Push2Heat

D3.2

Demonstration site at CDG - system design

V0.6

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Prepared by: Gianluca Abrami, Tommaso Toppi

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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: Air preheater of engine 1

WH: Working hour

PM: Paper Machine

HRSG: Heat recovery steam generator

HUS: Heat upgrade system

COP: Coefficient of performance

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PARTNERS

Partner short name	Legal name	Role
POLIMI	POLITECNICO DI MILANO	Local site coordinator
BONO	CANNON BONO ENERGIA	System integration
ENER	ENERTIME	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 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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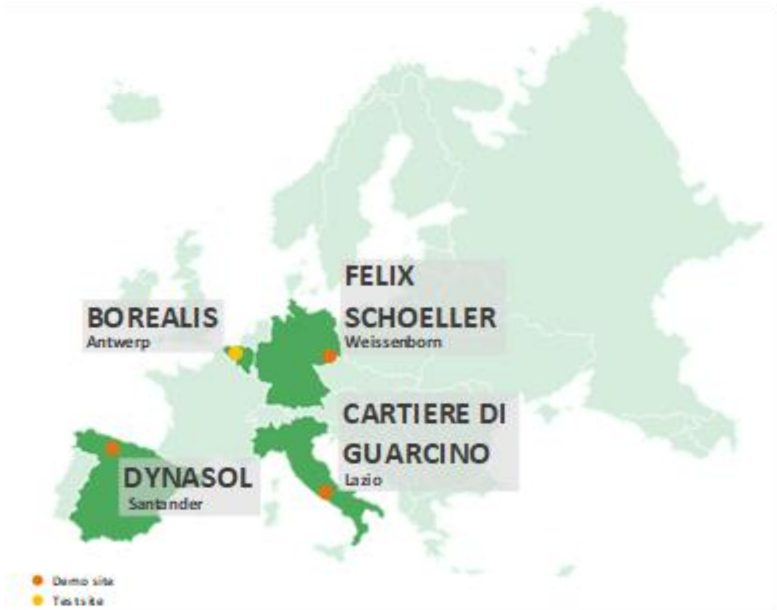

Figure 1: Heat upgrade systems in PUSH2HEAT

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

This report (deliverable D3.2) will focus on the results gained from analysing 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 installation. First engineering results undertaken among the involved partners will be presented and discussed.

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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 with turbocompressors). 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 analysing technical and infrastructural requirements in every operating system.

The involved partners and their role in Task 3.1 - Demo site 2 (Italy) are as follows:

- Cartiera di Guarcino (CDG): plant operator, support system integration.
- Bono Energia (BONO): demo site analysis and system integration.
- Enertime (ENER): heat pump manufacturer.
- Politecnico di Milano (POLIMI): demo site coordinator.

2.1 Overview of WP3 structure

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 products include Unicolor, Backer papers, 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

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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 nearby the plant and to maximize the production efficiency, to reduce the production cost as well as any paper waste.

2.1.1 CDG site layout

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.).

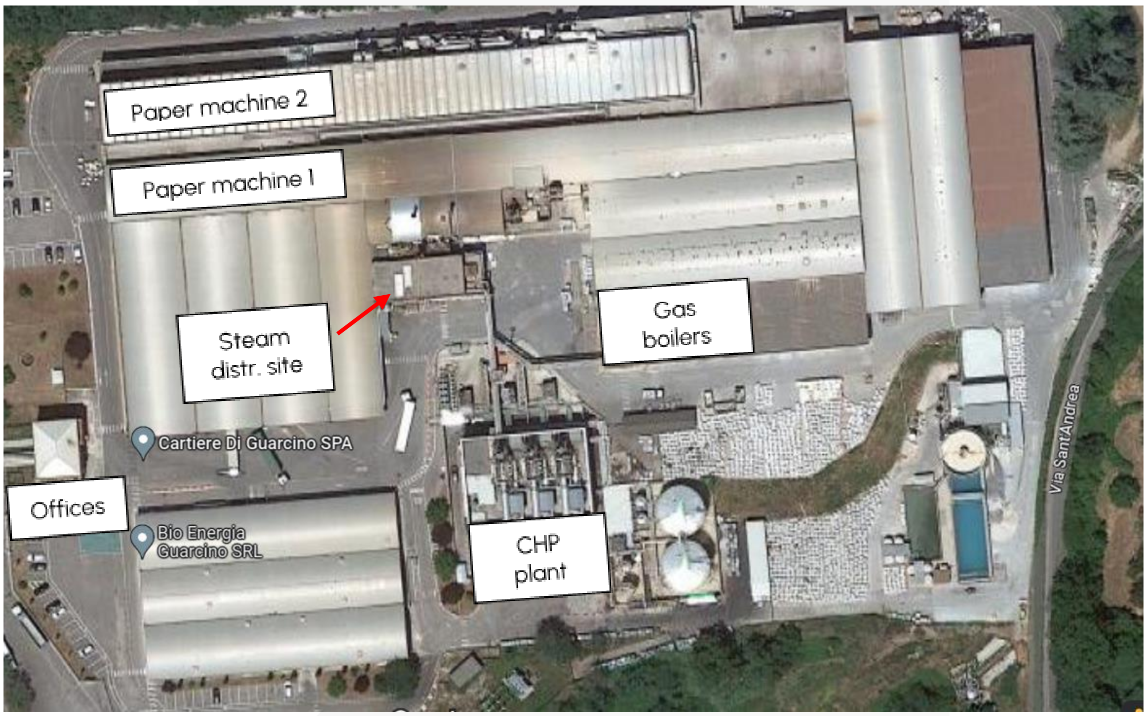

Figure 2: CDG and BEG aerial view

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 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 and 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 BEG to CDG for the period between 01/01/2022 and 25/06/2023.

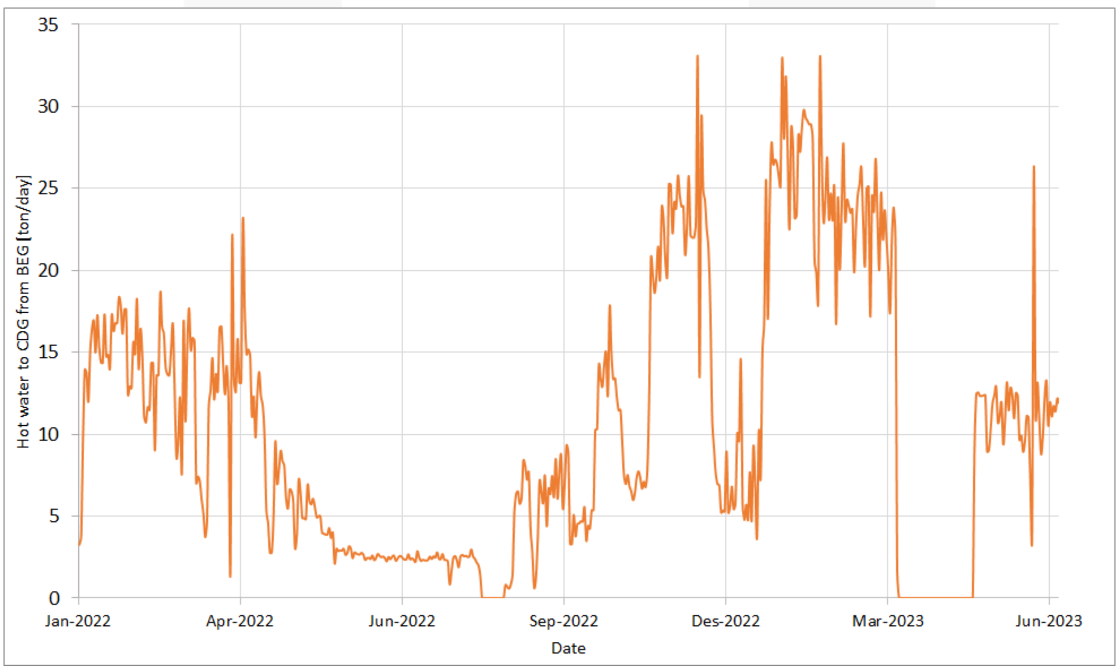

Figure 3: Hot water transferred from BEG to CDG for the period 01/01/2022 – 25/06/2023

As for CDG's electricity consumption, the plant typically consumes approximately 140 MWh per day, with nearly 100 % of this power being supplied by BEG, except for days when all the three

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engines of BEG are simultaneously out of operation. Figure 4 illustrates the daily electrical energy exported from BEG to CDG.

