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Heat Export from Supermarkets' Refrigeration Systems

Field Measurements and a Techno-economic Analysis

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Abstract

Supermarkets have a high energy demand where almost half of the energy is used within the refrigeration system. The refrigeration system utilises a cycle where heat is taken and rejected. The rejected heat could be recovered and utilised for other purposes, such as covering internal heating demand or be exported to other facilities. Implementation of heat recovery could create business opportunities between the supermarket and other actors involved.

The aim of this thesis was to investigate the potential for heat export from the refrigeration system in supermarkets to neighbours. Case studies were conducted on three different supermarkets in Sweden. This project evaluated field measurements for the current heat recovery within the systems, investigated heat recovery during optimal operation conditions as well as a techno-economic analysis of the heat recovery system.

All three supermarkets within the study recovered heat in the current configuration. In both CG Ytterby and CG Eskilstuna, the recovered heat covered the majority of the internal heating demand. Nevertheless, there was a great potential to recover more heat, since most of the heat was rejected through the gas cooler. The system was also limited by the discharge pressure and the return temperature in the heat recovery unit.

The techno-economic analyses indicated that all supermarkets had the potential to cover both internal heating demand with the recovered heat, as well as produce excess to export. It was observed to be more profitable to disconnect from the DHN and become self-sufficient. Heat export from supermarkets would create new innovative business models which can be profitable for both the supermarket and the heat consumer. To produce excess heat, the system had to operate at optimal conditions, increasing electricity usage and hence associated operational costs. This demonstrated the importance of revenues to make it an economically feasible solution.

Key words: Heat Recovery, Heat Export, Supermarkets, Refrigeration Systems, CO_2 Transcritical Booster Systems, Energy Efficiency.

Sammanfattning

Livsmedelsbutiker har ett högt energibehov där nästan hälften av energin används i kylsystemet. Kylsystemen använder sig av en cykel där värme tas upp och avges. Den värme som avges kan återvinnas och användas för andra ändamål, till exempel för att täcka internt värmebehov eller exporteras till andra fastigheter och därmed skapa affärsmöjligheter för livsmedelsbutiken.

Syftet med examensarbetet var att undersöka potentialen för export av värme från kylsystemet i livsmedelsbutiker. Fallstudier genomfördes för tre olika livsmedelsbutiker i Sverige. Projektet utvärderade fältmätningar för aktuell värmeåtervinning inom systemen, undersökte värmeåtervinning under optimala driftförhållanden samt utförde en teknisk-ekonomisk analys av värmeåtervinningsystemet.

Livsmedelsbutikerna i studien återvann värme i den nuvarande konfigurationen. I både CG Ytterby och CG Eskilstuna täckte den återvunna värmen större delen av det interna värmebehovet och det fanns en stor potential att återvinna mer värme, eftersom majoriteten av värmen släpps ut genom gaskylaren. Systemet begränsades även av trycket efter kompressorerna och returtemperaturen i värmeåtervinningsenheten.

De teknoekonomiska analyserna visade att alla livsmedelsbutiker hade potential att täcka internt värmebehov med den återvunna värmen, samt producera överskott för export. Det var även observerat att vara mer lönsamt att koppla från fjärrvärmenätverket och bli självförsörjande. Export av värme från livsmedelsbutiker skapar nya innovativa affärsmodeller som kan vara lönsamma för både livsmedelsbutiker och värmekonsumenter. För att producera överskottsvärme var systemet tvunget att drivas under optimala förhållanden, vilket ökade elanvändningen och därmed tillhörande driftskostnader. Detta visade på vikten av intäkter för att göra det till en ekonomiskt genomförbar lösning.

Nyckelord: Värmeåtervinning, värmeexport, livsmedelsbutiker, kylsystem, CO_2 transkritiskt booster-system, energieffektivitet.

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Abbreviations

Air Conditioning	AC
Business Model Canvas	BMC
Carbon Dioxide	CO_2
Carbon Dioxide Equivalent	CO_2-eq
Degrees Celsius	°C
City Gross	CG
Coefficient of Performance	COP
Combined Heat and Power	CHP
District Heating	DH
District Heating Networks	DHN
Domestic Hot Water	DHW
European Union	EU
Fluorinated Gases	F-gases
Greenhouse gas	GHG
Global Warming Potential	GWP
Guarantee of Origin	GOO
Heating Ventilation Air Conditioning	HVAC
Heating Ventilation Air Conditioning & Refrigeration	HVAC&R
Internal Rate of Return	IRR
Kelvin	K
Low Temperature	LT
Low Temperature District Heating	LTDH
Load Ratio	LR
Medium Temperature	MT
National Food Administration	NFA
Net Present Value	NPV
Ozone Depletion Potential	ODP
Pressure Ratio	PR
Swedish Crowns	SEK

Chapter 1

Introduction

The world faces large environmental problems related to greenhouse gas (GHG) emissions, which contributes to global warming and climate change (European Commission, n.d. (a)). These emissions come from different sources, two of which are combustion of fossil fuels and leakage of fluorinated gases in refrigeration systems. Energy demand and greenhouse gas emissions related to the building and construction sector have increased in recent years. In 2019, this sector accounted for approximately 33 % of the global energy demand and approximately 40 % of the world's direct and indirect CO_2 emissions (IEA, 2020). In a conventional or passive building's life cycle, around 72-94 % of the energy demand occurs during the operational part (Dilsiz et al., 2019; Azari, 2019). The building sector has great potential for reducing emissions as well as increasing energy efficiency, which will decrease the environmental impact (IEA, 2020).

Supermarkets account for approximately 3 % of the total Swedish energy demand. In supermarkets, around 47 % of the energy is used within the refrigeration system, followed by 27 % for lighting and 13% for ventilation and climate control. A reduction of energy demand in supermarkets can be achieved by heat recovery in the refrigeration system (Arias and Lundqvist, 2006). Replacing Fluorinated gases (F-gases) as refrigerants will decrease the environmental impact from refrigeration systems, since these gases have a high global warming potential (GWP) and ozone depletion potential (ODP) (Cecchinato et al., 2012). There are several environmental certification systems used by Swedish supermarkets. Some are used to certify the building, such as *BREEAM-SE* and *NollCO*$_2$, and others are used to certify the business, such as *Svanen* and *Bra Miljöval*. Environmental certification can help supermarkets to report and be aware of their energy demand, as well as use it as a tool in the work with continuous improvements regarding energy efficiency (BELOK, 2021).

One way to decrease the environmental impacts from supermarkets is to apply the concept of industrial symbiosis. Industrial symbiosis is when by-products from one industry are used as an input or raw product in another industry or sector (Fraccascia et al., 2020). In a supermarket, rejected heat from the refrigeration system can be recovered and used for other purposes, such as covering internal heating demand, defrosting coils in an evaporator, or exported to nearby buildings or the district heating network (DHN) (Arias and Lundqvist, 2006; Sawalha and Chen, 2010; Danfoss, 2017; Karampour et al., 2019). In this case, a cooperation between the supermarkets and other actors like the property owner and energy companies will be of interest (RELIVS, 2020). However, property owners may have limited knowledge of more advanced systems used in supermarkets and the potential for heat recovery, which in turn can lead to installation of less advanced systems with simpler maintenance. One potential solution can be to introduce legal requirements to utilise the recovered heat from refrigeration systems in supermarkets (BELOK, 2021).

1.1 Aim and Objectives

The aim was to investigate the potential for heat export from the refrigeration system in supermarkets. The following objectives were formulated in order to achieve this aim.

- To evaluate the performance of heat recovery in refrigeration systems.
- To analyse the possibility of covering internal heating demand with recovered heat from the refrigeration system, in order to improve overall energy efficiency and economic feasibility of the systems.
- To investigate the potential of heat recovery during optimal operating conditions for the refrigeration system and the possibility to export heat to neighbours.

1.2 Research Methodology

The research was carried out through case studies of three different supermarkets in Sweden. The first supermarket was City Gross (CG) located in Ytterby, the second supermarket was CG located in Eskilstuna and the third was Hemköp located in Lundby Park. A literature study was conducted in the first part of the research to gather valuable information and obtain knowledge within the area and evaluate previous research.

Thereafter a data collection of system parameters through field measurement was obtained from IWMAC, which is a web-based program providing a smart management system that monitors the facility. It offers back control with a complete overview of all the technical installations (IWMAC, 2021). A heat recovery model was created with field measurements from IWMAC which were synchronised to hourly means in the software Matlab. The model was used to calculate key performance parameters in Excel with the add-in program CoolProp (Figure 1.1). CoolProp is a library which contains thermophysical properties for fluids (CoolProp, n.d.).

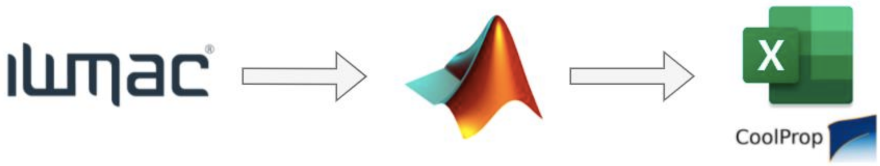

Figure 1.1: The methodology for the heat recovery model.

The heat recovery calculations were followed by a techno-economic analysis, where economic parameters in relation to the parameters of the specific technology were evaluated to classify the system's economic feasibility. Four different scenarios were considered for the techno-economic assessment: A Reference Scenario (S1), No Heat Recovery (S2), Total Heat Recovery-Local (S3) and Total Heat Recovery-Export (S4). Optimisations of refrigeration and heat recovery systems were done in a computational tool developed in Excel by Fabio Giunta and Samer Sawalha (Giunta, 2020). The tool uses the add-in program Refprop which is considered an alternative to CoolProp, a database with thermophysical properties for different fluids (NIST, 2021)

1.3 Scope and Limitations

The focus was to study heat recovery in the supermarkets for internal heating purposes and heat export. The location, type of building and size of the supermarket varied between the cases. One store was of large size in a stand-alone building, one was of medium size located adjacent to a shopping mall and one was of small size located in the bottom floor in an apartment building. All three stores were located in Sweden.

The annual heat recovery calculations were conducted for CG Ytterby and CG Eskilstuna between 2019-12-31 23:00:00 and 2020-12-31 23:00:00. The year chosen to investigate was 2020 since it was considered to be most successful with measured values in IWMAC and for stored information regarding the energy usage of both supermarkets. This year was a leap year and also the outbreak of Covid-19, which affected the behaviour of the customer and thereby most probably also the operation of the refrigeration system. Since Hemköp Lundby Park was opened in September 2021, the heat recovery calculations were conducted between 2021-10-01 00:00:00 and 2022-03-31 23:00:00. The thesis did not focus on energy efficiency measures outside the current refrigeration system in the supermarkets, such as the structure of the building or adding new components into the system.

The data collection was limited to the field measurements obtained from IWMAC and data provided by the store. The form and unit of collected data also limited the calculations and had to be considered. The placement of the sensors within the systems, as well as the accuracy can affect the quality of the measured values in IWMAC. The layout of the system did not provide the reader with information regarding where the measurements have been done and it may not be precisely the points required for the calculations.

The cabinets included in the refrigeration system called KA1 were included in the calculations for all supermarkets and also the cabinets in an additional system called KA2 for Eskilstuna. The ambient temperature affected the operation of the refrigeration system and also the possibility of heat recovery. The energy price for district heating and electricity was provided by invoices from CG Ytterby and CG Eskilstuna and affected the economic feasibility of the system. No invoices or heating demand were available from Hemköp Lundby Park.

The creation of a business model for heat export will be limited by agreements for the supermarket with energy companies or property owners. Also, the commitment from all these parties and the location of the store may limit the business opportunity. Only suggestions for business models were provided in this thesis, since more legal work regarding these agreements had to be conducted to create a viable model. In this thesis, three supermarkets have been studied, however the results could be used as guidelines for other supermarkets.

Chapter 2

Supermarket Energy Systems

The majority of the energy consumed within the supermarket occurs in: the refrigeration system, for lighting in the store, and in the Heating Ventilation Air Conditioning (HVAC) system (Arias et al., 2004). The refrigeration will enable the reduction and maintenance of the temperature of a product to below the ambient temperature and can thereby meet basic human needs and improve life by handling, storing and supplying food and providing air conditioning (AC) and climate control (Granryd et al., 2020, p.1-6). In supermarkets, both chilled and frozen food cabinets are used, requiring two different evaporating temperature levels, medium temperature (MT) and low temperature (LT) (Maouris et al., 2020). The lighting system is important to visualise the goods and food, as well as provide a general light in the store for both personnel and customers. However, a trade off with too much lighting could be the electricity consumption or heating up goods in the supermarket. Control systems for lighting, changing to low energy fluorescent lamps or LED, and installations of presence sensors could reduce the energy demand for lighting (Jensen et al., 2014). The usage of LED and CFL lighting may also increase the heating demand of the store during winter, but also decrease the cooling demand during summer, since they will emit less heat compared to traditional lighting. However, the benefits with energy efficient lighting will often dominate (Ruud et al., 2013). The HVAC-system controls the indoor climate in the supermarket and affects air quality, temperature and humidity. Recovered heat from the refrigeration system could be used in the HVAC-system to provide space heating or for domestic hot water (DHW) production, which would increase the overall efficiency of the system (Karampour and Sawalha, 2018).

2.1 Refrigeration System

The second law of thermodynamics will constrain refrigeration processes, where energy transfer from a low temperature source to a higher temperature sink requires the addition of an operating energy. The process could be used both in refrigeration systems and heat pumps (Granryd et al., 2020, p.27-62). Additionally, the process will be affected by the first law of thermodynamics where the energy transferred from the system will be equal to all the energy transferred into the system (Granryd et al., 2020, p.15-26). The heat rejected from the refrigeration system is the condenser load (Q_1) and the energy transferred to the system is the refrigerating capacity (Q_2) and the operating energy (E). The efficiency of the system can be calculated by the coefficient of performance (COP). By taking the ratio of Q_2 and E in the refrigeration cycle, one will obtain the efficiency COP_2 (Granryd et al., 2020, p.27-62).

The vapour compression cycle is driven by mechanical work, which also is the predominant operating energy input in applications of refrigeration. The vapour compression cycle includes four main components; an evaporator, a compressor, a condenser and an expansion device, together creating a closed loop (Figure 2.1). This cycle uses a working fluid called refrigerant. For pure refrigerants there is an important relation between saturated vapour pressure and temperature, where both increase proportionally. There are two heat transfer processes in this cycle, the first at the evaporator side with low temperature (T_2) and low pressure (p_2), where heat (Q_2) is absorbed by the refrigerant from the refrigerated space. The second at the condenser side with high temperature (T_1) and high pressure (p_1), where the heat (Q_1) instead is rejected to a cooling medium (Granryd et al., 2020, p.27-62).

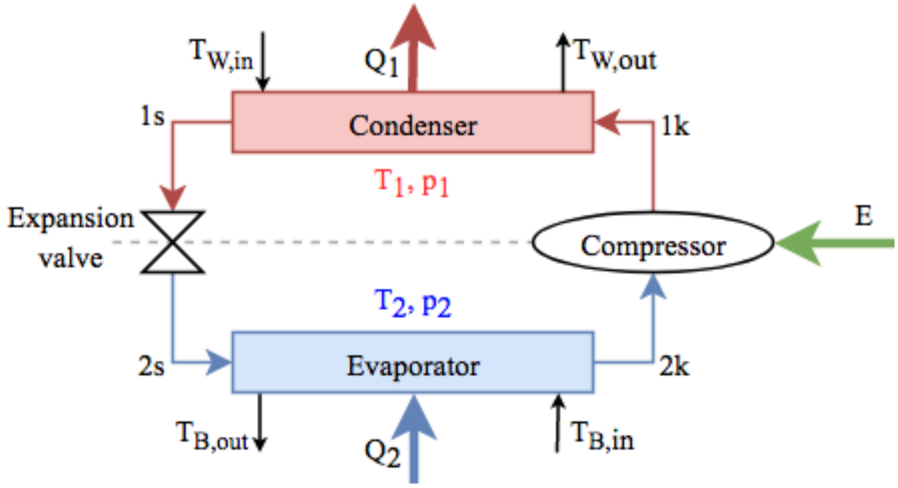

Figure 2.1: The vapour compression cycle in a refrigeration system.

The evaporator is one of the heat exchangers within the cycle, where the refrigerant will be evaporated by heat transfer from the heat source (Granryd et al., 2020, p.145-180). To enable this physical process, the temperature of the refrigerant (T_2) must be lower than the temperature of the heat source in the refrigerated space (Granryd et al., 2020, p.31). Such low temperatures can be obtained as the heat of vaporisation used to evaporate originates from the liquid itself, causing a reduction of the temperature (Granryd et al., 2020, p.145-180). In the evaporator, two different heat transfer phenomena occur; boiling and superheating (Granryd et al., 2020, p.145-180). Superheat is commonly applied to avoid any liquid entering the compressor, causing severe mechanical damage. A certain amount of superheat is therefore desirable and to which extent depends on where and how superheating occurs, as well as on the refrigerant (Selbas et al., 2006). The superheating of the vapour can be either internal or external. The internal superheat will be in the refrigerated space and increase both refrigeration effect and compression work, while the external superheat will be outside the refrigerated space and give rise to a negative effect (Granryd et al., 2020, p.27-62).

The compressor transfers the vapour from the evaporator, up to higher pressure and the inlet of the condenser (Granryd et al., 2020, p.79-144). It will create an important pressure difference and in conjunction with the expansion device, maintain that difference between the p_2 and p_1 of the cycle. The compression process requires additional work, which usually is supplied by an electric motor, enabling the rise to a higher temperature level (Granryd et al., 2020, p.33).

In the condenser the refrigerant will be condensed by heat transfer to the heat sink, where the heat will be rejected. The refrigerant enters the condenser as superheated vapour, and leaves the condenser as partially sub-cooled liquid (Granryd et al., 2020, p.181-194). To enable this physical process, the temperature of the refrigerant (T_1) must be higher than the temperature of the heat sink (Granryd et al., 2020, p.34). The amount of heat rejected will increase with the temperature lift and decrease with higher efficiency of the compressor (Granryd et al., 2020, p.181-194). In the condenser, three different heat transfer phenomena occur: de-superheating when the superheated vapour is cooled down to saturated vapour, condensation and subcooling when the saturated liquid is cooled down further (Granryd et al., 2020, p.181-194). Subcooling the liquid after the condensation can improve the performance of the cycle. Heat will be rejected at p_1 before the throttling process, decreasing the enthalpy of the liquid (h_s) and also the temperature (T_s) (Granryd et al., 2020, p.27-62).

The expansion device maintains the pressure difference between the evaporator and the condenser (Granryd et al., 2020, p.195-205). Through the throttling process in the expansion device, the pressure is reduced and the liquid is vaporised, turning some of the liquid into vapour. As the latent heat of vaporisation is taken from the fluid itself, the temperature will be reduced and the lower temperature level of the cycle will be created in the expansion valve. The enthalpy for the refrigerant before and after this process will be equal. The expansion device is also called the refrigerant flow control and has an additional purpose to regulate the refrigerant flow rate to the evaporator to match the heat flux (Granryd et al., 2020, p.35-36). It will also prevent the liquid from entering the compressor where it could cause damage (Granryd et al., 2020, p.35)

2.1.1 Refrigerants

Different refrigerants have different characteristics and the refrigerant needs to have suitable chemical, thermodynamic and physical properties which are adapted to the environment and the technology since leakages can occur (Granryd et al., 2020, p.63). The type of refrigerant used in the cycle has varied during the last decades, and before 1922, natural refrigerants such as ammonia (NH_3), carbon dioxide (CO_2) and sulphur dioxide (SO_2) were used. Since both ammonia and sulphur dioxide were toxic, it led to development of new synthetic refrigerants which were considered less toxic and more stable. However, in the 1970s it was discovered that these refrigerants had an ODP and a replacement of them was done. In the 1990s, the focus returned to the original natural refrigerants, since the synthetic refrigerants had environmental disadvantages in the form of both GWP and ODP (Granryd et al., 2020, p.64-66).

In 2015 the European Union (EU) introduced the F-gas legislation regarding limiting usage of refrigerants based on F-gases with a high GWP (European Commission, n.d.(b)). The magnitude of GWP represents how much impact emissions of one kg of the refrigerant have on the greenhouse effect compared to one kg of CO_2 emissions. Carbon dioxide equivalent (CO_2-eq) shows how large the emissions of greenhouse gases are from the refrigerant compared to an equal mass of CO_2. From 2020, it is not permitted to sell equipment containing refrigerant with a GWP higher than 2500, or refill refrigerant in older equipment with a higher CO_2-eq than 40 tonnes. The aim of these regulations is to phase out the usage of F-gases (Allt om f-gas, n.d). For supermarkets with a centralised refrigeration system larger than 40 kW, the limit of GWP was decreased to 150 in the beginning of 2022 (Karampour et al., 2016).

Due to the F-gas regulation, supermarkets are forced to replace older systems utilising refrigerants with high GWP values. In colder climates, the most common refrigerant to change to is CO_2 (R744) due to the low environmental impact (GWP=1 and ODP=0) and being neither toxic nor flammable (Maouris et al., 2020). Additionally, CO_2 possesses important thermo-physical properties such as high vapour density, latent heat, specific heat, volumetric cooling capacity and thermal conductivity as well as low viscosity (Polzot et al., 2016; RELIVS, 2020; Ge and Tassou, 2011). The investment costs associated with systems containing natural refrigerants are, as of today, no higher than for the conventional systems, and the CO_2 systems used in supermarkets are considered as more eco-friendly than conventional systems (Karampour et al., 2016).

2.1.2 CO_2 Systems

There are three different types of CO_2 systems: indirect systems, cascade systems and transcritical systems. After the return to natural refrigerants, the first usage of CO_2 in refrigeration systems was as a secondary fluid in indirect systems due to its good heat transfer characteristics and low viscosity, which considerably lowered pumping power and pump size compared to the conventional secondary fluids (Karampour et al., 2016). The second generation CO_2 system was the cascade system, which was first to be completely based on natural refrigerant. An additional refrigerant was included in the upper cycle to condense the primary refrigerant, CO_2. This would provide the opportunity for refrigerants that were environmentally harmful and unsafe to be used outside the sales area (Karampour et al., 2016), confined in the machinery room (Cecchinato et al., 2012). It included an intermediate heat exchanger, creating temperature differences that would decrease energy efficiency and also increase costs. Nevertheless, this would prevent operating in supercritical pressure mode and thereby be an appropriate solution for supermarkets in warm climates (Karampour et al., 2016).

The refrigerant CO_2 has a low critical temperature and high critical pressure of 31.1 °C and 73.8 bar, respectively. When solely using CO_2 as refrigerant, two different operating modes can be obtained (Cecchinato et al., 2012) depending on the temperature of the cooling medium. It can either be subcritical mode below the critical point or transcritical mode above (Figure 2.2). The transcritical conditions adopted when ambient temperature is close to or above critical temperature will contribute to large energy consumption compared to systems based on conventional refrigerants, as the increased pressure will require more compression power (Cecchinato et al., 2012 ; Polzot et al., 2016). Due to the high pressure, the CO_2 will not be condensated in a condenser and the heat exchange is instead done in a gas cooler (Andersson, 2021). Different measures could be adopted to either force subcritical mode or improve efficiency in all operation modes, reaching similar COP as conventional systems (Polzot et al., 2016). According to various research conducted in mild-cold climates when the ambient temperature is below 25 °C, the COP is either higher or equivalent to the COP of conventional systems (Karampour et al., 2016).

