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Techno-economic analysis of heat export from supermarket refrigeration systems: field measurements analysis of three case studies

Daniel STEUER*, Julia ALMEBÄCK, Rebecka MAGNIUS, Jaime ARIAS, Samer SAWALHA

KTH Royal Institute of Technology
Stockholm, 100 44, Sweden
*Corresponding author: dsteuer@kth.se

ABSTRACT

Heat recovery from refrigeration systems is a commonly applied measure to increase energy efficiency in supermarkets, upgrading the heat otherwise rejected to the atmosphere in condensers. The aim of this work is to investigate the technical potential and economic outcome of heat recovery and heat export in three different supermarkets. Field measurement data from three supermarket refrigeration systems with heat recovery are collected and used as a basis for computer modelling and simulation. Energy costs are gathered from the supermarkets and the profitability of heat recovery and heat export are evaluated. The results show that the supermarkets could save up to 40 % in annual operational costs for refrigeration and heating if disconnecting from the district heating network and producing all the required heating in the store with the refrigeration system, and up to 48 % if maximising the produced heat and selling the surplus to a neighbouring building.

Keywords: Commercial Refrigeration, Heat Recovery, Case Study, Techno-Economic, Field Measurements

1. INTRODUCTION

Supermarkets are energy intensive buildings with high refrigeration, ventilation, and lightning loads. They are a necessity of our modern lifestyle and their numbers are expected to keep increasing, making them an important target for efficiency improvement measures. These measures should contribute to reduced greenhouse gas emissions, energy use, and costs. One of the possible energy efficiency improvement measures is heat recovery from refrigeration systems, also referred to as heat reclaim (Arias and Lundqvist, 2006). The refrigeration system rejects a significant amount of heat that is typically released to the ambient air, as it is not by default useful in the building's heating system. To make it useful, supply temperatures must be high enough, which is achieved by increasing the head pressure (Sawalha, 2013).

Moreover, CO_2 as a refrigerant in commercial refrigeration has become the industry standard in some parts of the world, particularly in those with cold climates (Zolcer Skacanová & Battesti, 2019). There is a synergy in using CO_2 as refrigerant and recovering heat from the refrigeration system, as heat recovery from CO_2 refrigeration systems in trans-critical solutions can deliver high enough temperatures at competitive efficiencies (Sawalha, 2013). The rejected heat may at times even be higher than what is needed in the supermarket, in which case heat export to nearby consumers is a possible solution. However, a lack of awareness among the involved parties regarding the amount of heat which can be recovered, and at what efficiency, prevents the potential from being fully utilised. The main objective of this work is therefore to investigate the technical potential and economic outcome of heat recovery systems with the possibility to export heat from supermarkets.

2. CASE STUDIES

This work is based on three case studies of supermarkets of varying types in Sweden. They are located in Ytterby in Kungälv, in the city of Eskilstuna, and in Lundby Park in Gothenburg. General information about the supermarkets is summed up in Table 1. The performance and economic data are gathered for the whole year of 2020 for the Ytterby and Eskilstuna supermarkets, and from October 2021 to March 2022 for the supermarket in Lundby Park. All three supermarkets have CO_2 booster refrigeration systems that can operate trans-critically (see Fig. 1). They are also all connected to a district heating network (DHN), but are recovering heat from the refrigeration systems as well. This occurs in the de-superheater (see Fig. 1).

Table 1: Overview of case studies

Supermarket	Ytterby	Eskilstuna	Lundby Park
Size [m^2]	9,960	5,500	600
Neighbour	Stand-alone	Shopping mall	Residential
MT capacity [kW]	250	140	27
LT capacity [kW]	35	30	10
Heating demand, [MWh/year]	380	225	42
Heat recovered [MWh/year]	220	205	42

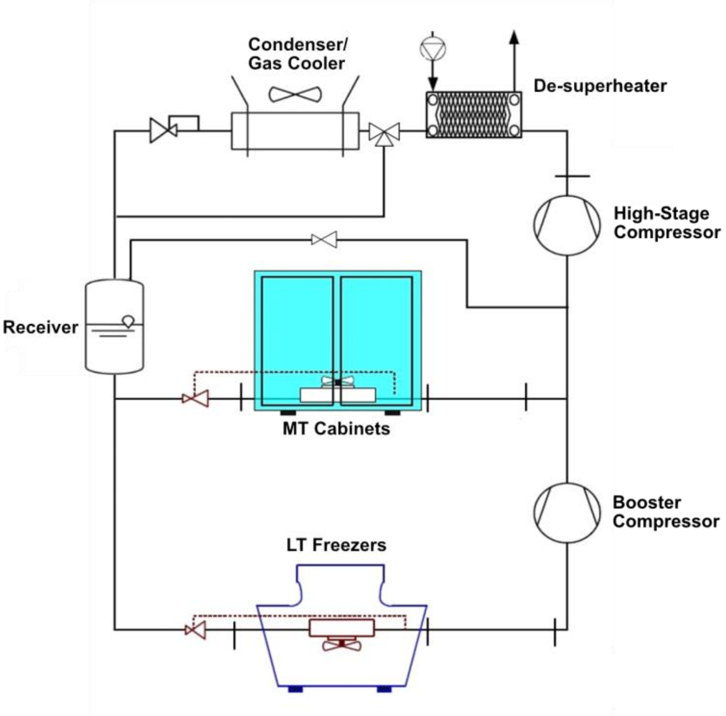

Figure 1: CO_2 booster refrigeration system including heat recovery de-superheater (Karampour, 2021)

3. METHODOLOGY

A field measurements analysis was firstly performed to estimate the actual electricity consumption and heat recovery from the refrigeration systems in the three supermarkets. The results of this analysis were used as a reference scenario and provided input data for the modelling and simulation of varying scenarios.

