Turning cooling into heating —How CO_2 refrigeration powers 100% space heating

In the Danfoss Smart Store, our CO_2 refrigeration system has done more than preserve refrigerated food —it has completely covered the store's space heating needs. From October 2023 to October 2025, the system delivered 100 MWh of heat for space heating without drawing a single kilowatt-hour from other sources, while 40 MWh of surplus heat was sold to the local district heating company.

This whitepaper explores the principles of heat recovery, the integration of refrigeration and heating systems, and the real-world learnings from operating the Danfoss Smart Store. We will share how to strike the optimal balance when using a CO_2 refrigeration system as a heat pump, unlocking both energy efficiency and sustainability gains.

Contents

Refrigeration refers to the process by which energy, in the form of heat, is removed from a low-temperature medium and transferred to a high-temperature medium.

Heat pumps may use the heat output of the refrigeration process, and may also be designed to be reversible, but are otherwise similar to air conditioning units.

↑ Source: Wikipedia

The supercritical carbon dioxide (sCO_2) cycle utilizes the critical point of CO_2 (31°C and 73.77 bar) to enable efficient heat recovery, particularly from low-grade waste heat sources. By operating above the critical point, CO_2 can exhibit properties of both a liquid and a gas, allowing for efficient heat transfer and power generation.

Critical point of CO_2:

The critical point defines the state where CO_2 transitions from a liquid and/or gas phase into a uniform supercritical phase with no separation between liquid and gas. In the supercritical phase, CO_2 can exhibit properties close to liquid or gas depending on state (pressure and temperature).

Supercritical CO_2 (sCO_2):

When CO_2 is maintained at or above its critical temperature and pressure, it exists in a supercritical state. This state allows for a higher heat capacity and temperature glide compared to traditional condensation, making it ideal for heating water. Supercritical is often referred to as transcritical.

System configuration

How it works

In summertime or at high ambient temperatures, a CO_2 supermarket refrigeration system typically runs at peak load due to the high load in the refrigerated display cases, and it often runs in supercritical mode because of the high ambient temperature at the gas cooler.

Heat from the refrigeration system is usually rejected to the ambient air via the gas cooler by controlling the gas cooler fans. However, if you want to recover heat from the refrigeration system a 3-way valve and a heat exchanger can be mounted before the gas cooler, enabling water to be heated by hot gas from the compressors.

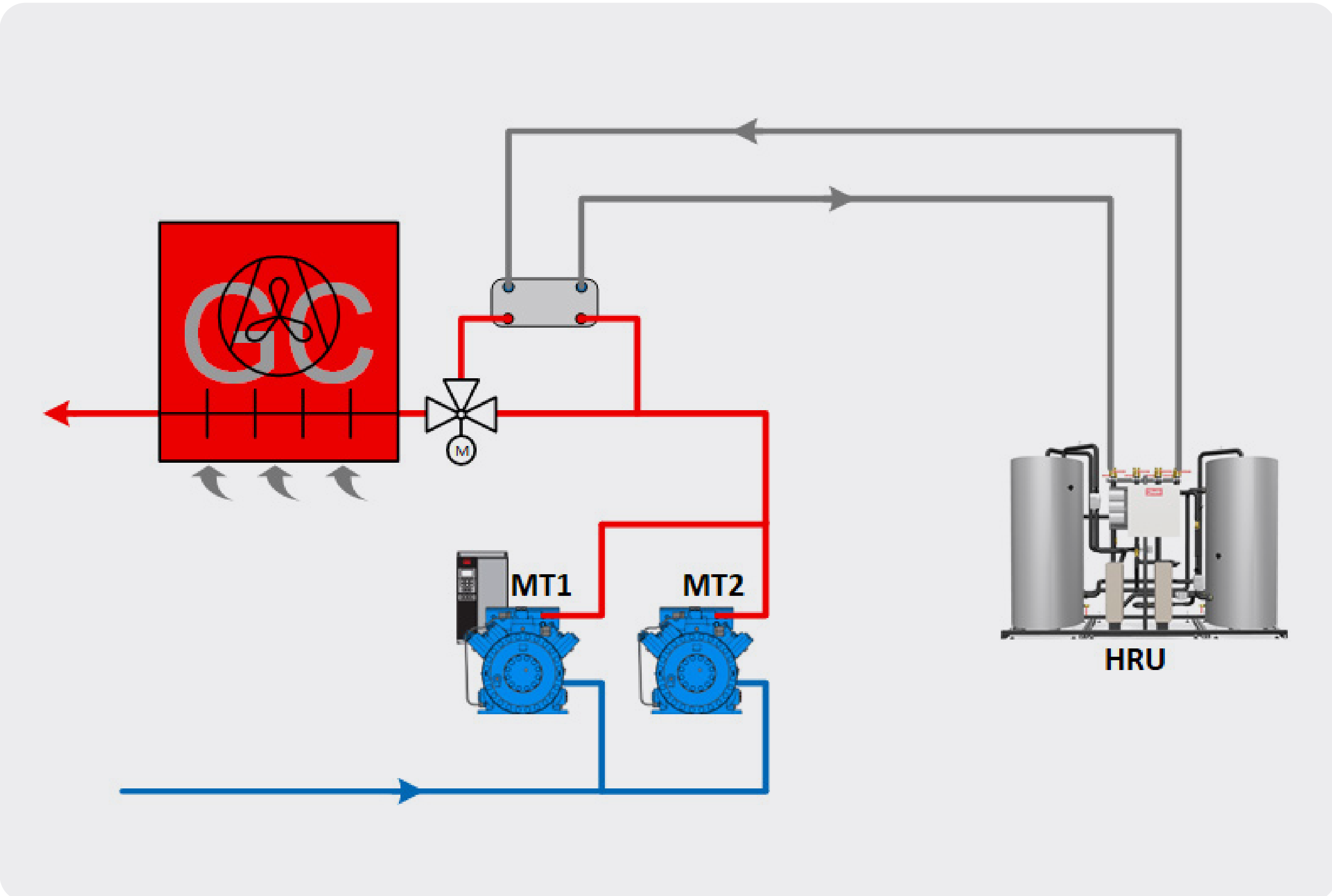

Figure 1. HRU connected to standard CO_2 pack

To create heat during cold periods with low load on the refrigerated cabinets and low ambient temperatures, the refrigeration system can be adjusted to work transcritical, similar to summer conditions.

To create sufficient load on the refrigeration system, a false load in the form of an extra evaporator can be mounted in parallel with the medium- or low-temperature cabinets and rooms depending on ambient temperature conditions.

The false load is typically an evaporator placed on top of the gas cooler to extract heat from the air, but it could also be a ground loop extracting heat from the ground via a heat exchanger. In the Danfoss Smart Store, the ground loop is connected to the medium-temperature suction line.

