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A Case Study of Heat Recovery: A Heat Pump in an Industrial Site

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ABSTRACT

Greenhouse gases cause global warming of the earth. Carbon dioxide is one of those gases. There are different sources of carbon emission such as industrial activities and deforestation. The application of energy efficiency in industrial environment is one lever to reduce carbon emissions. "Waste" heat represents a significant energy saving potential for industrial companies. Thanks to recovery technologies, waste heat resulting from a process that is not used by it can be recovered for other uses within the same plant or outside. In addition to the economic interest, the recovery of fatal heat is very virtuous from an ecological point of view if the recovered energy avoids the consumption of fossil fuel. It thus improves the carbon footprint of an industrial installation. This article is a case study in an industrial pharmaceutical site in France and explains how a heat pump has been implemented. All the steps of the methodology are detailed: deep analysis of waste heat from the site, calculation and measurement of the reuse potential and research of the most suitable technology to carry out this recovery. This study has permits to reduce by 1/3 site's carbon emissions.

Index Terms: *carbon emissions reduction, heat recovery, heat pump.*

I. INTRODUCTION

Fatal heat is the heat "lost" by an industrial process which releases thermal energy. This may be, for example, fumes from combustion, cooling water, vapors, steams, conditioning air, etc.

To recover the fatal heat, heat pump technologies are more and more used which make it possible to recover heat at low temperature and then to reinject it into a fluid at higher temperature [1, 2]. This equipment is complex and consumes electricity, but it nevertheless allows a more efficient heat transfer. They operate using a refrigerant that circulates in a closed loop through an evaporator, compressor, condenser, and expansion valve, and undergoes several changes of state (liquid/gas). This technology has become widespread over the past ten years.

For implementing a waste heat recovery system, the recovered energy must be able to be used, either by saving another primary energy source within the industrial installation, or by being sold nearby, to an industrialist or to an urban heating network. In addition to the purely technical aspects which are complex, it is also necessary to understand the possible intermittences of the recovered energies and the non-simultaneity between the recovered heat and the non-recovered heat.

This case study is about a successful implementation of a heat pump in a pharmaceutical company.

A. Strategy

The philosophy is to consider the energy required by the process and ensure that this energy is delivered in the most efficient way (deliver the maximum savings with minimal capital in the fastest possible timeframe).

For that each cooling/heating system on the site has been considered, first as a discrete system and then as a whole system (there is often the opportunity to combine systems).

It is more precisely a three-phase approach:

1. Before the central plant can be considered (where the large savings are realised), the user loads must be considered. This is the most important stage, and it ensures

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that the process conditions are met in the optimum way.

2. Following this, the distribution system must be analyzed to ensure that the utility is delivered at the correct conditions.
3. Once we have established the correct requirements for the users and distribution system, we can address the generation of the utility and consider energy reduction opportunities at the central plant.

B. *Heat pump introduction*

A heat pump in its simplest form is a refrigeration unit that utilizes the heat normally rejected for heating [3, 4]. The term heat pump is used to cover a variety of applications, including air source or ground source heat pumps, but these reject the cooling either into the air or into the ground and the cooling is wasted. The main purpose of an industrial heat pump is to always use the cooling and the heating to ensure the highest system efficiency.

C. *Refrigerant*

A refrigerant is a fluid that allows the implementation of a refrigeration cycle.

Figure 1 shows a pressure-enthalpy chart for the refrigerant R134a with a standard refrigeration cycle superimposed in red, and a heat pump cycle shown in blue [5].

