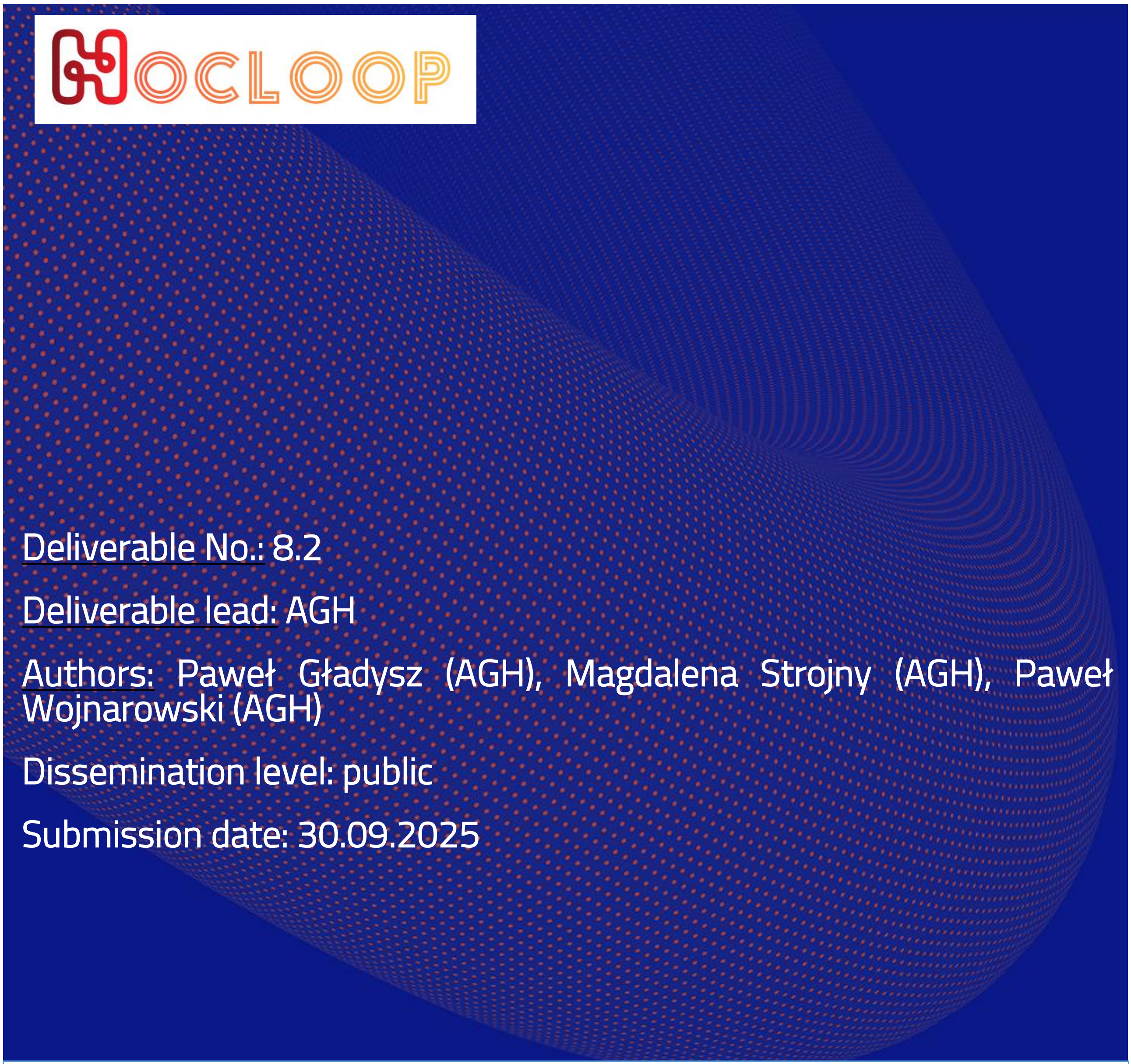
D8.2 Conceptual industrial designs



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LIST OF ABBREVATIONS

ACRONYM	DESCRIPTION
DAC	Direct Air Capture
DACCS	Direct Air Capture with Carbon Storage
EU	European Union
GHG	Greenhouse Gases
KPI	Key Performance Indicators
LPG	Liquefied Petroleum Gas
ORC	Organic Rankine Cycle
RES	Renewable Energy Sources

EXECUTIVE SUMMARY

The present document presents the results of simulations of the direct integration of the HOCLOOP concept in industrial processes, both considering present and future industrial energy systems. The following three main topics are approached, described, and evaluated:

- Conceptual pre-design development process with methods description.
- Key findings on the integrated process simulation studies.
- Three selected integrated industrial HOCLOOP cases for further pre-feasibility studies.

1. Introduction

1.1. Objective

The objective of Deliverable 8.2 is to develop conceptual pre-designs and perform integrated simulations of the HOCLOOP concept in combination with selected industrial energy systems. Building on the inputs from Tasks 4.1 and 4.2, and in alignment with Task 4.3, the work aims to define and evaluate both the underground loop and surface energy system configurations tailored to specific industrial applications. Detailed energy flow simulations were conducted to quantify the key performance indicators identified in Task 8.1, enabling a robust assessment of the proposed solutions. A multi-criteria analysis will be applied to compare the alternative designs and to select the most promising configuration, which will be further detailed through the preparation of the first preliminary Piping and Instrumentation Diagram (P&ID). In parallel, a process integration analysis will be carried out to investigate potential synergies between the HOCLOOP concept and the targeted industrial energy systems.

1.2. HOCLOOP system integration designs

Based on the description within T8.1 about the selection rationale, the industrial processes were categorized and assessed according to their suitability for integration with the HOCLOOP concept. The evaluation considered the temperature requirements of processes, distinguishing between low-temperature (<150°C), medium-temperature (150–400°C), and high-temperature (>400°C) applications. This classification allowed for the identification of industrial sectors such as pulp and paper, food and beverages, textile, chemical processing, as well as direct air capture application, where geothermal energy can serve as a stable and continuous heat supply. Furthermore, the assessment differentiated between direct and indirect applications of HOCLOOP. In cases where geothermal outlet temperatures are sufficiently high, direct applications such as water-based systems or flash steam configurations can be implemented to provide primary process heat. Conversely, for lower-temperature resources, indirect configurations involving heat exchangers and industrial heat pumps were considered to enhance temperature levels and extend applicability. The industrial demand and market potential in the EU was also analyzed to identify energy-intensive sectors with significant decarbonization needs.

Additionally, the potential for CO_2 emission reduction was quantified by estimating the carbon savings achievable when replacing fossil fuel-based heat sources with HOCLOOP under different operational scenarios and regional conditions.

Based on these criteria, a set of integration configurations was proposed, including systems with Organic Rankine Cycles (ORC), flash steam systems, heat pumps, and heat exchangers. These configurations were matched to the identified industrial demands along with results obtained for subsurface system simulation in Task 4.1, 4.2 and 4.3, enabling optimal use of geothermal energy across a range of processes. In the current report, the focus has been placed on the modelling and integration analysis of these selected configurations, assessing their energy performance, potential synergies with existing industrial energy systems, and overall contribution to improved efficiency and emission reductions.

*Table **1.** Selected industrial processes with the respective heating temperature ranges.*

Industry Sector	Industrial Process	Heat Demand Range	Type of medium used	HOCLOOP Integration
Pulp and paper	Paper Drying	60-80°C	Steam	Indirect
	Pulp Bleaching	130-150°C	Water/Steam	Indirect
Food and beverages	Pasteurization	60-80°C	Water/Steam	Direct/Indirect
	Sterilizing	110-120°C	Steam	Indirect
Textile Industry	Fabric Dyeing	70-90°C	Water	Direct
	Bleaching	60-100°C	Water	Direct
Chemical processing	Solvent distillation	140-250°C	Steam	Indirect
	Polymerization	200-300°C	Steam	Indirect
Direct air capture	CO_2 Adsorption & Desorption	60-120°C	Steam	Indirect
All/others	Pre-heating of fluids	60-90°C	Water/Steam	Direct/Indirect

1.3. Methods

The modelling of the proposed HOCLOOP integration configurations was conducted using the IPSEpro software, which is a simulation tool for thermodynamic process systems. This environment allowed for the creation of component-based process models that represent the behavior of energy systems on the surface. The methodology involves the development of customized process schemes for each configuration, including geothermal loops, heat exchangers, industrial heat pumps, Organic Rankine Cycle (ORC) units, and flash steam systems. These models were built to simulate the designs proposed in the earlier stages of the project.

Input data for the simulations were sourced from the results of previous tasks, which provided essential information such as geothermal reservoir characteristics, industrial process energy demands, and operational constraints. Within IPSEpro software, each model was calibrated with data to account for variations in temperature, pressure, mass flow rates and energy demand profiles.

The simulations provided set of outputs, including detailed energy and mass balances, temperature and pressure distributions across all components and the calculation of key performance indicators defined in Task 8.1. These outputs not only enabled a precise evaluation of the energy performance of each configuration but also facilitated the identification of operational challenges and opportunities for efficiency improvement. The generated results served as the basis for the subsequent multi-criteria analysis, where technical, economic, and environmental aspects were systematically assessed. This methodological approach ensured that the modelling outcomes were robust and directly applicable to the selection of the most promising HOCLOOP integration concepts for industrial deployment.

2. Conceptual Pre-Design Development

2.1. Process models development

This section presents the development of process models created to simulate and analyze the investigated system. The models were built using the IPSEpro software. Based on the results from Goleniów case from Task 4.2 following operational parameters were taken as an input to process models as well as the assumptions regarding respective system elements (Table 2).