Using invoices for heating and electricity provided by the supermarkets, the annual electricity costs of operating the refrigeration system and heating of the premises were also determined. An iterative steadystate model, developed at the Energy Technology department at KTH Royal Institute of Technology, was then used to simulate varying operational strategies for the refrigeration system. The model is based on Visual Basic Analysis integrated with the Refprop software for calculation of thermophysical properties. For a more detailed explanation of the model, the reader is referred to Giunta and Sawalha (2021). The results of the different strategies describe heat recovery and export from a techno-economic perspective.

3.1. Field measurements analysis

Historical data for the refrigeration system was provided by an IWMAC monitoring system (Kiona, 2023) and synchronized with linear interpolation in MATLAB to determine average hourly values (MATLAB, 2022). For the stores in Ytterby and Eskilstuna, the full year of 2020 was chosen for data collection. Due to limited availability, October 2021-March 2022 was chosen in the Lundby Park store. Compressors' volumetric and total efficiencies as polynomial functions of the pressure ratio were interpolated from manufacturer data. The volumetric efficiencies were then used to determine the total refrigerant mass flows with Eq. (1).

$$\dot{m}_r = \eta_S * \rho_{2k} * \dot{V}_S * (f_{measured}/f_{nominal}) \qquad \text{Eq. (1)}$$

In Eq. (1), $\dot{m}_r$ is the total refrigerant mass flow in kg/s, η_S is the compressor's volumetric efficiency, ρ_{2k} is the refrigerant density in kg/m^3 at compressor inlet, $\dot{V}_S$ is the compressor's swept volume in m^3/s , $f_{measured}$ is the measured frequency in Hz, and $f_{nominal}$ is the nominal frequency in Hz at which the design capacity is achieved. Eq. (1) was applied to both booster and high-stage compressors in Fig. 1. The compressor's electricity consumption was then calculated according to Eq. (2).

$$\dot{E}_{comp} = \dot{m}_r * (h_{1k,is} - h_{2k})/\eta_{tot} \qquad \text{Eq. (2)}$$

In Eq. (2), $\dot{E}_{comp}$ is the power required to operate the compressor in kW, $\dot{m}_r$ is the refrigerant mass flow in kg/s, $h_{1k,is}$ is the refrigerant enthalpy in kJ/kg at compressor outlet after isentropic compression, h_{2k} is the refrigerant enthalpy at compressor inlet in kJ/kg, and η_{tot} is the overall efficiency of the compressor. The recovered heat in the system was then calculated using Eq. (3).

$$\dot{Q}_{HR} = \dot{m}_r * (h_{1k,MT} - h_{shr2}) \qquad \text{Eq. (3)}$$

In Eq. (3), $\dot{Q}_{HR}$ is the heat recovered in kW in the de-superheater, $\dot{m}_r$ is the total refrigerant mass flow in kg/s, $h_{1k,MT}$ is the refrigerant enthalpy in kJ/kg at the MT compressor outlet, and h_{shr2} is the refrigerant enthalpy in kJ/kg at the de-superheater outlet (see Fig. 2).

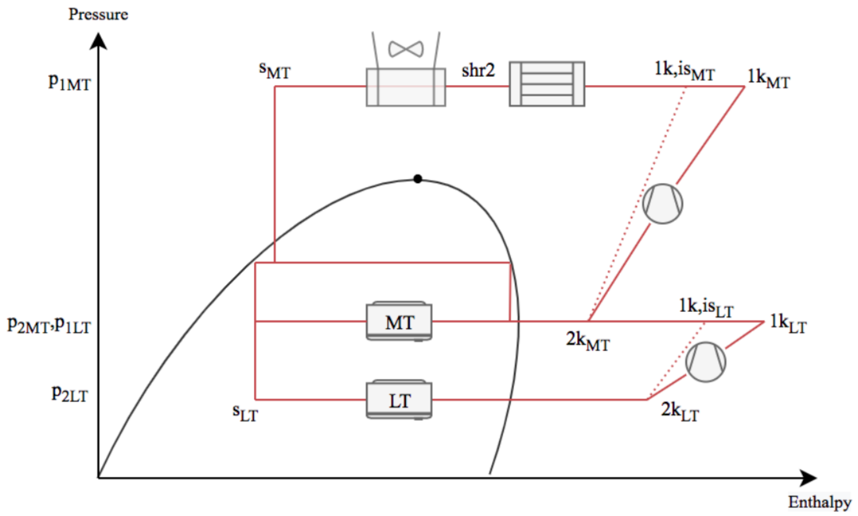

Figure 2: The CO₂ booster refrigeration system in an enthalpy-pressure diagram (Almebäck & Magnius, 2022)

3.2. Modelling and simulation of scenarios

The calculation model used the BIN hour method and its input data were ambient temperature profiles as independent variables. Then, refrigeration loads, design forward and return temperatures in the heating systems and for heat exports, heating demands, and electricity and district heating prices were constructed as functions of the ambient temperatures. The input values to the model are shown in Table 2 and were gathered in the field measurements. The DHN buying prices were calculated from the received invoices and vary according with the seasons, and the selling price of heat was assumed to be 50 % of the DHN buying price at all times. Although all prices and costs in this study were originally available in SEK, they are exchanged in this paper to EUR (€) with the average 2020 exchange rate of 10.5 SEK/€. The electricity prices in the model were average values from the invoices to the supermarkets and did neither show significant seasonal, nor geographical, variations; thus, a constant price of 114 €/MWh was used for all supermarkets.

Table 2: Input data to the calculation model

Supermarket	**Ytterby**	**Eskilstuna**	**Lundby Park**
MT ref. load [kW]	100-250	40-140	10-25
LT ref. load [kW]	20-35	12-30	3-9
Heating demand [kW]	20-220	15-70	5-25
T_evap, MT [°C]	-8	-8	-4
T_evap, LT [°C]	-33	-33	-28
T_supply, SH [°C]	30-50	30-50	30-50
T_return, SH [°C]	25-38	25-38	25-38
T_supply, sold heat [°C]	68	68	68
T_return, sold heat [°C]	35-45	35-45	35-45
P_DHN, buy [€/MWh]	58-210	76-210	58-210
P_heat, sell [€/MWh]	29-105	38-105	29-105

The investigated scenarios were Scenario 1: floating condensing (FC) operation, Scenario 2: heat recovery (HR) to match the internal heating demands of the stores, and Scenario 3: maximisation of heat recovery with export of surplus heat (HX) (see Table 3). FC operation refers to when condensing temperature/pressure is following the heat sink (i.e. ambient) temperature and kept as low as possible to minimise compressor power consumption.