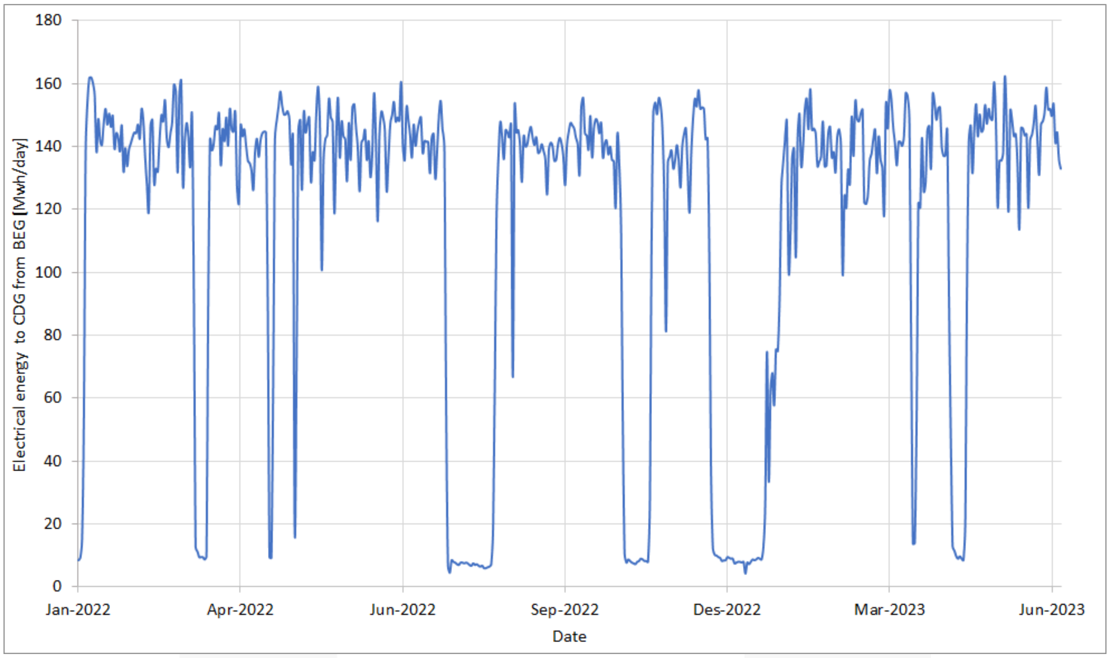

Figure 4: Electrical energy sold to CDG by BEG

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 13 t/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 fire 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/June/2023.

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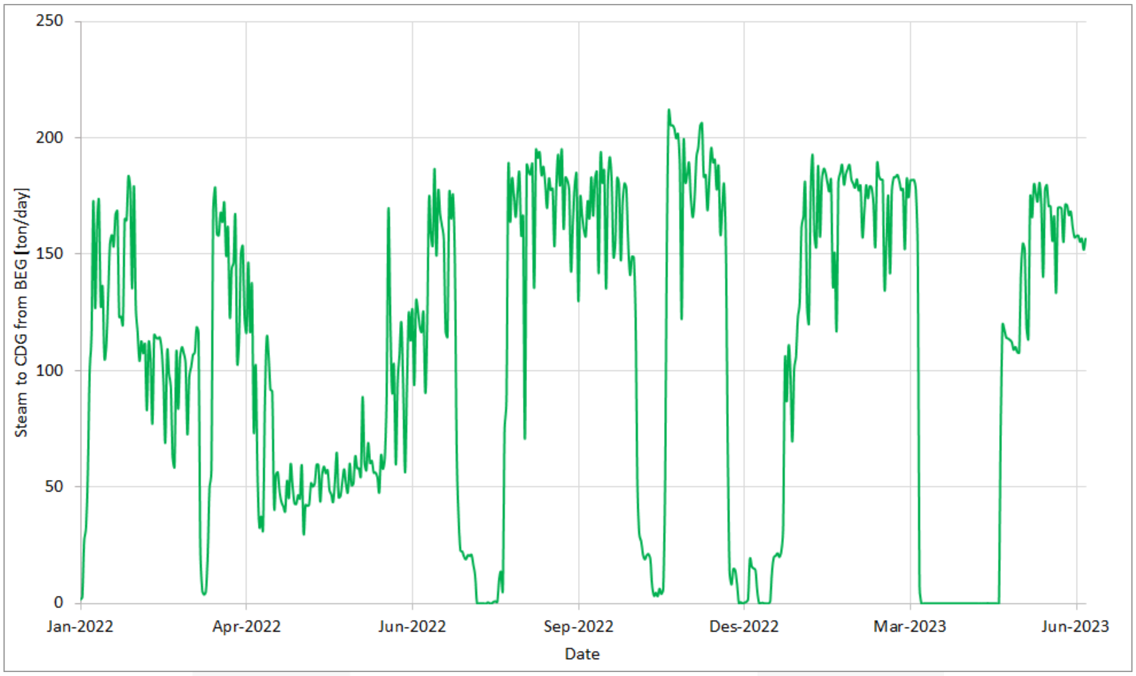

Figure 5: Steam transferred from BEG to CDG

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

Parameter	Unit	Value
Nominal capacity	t/h	15

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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 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 biomass 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. 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.

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

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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 (6.865 MW_{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 1 440 minutes (i.e. 24 hours) and the aim is to make the engine work at full load for 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.

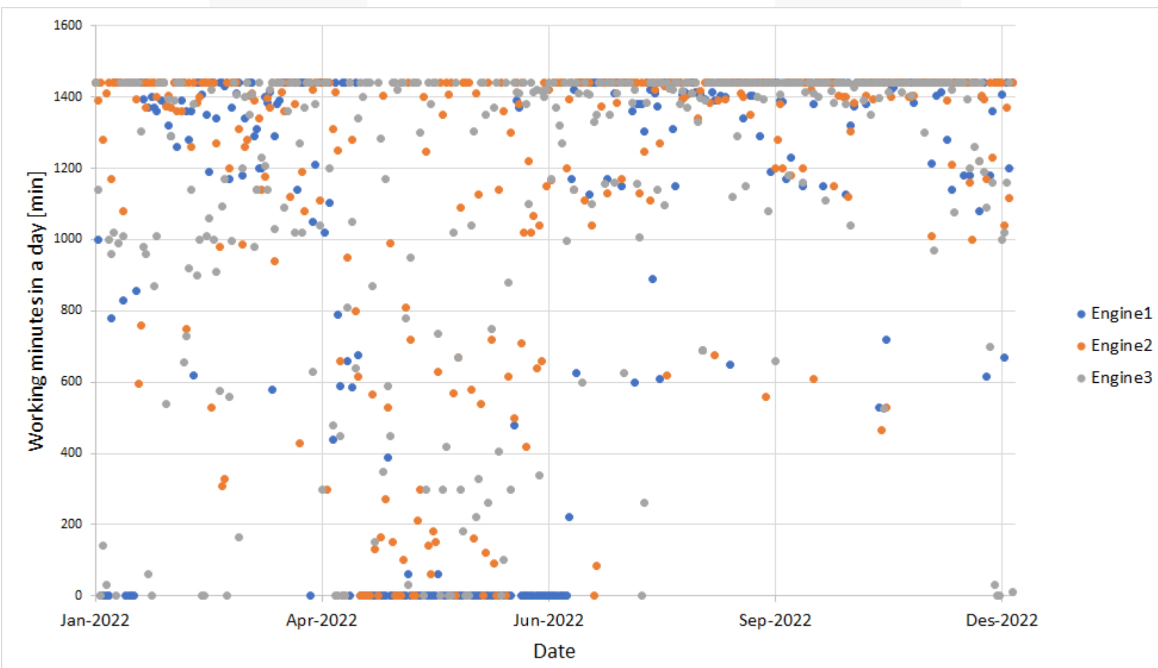

Figure 6: Daily working minutes of the three engines of the CHP plant in 2022

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

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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 HE are designed for 2 MW each, while the three A-M are dimensioned for 1.5 MW each.

