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Resurseffektiva kyl- och värmepumpssystem
samt kyl- och värmelager

The energy efficient supermarket of tomorrow

Morgondagens energieffektiva livsmedelsbutik

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Energimyndigheten

Förord

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Sammanfattning

Detta projekt undersökte ökning av effektiviteten i dagens koldioxidkylsystem i livsmedelsbutiker genom att analysera designmodifieringar och integrationsmöjligheter med andra energisystem i livsmedelbutiker.

Undersökningarna har baserats på teoretisk simulering och analys av fältmätningar från antal livsmedelbutiker på olika ställen i Sverige. Huvudparametrar som har undersökts är: värmeåtervinning vid två temperaturnivåer, tillhandahålla luftkonditionering genom kylsystemet, användningen av parallell kompressor, värmelagring i berg via borrhål, översvämmade förångare, mekanisk underkylning, och evaporativ avkylning av gaskylare.

Projektet definierade och presenterade analysen av det state-of-the-art integrerade CO2-systemet, som är energieffektivt, miljövänligt och allt- i- en kompakt lösning som kan täcka effektivt hela termiska krav i livsmedelbutiker i kall och varm klimat. Systemet ger minst 15% årliga energibesparingar jämfört med standard CO2-system och minst 25% jämfört med konventionella system med HFC i Stockholm-Sverige. Vilket gör systemet det mest energi- och kostnadseffektiva som kan installeras.

Projektet gav högkvalitativ detaljerad analys av fältmätningar som saknats i litteraturen inom området av livsmedelbutikers energisystem. Teoretisk simulering har verifierats av fältmätningsresultaten och utvidgats till att inkludera konventionella och framväxande alternativ. Den omfattande och detaljerade analysen som gjorts i detta projekt har inkluderats i 5 tidskriftsartiklar (4 tidskriftsartiklar har redan publicerats och ytterligare 1 artikel ska lämnas in inom en snar framtid). 8 konferensartiklar är utarbetade totalt (4 konferensartiklar är redan publicerade, 1 godkänd och kommer att publiceras i juni, 2 lämnats in för at publiceras i juni, och 1artikel ska lämnas in om två veckor).

En av konferensartiklarna prisades som den bästa uppsatsen vid konferensen och dessutom som den bästa uppsatsen på temat hållbarhet. En av examensarbete rapporterna vann priset från en regional förening i Spanien.

De detaljerade och dokumenterade resultaten i detta projekt kommer att ge mer uppmärksamhet åt miljövänlig teknik och kommer att höja kraven på framtida system för att vara effektivare och miljövänligare.

Nästa forskningssteg inom detta område förväntas fokusera på att demonstrera prestanda i det state-of-the-art energisystemet. I nuläget existerar inte systemet i en livsmedelsbutiks installation. Vissa nyinstallerade system kan ha några gemensamma

funktioner med det state-of-the-art systemet, men de behöver nödvändigtvis optimeras i design och kostnad. Ett demonstrationsprojekt kommer att erbjuda en stor möjlighet där forskare kan vara involverade i ett tidigt skede för att utforma det state-of-the-art systemet och samla all nödvändig information om fallstudien. Forskarna kan se till att systemet är instrumenterad, övervakat och utvärderat som om det skulle vara en testrigg som körs i ett laboratorium.

Summary

This project explored increasing the efficiency of today's CO2 refrigeration systems in supermarkets by investigating design modifications and integration possibilities with other energy systems in the supermarket.

The investigations have been based on computer simulation modelling and analysis of field measurements from number of supermarkets in different places in Sweden. Key parameters that have been investigated are: heat recovery at two temperature levels, providing air conditioning, parallel compression, ground energy storage, flooded evaporators, mechanical sub-cooling, and gas cooler evaporative cooling.

The project defined and presented the analysis of the state-of-the-art integrated CO2 system, which is energy efficient, environmentally friendly, and all-in-one compact solution able to provide the entire thermal demands of supermarkets efficiently in cold and warm climates. The system offers at least 15% annual energy savings compared to standard CO2 system and at least 25% compared to conventional systems with HFC's in Stockholm-Sweden; making the system the most efficient and cost effective that can be installed in Sweden today.

The project provided high quality detailed analysis of field measurements which has been missing in literature in the area of supermarket energy systems. The computer modelling has been verified by the field measurement results and expanded to include conventional and emerging alternatives. The extensive and detailed analysis done in this project has been included in 5 journal papers (4 journal papers published already and 1 more paper is to be submitted in the near future). 8 conference papers are prepared in total (4 conference papers are already published, 1 accepted to be published in June, 2 submitted to be published in June, and 1 to be submitted in two weeks). One of the conference papers won two prizes for the best student paper on the theme of sustainability the best overall student paper in major international conference and one of the MSc thesis reports won prize from regional association in Spain.

The detailed and documented results in this project will give more attention to environmentally friendly technologies and will put more pressure on the future systems to be more efficient and environmentally friendly.

The next research step in this area is expected to focus on demonstrating the performance of the state-of-the-art energy system. The system does not exist yet in a supermarket installation. Some newly installed systems may have some common features with the state-of-the-art system but they are not necessarily to be optimized in

design and cost. A demonstration project will offer great opportunity where researchers can be involved at early stage of designing the state-of-the-art system and gather all needed information on the case study. The researchers can make sure that the system is instrumented, monitored and evaluated as if it would be a test rig running in a laboratory.

Innehåll

1 Background

Supermarkets are the highest energy intensive commercial buildings consuming almost double the office building. They are responsible for consuming about 3-4% of the total annual electricity in industrialized countries and are the largest consumers in Europe of high GWP refrigerants. Therefore, the need is great for environmentally friendly and energy efficient systems for supermarkets.

Natural refrigerants are seen as a potential permanent solution where CO2 has been suggested as an environmentally friendly refrigerant and has been applied in the supermarket refrigeration sector in the past two decades. The present dominant CO2 refrigeration technology uses solely CO2 where the system can operate in the trans-critical region; such systems are referred to as CO2 trans-critical.

The research work on carbon dioxide in supermarket refrigeration at the Energy Technology Department at KTH started about 20 years ago with computer simulation modelling followed by experimental analysis of a real scale system in the laboratory to verify the theoretical findings. Then extensive detailed field measurements analysis has been conducted to study several systems in real installations.

The theoretical, experimental and field measurements analysis showed that well designed carbon dioxide systems has about 5-10% higher efficiency than a conventional HFC system. Recovering heat from the carbon dioxide system is an interesting possibility and can lead to about 6% reduction in annual energy use. These findings contributed to increased interest and spread of CO2 systems for supermarkets in Sweden.

The strive for more efficient and cost effective energy solutions for supermarkets is a continuous process; therefore, recent years witnessed several attempts to improve the efficiency of the CO2 refrigeration system by introducing system modifications and higher level of integration into heating and air conditioning systems in the supermarket. Some key features that came into attention are:

- Heat recovery at multiple temperature levels
- Providing air conditioning by the refrigeration system
- Parallel compression
- Seasonal thermal storage using the ground
- System control for highest efficiency
- Ejector solution

The research in this project answers the questions on how the modifications will influence the performance of the CO2 refrigeration system. Therefore, the most efficient and cost effective solution that covers all the thermal energy needs in the supermarket can be suggested with detailed energy performance characterization, the system is called the state-of-the-art solution.

The development in the area of supermarket's energy systems have been accelerating in the past years with new system solutions and refrigerants emerging all the time. This is why it is important to evaluate the performance of the state-of-the-art system against conventional systems and the key emerging alternatives.

This research work is especially important at this stage due to the recent EU F-gas regulations which will practically ban installing systems with HFC's in supermarket application starting from 2020,. The systems that will replace the HFC conventional solutions in future installations should be energy efficient and environmentally friendly. This project provides the most competitive system to replace the conventional solutions and puts pressure on other alternative technologies to be more efficient and environmentally friendly.

2 Implementation

The investigations in this project have been based on computer simulation modelling and analysis of field measurements from number of supermarkets in different places in Sweden. The software that has mainly been used in writing the calculation codes is Engineering Equations Solver (EES) [1]. The calculation codes were written by the researchers in the project, but mainly by the PhD student, Mazyar Karampour. The results of the theoretical models have been verified by comparing to reference cases in earlier research work done at KTH, it have also been compared to international research results and commercial calculation tools. Theoretical simulation results and the details of the modelling procedure are included in each of the journal publications attached to this report.

The data from the field measurements have been obtained via data acquisition systems, such as IWMAC[2] and LDS[3]. The analyzed supermarkets in this project have already been equipped with instrumentations for monitoring where it was also possible to download the data over the internet for time steps of about few minutes over years of operation. The downloaded data has then been processed in Excel templates prepared in this project. The field measurement analysis procedure has been explained in details in Paper I, paper II, and paper II.

In parallel, extensive literature review has been continuously conducted and updated, which can be clearly seen in the project publications.

The first two journal papers in this project (Paper I and Paper II) are based on the field measurements work that has been conducted in the project: “Field Tests of Supermarket Refrigeration Systems”. The project was co-financed by the Swedish Energy Agency and managed by IUC-SEK/Katrineholm. Extensive analysis of data of 11 supermarkets has been carried out, the project was concluded in 2011 but the valuable field measurement results were not published during the project period.

The work in the first two papers defined and characterized the energy performance of the standard CO2 system (reference), which has been used for comparison in the later stages in the project Most of the computer models that have been used in the first two papers to calculate the energy performance and the annual energy use have been developed within the activities of this project.

[1] S.A. Klein, Engineering Equation Solver (EES) V9, Fchart Software, Madison, USA, 2006. www.fchart.com.
[2] IWMAC, IWMAC, Centralized Operation and Surveillance by Use of WEB Technology, 2011. www.IWMAC.eu.
[3] LDS, Long Distance Service, Computer Software for Handling Data from Field Measurements, 2011.

The analysis in the third journal paper is based on field measurements data for an integrated system solution. The system is also modelled and compared with stand-alone HFC-based energy systems.

The fourth and fifth journal papers are based on modelling that uses the data from field measurements to support the assumptions of the key input parameters and to generate the energy load profiles.

The principal researcher in this project has been the PhD student Mazyar Karampour. Project leader and principal supervisor has been Samer Sawalha. Jaime Arias is an associate professor at the Energy Technology department who provided key calculations for energy load profiles using in-house calculation tool. Jörgen Rogstam from our partner Energi & Kylanalys supported in communicating with the partners to provide access to key installations, especially for the geothermal analysis. All the industrial partners in the project helped in providing access to field installations, engaged in discussions and provided valuable feedback on the research results.

Carlos Mateu-Royo is an exchange student who did his master thesis on the geothermal integration into supermarket's energy system. Adnan Ribic is another exchange student who did his master thesis studying the first CO2 system with ejector in Sweden.

3 Results

The results from the work in this project are summarized in the following sections which follow the sequence of the five journal papers produced during the project period. Much more details on the research work and the results can be found in the journal papers in the appendix.

Most of the research work presented in the first two papers has been conducted in the earlier projects on supermarkets funded by the Swedish Energy Agency, the projects titled:

Field Tests of Supermarket Refrigeration Systems", the project was managed by IUC-SEK. Extensive analysis of data of 11 supermarkets has been carried out. Concluded in 2011.

Comprehensive evaluation of refrigeration and heating systems in supermarkets, Effsys+ EP06". The project was run by KTH's and concluded in 2014.

The modelling tasks and writing of the first two papers have been conducted in this project where the results have been used as verified reference cases to be compared to in this project.

The third paper investigated via field measurements and modelling the modifications that are applied to the reference CO2 system. The energy performance of the modified (i.e. newer) system was compared to the reference solution.

The fourth paper theoretically studied the latest features, except geothermal, that can be applied to the CO2 refrigeration system for supermarkets where the most efficient and cost effective solution has been conclude and referred to as state-of-the-art system. The system has been compared to reference systems and emerging alternatives.

The fifth paper investigated the potential of using the ground as a heat source and for thermal storage in connection to the state-of-the-art system.

The first four papers are already published; however, the fifth one is in a well-developed draft which will be submitted in the near future to the International Journal of Refrigeration.

3.1 Paper I: Characterizing the performance of reference CO2 systems for supermarket refrigeration

Despite the high number of CO2 system installations in supermarkets in Sweden, which are usually well equipped with measurements, detailed analysis of their performance is missing where losses and potential improvements in the system can be investigated. This study investigates the refrigeration performance of three CO2 trans-critical solutions based on field measurements where the measurements were carried out in five supermarkets.

3.1.1 Existing CO2 Systems Description

At the early stages of applying CO2 in supermarket refrigeration, the two main CO2 system solutions that have been applied are the parallel and booster arrangements. As can be seen in Figure 1 the parallel solution consists of two separate circuits; one serves the medium temperature level cabinets and the other serves the freezers. Direct expansion (DX) is applied on both temperature levels. Two-stage compression is used for the low temperature level circuit. Since the temperature lift is relatively small on the medium temperature circuit then single stage compression is used.

In the booster system solution, similar to the units denoted as BO in Figure 2, the discharge of the booster compressor; i.e. low-stage compressor, merges with the superheated vapor exiting the medium temperature cabinets and the mixture enters the high stage compressor.

The systems analyzed in this paper are:

CO2 trans-critical system 1 (TR1)

The TR1 supermarket is located in the north of Sweden and has been open since autumn 2007. The estimated maximum compressor cooling capacity is 230 kW for medium temperature level and about 60 kW for low temperature level.

In this system there are four separated trans-critical units, two for the medium temperature cabinets and two for the low temperature. Each medium temperature unit is equipped with four single stage compressors. Each low temperature unit is equipped with 2 two-stage compressors.

