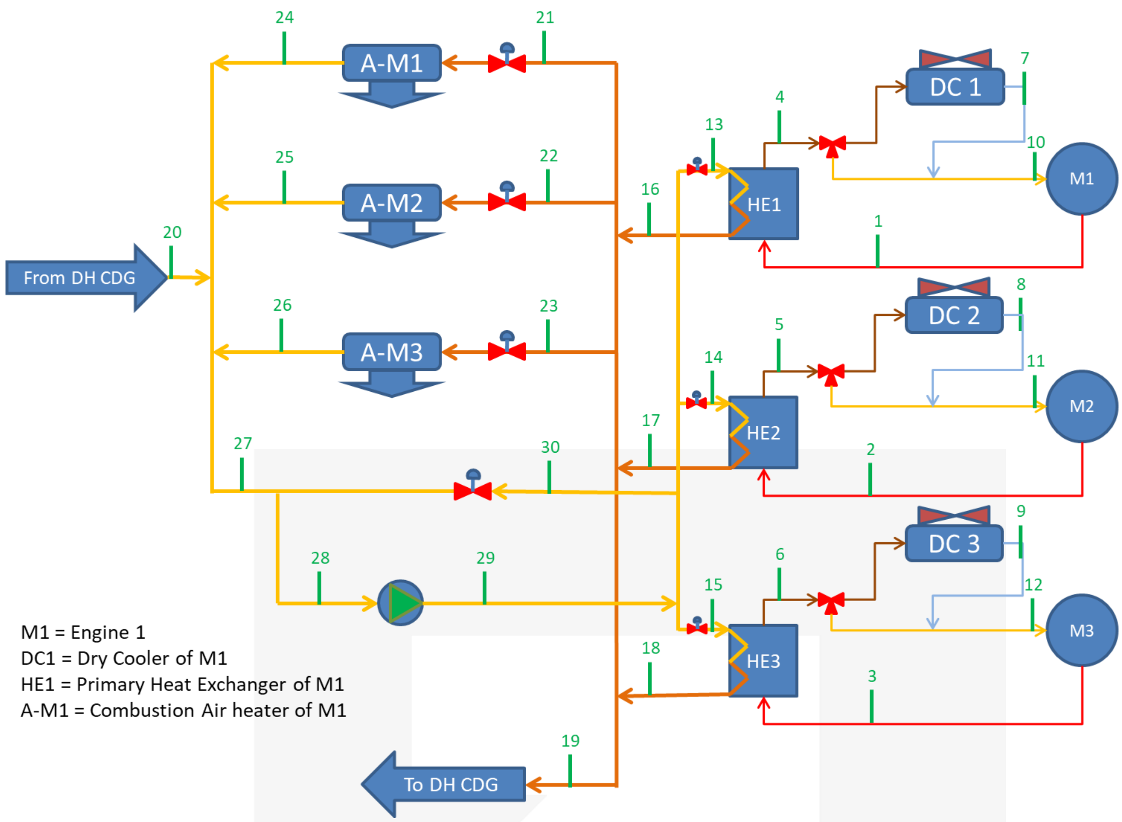

Figure 7: Schematic of water's cooling water circuit and its integration with the overall system

2.2.3 CDG steam pressure levels summary

CDG is characterized by a complicated steam collection & distribution system, consisting of many pipes and expansion valves. For the purpose of this project, two pressure levels are relevant:

- High pressure = 14.5 bar(a). It is the highest-pressure level reached in the plant, corresponding to the pressure of the vapor generated by the boilers. Such high pressure is justified by the need to keep the specific volume of the vapor low. This has a positive impact on the operation of the boilers, without significant effect on their efficiency. Moreover, the high-pressure level is exploited by steam ejectors (thermocompressors) distributed in the plant.
- Medium pressure = 6.5 bar(a). This corresponds to the pressure level required by the paper machines. The medium pressure vapor is generated by the flue gas treatment process (HRSG) and by the expansion of the high-pressure vapor.

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2.3 Initial concept for the heat upgrade system

The heat recovery process involves extracting waste heat from the cooling water system of the cogeneration plant. This cooling water will be conveyed to the heat upgrade system, where it will transfer valuable heat to the evaporator of the heat pump. The supply and return temperature of the cooling water are respectively around 90-92 °C and 70-72 °C, while the available flow rate was calculated to be around 100 m^3/h during the proposal phase. By cooling down this stream it is possible to recover around 2.1 MW of heat. Section 2.4 illustrates the different options that were evaluated for waste heat extraction.

Upgraded heat from the heat pump and MVR system will be available in the form of:

- Steam at 1310 kg/h of steam at 6.5 bar(a).
- 105 kg/h of saturated water at 6.5 bar(a)

The former will be generated mostly (1180 kg/h) within the heat pump's condenser, with a small portion derived from the evaporation of the water injected into the MVR for lubrication purposes. The latter is the remaining portion of the cooling water injected into the MVR that remains as saturated water.

Figure 8 presents the schematic of integration of the heat pump as per initial concept.

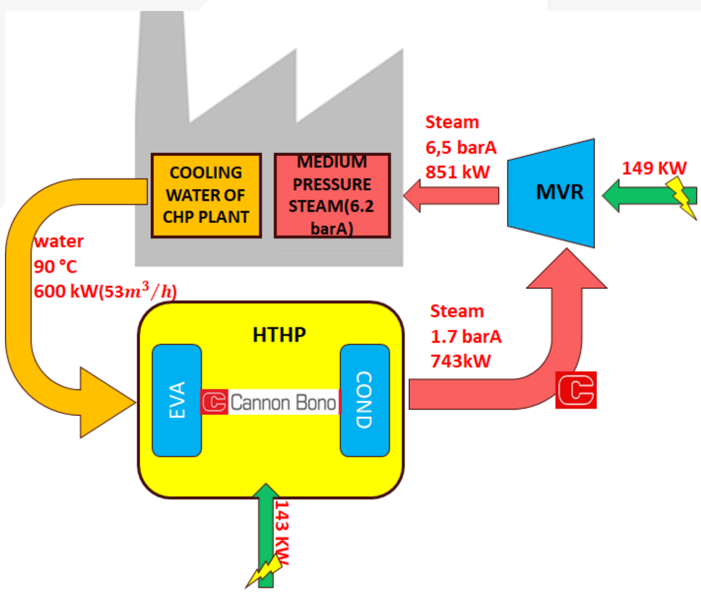

Figure 8: Schematic of heat pump integration as per initial concept.