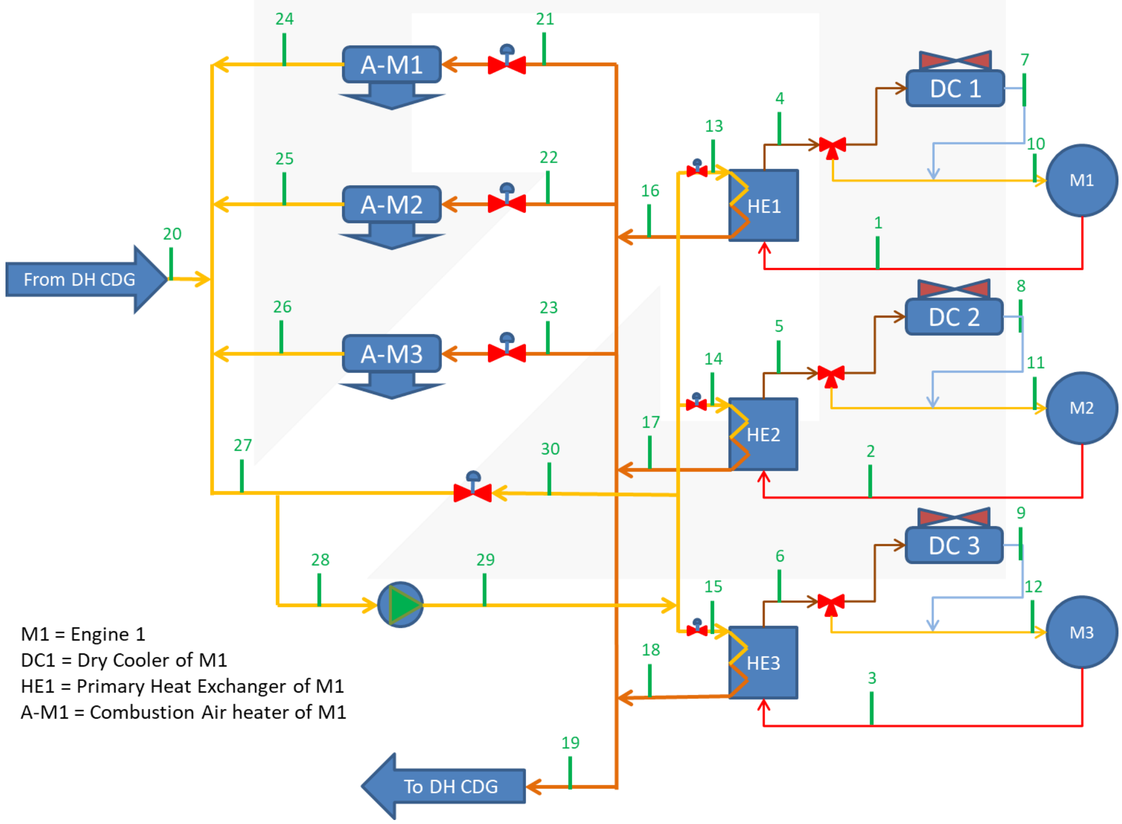

Figure 7: Schematic of water's cooling water circuit and its integration with the overall system

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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, three 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 a high pressure is justified by the need to keep the specific volume of the vapor high. 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.
- Low pressure = 1.8 bar(a). This corresponds to the pressure required by the vapor injected in the deaerator.

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 92-94 °C and 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 at the evaporator. Section 2.4 illustrates the different options that were evaluated for waste heat extraction.

Upgraded heat from the heat pump will be available in the form of steam at two different pressure levels:

- 3 140 kg/h of steam (2 042 kW) at 3.5 bar(a).
- 1 170 kg/h of steam (734 kW) at 1.8 bar(a).

The former will be generated within the heat pump's condenser, whereas the latter will be produced through the cooling process of the refrigerant in the subcooler.

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

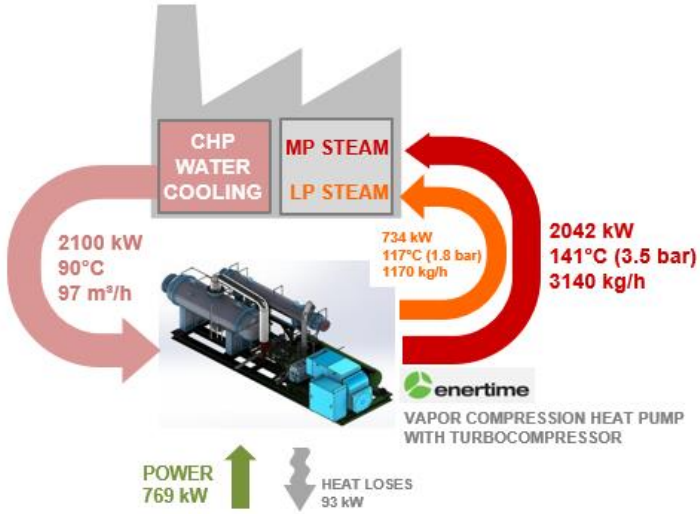

Figure 8: Schematic of heat pump integration as per initial concept

Moreover, a thermocompressor will be used to raise the pressure of the steam produced in the condenser from 3.5 bar(a) to 6.5 bar(a). By doing so, it will be possible to integrate the generated steam in the medium pressure collector, which is the one serving the paper machines. The 1.8 bar(a) upgraded steam, instead, will be delivered to the deaerator of the plant.

The heat source and sink requirements were slightly modified during the course of the project in term of pressure/temperature levels and flowrate. These modifications are illustrated in Section 2.4 and Section 2.5.

A basic description of a thermocompressor is provided in section 2.5.1 while details about the deaerator used in the plant are provided in section 2.5.2

The heat upgrade technology utilized in Demo Site 2 will be manufactured by ENERTIME, based on their high-temperature heat pump, featuring a two-stage centrifugal compressor, employing the environmentally friendly refrigerant R1233zd(E).

The predicted COP is approximately 3.6.

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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 power in DC1 (Q_Dc 1) 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.

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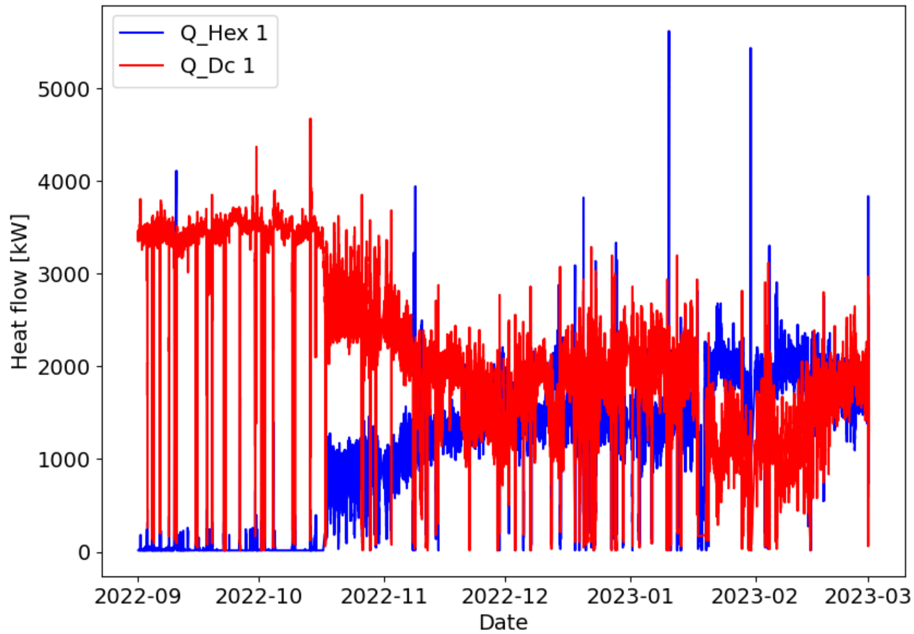

Figure 9: Heat flow of the primary Heat Exchanger (HE1) and Dry Cooler (DC1) of Engine 1

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

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 pump. This solution is applied 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 will be needed which results in a reduced operational hours for the heat pump.