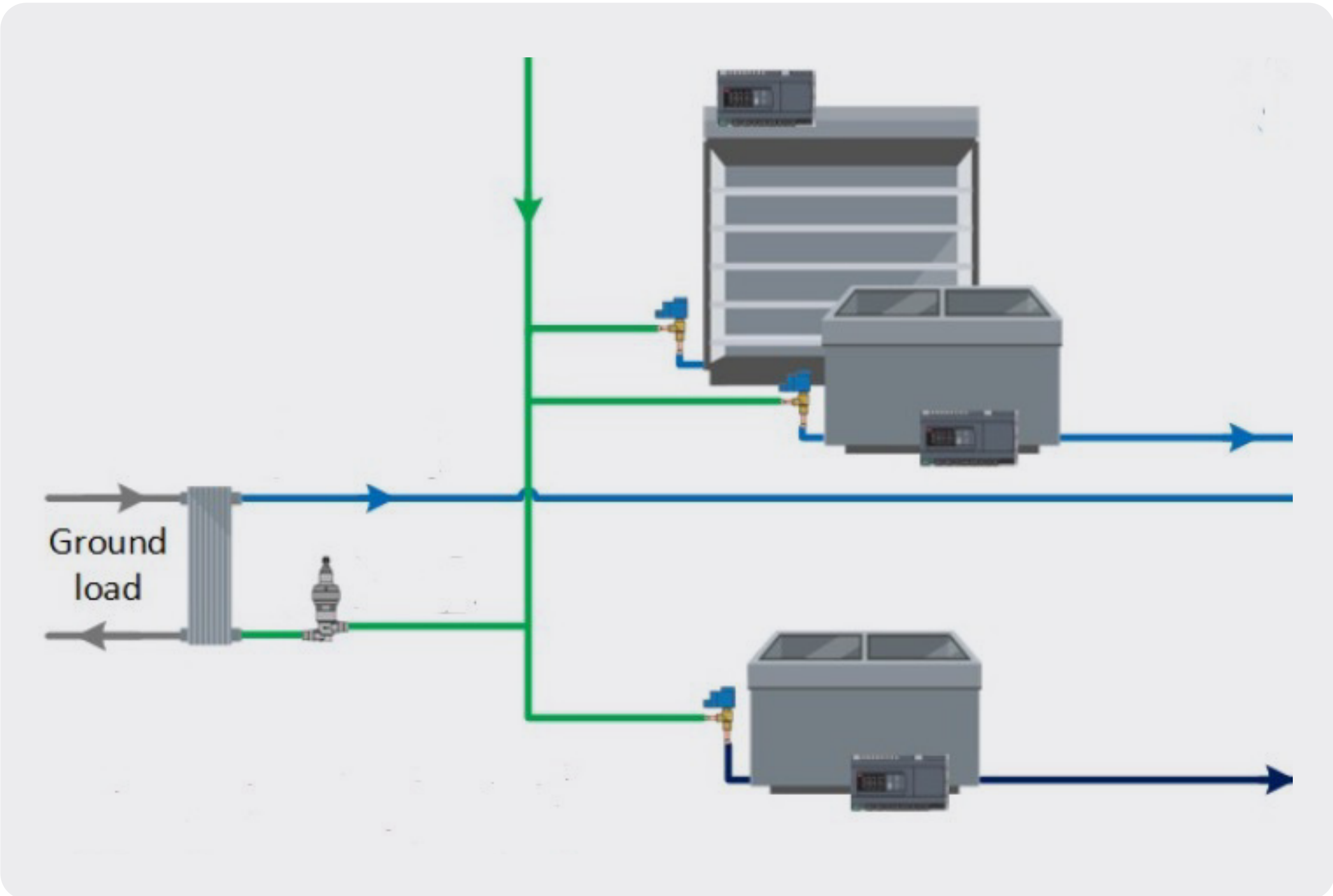

Figure 2. Connection of false load

Why heat recovery and CO_2 refrigeration are the perfect match

The principle behind effective heat recovery with CO_2

In common refrigeration systems with a condensation process, the pressure and temperature are tied together, but in transcritical CO_2 systems, pressure and temperature can be controlled individually. This provides possibilities for heat reclaim.

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During normal operation without heat reclaim, the high pressure is kept at a level where the optimum COP is obtained based on the achieved CO_2 temperature out of the gas cooler (following the red curve on Figure 3).

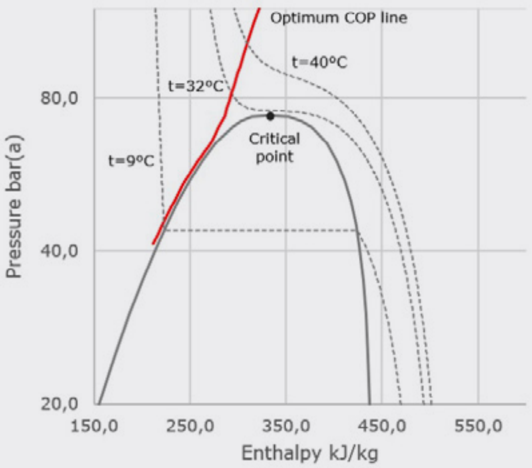

Figure 3. Optimum COP control

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In a CO_2 refrigeration system for cooling only, you would aim for the lowest possible high pressure, typically dictated by the ambient temperature and system design. In this example (Figure 4), the gas temperature out of the gas cooler Sgc is 9°C, resulting in high pressure controlled around 48 bar and the related discharge temperature around 50°C.

With gas temperature Shr2 out of the heat exchanger around 32°C, the ratio of heat that can be reclaimed is approximately 10%.

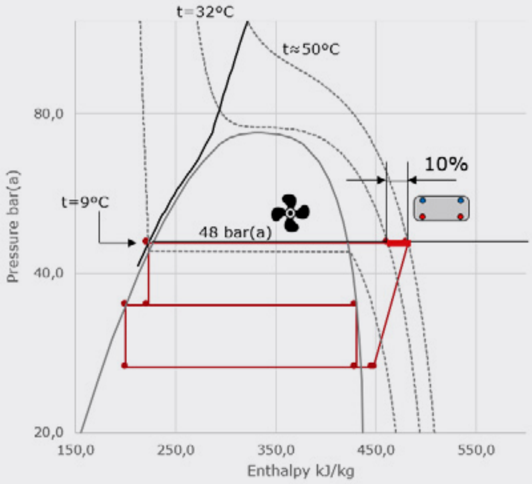

Figure 4. 10% heat reclaim at 48 bar

03

By increasing the pressure while keeping the temperature Sgc out of the gas cooler constant, the discharge temperature increases, as well, making it possible to reclaim a larger part of the heat rejection.

Increasing the pressure to 65 bar under the same conditions as before, the discharge temperature increases to approximately 80°C, and the ratio of heat that can be reclaimed increases to around 29%.

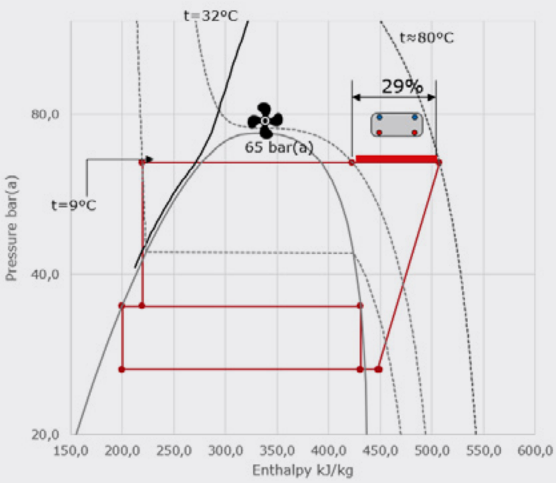

Figure 5. 29% heat reclaim at 65 bar

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Now increasing the pressure to 80 bar (above the critical point), the 32°C temperature curve moves radically to the left, while the discharge temperature increases to approximately 105°C, enabling around 74% of all rejected heat to be reclaimed.

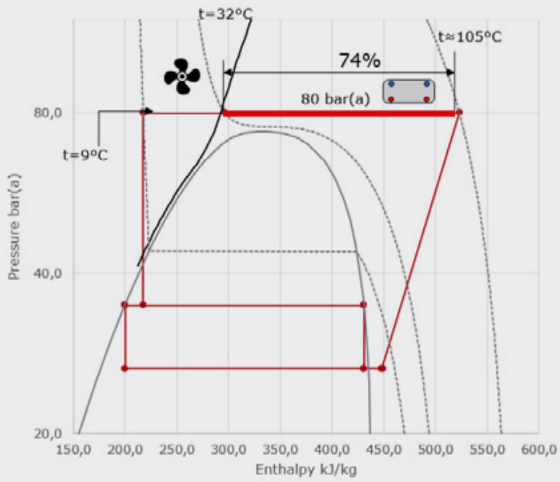

Figure 6. 74% heat reclaim at 80 bar

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To reduce heat rejection to the ambient, fan capacity is decreased until the fans are stopped. This will result in a loss of cooling capacity, but the system will compensate by cutting in more compressor capacity.