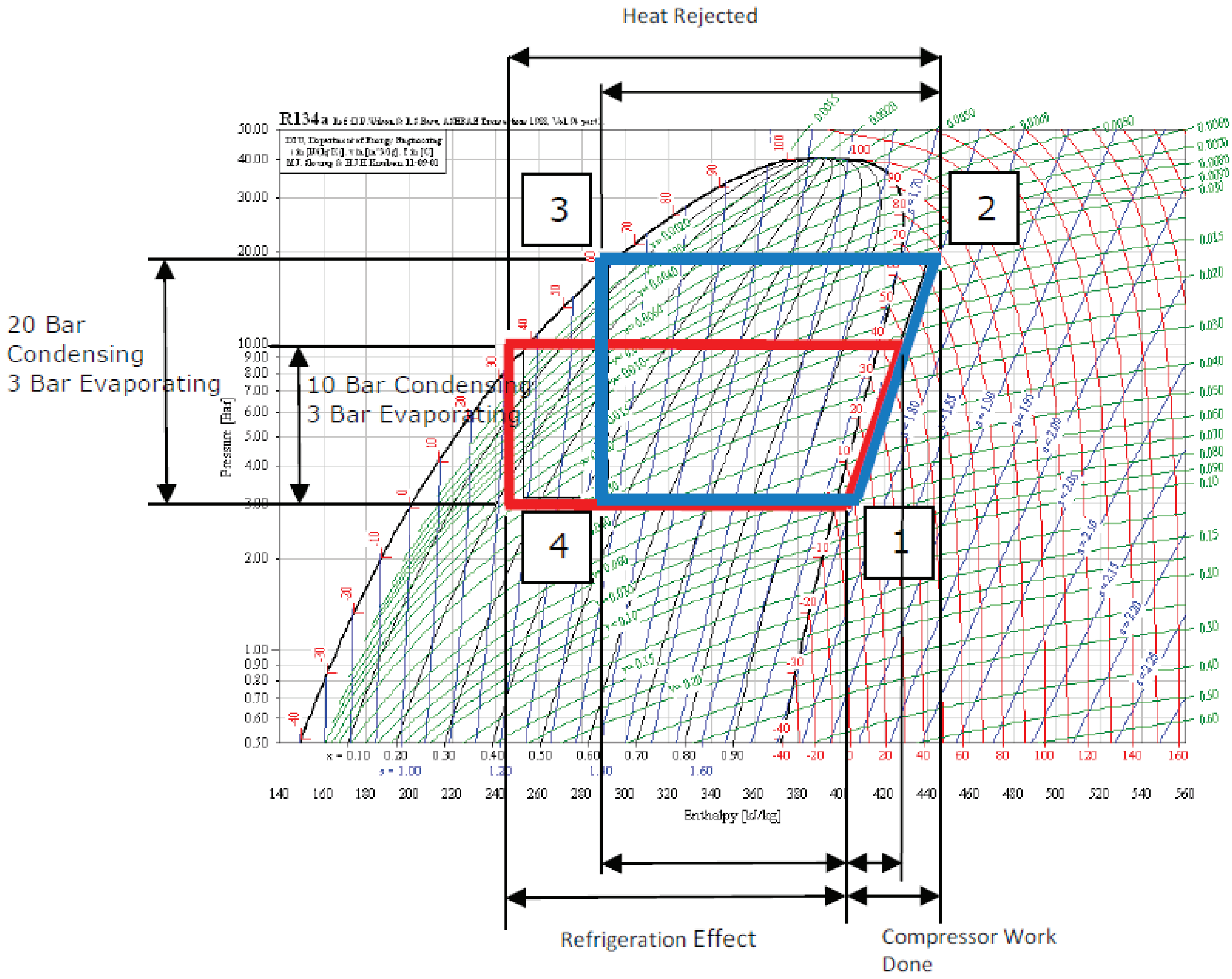

Fig. 1. Pressure-enthalpy chart for refrigerant R134a

As can be seen in figure 1, to create higher grade hot water we need to raise the condensing pressure/temperature, from 10 Bar (45°C) to 20 Bar (65°C). By raising the condensing pressure, this increases the work done of the compressor and the refrigeration duty is reduced. Heat pumps need to be considered as a heating device with cooling as a bonus.

The refrigerant is the working fluid of the system, and refrigerants have different properties that affect their suitability for heat pump applications [6]. To produce hot water at 85°C a condensing temperature of approximately 95°C and 56.6 Bar is necessary.

Research of the most suitable refrigerant for this study:

R404a – This is a common refrigerant, but it is not suitable for high temperature due to a low critical point of 71°C. For any temperature above this point, the refrigerant cannot be condensed and turned into a liquid. Many other refrigerants are of a similar nature.

R134a – This refrigerant has a higher critical point: 101°C at 39.7 Bar. This could be suitable for a heat pump application.

R717- Otherwise known as Ammonia. As soon as we look at high temperature heat pumps, we need to look at industrial refrigeration. The critical point of Ammonia is 132°C at 113 Bar, so we would be working well within the characteristics of the refrigerant. Ammonia has a major inconvenient: it is a health hazard.

R744 – Otherwise known as CO2, this is one of the oldest refrigerants and is currently going through a renaissance. CO2 has many properties that make it attractive for heat pumps, however, to produce hot water in the region of 85°C would require CO2 to work above the critical point of 74 Bar at pressures in the region of 120 Bar range and into the transcritical zone (120 Bar is the maximum pressure of the current compressor technology). Many supermarkets are adopting CO2 technology. However, this technology is still in its infancy, and has not been scaled up for larger industrial duties.

To summarize, whilst there are many refrigerants suitable for heat pumps, R134a is the best choice for this study. Ammonia equipment are also available, but these are bespoke and, whilst they can achieve a higher temperature of hot water, they are more expensive, and ammonia is a health hazard.

II. CASE STUDY DETAILS

A detailed study is launched because it allows the projected solution to be dimensioned, designed, and customized with precision. The first step was to analyze deeply the current chilled water (heat waste emitter) and hot water systems (heat waste receiver).

A. *Chilled Water System*

The chilled water system in the site comprises:

- 1 x 937kWt chiller as represented in figure 2; Manufacturer = Trane; Model = RTHD; Refrigerant= R134a; Manufactured in 2010; Fitted with Variable Speed Drive (VSD)
- 1 x 750kWt chiller; Manufacturer = Trane; Model = RTHC; Refrigerant= R134a; Manufactured in 1996
- 2 x 1005kWt chiller; Manufacturer = Trane; Model = RTHA; Refrigerant= R134a; Manufactured in 1992
- 3 x 15kWe fixed speed primary pumps
- 3 x 15kWe fixed speed condenser water pumps
- 2 x Cooling Towers (2066kWt and 1714kWt); Manufacturer = Evapco; Cooling Towers fitted with 15kWe Variable Speed Drive fan; Manufactured in 2010 and 2015
- A set of secondary pumps (from 1.5kWe to 17.5kWe)

The system is configured as a low loss header/balance tank system with fixed speed primary pumps and variable speed secondary distribution pumps. There are two balance tanks on the system, one is a smaller balanced tank located in the chiller plant room with three sets of small secondary distribution pumps, the other is a larger balance tank on the second level above the chiller plant room which has five sets of secondary distribution pumps.