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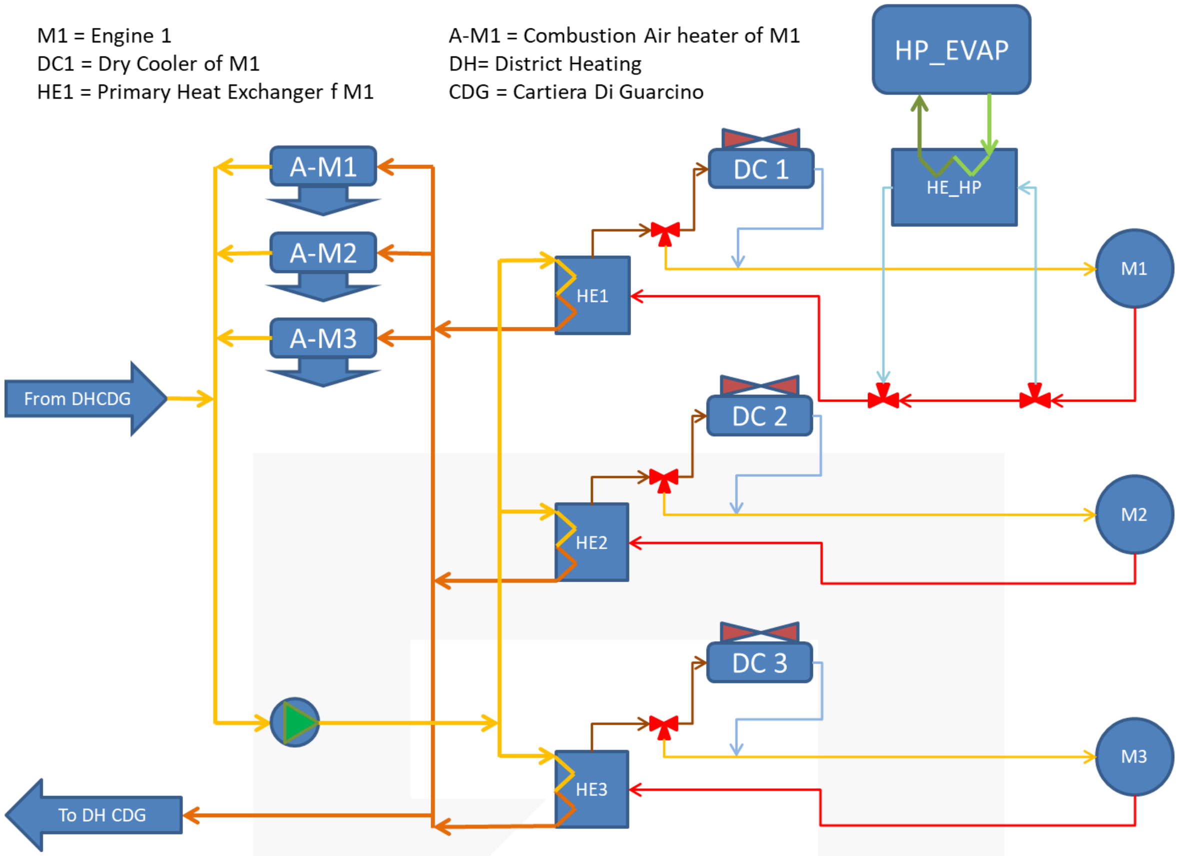

Figure 10: Schematic of scenario one for waste heat extraction applied on the cooling water circuit of M1

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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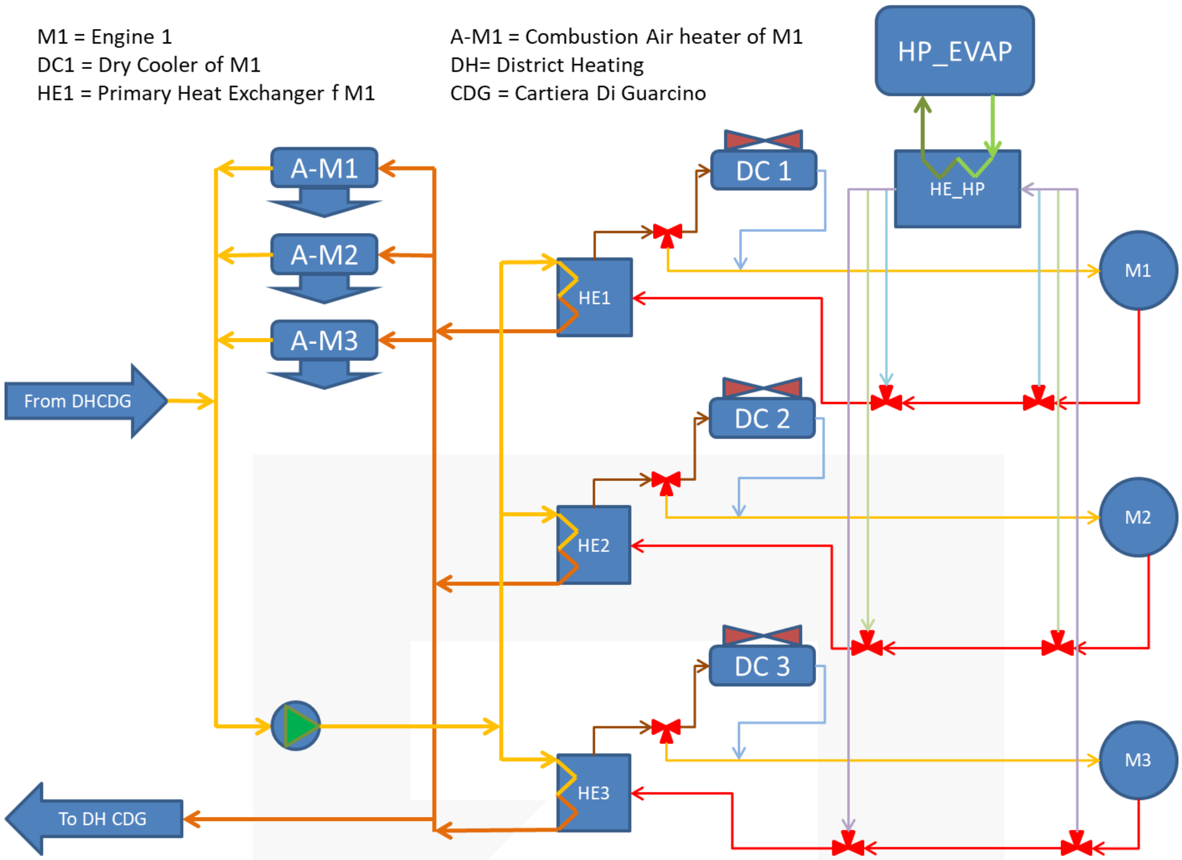

Figure 11: Schematic of scenario two for waste heat extraction

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 involved partners.

Scenario 3

The third solution is shown in Figure 12. It is simpler and easy 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 feed the evaporator of the HP directly. This avoids the need for additional piping that should have been installed in case of Scenario 1 and Scenario 2.

In this scenario, one should check whether the three primary heat exchangers (HE1, HE2 and HE3) are sized sufficiently to deliver the additional 2.1 MW of heat that is needed by the HP.

