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Optimising a supermarket refrigeration system with heat recovery to minimise operational costs

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ABSTRACT

This work is a case study of a small supermarket located on the ground floor of a residential building in Stockholm. The supermarket has a CO_2 refrigeration system with de-superheaters for heat recovery and water-cooled condensers/gas coolers using municipal water. The heat recovery system is connected both to the supermarket and to the residential building. This study evaluates the existing refrigeration system with field measurements data and investigates different system configurations and control strategies to minimise the operational costs from electricity and municipal water use. The results of the study demonstrate that the operational costs are reduced by 29 % in the existing solution, compared with no heat recovery, and that the costs can be reduced by further 31 % with a control strategy optimised for maximisation of heat recovery.

Keywords: Refrigeration, Carbon Dioxide, Supermarket, Heat Recovery, Field Measurements, Modelling

1. INTRODUCTION

Supermarkets are energy intensive buildings wherein refrigeration systems use a significant share of the energy. Some supermarkets in city centres have difficulties in rejecting heat from the refrigeration system condensers/gas coolers directly to the ambient air, due to a combination of their noise, perceived negative aesthetics, and high installation costs (Andersson, 2021). A viable solution for some supermarkets is to use district cooling as a heat sink. If district cooling is not a practically feasible solution, the supermarket may have to resort to using municipal water in an open loop.

Heat recovery, also referred to as heat reclaim, from refrigeration systems is a commonly applied measure to increase the overall energy efficiency in supermarkets (Arias and Lundqvist, 2006). At higher head pressure, heat from the condensers can be recovered at temperatures useful in buildings' heating systems. Previous studies have shown that all heating demands in the supermarket can be covered and that this can be done at high efficiency, where significant amounts of heat can be recovered for relatively low additional power consumption (Karampour, 2021).

This work is a case study of a small supermarket located in the ground floor of a multifamily building in the inner parts of Stockholm. Previously, an open-loop solution with municipal water was the only available heat sink, but the supermarket can now also recover heat, resulting in lower municipal water use. That is, increasing the amount of recovered heat simultaneously contributes to decreasing municipal water use. Furthermore, the amount of heat that can be recovered may occasionally exceed the heating requirements in the supermarket. On these occasions, supplying heat to the connected residential building is a possibility to recover even more heat and further reduce the municipal water use.

2. CASE STUDY

The studied supermarket is about 390 m^2, only considering the sales area, and 500 m^2 in total. It is located on the ground floor of a 3759 m^2 six-story residential building. Due to the slope of the ground, most of the store is located underground, with only a relatively small share of the external walls connected to ambient air. The building uses district heating and there are no chillers for air conditioning installed, as there is no need for it, which is typical for residential buildings in Sweden. The supermarket installed a new CO_2 refrigeration system in the summer of 2019, replacing a previous HFC-system. Subsequently, a heat recovery system was installed in January 2021.

The heat recovery system consists of a closed water loop connected to the refrigeration system and property heating systems (see Fig. 1). Heat is picked up in heat exchangers connected to the three condensers/gas coolers in the chillers of the refrigeration system, and the heated water is stored in three 500-litre accumulator tanks coupled in series. The first two tanks are connected by coil heat exchangers to the property's space heating system, and the third one pre-heats the property's domestic hot water (DHW) and heats up the supply air of the supermarket's ventilation system. When needed, the property's heating system picks up additional heat from the district heating connection, and the supermarket uses an electric heater for auxiliary heating of the supply air.

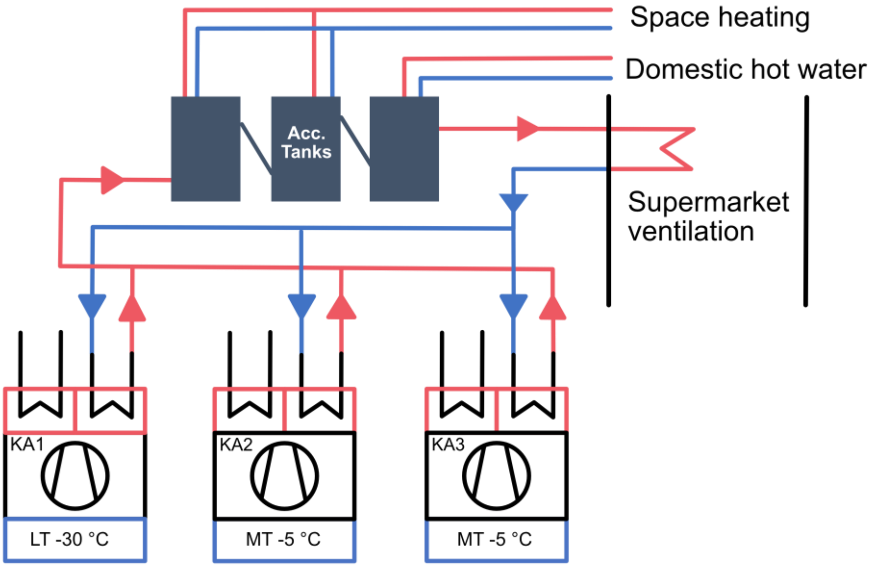

Figure 1: Layout of the heat recovery system

3. METHOD AND DATA COLLECTION

This work used historical field measurement data from the case study and modelling and simulation of the refrigeration system in Engineering Equation Solver (EES) and Microsoft Excel with the CoolProp wrapper for calculation of thermophysical properties (F-Chart Software, 2023; Bell et al., 2014). The model used the BIN hour method and was developed by Filip Josefsson at KTH Royal Institute of Technology (Josefsson, 2022). The model investigated different system configurations and its main purpose was to find the most optimal solution in terms of minimising operational costs for refrigeration.