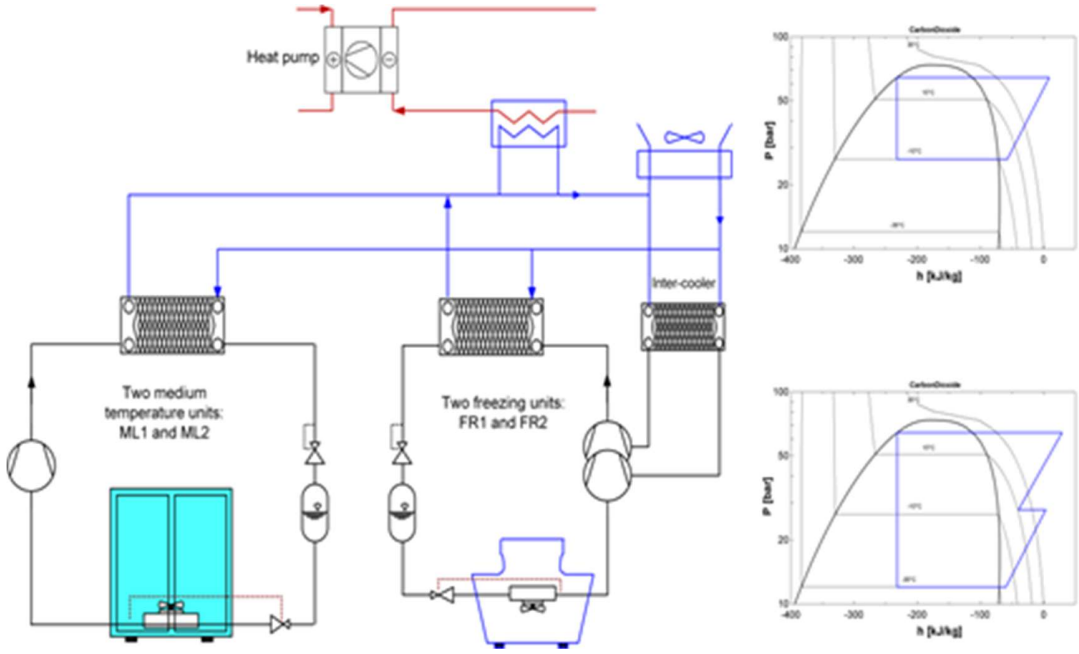


Figure 1: A simple schematic diagram of TR1 system (left) a sample P-h diagram for medium temperature stage (top-right) a sample P-h diagram for low temperature stage (bottom-right)

CO2 trans-critical systems 2 and 3 (TR2 and TR3)

The supermarket TR2 is located in the south-western coast of Sweden and has been open since august 2008. The maximal compressor cooling capacity is about 210 kW medium temperature level and about 70 kW for low temperature level. Figure 2 is a schematic of the TR2 system. There are three separated trans-critical units, two booster types (denoted as BO1 and 2) for the medium and low temperature cabinets with a load ratio (i.e. ratio between cooling capacities at medium and low temperature levels) of about 2, and one single stage unit for the rest of the medium temperature cabinets. Each booster unit has three compressors at the medium temperature level and two booster compressors. The separate medium temperature unit has four single stage compressors.

As can be observed in the schematic in Figure 2, heat is recovered from the refrigeration system through the de-superheaters for the use in space heating. The refrigeration system is sub-cooled by being connected to a ground source heat pump loop. The rest of the heat from the system is rejected directly to ambient.

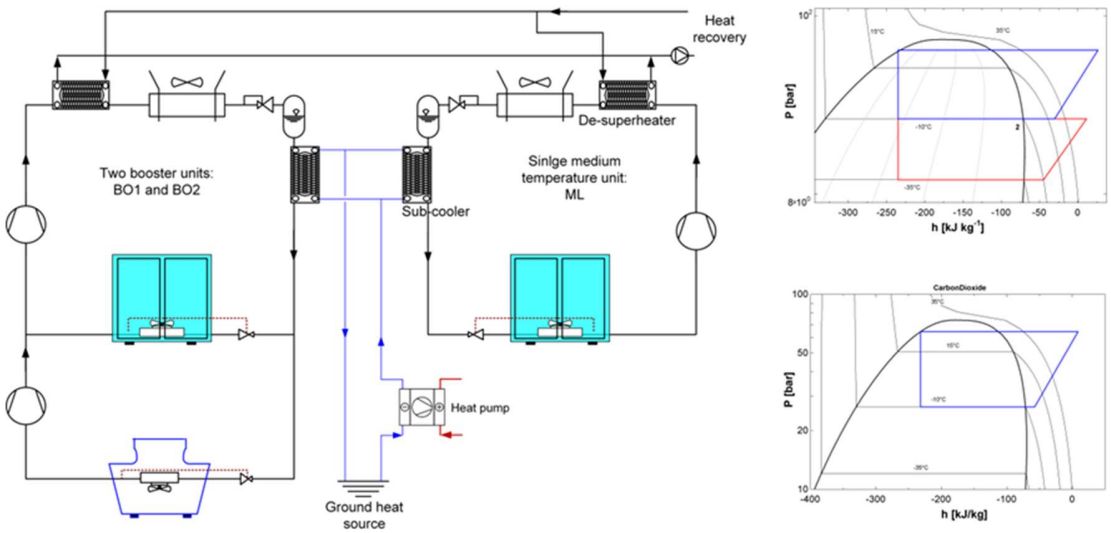


Figure 2: A simple schematic diagram of TR2 system (left) a sample P-h diagram for two stage booster unit (top-right) a sample P-h diagram for single medium temperature stage (bottom-right)

The supermarket TR3 is located in the south-western coast of Sweden and has been open since February 2010. The estimated maximum compressors cooling capacity is about 230 kW for the medium temperature level and about 60 kW for low temperature level. TR3 has two separate booster units similar to the units BO1 and BO2 in Figure 2, the system does not have ground source sub-cooling as in the case of TR2. One booster unit has four compressors at the medium temperature level and the other has five. Each unit has two booster compressors. As in the case of TR2 heat is recovered from the system via a de-superheater. The rest of the heat is rejected directly to the ambient.

CO2 trans-critical systems TR4 and TR5

TR4 and TR5 are booster systems that are similar in design concept but mainly differ in capacity and location. A simple schematic of the booster solution applied in systems TR4 and TR5 is presented in Figure 3.

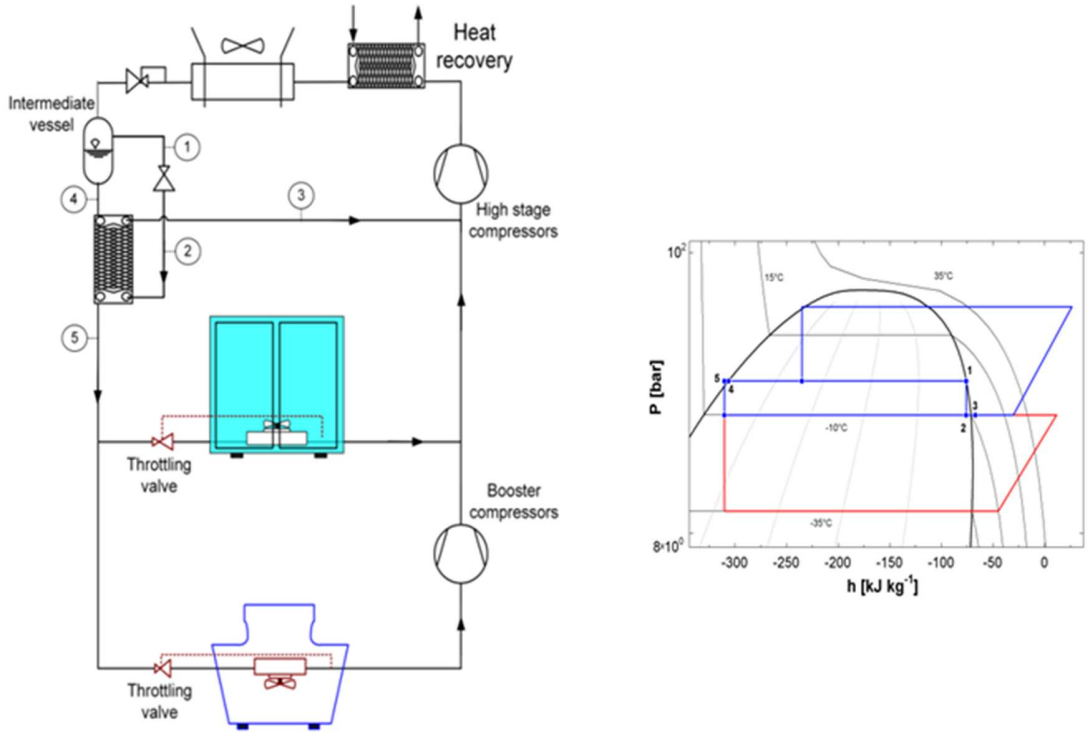
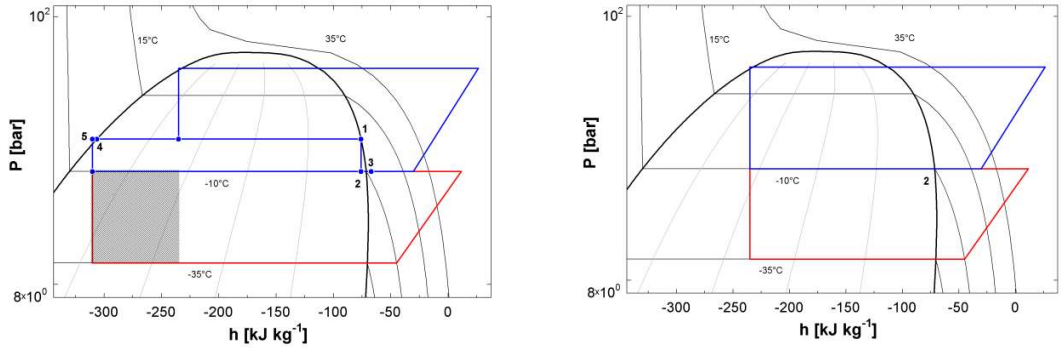


Figure 3: A simple schematic diagram of TR4 and TR5 systems (left) a sample P-h diagram (right)

The main difference between this solution and the booster system applied in TR2 and TR3 is the removal of the gas from the intermediate vessel which is then expanded in a heat exchanger to evaporate the liquid formed after the expansion, at the same time sub/further-cool the liquid before the expansion valves.

The removal of the gas from the intermediate vessel will reduce the throttling losses in the low stage cycle. The improvement on the cycle can be observed in the process plot in the P-h diagram in Figure 4a by the highlighted area. The booster system without the gas removal from the intermediate vessel will have the process plotted in Figure 4b.



a b

Figure 4: Plots of the processes of booster systems with (a) and without (b) gas removal from an intermediate vessel

It can be observed in Figure 4a that the achieved sub-cooling (point 4 to 5) is small, the calculation in this case is done for a Load Ratio (LR) of 3. The sub-cooling effect is expected to be small due to the relatively small vapor flow and the small temperature difference across the heat exchanger.

The two systems TR4 and TR5 are located in the southern part of Sweden, on the southwest and southeast coasts. Both systems have been in operation since the beginning of May 2010.

The maximal compressor cooling capacity in TR4 is about 25 kW for the medium temperature level and about 6 kW for low temperature level. TR5 is larger system with capacities of 130 and 30 kW at the medium and low temperature levels respectively. Each system consists of a single booster unit.

3.1.2 CO2 Systems Comparison

The medium temperature level COP's of the different systems are plotted against the condensing temperatures, in Figure 5, where the evaporation temperature for each system is indicated at the corresponding legend. Comparing the systems at the same condensing temperature will eliminate the influence of the temperature difference between condensing temperature and outdoors at the heat rejection side. System TR1 is the only system that has a coolant loop at the heat rejection side, as seen in Figure 1, which means that it will have higher condensing temperature than the rest of the systems when the systems are not controlled for heat recovery.

If the systems are controlled to recover heat then the discharge pressure and the corresponding condensing temperature at low outdoor temperatures will depend on the heating capacity needed to be extracted from the system, which will influence the cooling COP of the system. This will make it difficult to compare the cooling COP of the different

systems based on the outdoor temperatures, this is why the condensing temperature is used instead of outdoors temperature.

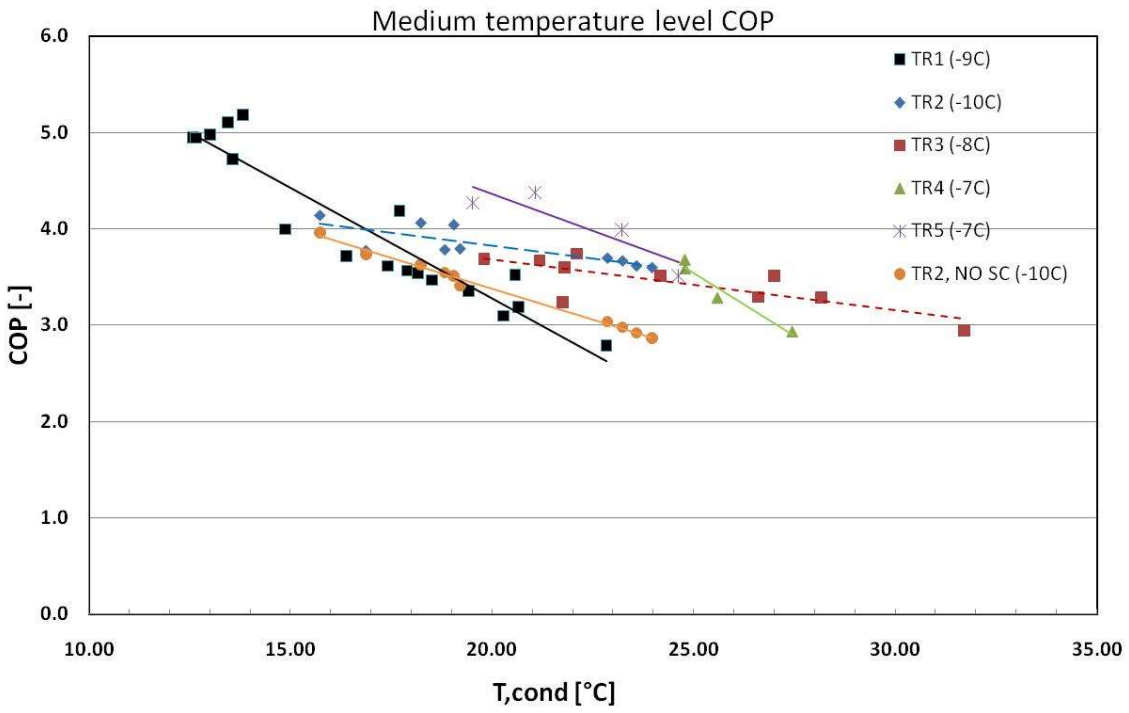


Figure 5: Medium temperature level COP's at different condensing temperatures for all systems. Evaporation temperature for each system is indicated at the plot's legend.