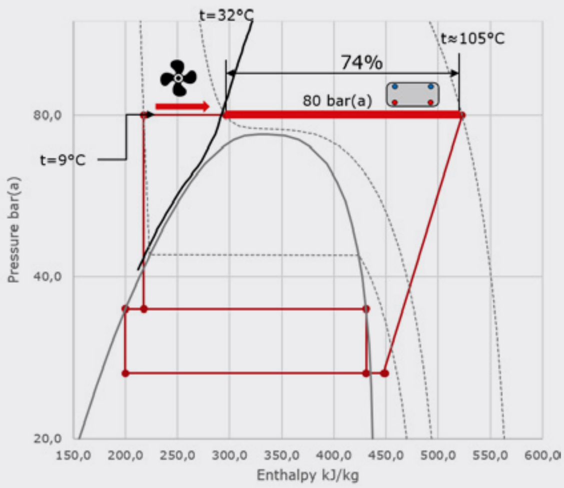

Figure 7. Reduced heat rejection to ambient

06

To avoid further heat rejection by natural convection to the ambient when the fans are stopped in heat recovery mode, an extra 3-way valve can be controlled to gradually bypass the gas cooler.

The control sensor for the gas cooler bypass valve is Shp, while control sensor for the gas cooler fans is Sgc.

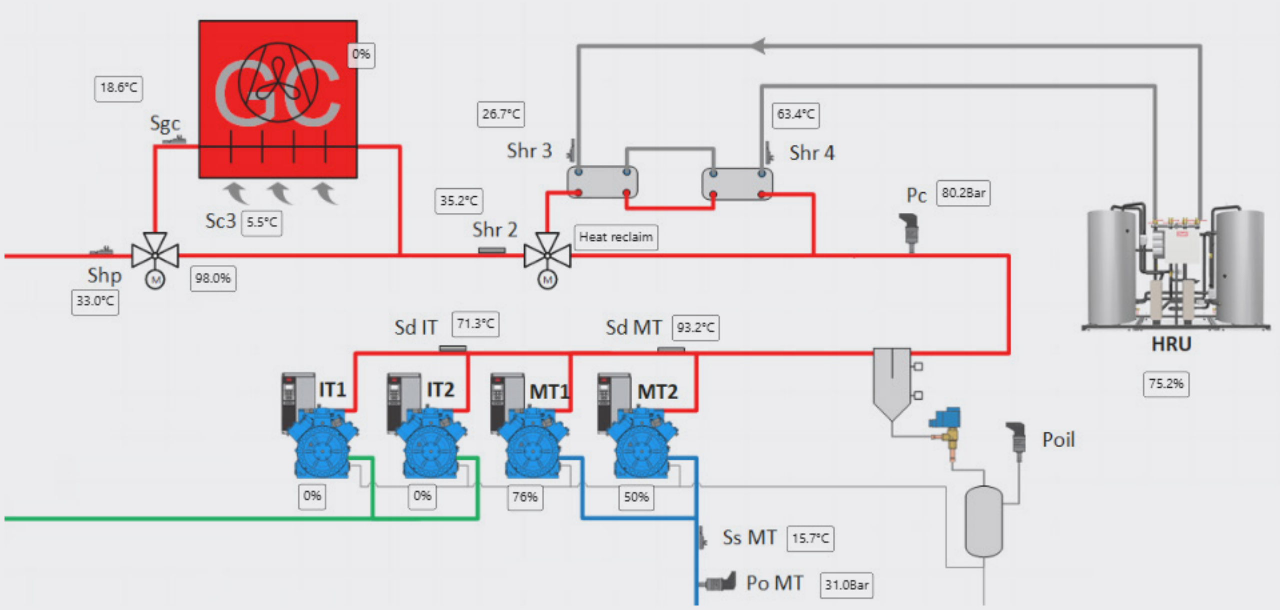

Figure 8. Advanced CO_2 pack with gas cooler bypass control

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When the gas cooler is bypassed with Shp controlled around 32°C at 80 bar, with a corresponding discharge temperature around 98°C, the ratio of heat that can be reclaimed is up to 100%.

To compensate for the loss of MT cooling capacity, the controller cuts in more compressor capacity. If all cabinets are satisfied and there is not enough load on the system to generate sufficient heat for space heating, then an extra load (false load) can be added to the refrigeration system.

Note that by increasing the pressure using slightly more energy in the compressors, a significantly larger portion of the heat can be recovered, making heat recovery in CO_2 systems very efficient.

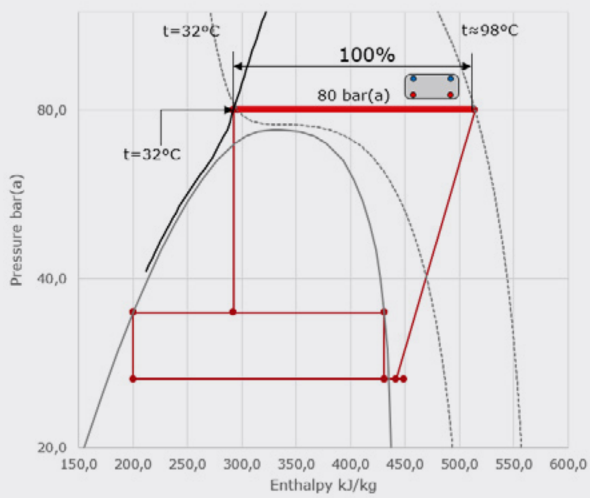


Figure 9. 100% heat reclaim with gas cooler bypass

A well-configured heat recovery system

Danfoss Heat Recovery Unit

The HRU (Heat Recovery Unit) is designed to recover the waste heat from CO_2 refrigeration installations. Recovered heat can be used for on-site heating purposes or returned to the district heating utility network. It is perfectly suited for supermarkets equipped with refrigerators. The system includes a heating substation with accumulation tanks.

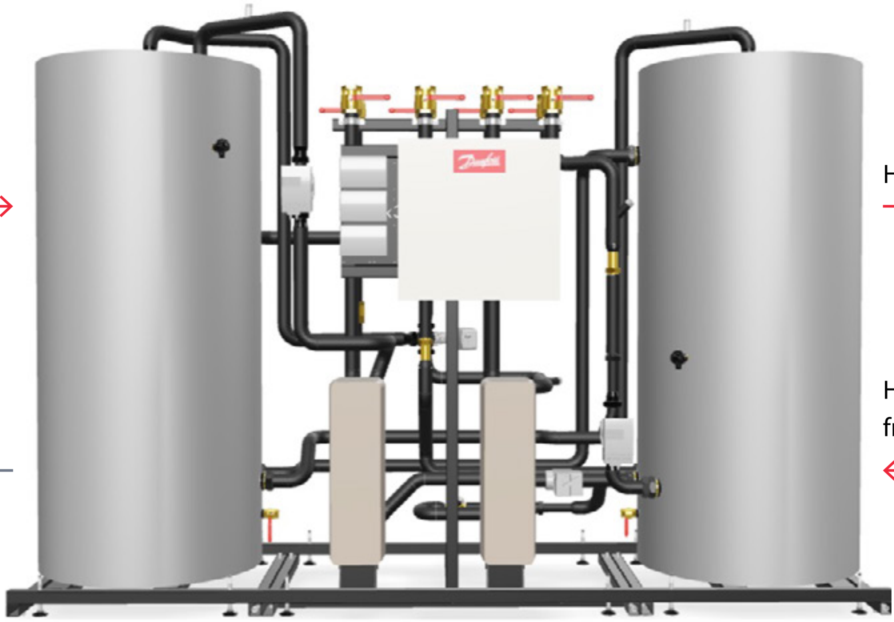
In the Danfoss Smart Store, a Danfoss Heat Recovery Unit (HRU) is installed between the refrigeration system and the heating system. If regulation faces operational constraints, the cooling system will have priority over heat recovery.

By means of a standard 0–10 volt signal (consumer request signal) from the HRU to a Danfoss CO_2 pack controller, the controller will adjust system operation to produce all the heat needed for space heating in both the supermarket and the Danfoss part of the building. In summertime, with high ambient temperature and limited heat demand for space heating, we can harvest excess heat energy from the refrigeration system to sell back to the district heating grid.