3.1. Field measurements

Historical data from the refrigeration system was collected through the company Huurre's web-based portal iTOP (Caverion, 2022). Data was collected for the period from February to November in 2021. Data on municipal water use were collected from a manual meter at 12 different occasions. Data from 2020 on the space heating demand for the whole building was provided by the property owner; the demand was then formulated as a linear function of ambient temperatures. The whole building's DHW use was only available as a yearly value of 950 m^3/year, corresponding to roughly 55 MWh/year if heated to 60°C from 10°C. In the absence of more accurate data, this yearly value corresponds to an hourly average of 6,3 kW (Andersson, 2021). The electricity price was fixed at 0.812 SEK/kWh, corresponding to 80 €/MWh, including grid fees and taxes. This information was provided by the supermarket manager. The water costs comprise of three components: a variable fee, utility fee, and a yearly fixed fee. The variable fee was 8.32 SEK/m^3 or 0.82 €/m^3. The utility fee is connected with costs of maintaining the supply piping network and the sewage treatment plant. The utility is paid yearly according with the consumers' total annual use following the prices in Table 1. The supermarket's total use of municipal water as a heat sink was 7755 m^3 between February 9th and November 23rd in 2021, corresponding to an average value of 1.13 m^3/h.

Table 1: Yearly water utility fee (Stockholm vatten och avfall, 2020)

Max m^3/year	Utility fee [€]
40,000	17,289
22,000	9,836
11,000	4,894
6,000	2,405
2,000	802
600	187

Based on the collected data, key variables were constructed as functions of the ambient temperature through linear curve fitting. The ambient temperatures were provided by a nearby weather station of the Swedish Meteorological and Hydrological Institute (SMHI, 2021). Some of the key variables were the refrigeration loads, heating demands, and municipal water supply temperatures.

The CO_2 refrigeration system includes three units: one low temperature (LT) and two medium temperature (MT) units. These are referred to as LT1, MT2, and MT3, and correspond to KA1, KA2, and KA3, respectively, in Fig. 1. The units have identical system layouts and are of direct-expansion type. All units also use single-stage compression and internal heat exchangers (see Fig. 2). The systems may operate in trans-critical conditions under high pressure, enabling delivery of higher water temperatures and higher capacities for heat recovery. Compressor efficiencies were extracted from the manufacturer data sheets and correlated to the pressure ratios. The compressor efficiencies were used to determine the refrigerant mass flows, which were then used to calculate the compressors' work, heat recovery, and heat rejected in the condensers/gas coolers.

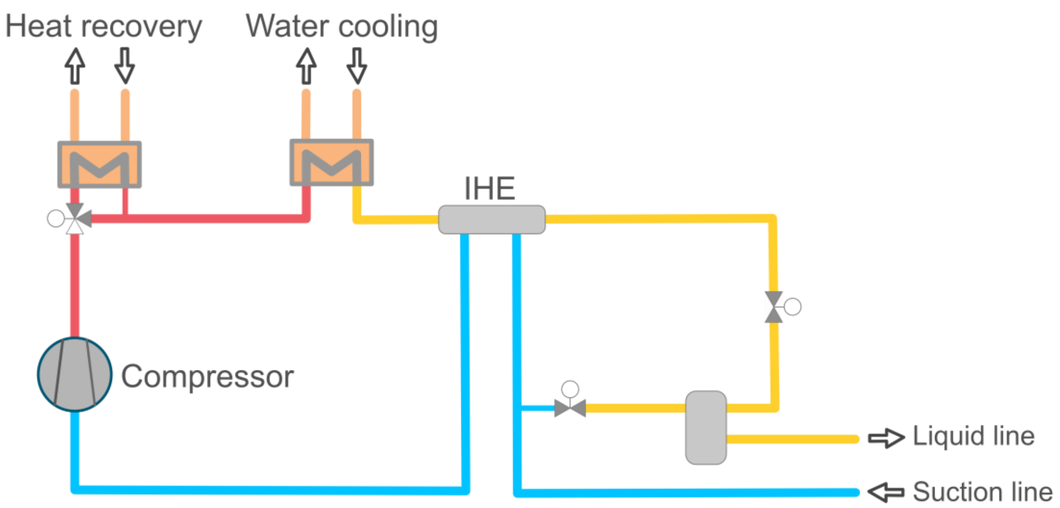

Figure 2: Schematic of the CO_2 refrigeration system

The supermarket is heated up by the supply air from the ventilation system, and the heating demand was calculated according to Eq. (1).

$$\dot{Q}_{vent} = \dot{m}_{air} * c_{p,air} * (t_{air,sup} - t_{amb}) \qquad \text{Eq. (1)}$$

In Eq. (1), $\dot{Q}_{vent}$ is the heating demand of the supermarket in kW, $\dot{m}_{air}$ is the mass flow of supply air in kg/s, $c_{p,air}$ is the specific heat of air at the mean temperature across the heat exchanger in kJ/(kg*K), $t_{air,sup}$ is the supply air temperature in °C, and t_{amb} is the temperature of the ambient air in °C. The mass flow of air was calculated as the product of volume flow and density at atmospheric pressure and mean temperature across the heat exchanger. The ventilation volume flow rate is 830 l/s when the store is open and 415 l/s when the store is closed. This information was gathered from documentation of the air handling unit (Flexit S30) provided by the company responsible for installing the ventilation system (Ravent AB). Lastly, the supply air temperature to the store was assumed to be constant at 20°C, as discussed in Andersson (2021).