Table 3. Overview of different operation scenarios

Scenario comparison	**Ref**	**Scenario 1: FC**	**Scenario 2: HR**	**Scenario 3: HX**
	Reference scenario	Floating condensing, no heat recovery	Heat recovery, no export	Heat export of surplus
Heat recovery	Yes	No	Yes	Yes
District heating	Yes	Yes	No	No
Heat export	No	No	No	Yes

The results of these simulations were then analysed and compared with the results of the field measurements analysis. The electricity consumption included in the calculations account for the refrigeration systems' compressors and gas cooler fans. All other electricity consumption is ignored because it is not scenario dependent. The district heating and heat recovery are for the supermarket building only, and the heat export describes a selling of heat to a theoretical customer. The feasibility of finding such a customer in practice varies with the case studies; to ensure comparability between them, all supermarkets are assumed to sell heat at a constant supply temperature of 68°C, which is high enough to sell to a DHN operator (Stockholm Exergi, 2023). Selling heat to a DHN operator will likely be less profitable than selling heat directly within a building, as the required supply temperature is likely to be the higher for the DHN operator. However, assuming different required supply temperatures in the case studies would make the comparison between them less coherent.

The technical results in each scenario include: the $\mathrm{COP_{HR}}$ and $\mathrm{COP_{sales}}$, defined in Eq. (4) and Eq. (5), electricity use for the refrigeration systems, district heating use, total heat recovered, and net operational costs.

$$COP_{HR} = \dot{Q}_{HR}/(\dot{E}_{HR} - \dot{E}_{FC}) \qquad \text{Eq. (4)}$$

In Eq. (4), $\mathrm{COP_{HR}}$ is the COP of heat recovery, $\dot{E}_{HR}$ is the compressor power for heat recovery in kW, and $\dot{E}_{FC}$ is the compressor power in kW for floating condensing operation. The heat included in $\dot{Q}_{HR}$ is only the heat used for space heating in the supermarkets, not exported heat. The $\mathrm{COP_{HR}}$ describes the technical performance of adjusting the control of a refrigeration system for heat recovery purposes.

$$COP_{sales} = \dot{Q}_{sales}/(\dot{E}_{sales} - \dot{E}_{HR}) \qquad \text{Eq. (5)}$$

In Eq. (5), $\mathrm{COP_{sales}}$ is the COP of heat sales to the DHN operators, $\dot{E}_{sales}$ is the compressor work in kW required for producing surplus heat for selling, and $\dot{E}_{HR}$ is the compressor power in kW for internal heat recovery. In this definition, the priority is given to recovering heat to the supermarket's building over exporting. The $\mathrm{COP_{sales}}$ describes the technical performance of adjusting the control of a refrigeration system for exporting heat when all required heat for internal demands is already being recovered.

Moreover, the justified costs of investments were used to relate the operational savings to costs of products, installation, maintenance and repairs. An interest rate of i = 6.5 %/year, inflation rate p of 4 %/year, and lifetime n of 15 years were assumed to calculate the net present value of the annual costs of refrigeration and heating of the premises; see Eq. (6). The assumed values were collected from ICA Gruppen (2019) and are claimed to represent a current standard for investment decisions in the Swedish supermarket sector. The difference of operational savings compared with the reference scenario make up the justified costs of investments in each scenario. In Eq. (6), $\mathrm{C_{S,n}}$ is the annual cost savings for n years and $\mathrm{NPV_n}$ is the net present value of the annual cost savings for n years.

$$NPV_n = C_{S,n} * (1 - (1 + (i - p)^{-n}))/(i - p) \qquad \text{Eq. (6)}$$

Lastly, a price ratio investigation was done to evaluate the impact of the price of buying electricity and heat, and the ratio of electricity price and price for selling heat. These price ratios are defined in Eq. (7) and Eq. (8) as $\mathrm{P_{ratio,HR}}$ and $\mathrm{P_{ratio,HX}}$.

$$P_{ratio,HR} = P_{el}/P_{heat,bought} \qquad \text{Eq. (7)}$$

In Eq. (7), $\mathrm{P_{el}}$ is the electricity price in €/MWh, and $\mathrm{P_{heat,bought}}$ is the district heating price in €/MWh. $\mathrm{P_{ratio,HR}}$ is used to investigate how the profitability of the HR scenario, compared with the FC scenario, is affected by price variations.

$$P_{ratio,HX} = P_{el}/P_{heat,sold} \qquad \text{Eq. (8)}$$

In Eq. (8), $P_{heat,sold}$ is the assumed price at which the supermarkets can sell heat to a neighbouring building. $P_{ratio,HX}$ is used to investigate the varying profitability of the HX scenario compared with the HR scenario, i.e. the benefit of further increasing the heat recovery for heat sales when heat recovery in the supermarket building is already fulfilled.

4. RESULTS AND DISCUSSION

4.1. Energy use and performance

The different head pressures in the scenarios affect the electricity use for refrigeration; see Fig. 3. It can be observed that the HR scenario significantly increases the electricity use compared to the FC scenario, and that the HX scenario further increases the electricity use compared with the HR scenario. The reference scenario lies in between the FC and HR scenarios, except for in the Lundby Park supermarket, where the reference and HR scenarios are the same. The annual electricity use for refrigeration is increased by 16-27 % in the HR scenario compared with the FC scenario. The HX scenario further increases the electricity use by 12-18 % compared with the HR scenario, and by 38-43 % compared with the FC scenario.