*Table **2.** Assumptions for process modelling*

Parameter	Value
Production temperature	70-100°C
Production pressure	1.2 MPa
Injection temperature	30-70°C
Injection pressure	1.3 – 6.5 MPa
Heat exchangers pressure drop	0.01 MPa
Minimum temperature difference in heat exchangers	10°C
ORC working fluid	n-pentane
Pump isentropic efficiency	90%
Pump mechanical efficiency	99%
Motor electrical efficiency	95%
Motor mechanical efficiency	99%
ORC generator electrical efficiency	95%
ORC generator mechanical efficiency	99%
ORC turbine isentropic efficiency	80%
ORC turbine mechanical efficiency	98%

Injection pressure depends on the mass flowrate of working medium and production temperature profile depend also on injection temperature, therefore in assessed cases and configurations the parameters were determined suitably.

a) Pulp and paper sector

The pulp and paper industry is characterized by high and continuous thermal energy demand, making it a promising sector for the integration of geothermal-based solutions within the HOCLOOP concept. Two processes with their heat consumption profile were selected in this sector: paper drying and pulp bleaching.

Paper drying typically requires thermal energy in the range of 60–80°C, which is commonly supplied through low-pressure steam. This temperature range aligns well with the capabilities of HOCLOOP, particularly when configured to deliver low-temperature heat directly or in combination with industrial heat pumps for improved efficiency. Paper drying is predominantly accomplished with steam. In virtually all paper mills, the wet paper web is dried by passing it over a series of steam-heated metal cylinder, even in smaller mills usually a boiler (or other source) provides low-pressure steam for the dryers. The steam indirectly heats the paper via the cylinder walls. Hot water is generally not used as the primary drying medium, because steam's latent heat transfer is far more effective for driving off moisture [1]. As the steam transfers latent heat, it condenses inside the dryer cylinders into hot condensate. This condensate is typically collected and returned to be reused. In modern efficient mills, a very high percentage of this condensate is recovered, often 90% or more is returned. Moreover, some tissue machines or specialty paper dryers use vacuum cylinders. The vacuum drum dryer uses low-pressure steam under vacuum to prevent damaging delicate paper grades [2].

Based on findings regarding process characteristics in pulp and paper industry, along with the results from Task 8.1, and considering the low-temperature heat demand of 80°C, an indirect configuration using a heat exchanger for steam generation was proposed (Figure 1).

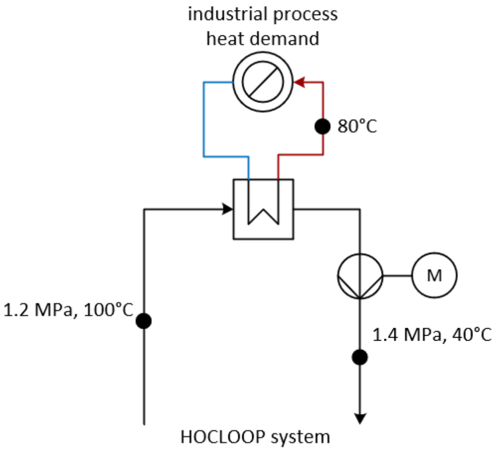

*Figure **1.** Paper drying integration configuration*

Pulp bleaching, on the other hand, involves higher temperature requirements, generally between 130–150°C, traditionally met using medium-pressure steam. In contrast to paper drying, the bleaching process typically uses direct heating. Steam is often injected directly into the pulp slurry to raise its temperature for the chemical reactions. This direct steam injection is a form of direct contact heating – the steam mixes with the pulp and condenses within it, therefore there is no separate condensate return from the bleach towers. The unit must be fed with makeup water to replace any steam used in direct-contact heating. The HOCLOOP system can support this demand either through hybrid configurations integrating heat pumps or flash steam systems to achieve the required temperature levels.

Based on findings regarding process characteristics in pulp and paper industry, along with the results from Task 8.1, and considering the temperature heat demand of 130 °C, an indirect configuration using a heat pump for steam generation was proposed (Figure 2).

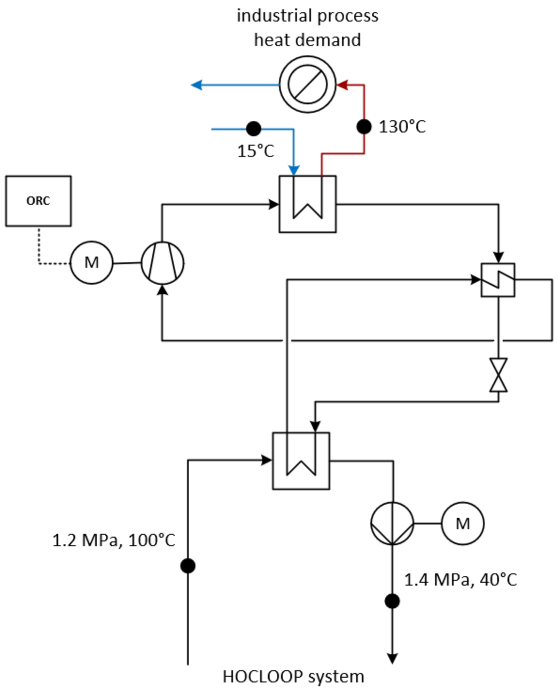

*Figure **2**. Pulp bleaching integration configuration*

Additionally, the heat pump can be powered either directly from the electricity grid or by electricity generated from a dedicated Organic Rankine Cycle unit.

B) <u>Food and beverages sector</u>

Similarly to pulp and paper sector, two processes where listed: pasteurization and sterilization, which differ in temperature requirements, heating medium and how the heating system operates.

Pasteurization is a mild thermal process (typically 60–80 °C for beverages such as beer, juice, milk) used to destroy pathogens and extend shelf life. In small to medium EU food and beverage plants, indirect heating via heat exchangers is most common. The product is heated by a hot water or steam circuit without direct contact in a closed loop. Direct contact heating (e.g. steam injection) is generally avoided, unless required by a specific high-temperature process [3].

Based on findings regarding process characteristics in food and beverage industry, along with the results from Task 8.1, and considering the low-temperature heat demand of 80 °C, a direct configuration was proposed (Figure 3).

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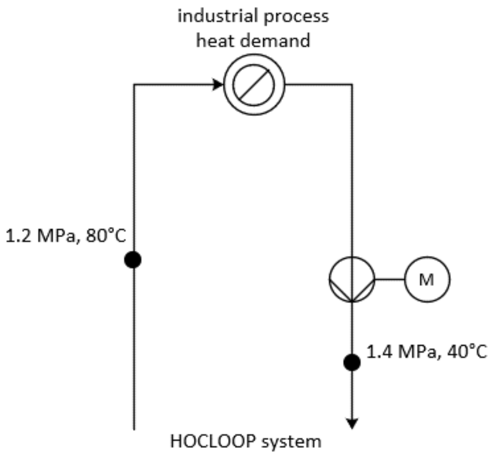

*Figure **3**. Food pasteurization integration configuration*

Sterilization in food processing involves higher temperatures (often 110-140 °C) to achieve commercial sterility. In small/medium facilities, this includes in-package sterilization and aseptic UHT processing of liquids prior to packaging. These processes rely mainly on steam as the heating medium, since pressurized steam is the most practical way to reach >100°C. In retort sterilization of packaged goods, the heating is an indirect process with respect to the food (steam or hot water heats the container, not mixed into the food itself). By contrast, UHT sterilization of liquid products can use direct product heating: culinary steam injection or infusion. In UHT plants, product may be pressurized and injected with high-pressure steam to instantly heat it to ~135–150 °C, then a flash cooler removes the added water. Although, alternatively, UHT can be done by indirect means (plate, tubular, or scraped-surface heat exchangers with steam on the hot side). Small and medium dairy processors in the EU often opt for indirect UHT systems for easier operation, unless they have the capability to handle steam injection and sterile flash cooling. Hot water alone is generally insufficient for sterilization. When steam releases its heat, it condenses to hot water [4].

Based on findings regarding process characteristics in food and beverage industry, along with the results from Task 8.1, and considering the temperature heat demand of 120°C, an indirect configuration using a heat pump for steam generation was proposed (Figure 4).

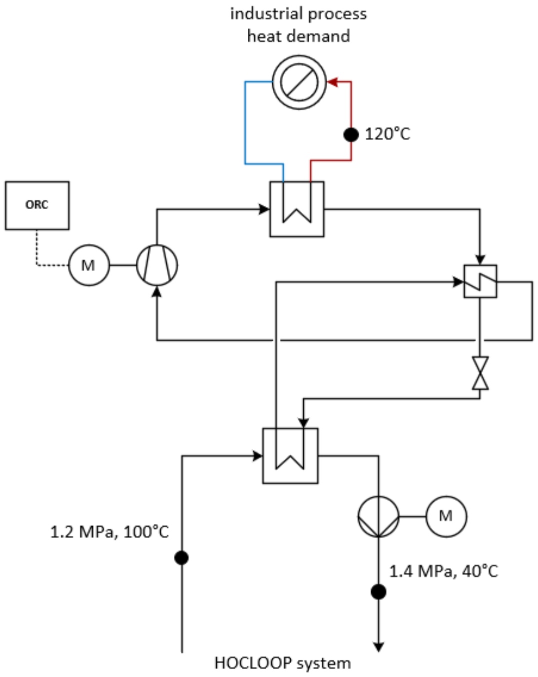

Figure ***4****. Food sterilizing integration configuration*

Additionally, the heat pump can be powered either directly from the electricity grid or by electricity generated from a dedicated Organic Rankine Cycle unit.

c) Chemical sector

Industrial solvent distillation units commonly use steam as the primary heating medium when the required temperatures are moderate (up to 180-200 °C). Low or medium-pressure steam (3-10 bar) is often supplied to reboilers or heating jackets, providing heat via condensation at a controlled saturation temperature. Some distillation units can be configured for various media, equipment can be heated by steam, pressurized hot water, or thermal oil, depending on site utilities. In Europe, many chemical plants have centralized steam systems for distillation heating, and thermal oil systems are employed when necessary for higher temperatures or precise control. The heating in solvent distillation is usually indirect. Steam or hot oil circulates through coils, reboiler heat exchangers, or jackets that transfer heat to the solvent without direct contact. This indirect method prevents contamination and allows reusing the heating medium [5].