In Figure 10, the connections to district heating are shown on the left-hand side, the water supply to the building is shown on the upper right-hand side, while the connection to the refrigeration system is shown on the lower right-hand side.

External heat source connection:
- Direct
- Indirect

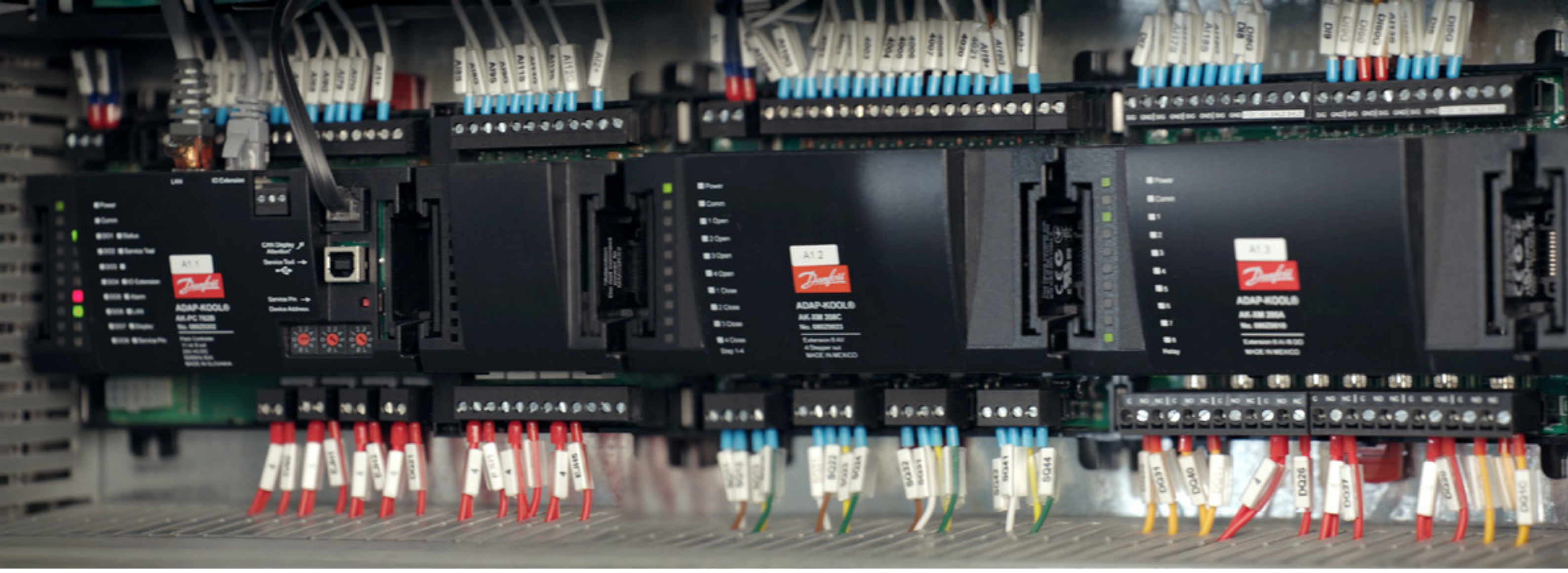
Option:
- Heat resale



Heating demand

Heat recovery from CO_2 system

Figure 10. Water connections to and from HRU



Robust communication between heat recovery and compressor rack

How the AK-PC 782 reacts to the consumer request from the HRU

The AK-PC 782 controller reacts to the HRU request (Figure 11) and, accordingly, it has an impact on the bypass valve of the heat recovery (V3hr), the pressure and temperature increase (Figure 12), and the modulating gas cooler bypass valve (V3gc).

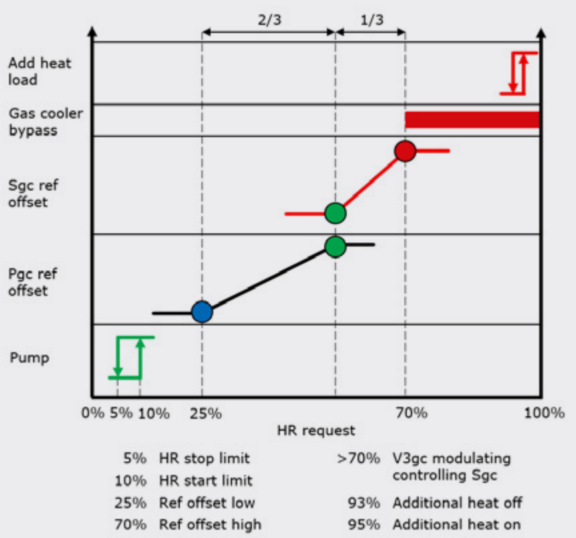


Figure 11. How AK-PC 782 reacts to HRU request

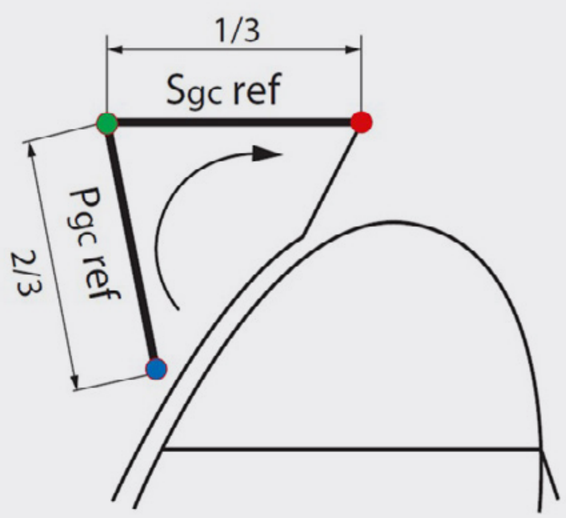


Figure 12. Pgc vs Sgc reference control

1. The signal should be above 20% to start bypassing the gas into the heat exchanger (using V3hr), and then the reference for the pressure Pgc is increased to "Pgc HR min".

2. The external voltage signal is registered (the higher the value, the greater the need for heat). The signal is converted by the controller to 0–100% capacity and will have the following impact:

A

On/Off bypass valve V3hr

When the pump is released to start in the Danfoss HRU and the request signal reaches the "HR start limit", the bypass valve V3hr opens for heat recovery. The valve V3hr goes into "bypass" when the "HR stop limit" is reached.

B

Pressure and temperature increase

The pressure is measured with the pressure transmitter Pgc and controlled with the high-pressure valve Vhp. Depending on the heat request, the pressure reference "Pgc ref" will be raised from "Pgc HR min" to "Pgc HR max" at 2/3 of the signal. "Pgc ref" is allowed to be higher than "Pgc HR max", when the "extra refrigeration capacity" ("extra compressors") function is activated.

After reaching "Pgc HR max", from 2/3 to 3/3 of the signal, "Sgc ref" is raised from "Sgc min" to "Sgc max ". The consequence of the increased gas cooler reference is a decrease in fan speed (Sgc min is calculated by the controller based on the set receiver pressure reference).

C

V3gc is modulating

The controller controls the fans and the valve to maintain energy-optimized operation (bypassing of the gas cooler is allowed only when the fans are at 0%, and vice versa). Shp is the control sensor used when the gas cooler is bypassed.

Importance of low return water temperature

In heat recovery operation mode, and with a water return temperature of 27°C (Figure 14) and a 5K temperature differential between the CO_2 exit and the water inlet, it is possible to recover all heat from the refrigeration system.

However, if the return water temperature increases from 27°C to 32°C (Figure 13), and the same 5 K temperature differential between the CO_2 exit and the water inlet is maintained, it will be possible to recover only 65% of the heat recovery potential. For the remaining part of the heat, it will be necessary to release it to the ambient via the gas cooler.

