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HEAT RECOVERY FROM CO_2 REFRIGERATION SYSTEM IN SUPERMARKETS TO DISTRICT HEATING NETWORK

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ABSTRACT

In the process of moving towards sustainable energy systems for future cities, the district heating system will have to be more dynamic and accessible to the different heating sources available in the society. A main potential heat source to be connected to the district heating network is the heat rejected from refrigeration systems in supermarket applications.

This paper investigates the main possible scenarios for recovering heat from supermarket refrigeration system with CO_2 as the refrigerant. The efficiency of the refrigeration system under the different heat recovery scenarios is studied with the aid of computer modelling. The cost of producing the recoverable heat is calculated and compared to market price from local district heating company. The total energy cost for running the system in the winter season in the different scenarios is also calculated.

This study shows that the best scenario is to recover heat for space heating in the supermarket building as a priority and then recover all or part of the remaining available heat to district heating. In an average size supermarket in Sweden, all the space heating demand can be recovered from the refrigeration system with space heat recovery COP (i.e. heating COP) of about 4.5 in average. To produce 1 kW heat supplied to district heating, 2/5 to 1/8 kW of compressor power is used; i.e. district heating recovery *COP* is 2.5-8. This scenario results in the lowest annual energy cost of the system, about 40% lower than the reference scenario, where the refrigeration system runs at floating condensing and space heating is delivered by district heating.

Keywords: Heat recovery, District heating, CO_2 refrigeration, Supermarkets, Modelling

1. INTRODUCTION

As society is shifting towards a more sustainable and efficient energy systems, the integration of energy systems can be particularly interesting, where heat recovery, thermal energy storage, and load shifting can lead to significant energy savings in the long run. Refrigeration systems in supermarkets are intensive energy users and have the potential to recover substantial amount of heat for space heating at high efficiency (Sawalha *et al.*, 2010). Recovering heat from the refrigeration system in the supermarket to be sold to district heating network is an interesting option to avoid dumping the heat from the system to the ambient air. In an average size supermarket in Sweden about 175 kW of heat can be recovered in the winter operation, if 50% of this heat is recovered to the district heating network then the demand of about 17 single family houses is provided by the supermarket's heat.

Following the trends of improving the efficiency of supermarket refrigeration system, CO_2 has been selected as the potential candidate to substitute common HFC refrigerants (such as R404A) due to its negligible effect to the global warming (CO_2 with the *GWP* of 1 as opposed to R404A with *GWP* of 3900). In the past years, northern Europe region has been using CO_2 trans-critical systems due to its relatively high efficiency in cold climates, particularly for outdoor temperature lower than 25°C (Sawalha *et al.*, 2017). Furthermore, as an advantage, CO_2 refrigeration system can recover heat to cover space heating demand in the supermarket with an average heat recovery (i.e. heating) COP of 4.5 (Sawalha, 2013).

One of the few research papers in the subject is the one presenting the work of Funder-Kristensen *et al.,* (2017) where cost optimization and CO_2 emission reduction have been studied for a CO_2 refrigeration system. The study showed that recovering heat to district heating offers the largest savings.

The study in this paper covers a number of scenarios and presents the results in COP values which can be conveniently used in cost analysis. The research work in this paper gains special interest in this period in Sweden because the concept of heat recovery to district heating has been applied by several utility providers, such as Fortum in Sweden (Fortum, 2017). This paper contains essential techno-economic investigation of heat recovery from refrigeration system of supermarket to district heating network. However, capital cost is excluded in this study as the installation costs will vary largely from one case to another.

2. SCENARIOS DEFINITION

This section starts with an introductory part about CO_2 refrigeration system as a general overview, which subsequently is followed by five possible scenarios of operation.

2.1 CO_2 Refrigeration System in Supermarkets

The details of the selected scenario represent an average size supermarket in Sweden with medium temperature and low temperature levels (freezer), accounting the temperature level of -10ºC and -30ºC respectively. Both cabinets have different cooling loads suitable for its operation, 100 kW in the medium temperature cabinet and 35 kW in the freezer. Aside from fulfilling the cooling demand, thermal comfort of the buildings also requires certain space heating demand which can be taken following the assumptions of an average size supermarket (Sawalha, 2017): at 10ºC outdoor temperature, 40 kW of heating demand is needed while 115 kW heating is necessary for -5ºC outdoor temperature, which is expressed in equation (1). Stockholm hourly outdoor temperature has been used as the basis for all calculation in this study.

