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Development and experimental characterization of an innovative adsorption chiller configuration for industrial cooling provision

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Abstract

The industrial sector in the EU accounted for 26.1% of final energy consumption. Electricity represented approximately 33% of this total, with around 150 TWh per year of electricity consumed to operate vapor compression chillers for process cooling—primarily at temperatures above 0°C.
In this background, the EU-funded RE-WITCH project is targeting the development and demonstration of innovative solutions exploiting low-grade waste heat, to provide process cooling in different plants, thus reducing the electricity consumption. One of the technologies under development is represented by a novel patented concept of adsorption chiller. It consists of two adsorber reactors working in counterphase, while the refrigerant, i.e. water, is contained in two separate vessels in its liquid phase and is distributed inside each adsorber reactor by means of hydraulic pumps. The refrigerant directly evaporates or condensates inside the adsorber reactor, over a pouring structure, and then carries over the cooling and condensation energy, that is exchanged with the external source and sink by means of plate heat exchangers.
A first full-scale prototype, with nominal cooling capacity of 20 kW has been developed. The system uses finned coil heat exchangers as adsorbers, embedded with microporous silica gel as the active adsorbent material. The design follows a modular approach, allowing multiple chiller units to be stacked together to meet the overall cooling demand of the process. Preliminary results are here presented, showing the ability of the technology to achieve up to 0.47 thermal COP with and EER above 30. A thorough characterization will be carried out at lab level in the coming months, to define complete performance map, identify the most effective control strategies to be implemented and identify the proper design improvements to be implemented for the next prototype that will be manufactured for the demonstration campaign in two industrial plants.

Keywords: adsorption chiller; COP; industrial cooling

1. Introduction

In 2020, the industrial sector in the EU accounted for 26.1% of total final energy consumption. This demand is primarily met by electricity (32.9%) and fossil fuels (48.5%), creating a strong dependence on these resources, many of which are imported from outside the EU [1]. Approximately 150 TWh per year of electricity is used for process cooling [2]—mainly in the food and beverage, tobacco, and light chemical industries—where cooling needs can represent up to 50% of total electricity consumption, typically for temperatures above 0 °C.

The industrial cooling market is currently expanding, with the U.S. market alone projected to grow at a compound annual growth rate (CAGR) of 10% between 2021 and 2027, and even higher growth expected in other regions [3]. Despite this expansion, the market remains dominated by electrically powered vapor-compression chillers because of their commercial maturity and reliability, which keeps thermally driven

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cooling technologies confined to niche applications. Yet, industrial processes in the EU generate an estimated 300 TWh per year of technically recoverable waste heat, about 35% of which is classified as low-grade (below 200 °C).

The development and validation of innovative thermally-driven cooling technologies could represent an alternative solution to reduce the electrical consumption in industrial cooling process, also valorizing low-grade waste heat sources. More specifically, the adsorption cooling technology has been proposed some decades ago, thanks to its ability to exploit low-temperature driving sources (e.g., 55-85 °C), the limited maintenance thanks to the reduced number of moving parts and the use of environmentally friendly materials, such as zeolites and silica gels, usually exploiting water as refrigerant [4]. Indeed, the adsorption chiller operating principle is based on the ability of some solid sorbent materials to be regenerated by low grade heat (waste/renewable heat), thermally compressing the refrigerant (water) thus replacing the mechanical compressor. A brief historical evolution of the different development stages of the technology, along with the companies who commercialized it, is represented in Figure 1. Each development stage presented some pros and cons. The first approach, marked as 1st Generation in Figure 1, reached the commercialization stage almost 30 years ago and is still, in large scale, employed. It is based on the so-called 4-chambers approach. Indeed, two adsorber reactors are connected to an evaporator and a condenser, each one included in a separated vessel. The connection among the different chambers is achieved by means of large vacuum valves, that guarantees the proper movement of the water vapor inside the machine. This system is flexible in operation, thanks to the use of separated evaporator and condenser heat exchangers, nevertheless, it results to be extremely expensive due to the use of large vacuum valves and vacuum vessels. Subsequently, the 2nd Generation was patented and put on the market in the first decade of the new millennium. The main innovation was related to the reduction to 2-chambers approach composed of an adsorber included in the same chamber with an evaporator/condenser. In this way, the need of large vacuum valves was reduced and, at the same time, the number of vacuum vessels was halved compared to the 1st Generation. On the other hand, having a heat exchanger acting alternatively as evaporator and condenser, depending on the cycle, was causing a performance reduction due to the need of re-conditioning the temperature level at each cycle, that was only partially compensated by an internal heat recovery process. Moreover, an external heat transfer interface towards the downstream process was always necessary, thus causing a further loss of efficiency due to the temperature losses in the system separation. Starting from the above-described experiences, recently, a novel approach was [5], reported as 3rd Generation in Figure 1. This solution tries to overcome most of the issues of previous designs, by providing the refrigerant (i.e. water) distribution in the liquid phase, thus making use of smaller valves (thanks to the higher density of the liquid compared to vapor) and having the direct evaporation and condensation inside the adsorber module, thus keeping the 2-chambers configuration. Moreover, the direct exchange between the liquid refrigerant and the external industrial process, by means of intermediate plate heat exchangers, allows to minimize the temperature level degradation both on the heat rejection and the cooling side. Clearly, this new design comprises also some challenges, related to the need of pumping liquid water inside the circuit at very low absolute pressure, requiring a properly sealed pumping technology, to guarantee the circuit tightness and careful design to avoid cavitation issues. The overall target of this new technology is to strongly reduce the costs both in terms of capital investment in the technology manufacturing and in the system adaptation and installation, thanks to the direct liquid refrigerant distribution, that increases the degree of freedom in customizing the integration according to the individual condition of the factory.