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

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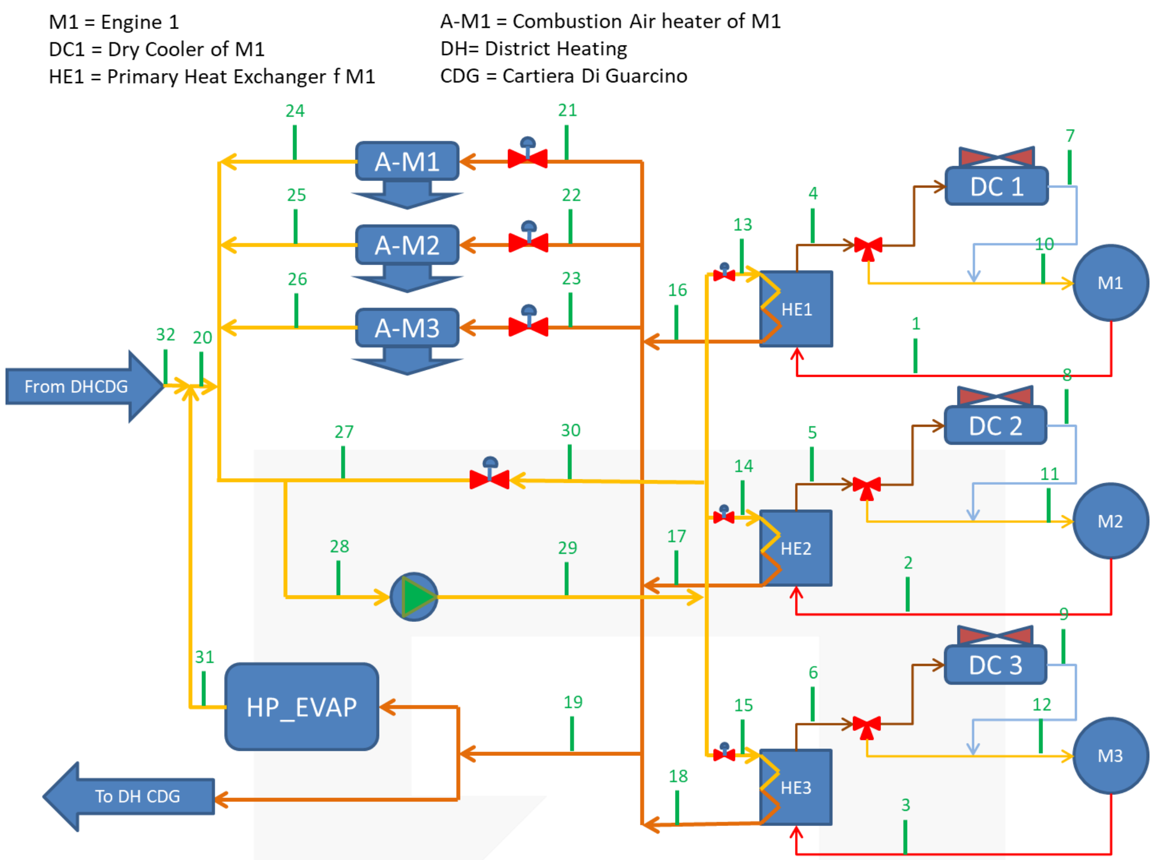

Figure 12: Schematic of scenario three for waste heat extraction

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. 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. It is noteworthy that from 15th October till almost mid-January, the transferred power remains around 1MW, 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 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 necessary for the heat pump evaporator (2.1 MW).

Therefore, one can calculate the minimum operating hour of the heat pump (availability of the waste heat) as follows:

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

Which results in almost 7 000 hours per year.

Figure 13 demonstrates the sum of energy transferred from primary to the secondary side in the 3 HE as well as the sum of the dissipated energy in the 3 DC in different months.

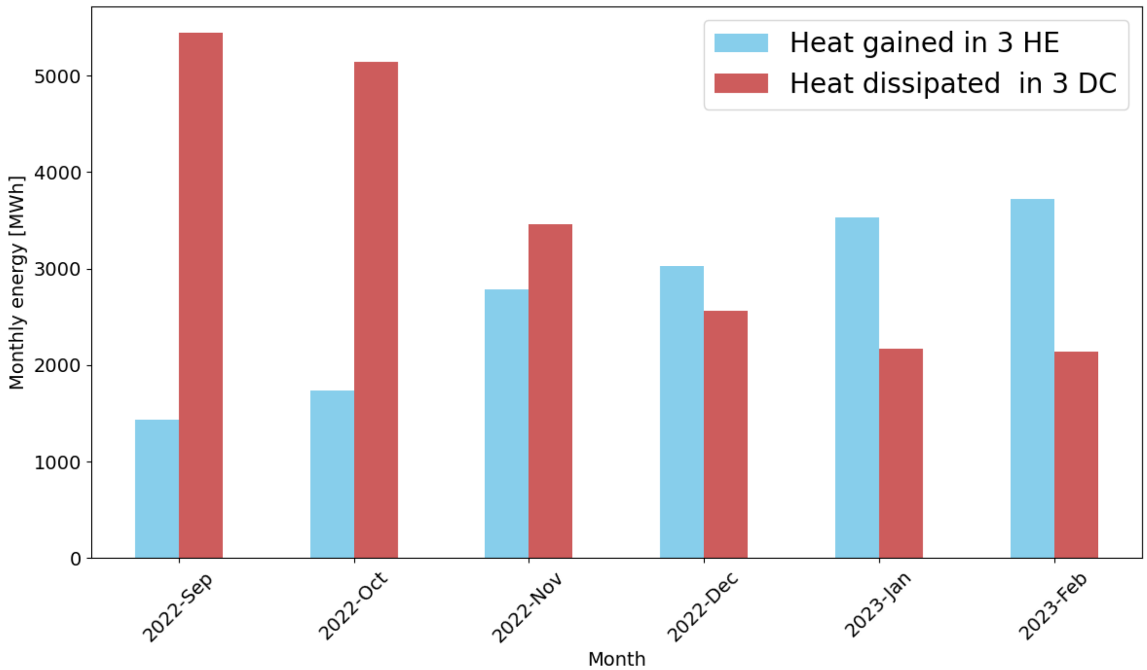

Figure 13: The total monthly energy dissipated by the 3 Dry-Coolers and recovered in the 3 Heat Exchangers

As it can be noticed, even for the mentioned critical months (Jan and Feb) the 3 Dry-Coolers dissipate about 2 100 MWh monthly, which corresponds to an average value of 2.91 MW, considering an operational time of 720 h per month. This implies that 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, two alternatives have been identified.

The first would require 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 additional 2.1 MW to be transferred to the secondary side and thus to the HP evaporator.

The second alternative, less expensive but also less effective than the first, would be to add an additional pump in parallel to the existing recirculation pump between points 28 and 29 in Figure 12. Benefitting of the fact that the existing HEs look oversized by about 15% from historical data,

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and increasing the flowrate of the secondary side of the three HEs, early calculation have demonstrated that around 900 kW of additional power could be transferred toward the secondary side. This additional heat could help the HP to operate closer to its nominal condition during the cold period. The flowrate of this additional pump will be controlled by the heat flow meter of the evaporator of the HP and it will not interfere with already existing system's functionality.

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:

- The main steam collector of the plant acts as the high pressure sink
- The deaerator acts as the low pressure sink

The two heat sinks will be described below

2.5.1 High pressure sink

The high-pressure sink of the heat pump 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 8 424 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 rarely 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 3.1

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

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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.