$$Q_{building} = -5 \cdot T_{outdoor} + 90 \qquad (1)$$

The refrigeration system in this scenario uses CO_2 as refrigerant. The system is a booster concept which is presented in Figure 1. The system is quite common in supermarket installations in Sweden in the past years. The computer model in EES (Engineering Equation Solver) software (Klein, 2015) is used to simulate each of the operation scenarios. EES contains built-in thermo-physical property functions to produce a numerical solution for a set of defined algebraic equations. The system in Figure 1 has two heat exchanges for heat recovery after the high stage compressor; however, in the studied scenarios none (i.e. no heat recovery), single, or two heat exchangers can be running.

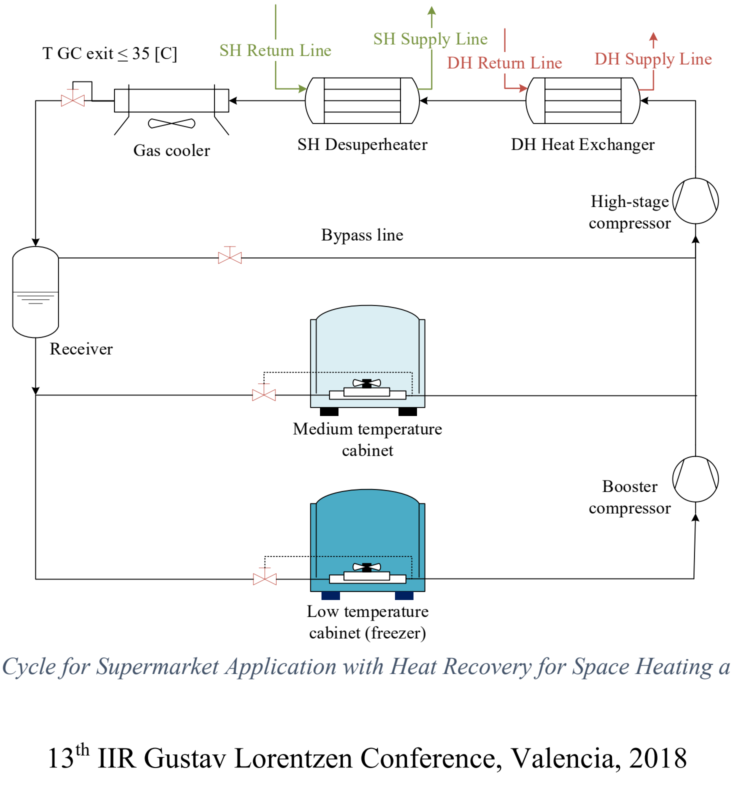

Figure 1 CO_2 Refrigeration Cycle for Supermarket Application with Heat Recovery for Space Heating and District Heating Network

2.2 CO_2 Refrigeration System and Heat Recovery Scenarios

Five main scenarios are developed, each scenario has its own configuration which is described in the following part.

1) Floating Condensing Refrigeration System with Heating from District Heating – The Reference Scenario (FC+DH)
   This is assumed to be the reference scenario where the refrigeration system is controlled to run at the lowest energy use possible for refrigeration where the condensing/gas cooler exit temperature followed the outdoor temperature with 5K difference. The minimum condensing temperature is assumed to be 10°C and the minimum temperature at the condenser/gas cooler exit is 5°C. In this scenario, the district heating covers space heating demand.
2) Floating Condensing Refrigeration System with Separate Heat Pump (FC+HP)
   The refrigeration system runs with floating condensing, similar to scenario 1. In this scenario the space heating demand is covered by a separate heat pump. *COP* of the heat pump is averagely chosen to be 3.5 (Miara *et al*., 2011).
3) Refrigeration System Controlled for Space Heating Heat Recovery (SH only)
   In this scenario, space heating demand is recovered from the refrigeration system by a de-superheater after compressor discharge. The return temperature from the space heating system is assumed to be 30°C, which is 5K lower than the CO_2 exit temperature from the de-superheater (i.e. assuming approach temperature difference equals to 5K). The system in this scenario is assumed to follow the control strategy for highest efficiency in heat recovery mode as explained in detail by Sawalha (2013).
4) Refrigeration System Controlled to Recovery Heat for Space Heating and Selling Heat to District Heating (DH (SH priority)) with supply temperature of at least 68ºC to DH network
   In this scenario, the system is assumed to recover heat in two heat exchangers (de-superheaters), following the schematic in Figure 1. In the first de-superheater after the compressor, heat is recovered to district heating network with return line temperature of 45°C. In the second de-superheater, heat is recovered to space heating with return temperature of 30°C. Approach temperature difference in both de-superheaters are assumed to be 5K. At low outdoor temperatures, as the space heating demand increases with the refrigeration system is in short of capacity in the second de-superheater, then less heat is recovered to district heating network (i.e. space heating is prioritized).
5) Refrigeration System Controlled to Recover/Sell Heat to District Heating Only (DH only) – same temperature level as in scenario 4
   In this scenario, the heat generated from refrigeration system is transferred directly to district heating network, without providing any space heating. The refrigeration system is modelled to run at 85 bar fixed discharge pressure.