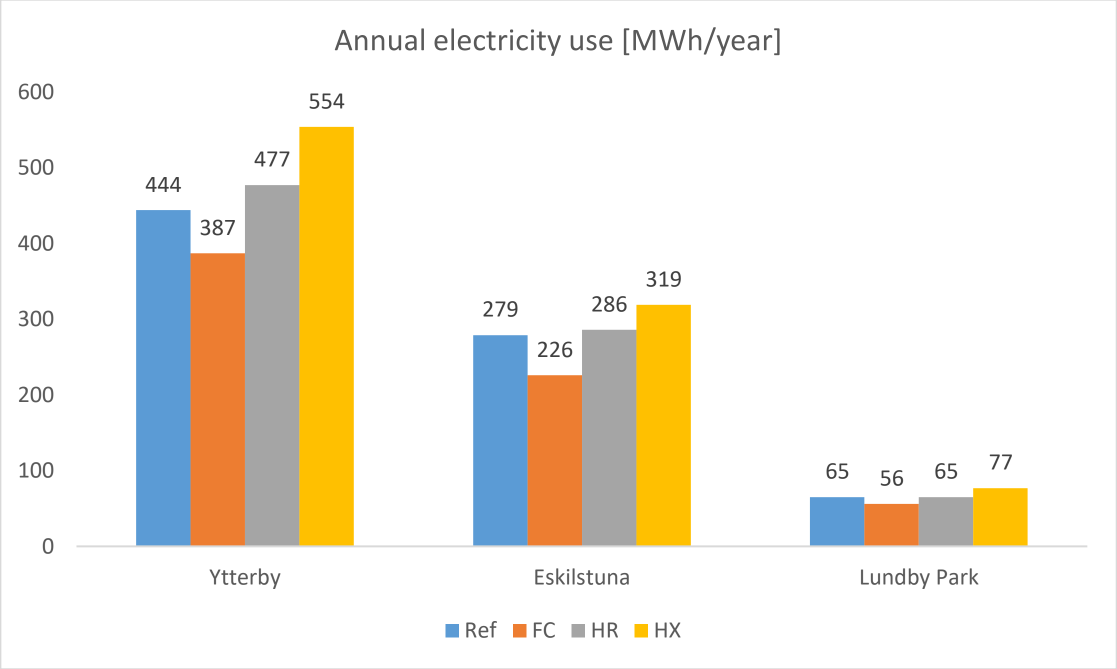

Figure 3: Annual electricity use in the studied scenarios

Moreover, Fig. 4 displays the annual amount of heat recovered, including exported heat, in relation to the heat demand of each supermarket. As no heat is recovered in the FC scenario, it is not included. All supermarkets are able to cover their internal heating requirements in the HR scenario, and export a further 79-172 % of that amount in the HX scenario, highlighting the technical potential of recovering surplus heat from the refrigeration systems. The reference scenarios show that the supermarkets are already covering significant shares of their space heating demands: between 59 % and 100 %. Fig. 4 should also be interpreted in relation to Fig. 3; by increasing the annual electricity use for refrigeration by 16-27 %, the heating demands in the supermarkets are entirely covered locally. Moreover, by increasing the annual electricity use for refrigeration by additional 16-18 %, or 38-43 % compared with the FC scenario, further 79-172 % of the supermarkets' heating demands can be produced as excess heat.

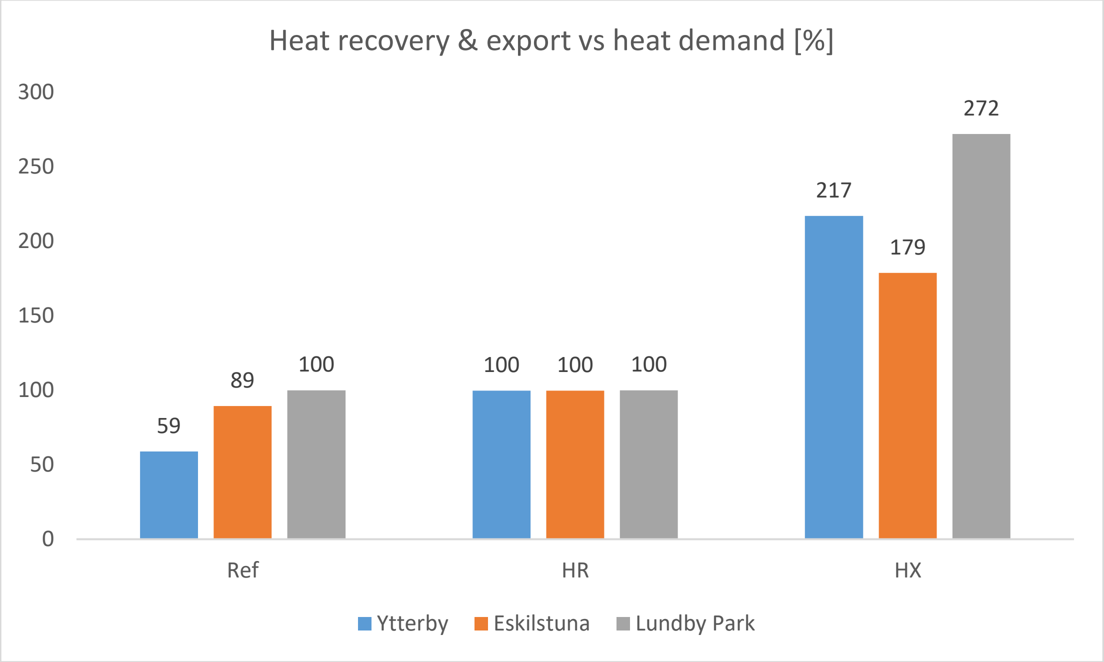

Figure 4: Sum of heat recovery and export as a share of heating demand

The respective efficiencies of heat recovery and heat export are described by the coefficients of performance, defined in Eq. (4) and Eq. (5). Fig. 5 illustrates the resulting $\mathrm{COP_{HR}}$ as a function of the ambient temperature in the three different supermarkets. The $\mathrm{COP_{HR}}$ converges towards infinity at the beginning of the heating season, during which the heat can be recovered without increasing the discharge pressure. The three graphs display the same pattern where the coefficient has a local minimum between 0°C and 5°C and a local maximum between -5°C and 0°C. The local minimum can be explained by the beginning of trans-critical operation, whereby more heat can be recovered in the de-superheater. The following local maximum marks the point at which the maximum discharge pressure is reached. To recover more heat, the gas cooler capacity is thereafter decreased, increasing the temperature at the expansion valve inlet. The MT mass flow and power consumption are therefore increased, decreasing the $\mathrm{COP_{HR}}$.