3.2. Modelling of the refrigeration system

The refrigeration system was modelled in EES. Performance indicators were calculated based on sets of equations taking input data from the key variables mentioned in section 3.1. The chosen indicators were discharge pressure, condenser/gas cooler exit temperature, compressor power, rejected heat in the de-superheater and in the condenser/gas cooler, and total operational costs. The total refrigerant mass flow and compressor power consumption were calculated by energy balances at the mixing point after the receiver, evaporators, and the internal heat exchangers.

Neither the flow of municipal water (on an hourly basis) nor the water outlet temperature in the condenser/gas cooler was available in the monitoring system, so an assumption had to be made for both. Constant temperature differences for the water of 17K in trans-critical operation and 14K in sub-critical operation were therefore assumed; these values were determined based on the average hourly municipal water use registered through the manual water meter.

An optimisation tool in EES was used to minimise the operational cost of the system by varying the discharge pressure and condenser/gas cooler outlet refrigerant temperature, which are the main influencing parameters on the amount of heat recovered and the power consumption of the compressor; see Eq. (2).

$$\min_{p_{dis}, t_{gc,out}} (\dot{E}_{el} * \mathrm{P_{el}} + \dot{m}_{water} * \mathrm{P_{water}}), \qquad \text{Eq. (2)}$$

In Eq. (2), $\dot{E}_{el}$ is the electrical power required to operate the compressor [kW], $\mathrm{P_{el}}$ is the electricity price [€/MWh], $\dot{m}_{water}$ the municipal water mass flow [kg/s], $\mathrm{P_{water}}$ the municipal water price [€/kg], p_{dis} is the discharge pressure [bar], $t_{gc,out}$ is the refrigerant temperature at the condenser/gas cooler outlet [°C], and t_{dis} is the discharge temperature [°C]. The maximum allowed discharge pressure was 79 bar (a constraint from the service company) and the de-superheater exit temperatures were allowed to vary between 32°C and the discharge temperature; 32°C as a lower limit is a constraint from the heating system return temperature.

Single point calculations were lastly executed over an ambient temperature range of -20°C to 30°C. The calculations had a step size of 5°C, and the BIN hour method was used to relate the results to the investigated time period. The BIN hours ranged from -12°C to 33°C at the given climate in Stockholm. In this way, the resolution of the operational costs for refrigeration was changed from temperature-based to annual.

3.3. Investigated scenarios

Four scenarios were investigated, including a reference scenario based on the field measurements analysis; this reference scenario is referred to as "historical data". In the historical data, field measurements during the investigated period were analysed. This scenario represents the actual system performance. The other three scenarios were modelled in EES.

In Scenario 1, no heat recovery was used, and all heat was rejected to the water-cooled condensers/gas coolers. The refrigeration system operated in floating condensing mode, keeping the head pressures as low as possible to minimise electricity consumption. The head pressure determines the condensing temperature, which was modelled with an assumed 7 K approach temperature difference in the condenser.

In Scenario 2, the heat recovery system was connected only to the supermarket itself through the heat exchanger in the ventilation air duct. No heat was provided to the residential part of the building. The refrigeration system was assumed to be controlled with an optimum strategy in heat recovery mode, as described in Sawalha (2013).

In Scenario 3, the heat recovery system was connected to both the supermarket and the property according to the layout in Fig 1. However, Scenario 3 differed from the historical data in the control of the system. Scenario 3 was assumed to be controlled for maximum heat recovery and optimum control for highest efficiency.

4. RESULTS

4.1. Field measurements analysis

This section describes the field measurements analysis of historical data. Fig. 3 illustrates the resulting refrigeration load in each unit. The refrigeration loads in the MT units vary from about 4 kW at -12°C to 14 kW at 30°C, with a somewhat lower peak load in MT2; the reason for the load difference between MT2 and MT3 at ambient temperatures above 10°C is not known, but it could be a control issue. The LT demand does not vary much throughout the year and resides between 5 kW and 7 kW. The evaporation temperatures in the MT units are, on average, -5.5°C and -5.3°C for MT2 and MT3, respectively. The LT unit has -26.2°C evaporation temperature on average. These average values are used as constants in the EES model, and the refrigeration loads as functions of ambient temperature were adapted to the data by linear curve fittings.