Thermocompressor

An anticipated in Section 2.3, a thermocompressor is used to upgrade the pressure level of the steam generated by the condenser. The main characteristic and the working principle of a thermocompressor for steam pressure upgrading is illustrated in this section, with reference to Figure 14

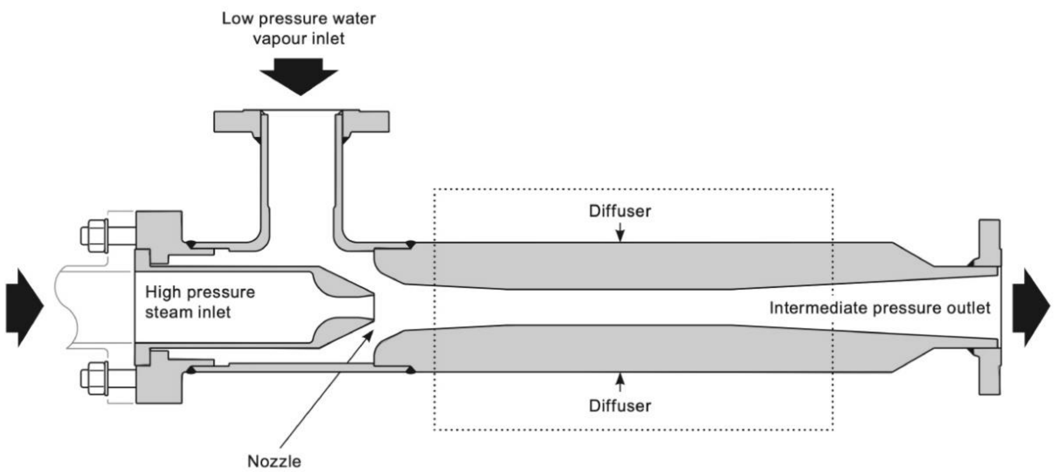

Figure 14: General layout of a thermocompressor for steam pressure upgrading

High pressure steam ("motive steam") is introduced in the thermocompressor through a nozzle, which increases the speed of the fluid, determining a low pressure region at the throat of the nozzle. Consequently, the low pressure steam is drawn in the system and entrained with the high pressure fluid. As the two streams mixes, they flow through the diffuser where the velocity of the mixture decreases while pressure increases. The result of the process is steam at an intermediate pressure between low and high pressure steam inlets. A precise actuator regulates the flow of the motive steam in order to obtain the desired outlet condition, minimizing the amount of necessary motive steam.

The thermocompressor that will be utilized in CDG is manufactured by Körting. The integration of the thermocompressor with the heat pump and with the overall system is described in Section 3.1.

2.5.2 Low pressure sink

The deaerator acts as the low pressure sink.

The thermal deaerator installed in CDG is a tray type one. A simplified representation is given in Figure 15.

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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.

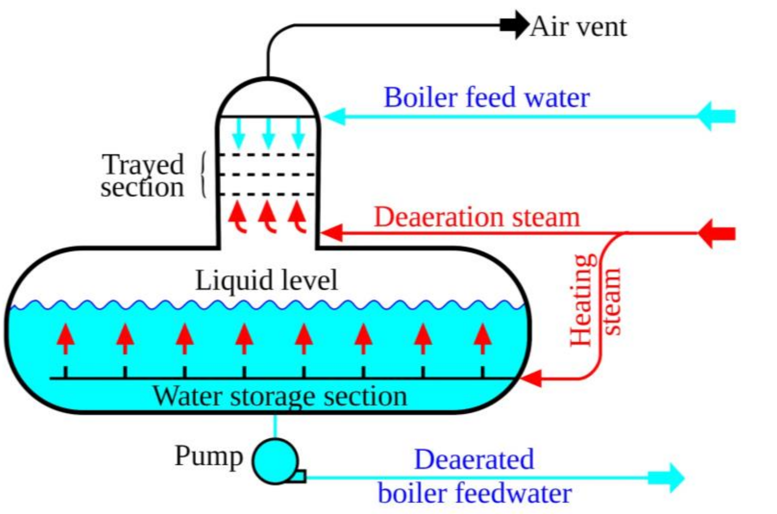

Figure 15: Simplified representation of a tray type deaerator

The water is collected inside the storage tank in the horizontal section: part of the steam is bubbled inside the tank throw 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, which is a waste of high-quality energy.

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3 Preliminary planning and basic engineering

3.1 Process integration of Heat Upgrade System

As clarified above, the heat pump will generate steam at two pressure levels

The high pressure steam will be generated using the heat pump condenser which will be designed to produce 3 t/h of saturated steam at 3.3 bar(a), This steam will be upgraded and fed to the steam header at 6.2 bar(a) using a thermocompressor.

In the case of demo site 2, the thermocompressor utilizes as motive steam the high-pressure (14.5 bar(a)) steam from the boiler. The steam ejector requires about 9 t/h of high-pressure motive steam to upgrade the 3 t/h steam from 3.3 bar(a) to 6.5 bar(a). It is noteworthy that the total 6.5bar(a) steam produced by this system will be 12 ton/h, that is still lower than the minimum consumption of the plant (14 t/h). This guarantees a steady consumption of steam produced by the heat pump at full load and leaves the duty of providing the missing steam to the boilers.

The low pressure steam will be produced in the subcooler. This will generate 1 t/h of steam at 1.8 bar(a) (saturated steam temperature of 117 °C). Part of the generated steam will be exploited by the deaerator, while the remaining will be used in the air pre-heater.

These aspects will be clarified in the sections "Condenser steam integration" and "Subcooler steam integration" below.

As demonstrated in Figure 16, the heat input to the evaporator is being monitored on the heat source side through two temperature sensors (inlet & outlet) and a flowrate meter (FT). These three elements are basically a virtual thermal energy meter (represented by the yellow area) that controls the pump of the evaporator circuit. The dashed line is a logic connection.

For what concerns the heat sink side, the temperature and mass flowrate of water at the inlet of the subcooler and condenser of the heat pump is being measured. At the outlet, instead, both temperature and pressure of the steam are being monitored in order to measure the delivered upgraded heat of each heat exchanger (condenser and subcooler).

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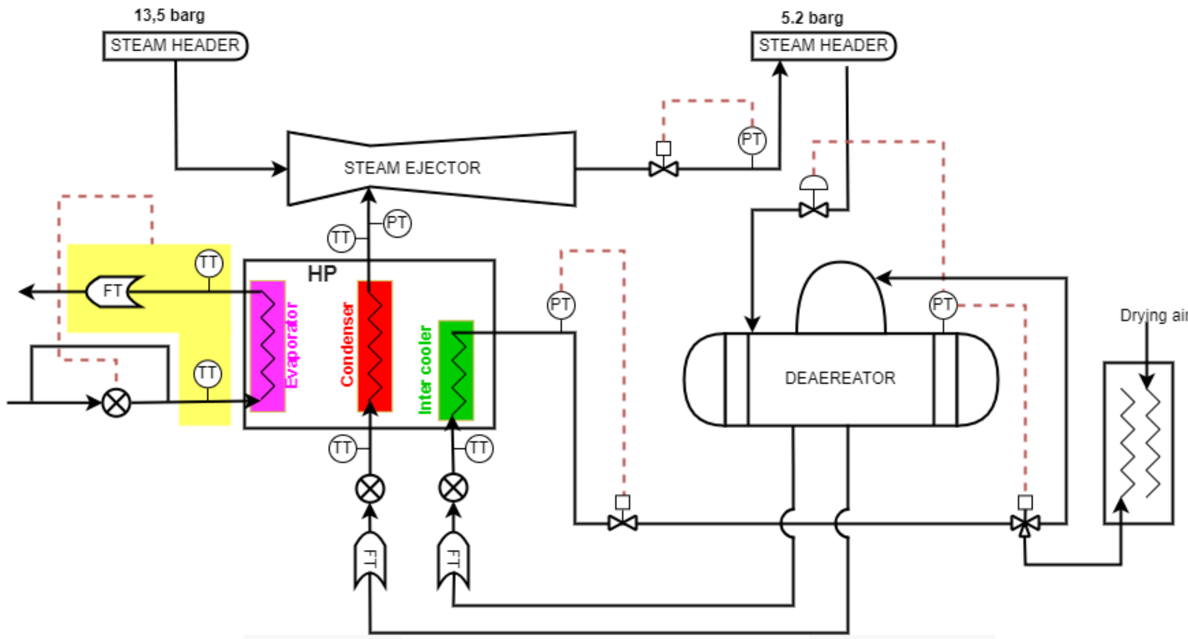

Figure 16: P&ID of HP integration

There are challenges to overcome regarding the discharge of the produced steam by the HP into the medium pressure steam header and deaerator.