3. METHODS OF ANALYSIS AND RESULTS

In this section, brief explanation of the analysis method and key results of this study are presented. The key results include the energy use and efficiency of the system in the studied scenarios. In addition, economic evaluation (price of generated heat) of each scenario is presented as well.

3.1 Energy Use Calculations

The refrigeration load provided by the high stage compressor ($Q_{MTtotal}$) is the total refrigeration loads at medium temperature and low temperature (freezer) levels with the energy use of the booster compressor added. The heat loss (HL) from the booster compressor is assumed to be 7% and extracted from the total load. Henceforth, the total refrigeration load at medium temperature level can be expressed in the following equation (2):

$$Q_{MTtotal} = Q_{MT} + Q_{LT} \quad (2)$$

Where

$$Q_{LT} = Q_{freezer} + E_{booster} \cdot (1\text{-}HL) \quad (3)$$

Which leads to

$$Q_{MTtotal} = Q_{MT} + Q_{freezer} + E_{booster} \cdot (1\text{-}HL) \qquad (4)$$

Compressor power consumption depends on the outdoor temperature at which the refrigeration system operates, since it affects the condensing/ gas cooler exit temperature the discharge pressure at which the system should run to recover the required heat for space heating and to the district heating network. With varying discharge pressure levels, compressor's performance at different pressure ratios are modelled according to manufacturer's specification data. Using the computer performance curves from the manufacturer data (Dorin, 2017), the power consumption of the compressor at different outdoor temperatures in each scenario is calculated, as presented in Figure 2. Please note that compressor power of the refrigeration system only is presented in the figure, also note that compressor power in floating condensing (FC only) will be used later to evaluate scenario 1 (FC+DH) and scenario 2 (FC+HP).

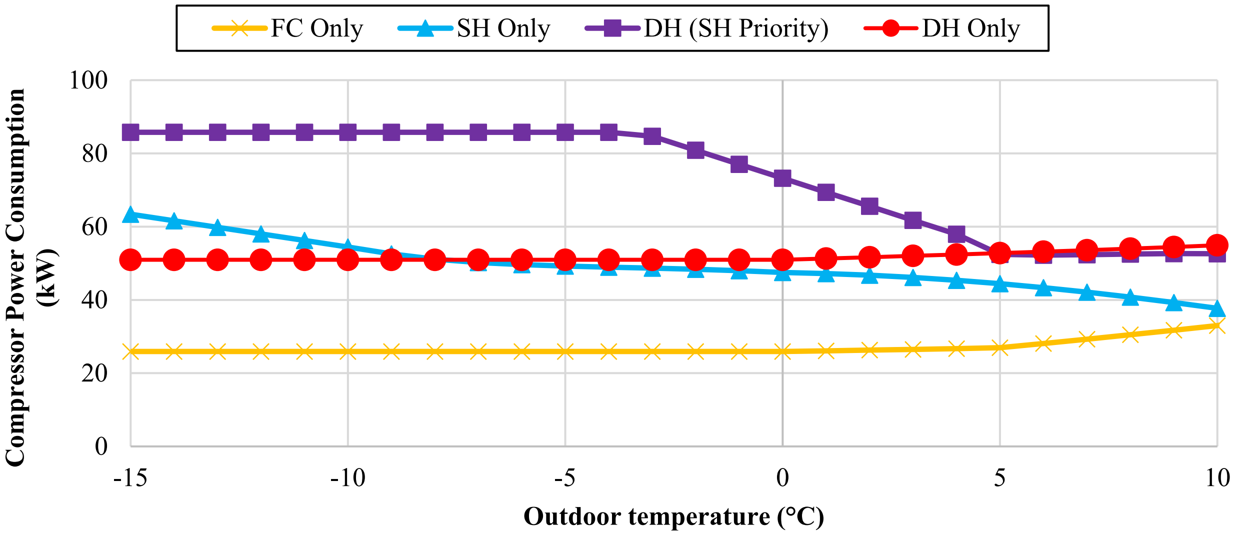

Figure 2 Compressor Power of Refrigeration System as a Function of Outdoor Temperature in the Different Scenarios