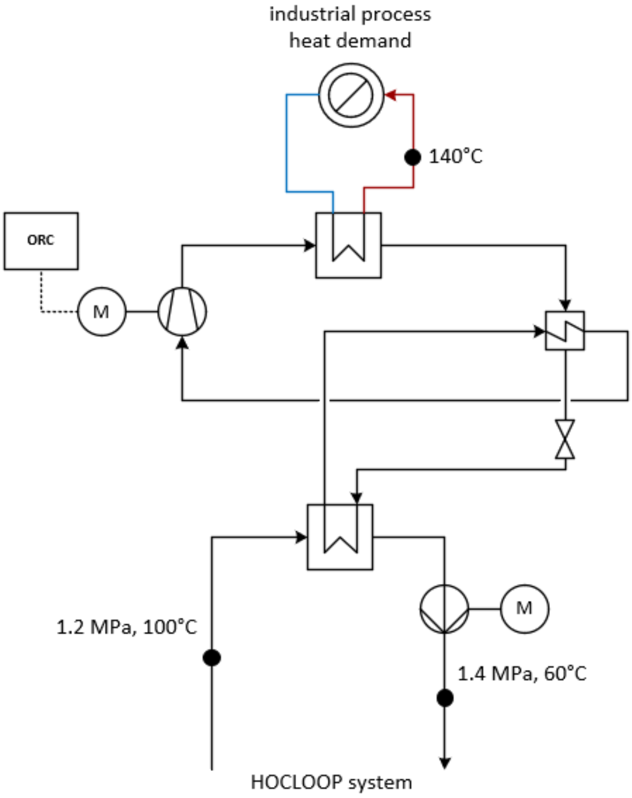

*Figure **5.** Distillation integration configuration*

In terms of polymerization processes, they require higher temperatures - especially polycondensation and certain addition polymerizations. In those cases, thermal oil systems are common. Thermal oil (or another synthetic heat fluid) can be heated to approx. 200-300°C in a fired heater or electric heater and circulated through the reactor jacket or external coils. This is often seen in processes like polyamide and polyester (PET) production or polymerization of styrene-based plastics, which need temperatures in the 200–300°C range. Because the required process temperatures are very high, using the HOCLOOP system with a production unit would not be efficient. Therefore, based on geological modelling results indicating geothermal temperatures of only up to 110°C, this process was excluded from further analysis.

d) Textile sector

Small to medium textile dyeing and bleaching facilities typically rely on steam or hot water as the primary heating media. In indirect heating setups steam, hot water, or even thermal oil can carry heat to the process. Steam is most widely used, supplied by onsite boilers, and can be delivered either as low-pressure steam injected directly into the bath or as higher-pressure steam circulating through coils/heat exchangers that heat indirectly. Hot water is also used, especially when process temperatures stay below 100°C. It may be circulated in jacketed vessels or heat exchangers for indirect heating [6].

Typical operating temperatures for batch dyeing and bleaching fall in the 60-100°C range. Many cotton and yarn dyeing cycles heat to 85-95°C for dye fixation or bleaching, while wool dyeing might run at around 60-90°C depending on dye class. Hot water can be used in a closed loop as the heating fluid in place of steam for example in a central hot-water boiler feeding jacketed machines, in which lower temperatures are needed. Indirect systems avoid diluting the bath and allow tighter temperature range

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control [7]. If a closed-loop hot water system is used, the water is continually recirculated between the heat source and the process equipment. The fluid leaves the dyeing machine at a lower temperature and returns to the heater to be reheated and sent out again. There is typically no discharge of the heating medium itself in such closed systems, only heat is exchanged.

Due to low heat demand in the assessed fabric dyeing process, the required mass flow would be too low to efficiently operate the unit. Therefore, both processes within analysed textile industry were assumed to be integrated and operate with the same temperature levels in direct heating loop (Figure 6).

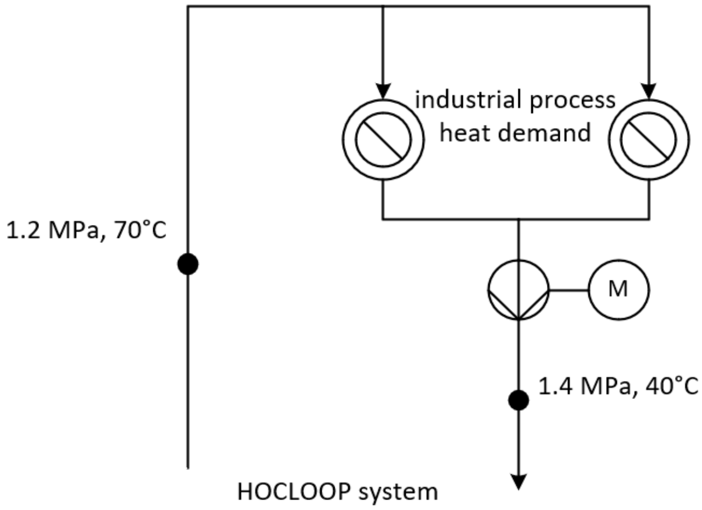

*Figure **6.** Fabric dyeing and bleaching integration configuration*

e) Direct air capture of CO_2

Commercial-scale Direct Air Capture use solid sorbent technology, which operates with low-grade heat input, typically around 80–120 °C, to regenerate the sorbent and release CO_2. Solid sorbent DAC units often require on the order of a few megawatts of thermal power to drive CO_2 desorption. This heat input usually constitutes the majority of the energy demand for solid DAC and can be supplied by waste heat or other low-carbon heat sources. Many modern DAC systems favour indirect heating with steam. In an indirect steam configuration, steam flows through heat exchangers that are in contact with the sorbent bed, transferring heat without the steam mixing with the sorbent or gas. This approach avoids adding extra water into the sorbent. Many solid-sorbent DAC designs (e.g. early Climeworks units) use a temperature-vacuum swing with indirect heating.

Assessed scale for DAC unit was 5200 tCO_2/year with 9.8 GJ/tCO_2 of heat demand. This gives approx. 1800kW_{th} of continuous heat requirement.

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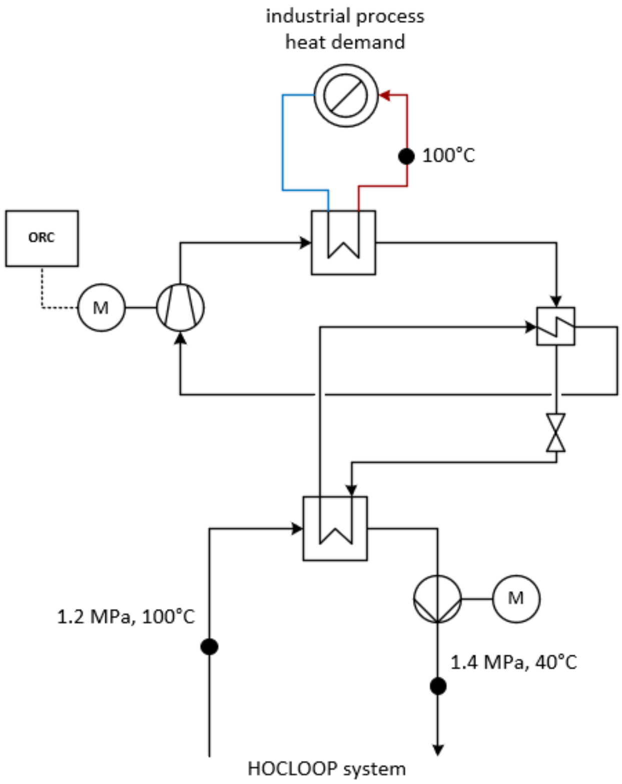

Figure **7.** DAC integration configuration

f) Others

Pre-heating of process fluids is a common operation in many industrial sectors, aimed at raising the temperature of liquids or gases before they undergo further processing. Pre-heating is usually carried out using steam or hot water as the heating medium. For low to moderate temperature requirements (below ~120 °C), hot water or low-pressure steam is commonly used, often supplied by an onsite boiler or waste heat recovery system.

In the analyzed case, hot water is utilized and system need to be supplied with fresh, makeup water.

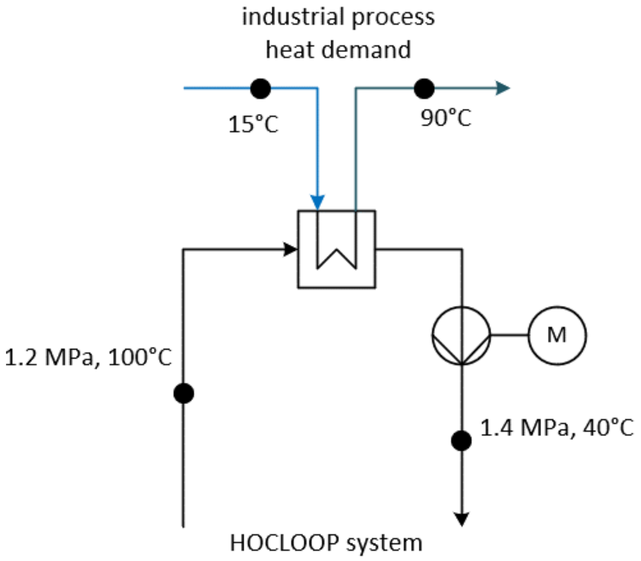

Figure **8.** Pre-heating integration configuration

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2.2. Integrated models simulation

Description of results obtained from simulations performed to quantify mass and energy balances and KPIs.