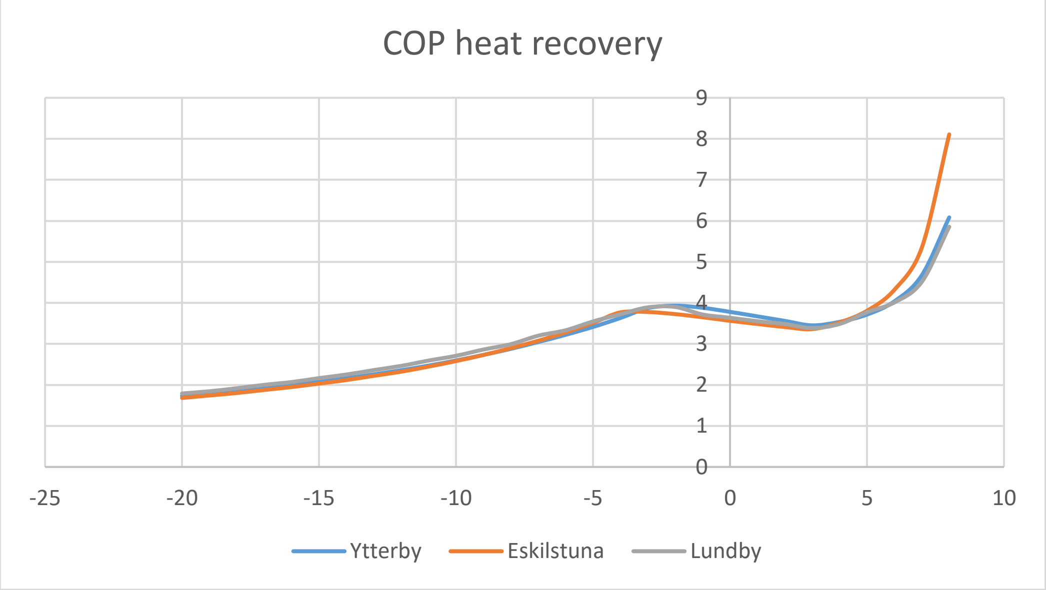

Figure 5: COP of heat recovery in the three studied supermarkets

Furthermore, Fig. 6 presents the $\mathrm{COP_{sales}}$ in the three different supermarkets. In all supermarkets, the $\mathrm{COP_{sales}}$ reach competitive values between 4 and 8 for relevant ambient temperatures. At 2°C ambient temperature the system operation becomes trans-critical in the HR scenario, leading to a decrease in the COP of sales. While the high values of COP_{sales} indicate that high amounts of heat can be exported with low additional electricity use, the price at which the heat can be sold will also have a significant impact on the profitability of heat export.

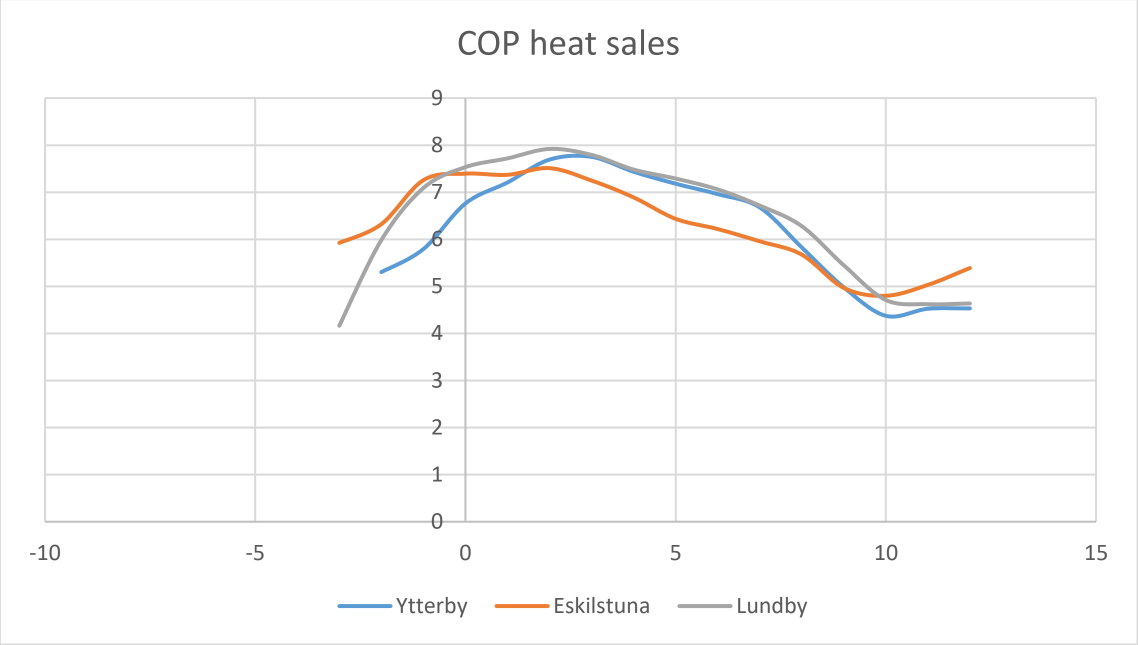

Figure 6: COP heat sales in the three studied supermarkets

4.2. Economic outcome and parametric study

The results of annual operation in the Ytterby supermarket are shown in Fig. 7. The figure illustrates how the decreased heating costs, and in the HX scenario the heat sales, offset the increased electricity costs. The reference scenario decreases the costs by 19 % compared with the FC scenario. In turn, the HR scenario decreases the costs by 17 % compared with the reference scenario and by 32 % compared with the FC scenario. Lastly, the HX scenario decreases the costs by 14 % compared with the HR scenario, 28 % compared with the reference scenario, and by 42 % compared with the FC scenario.