The chillers are run with a set point of 5°C. Site has 4 four Trane water cooled screw chillers.

Fig. 2. 937kWt chiller

The lead chiller (Trane RTHD variable speed screw compressor 937kWt) was installed in 2010. It has a relatively good design efficiency (COP) of 6.56 kWe/kWt when run with 27°C cooling water. The COP of the system improves when run with reduced cooling water temperatures but decreases when run at low part loads. The chiller runs with a chiller set point of 5°C with a refrigerant evaporating temperature of 3.7°C. The chiller is supplied with 23°C cooling water and runs with a refrigerant condensing temperature of 27.5°C.

The 750kWt chiller starts when the demand is high to assist the lead chiller. It is a fixed speed screw compressor chiller that utilizes R134a as a refrigerant. The chiller has the same COP than the biggest chiller. The other chillers also start depending on the demand to assist the two chillers already running (start priority order).
Most of the cooling loads are HVAC providing both room temperature control and dehumidification. There is also a small amount of cooling for the purified water plant, vacuum plant and others process equipment.

B. Hot Water System

The low temperature hot water system in the site comprises:

- 2 x 2500kWt gas fired hot water boilers: Manufacturer = Guillot
- 3 x 3kWe fixed speed primary pumps (duty/standby/spare)
- 2 x 15kWe VSD speed secondary distribution pumps (duty/standby) supplying hot water to process equipment
- 2 x 15kWe VSD speed secondary distribution pumps (duty/standby) supplying hot water to HVAC
- 2 x 3kWe VSD secondary distribution pumps (duty/standby) supplying hot water to the washer
- 2 x 1kWe VSD speed secondary distribution pumps (duty/standby) supplying hot water for domestic water system
- 2 x 0.75kWe VSD secondary distribution pumps (duty/standby) supplying hot water to Administrative Offices heating

Site has a central boiler control system which automatically stops and starts the boilers and primary pumps. This system also opens and closes the actuated hot water isolation valves on the boiler. The system is configured as a low loss balance/header system with fixed speed primary pumps and fixed speed secondary distribution pumps. Typically, one boiler primary pump is run per boiler.

The boilers such as the one represented in figure 3 are conventional water storage boilers with a large volume of hot water stored within the boiler. Such boilers have a typical efficiency of approximately 80%. When running at low boiler loads (i.e., less than 40%) the efficiency of the boiler will reduce slightly down to approximately 75% as the storage losses increase. The boilers control themselves to maintain the required hot water temperatures in the hot water system.

Fig. 3. Hot water boiler

The hot water system is run at different temperatures depending on the day of the week and the season. During the week the hot water system is run at 84°C, this is increased to 90°C in the middle of winter to enable the washer to maintain the required water temperatures when the inlet water temperature is low. Out of production hours, i.e., over the weekend the systems water temperature is reduced to 70°C as production plant is not in use.

The hot water user loads can be split into the following groups:

- **Washer water heater:** The washer heater is a heavy-duty heat exchanger which utilizes hot water to heat domestic water or purified water for use in the washer up to a minimum temperature of 55°C.

- **Washer drying air battery:** There is a drying process at the end of washing process which utilizes hot dry air generated by the washer drying battery. The washer drying battery is a relatively small heating battery that heats 100% fresh air up from ambient temperatures to 70°C.

- **Air Pre-treatment for Coating equipment:** Site has 4 coater units which require a supply of hot dry air. This hot dry air is generated using a combination of desiccant dryers and air heating batteries. Hot water is used to preheat the regeneration air on the desiccant dryers. The typical air temperatures achieved using the regeneration air preheaters is 60°C. The desiccant driers also have electric heating elements which are used to heat the regeneration air up to the required regeneration temperature of 120°C. When running, both the hot water heating and electric heating elements are run at 100% to maintain the required air regeneration temperature. If the temperature of the hot water is decreased below 80°C, the performance of the coating equipment is adversely affected. The coating machines also have a hot water heating coil which is used to heat the dried process air leaving the desiccant dryer. The temperature of the process air leaving the desiccant dryer is typically 30-40°C and needs to be heated to 60 to 65°C.

- **Heating batteries for desiccant dryers of heating ventilation and air conditioning (HVAC) systems:** Site has 20 desiccant dryer dehumidification units which are used to control the humidity levels in the rooms. The humidity set points in the rooms vary from 20 to 50% Relative Humidity (RH). Most of the desiccant dryers (17 of the 20 unit) utilize hot water to pre6 heat the regeneration air with electrical heating elements integral to the units being used to further heat the air up to the required desiccant regeneration temperatures. This regeneration temperature varies depending on the amount of dehumidification that needs to be achieved. The temperature of the air leaving the hot water air preheating batteries is at approximately 60°C. Site has a HVAC turndown procedure for weekend operation, where some HVAC units are turned off and other units have their temperature control and humidity control dead band limits extended.