This section presents the outcomes of the integrated model simulations developed to evaluate the performance of the proposed HOCLOOP configurations. The simulations were carried out to quantify mass and energy balances as well as to calculate the key performance indicators defined for the assessment. The following subsections describe the results obtained for each configuration and discuss their implications.

a) Pulp and paper

Throughout the analysed week, the drying process exhibits a fluctuation pattern, with periods of high activity followed by intervals of reduced operation. During working days, the heat demand reaches values close to 1.6 MW_{th}, while during low-demand periods it dropped to around 400 kW_{th}. The mass flow rate follows a similar trend, increasing proportionally to meet the higher thermal load and decreasing during reduced operation. Toward the end of the week, a prolonged phase of significantly lower demand is observed, with both heat demand and mass flow remaining at minimal levels. Over the entire period, the average mass flow rate is approximately 3 kg/s, reflecting the balance between fluctuating daily peaks and low-demand intervals.

To ensure a stable heat supply despite the fluctuations in process demand, the HOCLOOP system must be designed to continuously deliver this average mass flow rate, corresponding to the average operational requirement. Then, to effectively manage the periodic peaks, this constant geothermal output should be coupled with a thermal energy storage unit. The storage system would allow excess heat produced during low-demand periods to be accumulated and subsequently released during peak loads.

With assumed operating parameters, such installation with average mass flowrate of 11.4 kg/s and power of 0.76 MW_{th} corresponds to two HOCLOOP units.

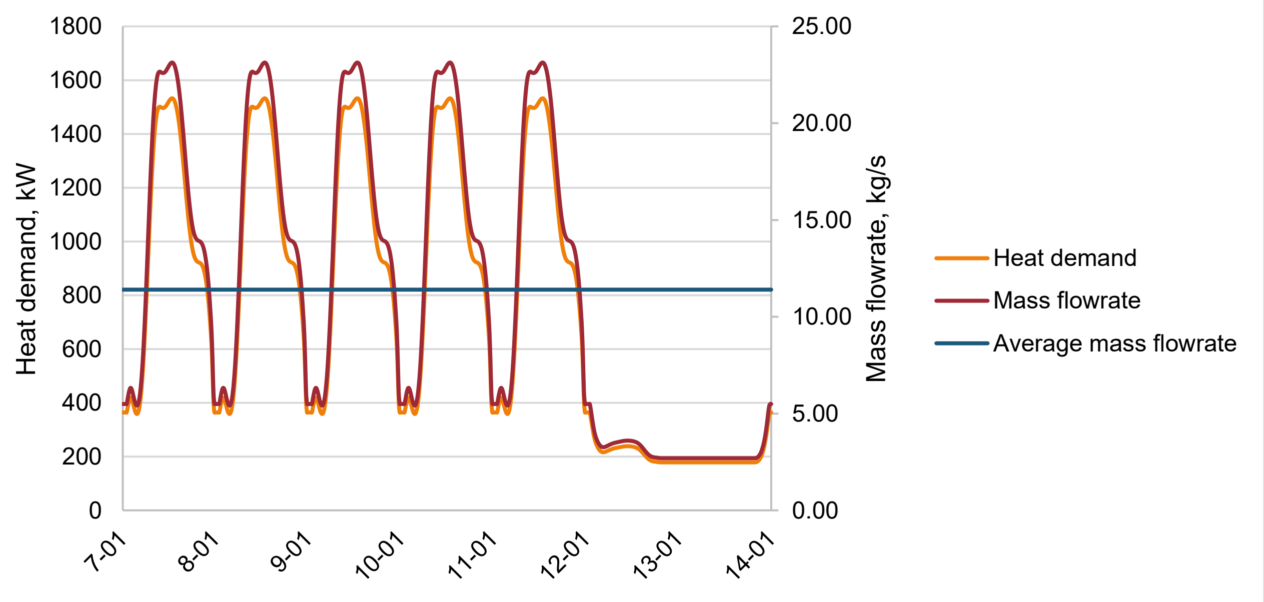

*Figure **9**. Heat demand and HOCLOOP water mass flowrate, paper drying process*

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Table 3. Paper drying process simulation values and results

Parameter	Value
Injection temperature	40°C
Injection pressure	1.4 MPa
Heat supply temperature (steam)	80°C
Working fluid average mass flow (from HOCLOOP)	11.4 kg/s
Injection pump average power	3.2 kW

On the other hand, the bleaching process is stable throughout whole week with heat demand of 1800 kW, therefore no need for additional thermal storage equipment.

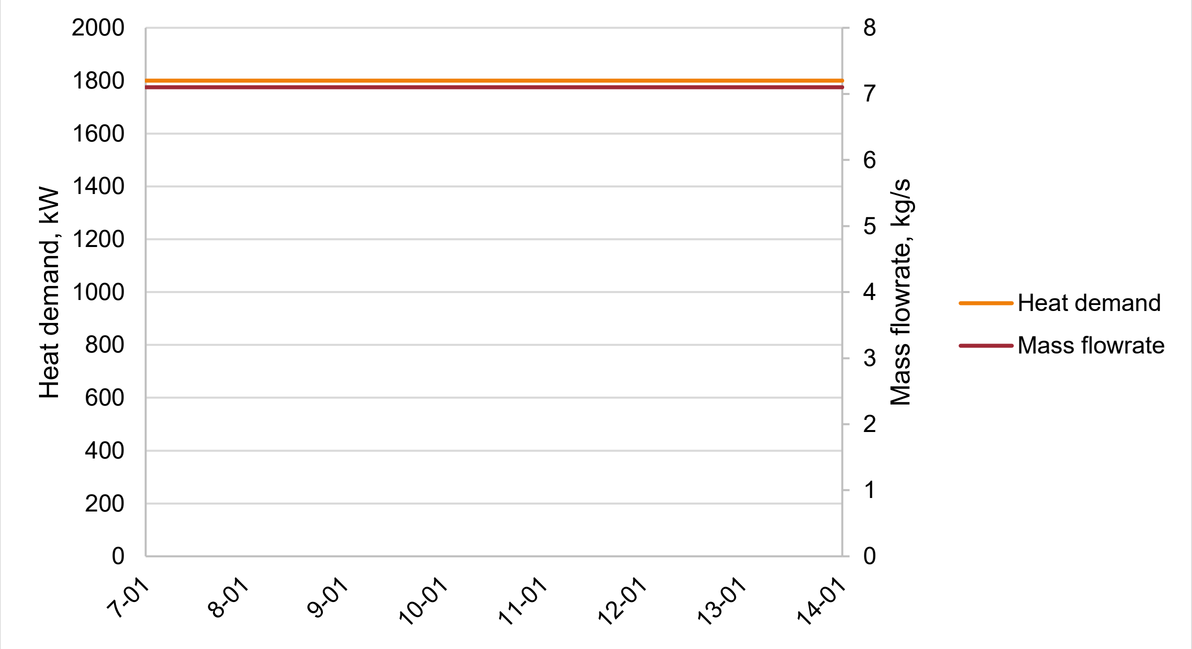

Figure 10. Heat demand and HOCLOOP water mass flowrate, pulp bleaching process

The mass flowrate needed to supply the heat pump is 7.1 kg/s, which can be obtained within one or two HOCLOOP units ensuring power demand of 1800 kW. Summarized results are presented in Table 4.

Table 4. Pulp bleaching process simulation values and results

Parameter	Value
Injection temperature	40°C
Injection pressure	1.4 MPa
Heat supply temperature (steam)	130°C
Working fluid mass flow (from HOCLOOP)	7.1 kg/s
Injection pump power	1.77 kW
Heat pump power	919.9 kW
Heat pump COP	1.96

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ORC generator power	921.7 kW
Additional stream to ORC (from HOCLOOP)	67.9 kg/s

However, since in paper drying the condensate is recycled back into the loop, it retains a relatively high temperature. As a result, the water requires cooling before being injected. This excess heat can instead be used to preheat the makeup water in the bleaching process, thereby improving the overall efficiency of the integrated system.

*Table **5.** Pulp and paper analysis results*

Process	Annual heat demand, MWh_{th}	Annual power demand, MWh_e	Average mass flow, kg/s	ORC power, kW_e	Amount of HOCLOOP units (20 m^3/h)
Paper drying	5 963.7	25.5	11.4	n/a	2
Pulp bleaching	14 191.2	7 266.7	7.1	921.7	2-3
Not integrated processes	20 154.9	7 292.2	18.5	921.7	3-4 (excl. ORC)
Integrated processes	20 154.9	6 105.2	17.3	767.4	3-4 (excl. ORC)

b) Food and beverages

During the analysed week, the process performs significant variability in energy use, with high heat loads observed on production days and a notable reduction during periods of limited operation. Peak demand reached around 3.3 MW_{th}, while the lowest demand dropped to approximately 0.9 MW_{th}. The mass flow rate adapted accordingly, increasing to meet higher energy requirements and falling during low-load intervals.

With the specified operational parameters, a system designed for an average mass flow rate of 13.2 kg/s would correspond to the performance of two HOCLOOP units.