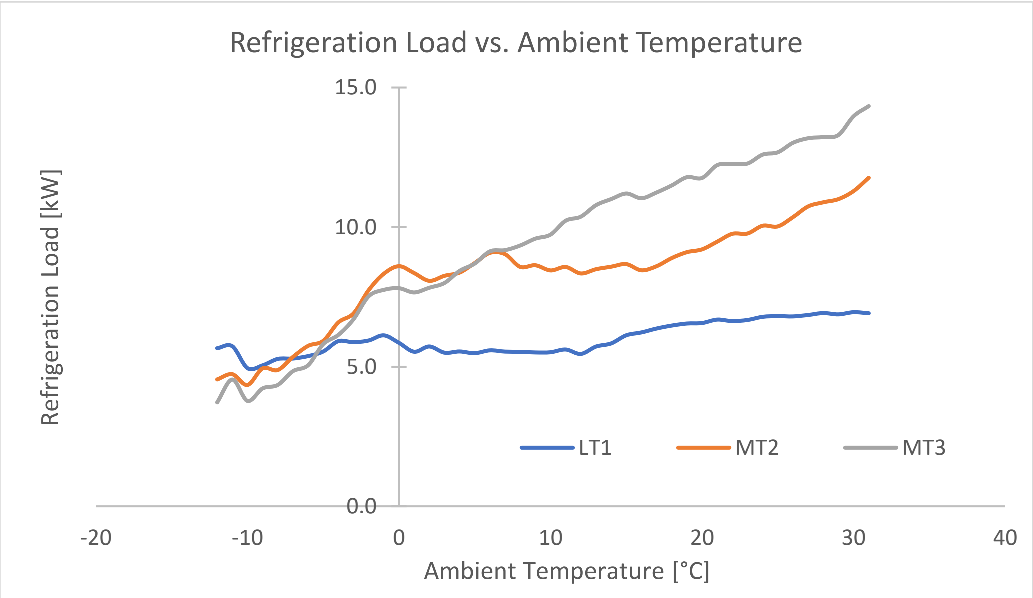

Fig. 3: Refrigeration load plotted against ambient temperature

Similarly, Fig. 4 illustrates the heating demands as functions of the ambient temperature. The plots are linearly fitted to field measurements data. The DHW demand is assumed constant at 6.3 kW. The internal heating demand of the supermarket decreases from 31 kW at -20°C to 0 kW at 20°C, and the space heating demand of the whole building decreases linearly from 140 kW at -20°C to 0 kW at 20°C. The supermarket's heating demand is also included in the whole building's space heating demand.

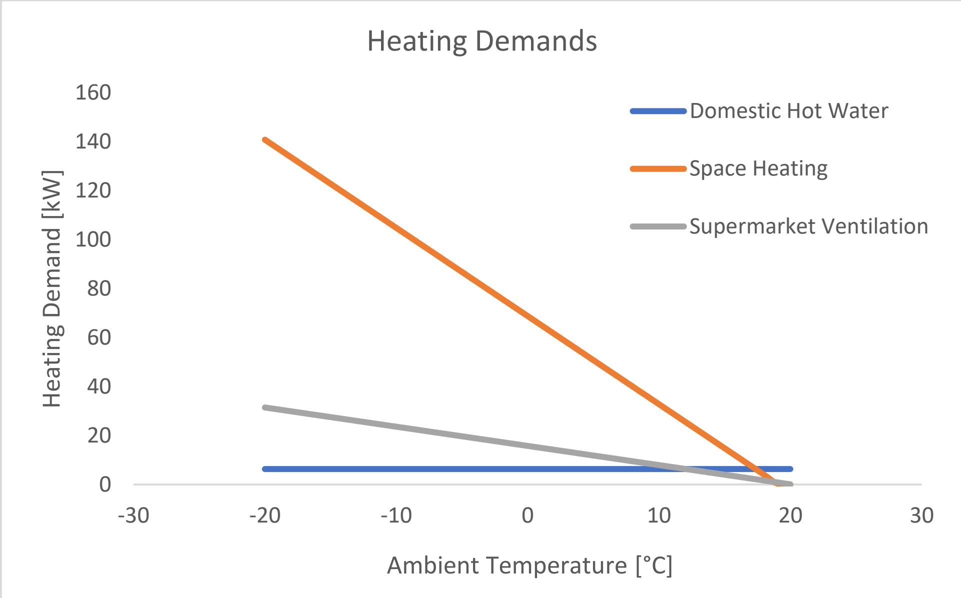

Figure 4: Heating demands as a function of the ambient temperature

The electrical power required to operate the compressors during the investigated period is illustrated in Fig. 5. The LT1 uses the most electrical power up to 12°C ambient temperature, after which it is surpassed by MT3. Recall that Fig. 3 illustrated that the LT load does not increase as significantly with ambient temperature as the MT load, explaining why the power consumption is also rather constant. The reason why the LT1 unit has relatively high compressor power compared with other units, given that its refrigeration load is lower, is that LT1 operates at a higher pressure ratio and lower efficiency than the MT units.