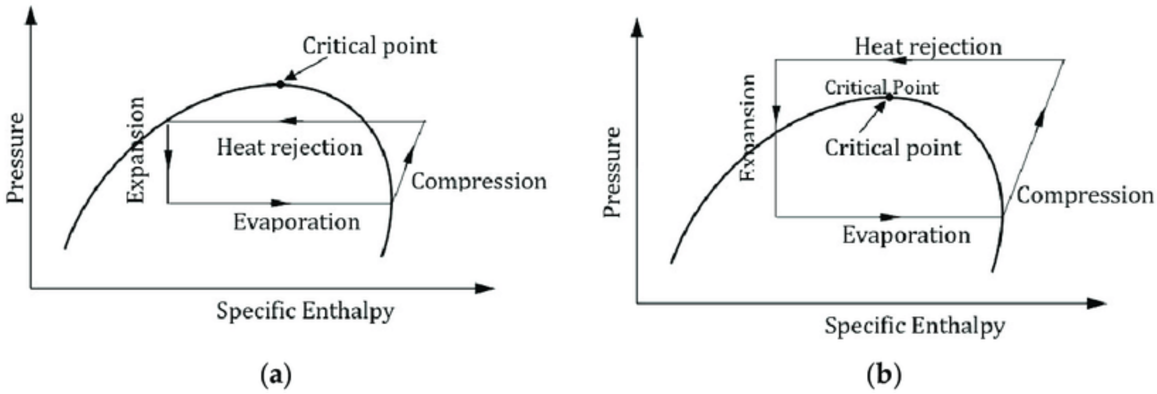

Figure 2.2: The process when operating in sub-critical mode (a), and when operating in transcritical mode (b) (Rony et al., 2019).

The pressure at the triple point is also relatively high at 5.2 bar, demanding the cycle to operate at higher pressures to prevent solidification of the refrigerant. Due to the high operating pressure, a large amount of heat can be recovered from transcritical systems, further used to cover heating demand of a supermarket. Though, a major challenge to consider is then to match heating and cooling demand (Maouris et al., 2020).

As a result of the F-gas legislation, the spread of using CO_2 transcritical systems has accelerated (Karampour and Sawalha, 2017) and in 2020 the number of installed systems was 29 000 in total, of which 26 100 were located in supermarkets and the rest in convenience stores and in the industry (Shecco, 2020). Transcritical systems have two main configurations, parallel and booster. The parallel layout uses two separate circuits in parallel, operating between ambient temperature and two evaporating temperatures, either medium or freezer, where the latter includes two-stage compression in the majority of the cases (Sawalha and Chen, 2010). The booster layout includes two compressors coupled in series to assure two evaporation levels, providing medium and low temperature (Figure 2.3) (Cecchinato et al., 2012). The CO_2 transcritical booster system is considered as the standard system solution in some parts of Europe, including Scandinavian countries (Karampour et al., 2016). It has undergone several modifications and improvements, creating new generations as state-of-the-art systems (Karampour et al., 2016). The usage of heat recovery has been further developed, contributing to development of an all-in-one integrated CO_2 solution (Karampour and Sawalha, 2017).

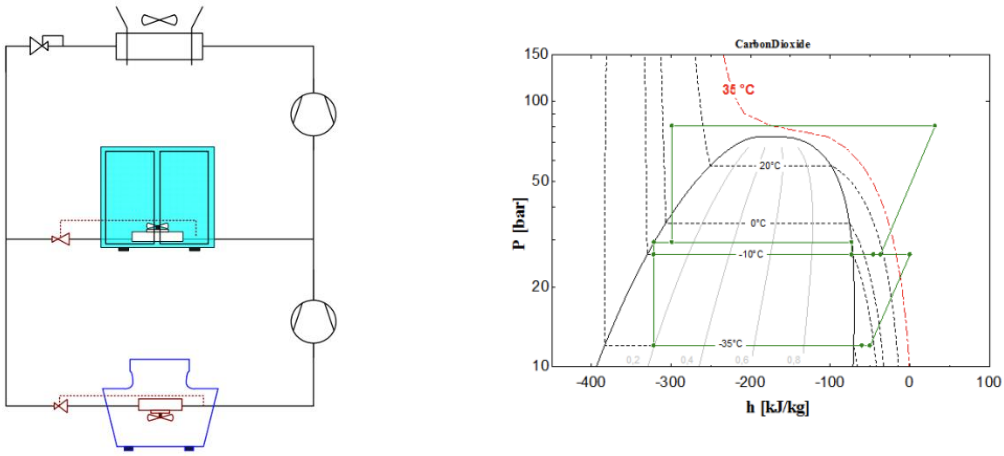

Figure 2.3: A schematic of the CO_2 transcritical booster system to the left (Sawalha and Chen, 2010) and the cycle illustrated in the log(p)-h diagram to the right (Karampour et al., 2016).

2.2 Energy Efficiency

Supermarkets are associated with a large energy consumption and thereby ecological footprint, which contributes to an increased greenhouse effect, making energy efficiency measures vital to consider. An increased energy efficiency could be obtained in both the refrigeration system and HVAC system, where improvement in the system design with more efficient components, control systems and integration can decrease the energy usage (Cecchinato et al., 2012). Though neither the food, personnel nor customers should be negatively affected when evaluating installation of energy efficient technologies in the supermarket. There are Swedish regulations by the National Food Administration (NFA), which regulates the temperature interval of different food storages. Nevertheless, both the personnel and the customers have the possibility to adjust their clothing depending on the indoor air climate (Lindberg et al., 2008). The ambient temperature affects the performance of the system and for a lower ambient temperature, less work is needed in the compressor which leads to a higher COP (Yusof et al., 2018).

2.2.1 Energy Efficiency Measures

One way to improve the energy efficiency in the system is to install doors or covers on open cabinets. In a study by Lindberg et al. (2008) the electricity demand could be reduced by more than 30 % by installation of doors. In open cabinets, the cold air could leak out to the store and hot and humid air could infiltrate the refrigerator. Hot and humid air will increase the energy use, creating a greater need for defrosting, and varying temperatures in the cabinets will affect the quality of the food. Furthermore, the installation of doors can improve the indoor climate for personnel and customers by contributing to a more balanced temperature and humidity in the store (Rolfsman et al., 2014; Lindberg et al., 2008). However, without leakages of cold air to the store, the need for Air Conditioning (AC) at warmer ambient temperatures in the summer may be required, due to temperature requirements for non-refrigerated products. Although, at winter time, doors could lower the heating demand of the building, since open cabinets lowers the indoor temperature (Jensen et al., 2014).

Two main innovative approaches are responsible for spreading and accelerating the usage of CO_2 transcritical booster systems within Europe. The first approach is to convert the single-purpose system into a multi-function system by integrating heating and air conditioning systems into the CO_2 system (Karampour et al., 2016). These integrated systems can provide an all-in-one compact solution and at the same time being environmentally friendly by using natural refrigerant and electricity for the compressor work. A great amount of space will be saved by using less refrigerant and fewer components than if utilising additional separate heating and AC units (Karampour and Sawalha, 2018). It will work as a "plug & play" energy system and provides the total, or a great share of all thermal demands in supermarkets (Karampour et al., 2016; Karampour and Sawalha, 2018). It will also provide better control communications between HVAC and refrigeration systems (HVAC&R) by reducing complexity connected to it, increasing the amount of recovered heat (Karampour and Sawalha, 2017; Karampour and Sawalha, 2018). The usage of these integrated systems has accelerated within retail refrigeration to save energy and increase efficiency. A common example is the usage of recovered heat from refrigeration systems for heating and/or DHW production (Shecco, 2020).

The second approach is to modify the standard CO_2 transcritical booster system by adopting innovative solutions to improve the performance. Some modifications are parallel compression, ejectors, flooded evaporators, mechanical subcooling, evaporative cooling and thermal storage (Figure 2.4) (Karampour et al., 2016). The most suited modifications to do will depend on several parameters, such as the climate, interactions between considered modifications, as well as the magnitude of the cooling and heating loads of the system (Karampour et al., 2016).

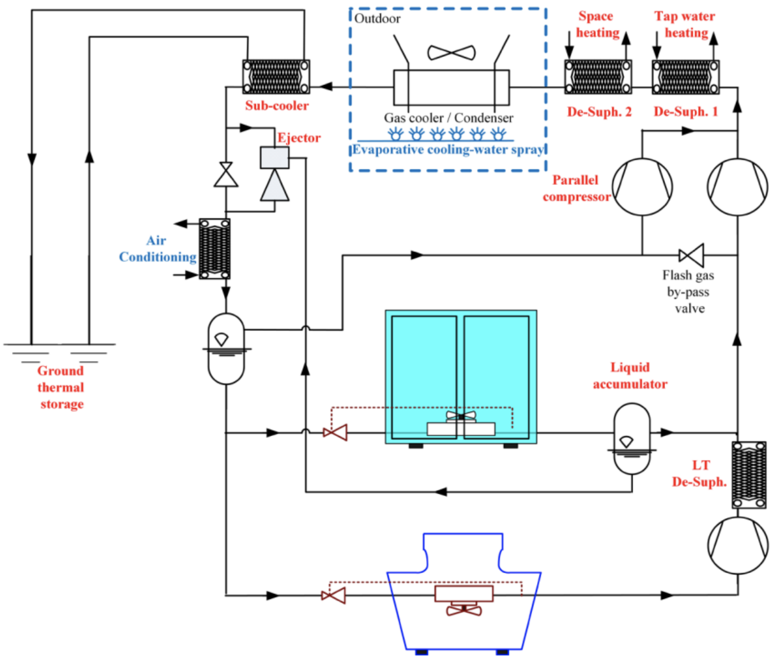

Figure 2.4: A CO_2 booster transcritical system in a supermarket including different energy efficiency measures (Karampour et al., 2016).

Parallel compression could be used, which compresses the flash gas to the high pressure side when leaving the receiver (Karampour et al., 2016). It will provide a higher suction pressure compared to high stage compressors, making it more efficient (Karampour and Sawalha, 2018). From various research it has been concluded that this modification can improve the energy efficiency of CO_2 systems by 10-15 % (Karampour et al., 2016). It is also proven to benefit CO_2 systems integrated with AC, operating in cold or mild climates (Polzot et al., 2016).

A modification appropriate in warm climates is the usage of ejectors. When the ambient temperature is high, the CO_2 system operates in transcritical mode and suffers from throttling losses in the high pressure expansion device, where some of these losses could be recovered with ejectors. Various research has shown that a multi-ejector can improve the efficiency of the system up to 20% (Karampour et al., 2016). Another modification appropriate in warm climates is evaporative cooling. Water is sprayed on the inlet stream to the gas cooler to avoid the refrigeration system to operate at high discharge pressure in the transcritical region. This will reduce the impact from the peak ambient temperature on the system and activate when ambient temperature is above 30-35 °C (Karampour et al., 2016). In Stockholm evaporative cooling will be activated every few hours and only contribute to annual energy savings of 1 % (Karampour and Sawalha, 2018). A mechanical subcooling unit can be installed to provide the necessary subcooling during summer. Various research has shown significant improvements of the COP when installing this unit in warm climates, nevertheless, this extra unit may contribute to expenses that need to be considered in the design stage (Karampour et al., 2016).

To improve the energy efficiency in all climates, flooded evaporation could be utilised. To be able to flood the evaporators, different methods could be used, such as ejectors, a pump circulation unit or internal heat exchangers (Karampour and Swalaha, 2018). When using liquid ejectors, evaporators will be enabled to operate without superheating. This contributes to a more efficient usage of the evaporator heat transfer area, increasing the evaporating temperature compared to conventional systems. A rough estimation is that the COP will increase with 2-3 % per degree of higher evaporation temperature. A study performed by Minetto et al. (2014) showed a 13 % decrease in compressor work when overfeeding the evaporator with an ejector (Karampour et al., 2016).

2.2.2 Heat Recovery

One of the most efficient measures to enable an increase of the total efficiency in a refrigeration system and decrease of the heating purchases is heat recovery. With proper system design and control, the rejected heat from the condenser can be utilised within the store through heat recovery, and can even be enough to be exported. The heat recovery potential for the refrigeration system depends on how well heating and cooling demands are matched. When the ambient temperature is low, the indoor relative humidity will also be low, which will affect the cooling demand for the cabinets and refrigeration system. However, at the same time, the heating demand will be higher. Therefore, it is important to consider the refrigerating capacity in relation to heating demand and seasonal profile in the design stage, to enable an efficient system providing all thermal demands (Sawahla, 2012).

The amount and supply temperature of recovered heat depends on different factors. The first factor is where the heat will be used, which could be internally in the store or building, or externally in other buildings by coupling the systems. The second factor is the condensing temperature T_1, which could change according to the heating demand. To provide more recoverable heat, an elevated condensation temperature is required, which also contributes to a higher electricity consumption (RELIVS, 2020).

This temperature rise could be achieved by increasing the discharge pressure, reaching the required supply temperature to the heating system. Also, an external heat pump can be used to raise the temperature or by allowing the CO_2 system to operate at transcritical mode (RELIVS, 2020; Rolfsman et al., 2014). The third factor is when the heat will be used, which could be used directly, after a shorter storing period in hot water tanks, or after a longer storing period by utilising geothermal boreholes.

To be able to take advantage of the heat produced when the demand is low, a thermal energy storage solution can be integrated into the refrigeration system, allowing for the excess heat to be used at a later time (Maouris et al., 2020). Seasonal energy storage solutions have been used in supermarkets in the northern and western part of Europe. The ground can be used as a heat sink for subcooling during summer and as a heat source for heating during winter since it will provide a fairly constant temperature compared to the ambient. Also short term solutions for thermal storage are adopted in supermarkets and most commonly used are hot water tanks (Karampour et al., 2016). According to a study performed by Nöding et al. (2016), the integration of a thermal storage solution in Germany lowered the power consumption by 8.5 % for a typical day in January (Karampour et al., 2016).

The amount of heat rejected at a certain temperature level will depend on the refrigerant, system configuration, and on the heat recovery solution used. If no heat is recovered, a floating condensation mode should be adopted. The heat demand should then be provided by a separate heating system since all heat will be rejected to the atmosphere (Karampour et al., 2016). Floating condensation decreases the operational costs in the system, as the pressure varies with the ambient temperature and different seasons. A smaller temperature lift between T_2 and T_1 is required in this case, which leads to a lower load for the compressor (Jensen et al., 2014).

Heat can be recovered by using a de-superheater located before the gas cooler/condenser, which is suitable when discharge temperature is relatively high, as in CO_2 systems (Figure 2.5c). The heating capacity is regulated by the expansion device by adjusting the discharge pressure. Two heat pump cascade solutions can be implemented. One delivers the rejected heat from gas cooler/condenser as low grade heat to a heat pump to be transferred to the HVAC system at a higher temperature level (Figure 2.5b). The other utilises a similar principle, but recovers the heat in a sub-cooler after the gas cooler/condenser (Figure 2.5d). The former will prevent the system to operate at high discharge pressure and the latter contribute with higher efficiency as it will decrease the gas cooler/condenser outlet temperature. Heat can also be recovered in a fixed-head pressure recovery solution (Figure 2.5a), where the required supply temperature in the HVAC system determines the discharge pressure, which is elevated when more heat is required. It includes a coolant (secondary fluid) which transfers the heat to the HVAC system from the gas cooler/condenser (Karampour et al., 2016). The first three mentioned solutions are suitable for CO_2 systems as they provide the possibility to operate at relatively low discharge pressure (Sawalha, 2012).

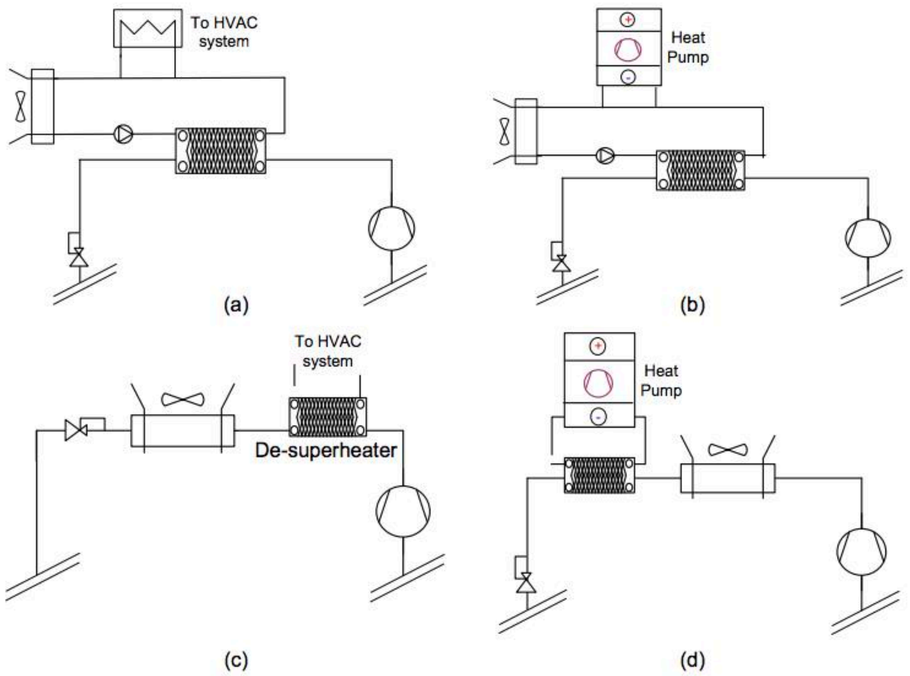

Figure 2.5: Different heat recovery solutions in refrigeration systems (Sawahla, 2012).

A study by Rolfsman et al. (2014) showed that a supermarket could decrease their heat demand covered by the DHN by 50 % by utilising heat recovery with a heat pump, contributing to cost savings. The recovered heat was used both for domestic hot water and space heating. Depending on the size of the supermarket, a research made by Frisk and Ramqvist (2018) indicates that the annual recovery of heat potentially lays between 1200 MWh and 3500 MWh.

2.2.3 Heat Recovery in CO_2 Systems

When increasing the discharge pressure above the critical point and shifting from operating in the subcritical to transcritical region, the amount of rejected heat will increase remarkably (Sawalha, 2012). As a result, the total efficiency of CO_2 transcritical booster systems is increased, making it one of the most energy efficient systems if utilising heat recovery (Karampour et al., 2016). The high temperature reached at the outlet of the compressor will provide the opportunity for heat recovery at different temperature levels. First level is between 50-70 °C, which can be used for domestic hot water, second level is between 40-50 °C, which can be used for instantaneous space heating and the last level is between 30-40 °C, which can be used for space heating with a heat pump, preheating of fresh air, air handling units or floor heating. The mentioned temperature levels can be achieved by rejecting heat by utilising three heat exchangers, one placed before the gas cooler, the gas cooler itself and one after the gas cooler. To reach the maximum COP, the discharge pressure has to be optimised at all these heat exchangers (Polzot et al., 2016).

To enable an efficient heat recovery process and increase the heating capacity, an appropriate control strategy should be adopted. Danfoss has suggested a control strategy with the first step to increase the discharge pressure to increase the amount of recoverable heat. The commercial refrigeration systems are designed for 120 bar pressure, though in practice, 100 bar is commonly adopted as a limit. When the pressure limit is reached, the gas cooler fan speed can be reduced to recover additional heat as it will contribute to a higher refrigerant temperature and enthalpy at the end of the gas cooler, increasing the available heat. To maximise the amount of recoverable heat, the gas cooler should be completely by-passed and the discharge pressure should obtain a maximum value. If there is still a need for recoverable heat, a false load MT evaporator could be utilised, contributing to additional cooling load. To meet this cooling load, the mass flow rate at MT compressors will be increased and thereby also increase the amount of rejected heat. It will lead to additional refrigeration requirements and decrease the total system efficiency (Maouris et al., 2020; Sawalha, 2012).

A study performed by Karampour and Sawalha (2018) of state-of-the-art integrated CO_2 transcritical booster systems indicated the importance of utilising heat recovery in two-stage, parallel compression, flooded evaporation and integration of AC. Other modifications, such as mechanical subcooling and evaporative cooling were considered to be arbitrary options and modifications on the low pressure side were concluded to be more consistent and promising than on the high pressure side. By combining flooded evaporation on MT- and LT-level, and parallel compression, a 13 % annual energy saving could be done. Economical calculations showed that heating from a CO_2 system is 50 % cheaper than DHN and 20 % cheaper than an air source heat pump.

2.3 District Heating Networks

In buildings, approximately 50 % of the global energy consumption is used for space heating and cooling as well as DHW production (IEA, 2011). DHN can decrease the overall energy consumption and greenhouse gas emissions by increasing the energy efficiency in the system, due to economies of scale and thereby improve utilisation of energy resources. Excess energy from different processes could be used as the heat source and work as a thermal energy storage, which reduces the peak load and balances the system (Jodeiri et al., 2022; Kuosa et al., 2022; Bossmann et al., 2019). DHN provides thermal energy which is produced from a centralised source and delivered to the consumer through a network to cover the heating demand.

District heating (DH) covers half of the heating demand within the residential sector in Sweden, and biomass is the largest energy resource and stands for approximately 84 % (Jodeiri et al., 2022; Giunta and Sawahla, 2021). It is vital to increase the efficiency of the networks to reduce associated CO_2 emissions. Lower operating temperatures reduces the heat losses in the networks, and to increase the share of renewables, both flexibility and decentralised production has to be adopted. This provides an opportunity for the integration of heat prosumers and energy storage solutions in the DHN, where excess heat can be recovered from refrigeration systems in supermarkets and utilised as a decentralised heat source (Giunta and Sawahla, 2021).

2.3.1 Generations of District Heating Networks

There are five generations of DHN with different heat carriers and energy production processes. The first and second generation have been phased out, the third and fourth generation are on the market and a fifth generation is in the development stage. The first generation utilised steam as the heat carrier and was produced in coal steam boilers or in combined heat and power (CHP) plants. The second generation used pressurised water over 100 °C produced in CHP plants with coal or oil as the fuel. The third generation uses pressurised water below 100 °C from large-scale or distributed CHP plants fueled by biomass or municipal waste, or boilers fueled by fossil fuels. The fourth generation can utilise lower temperatures at 50-70 °C compared to the previous generations and the heat can be produced in conventional plants, similar to the third generation, from excess heat and renewable resources (Jodeiri et al., 2022). The fifth generation will be designed for even lower temperatures close to the ground temperature to reduce losses and to be able to utilise low temperature heat sources, such as recovered heat from urban areas or heat from renewable resources. The temperature will then be increased locally at the consumer by heat pumps (Buffa et al., 2019; Skaarup Østergaard et al., 2022; Jodeiri et al., 2022).

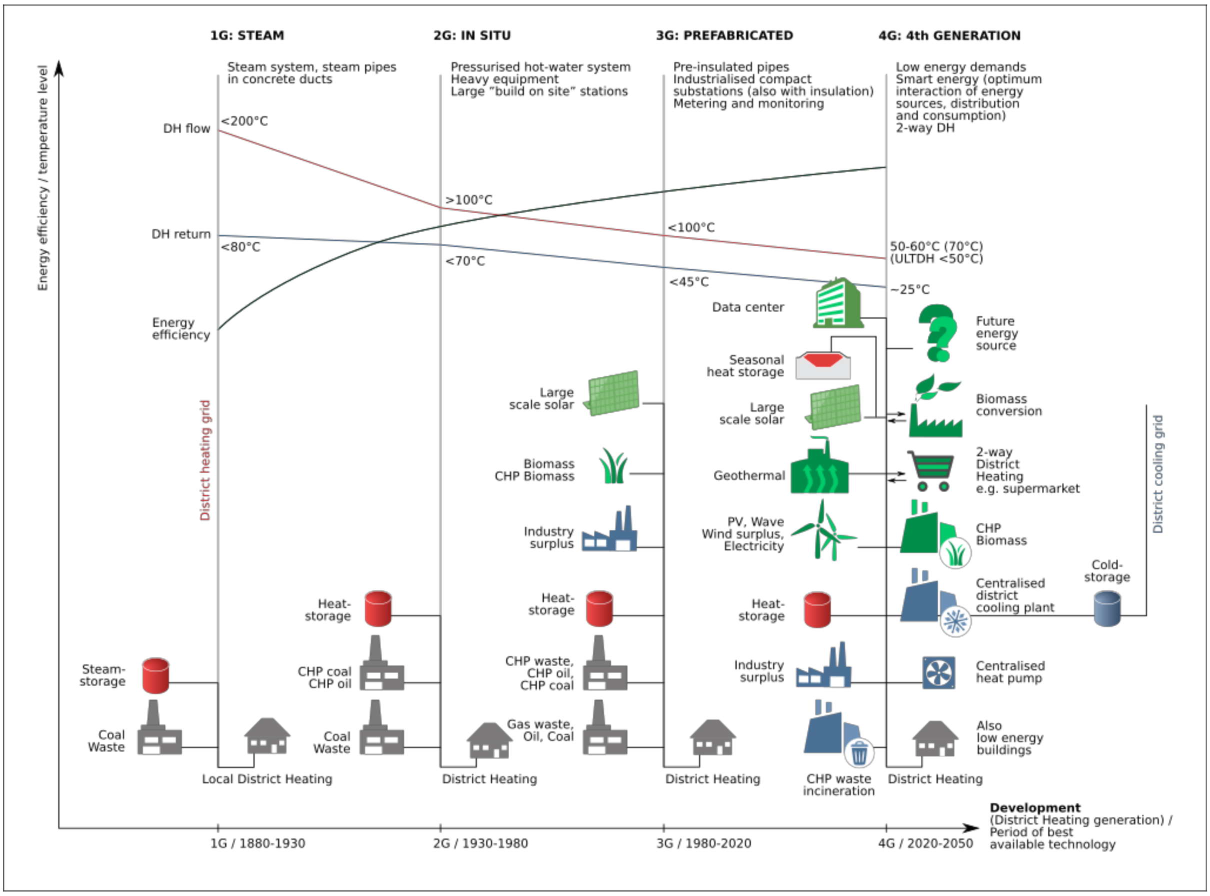

Figure 2.6: Generations for DHN (HögforsGST, 2020).