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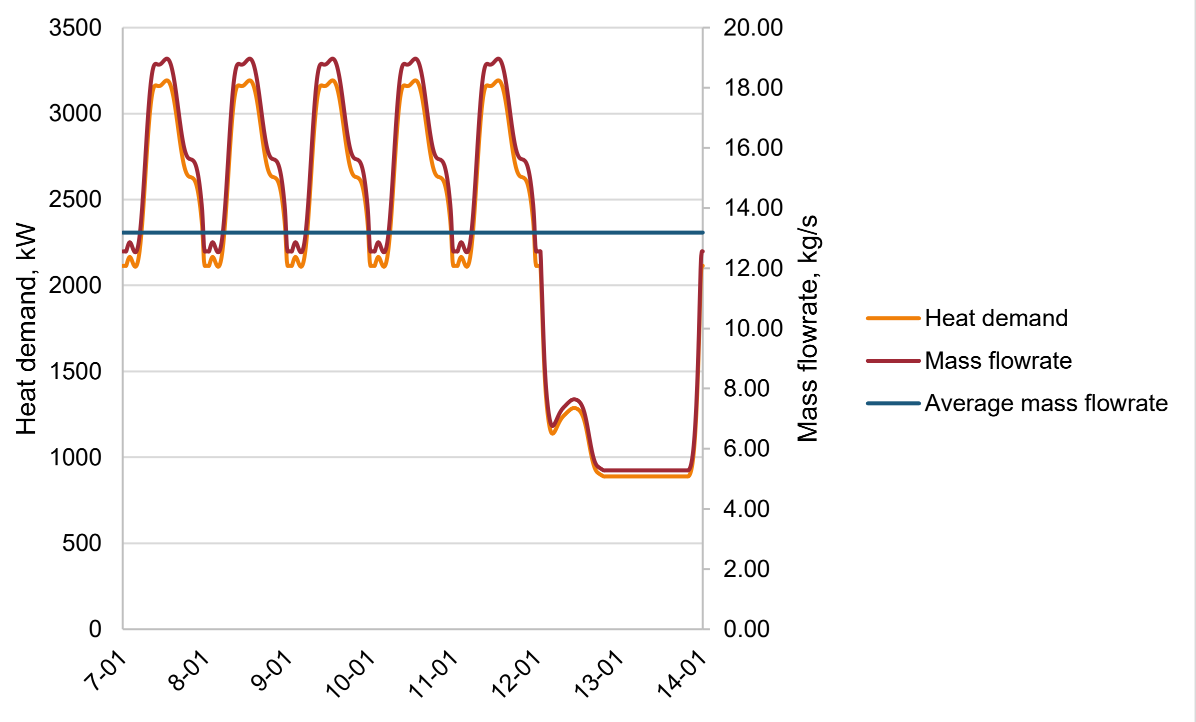

*Figure **11.** Heat demand and HOCLOOP water mass flowrate, food pasteurization process*

*Table **6.** Food pasteurization process simulation values and results*

Parameter	Value
Injection temperature	40°C
Injection pressure	1.4 MPa
Heat supply temperature (hot water)	80°C
Working fluid mass flow (from HOCLOOP)	13.2 kg/s
Injection pump average power	17.2 kW

The sterilizing process was assumed as stable throughout the week, with heat demand of 1754 kW_{th}.

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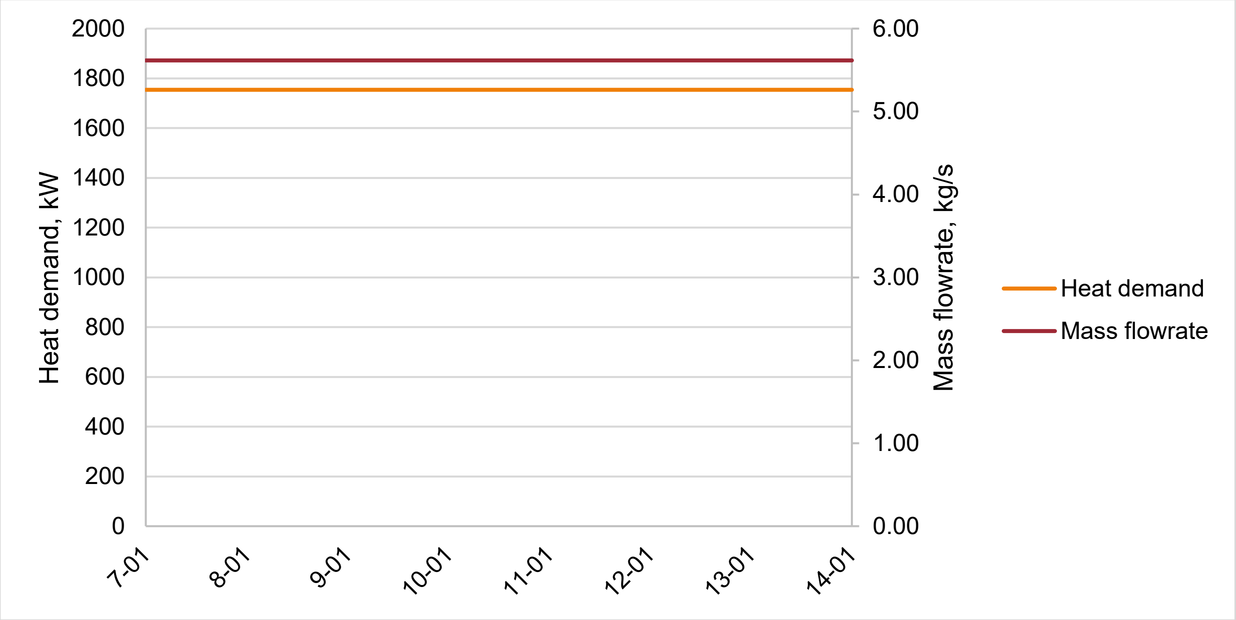

*Figure **12.** Heat demand and HOCLOOP water mass flowrate, food sterilization process*

The mass flowrate needed to supply the heat pump is 5.6 kg/s, which can be obtained within one or two HOCLOOP unit ensuring power demand. Obtained results are presented in Table.

*Table **7.** Food sterilization process simulation values and results*

Parameter	Value
Injection temperature	40°C
Injection pressure	1.4 MPa
Heat supply temperature (steam)	120°C
Working fluid mass flow (from HOCLOOP)	5.6 kg/s
Injection pump power	1.4 kW
Heat pump power	707.5 kW
Heat pump COP	2.5
ORC generator power	708.9 kW
Additional stream to ORC (from HOCLOOP)	51.7 kg/s

In the case of food and beverage industry processes, water from pasteurizing process was modelled at 40°C to match the requirements for reinjection, therefore no further integration of both processes is possible. Annual demands and further results are presented in Table 8.

*Table **8.** Food and beverage industry analysis results*

Process	Annual heat demand, MWh_{th}	Annual power demand, MWh_e	Average mass flow, kg/s	ORC power, kW_e	Amount of HOCLOOP units (20 m^3/h)
Food	17 528.2	135.6	13.2	n/a	2-3

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pasteurization					
Food sterilizing	13 828.5	5 589.0	5.6	708.9	1
Food and beverage case - not integrated processes	31 356.7	5 724.5	18.8	708.9	3-4 (excl. ORC)

c) Chemical industry

The analysed week is characterized by heat demand fluctuations from approximately 350 to 700 MW$_{th}$. Followed that, the working medium flowrate changes accordingly to provide the heat necessary to system. With the specified operational parameters, a system designed for an average mass flow rate of 7.4 kg/s would correspond to the performance of one or two HOCLOOP units.

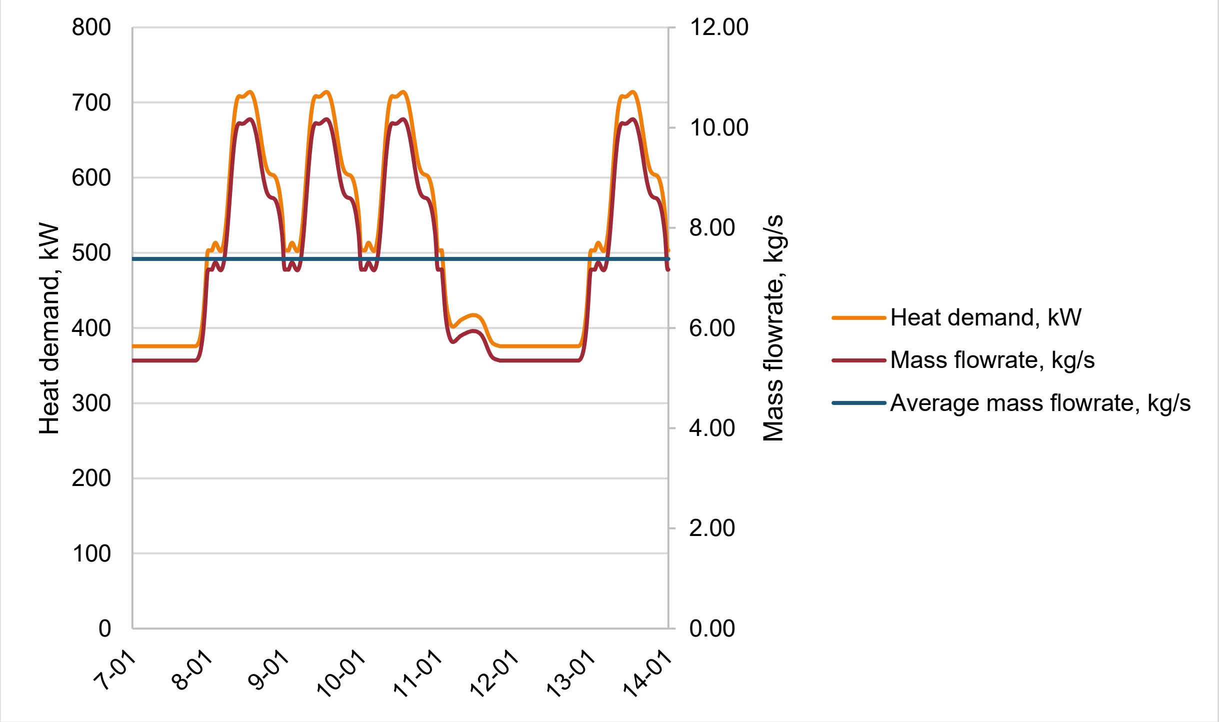

*Figure **13**. Heat demand and HOCLOOP water mass flowrate, distillation process*

The mass flowrate needed to supply the heat pump is 7.4 kg/s, which can be obtained within one or two HOCLOOP units ensuring the power demand. Obtained results are presented in Table 9.