By doing so, it will be possible to integrate the generated steam into the medium pressure collector, which is the one serving the paper machines. The heat source and sink requirements were slightly

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modified during the project in terms of pressure/temperature levels and flowrate. These modifications are illustrated in Section 2.4 and Section 2.5. A basic description about the deaerator used in the plant is provided in section 2.5.2. The heat pump utilized in Demo Site 2 will be manufactured by CANNON BONO, employing the environmentally friendly refrigerant R1233zd(E). The predicted COP of the heat pump is approximately 5.2 and the total calculated COP of the system (HTHP+MVR) is about2.93.

2.4 Analysis of potential heat source

As explained in the sections above, waste heat source is derived from the cooling water of the three engines of the CHP plant, that are shown in Figure 7.

Figure 9 provides some insights regarding the thermal power derived from the cooling water of engine 1. In fact, the graph reveals the share of thermal power recovered in HE1 (Q_Hex 1) and the dissipated thermal power in DC1 (Q_DC1) for the period between 01/09/2022 and 01/03/2023, that is the coldest period of the year, when engine combustion air pre-heating is needed and CDG district heating turns on. These values have been derived from the measured historical data of BEG, consisting of temperature measurement of all the numbered points of Figure 7 and water flowrate of points 1, 2, and 3. Therefore, one can easily calculate the heat duty of HE1, HE2, HE3, DC1, DC2, and DC3 with a simple energy balance. It is noteworthy that these data are stored with a sampling time of 13 seconds. It can be noticed from Figure 9 that by passing from the hot months towards the cold months of the year the share of HE1 increases and consequently the one of DC1 decreases as the combustion air needs to be pre-heated and the heating system of CDG turns on. A similar situation occurs if these calculations are repeated on HE2 and HE3.

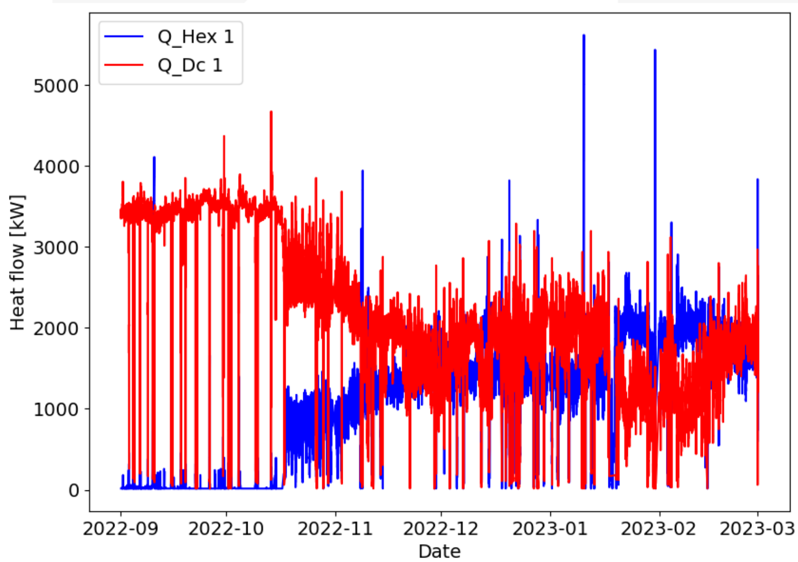

Figure 9: Heat flow of the primary Heat Exchanger (HE1) and Dry Cooler (DC1) of Engine 1

Three possible scenarios for heat extraction have been evaluated, and they will be described in the following:

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Scenario 1

The first solution is to install a heat exchanger on the primary cooling loop of one of the engines and prioritize functionality of this engine in order to guarantee maximum running hours for the heat upgrade system. This solution is applied exemplary to the primary loop of M1 in Figure 10. This option is constrained by the functionality of one engine, both from operating hours and load point of view. In fact, HE1, HE2 and HE3 are sized to transfer 2 MW each and almost 1.5 MW of this heat is needed in the cold season to pre-heat the combustion air of each engine in A-M1, A-M2 and A-M3 respectively. Because of that, extracting the amount of heat needed for the heat pump evaporator from a single primary circuit before the HE may cause malfunctioning of the heat exchangers A-M1, A-M2 and A-M3. The modifications needed for this solution need to be checked with the owner of the engines. Another possible issue is that the primary cooling water can be contaminated with the fuel from time to time as a failure of the sealing of the engine's head and maintenance would be needed which would result in reduced operational hours for the heat upgrade system.

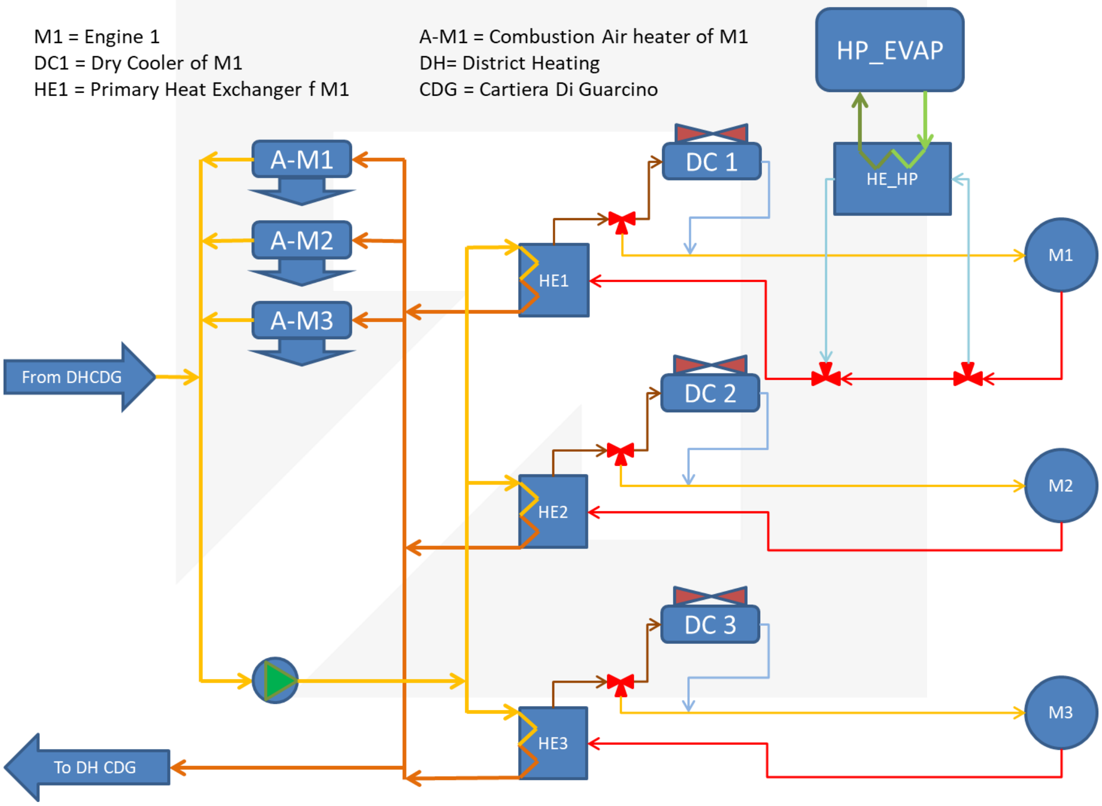

Figure 10: Schematic of waste heat extraction applied on the cooling water circuit of M1

Scenario 2

The dependency of the heat pump on a single engine can be solved by the second scenario that is shown schematically in Figure 11.