Previous research has demonstrated the benefits with Low Temperature District Heating (LTDH). One main advantage being the possibility to integrate a greater number of heat recovery resources with different temperatures (Arnaudo et al., 2021), making these networks a potential and flexible customer for low temperature excess heat from supermarkets (Zühlsdor et al., 2018). Instead of dumping the heat into the atmosphere, it could be recovered and exported to the DHN. During winter, around 175kW of heat can be recovered from a supermarket of average size in Sweden. If half of this amount would be exported to the DHN, it could cover the demand of around 17 single family houses (Raka Adrianto et al., 2018).

2.4 Heat Export from Supermarkets

The refrigeration system can be integrated and extended to a wider energy context, contributing to vital energy savings in the long term (Raka Adrianto et al., 2018). The location and size of the supermarket will affect the possibilities for heat recovery and export. Supermarkets of large or medium size and stand-alone buildings often have large refrigeration systems rejecting heat, and uses a more traditional heat recovery model where the internal heating demand is prioritised. However, during colder months when the transmission losses from the walls and roofs are significant, the recovered heat is often only sufficient for internal heating within the supermarket. Medium or small size supermarkets, located in a shopping mall or at the bottom floor of an apartment building, have lower transmission losses and heating demand compared to stand-alone buildings. This leads to a larger amount of excess heat from the refrigeration system. However, these stores often rent the premises and therefore have a small or limited impact on the building's ventilation and heating system, which makes it more difficult to export heat from the supermarket (RELIVS, 2020). The recovered heat can be used for different purposes, where the export should be prioritised last after space heating and domestic hot water demand in the supermarket (Danfoss, 2017). It is considered more beneficial to utilise the recovered heat within the building, than delivering the excess recovered heat to the DHN, as the supply temperature of 68 °C requires an elevated discharge pressure (RELIVS, 2020).

Traditionally, supermarkets are consumers of energy, although, with innovative solutions regarding flexible systems and business models, supermarkets can become prosumers. The design conditions of the refrigeration systems are set according to extreme summer weather, which demands a high cooling load. However, the nominal capacity is rarely fully utilised and around 65-70 % of installed compressor capacity may be unused. With solutions regarding export of heat, this capacity could be utilised for such additional service. Moreover, if the full potential capacity was to be utilised, both cost and emission savings of around 40 % and 60-70 %, respectively, can be achieved (Danfoss, 2017). Also, this capacity could during winter be utilised by extracting heat from the ground to cover heating demand, either within the store or to nearby facilities (Karampour et al., 2019). Nevertheless, utilising the full potential capacity also requires additional electricity by the compressors, which will require a power-to-heat strategy to reduce the overall associated CO_2 emissions. The power-to-heat will promote the usage of electricity for heat production at times when there is excess clean energy available, typically when the mismatch between electricity demand and available renewable resources occurs. Additionally, the limitations on the power grid distribution may create a need for importing electricity in some regions in Sweden, which can increase the CO_2 intensity as it may be generated from conventional power plants. These have low operational costs, contributing to low import prices, though also negative impacts on the environment. The supply of electricity should therefore be controlled and based on its carbon footprint by utilising power-to-heat (Arnaudo et al., 2021).

2.4.1 Business Models for Heat Export

As long as there is a customer to the service provided, the supermarket can have a potential business. The local opportunities and conditions will determine the specific set up for the system integration and a detailed business case has to be created for each individual case (Danfoss, 2017). Termens (RELIVS, 2020) describes three different business models for heat export from supermarkets: Economic Compensation, Zero-Sum and Win-win. Economic Compensation means that the property owner pays either a fixed or varied price for the exported heat. In this case, there would be quality requirements regarding temperature and flow of exported heat. Challenges connected to this model could be the resistance from property owners to financially compensate for the recovered heat, and also the increased operating costs associated with the quality assurance of the exported heat. Two supermarkets which incorporate this business model are COOP Rådhuset at Kungsholmen and ICA Maxi Stormarknad in Kumla.

Zero Sum means that the property owner offers free heating in return for the recovered heat from the supermarket without financial compensation. In the model for Zero-Sum, conflicts can arise depending on the amount of the heat exported.

Win-win means that the supermarket provides heat to the property owner without financial compensation. However, the supermarket could get lower operational costs in this case and an improved system efficiency. For example if the property owner has a geothermal installation where heat could be stored, and lower the discharge pressure, which in turn lowers the requirement for a cooling medium. Three supermarkets which all use the win-win strategy are COOP Alsike in Dammparkens shopping centre, ICA-nära Rosendal in Uppsala, and Hemköp in the shopping centre of Frölunda Torg.

In Europe, the DHN are often of a monopolistic structure where the infrastructure and distribution of energy is owned by companies, which also makes the investments. This can be an obstacle for new actors to export heat to the network. Innovative market designs are proposed which are similar to the power market, allowing more actors, such as supermarkets to export heat to the network (Faria at. al., 2022). One example of an innovative market design is the Open District Heating owned by Stockholm Exergi. The business solutions are based on the principle of Economic Compensation, and developed for supermarkets and other industries which produced excess heat. The supplier of heat is compensated in two ways, either through a fixed payment every month, or a variable payment depending on the delivered heat and the ambient temperature. The export of heat is flexible for suppliers, meaning they can choose the amount to export (Open District Heating, n.d).

The export of heat to the Open District Heating Spot is divided into three different ways, which require different temperatures and are also compensated differently. The first way is Prima, where the export heat is delivered to the supply line in the network and the supply temperature can vary between 68 °C and 103 °C. The second way is Mix, where the export heat is delivered to the supply line at a temperature of 68 °C. The third way is Return, where the export heat is supplied to the return line in the network and the temperature needs to be at a minimum of 3 °C higher compared to the temperature in the return line (Open District Heating, n.d). In the research by Faria et al., (2022) it is highlighted that these new innovative business models, where several actors can export heat, can lead to lower heat losses due to the distance and a reduction of CO_2 emissions.

2.4.2 Industrial Symbiosis for Supermarkets

The distribution of the benefits among the different involved parties may obstruct the creation of viable business models regarding export of excess heat. Concerning a cascade heat pump solution, either the utility company could own and operate it, compensated by the supermarket for providing access to a heat sink, or the supermarket could own it directly, compensated by selling excess heat to DHN. Furthermore, it would be more beneficial to act as a heat exporter during winter, since the feed-in tariffs for heat export will be lower during summer due to heating demand, temperature requirements, and availability of other competing heating sources are higher in the DHN. Moreover, during this period, the available heat from the supermarket will be larger but the demand lower, contributing to two contradicting effects and a reduced economical feasibility (Zühlsdor et al., 2018).

If the supermarket does not own the building, the type of lease contract between the supermarket and the property owner could include or exclude heating in the rent. If heat is included it could be a driving force for the property owner to work with energy efficiency improvements in the building to lower the total operational costs. However, if the investments need to be done within the supermarkets to increase the efficiency of the entire building, it could create an obstacle for improvements without compensation from the property owner. On the other hand, cold rent could motivate the supermarket to utilise recovered heat from the refrigeration system (Lindberg et al., 2018).

Giunta and Sawahla (2021) investigated possible control strategies for heat recovery in CO_2 refrigeration systems in supermarkets to cover internal heating demands and to sell the excess to the

DHN. The suggested strategies were presented as different scenarios, and evaluated from both techno-economic and environmental perspectives. The results showed that the usage of recovered heat to cover internal demand reduced annual energy costs by around 23 %. When also exporting heat, additional savings of 11–16 % were obtained from the profits and the emissions was reduced by 8-21% compared to when utilising recovered heat solely for internal purposes.

Zühlsdor et al., (2018) evaluated sector coupling and for which boundary conditions it became economically feasible. The research investigated two different possibilities to recover heat from refrigeration systems in supermarkets and export to LTDH networks: increasing gas cooler pressure to directly supply heat or installing a cascade heat pump to recover heat from lower temperatures. The former showed to be more promising during summer when the system operates at high pressures, lowering power consumption to reach operating point. The latter showed a higher COP during colder months and the extra investment could be compensated with increased incomes due to more heat being supplied at higher performance.

Karampour et al., (2019) investigated a state-of-the-art CO_2 transcritical booster system integrated with a geothermal storage and how this integration affected energy efficiency by studying different scenarios. In one of the scenarios, two cases were compared: a supermarket with and without coupling the energy system to a neighbouring facility. When the refrigeration system was integrated with geothermal storage and coupled with a neighbouring facility to enable heat export, savings of 19-31 % of the annual operation costs could be obtained, depending on the chosen energy price. This integrated concept was considered a good business opportunity for the supermarket owners, providing benefits for both owner and neighbouring consumer.

Energy companies could play a significant role in the development of business models for export of heat from supermarkets. When coupled with the DHN, the supermarkets could benefit from utilising the water as a cooling medium. This would enable heat to be rejected directly to the DHN when produced and also lower the demand for expensive cooling mediums, which also could create noise to the surrounding (Lindberg et al., 2018).

Chapter 3

Case Studies Supermarkets

Three supermarkets were part of this study, two CG stores and one Hemköp (Figure 3.1). The refrigeration system within all three stores uses CO_2 as the refrigerant and operates in both transcritical and subcritical mode, depending on operating point. CG is owned by Bergendahls, which is a family-owned chain with supermarkets (City Gross, 2022a). Hemköp is part of the Axfood concern, which is one of the largest grocery trade companies in the Nordic region. Axfood also owns a minority stake in CG (Axfood, 2022). Environmental work is part of the everyday activities in both food chains.

Figure 3.1: The food chains studied in this project.

CG works to reduce their energy consumption and the environmental impact from their systems. They only use renewable energy resources and utilise heat recovery from the refrigeration systems (City Gross, 2022b). CG stands for approximately 25 % of all supermarkets in Sweden which have the *Svanen* certification. In order for supermarkets to become certified with *Svanen*, environmental work throughout the business is required, where energy use and energy efficiency are one of the three most important parts. The certification requires an energy index below 2.0, and is calculated by the actual energy use divided by potential optimal energy use. A requirement from *Svanen* is that the supermarket needs to review its energy demand and efficiency in the business annually (Nordisk Miljömärkning, 2021; BELOK, 2021).

A goal of Axfood is to reach net zero emissions within their operations by 2030. The largest emissions related to the operation is from transports, leakages of refrigerants and energy usage. The energy intensity within the Axfood chain was reduced during 2021 due to energy efficiency improvements, such as installation of doors and covers on the cabinets, installation of LED-lamps and replacements of refrigerants with high GWP (Axfood, 2021).

3.1 Case I: City Gross Ytterby

The supermarket CG Ytterby is located in Kungälv municipality close to Gothenburg. The store is the main building in an old industrial property with a total area of 9955 m^2. The premises have been rebuilt and extended on several occasions, where the most recent construction took place in 2019/2020. The supermarket has historical measurements for both district heating and electricity consumption.

The refrigeration system provides cooling for both chilled and frozen cabinets with an installed cooling capacity of 290kW and 50kW, respectively. The system had seven compressors at MT-level and three compressors at LT-level. On MT-level, two compressors were of the type Copeland 4MTL-30X and the remaining five compressors were of type Copeland 4MTL-35X. On LT level, one was of the type Copeland 4MSL-08 and two were Copeland 4MSL-06. A heat recovery unit was connected to the system as well as a gas cooler and AC unit. The starting point for the heating season was found to be around 13 °C (Figure 3.2). At this point, the discharge pressure will no longer follow the ambient temperature. At colder temperatures during the heating season, the discharge pressure was controlled to have an approximate maximum of 80 bars, while at warmer temperatures above 30 °C, the discharge pressure reached a maximum limit of approximately 90 bars.

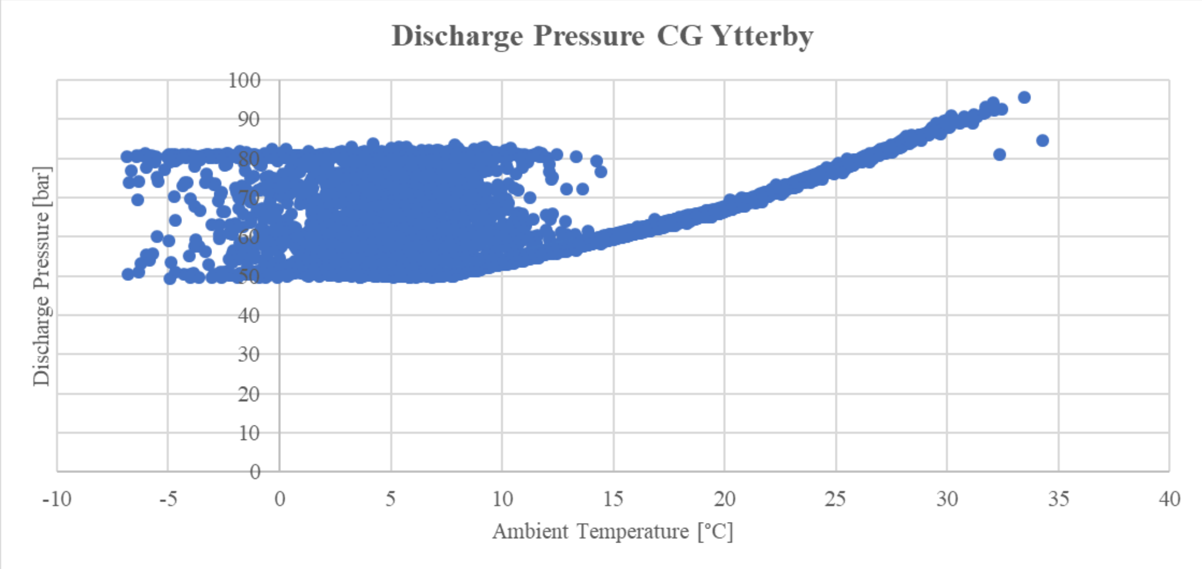

Figure 3.2: The relation between the measured discharge pressure and the ambient temperature in CG Ytterby.

The measured ambient temperature for 2020 at CG Ytterby is presented in Figure 3.3 with a trendline representing a moving average of 48 h. This year had a mild winter, which was considered warmer than usual (SMHI, 2020) and in the summer, high temperatures were observed in June, lower temperatures in July and higher temperatures again in August (SMHI, 2021).

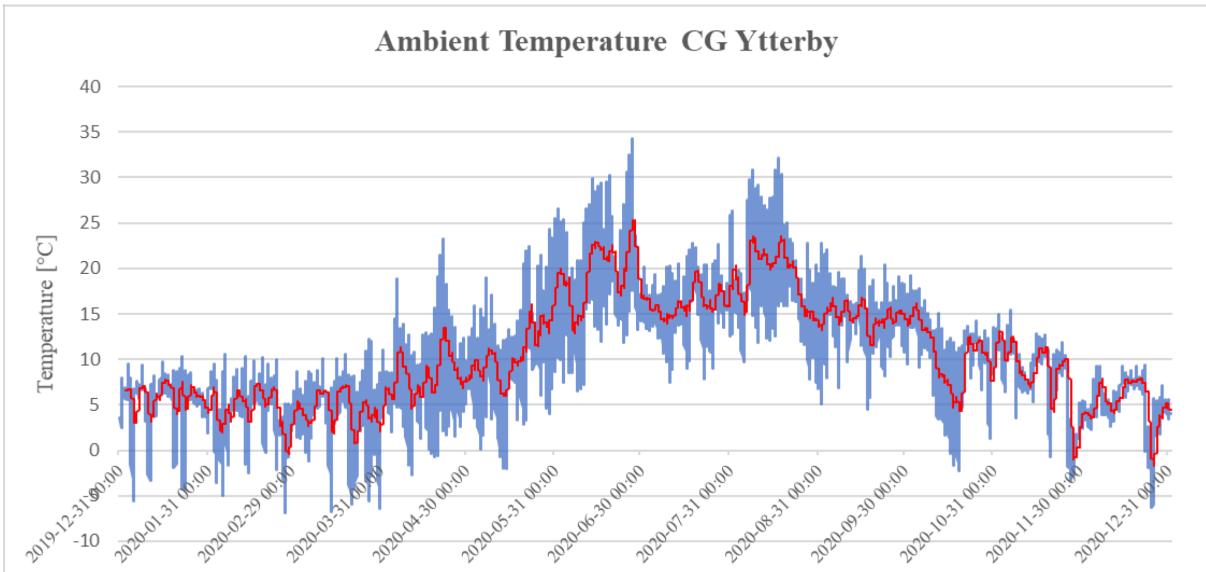

Figure 3.3: The measured ambient temperature at CG Ytterby 2020.

3.1.1 Energy and Economy

The electricity was purchased from Energi Försäljning Sverige AB and Kungälv Energy was responsible for the network. The total usage of electricity for the year 2020 can be found in Table 3.1. The electricity had a Guarantee of Origin (GOO) of 100 % hydropower. The GOO is an European energy certificate, used to prove that the electricity purchased originates from a specific energy source, most commonly used for renewable sources. However, with the complexity of today's network, it is difficult to guarantee that the bought electricity also is the one distributed to the store (Dahlin, 2010).

CG Ytterby was connected to Kungälv Energy, which utilises the Combined Heat and Power (CHP) plant Munkegärdeverket to produce both electricity and heat to the DHN. The plant is fueled on biomass. The temperature in the supply line is around 70–95 °C and the temperature in the return line is approximately 40-45 °C (Kungälv Energi, 2022). The amount of heat provided from the DHN for the year 2020 can be found in Table 3.1.

Table 3.1: Total electricity usage and total heat provided by the DHN for each month during 2020 in CG Ytterby [MWh].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity	180	173	170	159	164	176	171	183	164	169	167	187
DH	24.9	24.4	44.6	26.5	11.7	1.58	2.38	2.01	5.77	18.9	22.6	20.9

Total costs for all consumed power in the CG Ytterby during 2020 and total costs for DH is presented in Table 3.2.

Table 3.2: Total costs for electricity and DH for each month during 2020 for CG Ytterby [tSEK].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity	242	237	231	171	182	203	171	206	186	184	227	258
DH	25.1	24.7	37.3	26.1	13.5	10.0	10.5	10.4	11.6	14.5	22.7	22.0

The share of fixed and variable costs for DHN varied during the year (Table 3.3). The variable costs were dominating during winter when the energy demand was high, while during summer the share of variable costs were small and instead the fixed costs dominated.

Table 3.3: The shares of variable and fixed costs for DH during the year for CG Ytterby [%].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fixed Costs	40	39	27	37	74	97	95	96	84	62	38	41
Variable Costs	60	61	73	63	26	3	5	4	16	38	62	59

3.2 Case II: City Gross Eskilstuna

CG Eskilstuna is located on the western side of Stockholm. The store is located adjacent to a shopping mall and has a total area of 5484 m^2. The system was divided into two separate refrigeration systems on different floors, KA1 and KA2. In both KA1 and KA2, the system had four compressors at MT-level and three compressors at LT-level. Two of the compressors at MT-level were of type Bitzer 4KTC-10K-40S and two were of the type Bitzer 4HTC-20K-40P. At LT-level all three compressors were of type Bitzer 2HME-3K-40S. At each system, a heat recovery unit was connected as well as a gas cooler. The starting point of the heating season was found to be around 15 °C (Figure 3.4). At this point, the discharge pressure will no longer follow the ambient temperature. The discharge pressure was controlled to reach a maximum limit of approximately 90 bar, both during colder temperatures down to -7 °C and warmer temperatures up to 36 °C.

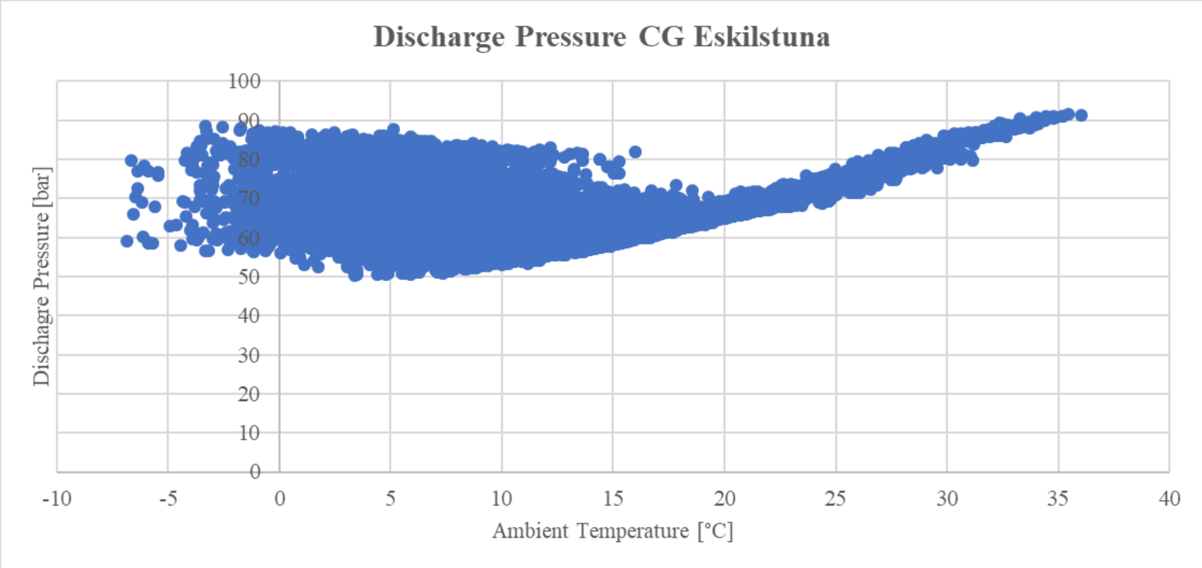

Figure 3.4: The relation between the measured discharge pressure and the ambient temperature in CG Eskilstuna.

The ambient temperatures for CG Eskilstuna during 2020 were similar as for CG Ytterby with mild temperatures during winter, high temperatures during June and August and a cooler July (Figure 3.5).