*Table **9.** Distillation process simulation values and results*

Parameter	Value
Injection temperature	60°C
Injection pressure	1.4 MPa
Heat supply temperature (steam)	140°C
Working fluid average mass flow (from HOCLOOP)	7.4 kg/s
Injection pump power	2.5 kW

Heat pump power	633.3 kW
Heat pump COP	1.3
ORC generator power	635.6 kW
Additional stream to ORC (from HOCLOOP)	50.5 kg/s

Annual demands and further results are presented in table below.

*Table **10.** Chemical industry analysis results*

Process	Annual heat demand, MWh_{th}	Annual power demand, MWh_e	Average mass flow, kg/s	ORC power, kW_e	Amount of HOCLOOP units (20 m^3/h)
Distillation	4 092.0	3 746.7	7.4	633.3	2-3

d) Textile industry

In case of textile sector, one process of fabric dyeing was assumed with variable heat demand, while bleaching was stable during the year. The results of integrated processes are presented below. Average water supply from HOCLOOP system accounts for around 7 kg/s, which provides necessary heat for continuous bleaching process (5.9 kg/s) and fluctuating mass flow for dyeing.

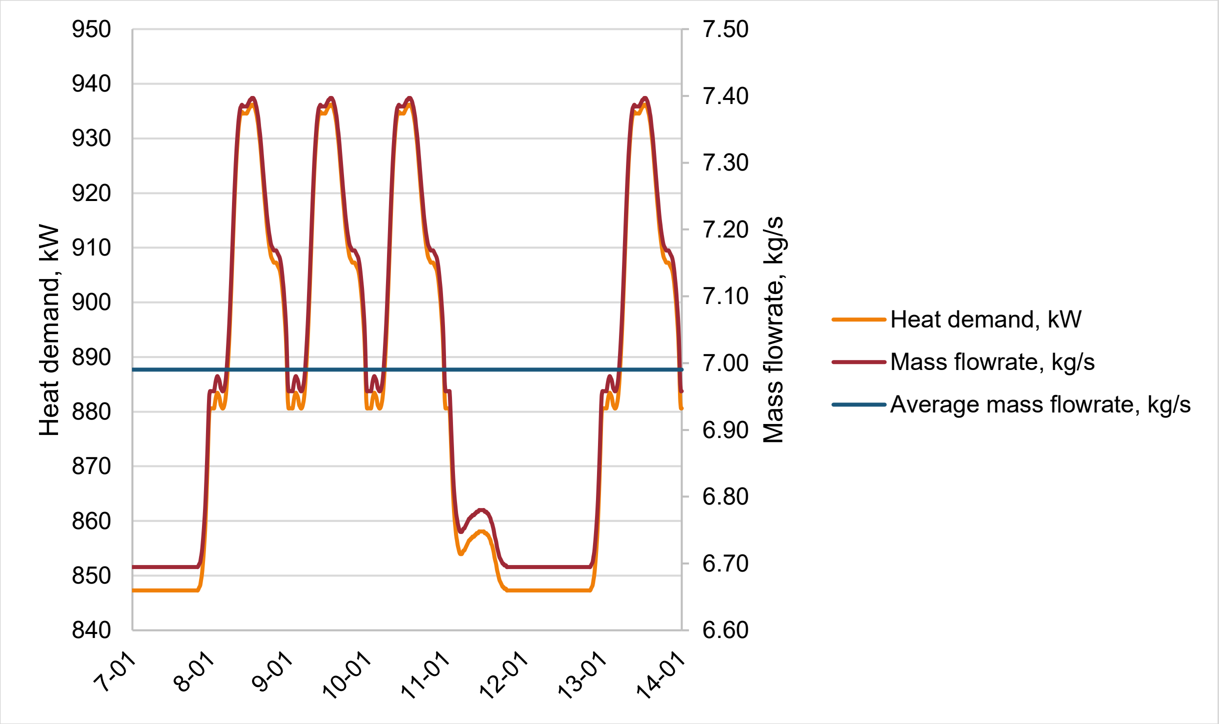

*Figure **14.** Heat demand and HOCLOOP water mass flowrate, integrated textile processes*

Obtained results from simulations are presented in Table 11.

*Table **11.** Textile processes simulation values and results*

Parameter	Value
Injection temperature	40°C

This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101083558

Injection pressure	1.4 MPa
Heat supply temperature (hot water)	70 °C
Working fluid average mass flow (from HOCLOOP)	7.0 kg/s
Injection pump average power	9.9 kW$_e$

Annual demands and further results are presented in table below.

*Table **12.** Textile industry analysis results*

Process	Annual heat demand, MWh$_{th}$	Annual power demand, MWh$_e$	Average mass flow, kg/s	ORC power, kW$_e$	Amount of HOCLOOP units (20 m^3/h)
Integrated textile processes (dyeing and bleaching)	6 985.3	78.3	7.0	n/a	1-2

d) Direct air capture

For the case of direct air capture, the heat demand was assumed to remain constant over the analyzed period, reflecting the stable thermal requirements of the regeneration process. The simulation results for the integrated system are shown below. The average heat supply from the HOCLOOP system is approximately 1.8 MW$_{th}$, corresponding to a stable water mass flow rate of around 5.7 kg/s. This continuous supply ensures the necessary heat for the DAC process without significant fluctuations in system performance.

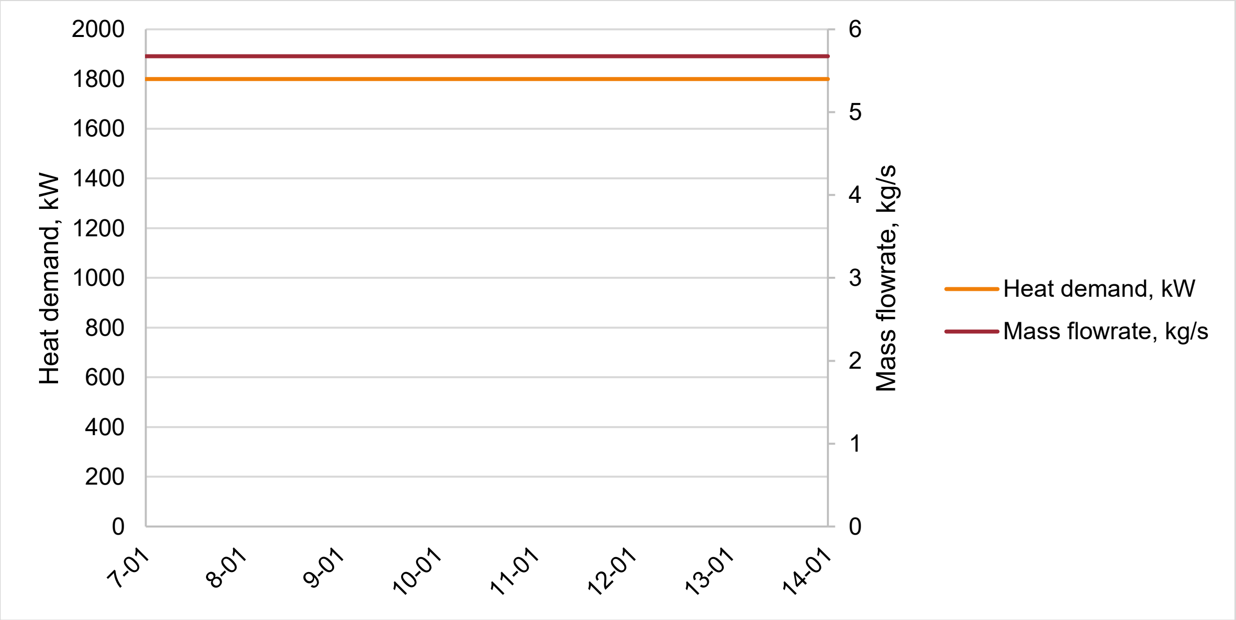

*Figure **15.** Heat demand and HOCLOOP water mass flowrate, direct air capture.*

Obtained results from simulations are presented in Table 13.

*Table **13.** DAC process simulation values and results.*

Parameter	Value
Injection temperature	40°C
Injection pressure	1.4 MPa
Heat supply temperature (steam)	100°C
Working fluid average mass flow (from HOCLOOP)	5.7 kg/s
Injection pump power	1.4 kW
Heat pump power	673.3 kW
Heat pump COP	2.7
ORC generator power	674.7 kW
Additional stream to ORC (from HOCLOOP)	49.1 kg/s

Annual demands and further results are presented in Table 12 below.

*Table **14.** Textile industry analysis results.*

Process	Annual heat demand, MWh_{th}	Annual power demand, MWh_e	Average mass flow, kg/s	ORC power, kW_e	Amount of HOCLOOP units (20 m^3/h)
Integrated textile processes	14 191.2	5 319.3	5.7	673.3	1 (excl. ORC)

e) <u>Others</u>

For the pre-heating process, the heat demand was assumed to be constant throughout the analyzed period. The simulation results are shown below. The average heat supplied by the HOCLOOP system is approximately 1.5 MW_{th}, with a corresponding steady water mass flow rate of around 6 kg/s.