- **Heating Batteries for HVAC room temperature control:** Some of the HVAC units also have small frost coils installed on the fresh air supply which is used to prevent the HVAC coils from freezing when outside ambient air temperatures are low (less than 0°C). They are relatively small heaters and are supplied from the same hot water pumps as the HVAC heating batteries. As these batteries are only heating air to 5-10°C there should be no issues with running these units with water down to 60°C if required.

- **Frost coils for HVAC equipment:** Some of the HVAC units also have small frost coils installed on the fresh air supply which is used to prevent the HVAC coils from freezing when outside ambient air temperatures are low (less than 0°C). They are relatively small heaters and are supplied from the same hot water pumps as the HVAC Heating Batteries. As these batteries are only heating air to 5-10°C there should be no issues with running these units with water down to 60°C if required.

- **Offices heating batteries:** There is a separate set of hot water secondary distribution pumps used for heating the offices for comfort control. Such as for the HVAC heating batteries, it is expected that these units will operate running with 60°C hot water as air off temperature of 18-22°C are required. The system is also very small with the secondary distribution pumps only being 0.75kWe.

- **Sanitary Water for Domestic Use: There is a separate sanitary** hot water circuit which circulates around the site for supplying 50°C water for hand washers, etc. This system is heated using hot water from the main hot water system via a heat exchanger in the plant room. There is a dedicated 1kWe pump set which is used to supply hot water to the heat exchanger. The pump is configured as an attemperation loop

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and controlled to maintain the 50°C sanitary hot water temperature in the system. The sanitary hot water system would be able to maintain the required temperature if the temperature of the main hot water system was reduced to 60°C.

III. HEAT LOST AND HEAT NEED

A. Heat Lost Capacity

To determine the heat lost capacity, all the data have been gathered and analyzed with the help of a software dedicated to chiller system. After calculation, the heat lost capacity of chilled water system is 15.8 GWh GCV/year (GCV = Gross Calorific Value) as shown in TABLE I.

TABLE I. HEAT LOST ESTIMATION BY CALCULATION

Heat Lost	Fluid	Flow (m^3/hour)	Temperatures		Power (kW)	Duration (hour/year)	Energy (MWh GCV/year
			Entry (°C)	Exit (°C)			
Cooling Towers	Water	200	25	23	418	8 751	4 957
Chillers	Water	297	7	4	986	8 751	10 833

Then, the calculations have been verified through measurement, thanks to instrument and software. Figure 4 represents flow, entry and exit temperatures.

Below is the correspondence of the curves in figure 4:

- Green curve = Flow; Average = 263 m3/h
- Red curve = Entry temperature; Average = 6.7°C
- Blue curve = Exit temperature; Average = 4.3°C

We can observe that calculation and measurement results are close (also the measuring accuracy of the devices is to be considered).

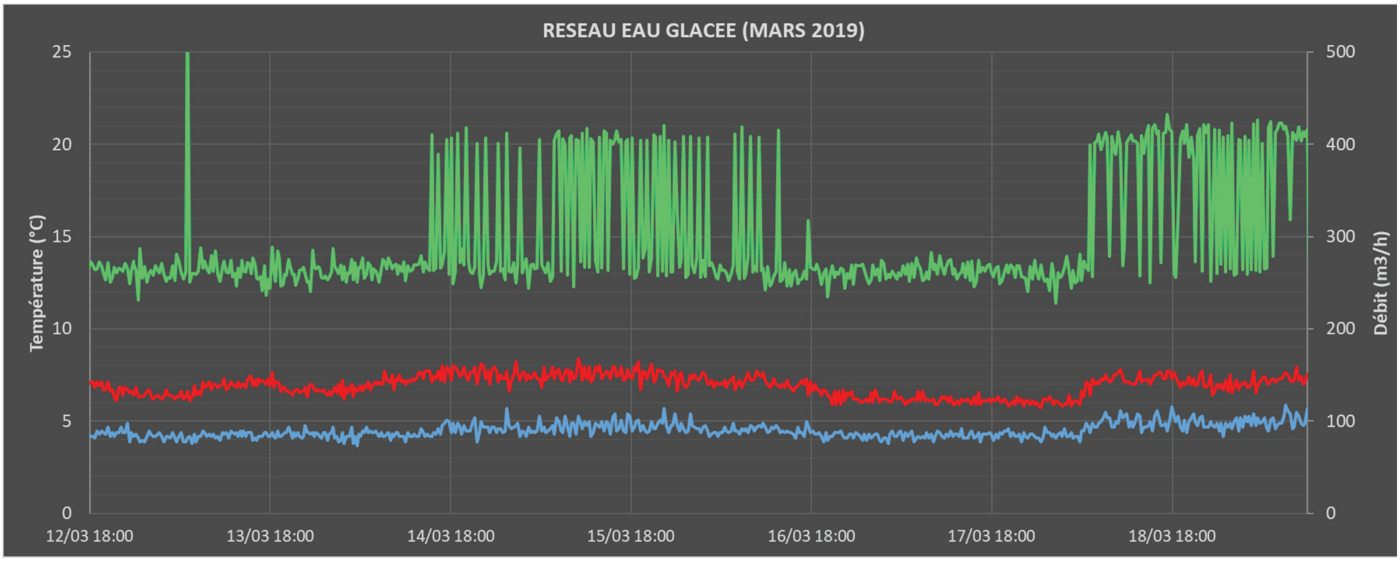

Fig. 4. Heat lost estimation by measurement

B. Heat Need

To determine the heat need, all the data have been gathered and analyzed with the help of a software dedicated to hot water system. After calculation, the site heat need is 4.9 GWh GCV/year as shown in TABLE II.