In this case, the heat pump is hydraulically connected with all the primary circuits through a heat exchanger.

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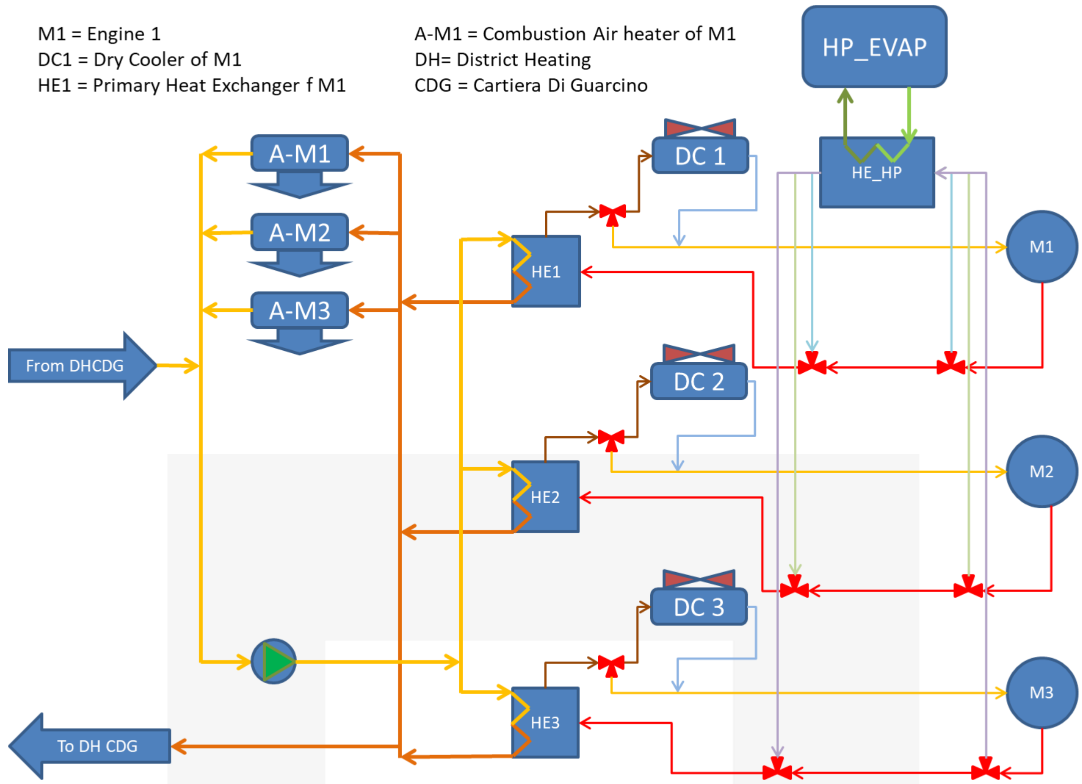

Figure 11: Schematic of scenario two for waste heat extraction

While being more flexible, this solution can be much more complicated from a control and cost point of view, which makes it less feasible. Thus, this solution is not followed by the partners involved.

Scenario 3

The third solution is shown in Figure 12. It is simpler to implement as there is no need to make major changes to the existing system of the cooling circuits of the engines. The secondary hot water that goes to CDG for heating purposes will be divided into two branches and one part will supply the evaporator of the HP directly, while the other portion will continue to serve the district heating system, as in the current configuration.In this scenario, one should check whether the three primary heat exchangers (HE1, HE2 and HE3) are sized sufficiently to deliver the additional 1.3 MW of heat that is needed for the heat upgrade system of Demo 2 and the AHT of Demo 3 or not. The amount of heat necessary for the heat pump evaporator (Demo 2) is equal to 0.6 MW, while for the AHT of Demo3 0.7 MW are required.

Among the partners involved, this scenario has been chosen as most suitable for the integration of a heat pump in CDG.

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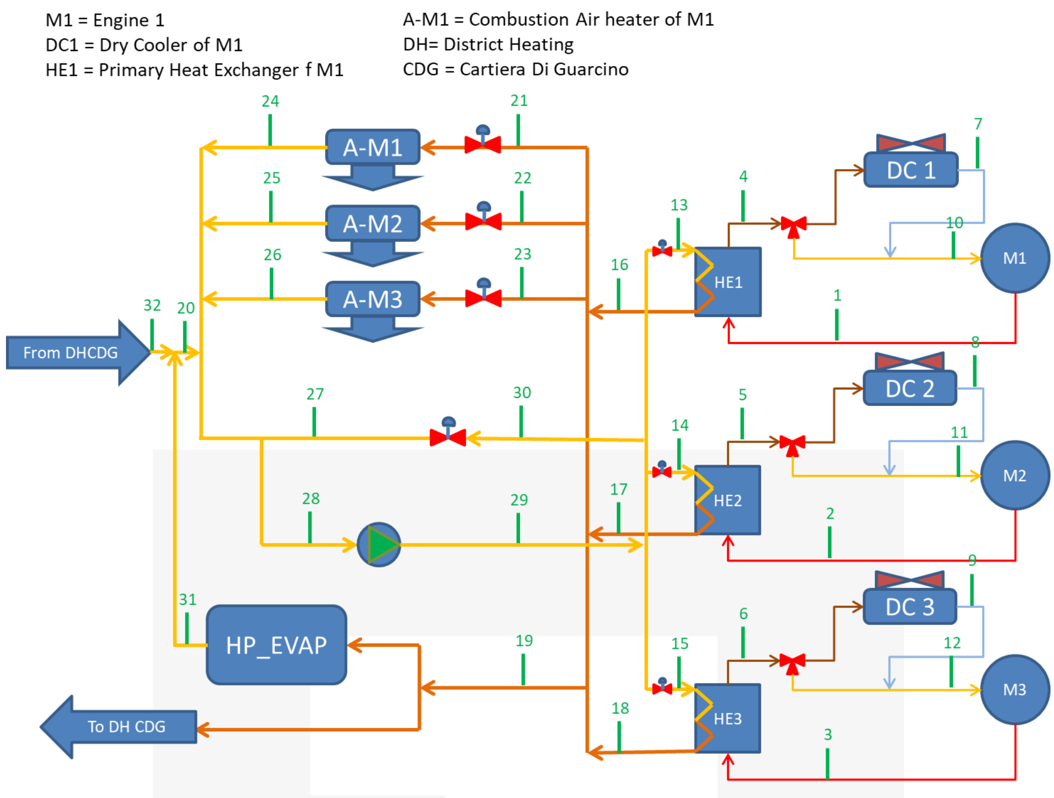