It can be clearly observed from Figure 2 that floating condensing (FC only) scenario has the lowest compressor power consumption in all outdoor temperature range. This is due to fact that the refrigeration system is only providing the refrigeration load, hence it is not controlled to recover heat and runs at lowest discharge pressure possible. When the refrigeration system provides the space heating *SH only*, then it runs at higher discharge pressure and therefore, its power consumption is higher than in floating condensing (FC only). When part of the heat is recovered to district heating network *DH (SH priority)*, then the system is forced to run at even higher discharge pressure than *SH only* scenario, thus the system can still provide all required heat to space heating. Furthermore, it can be notably seen in Figure 2 that the system in *DH (SH priority)* scenario has the highest compressor power input, particularly for outdoor temperature below 0°C as the system is being required to fulfill the high space heating demand and at the same time sell heat to district heating network. The power consumption of the system in *DH only* scenario is rather not affected by the outdoor temperature because it is controlled for fixed discharge pressure and gas cooler exit temperature (outdoor temperature plus 5K approach temperature). The power consumption of the refrigeration system in heat recovery scenarios will have to be put together with the amount of recovered heat to be able to judge on the system performance. Therefore, the study of coefficient of performance is presented in the following section.

3.2 Heat Recovery Coefficient of Performance (COP_{HR})

The study of COP_{HR} is essential to evaluate the heat recovery performance in the different scenarios. Fundamentally, the generated heat for either space heating (SH) purpose or district heating (DH) purpose can be related to the required compressor power to generate a kW of heat. The equations (5-7) describes the mathematical formula of $COP_{SH\ only,\ HR}$, $COP_{DH\ only,\ HR}$, and $COP_{DH,\ (SH\ priority),\ HR}$.

$$COP_{SH\ only,\ HR} = \frac{Q_{SH\ gen.}}{E_{SH,\ only} - E_{FC,\ only}} \quad (5); \quad COP_{DH,\ only,\ HR} = \frac{Q_{DH\ gen.}}{E_{DH,\ only} - E_{FC,\ only}} \quad (6)$$

$$COP_{DH\ (SH\ priority),\ HR} = \frac{Q_{DH\ gen.}}{E_{DH\ (SH\ priority)} - E_{SH,\ only}} \quad (7)$$

Power consumption used in the equations are obtained from Figure 2. The COP_{HR} results calculated by equations (5-7) are plotted in Figure 3.