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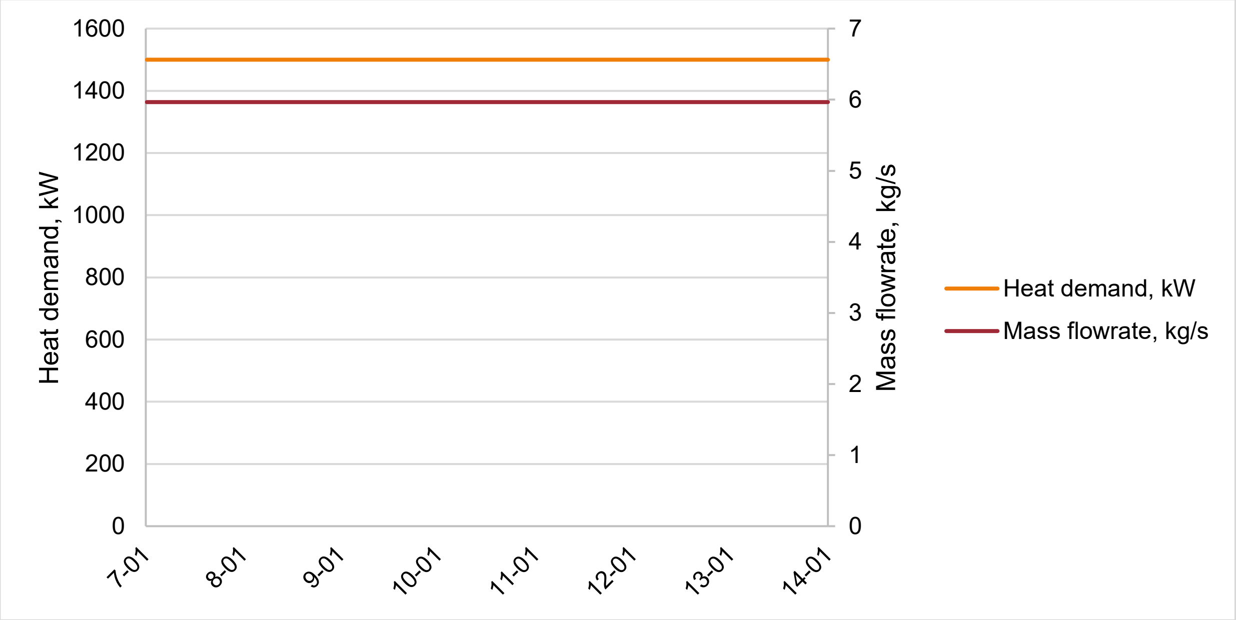

*Figure **16.** Heat demand and HOCLOOP water mass flowrate, pre-heating process*

Obtained results from simulations are presented in Table 15.

Table 15 Pre-heating process simulation values and results

Parameter	Value
Injection temperature	40°C
Injection pressure	1.4 MPa
Heat supply temperature (hot water)	90°C
Working fluid average mass flow (from HOCLOOP)	6.0 kg/s
Injection pump average power	1.8 kW_e

Annual demands and further results are presented in Table 16 below.

*Table **16.** Pre-heating analysis results*

Process	Annual heat demand, MWh_{th}	Annual power demand, MWh_e	Average mass flow, kg/s	ORC power, kW_e	Amount of HOCLOOP units (20 m^3/h)
Pre-heating process	11 826.0	13.8	6.0	n/a	1

2.3. Selection of promising pre-designs

Based on the analysis of energy requirements, integration feasibility, and environmental benefits**, three processes have been identified** as the most suitable candidates for detailed investigation: direct air capture (DAC), textile industry processes (fabric dyeing and bleaching), and pasteurization in the food and beverage sector. These processes present complementary characteristics that allow for a comprehensive evaluation of the HOCLOOP concept across different industrial applications.

Direct air capture is characterized by its high potential for emission reduction, as it enables the removal of CO_2 directly from the atmosphere. This process operates at relatively low regeneration temperatures of approximately 100°C, which are compatible with the heat output of the HOCLOOP system through heat pump application. The heat demand for DAC is stable over time, which simplifies system integration and allows for efficient use of geothermal resources without significant operational fluctuations. The constant load also facilitates the potential use of thermal energy storage to enhance system performance. From a climate mitigation perspective, integrating HOCLOOP with DAC offers a direct pathway to achieving negative emissions, making it a strategically valuable option for further study.

Textile industry processes, **particularly fabric dyeing and bleaching**, were identified as another promising area for detailed investigation. Both processes require low-temperature heat, typically within the range of 60-90°C, which can be efficiently provided by geothermal water without the need for additional upgrading technologies such as heat pumps. In addition, the heat demand for these processes falls within the operational capacity of modular HOCLOOP units. Fabric dyeing exhibits a variable but predictable heat consumption profile, while bleaching is characterized by stable demand throughout the year. These characteristics allow for the evaluation of system performance under both steady and fluctuating load conditions and provide an opportunity to assess the role of thermal storage in balancing demand variations. Furthermore, the possibility of direct use of geothermal water in some configurations enhances the integration potential.

The third selected process is **pasteurization in the food and beverage industry**, which is representative of low-temperature applications with high decarbonization potential. Pasteurization typically operates in the range of 60–80°C and is commonly heated using hot water or low-pressure steam. These conditions align well with the characteristics of the HOCLOOP system, enabling integration via indirect heat exchangers. The heat demand of medium-scale pasteurization facilities, typically around 1–2 MW, ensures continuous utilization of geothermal energy and supports efficient operation of the HOCLOOP unit.

The remaining analyzed processes were not selected for further investigation primarily due to their higher temperature requirements or complex integration needs, which reduce compatibility with the HOCLOOP concept. Processes in the pulp and paper sector, while partly matching the geothermal temperature range, either require steam conditions beyond the capabilities of the identified heat source or would need additional technologies. Chemical processes like solvent distillation and polymerization demand even higher temperatures, even up to 300 °C, which would necessitate high-pressure systems or auxiliary heating, significantly complicating integration. Likewise, sterilization in the food industry operates above the geothermal supply temperature and relies on pressurized steam, making direct use of geothermal heat unfeasible without upgrading technologies. Consequently, these processes were deemed less favorable compared to the selected options, where the geothermal system can be integrated more directly and efficiently.

3. Preliminary P&ID Plan

This section provides a generic Preliminary Piping & Instrumentation Diagram (P&ID) overview for each of the **three selected industrial integration cases**: Direct Air Capture, textile (fabric dyeing & bleaching), and food & beverage (pasteurization). The schematic descriptions outline the typical flow paths of heat transfer, core system components (such as pumps, heat exchangers, and control units), and key instrumentation points required for monitoring and control. In each case, the HOCLOOP geothermal loop is integrated with the industrial process to supply thermal energy, either directly through heat exchangers or with auxiliary equipment (e.g. heat pumps) for temperature boosting. The P&ID sketches are kept at a conceptual level, focusing on major equipment and control loops that ensure safe, efficient operation of the combined system.

3.1. Direct Air Capture (DAC)

In the **DAC integration**, the HOCLOOP closed-loop geothermal system provides thermal energy to drive the CO_2 sorbent regeneration process. The flow path begins with the geothermal working fluid (e.g. water or CO_2-based fluid) being pumped from the underground loop to a surface heat exchange unit. Given the DAC process's regeneration temperature of around 100 °C, an industrial heat pump is incorporated: the geothermal fluid releases heat in the evaporator of the heat pump, then returns to the subsurface after cooling. The heat pump's condenser generates a hot stream (low-pressure steam or hot water ~100–120 °C) that feeds the DAC unit's regenerator. In a common design, indirect steam heating is used – steam coils or a heat exchanger pass through the sorbent contactor, transferring heat without mixing steam into the sorbent or airflow. This avoids contaminating the sorbent and allows the condensed water to be recirculated. The core components include: the geothermal circulation pump, which maintains flow through the closed loop; the heat pump unit (with its compressor, evaporator, and condenser clearly indicated); and a regeneration vessel in the DAC system where CO_2 is released from the sorbent via heating.

Key instrumentation and control elements are placed to ensure efficient and safe operation. Temperature sensors (TIs) are installed at critical points, such as the geothermal fluid outlet (to monitor delivered heat temperature) and within the DAC regenerator (to maintain the target ~100 °C desorption temperature). Pressure gauges (PIs) and safety valves are positioned on the heat pump's high-pressure side and on the geothermal loop to protect against overpressure. A flow meter (FI) on the geothermal loop measures the working fluid circulation rate, ensuring it meets the required thermal output (~1.8 MW_{th} in the assessed DAC case). The heat pump includes control instrumentation: a pressure transducer on the compressor discharge and temperature probes on the evaporator/condenser to control the compression cycle. A central control unit (PLC) coordinates the system – for example, modulating the heat pump compressor and a three-way diverting valve on the geothermal loop to maintain setpoint temperatures. In practice, if the DAC plant's heat demand fluctuates, the control system could adjust geothermal flow or engage a small thermal storage buffer to smooth out transient loads, keeping the HOCLOOP operation steady. The preliminary P&ID thus ensures that the geothermal heat is delivered to the DAC process in a controlled manner, with all core components (pump, heat pump, heat exchangers) and instruments laid out for subsequent detailed design.

3.2. Textile industry (fabric dyeing and bleaching)

For the **textile integration**, the design serves the thermal needs of fabric dyeing and bleaching processes, which both require hot water in the ~60–95 °C range. The HOCLOOP system is configured in a direct heating loop supplying a closed hot-water circuit for the textile machinery. Geothermal fluid (hot water from the closed-loop well) is circulated through a primary heat exchanger that interfaces with the textile plant's heating circuit. In this configuration, a single geothermal heat loop provides energy to both dyeing and bleaching units, which have been combined at the same operating temperature for efficiency. The flow path is as follows: geothermal water at about 90 °C leaves the HOCLOOP outlet and enters a distribution manifold feeding two process heat exchangers – one associated with the dyeing vessels and another with the bleaching equipment. Inside these exchangers, heat is transferred to the process water that fills the dyeing/bleaching baths or jackets, raising their temperature to the required setpoint (for example, ~85 °C for dye fixation). The geothermal water, having given off heat (cooling down to 70 °C), merges and is pumped back into the subsurface loop to be reheated. Notably, no heat pump is needed here, as the geothermal output temperature is sufficient for the processes; this direct use simplifies the system and avoids intermediate conversions.