Figure 12: Schematic of scenario three for waste heat extraction

During the hot period of the year, when the ambient temperature is high, the three flow control valves (points 21, 22, and 23 in Figure 12), that are being controlled by the air outlet temperature, are almost closed as there is less need for air preheating. Also, the district heating request is very low in this period, hence HE1, HE2, and HE3 transfer a small amount of heat from the primary to the secondary circuit. Therefore, most of the heat derived from the engine cooling water is being rejected to the ambient by the three Dry-Coolers, thus the availability of waste heat is sufficient for both Demo 2 and Demo 3. The situation is shown in Figure 9 for the days up to 15th October for HE1 and DC1, and a similar pattern is followed by HE2/DC2 and HE3/DC3. From 15th October till almost mid-January, the thermal power transferred in the heat exchangers remains around 1MW, as shown in Figure 9, that is half of the maximum capacity of each heat exchanger. Starting from mid-March, the share of exchanged heat by HE1, HE2, and HE3 reduces again below 1 MW each which means that, apart from the period between 15th January to 15th March, the three heat exchangers together can guarantee at least 3 MW of waste heat to the secondary side.This amount of heat is more than what is overall necessary for the heat pump evaporator (0.6MW) in Demo2 and the AHT of Demo3 (0.7 MW). Therefore, one can calculate the minimum operating hours of the heat pump (availability of the waste heat) as follows:

$$OH_{HUT} = \sum_{15\ Mar\ 2022}^{15\ Jan\ 2023} \max\left(\frac{OH_{E1}}{day}, \frac{OH_{E2}}{day}, \frac{OH_{E3}}{day}\right)$$

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Which results in almost 7000 hours per year. Figure 13 demonstrates the sum of energy transferred from primary to the secondary side in the three heat exchangers (HE1, HE2, HE3) as well as the sum of the dissipated energy in the three dry coolers (DC1, DC2, DC3) in the months September 2022 until February 2023.

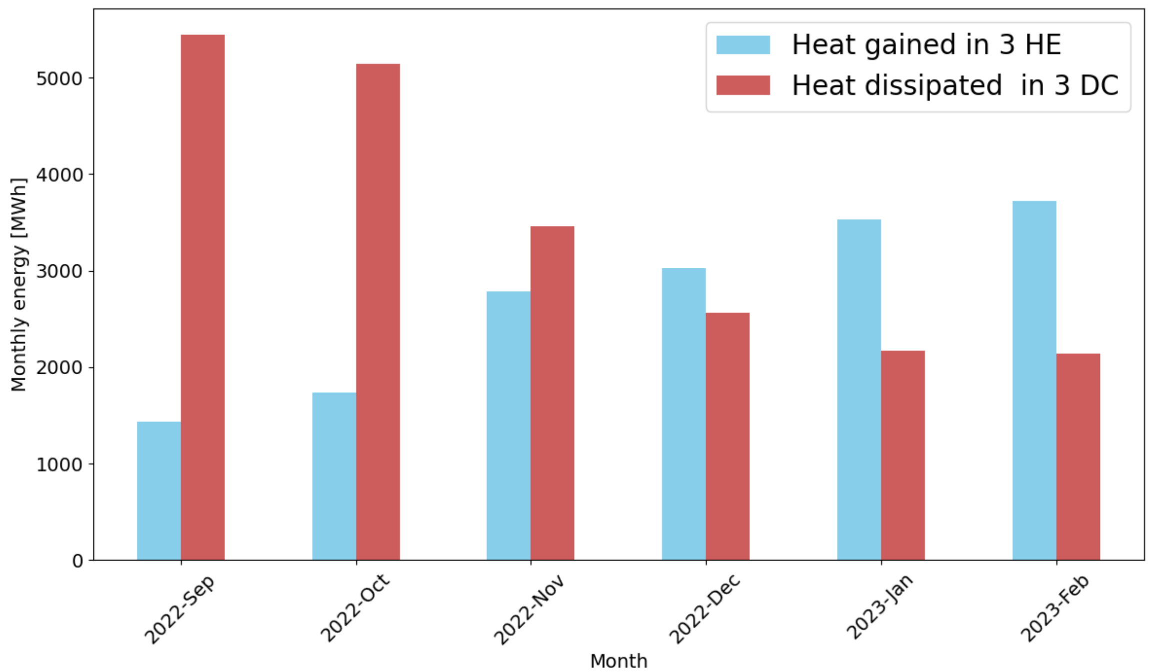

Figure 13: The total monthly energy dissipated by the dry coolers (DC1, DC2, DC3) and recovered by the heat exchangers (HE1, HE2, HE3)

As it can be noticed, even for the mentioned critical months (January and February 2023) the 3 dry-coolers dissipate about 2100 MWh monthly, which corresponds to an average value of 2.91 MW, considering an operational time of 720 h per month. This indicateshat additional heat is available to be transferred to the secondary side. In order to increase the amount of heat transferred from the primary to the secondary circuit, and thus the operational hours of the heat pump, a solution has been identified. This solution requires the replacement of the existing heat exchangers HE1, HE2 and HE3 with others with larger capacity (e.g. 2.7 MW each), able to guarantee the full operation of both HUT all the yearlong by transferring the needed 1.3 MW to the secondary side and thus to the HP and the AHT even in the case of one engine being off for repairment or lack of operating permission. Therefore the consortium decided to upgrade the three heat exchangers from 2 to 2.7 MW and guarantee maximum full load operation for both technologies, Demo 2 and Demo 3.

2.5 Heat sink requirements

In this chapter the requirements of the heat sink are analyzed in terms of steam flow rate and pressure level. The heat pump is characterized by two heat sinks, which are distinguished in terms of pressure level:

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- The main steam collector of the plant acts as the produced steam sink
- The deaerator acts as the produced hot water sink

The two heat sinks will be described below.