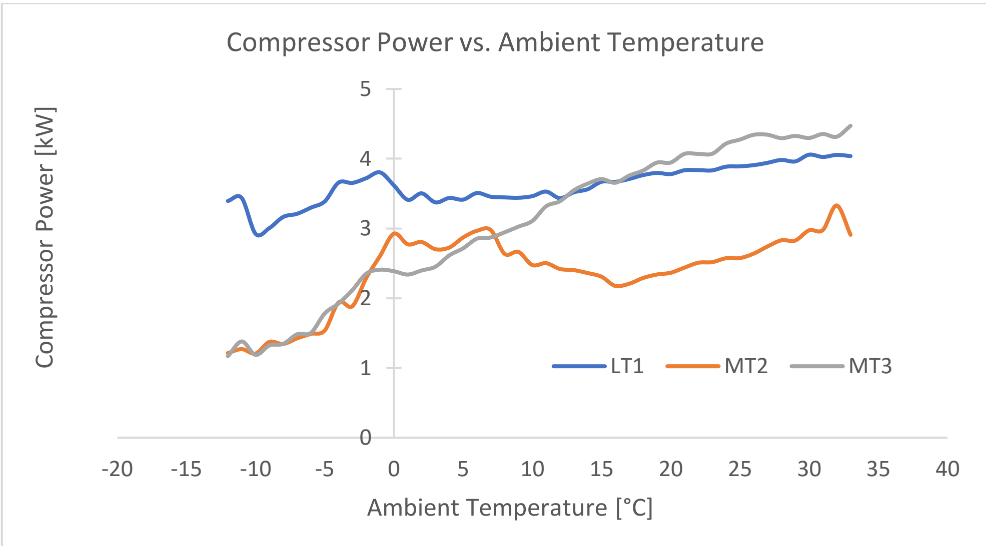

Figure 5: Compressor power consumption plotted against ambient temperature

4.2. Analysis of operation scenarios

The first parameter allowed to vary in the optimisation function is the discharge pressure. Fig. 6 illustrates how the operational strategy in each scenario varies with ambient temperatures. In Scenario 1, the discharge pressure of the compressors follow the supply temperature of the municipal water. The discharge pressure peaks at 59 bar at ambient temperatures above 10°C, and decreases linearly with temperature until the minimum of 48 bar is reached at -10°C ambient temperature.

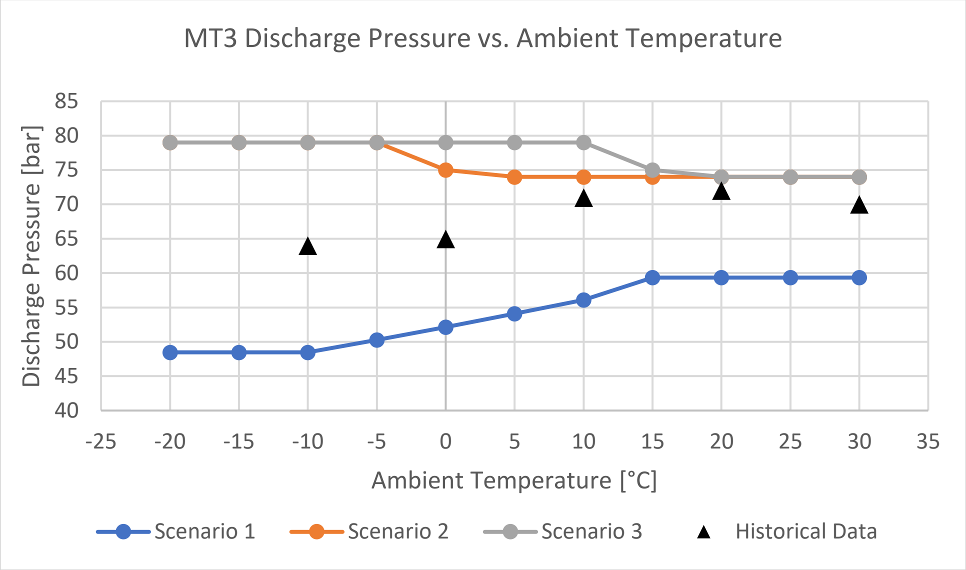

Figure 6: Discharge pressure in the different operation scenarios

In Scenario 2 and Scenario 3, the discharge pressures are kept at 79 bar at ambient temperatures below -5°C. This is the maximum allowed (by the service company) discharge pressure in the system, and the internal heating demand of the supermarket is high enough for all the heat to be rejected to the supply air of the ventilation system. Between ambient temperatures of 5°C and 20°C, the discharge pressures in Scenario 2 and Scenario 3 diverge. The reason for this is that the supermarket's internal heating demand is no longer high enough for the system to reject all the available heat to the supermarket. Therefore, the discharge pressure is in Scenario 2 lowered to match the internal heating demand. The discharge pressures in scenarios 2 and 3 then converge to 74 bar at ambient temperatures of 5°C or higher. The historical data illustrates a control strategy in between the other scenarios, in which the discharge pressures are higher than needed for floating condensing mode (Scenario 1). Still, heat recovery is not utilised to its full potential, leaving space for improvement on the system control.

The second parameter allowed to vary in the optimisation function is the refrigerant temperature at the condenser/gas cooler exit. For a given refrigeration load and evaporation temperature, an increase of the condenser exit temperature leads to higher power consumption in the compressor. Fig. 7 shows how this parameter differs in the scenarios for the MT3 unit. In Scenario 1, the condenser outlet temperature is lower than in all other scenarios for ambient temperatures below 15°C, after which all scenarios except for the historical data converge to 17°C.