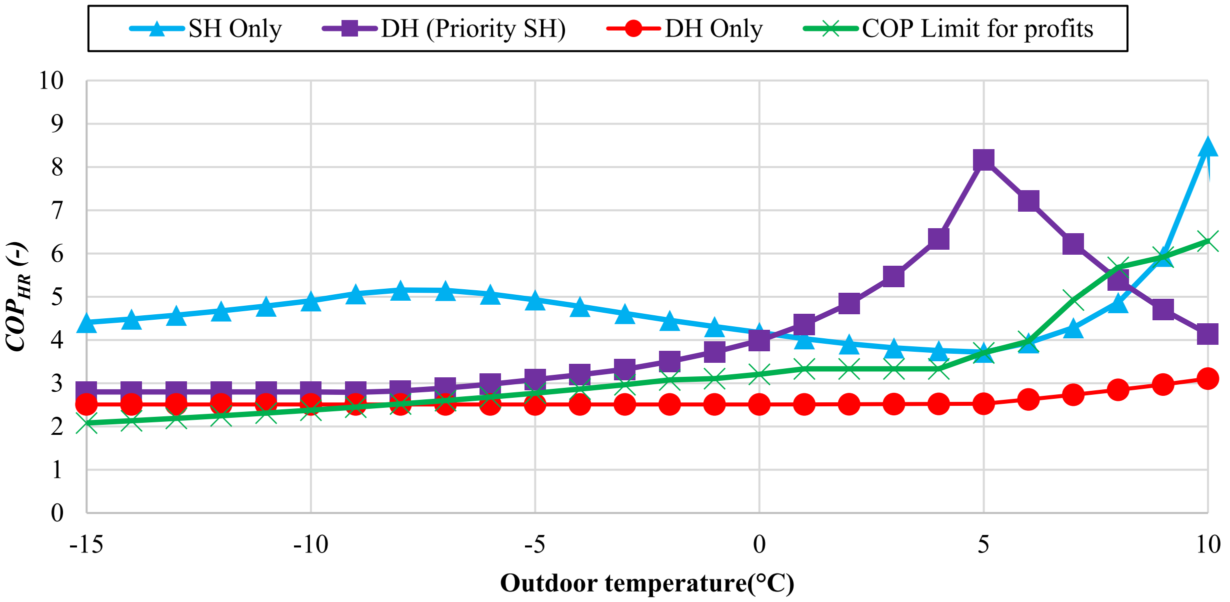

Figure 3 Heat Recovery Coefficient of Performance (COP_{HR}) for Different Scenarios in Different Outdoor Temperatures

The additional COP_{HR} plot in Figure 3 is the COP_{HR} below which no profit is made by selling heat to district heating. $COP_{HR\ (limit\ for\ profit)}$ is defined as:

$$COP_{HR(limit\ for\ profit)} = \frac{C_{el}}{BP_h} \quad (8)$$

Where C_{el} is the electricity price for commercial application (in this case supermarket) and BP_h is the buying price of heat offered by the district heating company in Stockholm. The price was taken from typical electricity price in the past year. These prices are used to define the profitability of this configuration ($COP_{HR\ (limit\ for\ profit)}$) as it combines the aspects of electricity and heating costs together.

It can be observed in Figure 3 that the *DH only* scenario has a relatively constant value of COP_{HR} = 2-3 at all outdoor temperatures, with a slight increment above 5°C. It can be obviously viewed that *DH only* scenario appears to be the least efficient and falls below the $COP_{HR\ (limit\ for\ profit)}$ for most of outdoor temperatures. In contrast, *SH only* has high value of COP_{HR} with values ranging between 4 and 5 for most of the outdoor temperatures. In the scenario where heat recovery is prioritized for space heating, the heat that is sold to district heating is generated at high COP_{HR}; $COP_{HR,\ DH\ (SH\ priority)}$ values up to 8 is reached and higher than the $COP_{HR\ (limit\ for\ profit)}$ for all the outdoor temperature range.

3.3. Cost for Producing Heat to Sell to the District Heating Network

To investigate the profitability of selling heat to district heating network at different outdoor temperatures the scenarios *DH (SH priority)* and *DH only* are analyzed. The price for producing heat (C_h) can be calculated using the following equation:

$$C_h = \frac{C_{el}}{COP_{DH,\ HR}} \quad (9)$$

Where $COP_{DH\ only,HR}$ and $COP_{DH(SH\ priority),HR}$ values can be read in Figure 3 and used in equation 9, similar to the research being conducted by Funder-Kristensen *et al.,* (2017).The prices for producing heat in *DH (SH* *priority)* and DH scenarios at different outdoor temperatures are plotted in Figure 4. The buying price (BP) for recovered heat from local district heating company is also potted in Figure 4.