2.5.1 Steam sink

The steam sink of the HUT is the main steam collector of the plant, which works at a pressure of 6.5 bar(a). This collector is currently supplied by steam produced by the boilers and by the HRSG of the CHP plant. As indicated in Section 2.2.1, around 23 t/h of steam at 6.5 bar(a) are used inside the two paper machines (PM1 and PM2), divided in 13 t/h consumed by PM2, while around 10 t/h by PM1. The machines PM1 and PM2 work almost at full load throughout the year, apart from two maintenance weeks, one in August and one in December each year. This results in a theoretical operation time of 8424 h/a. Further, the machines may have to stop due to problems in one of the subsections or for a change in production that can further reduce the operation time. However, even in those cases, the steam consumption of one machine stabilizes at about 30 % of the nominal consumption to maintain the temperature in the production parts. It is rare that both paper machines go out of operation at the same time. In the scenario where PM2, i.e. the machine with the higher steam demand, is out of operation, the steam required by the plant is still about 14 t/h. This consideration will serve as the basis for the heat pump integration with the sink, presented in Section 13.1 During the study of the plant process, it has been noticed that the pressure of the main steam collector can be reduced from 6.5 bar(a) to 6.2 bar(a) without affecting the operation of the paper machines. This allows the heat pump to reduce its supply temperature and pressure level, enhancing the performance, and thus it was considered as a design parameter for the heat pump.

2.5.2 Hot water sink

The hot water sink of the HUT is the thermal deaerator of CDG which is a tray type one. A simplified representation is given in Figure 14. A vertical dome section is mounted on the horizonal storage vessel. The feedwater inlet is usually in the upper part of the dome, while deaerator steam comes from the bottom of the vertical section. A set of perforated trays is placed inside the dome and helps to increase the performance of the crossflow of the two fluids, making the contact time longer. This way the steam strips the oxygen from water and then exits from a vent on the top.

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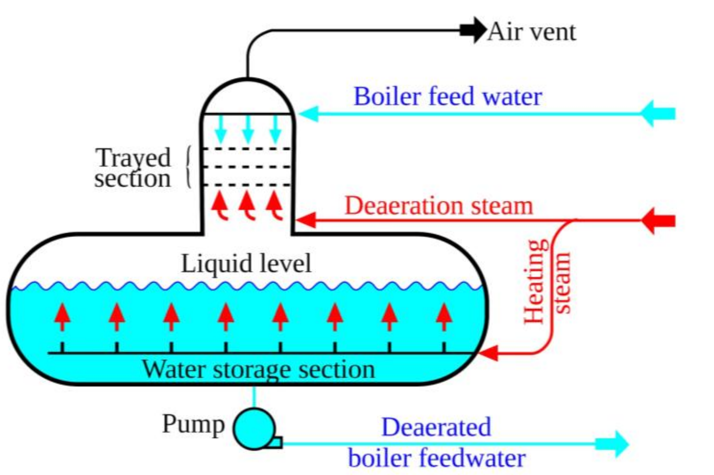

Figure 14: Simplified representation of a tray type deaerator

The water is collected inside the storage tank in the horizontal section: part of the steam is bubbled inside the tank through a sparger pipe. As in most industrial applications, CDG uses saturated steam coming from the low-pressure header. Oxygen scavenging from water requires at least 100 °C, so usually steam is used at slightly higher temperature. In CDG the working pressure of the deaerator is 1.2 bar(a) (105 °C). Currently, the 6.5 bar(a) steam that is being used for deaeration is expanded through a pressure reduction valve. The colder is the feed water getting inside the deaerator, the higher will be the steam needed for deaeration. Therefore, the 105 kg/h of saturated water at the outlet of the MVR will get mixed with the feed water to increase its temperature and brought back to the deaerator to reduce the steam needs.

3.Preliminary planning and basic engineering

3.1 Process integration of Heat Upgrade System

As clarified above, the heat pump will generate steam at an intermediate level which will then be upgraded by an MVR. The intermediate-pressure steam will be generated using the heat pump condenser which is designed to produce 1180 kg/h of saturated steam at 1.7 bar(a). This steam will be upgraded and fed to the steam header at 6.2 bar(a) using an MVR. Approximately, 235 kg/h of saturated liquid at 105 °C is derived from the deaerator and injected into the steam line at the suction side of the MVR (point 5 in Figure 15). Of this flow rate, 130 kg/h is evaporated through the

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compression process inside the MVR, while the remaining 105 kg/h exits as saturated water at 6.5 bar(a) (point 7). Therefore, the final steam production at the outlet of MVR will be 1310 kg/h at 6.5 bar(a) corresponding to a saturation temperature of 162 °C (point 8). Figure 15 shows a schematic representation of the heat pump coupled with the MVR, distinguishing between the vapor and liquid fluid states, whose properties can be found in Table 3.

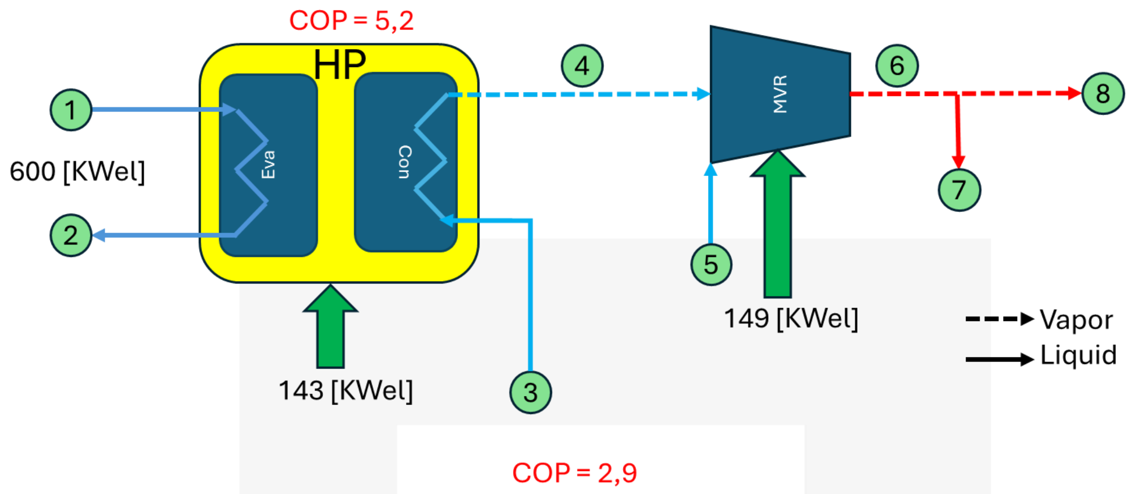

Figure 15: Heat pump and MVR schematic representation.