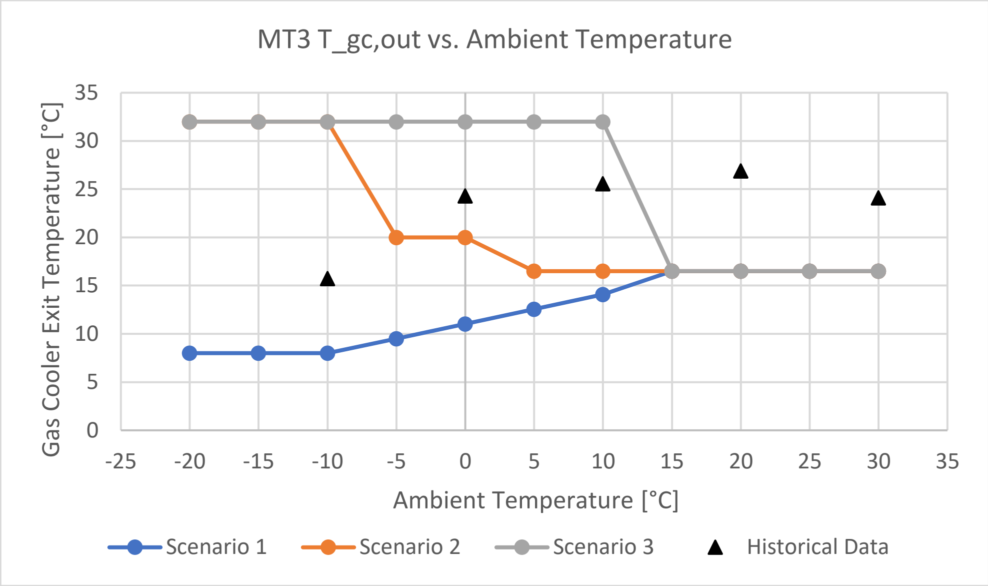

Figure 7: Refrigerant temperature at gas cooler outlet in the different operation scenarios

In scenarios 2 and 3, the refrigerant temperatures at the gas cooler outlet are 32°C for ambient temperatures below -10°C; this was actively defined as the minimum de-superheater exit temperature when heat recovery is maximised, as described in section 3.2. At ambient temperatures between -10°C and 15°C, the gas cooler exit temperatures in scenarios 2 and 3 diverge, as Scenario 3 allows for higher values when maximising heat recovery. The historical data have high condenser outlet temperatures, around 25°C, for ambient temperatures above 0°C. These high temperatures suggest that the actual performance of the system can be improved through better control.

Furthermore, the discharge pressures and condenser/gas cooler exit temperatures determine the power consumption of the compressors, as illustrated by Fig. 8. In Scenario 1, the compressor power consumption is the lowest at all ambient temperatures, ranging from 3 kW to 9 kW. This is expected, as the Scenario operates at the lowest discharge pressures and lowest condenser exit temperatures. For Scenario 2 and Scenario 3, the power consumptions are the same for ambient temperatures below -10°C; at these ambient conditions, the supermarket's capacity to recover heat is only enough for internal demands. Between ambient temperatures of -10°C and 15°C, however, the power consumption in Scenario 3 is higher than in Scenario 2. The historical data shows values in between those shown in the other scenarios.

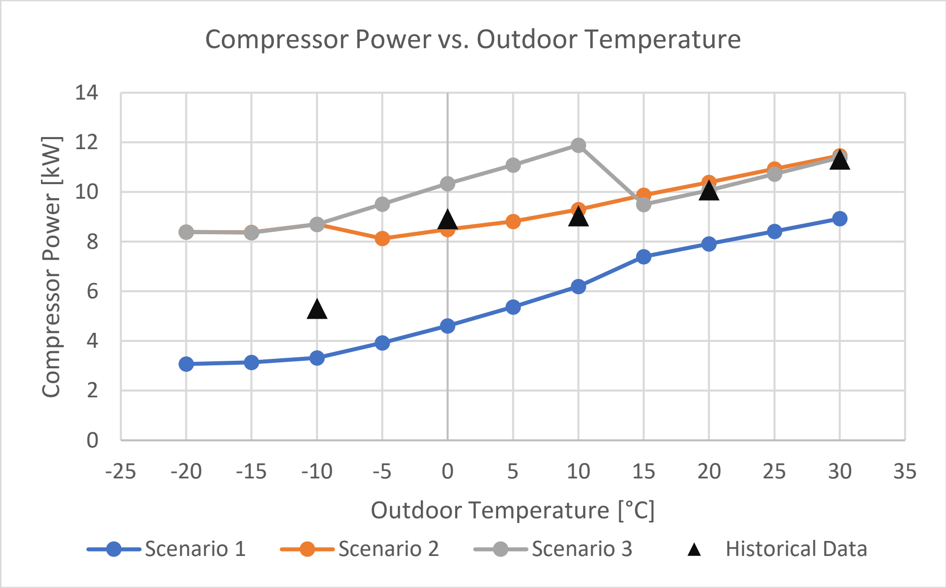

Fig. 8: Compressor power in the different operation scenarios

The higher compressor power consumption in Scenario 2 and Scenario 3 is a result of the drawback of the heat recovery strategy. The advantages, however, are the increased amount of heat that can be recovered and the reduced municipal water use for the condensers/gas coolers. Fig. 9 illustrates the amount of heat that can be recovered in the different scenarios. In Scenario 2, the heat recovery starts at 20°C ambient temperature and increases linearly up to about 24 kW at -10°C, after which the capacity is not enough to cover the internal heating demand. In Scenario 3, the heat recovery increases linearly with decreasing ambient temperature up to a maximum of 34 kW at an ambient temperature of 10°C. The refrigeration system capacity for heat recovery then reduces linearly with decreasing ambient temperature down to 23 kW at -10°C, where it converges with Scenario 2. The historical data follows a similar pattern as Scenario 3, but at lower levels.