In the framework of the EU-funded RE-WITCH project [6], this technology is under development in order to be demonstrated in two different industrial plants, to provide process cooling in the range between 100 and 200 kW. More specifically, this paper presents, for the first time, the conceptual design of the first 20-kW module of the adsorption chiller with a detailed description of its main features against the state-of-the-art adsorption chiller technologies. Furthermore, the preliminary testing campaign is described, to highlight the main operating features of the manufactured prototype. The performance analysis will be further investigated by means of a dedicated testing campaign at lab level in the coming months, to obtain a complete performance map under a wide range of operating conditions, investigate different control strategies and also identify the main design parameters to be improved for the next version of the adsorption chiller that will be manufactured for the demonstration campaign in the industrial plants.

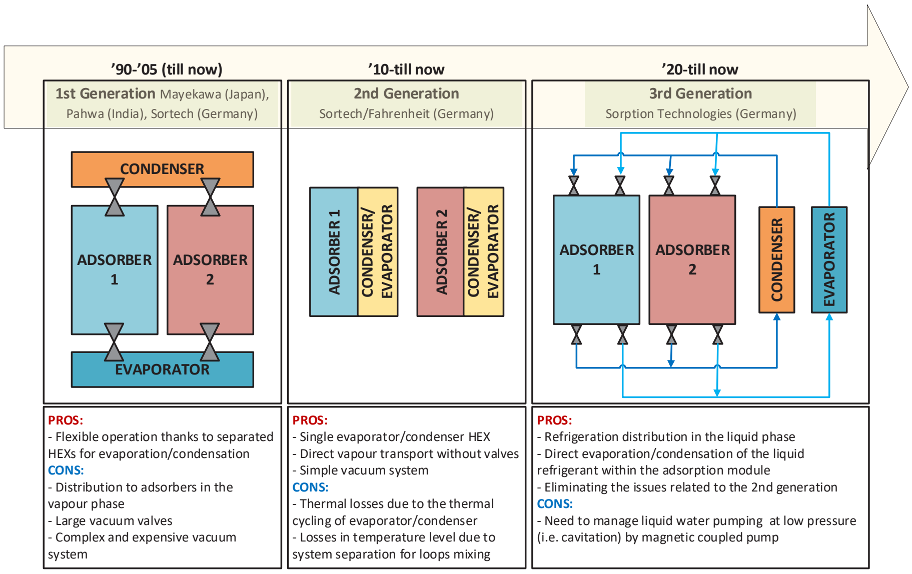

Figure 1: Historical evolution of the adsorption chillers architecture.

2. Prototype description

In this paragraph, the operating principle of the prototype as well as the main features of the manufactured machine are described.