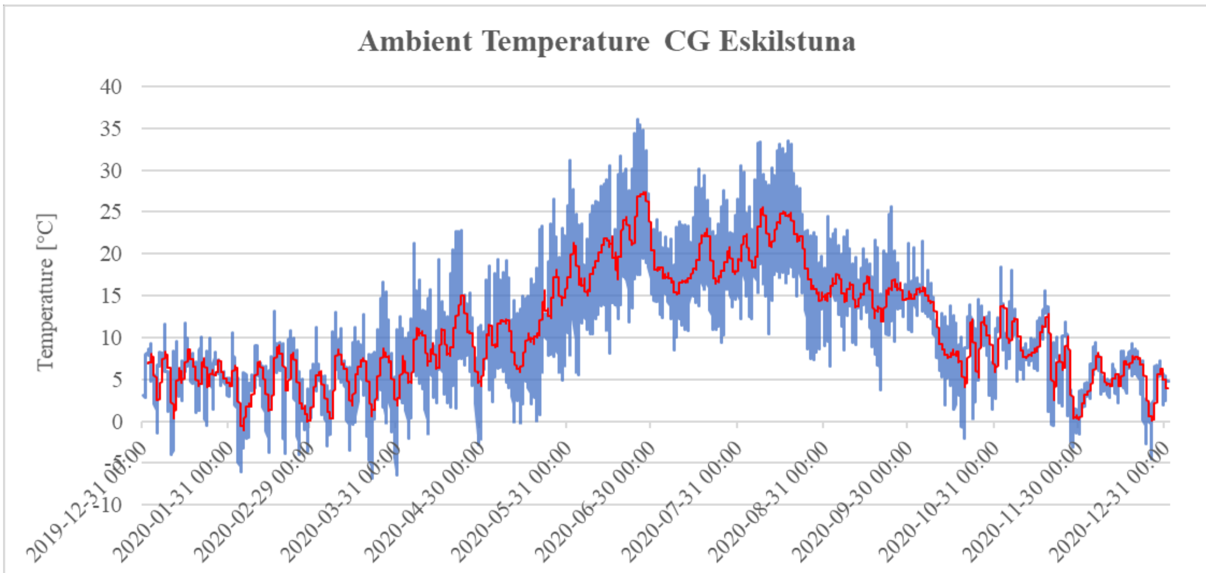

Figure 3.5: The measured ambient temperatures at CG Eskilstuna with a moving average of 48 h.

3.2.1 Energy and Economy

The electricity was purchased from Energi Försäljning Sverige AB and Eskilstuna Energi och Miljö was responsible for the network. Similar to CG Ytterby, the electricity had a Guarantee of Origin (GOO) of 100 % hydropower. CG Eskilstuna was connected to Eskilstuna Energi och Miljö, which delivered DH by utilising a CHP plant located in central Eskilstuna fueled on biomass (EEM, 2020). The amount of heat provided from the DHN and consumed total electricity for the year 2020 can be found in Table 3.4.

Table 3.4: Total electricity usage and total heat provided by the DHN for each month during 2020 for CG Eskilstuna [MWh].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity	111	103	109	107	114	128	127	134	116	116	109	111
DH	1.86	1.97	2.18	1.73	1.6	0	1.39	1.29	1.46	1.72	1.81	1.89

Total costs of all consumed power for CG Eskilstuna during 2020 and total costs for DH are presented in Table 3.5.

Table 3.5: Total costs for electricity and DH for CG Eskilstuna for each month during 2020 [tSEK].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity	139	133	137	128	139	162	141	164	145	139	132	141
DH	4.0	3.8	4.1	1.7	1.2	0	1.1	1.1	1.2	1.8	1.7	1.7

The share of fixed and variable costs for DHN varied during the year (Table 3.6). The fixed costs were dominating during winter when the energy demand was high, while during summer the share of fixed costs were smaller.

Table 3.6: The shares of variable and fixed costs for DH during the year for CG Eskilstuna [%].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fixed Costs	68	66	65	25	35	0	39	40	37	25	25	25
Variable Costs	32	34	35	75	65	0	61	60	63	75	75	75

3.3 Case III: Hemköp Lundby Park

The supermarket Hemköp Lundy Park is located in Gothenburg and opened in September 2021. The store has an area of 600 m^2 and is located on the entrance floor in a new residential building. The refrigeration system provides cooling for both chilled and frozen cabinets with an installed cooling capacity of 38 kW and 10 kW, respectively. The refrigeration system had three compressors at MT-level and two compressors at LT-level. On MT-level, all compressors were of type Bitzer 4MTE-7K but with different motor codes, one of 40S (Δ) and two of 40S (Y). On LT level, one was of type Bitzer 2KME-1K and one of type Bitzer 2MME-07K. A heat recovery unit was connected to the system as well as a gas cooler. The starting point for the heating season was found to be 13 °C (Figure 3.6). At this point, the discharge pressure will no longer follow the ambient temperature. The discharge pressure was controlled to reach a maximum limit of approximately 95 bar during the heating season and the highest considered temperature was 21 °C.

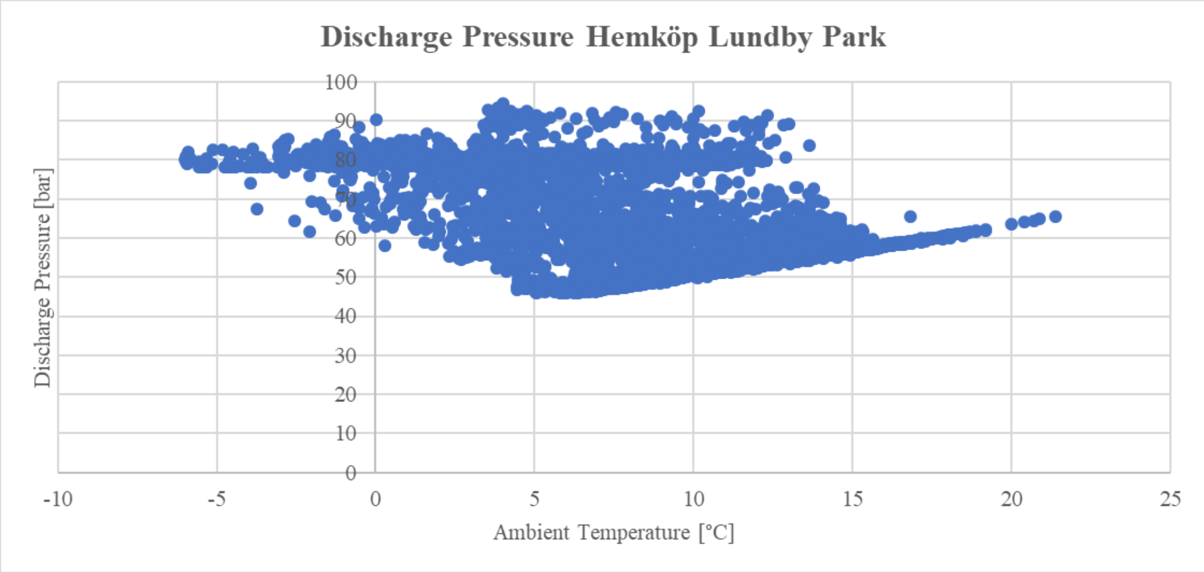

Figure 3.6: The relation between the measured discharge pressure and the ambient temperature in Hemköp Lundby Park.

The measured ambient temperature between October 2021 and Mars 2022 is presented in Figure 3.7.

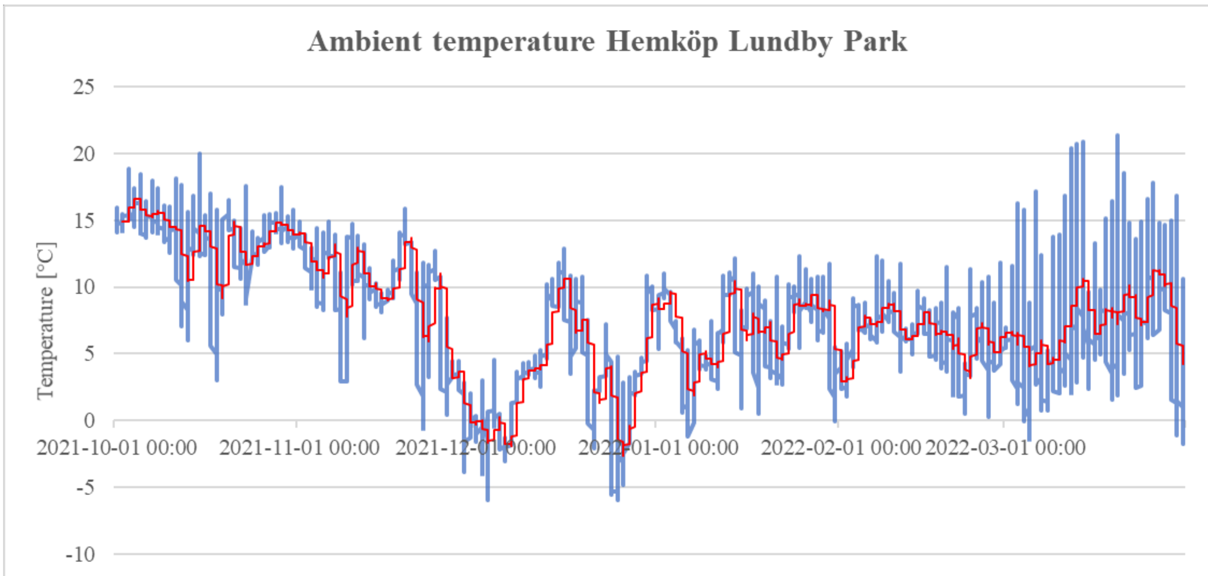

Figure 3.7: The measured ambient temperature at Hemköp Lundby Park with a moving average of 48 hours.

3.3.1 Energy and Economy

The heating demand was considered unknown, since no information was provided by the store. This may depend on the "lease contract", contributing to no invoices informing of consumed heat or electricity.

Chapter 4

Method

The refrigeration systems in the supermarkets were divided into MT and LT levels at the evaporator side and a heat recovery unit was located before the gas cooler (Figure 5.1). A heat recovery model was built to conduct annual heat recovery calculations for the supermarkets, thereafter an optimisation of the system and techno-economic assessment were performed.

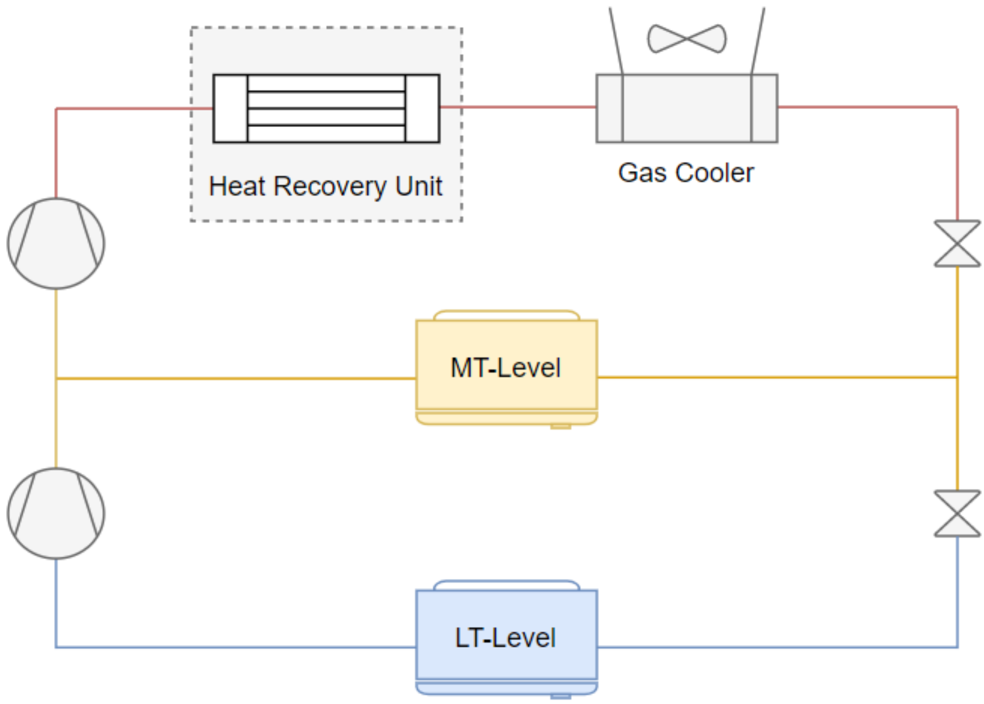

Figure 4.1: A simplification of the refrigeration system in the supermarkets.

4.1 Yearly Heat Recovery Calculations

The annual heat recovery from the supermarkets were calculated with data collected from IWMAC, and synchronised in Matlab. Thereafter a heat recovery model was built in the software Excel where Coolprop was used to find thermodynamic variables.

4.1.1 Data Collection and Synchronisation

Data collection from the three supermarkets were obtained from IWMAC. Historical data were collected for each parameter of interest and downloaded separately as csv-files. Since the parameters were measured at different times and different time intervals, a synchronisation to obtain hourly means was conducted for each parameter in the software Matlab. Parameters for temperatures and pressures were linearly interpolated between the different measurements, and thereafter an hourly mean was obtained from these interpolated values. The operating capacities of the compressors were only measured when changes occurred and therefore a synchronisation in Matlab was made, where the previous values were used for each time unit until a new measured value was obtained. Thereafter hourly mean of the capacities could be calculated.

The volumetric and isentropic efficiencies for the compressors were calculated from different tested conditions, providing values for refrigerating capacity ($\dot{Q}_2$) and power consumption ($\dot{E}$) and found in the product sheet for each identified compressor in the system, both at MT and LT level. For these conditions, different thermodynamic variables ($h_{2k}, h_s, s_{2k}, h_{1k,is}, h_{evap\_out}$ *and* ρ_{2k}) were found and with these, the mass flow was calculated (Equation 4.1), and thereafter the efficiency of the compressor (Equation 4.2).

$$\dot{m} = \frac{\dot{Q}_2}{(h_{evap\_out} - h_s)} \tag{4.1}$$

$$\eta_k = \dot{m} \cdot \frac{h_{1k,is} - h_{2k}}{\dot{E}} \tag{4.2}$$

The volume flow before the compressor ($\dot{V}_2$) was calculated from the mass flow ($\dot{m}$) and the density (ρ_{2k}) (Equation 4.3), thereafter the volumetric efficiency (η_s) was calculated (Equation 4.4) by using given swept volume ($\dot{V}_s$) for each compressor.

$$\dot{V}_2 = \frac{1}{\rho_{2k}} \cdot \dot{m} \tag{4.3}$$

$$\eta_s = \frac{\dot{V}_2}{\dot{V}_s} \tag{4.4}$$

Two different functions, one for the compressor efficiency (η_k) and one for the volumetric efficiency (η_s) were created by plotting the results against the pressure ratios (*PR*) (Equation 4.5). Trendlines for the efficiencies were obtained where the function for η_k was polynomial and the function for η_s was linear.

$$PR = \frac{p_1}{p_2} \tag{4.5}$$

4.1.2 Assumptions

To enable the calculations for the heat recovery, assumptions were made for missing parameters or missing information regarding the system.

IWMAC only measured one superheat per MT and LT-level and did not tell whether it was internal or external, and the value was assumed to be the summation of external and internal superheat. The internal superheat was assumed to be constant at 10 K (Karampour & Sawalha, 2018). The measured superheat at MT-level in CG Ytterby were temporarily negative during periods which were concluded to be non-realistic. Therefore, a minimum value of 10 K was used in the calculations, which was assumed to be a realistic minimum value when comparing to the measured superheat in both CG Eskilstuna and Hemköp Lundby Park.

In IWMAC the compressors were referred to as numbers and not identified by the type of compressors. To be able to calculate volume flows, an identification of the compressors had to be done. An “Equipment list” was provided by CG Ytterby and used to make assumptions for each of the compressors regarding the type. A schematic of the system was provided by CG Eskilstuna, where each of the compressors were denoted with a tag number which corresponded to a list of all compressors.

Since no such lists were provided by Hemköp Lundby Park, the operation pattern was compared to the other stores and assumed to follow a similar trend regarding size of the compressors.

The total isentropic efficiency was not given for the system, and when different types of compressors were used, the mean value of the compressor efficiencies were used for the calculations of h_{1k}. When calculating h_{1k}, heat losses from the compressor was assumed to be 10 % (Navarro-Peris et al., 2015). The discharge temperature measured in IWMAC was assumed to be accurate enough to use when calculating recovered heat. However, for the compressor power, the specific enthalpy was instead obtained from the total isentropic efficiency due to heat losses and to allow for a comparison between different operating modes (Giunta, 2020). The power consumption of the fans was only given for Hemköp Lundby Park, and for the other stores it was assumed to be a percentage of the gas cooler load in the system.

It was assumed that all recovered heat was used for space heating through the air handling unit. Total heating demand for CG Ytterby and CG Eskilstuna was assumed to be equal to the heat purchased from DHN and the recovered heat. Since the heating demand for Hemköp Lundby Park was not given, it was calculated by an average energy demand per square metre obtained from CG Ytterby and CG Eskilstuna.

Heating was assumed to be required when the ambient temperature was below a certain value obtained from a plot of discharge pressure against ambient temperature for each store. To keep the discharge pressure as low as possible in subcritical operation mode, the condensing temperature was assumed to depend on the ambient temperature (Giunta & Sawalha, 2021). Moreover, 7 K was added as long as the ambient temperature was above 3 °C and below the starting point for the heating season (Figure 4.2) (Karampour & Sawalha, 2018; Sawalha, 2012). When reaching this minimum temperature, subcooling was assumed to be included in the cycle from the cold ambient air. To avoid problems caused from formation of frost on the gas cooler, a minimum temperature at the gas cooler exit was assumed to be 5 °C. Between the ambient temperature of 3 °C and -2 °C, subcooling was increased linearly up to 5 K, thereafter the subcooling was held constant at this maximum value of 5 K (Sawahla, 2012).

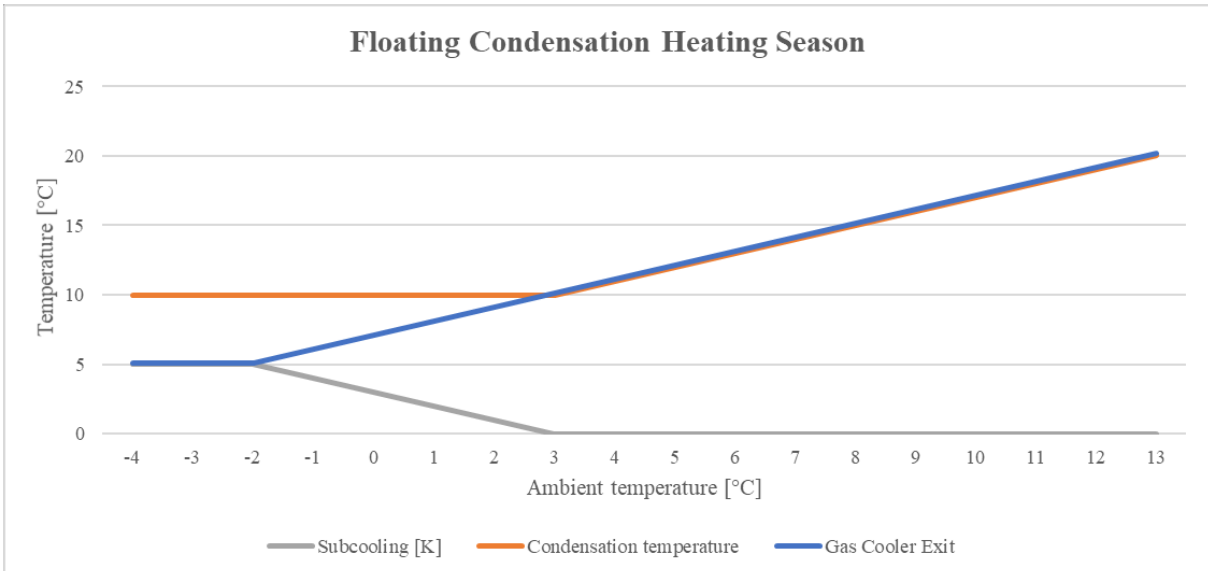

Figure 4.2: The condensation temperature as a function of the ambient temperature.

4.1.3 The Heat Recovery Model

A heat recovery model was created to calculate the energy transferred to the system and rejected from the system, as well as the performances (Figure 4.3).

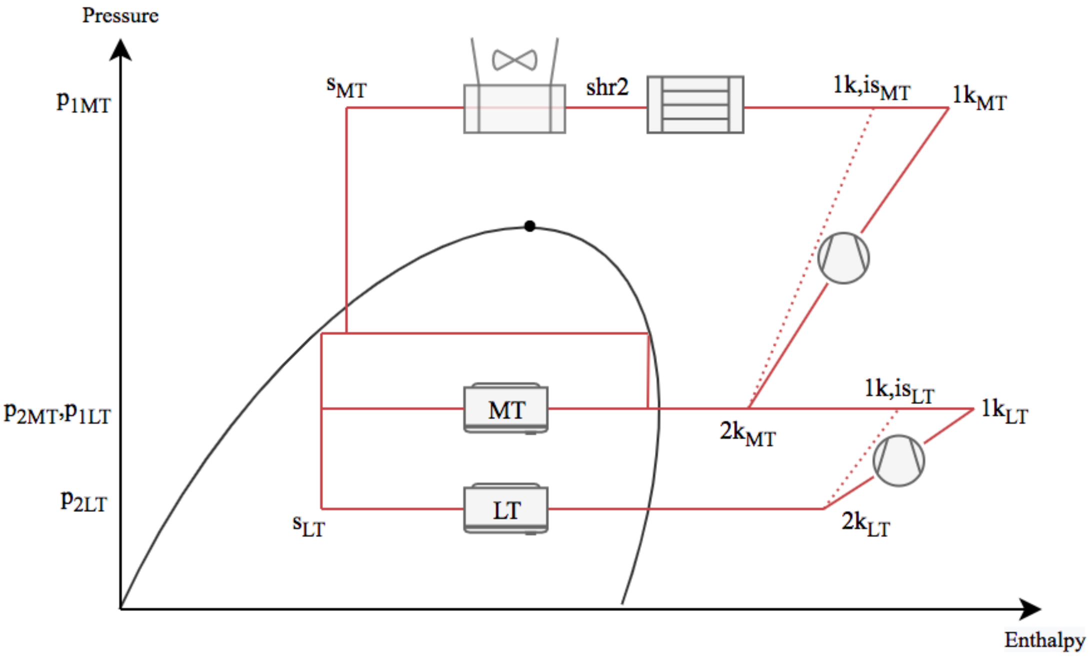

Figure 4.3: The CO_2 refrigeration system and thermodynamic variables illustrated in the log(p)-h diagram.

The synchronised values from Matlab were exported to Excel. Firstly, the mass flows in the system were calculated. To be able to calculate the total mass flow, the total volume flow was calculated over the high stage compressors. This was conducted by taking the swept volume from product guides, percentage of the capacities of the compressors from IWMAC, as well as volumetric efficiencies (Equation 4.6). The pressure, ($p_{2,MT}$) at the MT evaporator was found by the MT suction temperature. The found value and the discharge pressure from IWMAC were used to calculate the pressure ratio, which was used in the function for the volumetric and isentropic efficiencies. The individual volume flow for each compressor was added to obtain the total volume flow. The density (ρ_{2k}) before high stage compressors was found and the total mass flow was obtained from the density and total volume flow (Equation 4.3).

The operating points before the heat rejection ($h_{1k,MT}$), after heat recovery unit (h_{shr2}) and after gas cooler ($h_{s,MT}$) were found. With the total mass flow and enthalpies, the recovered heat and the heat rejected from the gas cooler were calculated (Equations 4.7-4.8). The total amount of rejected heat was the sum of $\dot{Q}_{recovery}$ and $\dot{Q}_{GC}$.

$$\dot{V} = \dot{V}_s \cdot Capacity \cdot \eta_s \tag{4.6}$$

$$\dot{Q}_{recovery} = \dot{m} \cdot (h_{1k,MT} - h_{shr2}) \tag{4.7}$$

$$\dot{Q}_{GC} = \dot{m} \cdot (h_{shr2} - h_{s,MT}) \tag{4.8}$$

To be able to calculate the refrigerating capacity in the evaporators, the enthalpies before and after the evaporators were found as well as the mass flow for each level were calculated.