The P&ID highlights core components such as the geothermal circulation pump, the main heat exchangers/jacketed vessels at the dyeing and bleaching units, and a potential buffer tank in the hot water circuit. The buffer tank (or thermal storage) can mitigate the low mass flow issue that would arise if only a single low-demand dyeing load was served – by combining the loads, the system maintains a higher flow rate, improving HOCLOOP operational stability. Key instrumentation points include temperature indicators at the outlet of each dyeing/bleaching unit to ensure the process fluids reach the target temperature range (e.g. a thermometer in the dye bath jacket). Control valves are installed on the geothermal feed lines to each heat exchanger, modulating flow based on demand; these valves are controlled by feedback from the process temperature sensors to maintain each bath's setpoint. Pressure indicators on the pump discharge and return lines monitor the loop pressure, and a flow sensor measures the total geothermal fluid circulation to confirm it meets the combined load requirements. The control system coordinates the split of flow between the dyeing and bleaching sections: for instance, if the bleaching line (steady load) requires continuous heat while the dyeing line is in a heating phase, the PLC will allocate flow to ensure neither process is starved of heat. Safety devices like relief valves and emergency shut-offs are also indicated, protecting equipment from over-temperature or over-pressure conditions. Overall, the textile P&ID emphasizes a simple, direct coupling of geothermal heat to industrial hot water use, with straightforward controls to handle the dual-process integration and variability in load.

3.3. Food & beverage (pasteurization)

In the **food & beverage pasteurization integration case**, the HOCLOOP system is intended to supply the gentle heat required for pasteurizing products such as dairy, juices, or beer. Pasteurization typically operates at 60–80 °C, often using hot water circuits or low-pressure steam in heat exchangers to indirectly heat the product. The proposed schematic uses a direct integration of geothermal heat via an indirect heating loop. The geothermal fluid (water at ~80 °C) is circulated from the HOCLOOP wellhead into a plate heat exchanger (PHE) that serves as the pasteurizer's heating source. On the other side of this heat exchanger flows the product or an intermediate food-grade hot water loop that transfers heat to the product. For example, in a milk pasteurizer, milk flows through a section of a PHE where it is heated by hot water; in our integration, the hot water is supplied by geothermal energy instead of a boiler. After passing through the exchanger, the cooled geothermal fluid (perhaps dropping to ~60 °C) is returned to the closed-loop well to be reheated underground. Because the required temperatures are well within the geothermal output range, no heat pump is needed, and the HOCLOOP can directly cover the process heat demand with only standard heat exchange equipment.

The P&ID for the pasteurization system features the primary geothermal circulation pump, the pasteurizer heat exchanger unit, and a circulation pump on the product side or secondary loop. Often, pasteurization systems have a recirculating hot water loop (sometimes called a heat recovery loop) to maintain precise temperature control; in this design, the geothermal exchanger heats that loop. Key instrumentation includes a temperature sensor at the pasteurizer outlet to ensure the product reaches the mandated pasteurization temperature (e.g. 72 °C for milk). This sensor feeds a controller that regulates a control valve on the geothermal hot water inlet to the PHE, throttling flow to maintain the exact temperature setpoint. Additional temperature transmitters may monitor the geothermal fluid inlet and outlet of the exchanger to track how much heat is being transferred. A flow indicator on the geothermal line confirms that sufficient flow (on the order of magnitude of a few kg/s, depending on a ~1–2 MW heat duty) is being supplied to meet the pasteurizer's needs. Pressure gauges on the geothermal loop and the secondary loop safeguard against any pressure buildup, and a relief valve is included on the hot water circuit as a safety measure (since closed-loop heating systems must prevent overpressure when valves close). The control scheme, managed by the central PLC or dedicated PID controllers, can include interlocks such that if the product temperature starts deviating or if flow is lost, the system triggers an alarm or shuts off the product flow to avoid under-pasteurization. The schematic also notes the potential for a small thermal buffer tank in the hot water circuit, which can store excess heat if the pasteurizer throughput momentarily drops (ensuring the geothermal source isn't rapidly throttled). Overall, the preliminary P&ID shows a straightforward heat exchanger-based integration where geothermal energy reliably replaces conventional heating for pasteurization, with all necessary instruments in place for temperature control, flow management, and safety.

4. Summary

The integrated simulations and Key Performance Indicator (KPI) evaluations carried out for the HOCLOOP-industrial configurations yielded positive results, underscoring the technical viability and benefits of these concepts. **Across all the three selected cases** – DAC, textile dyeing/bleaching, and food pasteurization – **the energy performance of the systems proved robust**. The geothermal closed-loop units were able to supply the required thermal energy to each process, either directly or through auxiliary heat pumps, while maintaining stable operating conditions. In quantitative terms, the HOCLOOP units (sized based on real geothermal output data) **could deliver on the order of hundreds of kilowatts to a few megawatts of heat continuously, aligning with the typical process demands**.

Importantly, **the simulations provided detailed mass and energy balances and allowed assessment of defined technical KPIs.** In all cases, the share of heat provided by renewable geothermal energy was essentially 100% during operation, aside from minor electrical inputs for pumps or compressors. This translates to a dramatic improvement in the processes' energy sustainability metrics, with near-elimination of on-site combustion emissions. From an operational feasibility perspective, the HOCLOOP integrations demonstrate strong compatibility with industrial process requirements. The geothermal system's steady heat output is naturally suited for processes with relatively constant demand (e.g. the DAC unit or continuous bleaching line), and the studies confirmed that such steady loads allow the HOCLOOP to operate at its design point continuously for optimal performance. In cases where the heat demand is variable or batch-oriented (such as fabric dyeing cycles or certain batch pasteurization schedules), the simulations showed that supplementary strategies can effectively handle the fluctuation. One key strategy is the incorporation of thermal energy storage: by producing a constant geothermal output sized to the average load and storing surplus heat during low-demand periods, the system can release this heat during peak demand periods. This was evidenced in scenarios analogous to the pulp & paper drying analysis and similarly would apply to textile dyeing – effectively buffering the geothermal energy to smooth out the demand curve. The combined dyeing/bleaching model explicitly evaluated such an approach, finding that a modest hot water storage tank could stabilize supply without significantly oversizing the geothermal loop.

No insurmountable operational challenges were identified: the equipment operates within standard temperature and pressure limits, and integration with existing plant controls is feasible. The analyses also checked for any feedback effects – for example, how fluctuations in process heat uptake might affect the geothermal well temperature or pressure. Results indicated that with proper control, the subsurface loop remains stable, as the closed-loop design inherently buffers the well conditions (heat extraction is gradual and self-regulating to some extent). The sectoral alignment of the results confirms that the HOCLOOP concept can be a cross-cutting solution for industrial heat decarbonization. Each case study aligns with a broader sectoral need: supplying ~80 °C hot water to food processing, ~60–100 °C heat to textiles, and ~100 °C heat to emerging DAC technology covers a wide spectrum of uses. This suggests that HOCLOOP systems could be deployed in various industries with minimal customization, beyond selecting the right surface interfacing components (heat exchangers, heat pumps) to match the process.

The integration studies highlighted synergies with existing infrastructure – for example, using the geothermal heat in standard secondary loops means factories can retrofit HOCLOOP with limited changes to their internal distribution system. In the textile and food plants, the geothermal system essentially displaces the fuel usage of traditional boilers while working in tandem with their established heat exchangers and process controls. For DAC, which is often a standalone facility, the HOCLOOP provides a renewable heat source that can be co-located, avoiding the need for grid electricity or gas to provide the significant thermal energy DAC units require.

Notably, the **environmental impact across sectors is strongly positive**: by integrating geothermal energy, each use case achieves a high degree of decarbonization. The analysis estimated that replacing fossil heat with HOCLOOP in these scenarios can reduce annual CO_2 emissions by several thousand tonnes per facility, depending on the baseline fuel and plant size, directly supporting industry and climate goals. Moreover, coupling geothermal with DAC has the compounded climate benefit of actively removing CO_2 from the atmosphere, illustrating how industrial symbiosis with innovative technologies can amplify sustainability outcomes. Strategic recommendations are proposed based on these findings, to guide the next steps in the HOCLOOP project and its stakeholders.

Thus, from the point of view of the Task 8.3: Pre-feasibility studies for the industrial-relevant HOCLOOP concepts, the three selected processes were identified. These studies will delve deeper into site-specific considerations, economic feasibility, and practical deployment issues for each of three integration case. For example, they will assess capital and operating costs, payback under various energy price scenarios, and any regulatory or permitting considerations for installing closed-loop geothermal systems on industrial sites. The pre-feasibility analyses should also explore optimization opportunities noted in this deliverable – such as the sizing of thermal storage, integration of ORC for power co-generation (to run heat pumps or feed electricity to the plant), and the use of alternative working fluids (e.g. CO_2-based fluids) to enhance performance. Finally, as a bridge to Deliverable 8.3, a comprehensive assessment of industrial synergies will be deployed. This will consolidate the insights from multiple sectors to identify common success factors and potential challenges when scaling up HOCLOOP integration. Deliverable 8.3 will thus provide a holistic evaluation – combining technical, economic, and environmental perspectives – of how HOCLOOP can synergize with industrial energy systems at large.

In conclusion, **Deliverable 8.2 has established a solid conceptual and analytical foundation demonstrating**

that horizontal closed-loop geothermal systems can effectively supply and decarbonize industrial heat in various settings identified in Deliverable 8.1 by means of process modelling and simulation studies. The next steps will translate this concept into detailed feasibility and implementation pathways, moving the HOCLOOP solution closer to real-world application and contributing to the EU's sustainable industrial transition.

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