TABLE II. HEAT NEED ESTIMATION BY CALCULATION

Heat Need	Fluid	Flow (m^3/hour)	Temperatures		Power (kW)	Duration (hour/year)	Energy (MWh HHV/year)
			Entry (°C)	Exit (°C)			
Hot Water (boilers)	Water	107	77	80	453	8712	4951

Then, as for heat lost, the calculations have been verified through measurement, thanks to instrument and software. Figure 5 represents flow, entry and exit temperatures.

Below is the correspondence of the curves in figure 5:

- Purple Curve = Flow; Average = 105 m3/h
- Green curve = Start Temperature; Average = 81.0°C
- Orange curve = Return Temperature; Average = 75.7°C

The heat lost can satisfy the site need on hot water. Nevertheless, there is a seasonality effect to take into consideration.

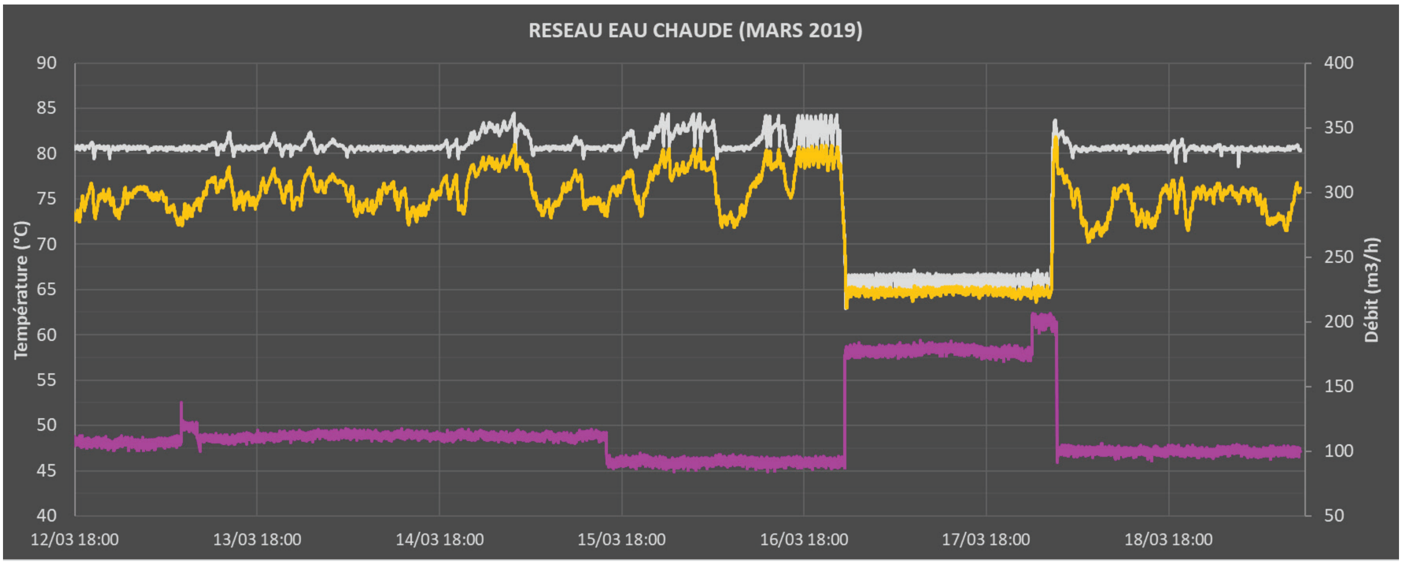

Fig. 5. Heat need estimation by measurement

C. Heat Pump Selected

The manufacturer of the heat pump is Ochsner (Austrian company). As seen in figures 6 and 7, it is an equipment with large dimensions.

Below are the main characteristics of the heat pump:

- Type of refrigerant and quantity: R134a/130 kg
- Heat pump weight: 4400 kg
- Range regulation: 50% to 100%
- Display touch screen
- Modbus communication
- System state: temperatures, pressures, time running operation, percentage load, electrical consumption, default fault, etc.
- Settings: art walk / stop via Modbus or contact, selecting set point, etc.