Point	Fluid	Mass flow	P	T	Vapor quality
-	-	[kg/h]	bar(a)	°C	-
1	H2O(Engine)	51433	3.0	90.0	0.00
2	H2O(Engine)	51433	3.0	80.0	0.00
3	H2O(Deaerator)	1180	1.7	104.8	0.00
4	H2O(Vapor)	1180	1.7	115.0	1.00
5	H2O(Liquid)	235	1.7	104.8	0.00
6	H2O(Vapor)	1415	6.5	162.0	0.93
7	H2O(Liquid)	105	6.5	162.0	0.00
8	H2O(Vap)	1310	6.5	162.0	1.00

Table 4: State points of the states reported in Figure 15

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Figure 16 provides a schematic representation of the heat upgrade system of Demo 2.

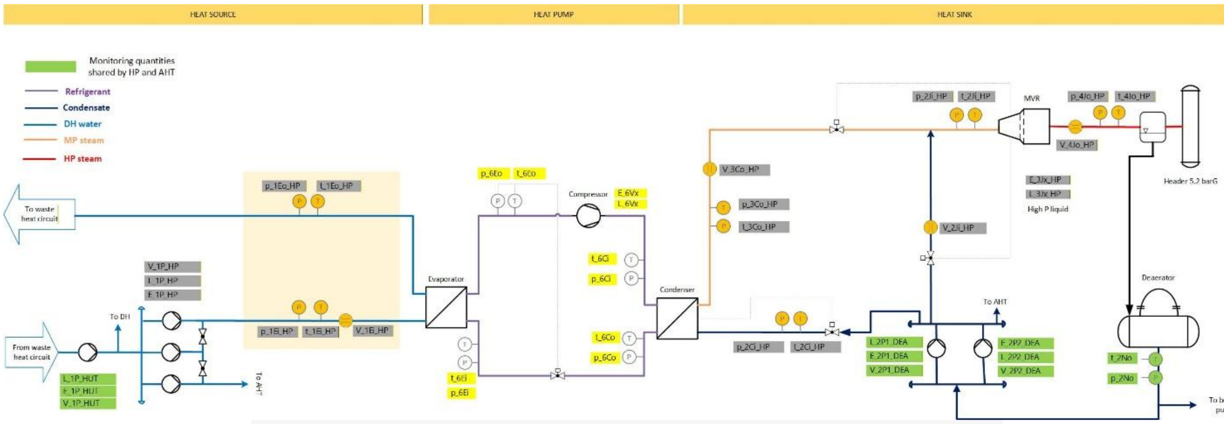

Figure 16: P&ID of HP and MVR integration

The heat pump, MVR and the heat sink circuits will be located on the ground floor of a building that collects all the heat utilities of the production site ("Steam distribution site" in Figure 2). The heat source circuit, instead, will span from the heat pump location to the waste heat source location ("CHP plant" in Figure 2).

The DH line today provides the energy used to heat the offices of the site. A new pipeline is foreseen to connect the heat source to the heat pump of Demo 2 and AHT of Demo 3. The connection line will provide around 120 t/h of water at a temperature of 90 °CC. The proper sizing is set for a 6 " line, to keep the average flow velocity lower than 1.5 m/s and to minimize the overall pressure drop, which is expected to be around 0.4 bar. After flowing through the evaporator, the water is returned to the main line circuit

The heat sink circuit consists of a pipeline connectingthe condenser of the heat pump to the MVR, and from the MVR to the medium pressure steam header, as shown in Figure 16.. The two systems combined produce 1 415 kg/h of steam at 6.5 bar(a). The steam at the outlet of the MVR has a vapor quality of about 0.93. The upgraded wet steam enters in a separator where it is split into two streams:1 310 of dry steam, directed to the process steam header, set at 6.2 bar(a) and 105 kg/h of saturated water at 6.5 bar(a), which issentto the deaerator.

3.2 Design parameters for the Heat Upgrade System

Considering the performed analysis described in previous sections, the design point of the Heat Pump is summarized in the following tables.

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Heat source circuit, connected to the evaporator:

Parameter	Unit	Value
Fluid	-	Water with 0 to 20% glycol in mass
Inlet temperature	°C	90
Outlet temperature	°C	80
Inlet pressure	bar(a)	3.0
Mass flow rate	kg/h	53 300
Nominal heat	kW_{th}	600

Table 5: Design point of the heat source circuit

Steam sink circuit, connected to the condenser:

Parameter	Unit	Value
Fluid	-	Inlet: Liquid water Outlet: Saturated steam
Inlet temperature	°C	105
Outlet temperature	°C	115
Inlet pressure	bar(a)	1.8
Outlet vapor quality	-	1.0
Mass flow rate	kg/h	1 180
Nominal heat	kW_{th}	740

Table 6: Design point of heat pump's heat sink

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Heat sink circuit for the MVR:

Parameter	Unit	Value
Fluid	-	Inlet: Saturated steam Outlet: Saturated steam & water
Inlet temperature	°C	115
Outlet temperature	°C	162
Inlet pressure	bar(a)	1.7
Outlet pressure	bar(a)	6.5
Inlet vapor mass flow rate	kg/h	1180
Inlet liquid mass flow rate	kg/h	235
Outlet vapor quality	-	0.926
Outlet mass flow rate	kg/h	1415

Table 7: Design point of the MVR's heat sink circuit

The heat pump that will be installed in CDG will be manufactured by Cannon Bono. Its main characteristics are summarized in Table 8.

Parameter	Unit	Value
HP Compressor type	-	Screw
Refrigerant employed	-	R1233zd(E)
Electricity consumption of Heat Pump	kW_{el}	143
Electricity consumption of MVR	kW_{el}	149
Coefficient of performance of Heat Pump (COP_{el})	-	5.2
Coefficient of performance of overall system (COP_{el})	-	2.9

Table 8: Design parameters for the heat upgrade system by Cannon Bono

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3.3 Layout of installation site

The waste heat source (i.e. the CHP plant) is about 60 m far from the installation site of the Heat Pump. Scenario 3 exploits the already existing rack and the pipeline that brings hot water to the district heating of CDG, thus length of the additional pipeline needed to connect the heat source to the evaporator will be around 5m. The hot water sink (i.e. deaerator) is situated approximately 25 m away from the HP, whereas steam heat sink is positioned roughly 6 m from the MVR outlet. For what concerns the installation area, the heat pump and the MVR are going to be positioned on the ground floor, as highlighted by the green area in Figure 17 and Figure 18.