2.1. Operating principle of the adsorption chiller

Figure 2a represents the conceptual layout of the developed adsorption chiller. As it can be noticed, the core of the machine is represented by the two adsorber reactors (AD1 and AD2) in which also the phase changers (evaporating/condensing structures) are integrated (PC1 and PC2). The refrigerant, water, is contained as liquid in equilibrium with its vapor inside two tanks at the bottom of the prototype, TKEV (evaporator tank) and TKCD (condenser tank). The water contained inside these two tanks is pumped by means of two submersible pumps (PumpEV and PumpCD respectively) [7]. The pumped water is firstly passed through a plate HEX (PHE_{EV} and PHE_{CD}), exchanging energy with the external source/sink, and then dropped inside the adsorber reactor onto the phase changers, to allow direct evaporation and condensation depending on the specific phase of the process. As for any adsorption chiller, the two reactors are operated in counterphase, accordingly, also in this configuration it is necessary to switch from adsorption to desorption operation and thus from evaporation to condensation on the refrigerant loop. For this reason, switching hydraulic valves are integrated in each circuit, to easily manage the switching from one phase to the other. Notably, thanks to the high density of the liquid water distributed inside the refrigerant loop, all these valves are characterized by a small diameter (i.e. DN25 or DN40) making their cost affordable compared to standard large vacuum valves commonly used in adsorption chillers where the refrigerant is distributed in the vapor phase. It has to be noted that, since the evaporator and condenser loop are interfaced with the external process by means of two plate HEXs, the medium temperature loop (i.e. the heat rejection loop) is split in two parallel branches, one connected to the condenser HEX and the other one extracting heat from the adsorber during the adsorption process. Accordingly, four different hydraulic loops are employed, allowing for a possible separation of the sinks used for heat rejection on the condenser and the adsorber. This also represents a peculiar feature of this configuration. Indeed, almost all the previous adsorption chiller configurations were employing a serial connection between adsorber and condenser, which was also penalizing the working cycle, due to the condensation happening at a temperature higher than the theoretical one. In this case, thanks to the parallel connection, the inlet temperature to adsorber and condenser is the same, thus realizing the 3-temperatures theoretical working cycle.

2.2. Manufactured prototype

The manufactured prototype is represented in Figure 2b, while connected to the testing rig.

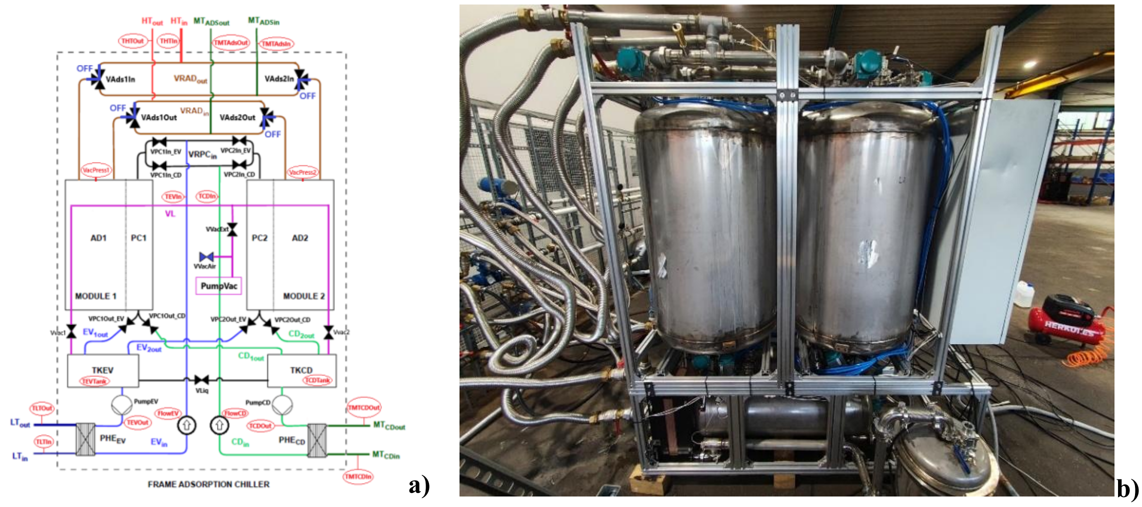

Figure 2: Prototype description: a) prototype system layout ; b) prototype manufactured and installed during the preliminary testing campaign.