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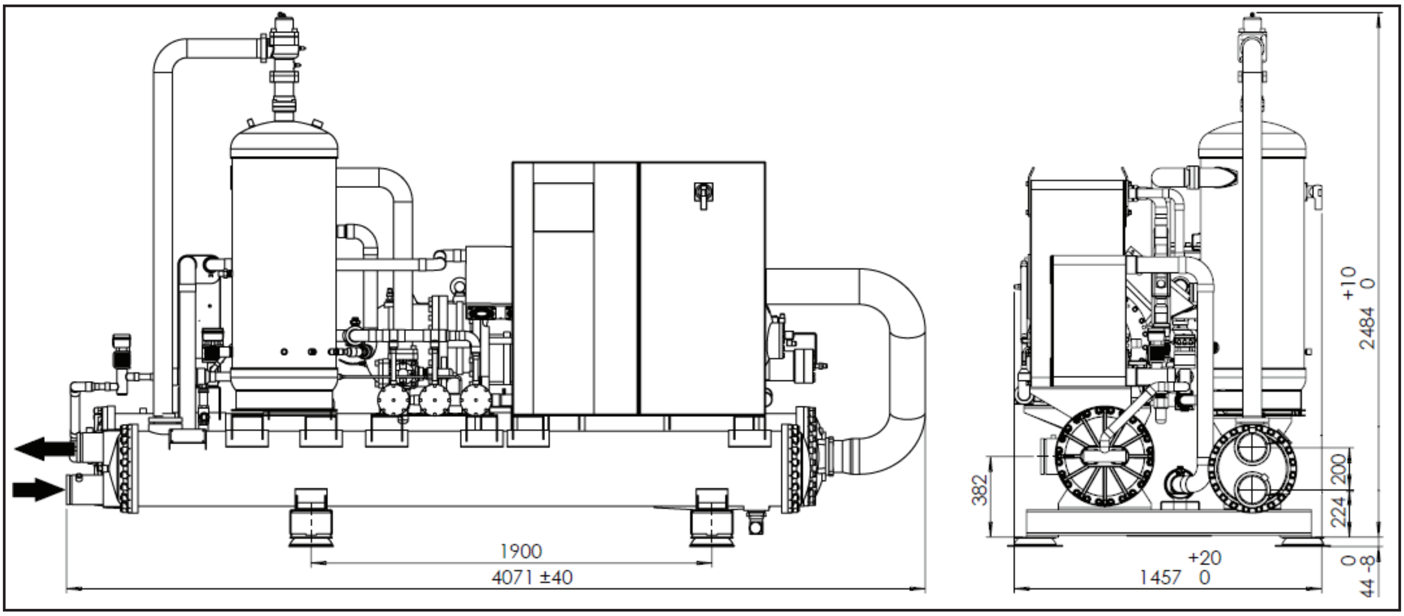


Fig. 6. Front and side drawings of the heat pump

Fig. 7. Rear view picture of the heat pump

D. Design of the Whole Heat Pump Installation

As shown in figure 8, the heat in the water entering in the cooling towers and the heat in the water entering the chillers are taken and reinjected in the hot water installation [7].

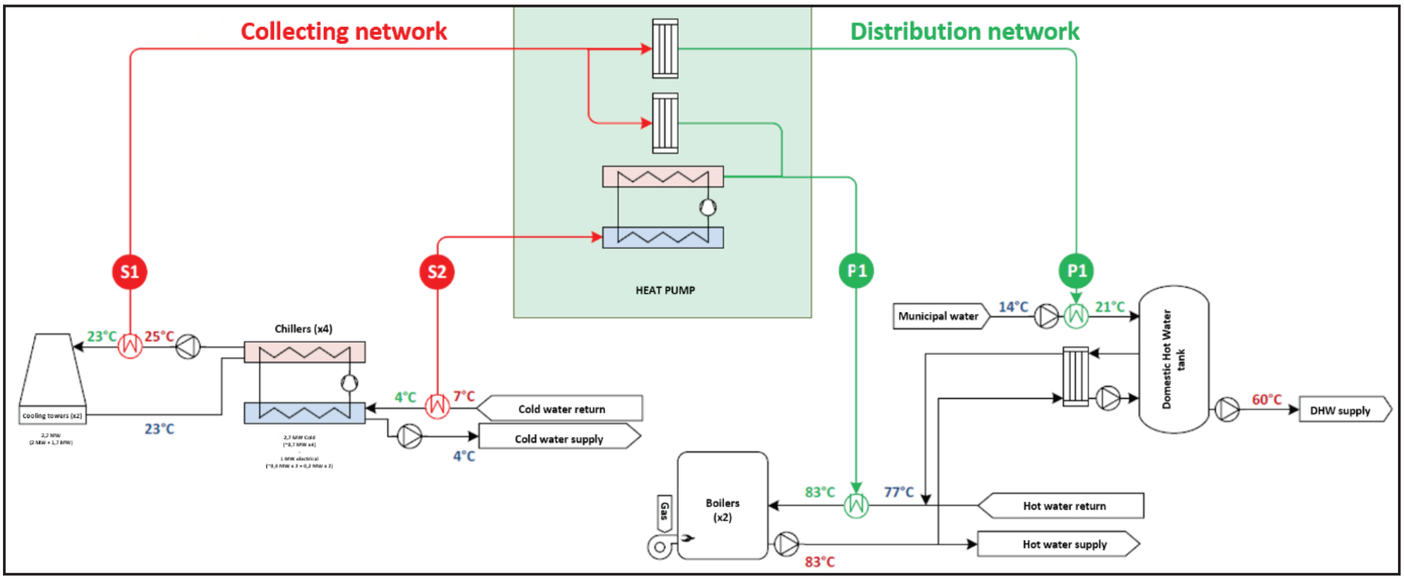


Fig. 8. Heat pump P&ID

Below are some key data:

- Combustion efficiency = 93%
- Distribution efficiency = 95%
- Distribution efficiency of the recovery network = 98%
- GCV (Gross Calorific Value) / NCV (Net Calorific Value) = 1.11
- Heat pump power = 680 kWt
- Installation COP = 2.8
- Temperature regime: 90/85 °C

Several equipment/elements are in place in addition to the heat pump itself:

- Production Skid
- A new electrical supply cabinet
- An insulated water tank (7 m3)
- Pipes network and insulation
- Heat-exchanger
- Instrumentation (temperature and pressure sensors...)
- Program logic controller (PLC)
- Variable speed drive pumps

E. *Heat Pump Future Performance*

The energy produced by the heat pump reduces by nearly 70% the energy (gas) used for the hot water loop as seen in figure 9.

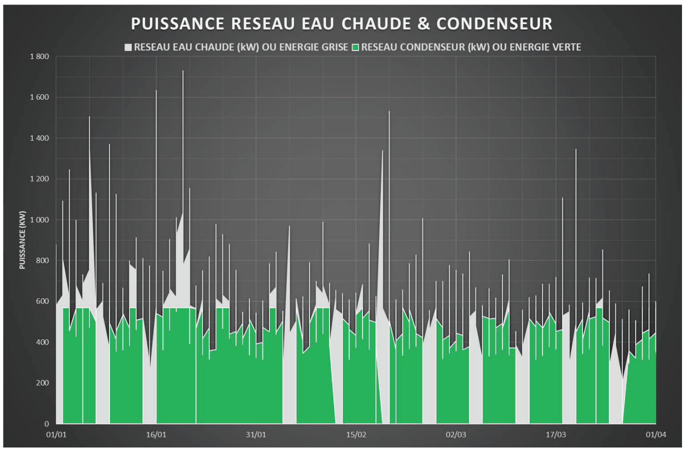


Fig. 9. Hot water system power (in gray) versus heat pump power (in green)

Figure 10 illustrates the savings on carbon emissions, water consumptions, and costs. Site's carbon footprint is reduced by 1/3, thanks to this major project.