Based on the plots in this figure and on the design of the systems and their performances, they can be divided into three groups; "TR1", "TR2 and TR3", and "TR4 and TR5". It can be observed that the system TR1 operates in a relatively low condensing temperatures though it has coolant loop at the warm side, this is mainly because it is installed in a location in the north of Sweden which is relatively cold and it is also not controlled for heat recovery.

Systems TR4 and TR5 on the other hand have been analyzed during a relatively warm period of the year, June to September, and they are located in the south of Sweden not far away from each other.

The difference in condensing temperatures between TR4 and TR5, observed in Figure 5, is due to better performance of the condenser/gas cooler in TR5; approach temperature difference is 1-2K compared to around 4K in case of TR4.

TR4 and TR5 have relatively high medium temperature COP compared to TR1. This can be attributed to several factors such as the lower internal superheat, higher efficiency of

medium temperature compressor, and higher evaporation temperature. External superheat is comparable between these three systems; around 8-9K.

As can be observed in Figure 5, the systems TR2 and TR3 have comparatively high COP at high condensing temperatures, i.e. the systems do not have the same drop in COP as in the cases of TR1, TR4 and TR5 with increasing condensing temperature. The reasons are mainly due to the use of the borehole sub-cooling in system TR2 and sub-cooling in the condenser/gas cooler in TR3. This is done in both systems when operated in the heat recovery mode. If the system TR2 is calculated without including the influence of the borehole sub-cooling then the plot labeled as “TR2, NO SC (-10C)” in Figure 5 can be observed to be at similar level to TR1 system.

Sub-cooling the supermarket refrigeration system by using a borehole is not a conventional solution therefore the improvements in COP in TR2 compared to the other systems can be argued to come from special system boundaries and not related to the refrigeration system solution. However, the system TR3 uses the cold ambient air to sub-cool the refrigerant in the heat recovery mode; up to 25K of sub-cooling can be observed. This control strategy of TR3 in heat recovery mode results in comparable COP to the system TR2 with borehole sub-cooling.

Similar trends of the medium temperature level COP’s can be observed for the low temperature level COP’s in Figure 6. The system TR1 has higher low temperature level COP than TR2 system without the influence of the borehole sub-cooling; this is mainly due to the heat removal from the inter-cooler in TR1 at the intermediate pressure level in the two-stage compressor, that can be seen in the schematic of units FR1 and FR2 in Figure 1.

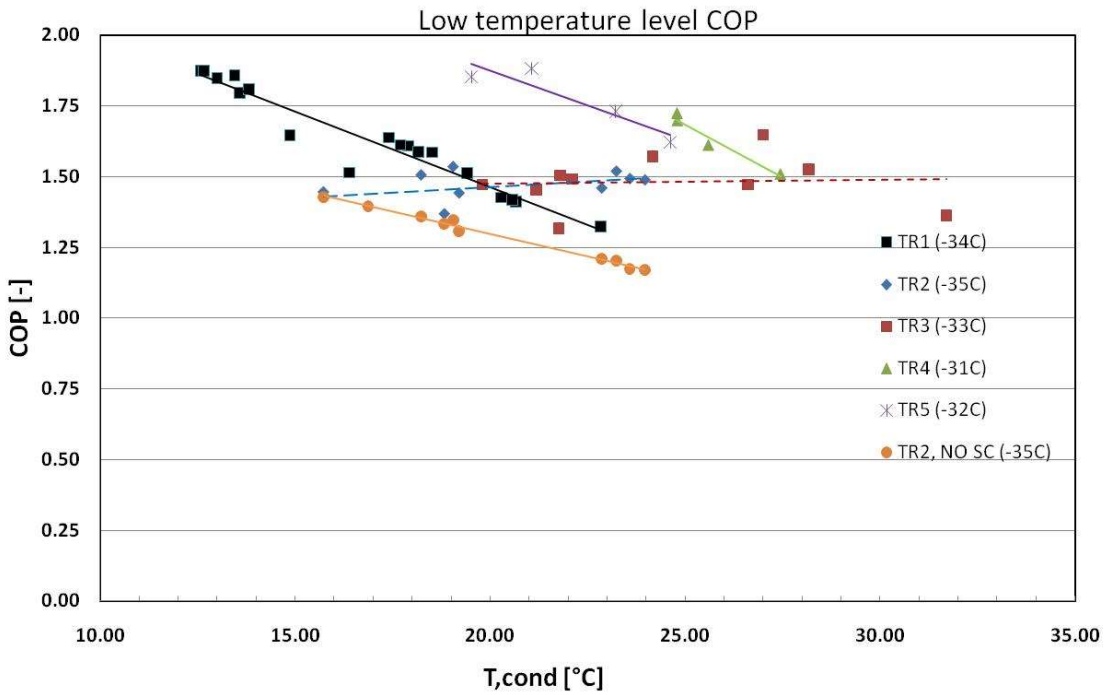


Figure 6: Low temperature level COP's at different condensing temperatures for all systems. Evaporation temperature for each system is indicated at the plot's legend.

The system solution applied in TR4 and TR5 shows the highest low-temperature level COP. Some of the reasons that can explain the relatively higher COP are: the higher evaporation temperature, low internal and external superheat, and the higher total efficiency of the booster compressors compared to the ones installed in TR2 and TR3; about 60% compared to 45%.

Another main reason that contributes to the higher low temperature level COP in the solution applied in systems TR4 and TR5 is the removal of the gas from the intermediate vessel which reduces the throttling losses in the low stage cycle.

In the systems TR2 and TR3, the sub-cooling effect on increasing the low temperature level COP at high condensing temperatures in heat recovery mode can be observed.

Combining the medium and low temperature levels COP's in a total COP with load ratio of 3 results in the plots presented in Figure 7.

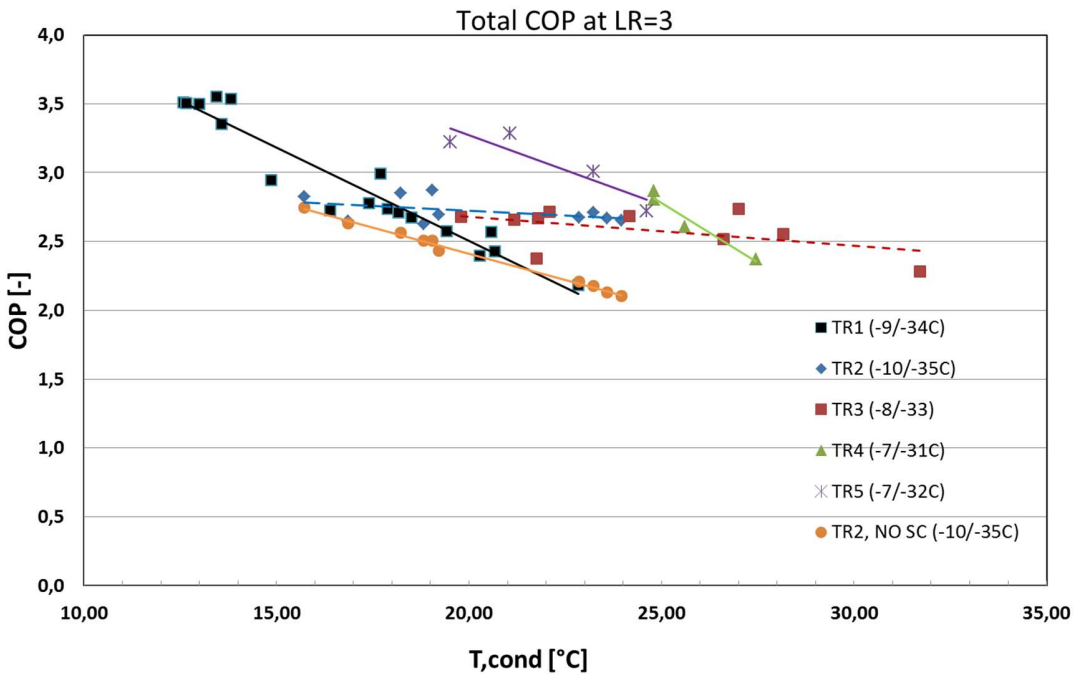


Figure 7: Total COP's at different condensing temperatures for all systems. Evaporation temperatures at medium and low levels for each system are indicated at the plot's legend.

It has to be observed that the systems have different average evaporation temperatures which are indicated at the plots' legends. The solution applied in systems TR4 and TR5 has the highest total cooling COP at most of the operating range; however, TR3 has higher COP at high condensing temperatures (i.e. discharge pressure) where high degrees of sub-cooling are achieved using the cold ambient air. It has to be noticed that the systems TR4 and TR5 were not tested during the winter period where heat recovery will be needed in relatively high capacities and then the sub-cooling effect on system improvement can be observed.

3.1.3 Conclusions of Paper I

Field measurements of five supermarkets using three different CO2 trans-critical solutions were analysed for periods of 4 to 18 months. It has been observed that the running mode of the systems (floating condensation or heat recovery) and the amount of sub-cooling have a significant impact on system performance. Higher sub-cooling provides higher cooling COP at certain cooling capacity. This can be clearly seen in the results of systems TR2 and TR3 in running in the heat recovery mode.

Systems TR4 and TR5 using transcritical booster system with gas removal from the intermediate vessel have the highest total COP. Gas removal from the intermediate vessel leads to higher low temperature level COP. Other reasons for this higher energy

efficiency are 1-3K higher evaporation temperatures, lower internal and external superheat, and 10-15% higher total efficiency of booster compressors compared to TR2 and TR3. These parameters highlight the importance of suitable control for internal superheating, good insulation to reduce external superheating and using compressors with highest efficiency available.

Analyzing the performance of these five CO2 supermarket refrigeration systems indicates a trend of improvement in energy efficiency by up to 35-40% higher total COP comparing TR4-TR5 with TR2-TR3 or TR1, as TR1 is the oldest system installed (2007) and TR4 and TR5 are the newest ones (2010).

3.2 Paper II - Comparing reference CO2 system to conventional

This part of the study investigates the performance of HFC refrigeration systems for supermarkets and compares the performance with CO2 trans-critical solutions. The investigated HFC system solutions are typical in supermarkets in Sweden. The analysis in this study is based on field measurements which were carried out in three supermarkets in Sweden. The results are compared to the findings from Paper I where five CO2 trans-critical systems were analyzed.

Using the field measurements, low and medium temperature level cooling demands and COP's are calculated for five-minute intervals, filtered and averaged to monthly values. The different refrigeration systems are made comparable by looking at the different COP's versus condensing temperatures. The field measurement analysis is combined with theoretical modelling where the annual energy use of the HFC and CO2 trans-critical refrigeration systems is calculated.

3.2.1 HFC Systems description

The three HFC systems analyzed in this paper are variations of the same technical solution which is presented in a simple schematic in Figure 8. The system consists of two parallel refrigeration units; one serves the medium temperature level (ML) cabinets and the other serves the low temperature level cabinets; i.e. freezers (FR). Cooling is provided to the ML cabinets by a heat transfer fluid (referred to as brine in this paper) in indirect loop arrangement, while direct expansion (DX) is applied on the freezers. The liquid after the condenser is sub-cooled on both ML and FR units with the use of a separate heat exchanger; denoted as sub-cooler. The two refrigeration units are not completely isolated, since the FR unit is sub-cooled by the brine at the ML level.

ML and FR units are equipped with internal (or suction line) heat exchangers (IHE) to provide further sub-cooling in the liquid line by superheating the relatively cold vapor at the compressor's suction line. Electronic expansion valves are used in the ML cabinets while thermostatic expansion valves are used in the freezers.

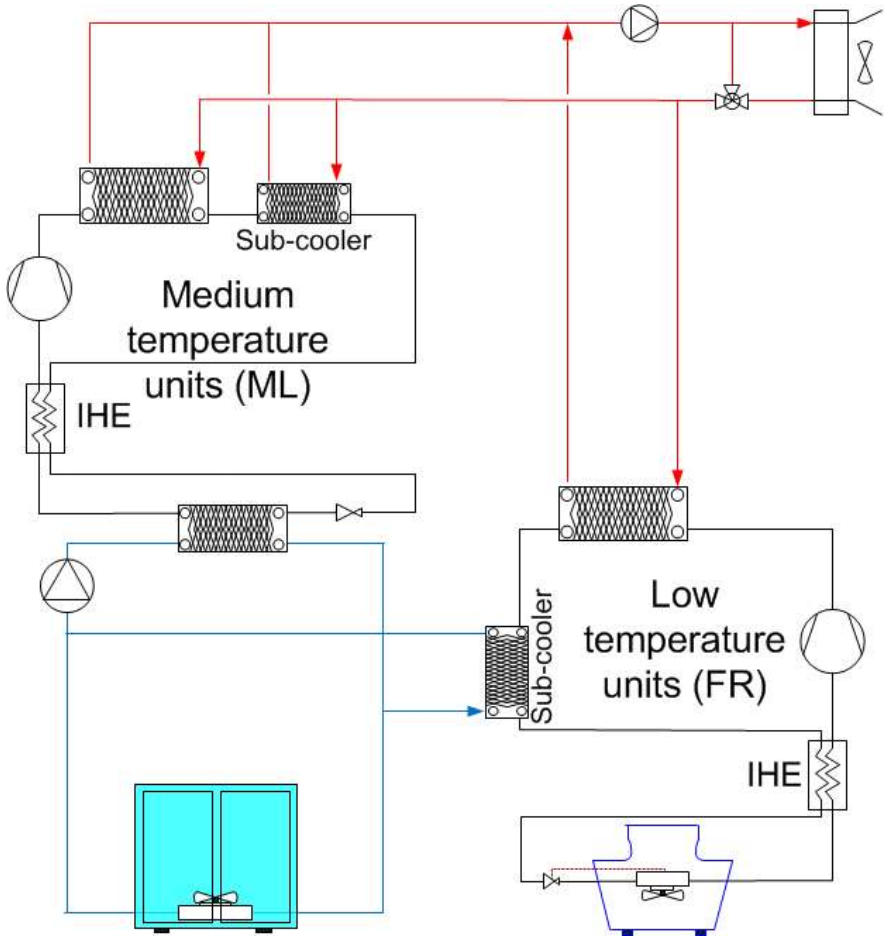


Figure 8: A simple schematic diagram of the reference refrigeration system (RS), valid for the three cases studies: RS1, RS2, and RS3.