At the LT-level, the evaporating pressure, ($p_{2,LT}$) was calculated by using the LT suction temperature. The obtained value and $p_{2,MT}$ were used to calculate the pressure ratio. The mass flow was calculated by following the same steps as for the total mass flow. The enthalpies $h_{2k,LT}$ and $h_{s,LT}$ were found, and with these and the mass flow, the refrigerating capacity on LT level was calculated (Equation 4.9).

$$\dot{Q}_{2,LT} = \dot{m}_{LT} \cdot (h_{2k,LT} - h_{s,LT}) \tag{4.9}$$

At MT-level, the mass flow was instead calculated by taking the difference between the total and the mass flow on LT-level (Equation 4.10). The enthalpies $h_{2k,MT}$ and $h_{s,MT}$ were found and with these and the mass flow, the refrigerating capacity on MT-level was calculated (Equation 4.11). The total amount of refrigerating capacities was the sum of $\dot{Q}_{2,LT}$ and $\dot{Q}_{2,MT}$.

$$\dot{m}_{MT} = \dot{m}_{total} - \dot{m}_{LT} \tag{4.10}$$

$$\dot{Q}_{2,MT} = \dot{m}_{MT} \cdot (h_{2k,MT} - h_{s,MT}) \tag{4.11}$$

To be able to calculate the compressor power, the enthalpies before and after the compressors were found. An isentropic compression was assumed and together with a mean value of the compressor efficiencies, the enthalpy for the real compression, h_{1k} was calculated including the heat losses (Equation 4.12). Similar steps were conducted for both levels. The compressor power was then calculated with the mass flow and enthalpies for each level, $\dot{E}_{MT}$ and $\dot{E}_{LT}$ (Equation 4.13). The total amount of compressor power required into the system was the sum of $\dot{E}_{MT}$ and $\dot{E}_{LT}$.

$$h_{1k} = \frac{h_{2k} + (h_{1k,is} - h_{2k}) \cdot 0.9}{\eta_k} \tag{4.12}$$

$$\dot{E} = \dot{m} \cdot (h_{1k} - h_{2k}) \tag{4.13}$$

The fans in the system contributed to additional power consumption. The capacity factor was calculated from values regarding actual power consumption and installed capacity obtained from the product sheet of the refrigeration system in Hemköp Lundby (Equation 4.14). The power consumption of the fans for all stores was then calculated with rejected heat from the gas cooler (Equation 4.15). The total amount of power consumption of the system operating in heat recovery mode ($\dot{E}_{HR}$) was the sum of compressor power and fan power.

$$Capacity\ Factor = \frac{Actual\ Power\ Consumption}{Installed\ Capacity} \tag{4.14}$$

$$\dot{E}_{fans} = Capacity\ Factor\ \cdot Q_{GC} \tag{4.15}$$

The required compressor power was also calculated for when operating in floating condensation mode without recovering any heat. The refrigerating capacity was assumed to be the same as when operating in heat recovery mode. Solely the cycle on MT-level where the heat recovery occurred was changed, and the cycle on LT-level was excluded from the calculations and when considering the total compressor power, the value calculated for low stage compressors in heat recovery mode was used.

By plotting the ambient temperature and discharge pressure when operating in heat recovery mode the starting point of the heating season was obtained (Figure 3.2, Figure 3.4 and Figure 3.6). Above that point, the system always operated at floating condensation without heat recovery, meaning the same values from IWMAC could be used and no new thermodynamic variables had to be found. During the heating season, the condensing temperature was calculated from assumptions in section 4.1.2 and the discharge pressure from this temperature by using Coolprop.

New mass flow on MT-level was calculated by utilising the refrigerating capacity. The enthalpy after the heat rejection and before evaporator at MT level ($h_{s,MT}$) was found and different inputs depending on the ambient temperature. The total mass flow was calculated as the sum of the new mass flow on MT-level and the mass flow on LT-level in heat recovery mode.

The enthalpy after high stage compressors (h_{1k}) was calculated in the same way as when operating in heat recovery mode (Equation 4.12). The enthalpy before the high stage compressors ($h_{2k,MT}$) was the same. The compressor power was calculated with the new total mass flow and enthalpies for MT-level (Equation 4.13). Also, power consumption of fans was calculated in a similar way as for heat recovery mode. The total amount of power consumption for when operating in floating condensation mode ($\dot{E}_{FC}$) was the sum of the calculated power for MT, the power required for LT level when operating in heat recovery mode and the power for fans.

Different coefficients of performance were calculated ($COP_{2,tot}$ and COP_{HR}) (Equations 4.16-4.17). The latter was the COP to consider when evaluating the system for when operating in heat recovery mode (Sawalha, 2012).

$$COP_{2,tot} = \frac{\dot{Q}_{2,MT}+\dot{Q}_{2.LT}}{\dot{E}_{MT}+\dot{E}_{LT}} \tag{4.16}$$

$$COP_{HR} = \frac{\dot{Q}_{recovery}}{\dot{E}_{HR}-\dot{E}_{FC}} \tag{4.17}$$

4.2 Techno-economic Analysis

A techno-economic analysis of the refrigeration system was conducted for each supermarket by creating four different scenarios with different operating conditions and purposes (Table 4.1). Costs for electricity and DH, as well as revenues from heat export were included in the analysis.

Table 4.1: The considered scenarios in the analysis.

	S1	S2	S3	S4
	Reference Scenario	No Heat Recovery	Total Heat Recovery-Local	Total Heat Recovery-Export
Heat Recovery	*Yes*	*No*	*Yes*	*Yes*
DH	*Yes*	*Yes*	*No*	*No*
Heat Export	*No*	*No*	*No*	*Yes*

The first scenario was called the Reference Scenario (S1) and was considered as the base scenario with the current configuration. In this scenario the system was operating in heat recovery mode during the heating season and also bought heat from the DHN to cover internal demand. In the second scenario, No Heat Recovery (S2), the system was operating in floating condensation mode and bought all heat from the DHN. In the third scenario, Total Heat Recovery-local (S3), the system was completely disconnected from DHN and all internal space heating demand was covered with recovered heat. The fourth scenario, Total Heat Recovery-export (S4) was similar to S3, but the heat recovery was maximised to provide additional recovered heat for export to nearby buildings.

4.2.1 Scenarios

The computational tool was used with an annual optimisation for each store (Giunta, 2020). Different ambient temperature profiles were created for input parameters, which were values obtained from the heat recovery model ($\dot{Q}_{2,MT}$, $\dot{Q}_{2,LT}$ and $\dot{Q}_{recovery}$), field measurements (T_{supply} and T_{return}) and given values from the store (amount of bought DH and costs for DH). Additional changed input parameters were temperature for when heating season started, costs for electricity and bin hours.

To enable a comparison regarding power consumption for the system and associated electricity costs, all scenarios were optimised in the computational tool. For S1, the space heating demand was obtained by only including $\dot{Q}_{recovery}$ and excluding the amount of bought DH. For S2 and S3, the space heating demand was obtained by including both $\dot{Q}_{recovery}$ and amount of bought DH. From the results, two solutions were presented, one for operating in floating condensation mode (S2) and one for operating in heat recovery mode (S3). For S4, the heating demand was maximised to find the limit and highest potential for heat recovery at each ambient temperature.

To also account for the heat bought from DHN, additional calculations were performed for S1 and S2. When operating in S2, all internal heating demand was covered by the DHN, adding to the amount of heat bought from DHN.

4.2.2 Costs

All costs, both variable and fixed, were collected from invoices, where the electricity costs included both purchased electricity and electric network. The costs for DH from the invoices were used directly for S1, while for S2 a cost per kWh was calculated from an ambient temperature profile. This profile was used since the costs varied during the months.

The provided invoices for the purchased electricity considered the total electricity usage within the store, meaning the specific costs for the power consumption of the refrigeration system had to be calculated separately. The fixed costs were calculated to kWh and added to the variable costs for each month. An average value was obtained from these monthly costs of 1.2 SEK/kWh for CG Ytterby and Hemköp Lundby Park and of 1.22 SEK/kWh for CG Eskilstuna and used as input to the tool.

The selling price of recovered heat to export in scenario S4 was set to a variable price depending on the ambient temperature. The heat production cost by COP_{HR}, the electricity price and the price for DH were considered to obtain a reasonable selling price. The price chosen was 60 % of the minimum cost of either electricity or district heating, the price was at the same time higher than the heat production price obtained from COP_{HR}.

4.2.3 Investment costs

Additional calculations were performed for estimating the maximal investment cost for S3 and S4 in each supermarket. A value for the investment (C_0) was obtained from the NPV, by making it equal to 0. The value obtained was then a value of the investment when it would neither add nor subtract value, and then recommend a value was to be below this limit (Equation 4.18). The cash flow (R_t) was the difference between the total operational costs for the reference scenario and the total costs for the considered scenario, since it will depict the annual savings in cash made by choosing to follow a different scenario. The lifetime was set to 15 years and the rate used was 6.5 %, a common discount rate for supermarkets in Sweden (ICA gruppen, 2019). During this lifetime, no other single costs have been included in the cashflow. This rate will then be considered as the Internal Rate of Return (IRR), since it is the rate obtained when having a NPV of 0.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} - C_0 = 0 \qquad (4.18)$$

Chapter 5

Results

The results regarding heat recovery in the supermarkets are presented in this chapter together with costs and cost savings connected to the recovered heat. Thereafter the possibility for heat export was evaluated for each store. The recovered heat from the refrigeration system varied with the ambient temperature and had hourly, daily and seasonal cycles in all three supermarkets. The results for the refrigeration system are presented as daily moving averages.

5.1 City Gross Ytterby

Recovered heat from the refrigeration system was the dominant heat source during the measured time period and covered approximately 60 % of the heating demand. During the year, the majority of the heat was rejected through the gas cooler (Figure 5.1). The total recovered heat for the whole year was 300 MWh and the total rejected heat through the gas cooler was 1200 MWh, corresponding to 75% of the total rejected heat from the refrigeration system. When the ambient temperature was low, more heat was recovered in the heat recovery unit and during warmer months, when there was no demand for space heating, the system operated in floating condensation mode. The highest peak of the gas cooler occurred 2020-06-27 at 12:00-14:00, during the warmest measured ambient temperature of the year. During these hours, all high stage compressors operated at maximum capacity simultaneously as the capacity for the low stage compressors decreased to the lowest capacity measured during the year. In January, February and December, the system recovered more heat compared to other months, which affected power consumption and the mass flow in the system. The operation of the compressors was noticed to have large variations which affected parameters in the whole system (Appendix A: Figure A1 and Figure A4).

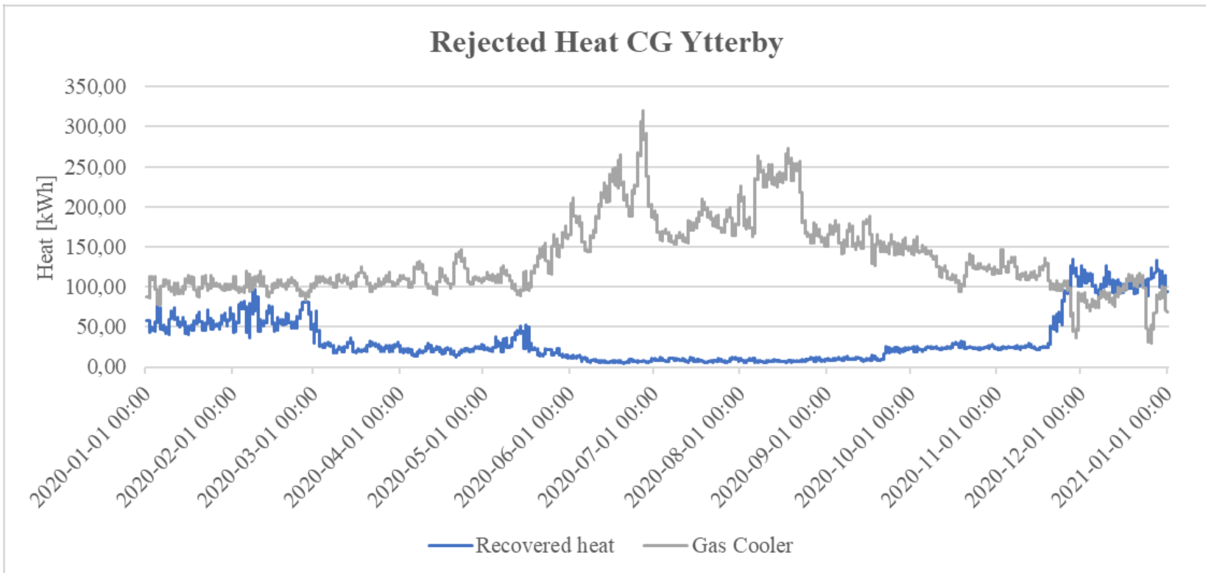

Figure 5.1: Rejected heat in the heat recovery unit and gas cooler in CG Ytterby.

The inlet and outlet temperature in the heat recovery unit at the water side varied during the year (Figure 5.2), and had an average temperature difference between the inlet and the outlet of 6.4 K. The heat recovery unit was by-passed during warmer months, resulting in a low temperature difference and high temperatures up to 70 °C for both inlet and outlet. At lower ambient temperatures, the temperature difference increased, resulting in more recovered heat.

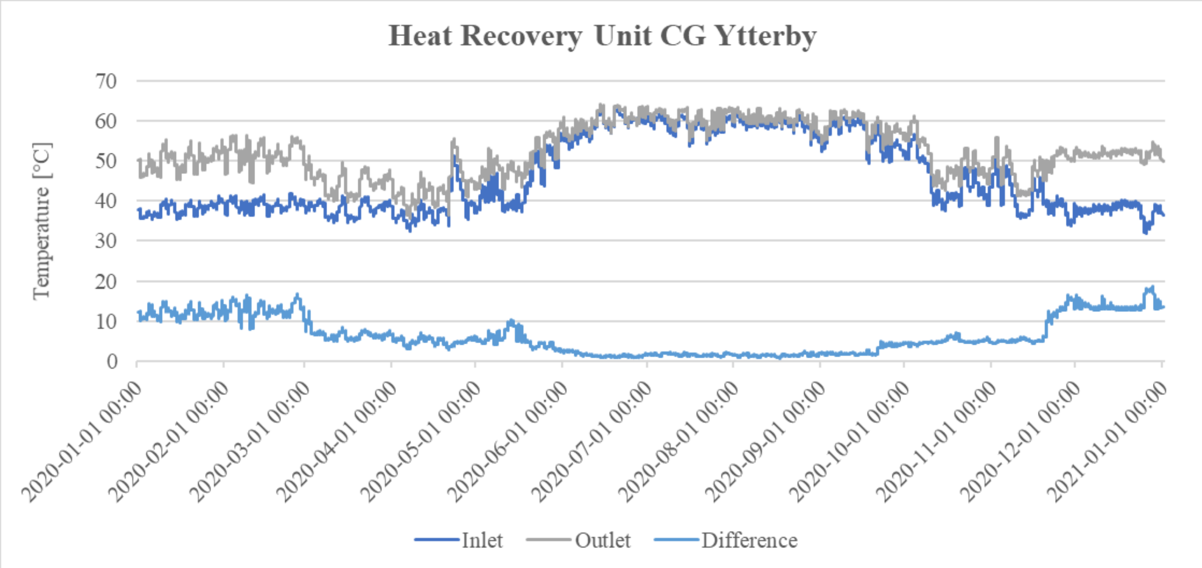

Figure 5.2: The inlet and outlet temperatures of the heat recovery unit together with the total difference for CG Ytterby.

The refrigerating capacity at LT-level (-33 °C) varied during the day and was almost stable with an annual average of 27 kWh (Figure 5.3). The refrigerating capacity at MT–level (-8 °C) varied with the ambient temperature, indoor relative humidity and the mass flow in the system (Figure 5.3). During higher temperatures in the summer, the system reached a higher demand for cooling. In January, February and December, the system consumed more compressor power to elevate the pressure and utilise heat recovery, which also increased the refrigerating capacity. The average load ratio (LR) of refrigerating capacities between MT- and LT-level was 3.8.

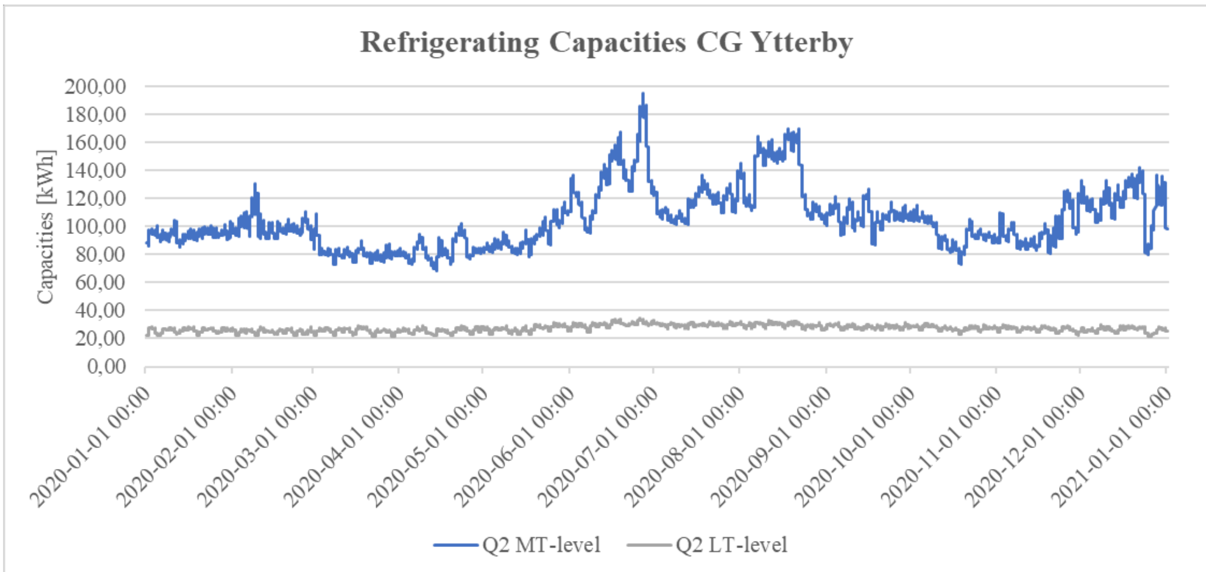

Figure 5.3: The refrigerating capacities on MT- and LT-level in CG Ytterby.

The $COP_{2,total}$ had hourly variations with an average value of 3.5 (Figure 5.4). During the heating season, the COP_{HR} had large hourly variations and above the heating season the system operated in floating condensation mode resulting in a COP_{HR} equal to zero (Figure 5.4).

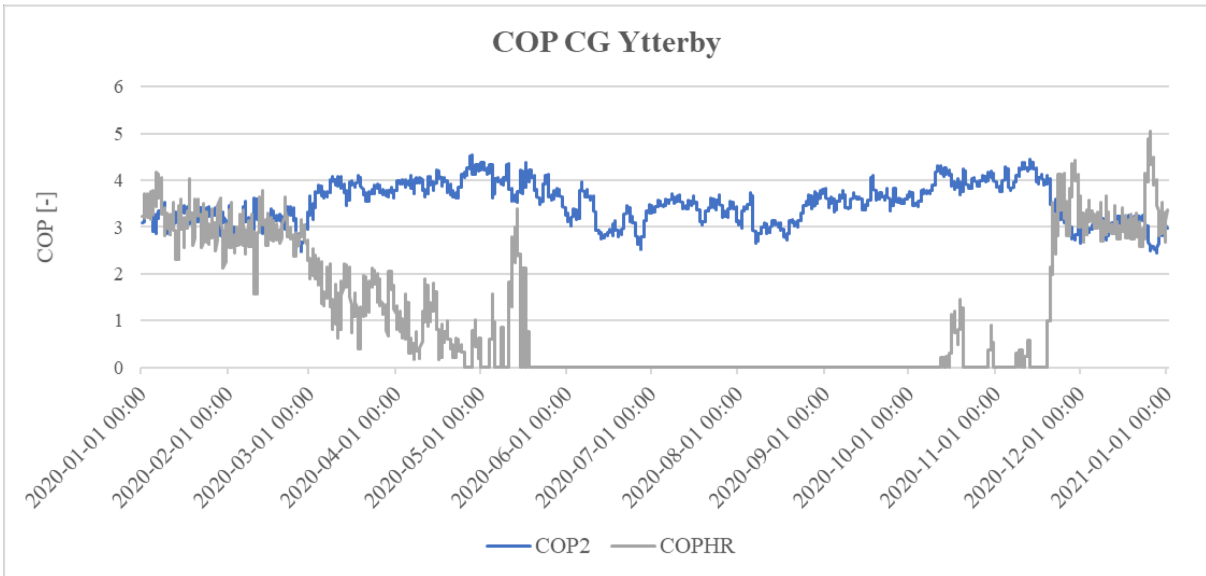

Figure 5.4: The COP_2 and COP_{HR} for the refrigeration system in CG Ytterby.

5.1.1 Techno-economic Analysis

A comparison was conducted between the four different scenarios regarding the total annual operational costs for consumed power in the refrigeration system, as well as the heat bought from DHN (Figure 5.5). The costs for electricity were lower for S2 compared to S1, however since the system did not utilise heat recovery to cover internal heating demand, more heat needed to be purchased from the DHN. This resulted in the highest total operational cost among all scenarios, approximately 37 % higher per year than for S1. The electricity demand was higher for S3 compared to S1 since the system operated at an elevated discharge pressure to provide more recovered heat. Although, disconnecting from the DHN could contribute to savings up to 20 % per year compared to S1. The highest electricity demand was observed in S4, due to maximising the discharge pressure during the whole heating season. Though, when including the revenues obtained from the heat export, the lowest total cost was achieved with annual savings up to 50 %, depending on the selling price of the heat. In S4, the average heat production cost based on COP_{HR} was 0.38 SEK/kWh.

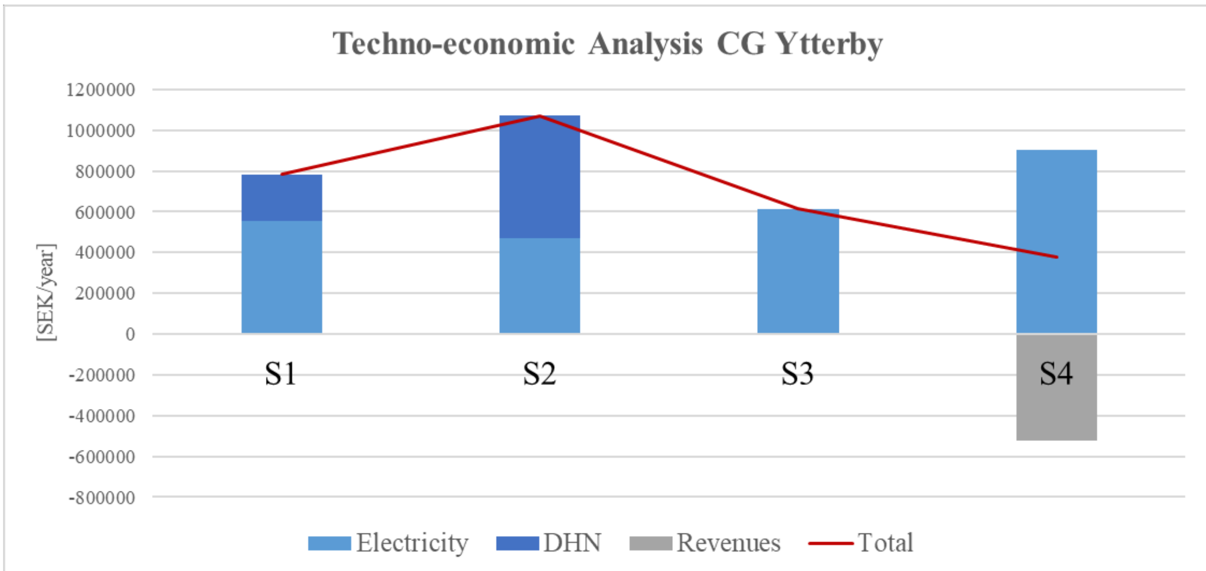

Figure 5.5: The results for the different scenarios in the techno-economic analysis for CG Ytterby.

The maximum investment cost for the systems in both S3 and S4, to still be profitable with a positive NPV, can be observed in Table 5.1.

Table 5.1: Maximum investment costs in S3 and S4 for CG Ytterby [MSEK].

	S3	**S4**
Investment cost	1.57	3.78

In S4 approximately 840 MWh of recovered heat annually could be exported. The potential for heat recovery varied with the ambient temperature and the amount of recovered heat was compared to the internal heating demand of the store (Figure 5.6). For all temperatures, the recovered heat was larger compared to the heating demand.