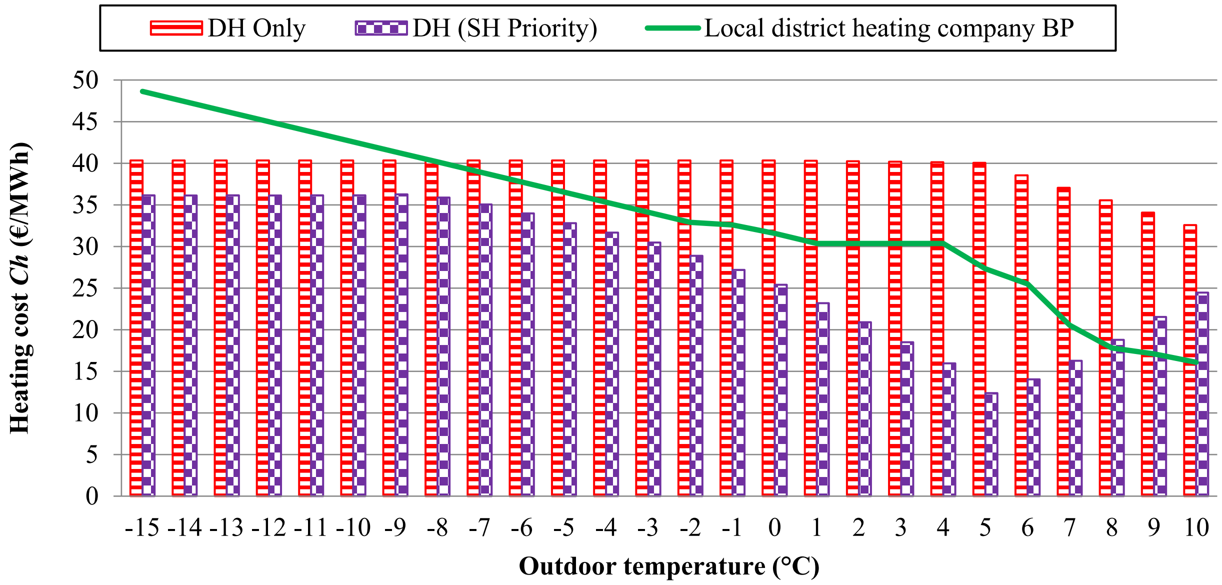

Figure 4 Cost of Producing Heat for District Heating and the Buying Price from District Heating Company

Analyzing the results in Figure 4, it is evident that producing heat in *DH only* scenario costs more than in *DH (SH priority)* scenario at all outdoor temperatures. The cost of producing heat in *DH (SH priority)* is lower than the buying price offered by district heating company at almost all outdoor temperatures. In the *DH only* scenario, profit is made only at quite low outdoor temperature, lower than -8°C. The amount of heat recovered to district heating is different depending on the scenario; Therefore, the total annual energy cost in the different scenarios is calculated and presented in the following section.

3.4 Energy Cost Comparison of Heat Recovery Scenarios

To comprehensively evaluate the economic outcomes of all scenarios, the energy use (electricity and heat) and generation (heat) for each scenario for the winter season is calculated and presented in Figure 5. The total energy cost for running the system in each scenario is also presented in Figure 5. The cost of heat bought from district heating is assumed to be 50€/ MWh which is typical for Stockholm in the past year. Please note that negative values for energy in the plot means that energy is generated/sold.

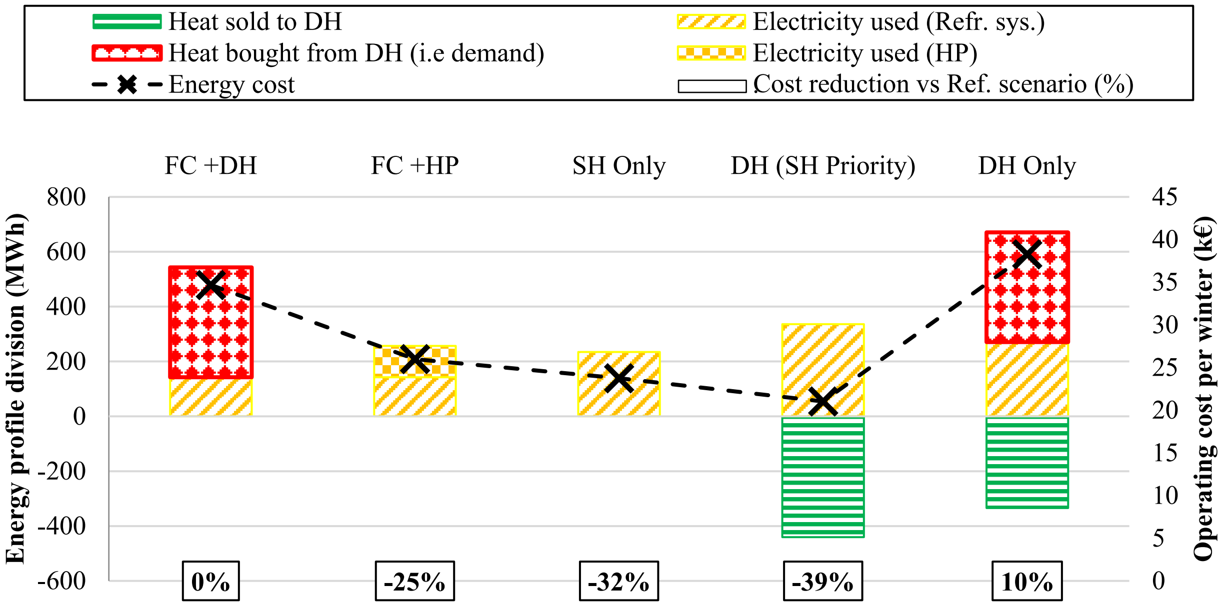

Figure 5 Energy use, heat generation, and running cost during the winter season for Different Scenarios