As it can be noticed, the adsorber reactors consist of two large cylindrical vessels. The cylindrical shape was selected due to the large diameter of the reactor necessary to allocate both adsorber HEX and phase changers. Thus, employing this shape, the manufacturing cost can be minimized by making use of standard size cylinders and reducing the thickness of the reactor itself, thanks to the higher resistance to the mechanical stresses induced by the vacuum conditions under which the machine is operating. At the same time, this configuration requires less effort in the manufacturing process, employing standard welding procedures compared to more complex solutions (e.g. parallelepiped chambers). Similarly, at the bottom, two small cylindrical vessels are placed horizontally to hold the liquid refrigerant and are interfaced to two submersible pumps used to transport the refrigerant inside the machine' piping.

The selected adsorbent material is a microporous silica gel, this was chosen thanks to its wide availability on the market coupled with its reduced cost, which, at this stage, makes it as the only option for a large scale commercialization of this technology. The adsorber is then obtained by embedding the adsorbent material spheres inside a commercial finned tube bundle HEX.

The main features of the manufactured prototype are summarized in Table 1.

Table 1: Main features of the manufactured adsorption chiller prototype.

Nominal cooling capacity	20 kW
Overall dimensions (L x W x H)	1.74 x 08 x 2.10m
Weight	ca. 800 kg
Adsorbent material per each adsorber	ca. 75 kg
Submersible pump	EBARA BEST/A 2

3. Preliminary characterization results

The manufacturing of the prototype was recently completed and, at this stage, only the preliminary characterization was performed, which can be considered as a sort of pre-commissioning phase, to make sure that the machine is operating as planned. In the following, the obtained results are presented.

Table 2 summarizes the selected testing conditions. Different inlet temperatures were set at each loop, namely, high, medium and low temperature, while the flow rates were kept constant for all the performed tests. Also the cycle phases allocation was always the same under the different conditions, characterized by equal adsorption and desorption duration, set to 350 s each, as well as same duration for pre-cooling and pre-heating phases, 35 s each. Moreover, a fifth phase, with 30 s duration is included at the end of each complete cycle, necessary to transfer the refrigerant from the condenser to the evaporator tank. It represents a phase equivalent to the standard lamination happening in a machine with separated condenser and evaporator, where the refrigerant stored in the condenser is laminated down to the evaporator pressure using a capillary tube.

Table 2: Preliminary testing campaign performed.

Test N.	HT Inlet T [°C]	MT Inlet T [°C]	LT Inlet T [°C]	HT Flow rate [m³/h]	MT Flow rate [m³/h]	LT Flow rate [m³/h]
1	85	32	20	7.55	12.06	7.55
2	85	32	16	7.55	12.06	7.55
3	85	32	12	7.55	12.06	7.55
4	75	32	16	7.55	12.06	7.55
5	75	27	16	7.55	12.06	7.55

The testing procedure implemented a standard approach, according to the following stages:

- starting phase, during which the steady state conditions were reached in each hydraulic circuit in terms of inlet temperature and heat transfer fluid flow rate;
- measuring phase, during which at least 5 consecutive operating cycles were monitored and acquired. All the relevant parameters, temperatures, flow rates, pressures, electric consumption, were monitored;
- post processing phase, during which the acquired data are processed to evaluate the main performance indicators, such as thermal COP, Energy Efficiency Ratio and average cooling power.

The definitions of the performance indicators are reported below.

Thermal COP:

$$COP = \frac{Q_{LT}}{Q_{HT}} \tag{1}$$

Where Q_{LT} [kJ] is the cooling energy measured over the five consecutive cycles; Q_{HT} [kJ] is the high temperature driving energy again evaluated over the five consecutive cycles.

Energy Efficiency Ratio (EER):

$$EER = \frac{Q_{LT}}{Q_{El}} \tag{2}$$

Where Q_{El} [kJ] is the electric energy consumption internal to the chiller, due to the pump necessary to let the refrigerant flowing inside the machine as well as the other auxiliaries (e.g. valves, compressor for activating the pneumatic valves etc.)

Average Cooling Power (P_LT_{AVE}):

$$P_{LT_{AVE}}\,[kW] = \frac{Q_{LT}\,(cycle)}{\tau_{cycle}} \tag{3}$$

Where Q_{LT}(cycle) [kJ] is the cooling energy measured during each cycle; τ_{cycle} [s] is cycle time.