The three supermarket refrigeration systems in this study are typical solutions in Swedish supermarkets; therefore, they are referred to as Reference Systems 1, 2 and 3, denoted as RS1, RS2 and RS3. The systems are located at different sites in Sweden. RS1 is in the small town of Arvidsjaur which is in the north of Sweden. RS1 is in operation since October 2008 with design cooling capacities of 87 and 18 kW for ML and FR units respectively; both ML and FR units use R404A as refrigerant. Two frequency controlled compressors operate in tandem in both ML and FR units.

The supermarket RS2 is placed in Tumba-Stockholm and in operation since October 2008. The design cooling capacity is 175 kW at ML and 36 kW at FR. RS2 refrigeration system consists of four units. Two units for ML with R407C as refrigerant, each ML unit has two frequency controlled compressors working in tandem. The other two units work with R404A and serve the freezers; each unit has a single frequency controlled compressor.

RS3 has been running since March 2008 in Birsta-Sundsvall, in the center-east part of Sweden. RS3 is the largest of the three HFC systems in this study with cooling capacities of 410 and 81 kW for ML and FR respectively. RS3 has two ML units using different type of refrigerant; R404A and R407C. Each unit has two frequency controlled compressors working in tandem. The freezers are served by two R404A units with a single frequency controlled compressor.

RS3 is the only system in this study that has the heat recovery function; where a heat pump is connected to the indirect loop at the condensers. However, the pressure of the high stage in the refrigeration units in RS3 is controlled in floating condensation mode; the heat recovery does not contribute to extra power consumption in the refrigeration cycle.

3.2.2 HFC system comparison

The different COP's of RS1, 2 and 3 are plotted against the condensing temperatures, in the following figures, where the average evaporation temperature for each system is indicated at the corresponding legend. Comparing the systems at the same condensing temperature will eliminate the influence of the temperature difference between condensing temperature and outdoors at the heat rejection side. This will bring focus on the performance of the refrigeration system.

COP at medium temperature level (COP_{ML}) for the three reference systems are plotted in Figure 9 against the condensing temperatures.

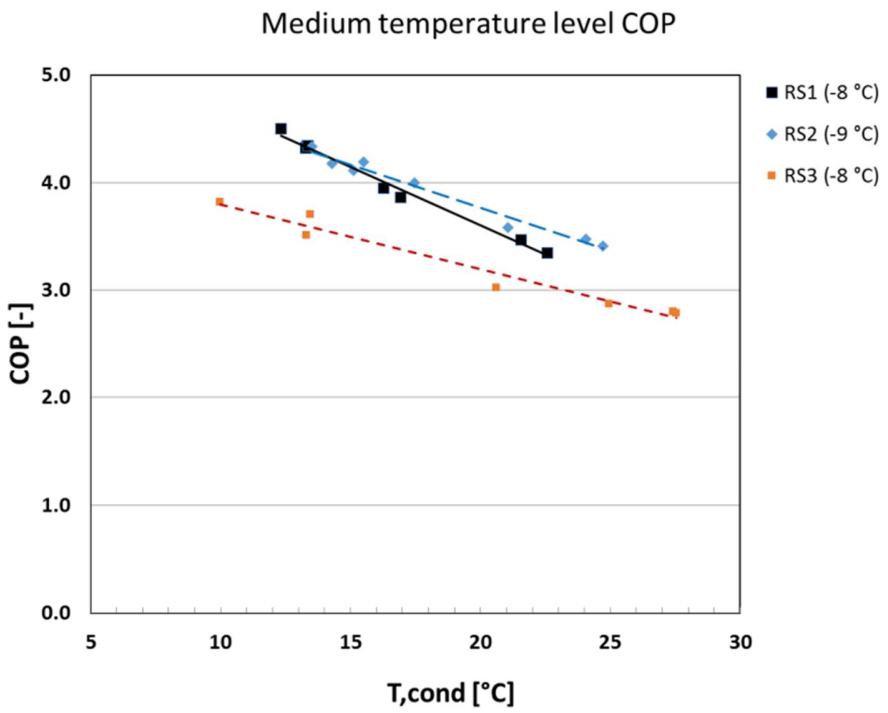


Figure 9 – COP_{ML} at different condensing temperatures for RS1, 2 and 3. Evaporation temperature for each system is indicated at the plot's legends.

It can be observed in Figure 9 that RS1 and RS2 have similar COP_{ML} values while RS3 has lower by about 14-20%, which can be attributed to the high electric power consumption of the circulation pumps at condenser and evaporator loops consumed in RS3; 12kW in total compared to 3kW for RS1 and 6KW for RS2. This corresponds to 20, 18 and 24% of overall compressors power for RS1, RS2 and RS3 respectively at condensing temperature of about 25◦C.

Low temperature (freezers) COP (COP_{FR}) is plotted versus the condensing temperature for the three systems in Figure 10.

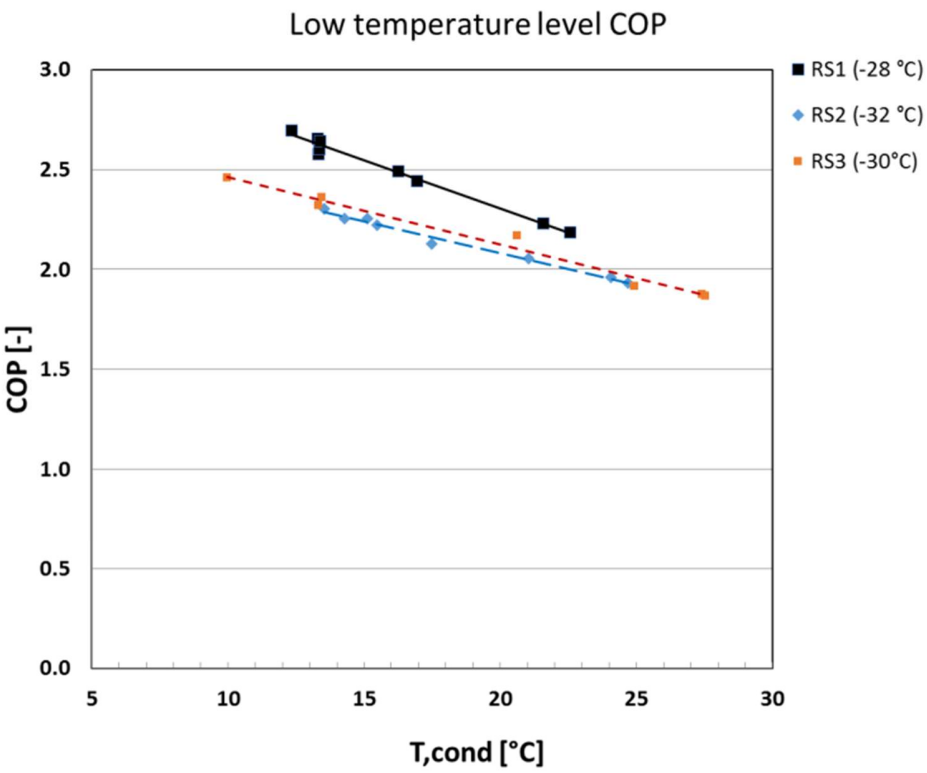


Figure 10 – COP_{FR} at different condensing temperatures for RS1, 2 and 3. Evaporation temperature for each system is indicated at the plot's legends.

It can be observed in Figure 10 that the RS1 has the highest COP_{FR} which is mainly due to the higher average evaporation temperature compared to RS2 and RS3. It can be also observed that despite the higher evaporation temperature in RS3 compared to RS2, still COP_{FR} for both systems are quite similar; the reason for this is related to the higher pumping power in RS3.

Combining the COP_{ML} and COP_{FR} in a total COP for load ratio of 3 results in the plots presented in Figure 11.

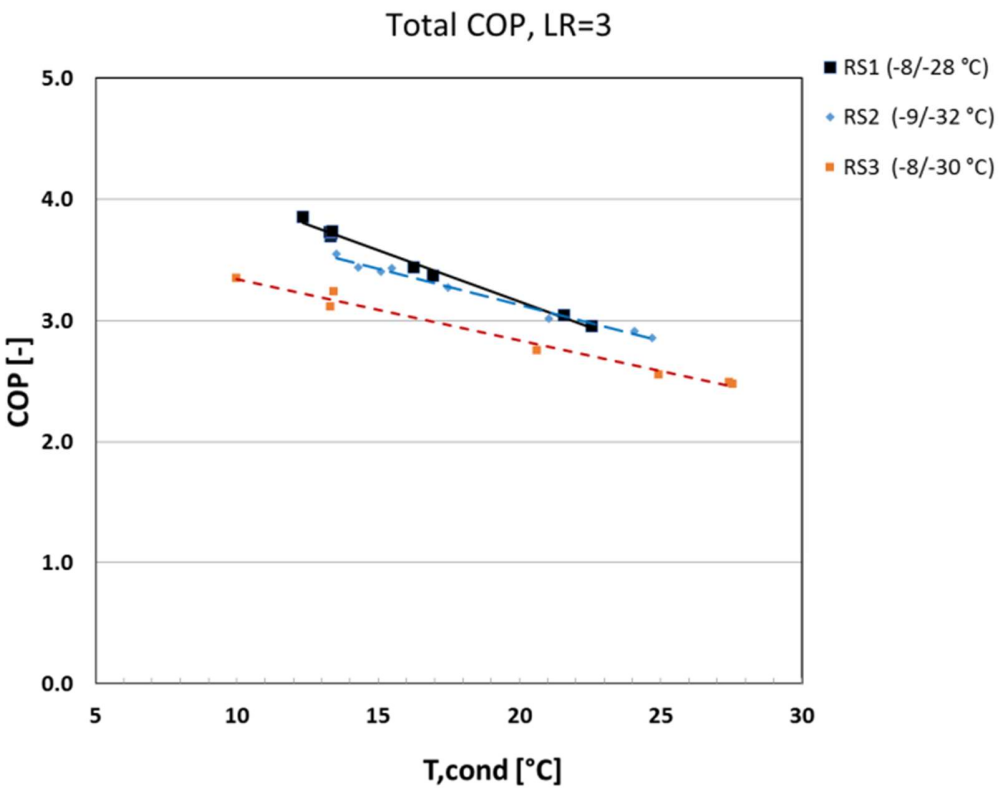


Figure 11 – COP_{tot} at different condensing temperatures for RS1, 2, and 3. Evaporation temperatures at ML and FR for each system are indicated at the plot's legends.

The reference systems have similar design and the boundary conditions are comparable, this is why the systems have comparable COP_{tot} values as can be observed in Figure 11. The main reason for the lower COP_{tot} value for RS3 is the relatively lower sub-cooling in the ML units and the higher pumping power as result of an installed capacity much higher that the measured cooling loads.

3.2.3 Comparison between HFC and CO2 refrigeration system

Field measurement results

The CO2 trans-critical systems discussed in Paper I are referred to as TR1, TR2 (NO SC), TR3, TR4, and TR5. TR3 has been excluded from the comparison because it had strong effect of sub-cooling in heat recovery mode, especially at high discharge pressures, which makes a direct comparison with HFC systems inconclusive.

COP_{ML} and COP_{FR} for all the RS and TR systems are comparable since the definition of the COP is the same; it is the ratio of the cooling demand (at ML or FR) to the electric power consumed to provide the cooling demand. The necessary energy balance

calculations have been made for the different system groups to fulfill this definition. COP_{tot} is calculated for a load ratio of 3 ($COP_{tot,LR=3}$).

COP_{ML} at different condensing temperature for all systems are plotted in Figure 12. Since the results of RS's discussed in the previous section show comparable results the three systems are presented in this section as single system (denoted as RS123) with a range of COP covering the points presented in previous section. The main reason for such presentation format is to have an easy visual presentation of the results since the number of systems presented in the plot is large.