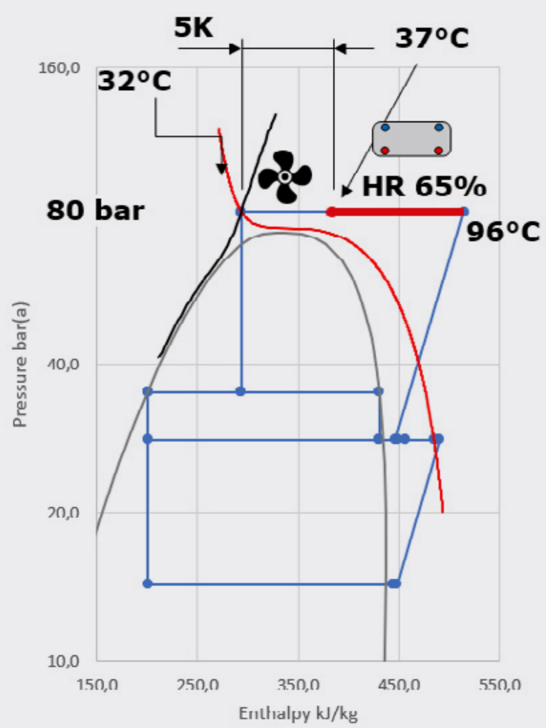


Figure 13. 32°C water temperature

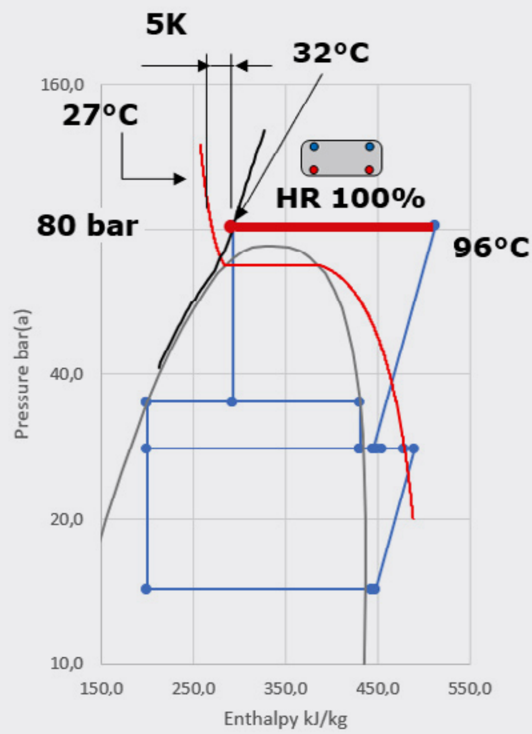


Figure 14. 27°C water temperature

Results

In the following charts (Figure 15, 16, 17, and 18), cumulative heat energy consumption for the building can be seen along with the ambient temperature for four different months. Since April 2025, we also have historical data for the consumer request (heat demand) signal.

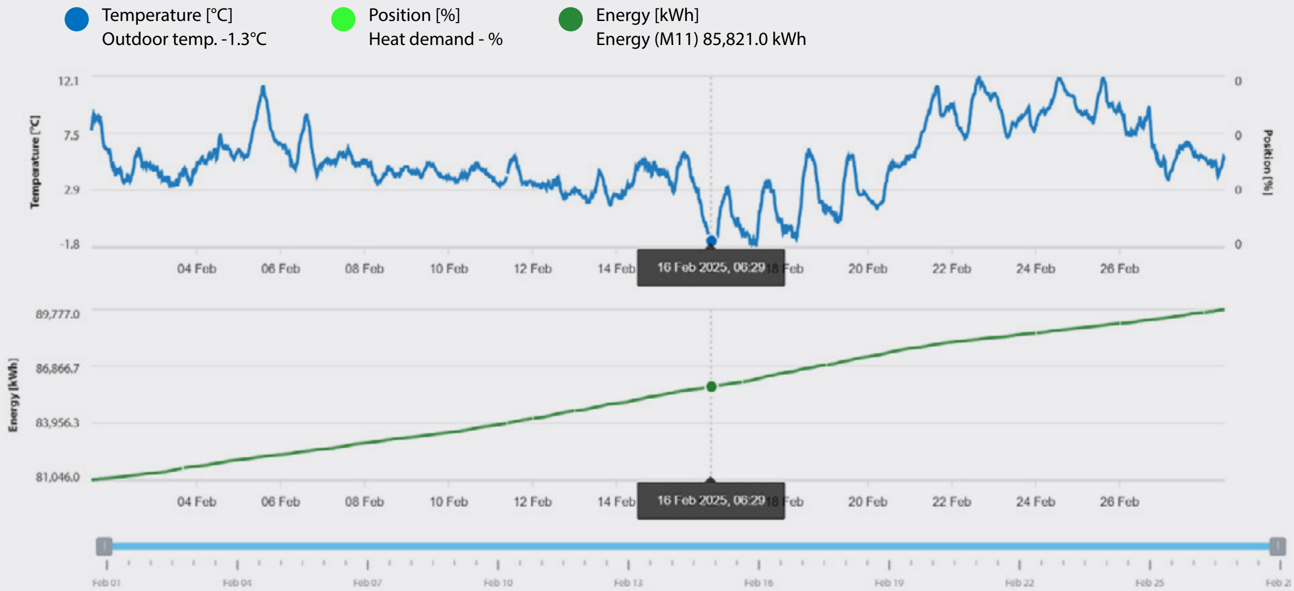


Figure 15. Ambient temperature and cumulative energy consumption for heating for February 2025

In February 2025, we see the highest heating demand (89.8 MWh - 81.1 MWh = 9.7 MWh, equal to an average of 347 kWh per day).

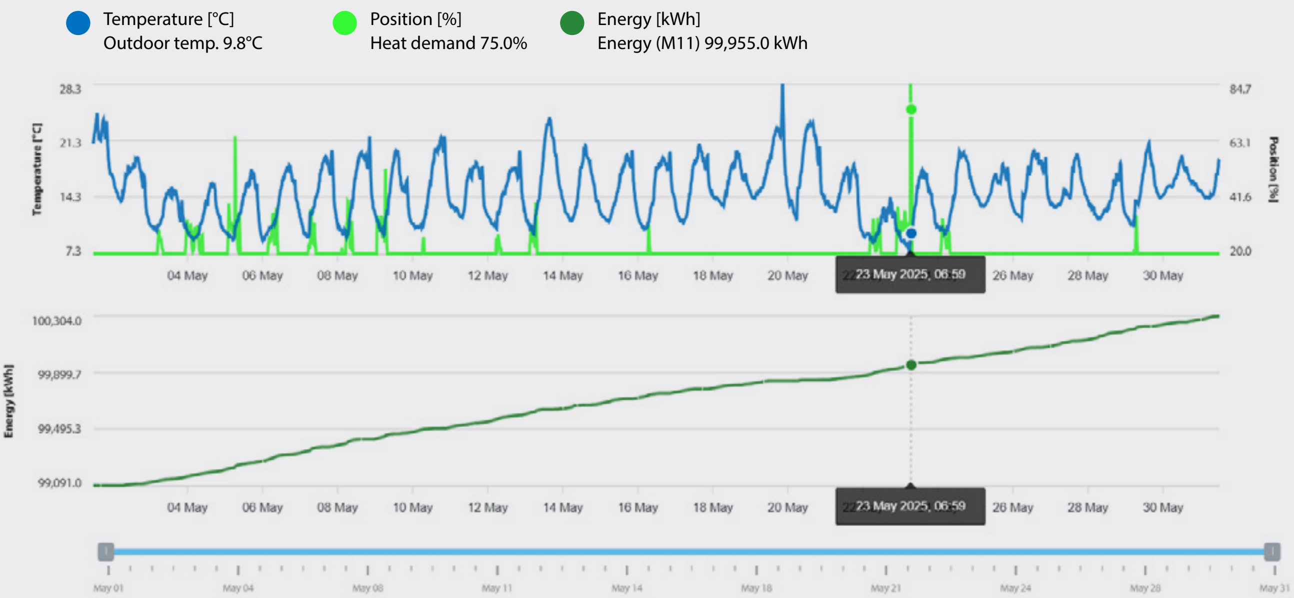


Figure 16. Ambient temperature, energy consumption for heating, and heat demand for May 2025

In May 2025, most heat energy (100.3 MWh - 99.1 MWh = 1.2 MWh, equal to an average of 39 kWh per day) was supplied without increasing the pressure in the refrigeration system. The major part of the heat supplied to the building was excess heat from the refrigeration system (when heat demand = 20%).