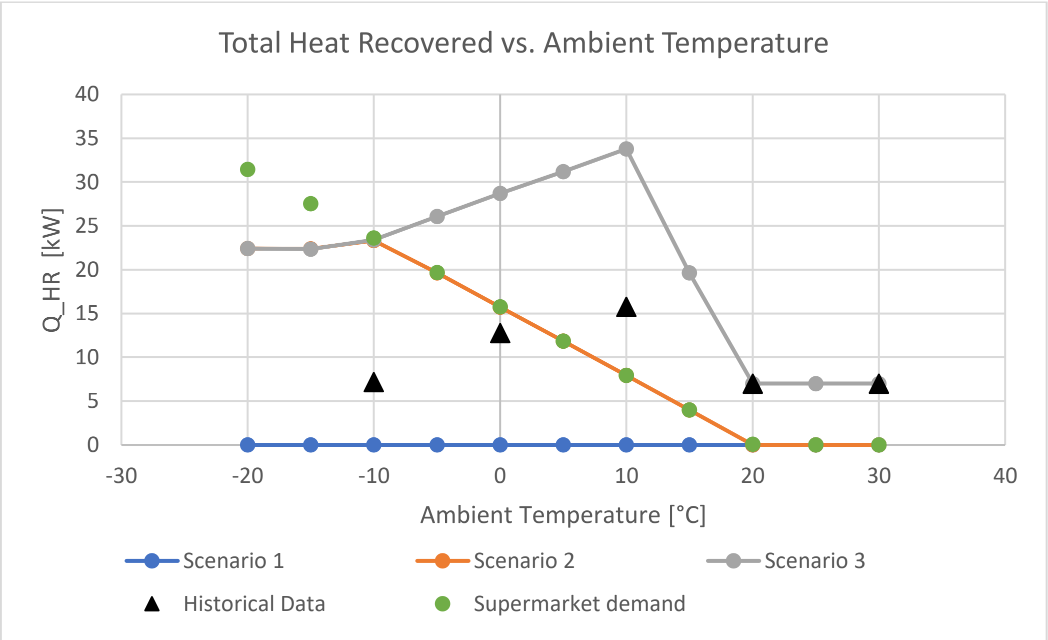

Figure 9: Heat recovery in the different operation scenarios

The reduced use of municipal water as a heat sink is illustrated in Fig. 10. Scenario 1 has the highest water use during all outdoor temperatures, ranging between 1-2.4 m^3/h. In Scenario 2, the water use is lower at all points and is completely eliminated at ambient temperatures of -10°C or lower. In Scenario 3, the water use is almost eliminated already at 10°C ambient temperature.

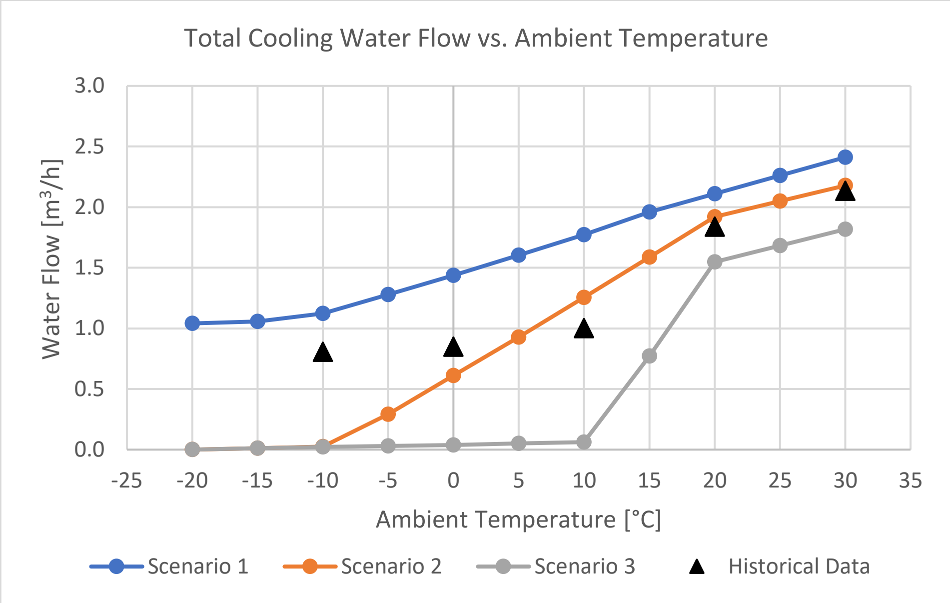

Figure 10: Municipal water use for condenser cooling in the different operation scenarios

The costs of operating the refrigeration system consists of the electricity and cooling water costs. Fig. 11 summarizes the total costs of operation in all the scenarios over the investigated period. The figure shows that the water costs dominate, making the scenarios with the lowest water use the cheapest solutions. Scenario 2 reduces the total costs by 26 % compared with Scenario 1, despite 49 % higher electricity costs. Scenario 3 further reduces the costs by 35 % compared with Scenario 2, or 51 % compared with Scenario 1.