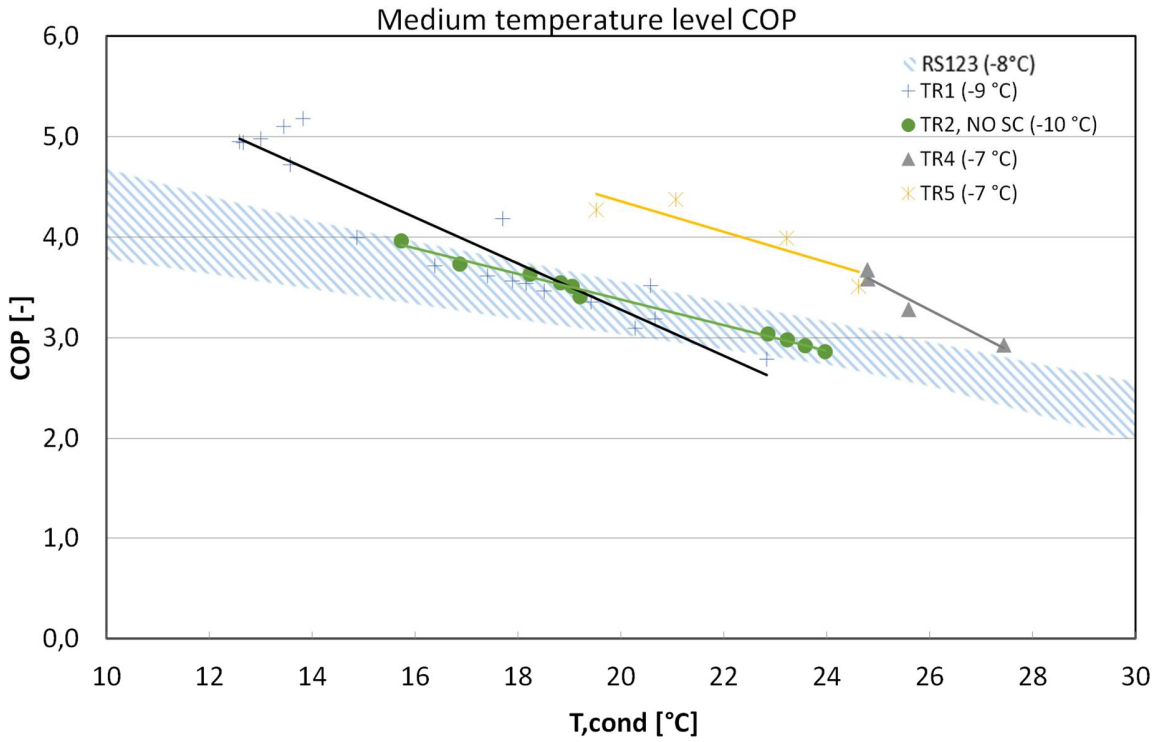


Figure 12 – COP_{ML} at different condensing temperatures for CO2 systems compared with the three RS's (RS123). Evaporation temperature for each system is indicated at the plot's legends.

It can be observed in Figure 12 that the relatively new CO2 systems, TR4 and TR5 have higher COP_{ML} than RS123 for condensing temperatures lower than about 25°C. The older systems TR1 and TR2,NO SC have generally comparable or lower COP_{ML} than RS123, except for condensing temperature lower than 15-16°C where TR1 and TR2,NO SC have higher COP_{ML}.

COP_{FR} for all systems at different condensing temperatures are plotted in Figure 13. It can clearly be observed in the plot that RS123 has much higher COP_{FR} than all the TR systems.

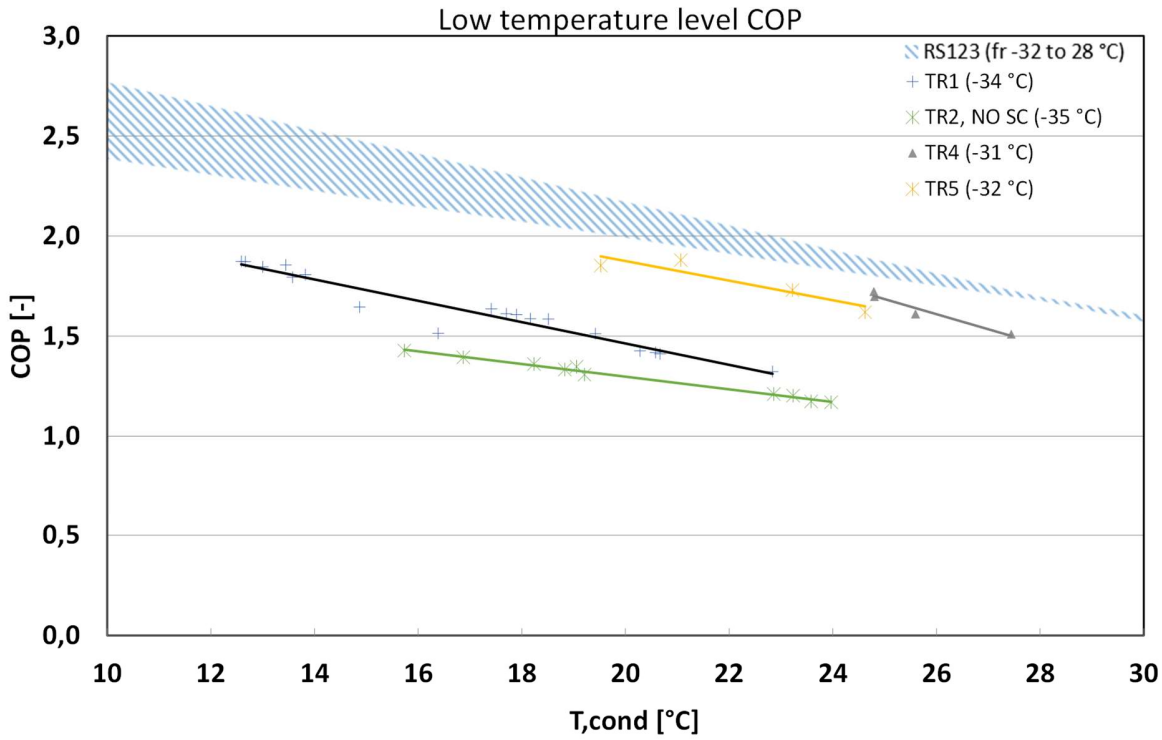


Figure 13– COP_{FR} at different condensing temperatures for CO2 systems compared with the three RS's (RS123). Evaporation temperature for each system is indicated at the plot's legends.

A main reason for the high COP_{FR} for RS123 is the use of ML unit to sub-cool the FR unit, resulting in quite low temperature (-3 to -2°C) of the liquid line before the IHE in the FR unit, this applies to all RS's. The obtained sub-cooling in FR units from the ML units varies between 12 and 30K in RS's, which depends on the condensing temperature.

Using COP_{ML} and COP_{FR} to calculate $COP_{tot,LR=3}$ results in the plots in Figure 14.

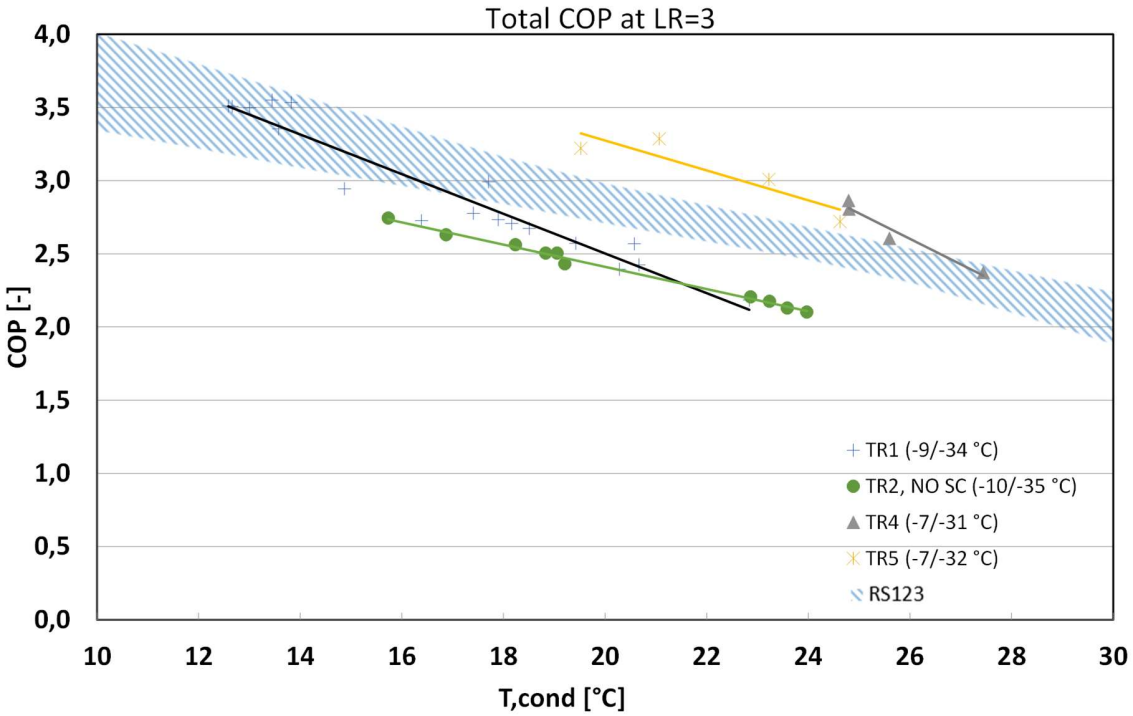


Figure 14 – COP_{tot} at different condensing temperatures for CO2 systems compared with the three RS's (RS123). Evaporation temperatures at medium and low levels for each system are indicated at the plot's legend.

The dominant effect on COP_{tot} at load ratio of 3 is the COP_{ML} where TR4 and TR5 have relatively high values, which is reflected on the results of $COP_{tot,LR=3}$. TR4 and TR5 have higher $COP_{tot,LR=3}$ at condensing temperatures lower than about 25°C. TR1 and TR2 (No SC) have generally lower $COP_{tot,LR=3}$ than RS123.

Modelling results

In order to calculate the annual energy use of CO2 systems and RS computer models have been developed. The computer models calculate the COP of the systems at different outdoor temperatures. The three systems that have been modelled are: RS, CO2 system in old installations, and CO2 system in new installations. The modelled RS represents the three reference systems presented in this paper, the older CO2 system represents the solution in TR1 and TR2 (NO SC) systems, and the newer CO2 systems represents the solution in TR4 and TR5 systems.

The calculated COP_{tot} for the three systems at different condensing temperatures are plotted in Figure 15. COP_{tot} from the field measurements for RS123 are also plotted.

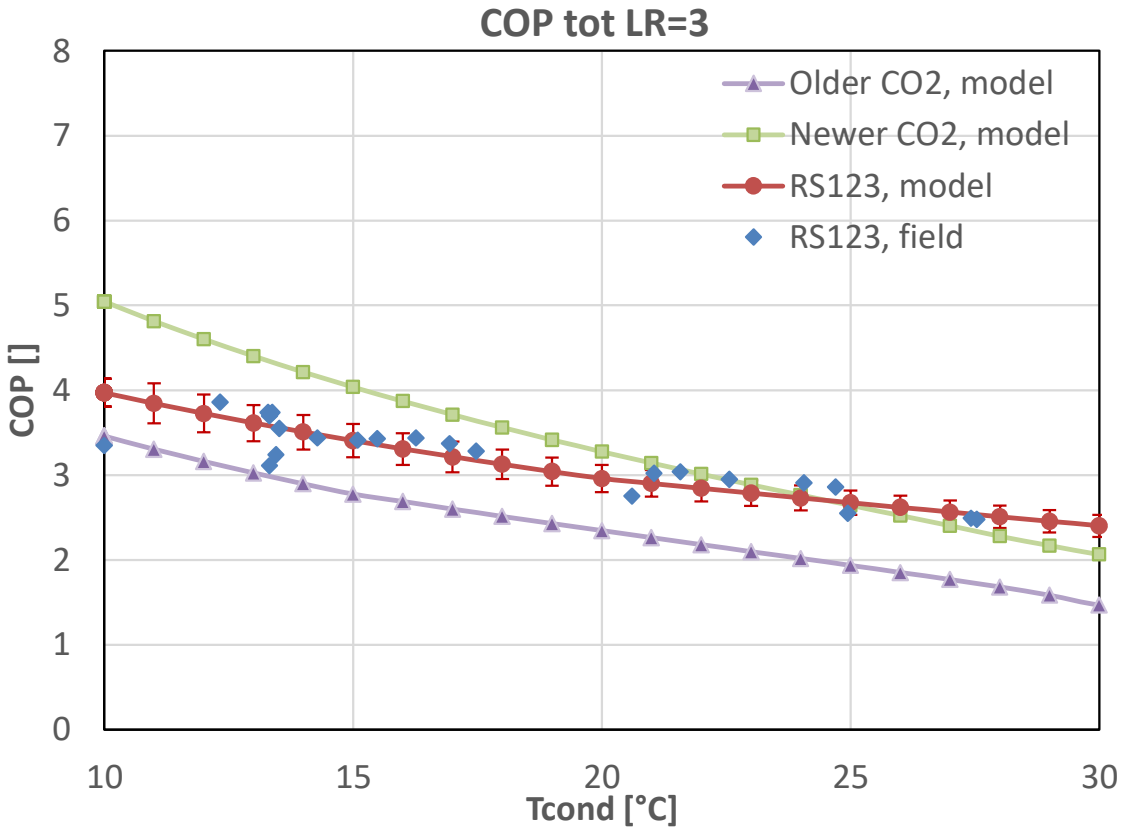


Figure 15 – Plots of calculated $COP_{tot,LR=3}$ of older CO2 systems, newer CO2 systems, and RS. Field measurement values for RS123 are also plotted.

As can be observed in the plots in Figure 15 good agreement is evident between the modelled and field measurement's COP_{tot} for RS123. It can also be observed that the older CO2 systems have lower efficiency than RS at all modelled condensing temperatures. However, the newer CO2 system solutions have higher COP_{tot} than RS at condensing temperatures lower than about 24°C.

Based on the field measurement data, 5K can be assumed as temperature difference between condensing and outdoor temperatures for CO2 systems. However, for RS, 10K is assumed due to the use of indirect loop for heat rejection; i.e. brine loop connecting the condenser and the dry cooler, as can be observed in the schematic in Figure 8. COP_{tot} at load ratio of 3 for newer CO2 systems and RS versus outdoor temperatures are plotted in Figure 16. COP_{ML} and COP_{FR} versus outdoor temperatures for the same systems are plotted in Figure 17. Minimum condensing temperatures for both systems in this calculation is assumed to be 10°C.