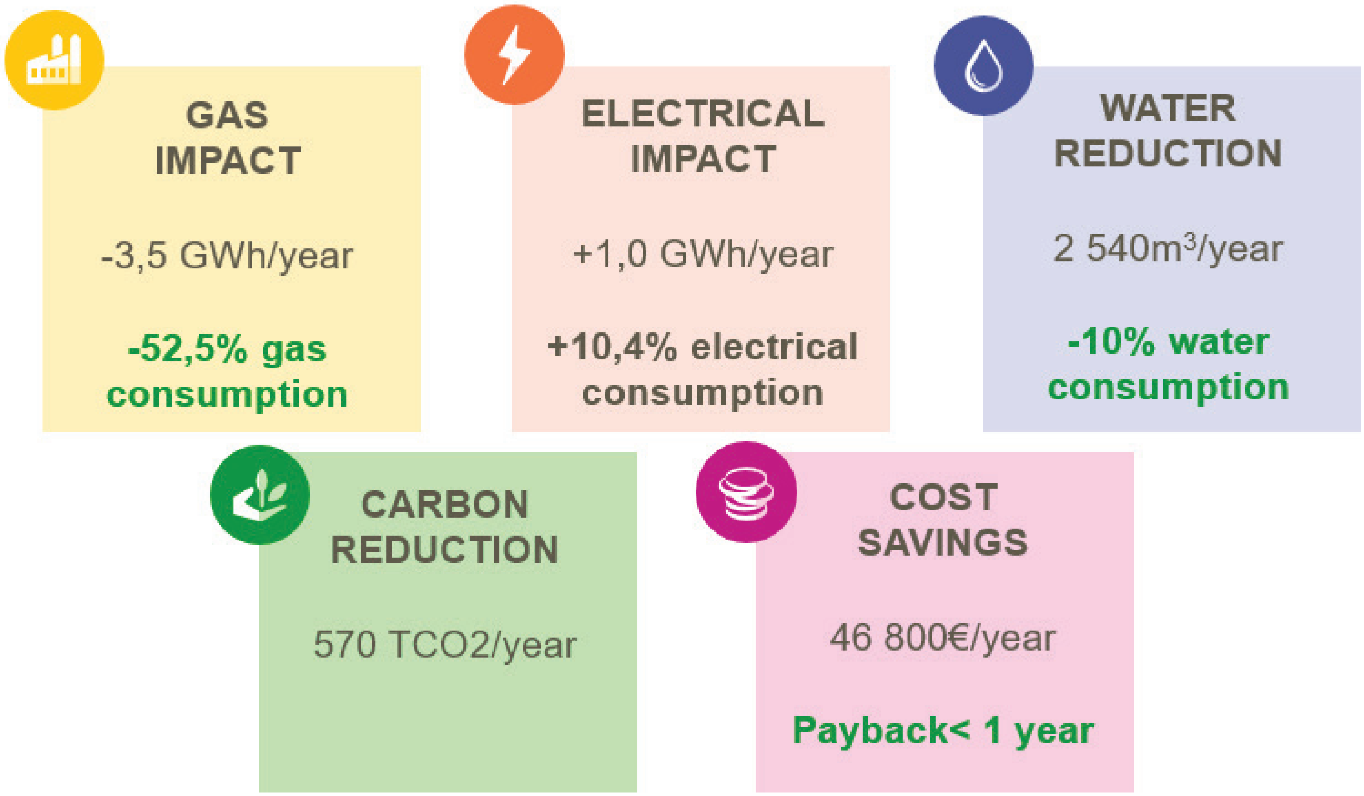
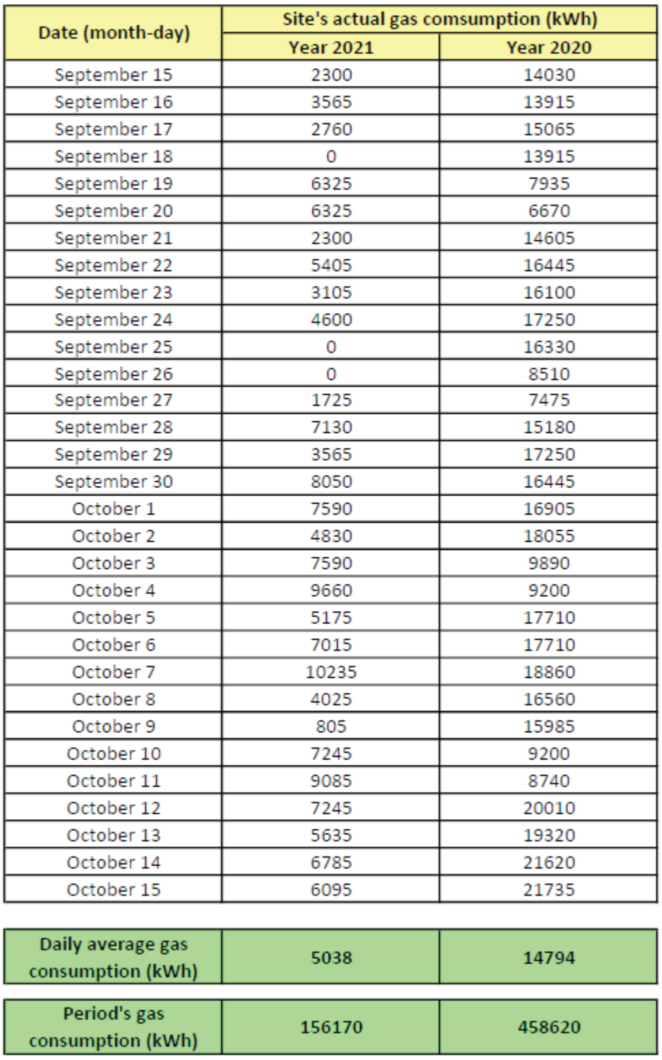


Fig. 10. Heat pump savings

Installation status and performances are monitored through a dedicated supervision.

F. *Actual Performance of the Heat Pump*



Date (month-day)	Site's actual gas comsumption (kWh)	
	Year 2021	Year 2020
September 15	2300	14030
September 16	3565	13915
September 17	2760	15065
September 18	0	13915
September 19	6325	7935
September 20	6325	6670
September 21	2300	14605
September 22	5405	16445
September 23	3105	16100
September 24	4600	17250
September 25	0	16330
September 26	0	8510
September 27	1725	7475
September 28	7130	15180
September 29	3565	17250
September 30	8050	16445
October 1	7590	16905
October 2	4830	18055
October 3	7590	9890
October 4	9660	9200
October 5	5175	17710
October 6	7015	17710
October 7	10235	18860
October 8	4025	16560
October 9	805	15985
October 10	7245	9200
October 11	9085	8740
October 12	7245	20010
October 13	5635	19320
October 14	6785	21620
October 15	6095	21735

Daily average gas consumption (kWh)	5038	14794

Period's gas consumption (kWh)	156170	458620

Fig. 11. Actual site's gas consumption from mid-September to mid-October 2021 versus 2020

Figure 11 shows that site's gas consumption has been reduced by 66%, mainly thanks to the heat pump. Other factor can impact site's gas consumption such as production and external temperature (10% in this period). Gas consumption reduction is aligned with estimation (remind = 52.5%).

IV. CONCLUSION

This paper adds to the literature on heat recovery (with a heat pump) a new case study. Where a chilled water system exists, the opportunity to install a water source heat pump for reducing consumption and therefore carbon emissions should be studied.

For a successful implementation of a water source heat pump the system emitting the heat lost and the system receiving this heat lost have been deeply analyzed. Estimations have been made through calculation and measurement. The heat pump has been dimensioned and selected based on those last elements and on technical research on refrigerant.

Then, the estimated savings (reduction of carbon emissions by 1/3) have been confirmed after the implementation and commissioning of the heat pump.

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