Figure 3a and b present the dynamic evolution of both temperatures and powers measured during a reference cycle, using 85 °C as inlet HT temperature, 32 °C as inlet MT temperature and 20 °C as inlet LT temperature. As it can be noticed, the inlet temperatures are kept almost constant throughout the test, with a slight oscillation of ±1.5 °C, due to the control of the testing rig. The dynamic temperature evolution is the typical one of an adsorption chiller, where the temperature difference across the adsorber, both in desorption (HT) and adsorption (MT_Ads), is varying a lot during the cycle, depending on the degree of saturation of the adsorbent material. Indeed, a peak temperature difference, and power, is highlighted at the beginning of the cycle, with a progressive reduction when the cycle progresses. On the other hand, both cooling and condensation temperature differences and power are more stable, this is due to the presence of the refrigerant tanks at the bottom of the machine, that smooths the temperature fluctuation on both cold and medium temperature cycle. As it can be seen in Figure 3b, only HT and LT power are reported, since the MT cannot be directly calculated in this testing rig configuration, since the flow meter is measuring the entire flow provided to the MT circuit with no distinction between condenser and adsorber. Nevertheless, as it can be noticed from the above-reported performance figures, the direct measure of the Q_{MT} is not necessary to evaluate the performance. In the same picture, also the electric power is reported, resulting in a quite flat value, slightly above 500 W. This confirms the extremely low electric consumption expected for this machine.

Starting from the data above reported, measured for each testing conditions, as well as the performance indicators described, Figure 4 summarizes the obtained results, trying to elucidate the effect of LT inlet temperature (Figure 4a), MT inlet temperature (Figure 4b) and HT inlet temperature (Figure 4c).

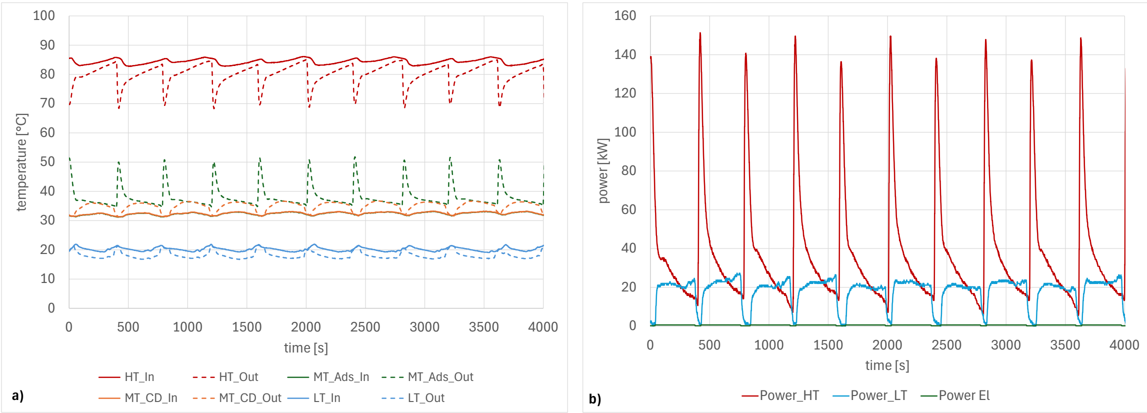

Figure 3: a) temporal evolution of inlet and outlet temperatures in the four circuits of the adsorption chiller and, b) thermal and electrical power measured, during the reference test: HT_In: 85 °C, MT_In: 32 °C, LT_In: 20 °C.