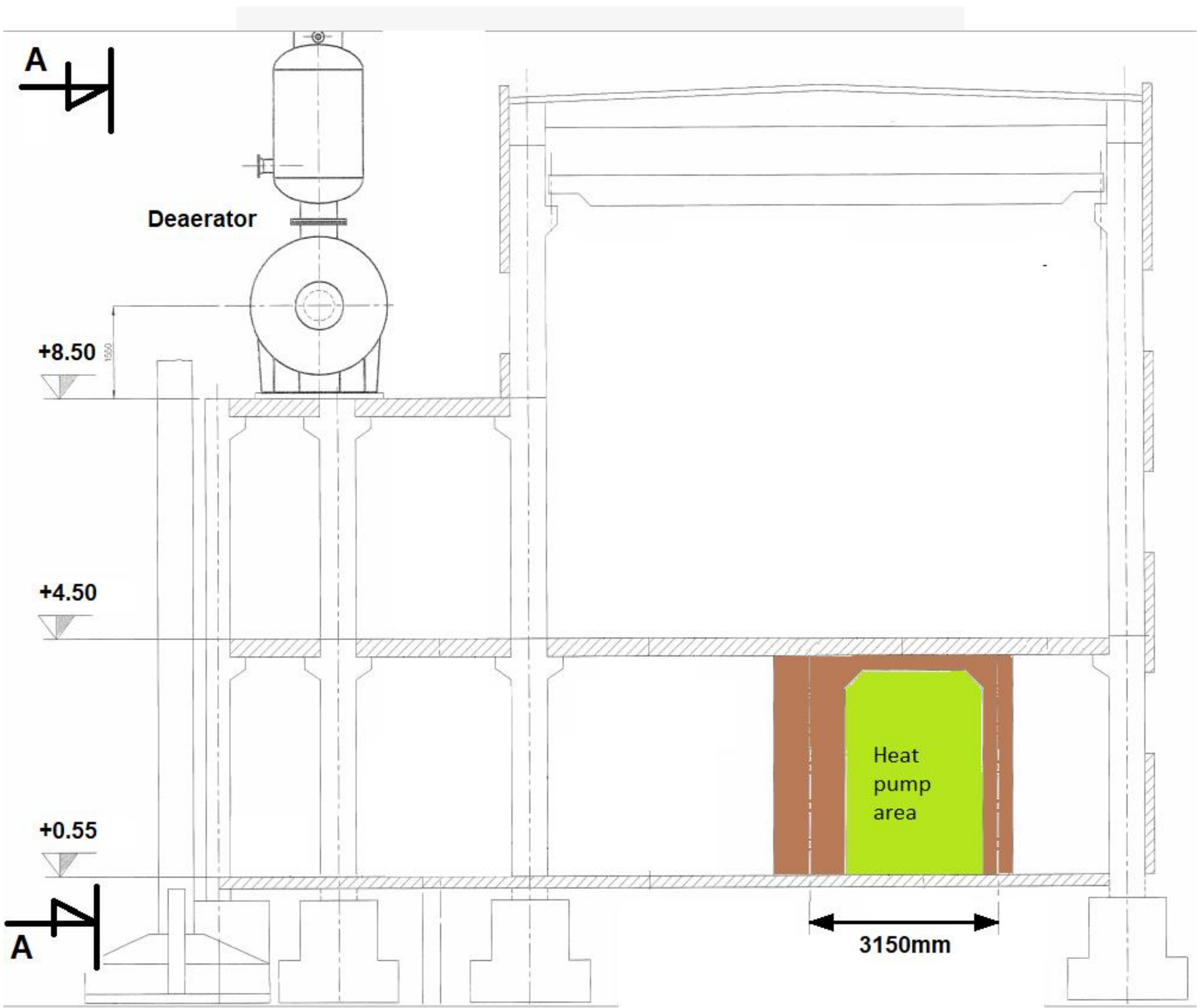

Figure 17: Heat pump installation area section B-B view

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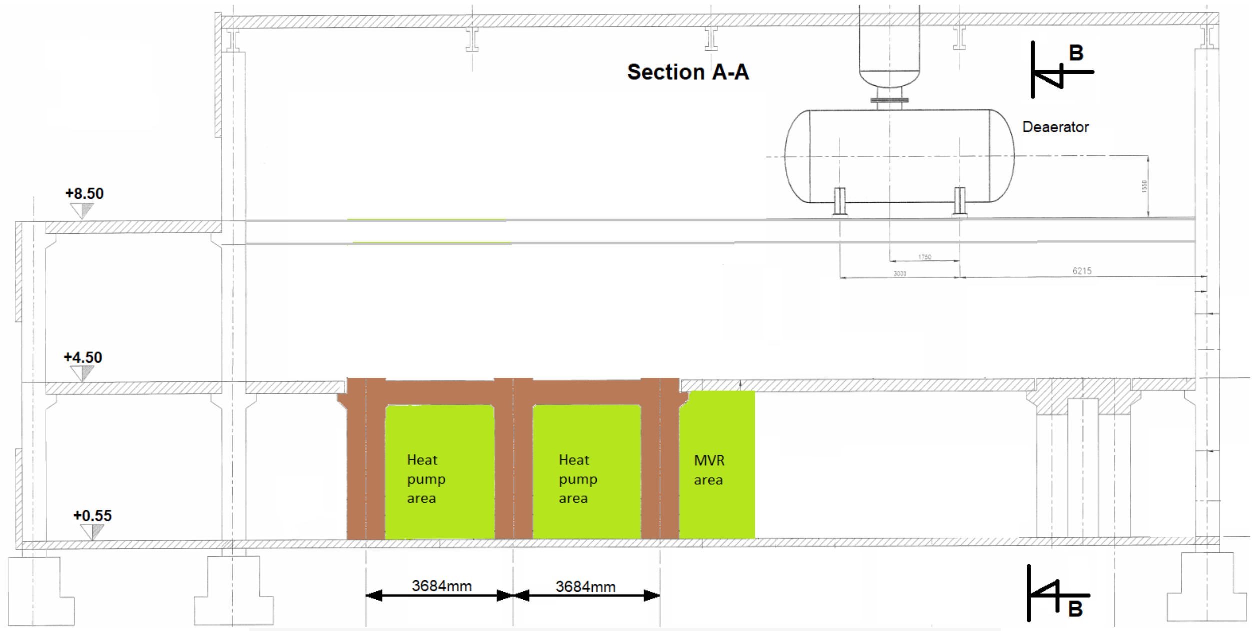

Figure 18: Heat Pump installation area section A-A view

The available height is about 3.65 m, of which around 3.3 m can be utilized since there are some under roof existing piping. The heat pump is 2.2m high and therefore there is no physical constaint in locating the HP in the proposed position. The identified location of the heat pump is the most suitable because it is close both to hot water sink (deaerator on +8.50 m level) and steam heat sink (6.2 bar(a) steam header on the same level), as shown in Figure 19. The heat pump and MVR are located on the bottom left side of the Figure 19.