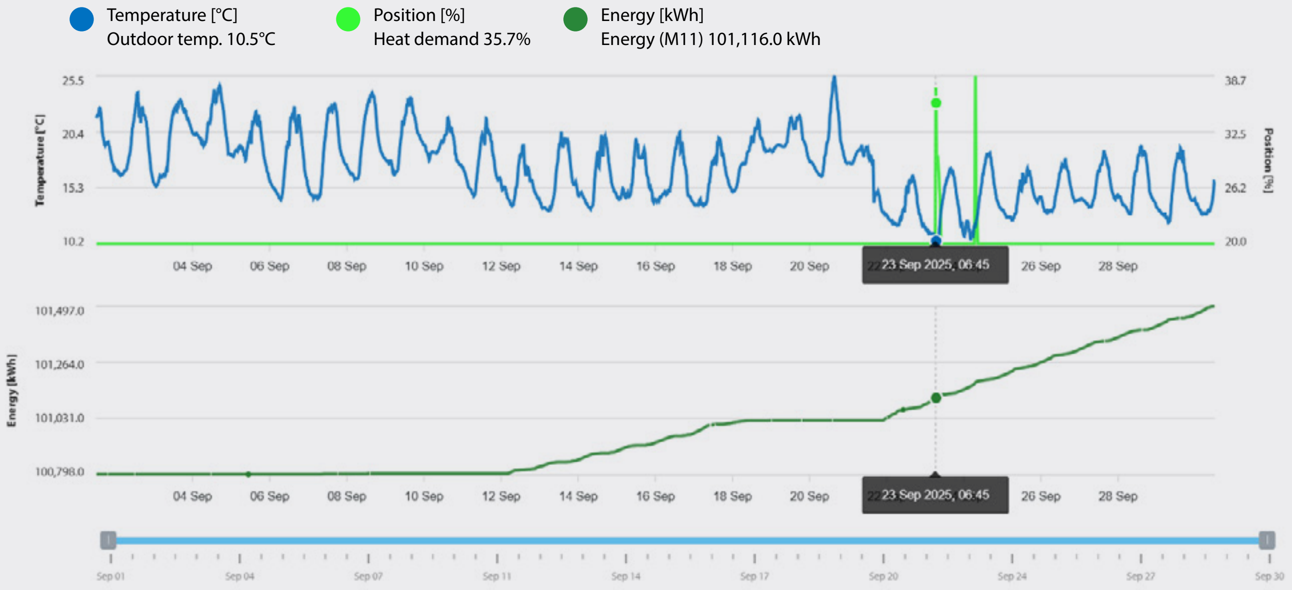


Figure 17. Ambient temperature, energy consumption for heating, and heat demand for September 2025

In September 2025, the heating season started with nearly all heat for the building produced without increasing the pressure in the refrigeration system (101.5 MWh - 100.8 MWh = 0.7 MWh, equal to an average of 23 kWh per day).

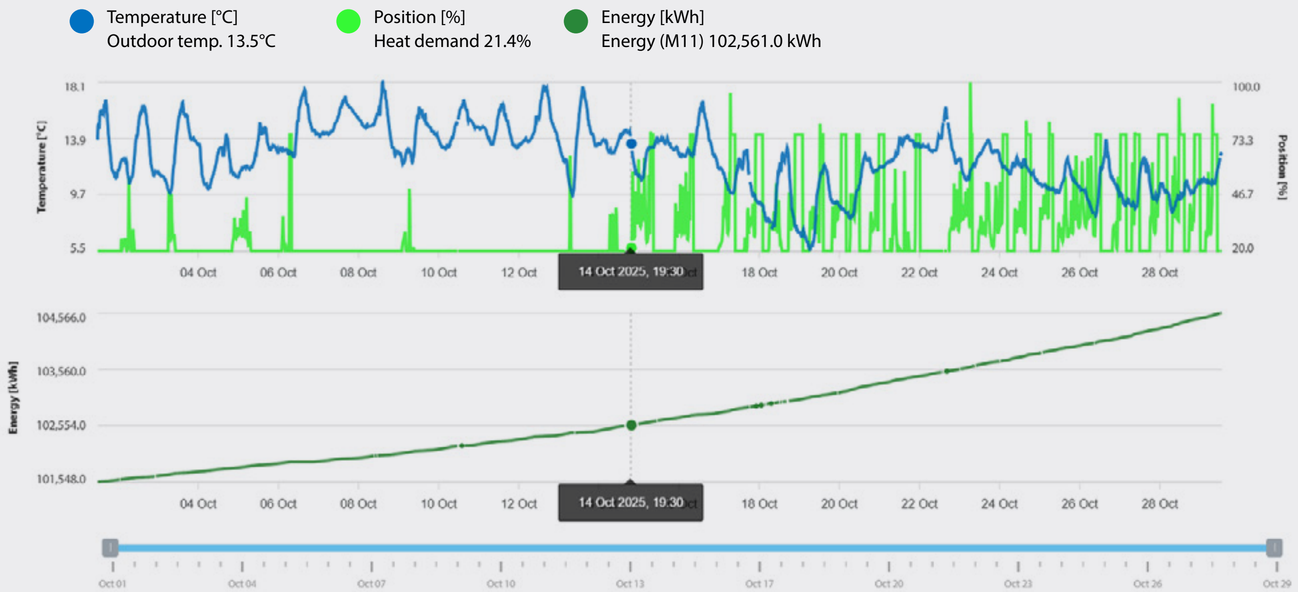


Figure 18. Ambient temperature, energy consumption for heating and heat demand for October 2025

From mid-October 2025, more heat was needed (104.6 MWh - 101.6 MWh = 3 MWh, equal to an average of 107 kWh per day), which is why the heat demand signal from the HRU is increasing.

Monthly and daily average heat energy consumption for space heating

Month	Space heating per month	Space heating avg. per day
February	9.7 MWh	347 kWh
May	1.2 MWh	39 kWh
September	0.7 MWh	23 kWh
October	3 MWh	107 kWh

In the Danfoss Smart Store, more than 50 energy meters are installed, and one of the meters measures the energy consumption of the CO_2 compressor pack.

Looking at the daily average energy consumption for the CO_2 refrigeration pack, consumption peaks in the summer period due to the high refrigeration load on the refrigerated cabinets and the AC load, which is integrated in the CO_2 refrigeration pack.

In April and May, when ambient temperatures fluctuate between 12 and 20°C, both the refrigeration and the heating load are low, and most heating demand is supplied with excess heat without increasing the pressure in the refrigeration system. In the CO_2 pack controller, Pgc min and Pgc HR min are both set to 50 bar.

From October, the heating demand rapidly increases, peaking in February with the highest heating demand.

In the period from May until the end of September, the heating demand for the building is very limited, but there is the possibility of selling excess heat to the district heating grid.