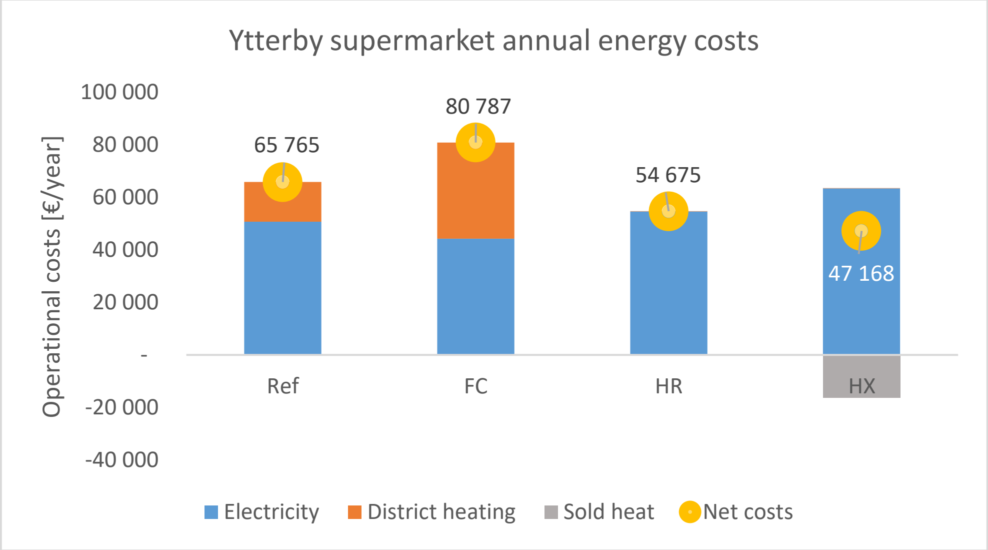

Figure 7: Ytterby supermarket annual operational results

Moreover, Fig. 8 illustrates the results of the annual operation in the supermarket in Eskilstuna. In the Eskilstuna supermarket, the reference scenario decreases the costs by 19 % compared with the FC scenario. The HR scenario decreases the costs by 14 % compared with the reference scenario and by 40 % compared with the FC scenario. The HX scenario decreases the costs by 13 % compared with the HR scenario, 26 % compared with the reference scenario, and by 48 % compared with the FC scenario.

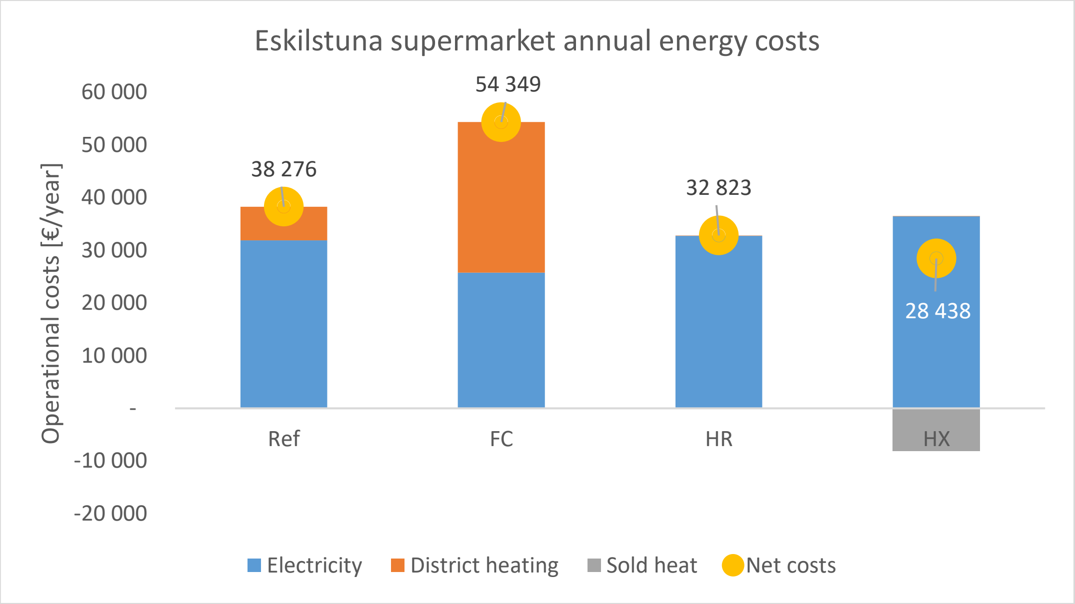

Figure 8: Eskilstuna supermarket annual operational results

Fig. 9 illustrates the results of annual operation in the supermarket in Lundby Park. The reference/HR scenario decreases the costs by 24 % compared with the FC scenario. The HX scenario decreases the costs by 15 % compared with the HR scenario and by 36 % compared with the FC scenario.