Condenser steam integration

Since centrifugal compressors do not perform well when working far from their design point, in case of partial load operation conditions the steam outlet pressure and flowrate from the condenser will be lower than 3.3 bar(a) and 3 t/h respectively. Consequently, the steam ejector will not be able to upgrade the steam to the required pressure level of the steam header (i.e. 6.2 bar(a)). This would cause a back flow from the steam header towards the outlet of the steam ejector until the condenser of the HP gets pressurized to a level that the steam ejector can overcome the pressure drops of the line between the ejector outlet and the steam header inlet, discharging the steam inside the steam header. This unsteady situation is to be avoided and that is why a one direction shut-off valve is needed at discharge side of the steam ejector.

Subcooler steam integration

The same challenges of the condenser can be extended for the subcooler. In fact, to avoid the backflow of steam from the deaerator towards the subcooler, a one direction shut-off valve is needed on the line between subcooler outlet and deaerator inlet.

Moreover, the deaerator may request steam in a discontinuous manner, while the heat pump is supposed to operate at full load. There may be situations in which the deaerator will not require steam, but the subcooler needs to keep working to cool down the refrigerant. Therefore, a 3-way valve is foreseen on the subcooler discharge line which deviates the excess low-pressure steam

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towards another heat exchanger, that is responsible for partially heating the air used in dryer of the paper machine (see Figure 16)

3.1.1 Hydraulic configuration

The heat pump is a multi-input/multi-output system to be fitted inside the complex heat distribution network of a paper mill.

The heat pump and the heat sink circuits will be located at the first 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 and 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. The connection line will provide around 90 t/h of water at a temperature of 90 °C. The proper sizing is set for a 6 " line, to keep the average flow velocity lower than 1.5 m/s, to minimize the overall pressure drop.

Once the water reaches the HP it goes through the evaporator, a heat exchanger with approximately 0.9 bar pressure drop, and then comes back to the main line circuit.

The heat sink 1 circuit connects the subcooler with the deaerator. It is a two phase system: the feedwater coming from the deaerator changes its physical state inside the subcooler in the heat pump, becoming saturated steam. The challenge is to minimize the pressure drop among the two equipment (the HP and the deaerator) to deliver the steam at around 1.2 bar(a) in order to perform the degassing process. The overall pipe length is around 35 m. The piping size will be 4", determining an overall pressure drop of 250 mbar. The remaining main losses are concentrated on the isolation valve.

The heat sink 2 circuit connects the condenser with the medium pressure steam collector. First, a thermo-compressor increases the steam pressure from the HP condenser outlet pressure (3.3 bar(a)) up to 6.5 bar(a). The thermo-compressor utilizes around 9 t/h of high-pressure steam (14.5 bar(a)) to elevate the steam coming from the HP. The final balance leads to an overall 12 t/h of steam at 6.5 bar(a) which is directed to the process steam header, set at 6.2 bar(a). The thermo-compressor will be directly coupled on the above the heat pump, so the pressure drop between the heat pump and the thermocompressor is negligible.

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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.

Heat source circuit, connected to the evaporator:

Parameter	Unit	Value
Fluid	-	Liquid water
Inlet temperature	°C	90
Outlet temperature	°C	69.3
Inlet pressure	bar(a)	3.0
Mass flow rate	kg/h	86 887
Nominal heat	kW_{th}	2 100

Table 3: Design point of the heat source circuit

Heat sink 1 circuit, linked with the subcooler:

Parameter	Unit	Value
Fluid	-	Inlet: Liquid water Outlet: Saturated steam
Inlet temperature	°C	105
Outlet temperature	°C	116.9
Inlet pressure	bar(a)	1.8

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Outlet vapor quality	-	1.0
Mass flow rate	kg/h	1 000
Nominal heat	kW_{th}	628.1

Table 4: Design point of the sink 1 circuit

Heat sink 2 circuit, linked with the condenser:

Parameter	Unit	Value
Fluid	-	Inlet: Liquid water Outlet: Saturated steam
Inlet temperature	°C	105
Outlet temperature	°C	136.8
Inlet pressure	bar(a)	3.3
Outlet vapor quality	-	1.0
Mass flow rate	kg/h	3 000
Nominal heat	kW_{th}	1 907.4

Table 5: Design point of the heat sink circuit 2

The heat pump that will be installed in CDG will be manufactured by ENERTIME. Its main characteristic are summarized in Table 6

Parameter	Unit	Value
Compressor type	-	Centrifugal
Compressor stages	-	2
Refrigerant employed	-	R1233zd(E)
Electricity consumption	kW_{el}	704
Coefficient of performance (COP_{el})	-	3.6

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Table 6: Design parameters for the heat pump by ENERTIME

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.

Conversely, the incorporation of heat sink circuits necessitates the installation of new racks. Heat sink 1 is situated approximately 25 m away from the subcooler, whereas heat sink 2 is positioned roughly 35 m from the steam ejector outlet.

For what concerns the installation area, the heat pump is supposed to replace an old water tube boiler that has been out of use for years (the green area in Figure 17 and Figure 18). The former boiler was placed on the first floor of the building at 4.5 m from the ground level as demonstrated in Figure 17.

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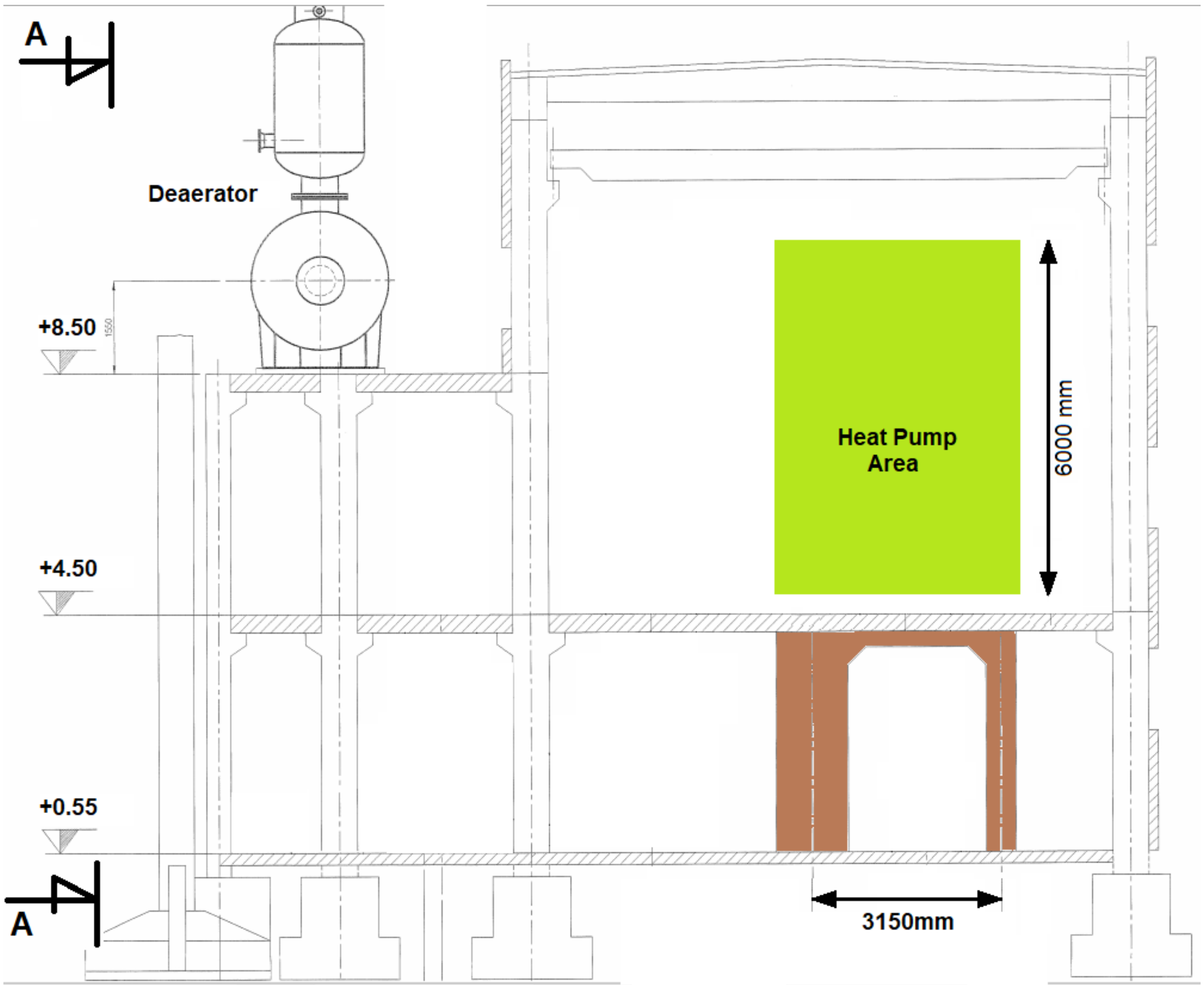