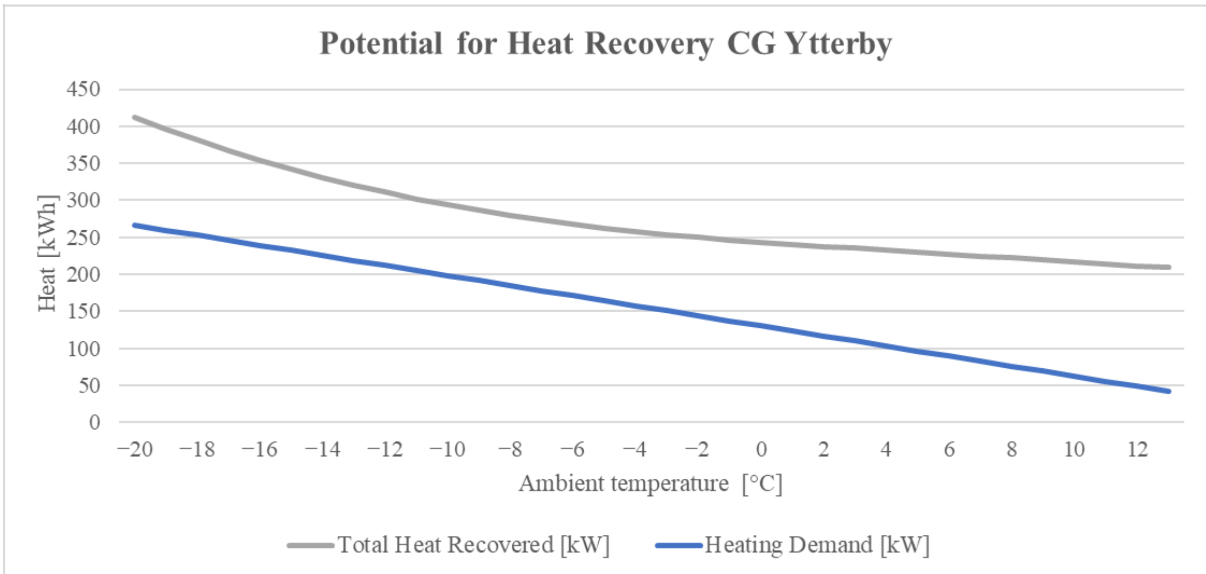

Figure 5.6: The potential for heat recovery in S4 for different ambient temperatures compared to the heating demand of CG Ytterby.

5.2 City Gross Eskilstuna

The recovered heat from the refrigeration system covered 90 % of the heating demand during the measured period. During colder months, the recovered heat followed a similar trend as the rejected heat through the gas cooler, though with a lower mean value (Figure 5.7). During the warmer months, the rejected heat through the gas cooler dominated. The total recovered heat for the whole year was 160 MWh and the total rejected heat through the gas cooler was 790 MWh, corresponding to 80% of the total rejected heat from the refrigeration system. The operation of the compressors was noticed to have large variations which affected parameters in the whole system (Appendix A: Figure A2 and Figure A5).

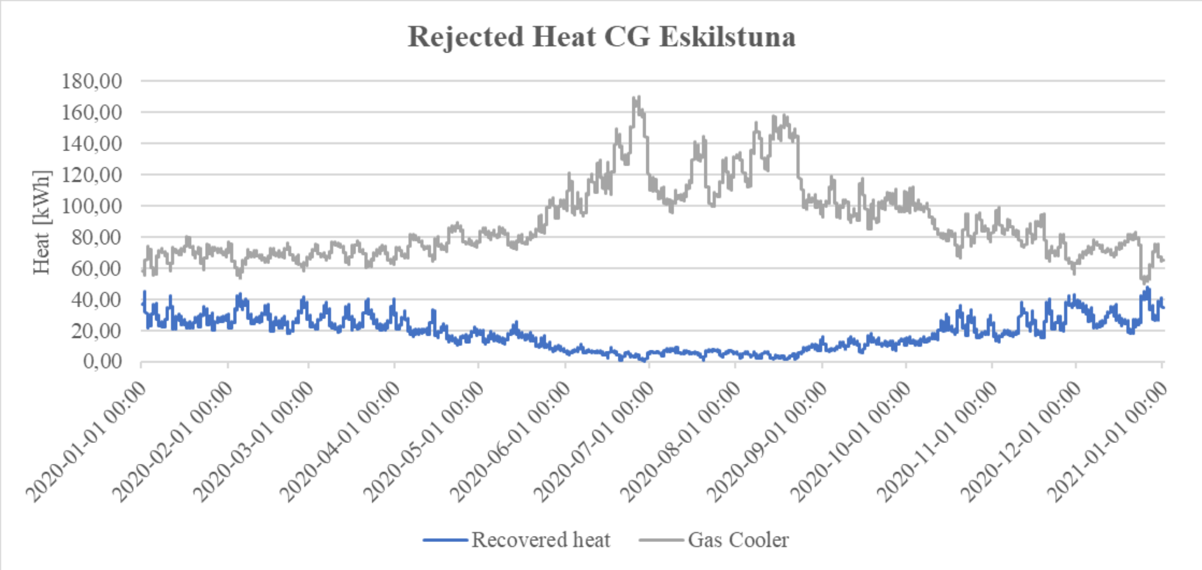

Figure 5.7: Rejected heat in the heat recovery unit and gas cooler in CG Eskilstuna.

The inlet and outlet temperatures in the heat recovery unit at the water side had large variations (Figure 5.8). At lower ambient temperatures, the temperature difference increased, resulting in additional recovered heat. The annual average temperature difference in the system was 5.5 K.

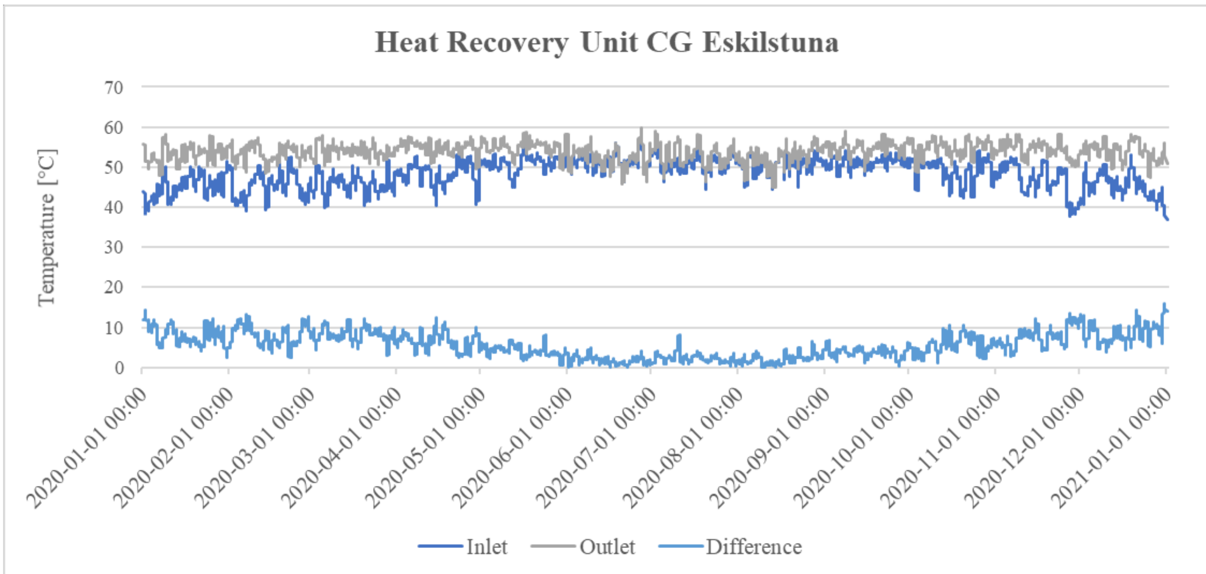

Figure 5.8: The mean inlet and outlet temperatures from KA1 and KA2 of the heat recovery unit together with the total difference for CG Eskilstuna.

The refrigerating capacity at LT-level (-30 °C) varied during the day and was almost stable with an annual average of 20 kWh (Figure 5.9). The refrigerating capacity at MT–level (-5.5 °C) followed the same trend as the ambient temperature, indoor relative humidity and the total mass flow in the system and was fairly constant during the beginning and end of the year (Figure 5.9). At higher ambient temperatures in the summer, the supermarket reached a higher demand for cooling. The annual average LR between the refrigerating capacities at MT- and LT-level was 3.5.

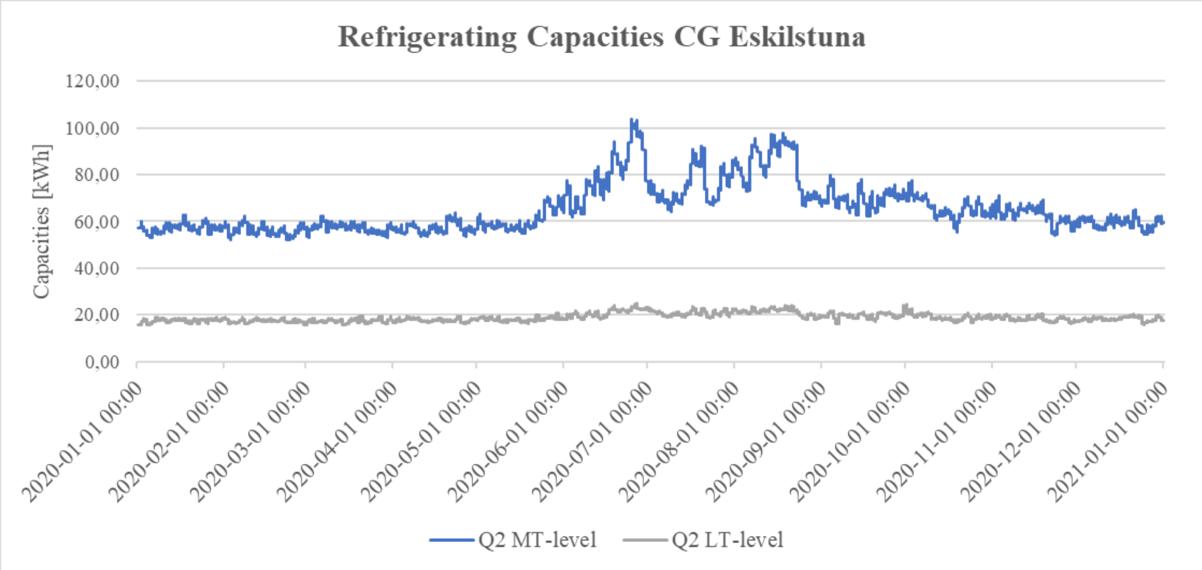

Figure 5.9: The refrigerating capacities on MT- and LT-level in CG Eskilstuna.

The $COP_{2,total}$ had seasonal and hourly variations with an annual average of 3.3 (Figure 5.10). During the heating season, the COP_{HR} had large variations between approximately 0.25 and 2.5 (Figure 5.10). Above the heating season, the system operated in floating condensation, resulting in a COP_{HR} equal to zero.

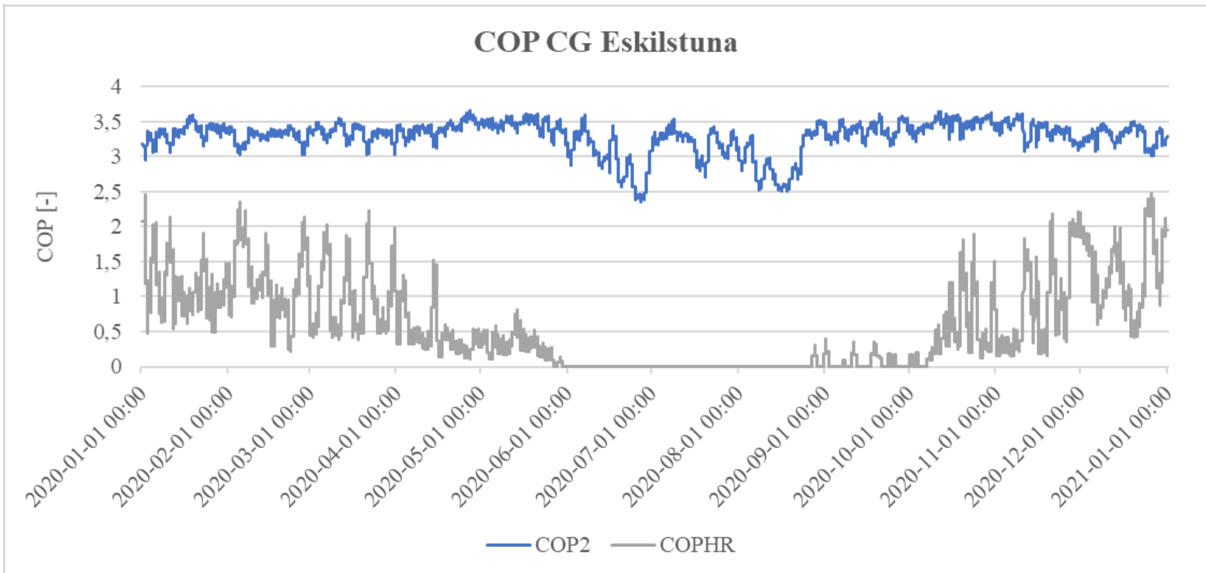

Figure 5.10: The COP_2 and COP_{HR} for the refrigeration system in CG Eskilstuna.

5.2.1 Techno-economic Analysis

A comparison was conducted between the four different scenarios (Figure 5.11). The results followed a similar trend as for CG Ytterby, where S2 had the highest total operational costs among all scenarios, 44 % more expensive compared to S1. Since 90 % of the heating demand in S1 was provided by heat recovery, the difference in total costs was modest between S1 and S3. However, when increasing the heat recovery share to 100 % in S3, the annual cost savings reached 4 %. The lowest total cost was observed for S4, where annual cost savings up to 44 % could be obtained compared to S1. The heat production price based on the average COP_{HR} was 0.50 SEK/kWh.

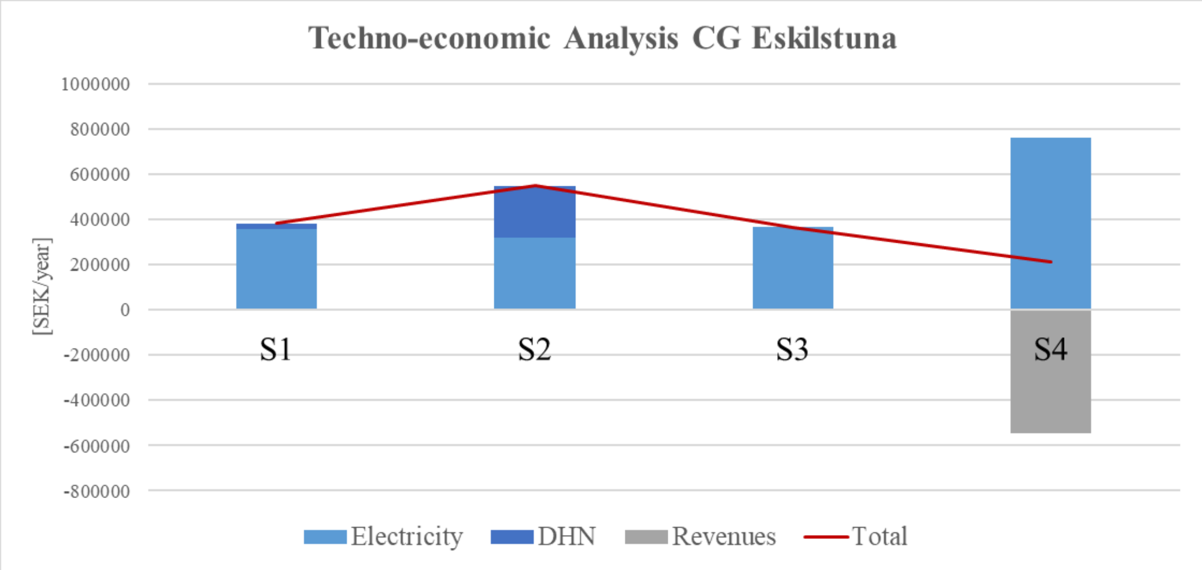

Figure 5.11: The results for the different scenarios in the techno-economic analysis for CG Eskilstuna.

The maximum investment cost for the system in both S3 and S4, to still be profitable with a positive NPV, can be observed in Table 5.2.

Table 5.2: Maximum investment costs in S3 and S4 for CG Eskilstuna [MSEK].

	S3	**S4**
Investment cost	0.15	1.6

In S4 approximately 860 MWh of recovered heat annually could be exported. The potential for heat recovery varied with the ambient temperature and the amount of recovered heat was compared to the internal heating demand of the store (Figure 5.12). A low heating demand resulted in great potential for heat recovery and heat export.

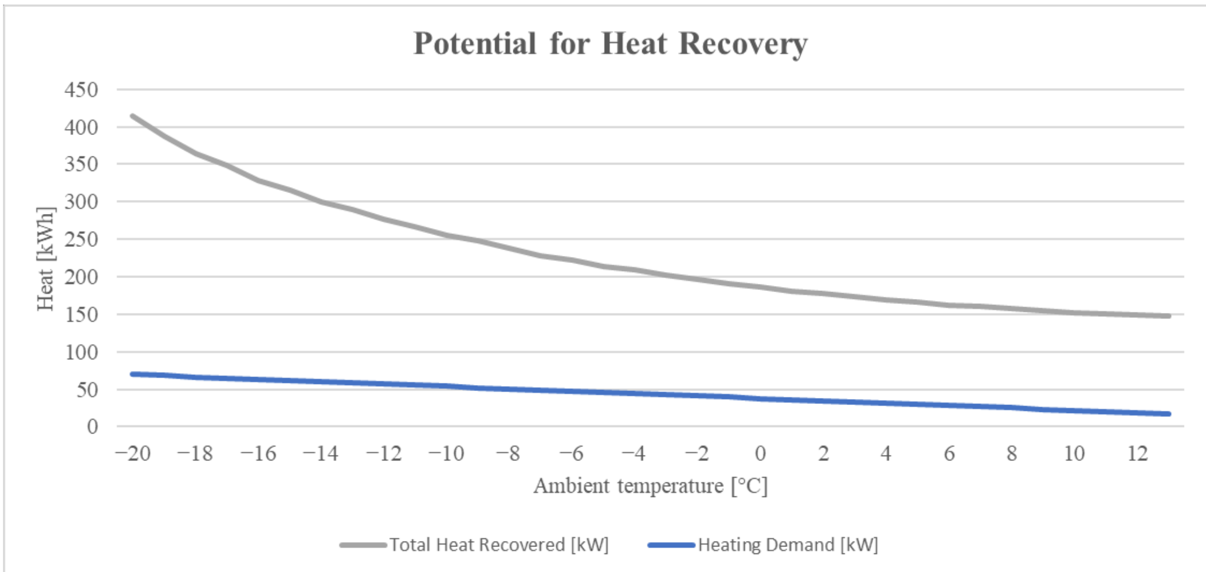

Figure 5.12: The potential for heat recovery in S4 for different ambient temperatures compared to the heating demand of CG Eskilstuna.

5.3 Hemköp Lundby Park

The recovered heat and rejected heat from the gas cooler varied during the studied period, where the former had a few random peaks in October and November (Figure 5.13). The recovered heat was increased in December and January, and was occasionally higher than the rejected heat from the gas cooler. The total recovered heat during the measured time period was 33 MWh and the rejected heat through the gas cooler was 61 MWh, which was approximately 50 % of the total rejected heat from the refrigeration system. Different control strategies could be observed, and from the middle of December to the middle of February, a fixed pressure was adopted which gave a fairly high and constant amount of recovered heat, while in the rest of the period the amount varied considerably, though with a more stable mean value (Appendix A). The operation of the compressors was noticed to have large variations which affected parameters in the whole system (Appendix A: Figure A3 and Figure A6).

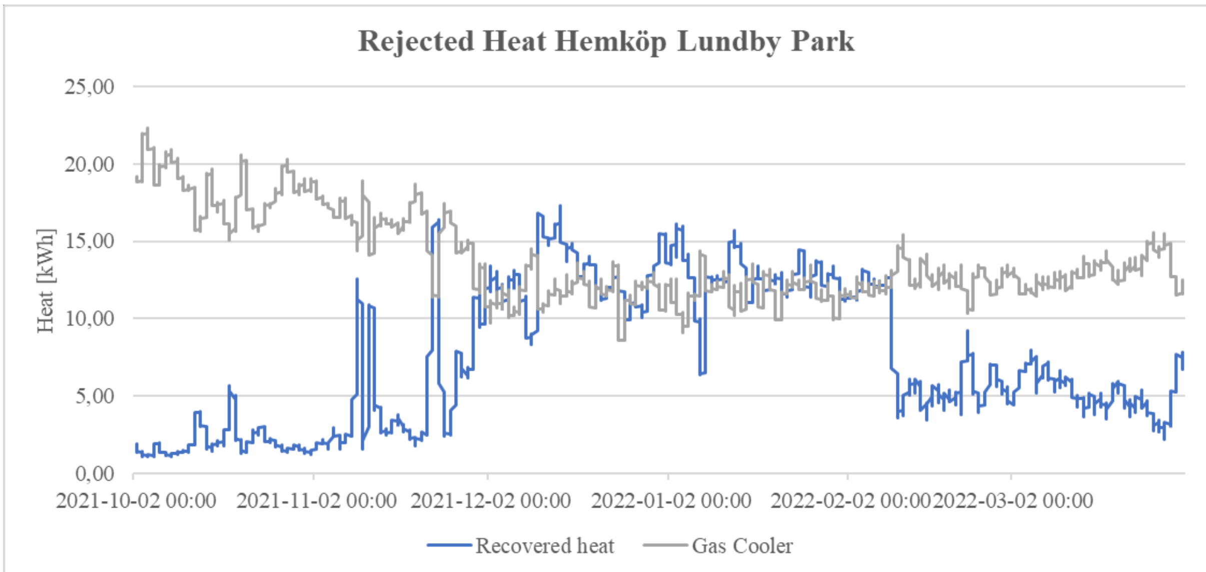

Figure 5.13: Rejected heat in the heat recovery unit and gas cooler in Hemköp Lundby Park during the time period.

The average temperature difference between inlet and outlet in the heat recovery unit at the water side was 8.0 K. During the first two months, the temperature difference was quite low compared to later during the measured period, when the system had a higher temperature difference and could recover more heat (Figure 5.14).

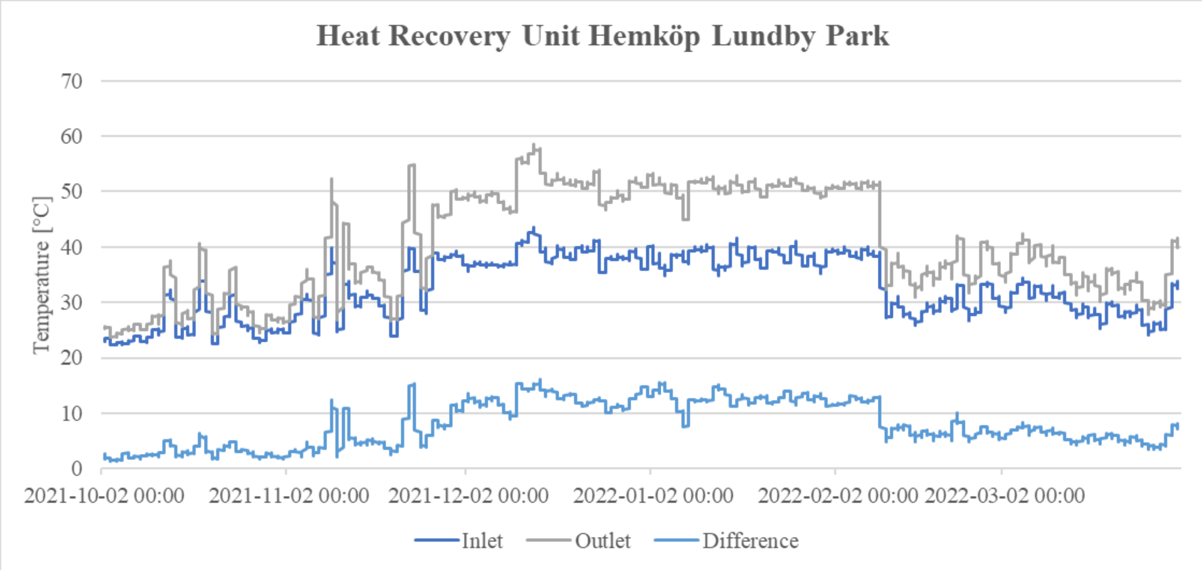

Figure 5.14: The inlet and outlet temperatures of the heat recovery unit together with the total difference for Hemköp Lundy Park.