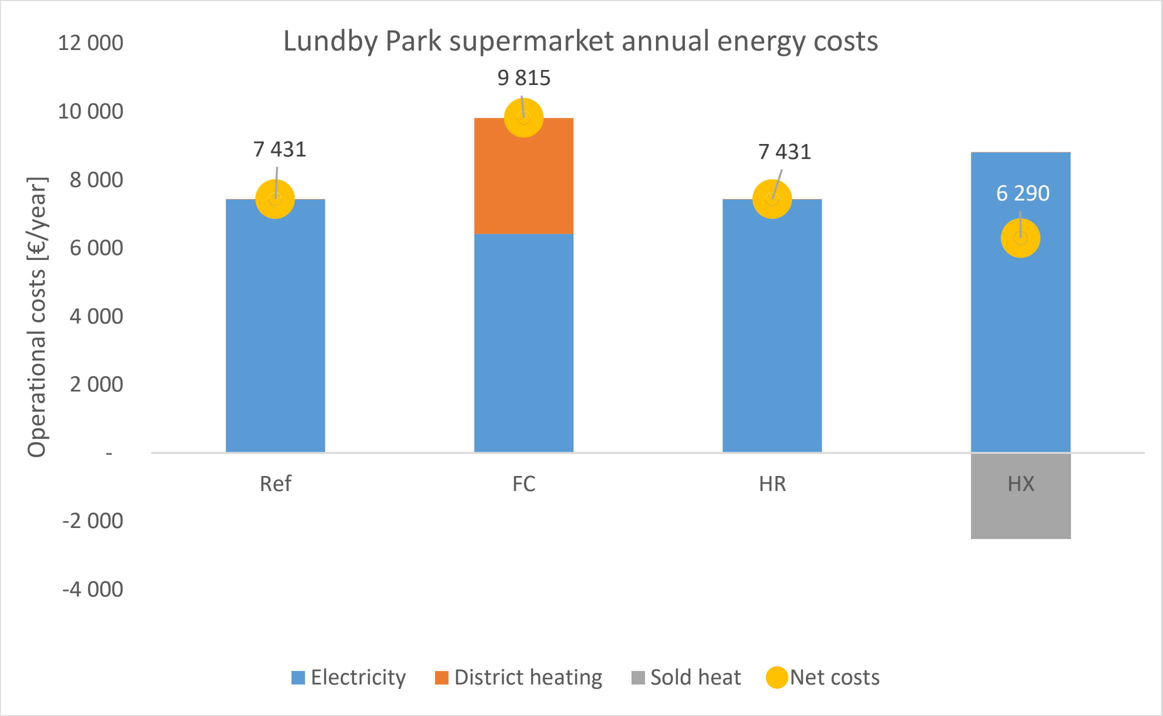

Figure 9: Lundby Park supermarket annual operational results

The results indicate that significant operational savings can be achieved under the prevailing energy prices from 2020. The operational savings in the scenarios are translated to justified investment costs according to Eq. (6), the results of which are summed up in Table 3. The negative justified investment costs for the FC scenario should be interpreted as a positive justified investment cost for the reference scenario, compared with an FC scenario without heat recovery.

Table 3: Justified investment costs for each operation scenario [€]

Supermarket	Ytterby	Eskilstuna	Lundby Park
FC	**-185,988**	**-198,998**	**-29,531**
HR	**137,300**	**67,519**	**-**
HX	**230,264**	**121,818**	**14,124**

The results of the reference scenarios illustrate the benefits of recovering heat in the capacity that is being done already in each supermarket, as illustrated by Fig. 7, Fig. 8, Fig. 9, and Table 3. Although the FC scenarios have the lowest electricity use for refrigeration, all heating of the premises must be supplied by a separate source; in this case, district heating. Exactly how high savings that can be achieved depends on the price ratios defined in Eq. (7) and Eq. (8). Fig. 10 illustrates how the savings from heat recovery decrease with increasing price of electricity relative to that of bought heat. In the HR scenario, a price ratio of about 4 is the break-even for making operational savings in the Ytterby supermarket. However, the operational savings need to be higher than just above 0 %, as the investments needed are competing with alternative options, given an assumed opportunity cost of capital. A price ratio of about 2.5 yields roughly 10 % annual savings in all supermarkets; investments with savings below 10 % are likely to be unattractive in practice. The price ratio actually used in the main study varies with the seasons between 0.55 and 2, as marked on the x-axis in Fig. 10.

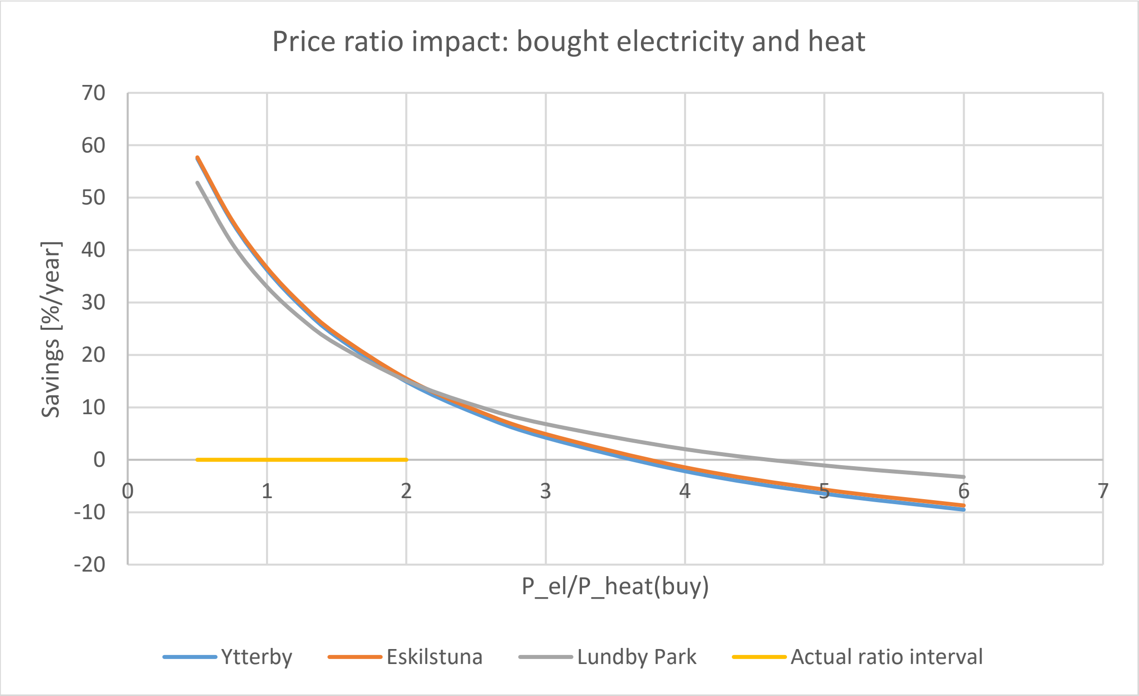

Figure 10: Investigation of impact of price ratio between bought electricity and heat. The savings are for the HR scenario compared with the FC scenario.