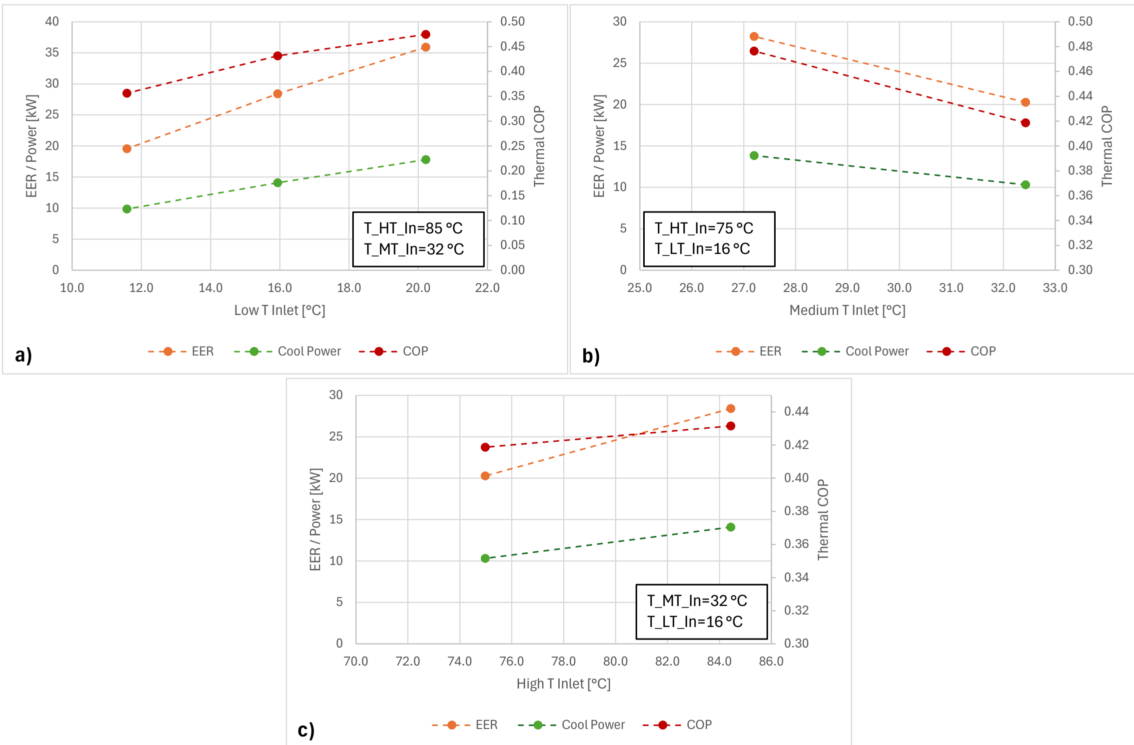

Figure 4: Preliminary results of the prototype testing: a) effect of the low temperature inlet (at constant high and medium inlet temperature); b) effect of the medium temperature (at constant high and low inlet temperature); c) effect of the high inlet temperature (at constant medium and low inlet temperature).

As it can be noticed, the thermal COP is varying in a range between 0.36 and 0.47, considering the use of silica gel as adsorbent material, this looks in line with previous results reported in the literature for small-size adsorption modules [8]. This confirms that, despite the modification of the chiller architecture, no major impact on the achievable performance is highlighted, confirming a good heat and mass transfer inside the reactor and a high efficiency of the integrated phase changers. At the same time, the EER varies in a range between 20 and 36, resulting in a very promising technology to reduce the electricity consumption due to cooling demand in industrial processes. For what it concerns the cooling power, as expected it is strongly affected by the evaporation temperature, dropping from about 18 kW when the evaporation inlet temperature is 20 °C down to 10 kW when the evaporation inlet temperature is slightly below 12 °C (considering HT inlet temperature of

85 °C and MT inlet temperature of 32 °C). It is interesting also to note that the COP is only marginally affected by the inlet HT temperature, while the power and the EER are more impacted with a reduction of about 27% passing from 85 °C down to 75 °C. The different behavior between COP and EER is related to the fact that the COP is linked to the working cycle, meaning that, once the conditions are varied, both Q_{HT} and Q_{LT} vary in the same way, thus keeping the ratio almost constant. Differently, the electric consumption is always the same, thus the cooling power reduction is reflected in a proportional EER reduction

Overall, the results are encouraging and will be further deepened in the coming months to define the final design of the chiller.

4. Conclusions and next steps

This paper presented the conceptual design and preliminary experimental characterization of an innovative adsorption chiller concept for industrial cooling applications. The target of this technology is to achieve lower manufacturing cost and easier integration in existing industrial processes.

The first 20-kW module manufactured was described and the preliminary testing campaign introduced, showing good results in terms of thermal COP, varying in a range between 0.36 and 0.47, and EER which reached values up to 36.

The preliminary results did not consider other aspects such as the optimal control strategy, the cycle time allocation, the variation of the heat transfer fluid flow rate and other possible factors affecting the achievable performance. It will be then further investigated and characterized at in the coming months, aiming at optimizing its operation and defining review design routes that will be implemented in the larger scale prototypes that will be manufactured for the demonstration campaign that will take place in two industrial plants, a brewery and a paper mill, starting from 2027. Starting from the experimental results obtained in the lab, also an optimization through numerical modelling will be carried out.

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