The refrigerating capacity was fairly stable at LT-Level (-28 °C) with an average of 5.8 kWh. At MT-level (-4 °C) a few random peaks could be observed during the period, and an increase of the mean value during December and January when the ambient temperature and indoor relative humidity dropped (Figure 5.15). The average load ratio between the refrigerating capacities at MT- and LT-level during the measured period was 2.0.

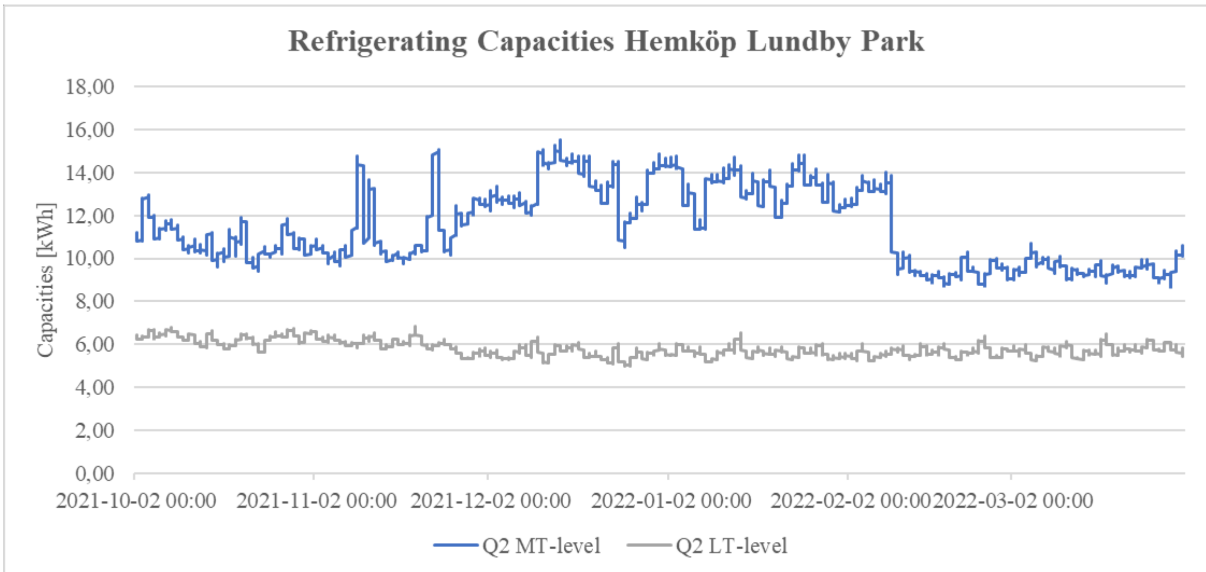

Figure 5.15: The refrigerating capacities on MT and LT-level in Hemköp Lundby Park.

The total COP_2 varied during the measured period with an average of 3.3 (Figure 5.16). The highest values for COP_2 were obtained between the middle of February to the end of March. The COP_{HR} varied between 0 and 3.5 during the period (Figure 5.16). In the end of November, the system started to recover more heat, resulting in a higher COP_{HR} and larger variations.

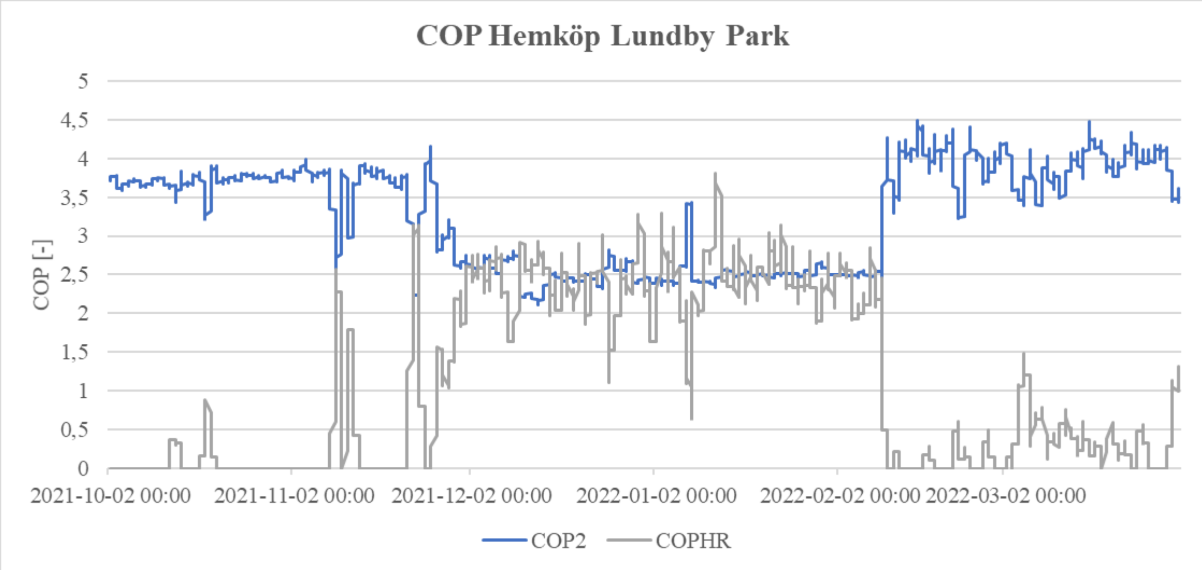

Figure 5.16: The COP_2 and COP_{HR} for the refrigeration system in Hemköp Lundby Park.

5.3.1 Techno-economic Analysis

During the measured period between October and April, a comparison was conducted between the four different scenarios (Figure 5.17). The operational costs for Hemköp Lundby Park followed a similar trend as for both CG Ytterby and CG Eskilstuna. If compared to S1, S2 was 60 % more expensive and S3 could reach cost savings up to 7 %. Unlike the other supermarkets, the operational costs in S4 was in the same magnitude as the revenues from heat export, resulting in a close to profitable scenario. In S4, the system could obtain 99 % cost savings compared to S1, and the heat production price based on the average COP_{HR} was 0.40 SEK/kWh.

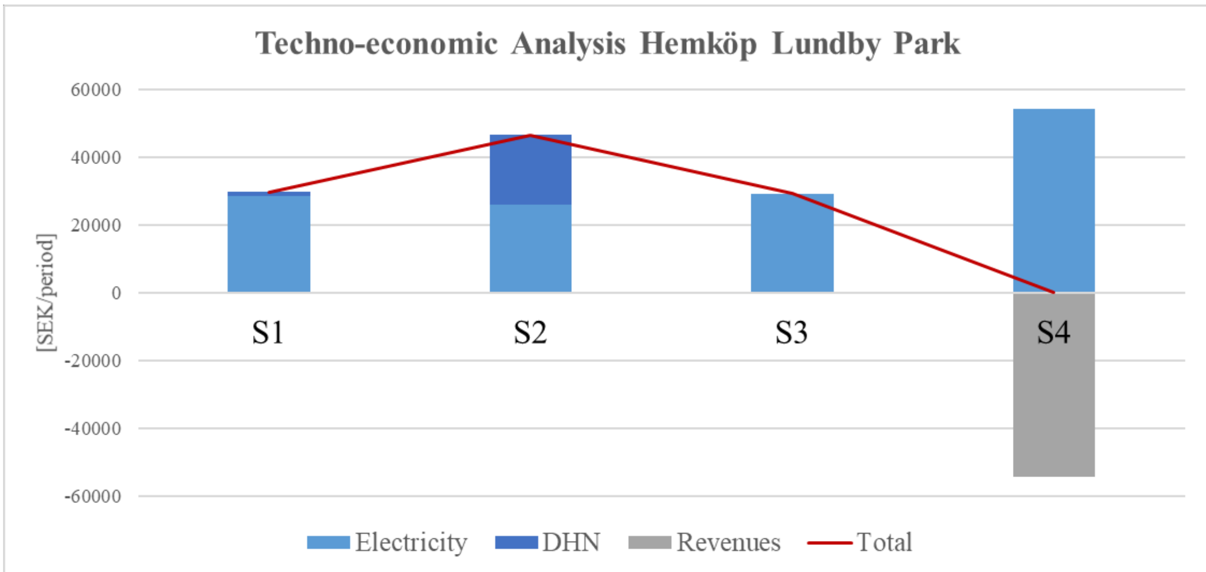

Figure 5.17: The results for the different scenarios in the techno-economic analysis for Hemköp Lundby Park.

The maximum investment cost for the system in both S3 and S4, to still be profitable with a positive NPV, can be observed in Table 5.3.

Table 5.3: Maximum investment costs in S3 and S4 for Hemköp Lundby Park [MSEK].

	S3	**S4**
Investment cost	0.004	0.27

In S4, approximately 89 MWh of recovered heat could be exported during the period. A low heating demand resulted in great potential for heat recovery and heat export (Figure 5.18).

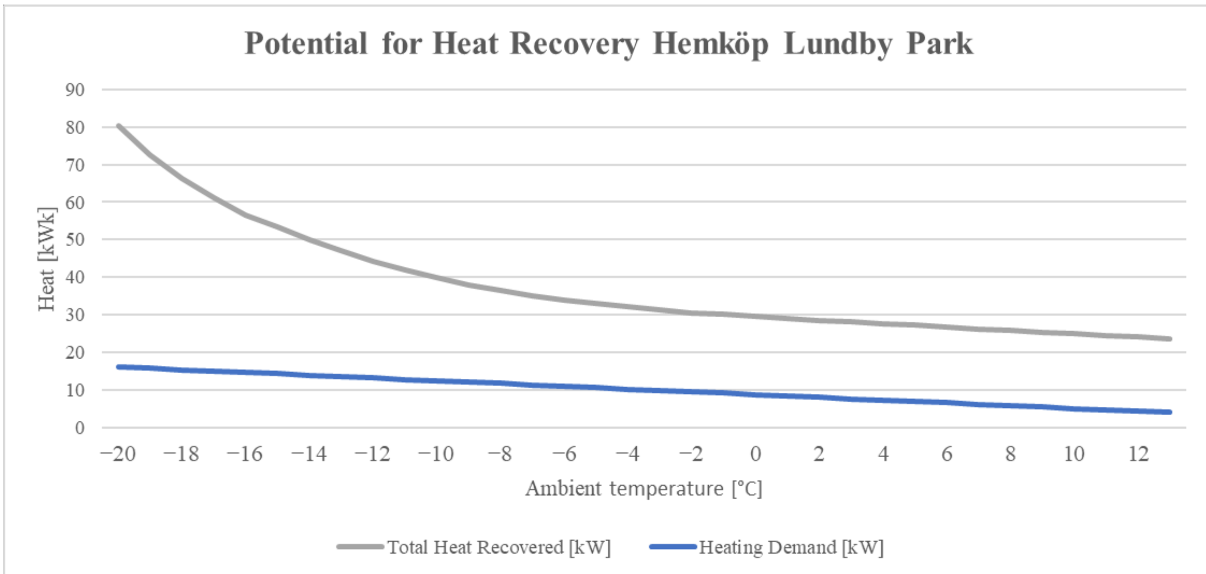

Figure 5.18: The potential for heat recovery in S4 for different ambient temperatures compared to the heating demand of Hemköp Lundby Park.

Chapter 6

Discussion

This section includes discussions about the heat recovery and the performance of the current refrigeration systems, the results from the techno-economic analysis, and potential business models for heat export. Furthermore, sustainability connected to the project and the project's validity and reliability will be discussed.

6.1 Heat Recovery in the Current System

With the current operation conditions for the refrigeration system for both CG Ytterby and CG Eskilstuna, the recovered heat covered the majority of the internal heating demand. However, for all three supermarkets there was a great possibility to recover even more heat. The control of the systems was considered to be inadequate as the nominal capacity of the compressors was not fully utilised and some were switched on and off, contributing to an ineffective operation. Such an ineffective operation could be considered more harmful to the system than operating at optimal conditions. The maximum discharge pressure observed was slightly above 90 bar and only during shorter periods. This means that there was a potential to raise this value by utilising the unused installed capacity of the compressors, since the limit could be up to 100 bar. Generally high return temperatures were observed in all three supermarkets and the temperature differences in the heat exchanger was small, which also implied that the heat recovery could be increased. An unusual behaviour of the system was observed during warmer months where heat was recovered in both CG stores. This could be due to either a heating demand during lower temperatures or simply a measurement error, since the system should be controlled to not recover heat. However, if the system actually recovered heat, it was considered to be for free and could be used for other purposes than space heating, such as DHW production within the store or stored if possible.

The results from the heat recovery model illustrated an unstable system for Hemköp Lundby Park compared to the other two stores. The store was newly opened, meaning the system may have a hard time to adapt, and also prediction of energy usage could be difficult as no previous information to rely on existed. This illustrated picture of the system may not be honest and reliable, as it is obtained from the first 6 months of operation. Different control strategies could be observed, which may be an indication of trial and error to find the best operation conditions for the system. The available time period included the colder months of the year, meaning the highest possible temperature was not accounted for. Therefore, it is important to evaluate the system for a whole year.

The average total COP_2 for both CG Ytterby and Hemköp Lundby Park was 3.5 and for CG Eskilstuna 3.3. These are fairly high values, meaning less electrical work is needed to remove heat from the refrigerated space. Commonly, when the ambient temperature drops, the COP_2 will increase as a consequence of lower discharge pressure and less work required in the compressors. When illustrating the relations between the discharge pressure, COP_2 and ambient temperature, such a trend of a decrease in pressure and increase of COP_2 with lower ambient temperature could be observed. When reaching the start of the heating season, the discharge pressure will be raised to recover more heat and cover the heating demand, which will lower the COP_2, which can also be observed. Though both COP_2 and discharge pressure will vary between lowest value and highest during the heating season. Only the total COP_2 was considered in the calculations, however the load ratio for MT-level and LT-level was calculated. This showed an uneven division of the loads among the levels, where the MT-level stood for the majority of the cooling load in all supermarkets. Therefore, it may be more efficient to make improvements on MT-level, as it dominates the results, and a large difference can be obtained compared to when changing parameters on LT-level.

The heat to reject from the system will be the sum of the energy added, meaning recovered heat can be increased either if the cooling load increases or if the compressor power increases. If increasing the cooling load, the potential for heat recovery will depend on the match between cooling and heating demand where the ambient temperature and indoor relative humidity will have an impact on the operation of the refrigeration system. There will be contradicting events, as there is a greater demand for heating during colder days, when there is a smaller demand for cooling, meaning less cooling load and hence less recovered heat.

The discharge pressure varied during the year and also a bit from store to store. During the warmer months, the pressure could be observed to follow the ambient temperature (Appendix A: Figure A4, Figure A5 and Figure A6) for CG stores to minimise electricity consumption in the compressors, with some peaks in June and August. Such an increase in discharge pressure may be unnecessary from a heat recovery perspective for the studied supermarkets where the recovered heat was used for space heating purposes. It will solely increase the amount of rejected heat in the gas cooler, which also was observed in the results. In other words, there was a great potential for utilising the rejected heat for DHW production or storing, either through seasonal storage by utilising the ground, or through short term storage solutions as hot water tanks. Since a different period was evaluated for Hemköp, a comparison was obstructed between all the stores, but a fixed pressure was observed in the refrigeration system during December to February, contributing to a more stable heat recovery observed in the results (Appendix A: Figure A6 and Figure A3).

Increasing the discharge pressure would commonly not affect the cooling load, though, the cooling load on MT-level was noticed to follow the same trend as the high stage compressors. The cooling load depends on the mass flow, h_s and $h_{evapout}$, where the last one depends on internal superheat. By varying theses enthalpies and mass flow, it was noticed that the mass flow dominated. The mass flow on MT-level depends on the total mass flow which was calculated from the volume flow in the compressors, meaning the mass flow on MT-level will follow the same behaviour, since the mass flow on LT-level is fairly constant. During the warmest day of the year, CG Ytterby had to run all high stage compressors to allow high enough mass flow to provide necessary cooling load, which affected parameters in the whole system.

The internal superheat and the external superheat will affect the system differently. If varying the internal superheat, an increase over the chosen constant value of 10 K will increase the refrigerating capacity. When increasing the sum of superheats, the refrigerating capacity instead decreased, meaning the external superheat contributed with a negative impact on refrigerating capacity. A negligible change in compressor power could be observed when varying the superheats, meaning a change in superheat did not have a large impact on the electricity usage. To improve the performance, the external superheat should be reduced.

Only one heat exchanger was utilised in the supermarkets, though there is a great potential for utilising several within the system. Additional heat exchangers can either be placed before the current one, between the current one and the gas cooler or after the gas cooler. If placing a de-superheater before the current one, the system could recover heat at a higher grade, which could then serve other purposes than space heating, such as providing DHN or for DHW production. A de-superheater placed between the current one and the gas cooler can be connected with an external heat pump to upgrade the heat. To enable the disconnection from the DHN, the supermarkets have to be able to cover the total internal demand. This will create a requirement of high-grade heat for DHW and the demand for a heat exchanger before the current one.

Heat can also be recovered in a sub-cooler placed after the gas cooler, to take advantage of low-grade heat to be used as for example floor-heating. Since all supermarkets rejected most of the heat through the gas cooler, this solution could be beneficial to consider. By including subcooling in the system, the COP will be increased. To increase the heating capacity, the control strategy discussed in 2.2.4 should be adopted. When the maximum limit is reached for the discharge pressure, the speed of the fans in the gas cooler should be decreased to increase the amount of recovered heat. The maximum heating capacity is reached when discharge pressure has reached maximum level at highest COP and the gas cooler is turned off or bypassed.

6.2 Heat Recovery in the Techno-economic Analysis

The supermarkets considered in this study had the potential to cover internal heating demand with recovered heat and also produce excess heat to export. The results from the techno-economic analysis showed similar trends among all three supermarkets:

- S1 gave the second highest total cost after S2.
- S2 had the lowest electricity consumption among all scenarios, however, covering the total heating demand with DH was more expensive and contributed to the highest operational costs.
- S3 had the lowest operational costs and second lowest total cost, which indicated that it was beneficial to disconnect from the DHN. In CG Eskilstuna, the cost difference was modest between S1 and S3, since the current configuration only bought a small amount of heat from DHN, however S3 was still more profitable.
- S4 was the most profitable scenario if the supermarket could obtain revenues from heat customers. However, this scenario had the highest or second highest operational costs, since the system consumed more power in order to increase the discharge pressure to recover more heat.

Since no investment costs were considered in the computational tool, a separate calculation was done to estimate such a cost. For all supermarkets the maximum investment cost with the chosen rate and lifetime could be higher for S4, since the revenues will contribute with a positive value to the annual cash flow. If the investment costs were to exceed the calculated, it will result in a negative NPV, meaning an unprofitable investment. If increasing the lifetime, a higher investment cost can be obtained for both scenarios, while increasing the rate will decrease the possible investment cost. The high investment cost in S4 for both CG stores could enable the required investments for heat export. This cost could be even higher if increasing the price for sold heat, since the price is 60 % of the lowest price of either district heating or electricity.

For S4, the optimal conditions are chosen, contributing to a high amount of recovered heat. This amount will both depend on outdoor conditions, refrigerating capacity and compressor power, and a pressure above critical point contributes to a large increase in recovered heat. The results for S4 are accounting for all heat to be sold, which in reality will not be possible. There will be heat losses during transportation and mismatches in supply and demand, lowering the actual sold and used heat. This will lower the revenues and may contribute to a higher selling price to enable the store to still make a profit. Nevertheless, a higher price could obstruct the value proposition of cheap heat and lower the interest to buy.

In Hemköp Lundby Park, the operational costs were almost equal to the revenues in S4 which may depend on different factors. The studied period was during colder months when the heating demand was higher and if Hemköp Lundby Park would have been evaluated for a whole year, similar results in S4 as both CG Ytterby and CG Eskilstuna could have been observed. Another factor could be the operating conditions with the lowest return temperature of the stores and also lowest gas cooler capacity chosen by the tool. The results could also depend on the assumptions made regarding space heating demand and costs, since such information was not provided by the store. The results indicated that the store could cover the internal heating demand, though it may be good for the store to analyse its lease contract and costs associated with the electricity consumption and heating, to check if they should renegotiate their agreements with the property owner.

The cold rent in CG stores could be considered a driving force to reduce the amount of heat bought and thereby the associated heating costs. The DH cost was divided into fixed and variable, where the shares differed depending on considered location. For CG Ytterby, the fixed costs dominated while it was the opposite for CG Eskilstuna. This contributed to a higher cost per kWh during warmer months for CG Ytterby, though it usually is lower as the demand is decreased, which can also be observed in the results of the total costs for DH. In other words, the prices will differ depending on location and affect the result to being less or more profitable. This could be an extra driving force for CG Ytterby to disconnect from the DHN.

The return temperature in the heat exchanger at the water side was important to consider, as it affected the heat recovery of the system. During the heating season, the return temperatures varied between 45-25 °C for all the stores. Higher return temperatures were found in the CG stores compared to Hemköp Lundby Park, and it was beneficial to have a lower return temperature to obtain more recovered heat, which is in accordance with the literature.

Even if the refrigeration demand was larger in CG Ytterby compared to CG Eskilstuna, CG Eskilstuna could recover more heat. If studying the results from the computational tool, it could be observed that CG Eskilstuna had a lower gas cooler capacity, contributing to a higher temperature before the expansion valve. However, CG Eskilstuna had a higher total power demand which lowered the COP_{HR}. Another reason for the larger amount of recovered heat in CG Eskilstuna could be a longer heating season, which started already at 15 °C compared to 13 °C in CG Ytterby. A longer heating season contributed to more BIN hours when heat was recovered, increasing the total recovered heat. In Hemköp, the lowest minimum value of the return temperature close to 25 °C was observed, which contributed to the highest potential to recover heat in relation to the size of the refrigeration system.

The supply and return temperature at the water side are also important to consider when deciding where to export the excess heat. These have to match the temperature requirements of the heat consumer, for the supermarkets to be able to provide enough heat to cover the demand. If there is a mismatch in temperature, an increase or decrease may be necessary, which requires additional measures to be taken. Also, the heat consumers will affect the return temperature to the system. Therefore, the consumers will have temperature requirements regarding the usage of heat since a high return temperature will have a negative effect on the refrigeration system. To make most use of the heat, a proper control strategy should be chosen. If choosing to place two desuperheaters before the gas cooler, the first one will provide high grade heat, making it inefficient to use for space heating. Instead, it may be more beneficial to produce DHW or couple the heat exchanger with the DHN, to avoid waste of heat.

When the discharge pressure is above the critical point for CO_2 systems, it is possible to recover more heat per unit increase in pressure. Such a measure was evaluated in the computational tool, where the discharge pressure was optimised during the heating season and the system operated in optimal conditions for heat recovery. The tool decreased the gas cooler capacity, by either turning it off or by-passing, to enable a higher heat recovery. In other words, all changes made to optimise the system could be conducted without changing the configuration of the system and is therefore considered easier to adopt. There are other energy efficiency measurements to implement where some are mentioned in chapter 2.2.1, although, those require changes in the configuration. These may not affect the electricity usage in the same magnitude as the ones conducted in the tool, but instead contribute to investment costs vital to consider.

6.3 Business Models for Heat Export

All three supermarkets have the possibility to operate the system at optimal conditions to recover enough heat to export. This will provide an important business opportunity and additionally, industrial symbiosis can be achieved where heat from supermarkets could be utilised in other buildings. The chosen scenarios will depict different ways to operate and control the refrigeration system and the most proper solution to choose will depend on individual conditions and goals of the supermarket. The location of the store will affect the convenience of S4, where neighbouring buildings or apartments will ease the coupling and export of heat.