Figure 17: Heat pump installation area section B-B view

The weight of the heat Pump will be carried by means of 6 already existing reinforced concrete columns (brown color in Figure 17 and Figure 18). Three of them have a cross-section area of 1200x980 mm and the other three a cross-section area of 500x980 mm. The inter-axis between the columns are 3684 mm and 3150 mm

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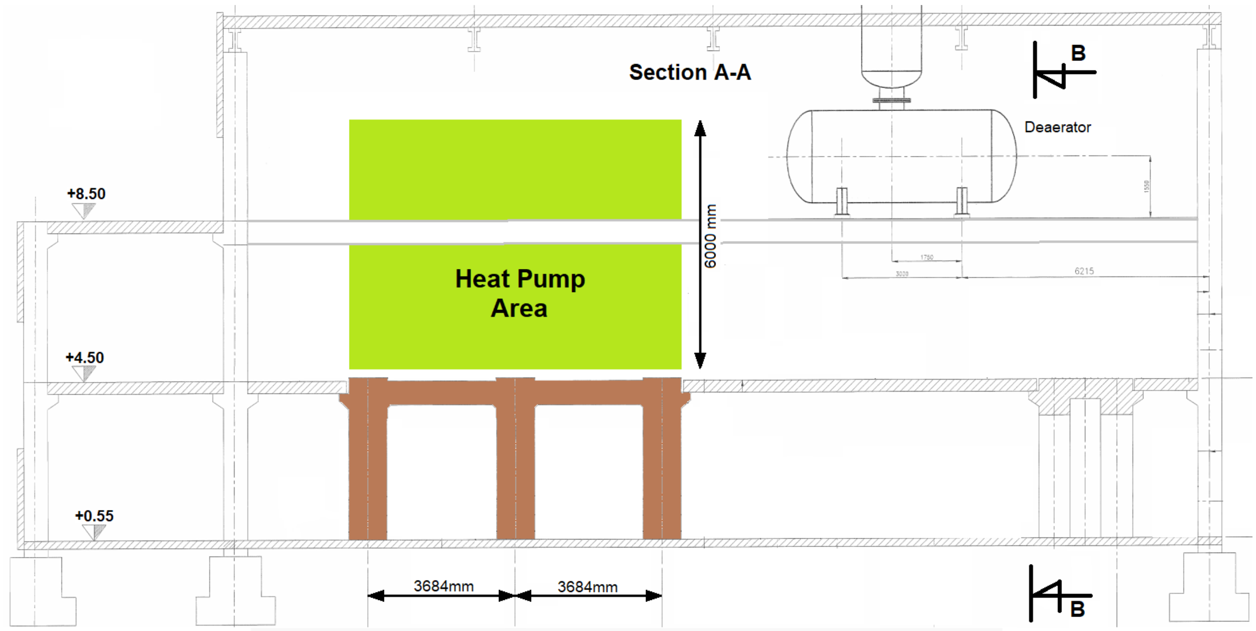

Figure 18: Heat Pump installation area section A-A view

The available height is about 9 m, of which around 6 m can be utilized easily. The former boiler was about 22 tons, but the columns are designed to bear significantly higher loads. Thus, the evaluation of the maximum weight allowed by the columns, considering the age and possible degradation, is currently ongoing.

The identified location of the heat pump is the most suitable because it is close both to heat sink 1 (deaerator on +8.50 m level) and heat sink 2 (6.2 bar(a) steam header on +0.55 m level).

It is noteworthy that the only way to take out the old water-tube boiler and insert the new Heat Pump into the building is to remove the roof using a crane. Precise timing is needed to align the two operations to reduce the costs of crane transportation and site occupation.

3.4 Control concept and control integration

A. Heat source control:
   Referring to Figure 16, the total extracted heat from the heat source can be measured with combination of a two temperature sensors (at the inlet and outlet of the evaporator external circuit) and one flowmeter, which will be placed at the outlet of the evaporator.

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Moreover, a pump will be installed at the inlet of the evaporator. This will be controlled by the mentioned power meter to guarantee the design load of the evaporator (2.1 MW)

B. Heat Sink 1 control:
As explained in Section 3.1, the subcooler will generate around 1 t/h of the saturated steam. An automatic 3-way valve is foreseen on the inter-cooler discharge line (see Figure 16). The purpose of this valve is to deviate the excess 1.8 bar(a) steam towards the drying machine air pre-heater whenever the deaerator consumption goes lower than inter-cooler production.

C. Heat Sink 2 control:
The steam ejector foreseen for upgrading the pressure level of steam produced by the condenser of the HP is equipped with an internal controller that regulates the motive steam mass flowrate and nozzle position to guaranty 6.5 bar(a) steam at the discharge flange of the ejector. It is noteworthy that the control margin of steam ejector is quite low, which indicates that the HP should always work very close to the nominal condition for the system to reach a steady operation condition.

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 pump. Specifically, data on the thermal energy supplied by the heat source and the thermal energy provided to the heat sink will be gathered.

In addition, electrical measurements of various components will be conducted, including the 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 thermocompressor, 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.

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

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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. Understanding the interplay between various heat sources will help optimize the overall energy usage and efficiency of the facility.

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

Sensor set up

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

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

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

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.

Fehler! Verweisquelle konnte nicht gefunden werden. highlights the transfer of information and measurement data within the monitoring concept.

Figure 19: 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.

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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.

Current work and up-coming next steps

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

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

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

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

3. Commissioning of the sensors and data acquisition:

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

4. Commissioning of data transmission and evaluation:

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

5. Visualization of KPIs and plant parameters:

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

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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 requirements" the involved partners have undertaken a comprehensive exploration related to the installation of a two-stage vapor compression heat pump 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 device.

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

The former was chosen after having investigated three possible solutions. In the end, scenario named Scenario 3 was chosen as the most suitable solution. This involves the extraction of waste heat from the cooling circuit of the engines of the cogeneration plant of the demo site. Data analysis have 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 2.1 MW of waste heat at a temperature of 90 °C was selected as a design parameter for the heat pump.

Two different heat sink circuits were identified. These are characterized by a pressure level of 1.8 bar(a) and 6.5 bar(a) respectively. The former connects the subcooler of the heat pump with the deaerator of the demo site, while the latter links the condenser with the medium pressure steam collector. A thermocompressor is present between the condenser and the steam collector to raise the pressure of the steam generated by the condenser from 3.3 bar(a) to 6.5 bar(a). The nominal heating capacity of the subcooler and of the condenser were calculated to be respectively 628 kW and 1.9 MW.

The design parameters of the heat pump have been assessed. This is characterized by a two-stage centrifugal 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 new pipelines. The predicted COP is 3.6

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.

The delivery and installation of the heat pump is foreseen for November 2024.

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