As it can be observed in Figure 5, *DH (SH priority)* scenario has the lowest energy costs among the studied scenarios, it has 39% lower energy cost compared with the reference scenario (FC+DH). *SH only* scenario has the second-lowest energy cost, about 7% higher than *DH (SH priority)*. It can also be observed in the figure that *DH only* scenario costs the most to run. Henceforth, supermarkets that run under the conditions presented in this study should recover heat for its space heating needs as priority while on top of that selling its extra heat to the network. However, it has to be pointed out that the difference in the total energy cost for running the system in scenarios *DH (SH priority)* and *SH only* may diminish or even reverse when the installation cost, or additional taxes in *DH (SH priority)* scenario are taken into consideration, which is not included in the analysis in this paper.

4. CONCLUSIONS

This study investigated the main possible scenarios for recovering heat from supermarket refrigeration system with CO_2 as the refrigerant. The efficiency of the refrigeration system under the different heat recovery scenarios is studied with the aid of computer modelling. The cost of producing the recoverable heat is calculated and compared to market price from a local district heating company. The total energy cost for running the system in the winter season in the different scenarios is also calculated.

Five different scenarios are defined and studied. The results show that producing heat only to district (*DH only* scenario) results in almost flat heat recovery COP of 2-3. The cost of producing heat in this scenario is higher than the buying price from the local district heating company at most of the investigated range of outdoor temperatures, profit is made only at outdoor temperatures lower than -8°C. This scenario results in the highest energy cost to run.

The best scenario is to recover heat for space heating in the supermarket building as a priority and then recover all or part of the remaining available heat to district heating (i.e. *DH (SH priority)* scenario). In an average size supermarket in Sweden, all the space heating demand can be recovered from the refrigeration system with space heat recovery COP of about 4.5 in average. To produce 1 kW heat supplied to district heating in this scenario, 2/5 to 1/8 kW of compressor power is used; i.e. district heating recovery COP is 2.5-8. This results in lower cost to produce heat than the buying price from the district heating company at most of the studied outdoor temperatures.

This scenario *DH (SH priority)* has the lowest energy costs in the winter season among the studied scenarios, it has 39% lower energy cost compared with the floating condensing reference scenario (*FC+DH*). Recovering heat to space heating only (*SH only* scenario) has the second-lowest energy cost, approximately 7% higher than *DH (SH priority)* scenario.

Supermarkets that run under the conditions presented in this study should recover heat for its space heating needs as priority while on top of that selling its extra heat to the network.

NOMENCLATURE

GWP	global warming potential	COP	coefficient of performance
COP_{HR}	COP heat recovery	$COP_{DH, HR}$	COP_{HR} of district heating
p_1	discharge pressure of compressor (bar)	$COP_{SH, HR}$	COP_{HR} of space heating
FC+DH	floating condensing with district heating	FC+HP	floating condensing with heat pump
SH	space heating only	DH (SH priority)	space heating priority with district heating
Q_{MT}	refrigeration load at med-temperature level cabinets (kW)	$Q_{MTtotal}$	total cooling load at med-temperature level (kW)
Q_{LT}	load at medium temperature level coming from low temperature level demand (kW)	$Q_{freezer}$	refrigeration load at low-temperature level freezers (kW)
$Q_{SH\ gen.}$	generated heat for SH purpose (kW)	$Q_{DH\ gen.}$	generated heat for DH purpose (kW)
$E_{booster}$	booster compressor power consumption (kW)	HL	heat losses from compressor, in percentage of total compressor power
E_{FC}	compressor power consumption in FC scenario (kW)	$E_{SH\ input}$	compressor power consumption in SH scenario (kW)
$Q_{building}$	internal space heating demand (kW)	$T_{outdoor}$	outdoor temperature (°C)
C_h	heat generation cost (€)	C_{el}	cost of electricity to run the system (€)
BP_h	buying heat price from utility company (€)		

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