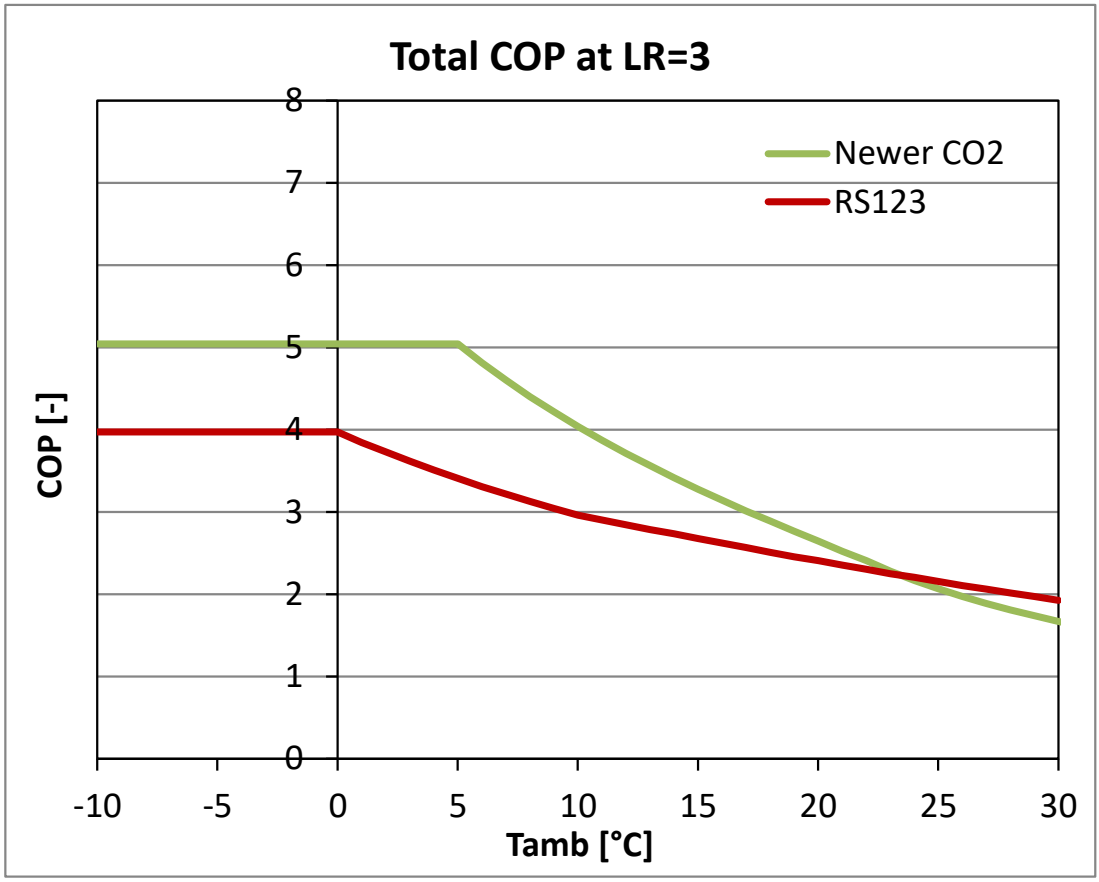


Figure 16 – $COP_{tot,LR=3}$ versus outdoor temperatures for newer CO2 systems and RS

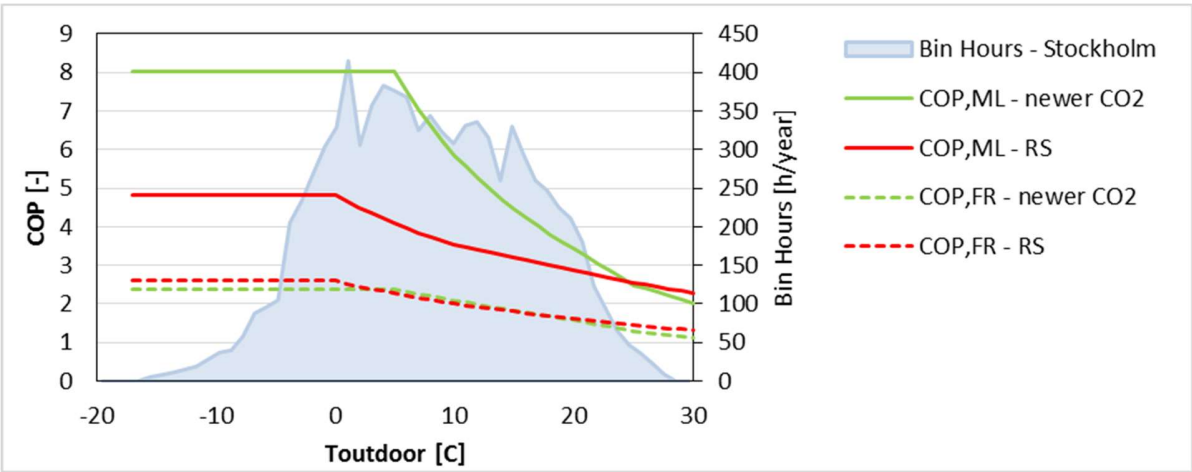


Figure 17 – COP_{ML} and COP_{FR} comparison as function of outdoor temperature of the modelled refrigeration systems for RS123 and newer CO2 system. Bin hour temperature data for Stockholm are included.

The plots of COP_{tot} at LR of 3 in Figure 16 show that newer CO2 systems have higher efficiency than RS for outdoor temperatures lower than about 24°C. The main contribution to the high COP_{tot} in newer CO2 systems comes from COP_{ML} which is much higher in newer CO2 systems compared to RS, as can be observed in Figure 17. However, COP_{FR} for both systems are comparable.

In order to calculate the annual energy use of the systems, the cooling demand profile as a function of the outdoor temperature is assumed to change linearly between maximum capacity of 200 kW at 35°C and 50% of the maximum capacity at 10°C ambient, below which the capacity remains constant. The cooling demand at the low temperature level is assumed to be constant at 33 kW, independent of the ambient temperature. These assumptions used for the cooling capacities are based on analysis of field measurements data and representative of an average size supermarket in Sweden.

Using the COP values in Figure 17 and the assumed load profiles for an average size supermarket in Stockholm/Sweden, the annual energy use for new CO2 systems and RS can be calculated. The bin-hour temperature profile for Stockholm is reported in Figure 17. Hourly average temperature is lower than 24°C for more than 95% time in a year; CO2 systems have nearly always better performance in a cold climate region as Stockholm area.

The energy consumption calculations show that RS has an annual energy use of about 405MWh while new CO2 system uses 20% less energy; i.e. about 322MWh. For lower LR the newer CO2 system will still have lower annual energy use because the COP_{FR} of both systems are comparable, as observed in Figure 17. The savings in annual energy use in newer CO2 systems will still be around 20% if the load at the low temperature level is increased to 50 instead of 33kW in this calculation.

The analysis in this section was done to Stockholm city in Sweden; however, the COP plots and the calculation method, which was explained in details, can be used to analyze the performance of the systems in other climates.

3.2.4 Conclusions of Paper II

Field measurements of three supermarkets in Sweden using typical HFC refrigeration system solution were analyzed for periods of 7 to 9 months. The reference systems were compared to CO2 trans-critical systems. The different refrigeration systems are made comparable by looking at the different coefficients of performance (COP's) versus condensing temperatures. The field measurement analysis is combined with theoretical modelling where the annual energy use of the HFC and CO2 trans-critical refrigeration systems was calculated.

Comparing the field measurement results of COP's for RS and CO2 systems shows that the new CO2 systems have higher COP_{ML} than RS and old CO2 systems. COP_{FR}, however, is higher for RS123 compared to new and old CO2 systems, this is mainly due to the positive effect of the large sub-cooling (10-30K) of FR by ML units.

Calculation models for RS and CO2 systems have been developed in order to calculate annual energy use of the systems. The computer models were used to calculate the COP's of the systems at different outdoor temperatures. The calculation results show that COP_{ML} for the new CO2 system are higher than RS while COP_{FR} are at the same level. $COP_{tot,LR=3}$ for the new CO2 system is higher than RS for outdoor temperature lower than 24°C.

Based on the modelling results, the annual energy use of the new CO2 system in an average size supermarket in Stockholm is about 20% lower than RS system.

The detailed analysis done in this study (Paper I and Paper II) proves that new CO2 trans-critical refrigeration systems are more energy efficient solutions for supermarkets than typical HFC systems in Sweden. The analysis method and results presented in this study can be used to expand the analysis for different case studies in other climate conditions which will help verifying the potential of CO2 trans-critical solution in other countries.

3.3 Paper III - Studying improved CO2 system (integrated solution)

The studies in the first two papers show that a booster CO2 system with flash gas by-pass at intermediate pressure level has the highest COP among the compared solutions; therefore, it has been used as the reference CO2 system solution.

This paper investigates energy efficiency of an integrated CO2 trans-critical booster system installed in a supermarket in Sweden. The supermarket has applied several features to improve energy efficiency of the reference system solution including heat recovery for space and tap water heating, air conditioning (AC), and parallel compression.

Using field measurements data, the system performance is evaluated in a warm and a cold month. Furthermore, this integrated energy system concept is modelled and compared with stand-alone HFC-based energy systems.

3.3.1 Integrated CO2 Trans-critical System Description

The integrated CO2 trans-critical booster system is installed in a supermarket located in the center of Sweden. The supermarket has been in operation since September 2013. A simple schematic of the integrated CO2 system is shown in Figure 18. The system provides the refrigeration, air conditioning, and a share of the heating demands. Heat recovery from the CO2 system is the primary heating system and district heating is used as the auxiliary heating source.

The system can be explained following the numbering indicated in Figure 18. The system is composed of three compressor units: low temperature (LT) (1), medium temperature (MT) (2) and parallel (3) compressors. The hot gas discharges from the MT and parallel compressors mix and pass through two heat exchangers called de-superheaters via which heat is recovered. The first de-supeheater (4) provides tap water heating with a forward temperature of about 55-60°C. The second de-superheater (5) is for space heating providing the hydronic system of the space heating network with a forward temperature of 35-45°C, depending on the building's heating demand. This heat is used mainly in floor heating and radiators.

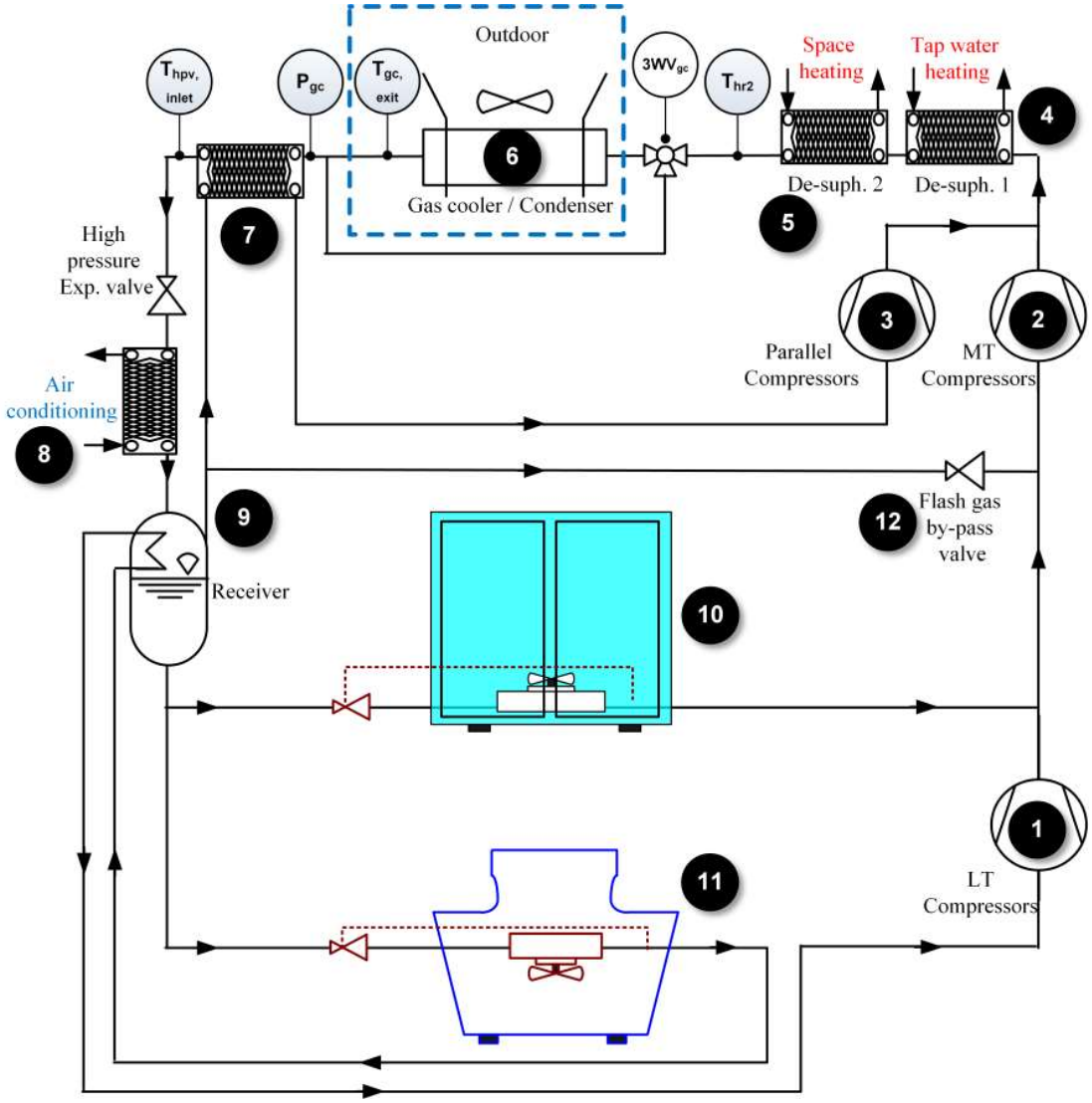


Figure 18: Schematic of the CO2 integrated system

When the heat to be rejected from the system is higher than the heating demands, a gas cooler (6) on the roof of the supermarket is used to reject the excess heat to the ambient. A heat recovery control strategy is applied to regulate the gas cooler pressure and exit temperature of refrigerant from gas cooler. In this control strategy the gas cooler maybe by-passed using the 3-way valve; so all heat from the refrigeration system is recovered in the de-superheaters, usually when the ambient temperatures are very low. The gas cooler pressure P_{gc} follows an algorithm for the maximum COP in summer trans-critical mode. This mainly occurs when T_{amb} is higher than 25°C.