Month	Days	Total kWh	Avg Daily kWh
Oct 2025	30.64	4839.6 kWh	158.0 kWh
Sep 2025	30.00	5252.4 kWh	175.1 kWh
Aug 2025	31.00	6304.3 kWh	203.4 kWh
Jul 2025	31.00	6798.4 kWh	219.3 kWh
Jun 2025	30.00	4786.8 kWh	159.6 kWh
May 2025	31.00	4424.7 kWh	142.7 kWh
Apr 2025	30.00	4280.7 kWh	142.7 kWh
Mar 2025	31.00	5000.9 kWh	161.3 kWh
Feb 2025	28.00	5307.7 kWh	189.6 kWh
Jan 2025	31.00	5582.5 kWh	180.1 kWh
Dec 2024	31.00	5044.5 kWh	162.7 kWh
Nov 2024	30.00	4599.6 kWh	153.3 kWh
Oct 2024	31.00	4662.2 kWh	150.4 kWh
Sep 2024	30.00	5986.0 kWh	199.5 kWh

↑ Figure 19. Monthly and daily average energy consumption for the remote CO_2 pack

Comparing the daily average energy consumption for the CO_2 refrigeration pack in February with that in May, only 1 kWh of extra electricity to the CO_2 refrigeration pack is used to generate 6.6 kWh of heat, making it very attractive to recover and produce heat with the refrigeration system.

Electrical energy usage for the CO_2 pack vs. heat produced for space heating

Month	Heat production	Energy consumption	
February 2025	347 kWh/day	189.6 kWh/day	Refrigeration + heat production
May 2025	39 kWh/day	142.7 kWh/day	Refrigeration + excess heat
Extra heat / kWh elec.	308 kWh/day	46.9 kWh/day	6.6 kWh heat / 1 kWh of elec. energy

Resale of excess heat

In summertime, with ambient temperatures above 20°C and high humidity, there is a high load on the refrigeration system, making it possible to produce excess heat above 63°C water temperature, which is the minimum temperature our district heating supplier can accept when buying heat from us.

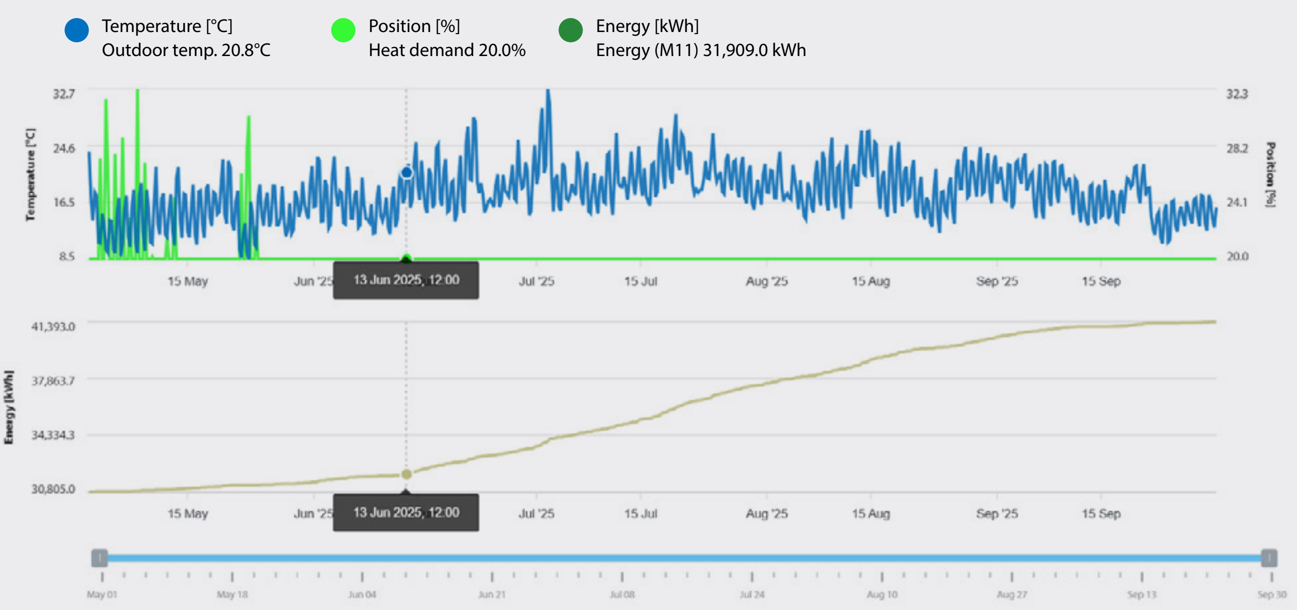


Figure 20. Ambient temperature, heat demand, and excess heat energy sold from May until September

As can be seen in Figure 20, sales of excess heat energy delivered back to the district heating supplier were possible from May until September. The amount of heat energy that has been delivered is 41.4 MWh - 30.8 MWh = 10.6 MWh. Unfortunately, the return temperature in the district heating system in our area is above 43°C, making it possible to recover and sell only a fraction of the available heat.

How to ensure low return temperature in the heating system

Due to excellent stratification in the HRU, the water return temperature is 25.5°C, allowing a water temperature as low as 26.1°C to enter the heat exchanger for the refrigeration system (see Figure 21).

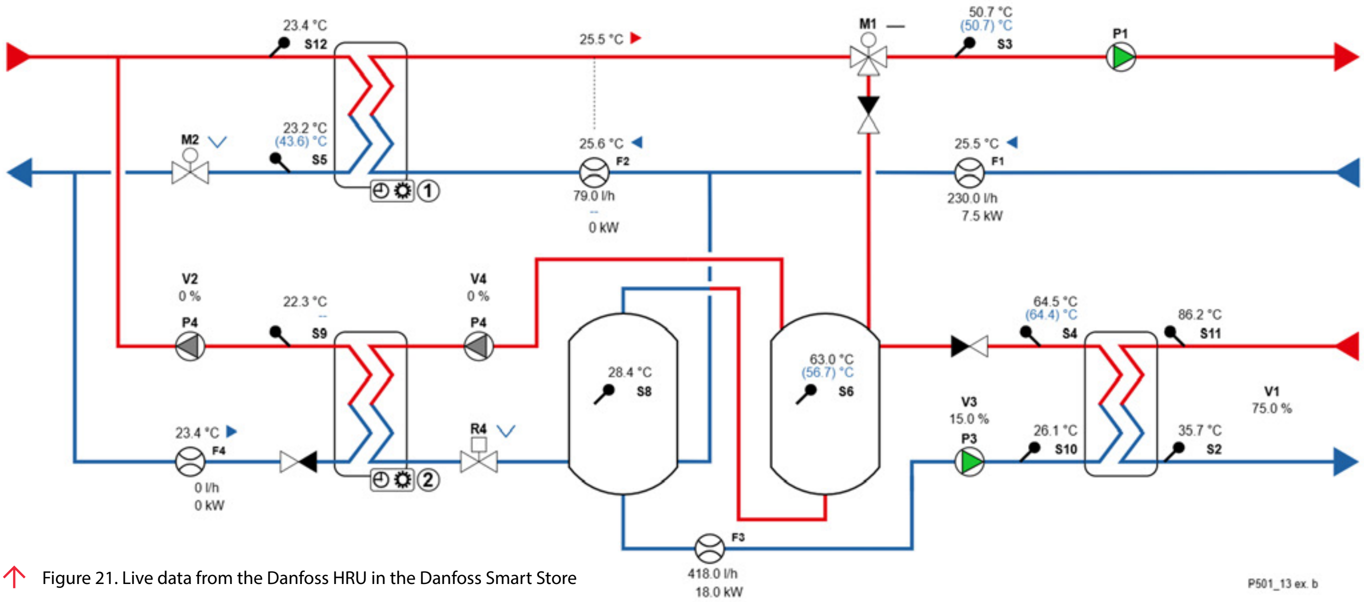


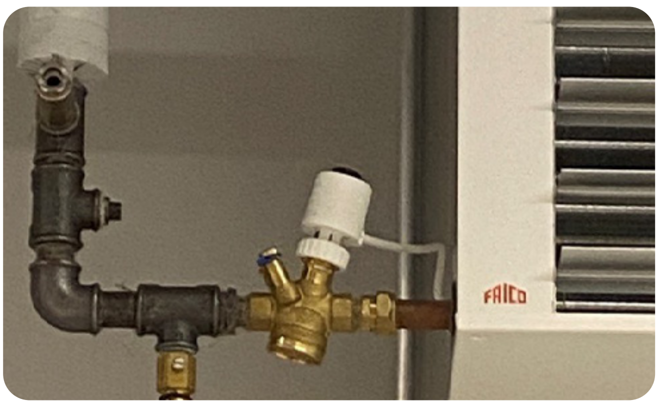
Figure 21. Live data from the Danfoss HRU in the Danfoss Smart Store

A low water return temperature from the building is only possible due to excellent water flow hydronic balancing in all parts of the heating system.