The historical data has the same system solution as Scenario 3 but is not controlled for maximum heat recovery, and therefore ends up having higher total costs than Scenario 3 but lower than Scenario 2, in which the system can only reject heat to the supermarket. Comparing the historical data with Scenario 1 shows the profits the supermarket has already achieved since installing the heat recovery system, namely operational cost savings of 29%. However, if controlled for maximum heat recovery, as in Scenario 3, the supermarket could save an additional amount of €5,456. This corresponds to cost savings of further 31%.

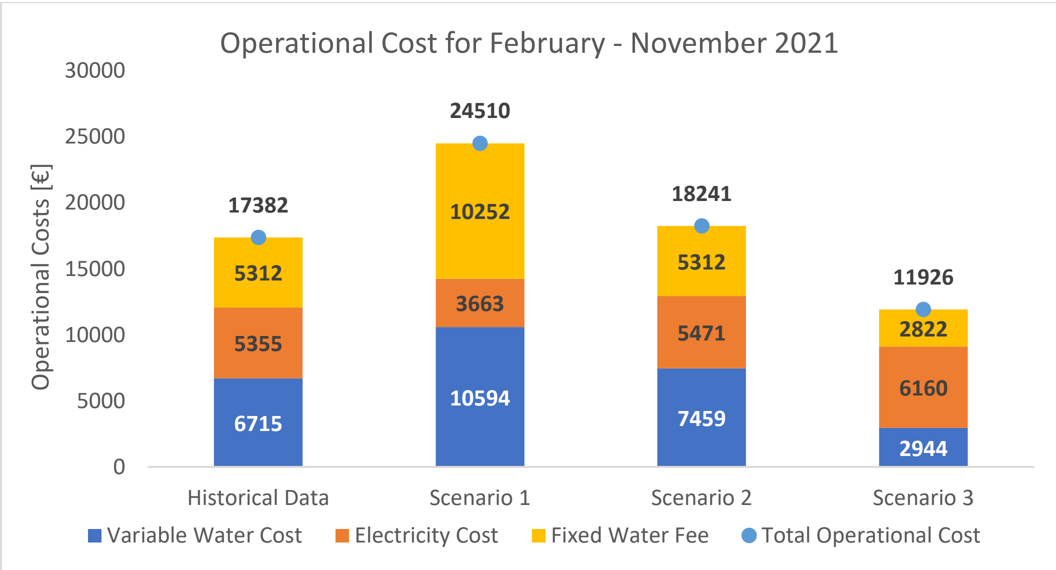

Figure 11: Total costs for refrigeration in the different operation scenarios

5. DISCUSSION AND CONCLUSIONS

The results demonstrate the significant potential of heat recovery in the supermarket just to minimise the municipal water use. It is clear that the additional electricity consumption is not nearly as costly as using the high amounts of cooling water as before. However, the profits could change under different price ratios between water and electricity.

Moreover, the main reason for the supermarket to install the heat recovery system is stated by the owner to be a reduction of municipal water use, rather than focusing on the heat itself. As the supermarket had a gross lease, where a fixed payment for heating was included in the rent, regardless of the amount of heat that was actually used, a reduced use of heat from the building's energy central had no financial gain. This is why the heating of the supermarket and exported heat to the building are not attributed economic values in the calculations. If they were, the scenarios involving heat recovery, i.e. Scenario 2 and Scenario 3, and the historical data, would be even more competitive from an economic point of view. Indeed, the supermarket has since the beginning of this project managed to remove heating of the premises entirely from the lease contract, and are now relying on their refrigeration system only for heating of their premises. In this way, they removed a fixed payment of 70,000 SEK/year, corresponding to about 6,900 €/year. It is clear from the results in Fig. 11 that 6,900 €/year is a significant share of the energy-related costs in the supermarket.

To conclude, this study investigates a case study of a supermarket in a residential building where a heat recovery system is installed for the refrigeration system. The refrigeration system previously rejected all condenser heat to municipal water in an open-loop solution. This work shows, through field measurements and computer modelling, the operational benefits of recovering heat and controlling the system for maximised heat recovery. The strategies involving heat recovery are beneficial even without consideration to the value of covering the heat demand; the reduced municipal water use alone more than compensates for the additional electricity use entailed by the operational strategies of the scenarios. Over a 10-month period, the studied supermarket makes 29 % savings in operational costs for refrigeration compared with a system without heat recovery. If controlling the system for maximum heat recovery, the supermarket could save further 31 % in operational costs for refrigeration during the period.

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NOMENCLATURE

$\dot{Q}$	Heat transfer [kW]
$\dot{m}$	Mass flow [kg/s]
c_p	Specific heat [kJ/kgK]
t	Temperature [°C]
$\dot{E}$	Electrical work [kW]
p	Pressure [bar]
DHW	Domestic hot water
EES	Engineering Equation Solver
LT	Low temperature
MT	Medium temperature
P	Price [€/MWh], [€/kg]

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