The impact of the price ratio of bought electricity and the selling price of heat is shown in Fig. 11. It shows on the extremes that when the prices are equal, the cost savings are about 90 % in the Lundby Park supermarket, about 75 % in the Ytterby supermarket, and about 50 % in the Eskilstuna supermarket. The price ratio cannot fall below 1, in which case it would be profitable to produce heat with electric heating and sell it for a profit.

When the ratio increases, that is when the electricity price increases relative to the selling price of heat, the cost savings decrease and reach 0 % at a price ratio of about 6. The price ratio used in the main study varies among the seasons between 1.09 and 4, as marked on the x-axis in the figure. The savings fall down to 10 % at price ratios between 3 and 4, below which the investments are likely to become unattractive.

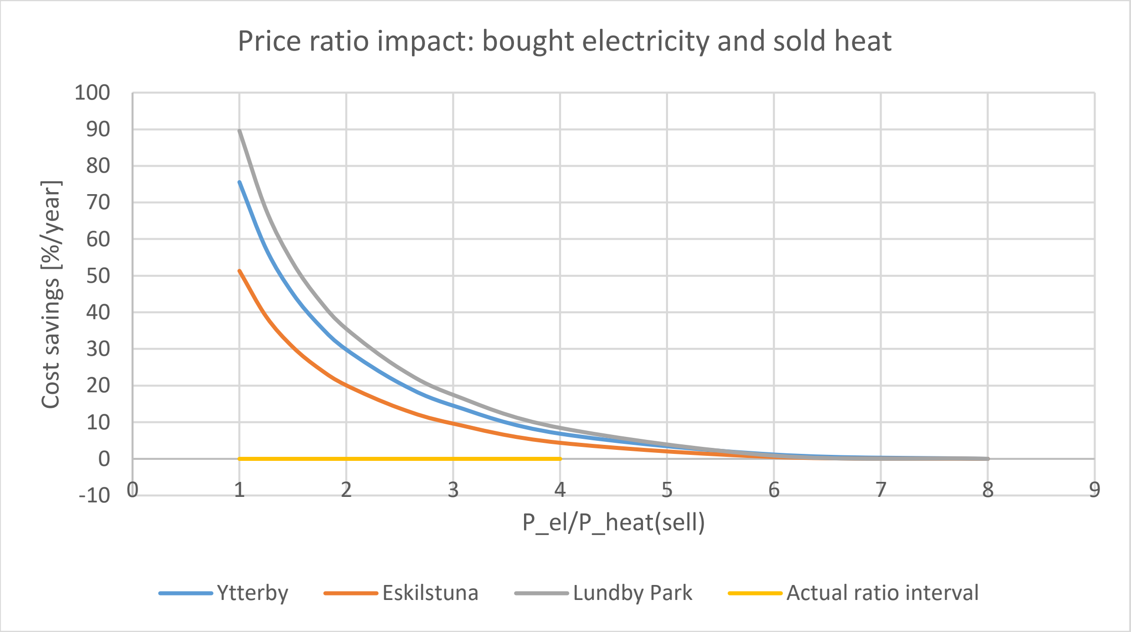

Figure 11: Investigation of impact of price ratio between bought electricity and sold heat. The savings are for the HX scenario compared with the HR scenario.

5. CONCLUSIONS

The aim of this work is to investigate the technical feasibility and economic outcome of heat recovery systems in three different types of supermarkets. In order to recover all the required heat within the premises, compared with no heat recovery, the annual electricity use for the refrigeration systems in the supermarket increases by 16-27 %. Moreover, the annual electricity use is increased by 38-43 % when maximising heat recovery and selling the surplus, rendering an annual heat production between 179 % and 272 % of each supermarket’s own space heating needs. When the ambient temperature is above -5°C, all supermarkets recover heat at acceptable efficiencies, with COP’s above 3. The COP of heat sales reaches values as high as 7-8 between 0°C and 5°C ambient temperature. The results show that under the energy prices of the time in 2020, the supermarkets could save between 24 % and 40 % in annual refrigeration and heating costs if recovering all the required heat from the refrigeration system, and between 36 % and 48 % if maximising the produced heat and selling the surplus. Two price ratio analyses indicate that heat recovery for internal demands reaches a minimum of 10 % of annual cost savings, as long as the electricity price is less than 2.5 times higher than the heating price. In addition, the maximisation of heat recovery with surplus heat sales reaches 10 % cost savings as long as the electricity price is less than 3-4 times higher than the heat selling price, depending on the supermarket.

To conclude, this work therefore demonstrates the economic viability of heat recovery and heat export in supermarkets. The results also verify that the profitability of heat recovery and heat export is robust against moderate variations in electricity and district heating prices.

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NOMENCLATURE

ρ	Density [kg/m^3]	MT	Medium temperature
η	Efficiency [-]	LT	Low temperature
$\dot{V}$	Volume flow [m^3/s]	DHN	District heating network
$\dot{m}$	Mass flow [kg/s]	COP	Coefficient of performance
$\dot{Q}$	Heat transfer [kW]	NPV	Net present value [€]
f	Frequency [Hz]	P	Price [€/MWh]
T	Temperature [°C]	i	Interest rate [%/year]
$\dot{E}$	Work [kW]	p	Inflation rate [%/year]
h	Enthalpy [kJ/kgK]	N	Number of years

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