The Business Model Canvas (BMC) can aid in developing new business models for heat export (Ching and Fauvel, 2013). In the BMC it is vital to consider the key partners, key activities and key resources (Appendix B). Key partners could be the supermarket owner, property owner and the neighbours consuming heat. The main responsibility will be held on the supermarkets, which has to realise this business opportunity by implementing changes in the energy system, conveying benefits with potential customers and negotiating possible agreements of coupling systems. The agreements will be decided with the property owner, who can affect the lease contract, or the design of the HVAC system, which could either simplify or complicate the heat export. Without interest from neighbours or other parties to buy heat from the supermarket, it is difficult to build a viable business model. The price for exported heat in this study is therefore set to be economically beneficial for the heat consumer if choosing the supermarket as provider rather than the DHN. The price for the exported heat was decided by a break-even limit found from COP_{HR}, electricity price and DH price and was the same for all stores. If the price is raised, it will increase the revenues to the supermarket, but also negatively affect the interest to buy.

Key activities could be the control strategy for the refrigeration system, which affects the supply temperature and amount of heat to be exported, the installation of new components, which allows for system coupling, and the maintenance and support when the system is up and running.

Key resources are financial resources, physical resources in the form of the equipment needed, and human resources in the form of knowledge. Since the personnel in the supermarket, property owner and neighbours could have limited knowledge regarding the operation of the system and other key activities, it could be favourable to have an energy specialist who is responsible for the whole system and the system coupling between properties as well as the maintenance and support.

The value proposition would be to provide the heat consumers with clean and cheaper energy compared to both DH and electricity, which would create cost savings. To enable this, the supermarket needs to evaluate its system and reach awareness from the other key partners involved. With the property owner, who is responsible for the building and common heating systems there will be a personal and direct contact, while a more indirect and formal contact with the heat customers will be held. To demonstrate the potential of the refrigeration system, the supermarkets should start with being self-sufficient with heat.

The customer segment will vary between the three supermarkets where the location and neighbours will affect the possibilities. CG Ytterby is located in a stand-alone building, which limits the heat export to neighbours. However, an office is located in the same building where the heat could be exported. CG Eskilstuna is located adjacent to a shopping mall which can create possibilities to export heat to stores in the mall. Hemköp Lundby Park is located on the bottom floor in an apartment building where heat could be exported to the apartments in the building. The location in a shopping mall or apartment building will reduce transmission losses, contributing to a lower heating demand compared to a stand-alone building. The heating demand will vary between the consumers' demand for space heating and the residents' behaviour. Apartments also use a larger amount of DHW compared to offices and stores in shopping malls. If there is no interest regarding the exported heat from the neighbours, the supermarkets could consider an agreement with energy companies and export heat to the DHN since they are already connected.

There will be costs to consider, such as investment costs, maintenance costs and an increased electricity costs for the refrigeration system to enable operation at optimal conditions. Although, the business will also involve a revenue stream from the exported heat, and cost savings will be obtained by covering internal heating demand with heat recovery.

6.4 Sustainability Aspects

Supermarkets are an energy intensive industry which makes it vital to consider energy efficiency measures connected to it. Heat recovery and heat export will affect all three dimensions of sustainability which will be discussed further.

Exporting heat has to be considered from a social and technical aspect, since the complexity will increase when coupling several systems. If the systems are designed and dimensioned to be coupled, it would ease the coupling, which otherwise has to be adapted to each individual system. Cooperation will be required between different partners, where communication will be important to enable such cooperation. The role as a heat producer and supplier comes with requirements regarding the quality and availability, where the expectations may be high. In the beginning, before the system has stabilised, these expectations can be harder to satisfy. There will also be requirements on the consumers regarding quality to provide the refrigeration system with a low return temperature. The lack of knowledge of heat recovery for all the partners involved could limit the interest to adopt changes to allow for heat export. These social and technical factors may complicate the possibility for heat export from supermarkets.

Heat recovery and heat export will be associated with different costs, such as investment costs for new equipment and increased operational costs when optimising the system, but also contribute to cost savings by disconnecting from DHN and revenues from sold heat. These economical aspects are vital to consider as they will decide if the business is profitable. If there is no interest and no customer willing to pay for the exported heat, there will be no revenues and hence no profit business. However, it would be a win-win situation for both the customer and the supermarket since the price for exported heat will be cheap, but still high enough to create a revenue stream. It will also be economically favourable for the supermarket to solely cover the internal heating demand with recovered heat, and it will not require additional investments in new equipment. Since all supermarkets in this study reject the majority of heat through the gas cooler, there is a great potential to take advantage of this heat by optimising the existing heat recovery system or utilising extra de-superheaters. The profitability of the heat recovery will depend on the location, since the electricity price varies in different regions in Sweden.

Supermarkets could adopt a more circular mindset by optimising energy flows by heat recovery. All supermarkets in this study have replaced refrigerants with CO_2, which is considered more environmentally friendly compared to other more traditional refrigerants. This could contribute to both energy and GHG savings connected to the system. Additional electric power is required to increase the amount of recovered heat, which will increase the demand on today's power production. To ensure a sustainable heat recovery, the electric power has to be produced from renewable energy sources, which have a limited availability due to intermittency and installed capacity. Since the power demand is increasing faster than the development of renewable energy technology, a sustainable transition could be obstructed. It will also be difficult to ensure the origin of the used electricity, as the network is complex and the bought may not be the one delivered. It is not certain that heat recovery has a lower environmental impact than DH from the current large-scale CHP plants since this could depend on the energy production. CHP-plants are already built with its network and operate on biofuel to produce both power and heat, which makes them both efficient and environmentally friendly. Nevertheless, heat recovery could be a great option for supermarkets which are missing the possibility to connect to a DHN or utilise other heating sources.

6.5 Validity and Reliability

The results from the research were analysed based on validity and reliability. Validating the results is important as it depicts the accuracy of the results and whether there is an agreement with what has been examined. High reliability indicates high quality of the results and by repeating the research, similar results can be reached.

6.5.1 Data Collection and the Heat Recovery Model

The availability of data will affect the possibility to validate the result. If possible, the calculated results have been validated with measured values from IWMAC or given values from the stores. In this research, three different types of supermarkets were analysed and also several individual parameters were considered during the measured periods, which increased the reliability and enabled a comparison of the results among the stores. The prices have been validated with invoices and typical prices for electricity and DH. The majority of the data in the calculations were based on field measurements and only a few assumptions were made. When data was missing, the assumptions were based on literature or measurements from the other stores to obtain as high reliability as possible. Since no information was provided by Hemköp Lundby Park regarding energy demand, bought DH or invoices, the calculations were based on the other two stores which could affect the validity and reliability of the results.

The software IWMAC had limited information and descriptions regarding different parameters and measurement points. It was not obvious what was included in different measurements or where the measuring points were located, which could affect the quality of the results.

Only one superheat was measured at each level in IWMAC, meaning assumptions had to be made regarding internal and external. Also, for CG Ytterby, negative values of superheat were measured, which was not reasonable. These uncertainties may affect the results from the model and there is a potential to improve the superheat within the system. The measured value was chosen to be the sum of external and internal, with a constant value of internal superheat. This obstructed the understanding of the impact from both internal and external superheat. The calculated compressor power was compared to a measured value of the power used in the refrigeration system from IWMAC for the CG stores. For CG Ytterby, these values coincide fairly well, though for Eskilstuna the calculated values were lower. Also noticed was a lower value of $Q_{recovery}$ for Eskilstuna compared to measured values in IWMAC and given from the store. This was considered to be a consequence of the low swept volume of the compressors used in the system compared to for Ytterby.

As mentioned, the chosen year to investigate for the CG stores was 2020 when the Covid-19 had its outbreak around the world. This pandemic affected everybody and most certainly the habits of the customer, which in turn affected the cooling load and heating demand within the store. If chosen another year, the results may have looked different and probably been more stable. The pandemic was not the only thing that distinguished this year, it was a leap year and a warm winter in Sweden. The warm winter lowered the internal heating demand and also increased the required cooling load of the refrigeration system.

6.5.2 The Techno-economic Analysis

The power consumption was optimised for all scenarios to enable a reliable comparison between the different scenarios. The results from the techno-economic analysis depended on the BIN hours, which was based on the ambient temperature. Input parameters in the computational tool were also dependent on the ambient temperature profile, which means that the result can vary from year to year depending on the temperature. By creating a profile as input, average values were used in combination with interpolation, which can contribute to an increase or decrease of the value which may not reflect reality.

The costs used in the techno-economic analysis were based on the invoices in combinations with assumptions and interpolations, which may contribute to uncertainties. Solely the costs for DH in S1 was taken directly from the invoices and considered reliable. For Hemköp Lundby Park, no costs were given from the store and the techno-economic analysis was built on the invoices for Ytterby since the stores are located in the same area. The fixed costs were converted to variable costs, depending on the used energy, which may not depict an honest picture as they may depend on several more parameters, such as size of the store and agreements. The values from the results should therefore not be analysed on a detailed level, but rather be used as an indicator to whether the scenario is economically feasible or not. The electricity price used in the computational tool was a constant value obtained from average values for each month, where the fixed costs were converted to per kWh and added to the variable costs. Today’s environment is changing, and inputs used in the calculations for this project may be considered faulty in a similar analysis performed on today’s system. Due to the increased reliability of intermittent energy sources the electricity prices have increased significantly during colder months. Such an increase was not relevant during 2020 and not considered. Additionally, the dependence on other countries, richer in natural resources, will affect the prices and availability. Measurements over several years could strengthen the reliability of the analysis since both ambient temperature and costs may vary between different years.

Chapter 7

Conclusion

Supermarkets can contribute to a large environmental impact associated with the energy consumption and the used refrigerant within the system. The refrigeration system has a high energy demand, while also rejecting large amounts of heat with the potential to be recovered, which could create business opportunities for the supermarket. A proper control strategy should be used to optimise the system and enable all internal demands to be covered. Such a control strategy could differ from store to store, depending on individual conditions. Important parameters to focus on when changing the system are return temperature and discharge pressure, as these will affect the amount of recovered heat and consumed electric power. It is also important to achieve a more stable operation of the system.

To conclude, all three supermarkets have the potential to cover both internal heating demand with the recovered heat from the refrigeration system, as well as produce excess heat to export. An observed trend from all three supermarkets in the techno-economic analysis is that it is economically favourable to disconnect from the DHN and cover the internal heating demand with recovered heat. There is also a good potential for a business model if the supermarket has a neighbour who is willing to pay for the exported heat. This could be seen as a win-win situation, since the supermarket could provide cheaper and clean energy compared to the alternatives DH and electricity, which would lead to cost savings for the neighbour. The supermarket would at the same time obtain revenues which lowers the total operational costs for the system compared to solely covering internal demand. Nevertheless, in reality, heat losses will occur, either during transportation or due to mismatch of supply and demand, reducing the revenue stream. Therefore, the selling price will have to be analysed to be in favour both for the store and customer. To simplify heat export, systems should be designed to be coupled, and it will require cooperation with increased communication and knowledge for all involved parties. Also, the potential has to be shown to create an understanding and interest among consumers and proper agreements need to be negotiated. The main responsibility will be held on the supermarket to realise these opportunities, where legal requirements or policies could aid in the matter.

7.1 Future Studies

Aspects not covered nor considered in this research could be conducted in future studies to enrich the knowledge and understanding within the area and some are listed below:

- Investigating the engagement and opportunities from several stakeholders' perspectives, such as the supermarket, the property owner, and heat consumers. Thereafter investigate the possibility for energy agreements.
- Investigate the coupling of energy systems and conduct more thorough economical calculations regarding investment costs.
- Investigate the environmental impacts associated with utilising heat recovery to cover internal demand compared to when utilising DHN or other heating sources.
- A comparison of different years since the operation of the system may differ depending on the ambient temperature.
- Implementing recommended changes and strategies to optimise the system and investigate how it works in practice. Investigate how the recovered heat is used within the supermarket and how it could become more efficient.

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Appendices

Appendix A: Heat Recovery and Discharge Pressure

Hourly means for the heat recovery (Figure A1-A3) and discharge pressure (Figure A4-A6) in the supermarkets. The red and yellow line represents daily moving averages.

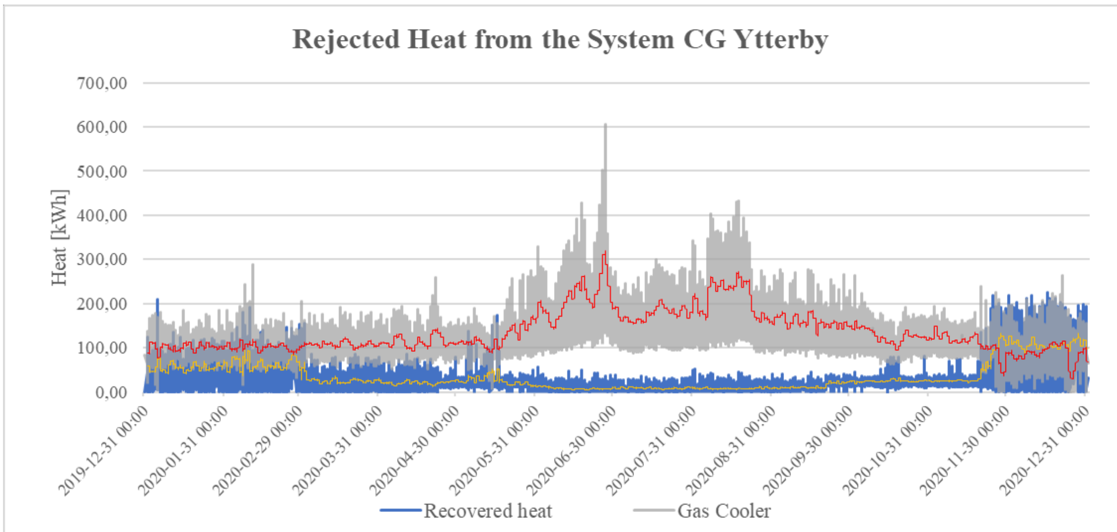

Figure A1: Hourly variations for the rejected heat in CG Ytterby.

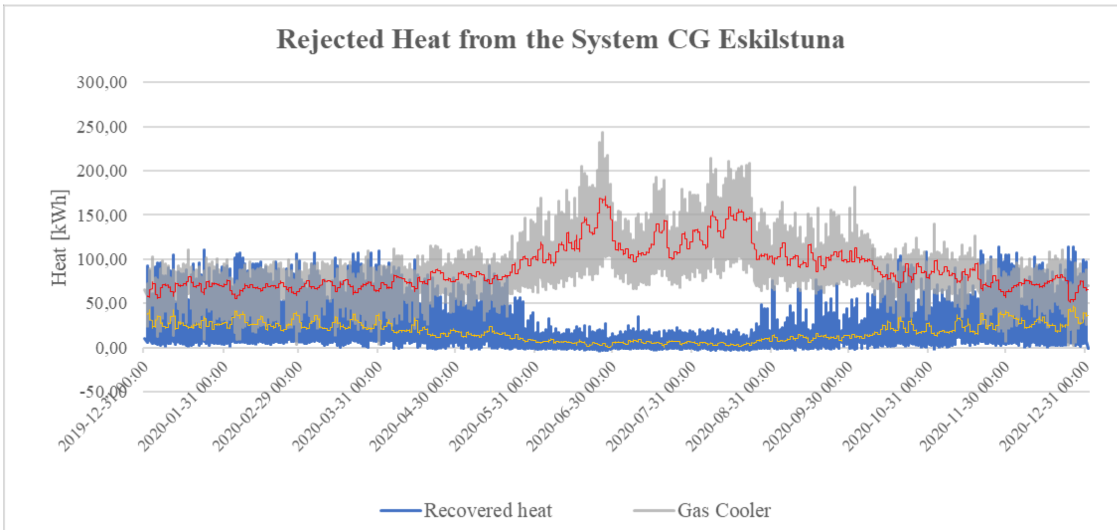

Figure A2: Hourly variations for the rejected heat in CG Eskilstuna.

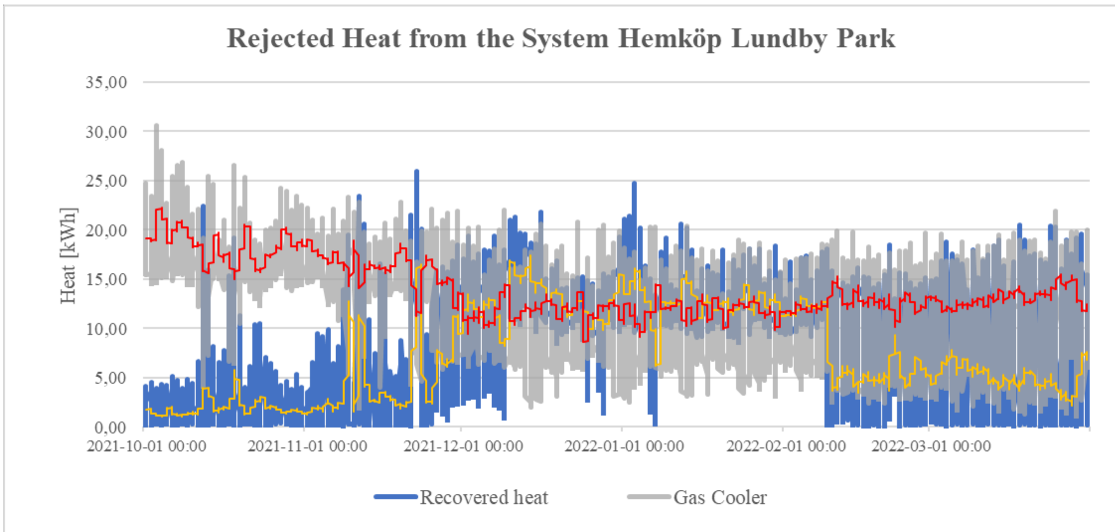

Figure A3: Hourly variations for the rejected heat in Hemköp Lundby Park.

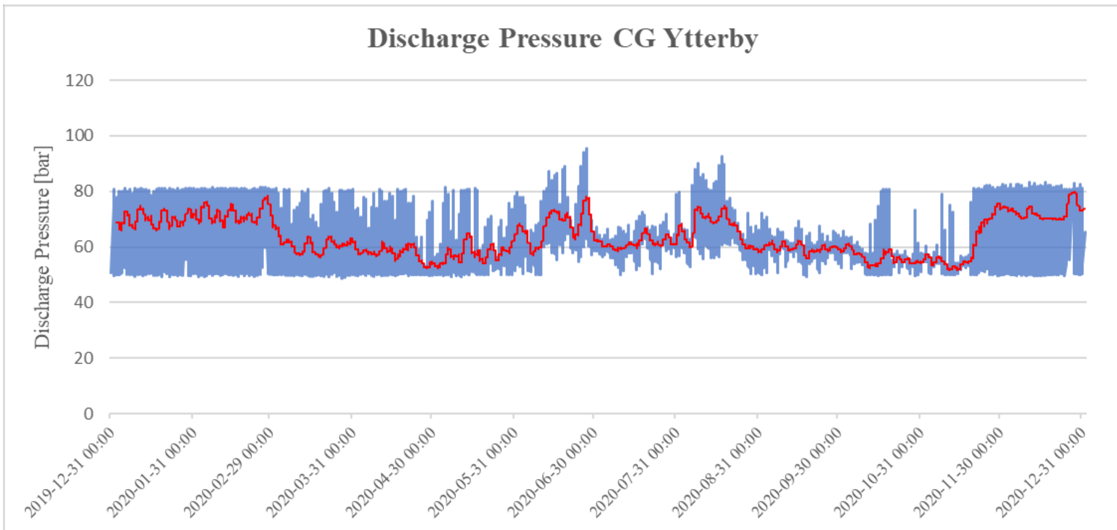

Figure A4: Hourly variations for the discharge pressure in CG Ytterby.

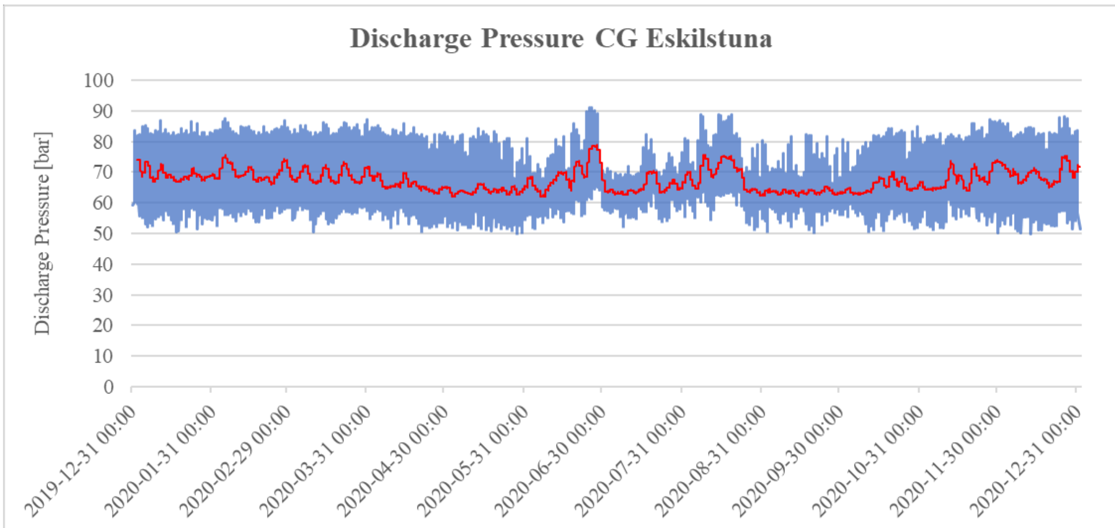

Figure A5: Hourly variations for the discharge pressure in CG Eskilstuna.

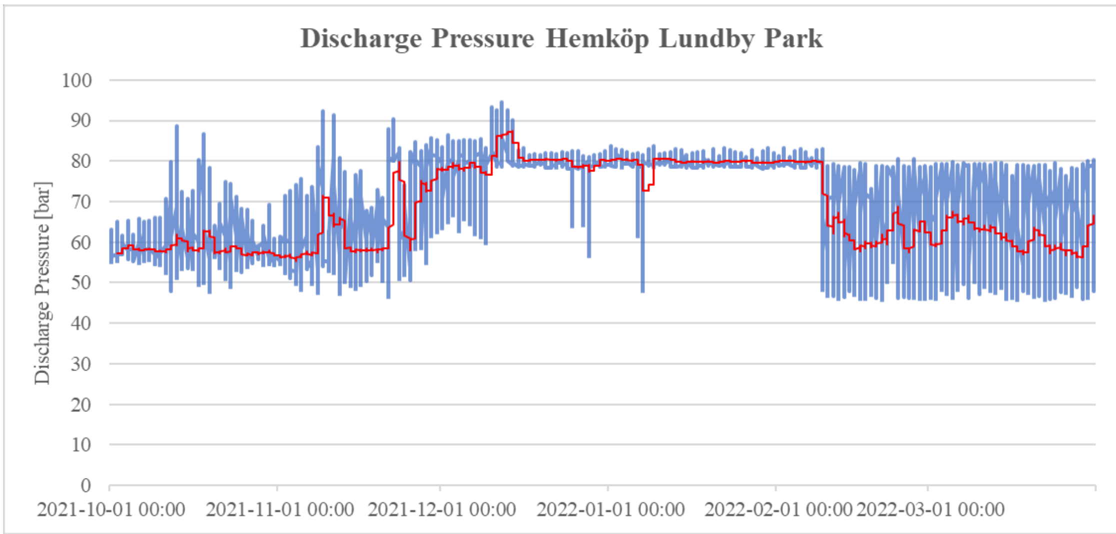

Figure A6: Hourly variations for the discharge pressure in Hemköp Lundby Park.

Appendix B: Business Model Canvas

<table>
<tr>
<td rowspan="2">Key Partners

The supermarket

The neighbour

The property Owner

Energy specialist</td>
<td>Key Activities

Heat Export

System coupling

Maintenance

Support</td>
<td rowspan="2">Value Proposition

Cheaper and clean heat

Cost savings

Increase circularity</td>
<td>Customer Relationships

Personal contact with property owner

Formal contact with heat consumers</td>
<td rowspan="2">Customer Segments

Heat consumers</td>
</tr>
<tr>
<td>Key Resources

Financial resources

Equipment

Knowledge</td>
<td>Channels
Direct contact with property owner

Indirect contact with heat consumers</td>
</tr>
<tr>
<td colspan="2">Cost Structure

Investment costs

Increased operating costs</td>
<td colspan="3">Revenue Stream

Revenues from sold heat</td>
</tr>
</table>

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