A very important component in heating systems is the Danfoss AB-QM, a pressure-independent control valve (PICV), which limits the maximum flow and at the same time functions as a control valve that can be operated by several different types of Danfoss actuators.

By implementing AB-QM valves in the mixing loops across floor heating, radiator circuits, heating coils in air handling units, and heating fan coils, it is possible to reduce pump capacity using variable-speed circulation pumps, but most of all, it is possible to limit or control the water return temperature by installing a NovoCon solution.

Mixing loop with AB-QM valve and NovoCon® actuator



Heating fan coil with AB-QM valve and On-Off actuator

Results

Heat recovered from the refrigeration system by the Heat Recovery Unit

As shown in Figure 22, the total amount of heat recovered from the refrigeration system into the HRU from November 1st 2024 until November 1st 2025 (one full year), was 144.06 MWh - 89.1 MWh = 54,96 MWh. Out of this, 44 MWh was used for space heating, and the remainder was sold to district heating

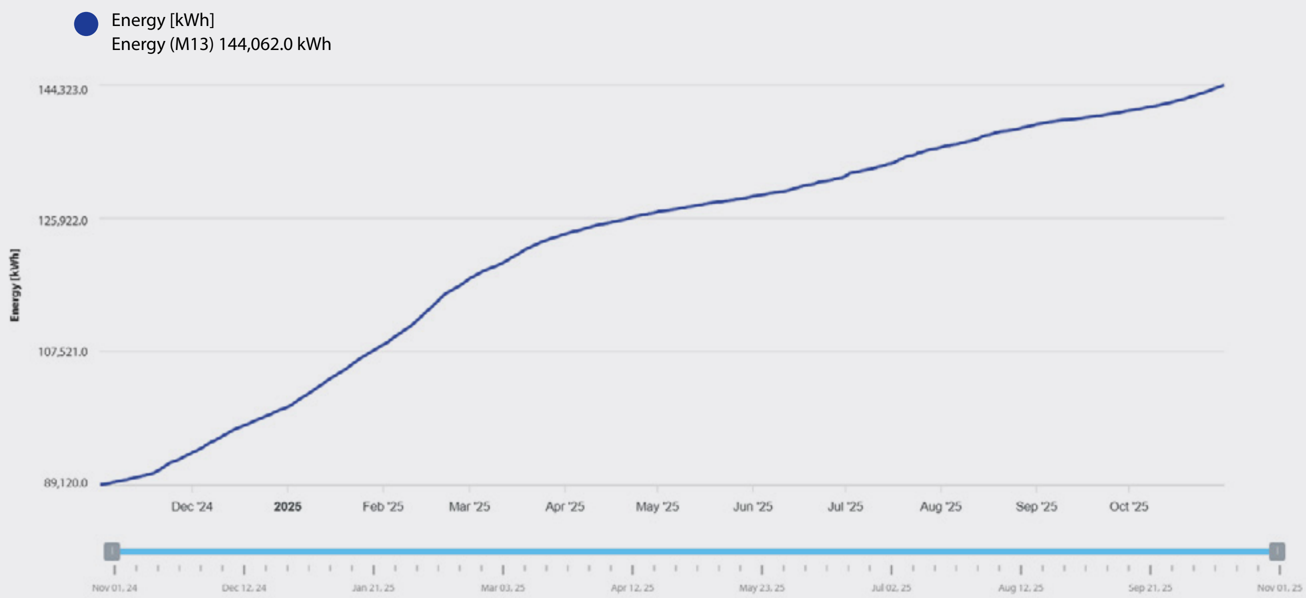


Figure 22. Heat energy recovered from the CO_2 pack by the Heat Recovery Unit

In the Danfoss Smart Store, all heat for space heating has been produced by the CO_2 refrigeration system since October 2023, when the possibility of importing heat energy from district heating was disabled in the HRU controller. Zero energy has been purchased from district heating since mid-October 2023 (see Figure 23).

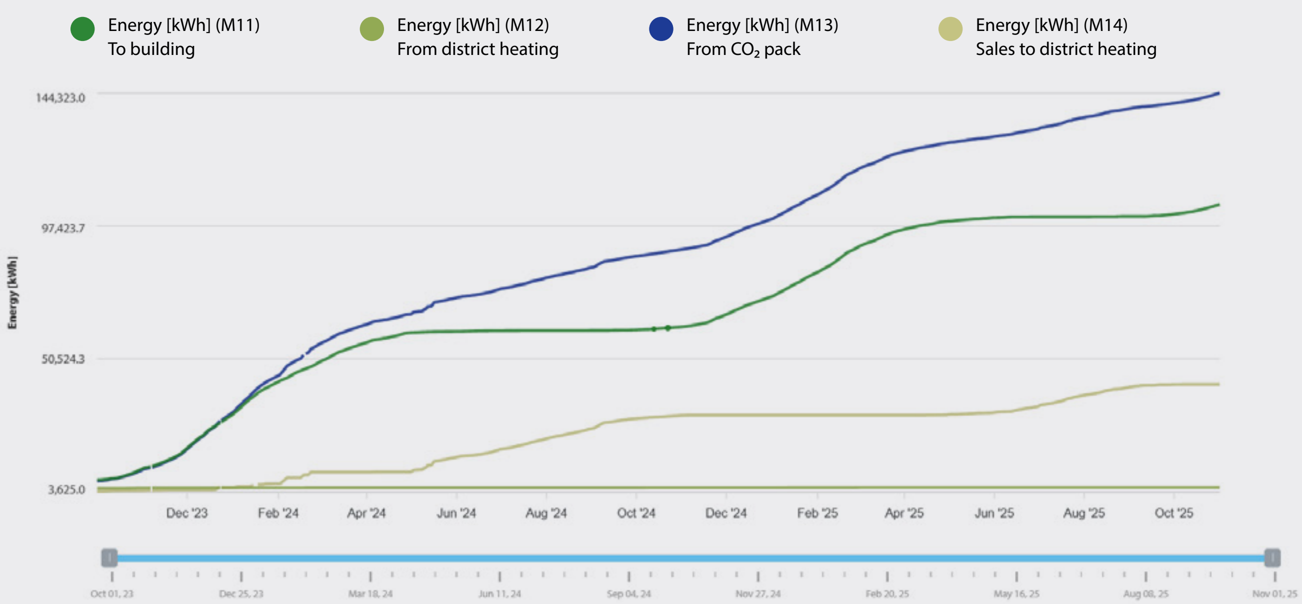


Figure 23. Heat energy to/from HRU

Payback time depends on the cost of alternative heat sources, heat demand, as well as installation cost. Going back 3–4 years, when gas prices were peaking, we saw a payback time below two years. From this perspective, investing in heat recovery is a safe and climate-friendly investment.

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Learnings

To maximize the amount of heat that can be recovered from the CO_2 refrigeration process, it is crucial to seek the best compromise between the refrigeration control and the heating control. What is most important, is to preserve a low return temperature from the heating system, thereby allowing a low CO_2 gas temperature out of the heat exchanger.

In a Danfoss system with an AK-PC CO_2 pack controller and a Danfoss Heat Recovery Unit, the cooling system will have priority over heat recovery. In other words, if the heat recovery compromises the integrity of the refrigeration, heat recovery is abandoned or reduced. In such situations, the HRU controller can compensate by importing heat from district heating or other parallel heat sources.

In the Danfoss Smart Store, all heat for space heating is provided by the CO_2 refrigeration system. In February (statistically the coldest month), we produced 6.6 kWh of extra heat for every 1 kWh of electricity consumed, compared to the month of May, when the refrigeration load was low and space heating was supplied by surplus heat.

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