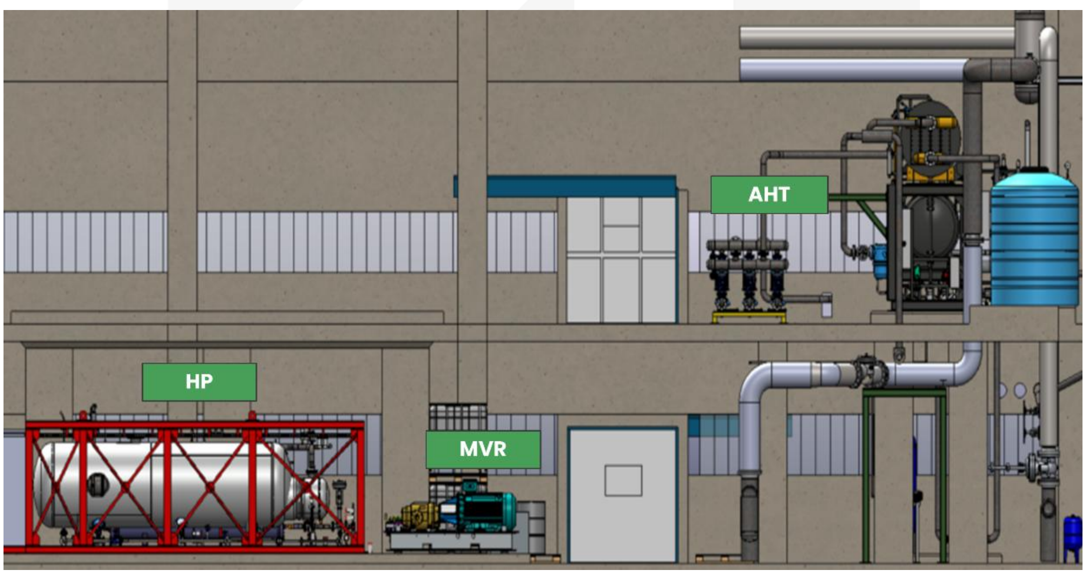

Figure 19: heat pump and MVR layout position in CDG.

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3.4 Control concept and control integration

This section describes the control strategy of the heat upgrade system to be installed in Demo 2. The objective of the control system is to ensure stable, efficient, and reliable operation of the heat pump, maintaining the required operating conditions on both the heat source and heat sink sides.

The following subsections detail the control approaches adopted for the three circuits that are connected to the heat upgrade systems, i.e. the heat source, the hot water sink, and the steam sink circuits.

A. Heat source control:
   Referring to Figure 16, the total extracted heat from the heat source can be measured with combination of two temperature sensors (at the inlet and outlet of the evaporator external circuit) and one flow meter, which will be placed at the outlet of the evaporator. These three elements are basically a virtual thermal energy meter (represented by the yellow area in Figure 16) that controls the pump of the evaporator circuit by controlling the inverter linked connected to it in order to guarantee the design load of the evaporator (600 kW).
B. Steam sink control:
   The heat pump steam outlet pressure is kept constant (1.7 bar(a)) by a PID controller on the pressure of the condenser which adequately adjusts the compressor's speed. On the other hand, the MVR's speed is adjusted in a way to keep the discharge pressure at 6.5 bar(a) so that the steam can flow in a steady state manner to the steam header that has a pressure of 6.2 bar(a).

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 CDG. To achieve this, the focus is on measuring the energy flows surrounding heat upgrade system. Specifically, data on the thermal energy supplied by the heat source and the thermal energy provided to the heat sinks will be gathered. In addition, electrical measurements of various components will be conducted, including the compressors, control system, heat source pumps, 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. The monitoring concept focuses not only on the heat pump, but on the whole system, including the mechanical vapor recompressor, the pumps of the primary circuits and the existing heat source (i.e. boilers and CHP plant) Moreover, the potential impacts of the heat pump 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.

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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. 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 temperature and pressure sensors to measure the heat generated by the heat source and the heat consumed by the heat sink and 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. 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 20 highlights the transfer of information and measurement data within the monitoring concept.

Figure 20: 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. All Datapoints which are gathered within the Push2Heat monitoring are listed in the data point list.

Monitoring protocol development consists of the following steps:

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1. Determination of measuring points based on the plant layout.
2. Selection of communication protocols to the Supervisory Control and Data Acquisition (SCADA) system and process control technology.
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 configured. The sensors undergo careful calibration and testing to ensure accurate measurements.
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.
5. Visualization of KPIs and plant parameters: Specific dashboards, charts, and graphs that present essential Key Performance Indicators (KPIs) and relevant plant parameters in an easily understandable format are created.

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.

4.Conclusion

In Deliverable 3.2 “Demonstration site at CDG – system design” the involved partners have undertaken a comprehensive exploration related to the installation of a high temperature vapor compression heat pump coupled in series with a mechanical vapor recompression (MVR) in Cartiera di Guarcino, a paper machine plant, conducting an analysis of the energy requirements of demo site and the basic engineering related to the installation of the system.

The potential heat source and sink of the heat pump were analyzed in depth.

The extraction of waste heat from the cooling circuit of the engines of the cogeneration plant of the demo site was identified as most suitable solution. A data analysis has demonstrated that the availability of the heat source strongly depends on the period of the year. Excluding the quarter January – March, a sufficient capacity to supply the heat pump was found to be available without introducing substantial modifications to the plant layout. An average availability of 600 kW of waste heat at a temperature of 90 °C was selected as a design parameter for the heat pump. If the existing heat exchangers were to be replaced with higher-capacity units, it would also be possible to exploit the additional waste heat available during the January–March period.

Two different heat sink circuits were identified. These are characterized by a pressure level of 1.2 bar(a) and 6.2 bar(a) respectively. The former connects water from the separator of the MVR to the deaerator of demo site, while the latter links the steam from the separator with the medium pressure steam collector. The nominal heating capacity of the overall system was calculated to be 854 kW, utilizing 292 kW of electricity.

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The design parameters of the heat pump have been assessed. This is characterized by a twin screw compressor employing the refrigerant fluid R1233zd(E). The location of installation has been selected with the aim of being close to both heat sinks, limiting the need for unnecessary long piping. The predicted COP is 2.9.

Eventually, a control concept has been defined. The purpose is to allow the heat pump to work at nominal load throughout most of the year.

Operational tests of the heat pump will be carried out in BONO in February 2026. Following the completion of these tests, the heat pump will be shipped to CDG, where system integration is scheduled to be finalized by the end of March 2026. This will be followed by the commissioning phase, planned for April 2026.

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