CO2 exiting the gas cooler flows in a sub-cooler (7) and is cooled by a cold vapour stream; suction line heat exchanger at the parallel compressors side. However, the sub-cooling effect has been found to be very insignificant. The sub-cooled liquid is expanded by a

high pressure regulating valve and enters an air conditioning heat exchanger (8). This evaporator is connected to the air conditioning system with forward and return temperatures of about 7 and 12°C. CO2 mass flow rate is too high in relation to AC demand in this heat exchanger, so complete evaporation is never achieved.

The two-phase CO2 fluid leaving the air conditioning evaporator enters a receiver (9) where vapour and liquid are separated. The liquid stream is fed to the medium temperature cabinets (10) and low temperature freezers (11). The vapour in the receiver has two paths; the first path is expanding into the suction line of MT compressors through the by-pass valve (12), known as “flash gas by-pass” and it is the most commonly applied, the second path is direct to the parallel compressors (3) suction line. The refrigerant can go in either one of the paths or both paths simultaneously. The parallel compression path is more efficient because the parallel compressors suction pressure is higher than MT compressors suction pressure.

Managing the receiver vapour and regulating the receiver pressure are important parameters for the operation of the system since the AC forward temperature is affected by receiver pressure. Another ad-hoc solution used in this system is to condense part of the vapour in the receiver by a cooling coil from the LT return gas of the freezers. However, this cooling effect has been estimated to be small.

3.3.2 Energy Performance Analysis

In the following sub-sections, energy efficiency of the system to provide the different cooling and heating demands is evaluated.

Coefficients of performances (COPs)

Figure 19 shows the 15-min. averaged total system COP (COP_{tot}), total refrigeration COP (COP_{ref}), medium and low temperature refrigeration COPs (COP_{MT} and COP_{LT}) for January and July 2014. The COPs have been discussed for winter and summer cases separately in the following text.

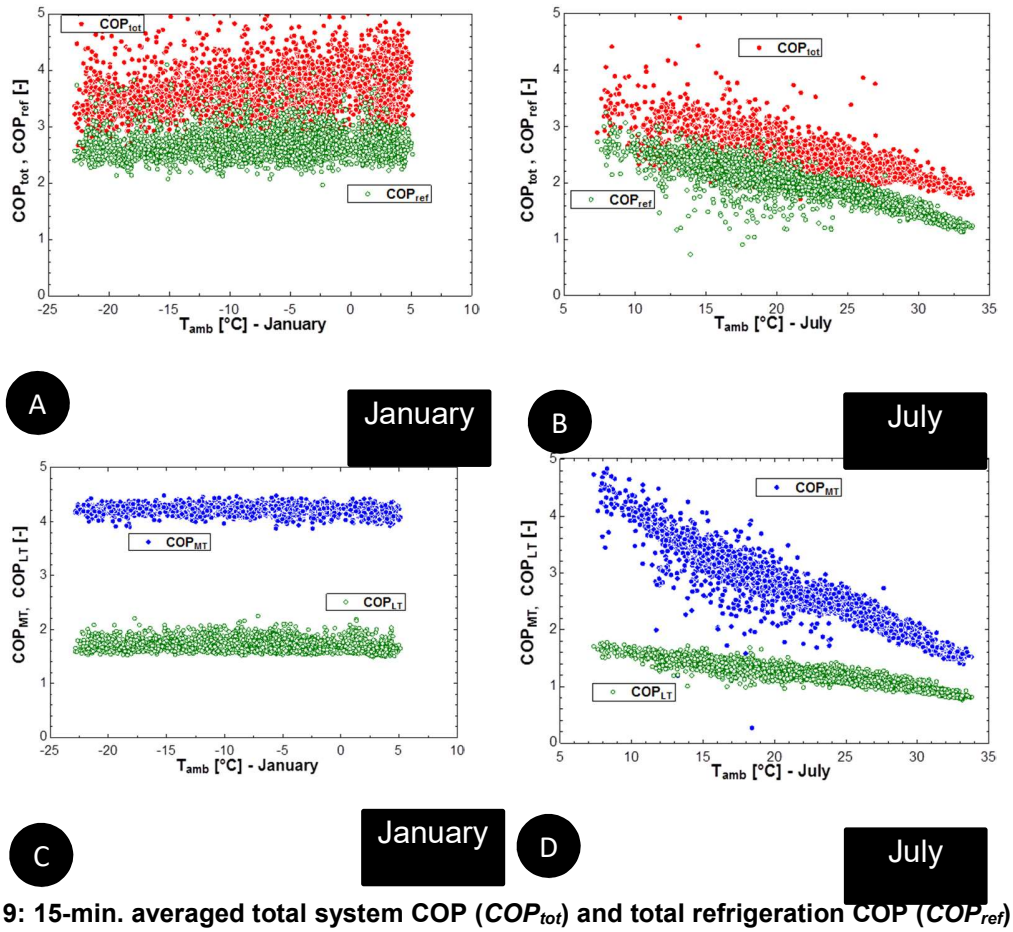


Figure 19: 15-min. averaged total system COP (*COP_{tot}*) and total refrigeration COP (*COP_{ref}*) for (A) January 2014 and (B) July 2014, 15-min. averaged medium temperature COP (*COP_{MT}*) and low temperature COP (*COP_{LT}*) for (C) January 2014 and (D) July 2014

- ***Winter case***: most of the loads including $\dot{Q}_{MT}$, $\dot{Q}_{LT}$, $\dot{Q}_{TWH}$ and $\dot{Q}_{SPH}$ have narrow range of variations in winter. Furthermore, the gas cooler pressure P_{gc} is fixed to 80-85 [bar] for ambient temperatures lower than 0°C. The minimum floating condensing pressure is also fixed to 45 [bar]. The exit temperature from the de-superheat for space heating (Thr_2 in Figure 18) is rather constant at about 35°C and the inlet temperature to the high pressure control valve ($T_{hpv,inlet}$) is about 30°C. The gas cooler is by-passed frequently in this period. All these narrow changes in loads and boundary conditions of the system lead to a horizontal trend in performance, as can be observed in the plots of COP_{tot}, COP_{ref}, COP_{MT} and COP_{LT} in Figure 19-A and Figure 19-C.

- ***Summer case***: when T_{amb} is lower than 15°C, the integrated CO2 system provides refrigeration, heating and AC simultaneously. This explains the difference between COP_{tot} and COP_{ref} points at the left end in Figure 19-B. The reason for simultaneous heating and AC demands in T_{amb} region of 10-15°C could be the different demands and set points in different HVAC zones of the supermarket. At T_{amb} lower than 15°C the system runs in floating condensing mode with low P_{gc} of 50-55 [bar], corresponding to 14-18°C

condensation temperature. This region is where relatively high values for COP_{ref}, COP_{MT} and COP_{LT} are reached; occurring mainly during occasional cold July nights.

For ambient temperatures between 15-25°C, parallel compression is used frequently. When T_{amb} is higher than 25°C, mainly in summer mid-days, the system operates in trans-critical mode. Parallel compression is the only vapour management method used in this region. The reason for the clear difference between COP_{tot} and COP_{ref} in this region is that AC load is provided at higher evaporation temperature comparing -8°C without PC and 5°C with PC. This increases the total COP of the system, compared with the refrigeration COP.

Figure 20 shows 15-min. averaged heating COP_{HR} in the winter (left) and air conditioning COP_{AC} in the summer (right).

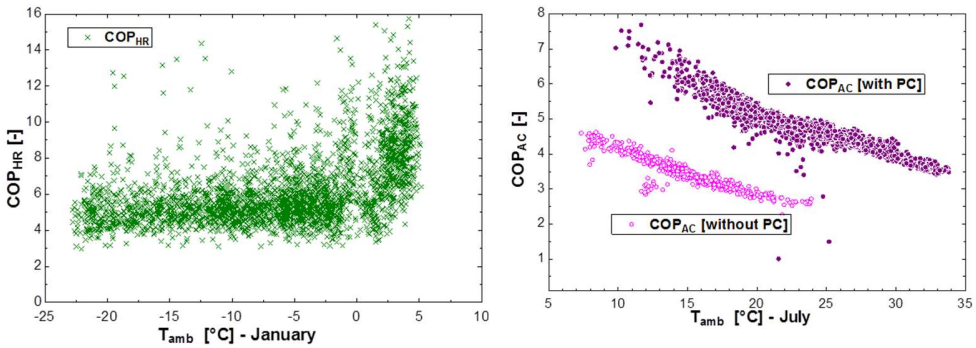


Figure 20: 15-min. averaged heating COP (COP_{HR}) (left) - Air conditioning COP (COP_{AC}) with and without parallel compression (right)

- COP_{HR}: heat is recovered with COP_{HR} ranging between 4 and 6 for ambient temperatures lower than 0°C. The definition of COP_{HR} considers Q_{SPH} and Q_{TWH} combined and as a single heating demand. This makes it directly comparable to heating COP of a heat pump (referred to usually as *COP1*) since the CO2 system heat recovery control is mainly governed by space heating demand. This range of COP_{HR} is as, or more, efficient than the majority of the commercial heat pumps in the market. As can be observed in Figure 20, COP_{HR} has much higher values for the ambient temperatures within the 0-5°C range, because the heat is almost recovered for free from the system; i.e. discharge pressure is slightly increased to recover heat.

- COP_{AC}: COP_{AC} values for July are shown in Figure 20-right. To investigate the importance of using parallel compression (*PC*) when air conditioning is supplied by the integrated CO2 system, COP_{AC} values for the cases “with-” and “without parallel” compression, abbreviated as “with PC” and “without PC”, have been set apart by color.

As can be seen in this figure, PC is rarely used for T_{amb} < 12°C and it is always used for T_{amb} > 24°C. For ambient temperatures between 12 and 24°C, the comparison shows that the average COP_{AC} "with PC" is about 65% higher than "without PC" case. Consequently, COP_{tot} is also 7% higher when parallel compression is used during the air conditioning delivery of the system; this is not shown in this plots but extracted from the corresponding field measurement data. The reason PC is not used continuously in the warm season is the minimum capacity of parallel compressors; they require a minimum flow rate, and for the cases which there is not enough vapour in the receiver, PC compressors cannot be switched on.

Annual electricity use comparison study

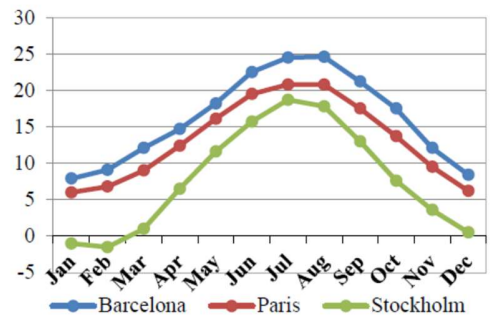
The integrated- and stand-alone energy systems in supermarkets are evaluated and compared using computer modelling. Barcelona, Paris, and Stockholm are selected as three cities representing warm, mild and cold European climate conditions. The monthly average climate data are plotted in Table 1. Three energy system solutions for Barcelona and Paris and four systems for Stockholm are compared. The energy system solutions are as follows, as summarized in Table 1:

- **System solution 1 (S1)**: an integrated CO2 system similar to the system presented in this paper which provides refrigeration, heating, and air conditioning. Parallel compression is used for summer case when Tamb >12°C.
- **System solution 2 (S2)**: a standard CO2 trans-critical booster system with heat recovery and flash gas by-pass (no parallel compression). Air conditioning is provided by a stand-alone R410A system.
- **System solution 3 (S3)**: an R404A direct expansion with separate MT and LT units for refrigeration. This refrigeration system is not conventional in Sweden due to large HFC charge needed. Heating is provided by an air source R407C heat pump system and air conditioning by a stand-alone R410A system. This solution is considered as the reference system in this energy use comparison study since its refrigeration system is the most conventional system solution in many European supermarkets.
- **System solution 4 (S4)** – only for Stockholm: standard conventional HFC refrigeration system in Sweden is an indirect R404A system as shown in Figure 8. The heating and AC systems in S4 solution are similar to S3.

Table 1: Energy systems and ambient temperatures for Barcelona, Paris, and Stockholm

	Refrigeration	Heating	AC
S1: Barcelona-Paris-Stockholm	CO_2 booster Ref + HR + AC + PC		
S2: Barcelona-Paris-Stockholm	CO_2 booster + HR		R410A AC
S3: Barcelona-Paris-Stockholm	R404A DX	R407C HP	R410A AC
S4: Stockholm	R404A indirect	R407C HP	R410A AC

Monthly average ambient temperature [°C]



An average size supermarket in Sweden is used as a case study to simulate the performance of the systems S1-S4 in the three cities. The majority of temperature boundaries in the systems S1-4 are kept similar. Some of the minor differences between the boundaries include 5 K difference between condensing and outdoor temperatures in CO2 gas coolers and HFC DX condensers while it is assumed to be 10 K for indirect HFC system. Furthermore, AC evaporation temperature for the CO2 system is kept as 6°C in AC flooded evaporator but it is assumed 0° in DX HFC evaporators.

The results of the annual electricity use comparison are shown in Figure 21. On the left y-axis, the annual electricity used for refrigeration, heating, and AC can be read. On the right y-axis, total electricity use ratio of different solutions can be compared with 100% of S3 reference system solution. For example, when 112% is read on the right y-axis for S1 in Barcelona it means that it uses 12% more electricity compared to S3 reference system.

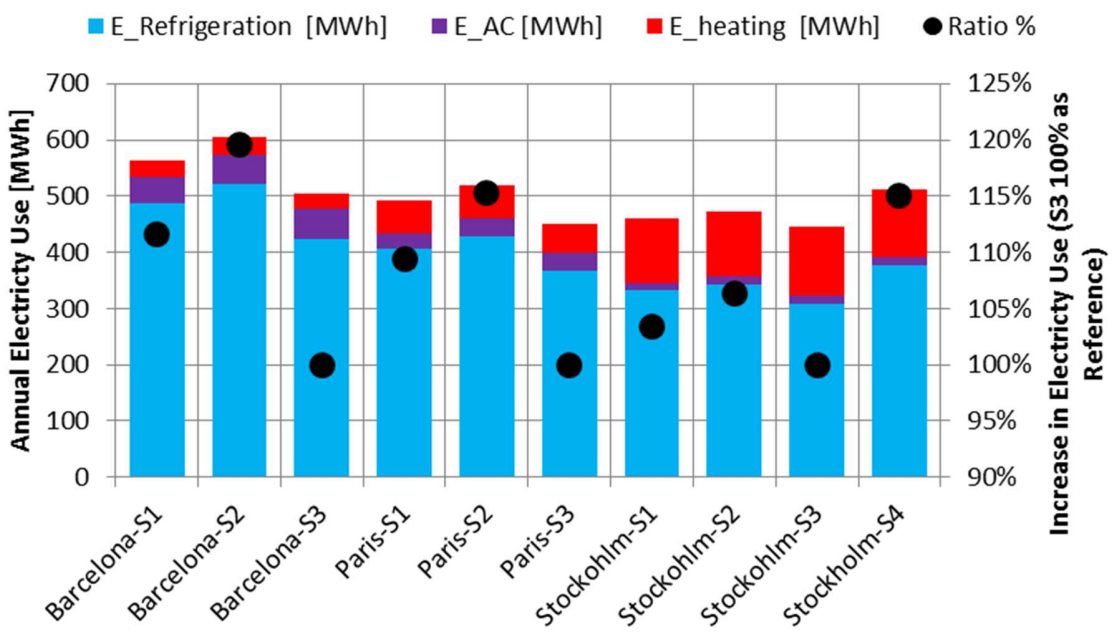


Figure 21: Annual electricity use comparison of energy systems S1-3 in Barcelona, Paris, and Stockholm. S4 is only in Stockholm.

As can be observed in the figure, CO2 integrated system (S1) is the best alternative solution in Stockholm. CO2 S1 and S2 solutions consume about 11% and 8%, respectively, less electricity than the S4 solution, which is the conventional HFC solution in Sweden. CO2 S1 and S2 solutions use 9% and 15% higher electricity than HFC S3 system in Paris, respectively, and 12% and 20% higher electricity in Barcelona.

Comparing AC electricity use of CO2- and R410A-based systems, CO2 S1 integrated system consumes about 19% less electricity in Stockholm, 17% less in Paris and 12% less in Barcelona. This implies that integration of AC into the CO2 refrigeration system results in a decrease in AC electricity consumption. This advantage of the CO2 integrated system versus HFC solutions is more significant in mild-cold climates.

The electricity use of CO2 S1 and S2 systems for heating is 5% less than HFC heat pump in Stockholm while it is 14% higher in Paris and 11% higher in Barcelona. The reason that HFC heat pump is more efficient than heat recovery from the CO2 system in Paris and Barcelona is that this heat pump is air source and in mild winter conditions it has higher heat source temperature compared with the CO2 heating system.

To conclude, what can be interpreted from this comparison study is that CO2 integrated solution (S1) offers an energy-efficient, environmentally- friendly and compact all-in-one solution for cold climates; however, some new modifications in this technology are required to increase its energy efficiency in warmer climates.

3.3.3 Conclusions of Paper III

This paper investigated the key operating parameters and energy efficiency of an integrated CO2 trans-critical system installed in a Swedish supermarket. Heating and air conditioning are integrated into the CO2 trans-critical booster refrigeration system in this supermarket. The supermarket has applied several features to improve energy efficiency including heat recovery for space and tap water heating, providing air conditioning, and the use of parallel compression.

Using field measurements data, the key operating parameters in the CO2 system are studied in selected warm (July 2014) and cold (January 2014) months. The daily- and hourly-averaged cooling and heating loads and COPs are analysed to explore the system performance in day-night and winter-summer running conditions. Furthermore, the integrated energy system concept is modelled and compared with separated stand-alone energy systems in three different European climate conditions; Stockholm for cold, Paris for mild and Barcelona for warm climates.

Summer period performance analysis shows that the system runs in sub-critical floating condensing mode when the outdoor temperature is lower than 25°C. For higher outdoor temperatures the system runs in trans-critical mode where the gas cooler pressure follows an optimization algorithm to maximize the COP of the system. The pressure in the receiver is regulated to provide the AC system with the required 7-8°C forward secondary fluid. Parallel compression is used as the regulator of the receiver pressure for ambient temperatures higher than 25°C, while for ambient temperatures lower than 15°C flash gas by-pass valve is used. Both of these receiver pressure control strategies are used in the 15-25°C ambient temperatures region. The importance of parallel compression usage during AC delivery has been studied; it is found that COP_{AC} and COP_{tot} of the system are 65% and 7% higher using “AC with PC” compared with “AC without PC”, respectively. Air conditioning (AC) study shows that AC is delivered with high COP values in the case of using parallel compression.

Winter period performance analysis shows that the high pressure side of the system is controlled for heat recovery. The pressure is fixed to 80-85 [bar] and the gas cooler is by-passed to recover the entire rejected heat when the ambient temperature is very low.

The heat recovery function of the system is analysed for both tap water and space heating circuits. The measurements analysis shows that the system is able to provide the required tap water temperature of 55-60°C throughout the year. The system is also able to provide the space heating forward temperature of up to 45°C. Furthermore, heat recovery study proves that CO2 system provides the heating demands with high COP_{HR} values, usually within the 4-6 range. This efficiency is comparable to the majority of commercial heat pumps in the market.

Using computer simulation models, the CO2 integrated system is compared with other alternatives of energy systems in supermarkets, it is shown that the system consumes about 11% less electricity than stand-alone conventional HFC solutions for refrigeration (i.e. indirect HFC), heating and AC in north of Europe. In this region, the integrated heating and AC functions of the CO2 integrated system consume about 5% and 19% less electricity, respectively, compared with stand-alone HFC heat pump and AC systems. The electricity use for AC in the CO2 integrated system is found to be always lower than stand-alone HFC units, 17% less in Paris and 12% less in Barcelona. However, total electricity use for refrigeration, heating, and AC is higher for CO2 integrated system compared to conventional HFC in central and southern Europe; by 9-15% in Paris and by 12-20% higher in Barcelona. The conventional refrigeration system in central and southern Europe is assumed to use direct expansion HFC concept.

The energy efficiency study of the integrated CO2 system functions confirms that it can be used as an environmentally friendly all-in-one supermarket energy solution suitable for cold climates. For the integrated CO2 system to be considered as an efficient solution in mild and warm climates key modifications may need to be applied; such as flooded evaporation, by the use of ejector(s) or pump circulation, mechanical sub-cooling, and gas cooler evaporative cooling.

3.4 Paper IV - Evaluate the state-of-the-art CO2 system

This paper investigates the integrated and state-of-the art features of CO2 trans-critical booster systems. The main objective is to identify the most promising solutions in terms of energy efficiency impacts.

First, the performance of modified features and integrated functions have been compared with the standard CO2 system and alternative heating and air conditioning solutions. Subsequently, the performance of the defined state-of-the-art CO2 system is compared to natural refrigerant-based cascade and HFC/HFO-based DX and indirect refrigeration solutions operating in cold and warm climates.

3.4.1 System Description: CO2 systems, conventional, and possible alternatives

CO2 Standard and State-of-the-Art Systems

The schematic of a standard CO2 trans-critical booster system and its sample P-h diagram is shown in Figure 22-left. Some features are considered standard in this system due to their proven positive impact on efficiency. Such features are: flash gas by-pass, heat recovery (HR), high pressure optimization control, glass doors-lids on freezers and cabinets, and one variable speed compressor in each compression unit.

This standard solution has been subject to continuous modification to increase its energy efficiency. In this paper, the most promising modifications are studied in order to identify the key features of a state-of-the-art (SotA) system.

A schematic of a SotA system with its key features and its sample P-h diagram is shown in Figure 22-right. The most important measurements including compressor electric powers and pressures are shown in this figure. The loads are also shown including medium temperature refrigeration $\dot{Q}_{MT}$, low temperature refrigeration $\dot{Q}_{LT}$, air conditioning $\dot{Q}_{AC}$, tap water heating $\dot{Q}_{TWH}$, and space heating $\dot{Q}_{SPH}$. The latter three integrated loads are shown schematically in the P-h diagram.

One of the major differences from the standard system is on running the MT and LT evaporators in flooded evaporation condition. The evaporators are run in DX condition in the CO2 standard system. It means a section of the evaporator is specified for super-heating of the refrigerant. It is widely known that the heat transfer coefficient in the two phase flow region is significantly higher than this single phase super-heater section of the evaporator. On the contrary, the flooded evaporator takes the advantage of liquid CO2 evaporation down to the exit of the evaporator. This higher heat transfer coefficient and no super-heating results in higher evaporation temperatures compared to the conventional DX systems. Methods for how to implement flooded evaporation are

discussed later in this paper. Another difference is on processing the vapour out from the receiver, where parallel compression (PC) is used to compress this vapour at higher suction pressures compared to the case in the standard system. Heat recovery in the SotA system is provided in two stages (i.e. heat exchangers in series) for tap water and space heating. Two-stage heat recovery might provide a better separated control for the desired demands and also helps avoid the pinch point occurrence inside the de-superheater, which is more probable in one-stage heat recovery.

Integration of air conditioning (AC) into the CO2 booster system is a compact solution. This can be done by adding a heat exchanger between the high pressure regulating valve and the receiver. An alternative AC heat exchanger arrangement is a thermosiphon loop fed from the liquid part of the receiver. AC delivery should be accompanied by running parallel compressors.

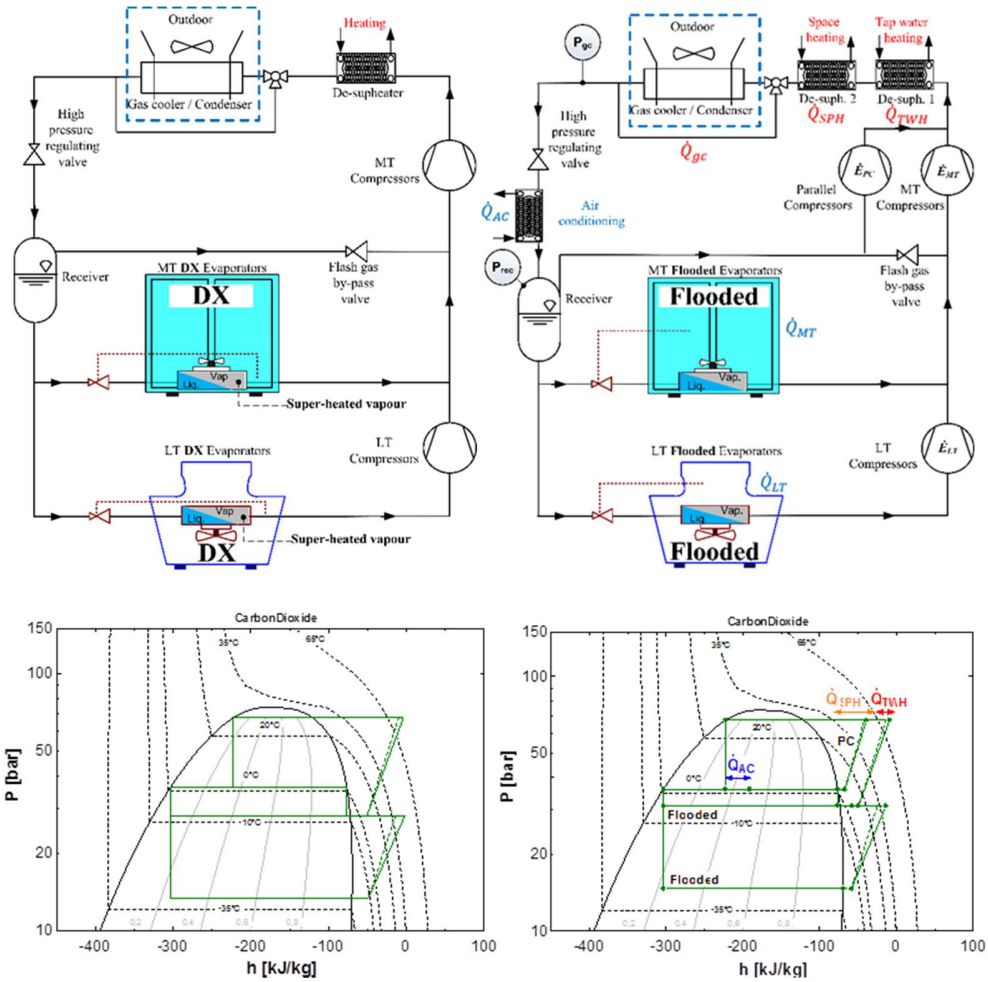


Figure 22: Schematic and P-h diagrams of a standard CO2 booster system (left) a SotA CO2 booster system (right)

Direct expansion (DX) and indirect HFC/HFO solutions

The most conventional supermarket refrigeration solution in Europe is an R404A DX with separate MT and LT refrigeration units. This refrigeration system represents the present conventional system on the European market. However, this solution is being phased out due to its high GWP (GWP = 3922). The suggested drop-ins for R404A are mixtures of HFC and HFO (non-saturated HFC) refrigerants or just mixture of HFCs. R448A (GWP = 1387), R449A (GWP = 1397) and R407H (GWP = 1495) are some of these HFC or HFC/HFO mixtures which may replace R404A in some supermarkets in Europe. In this study, R449A is selected to represent this new generation of synthetic refrigerants.

The conventional refrigeration system in Sweden has been an indirect R404A system as the one shown in Figure 8.

Cascade Ammonia-CO2 and Propane-CO2 solutions

An alternative solution to the CO2 booster system is a cascade system where ammonia or propane can be used on the high stage. A cascade system configuration is shown in Figure 23. The cascade system is composed of CO2 in the LT and MT refrigeration loops and ammonia or propane on the high stage. To confine the charge of high stage refrigerant and minimize the leakage risks, the heat from the high stage is rejected to the ambient through an indirect secondary fluid loop. CO2 in the LT stage is flooded using internal heat exchanger (IHX) and is flooded with pump circulation in the MT loop. On the high stage, an IHX is used so as to provide sub-cooling at the exit of the condenser and super-heating at the compressor inlet.

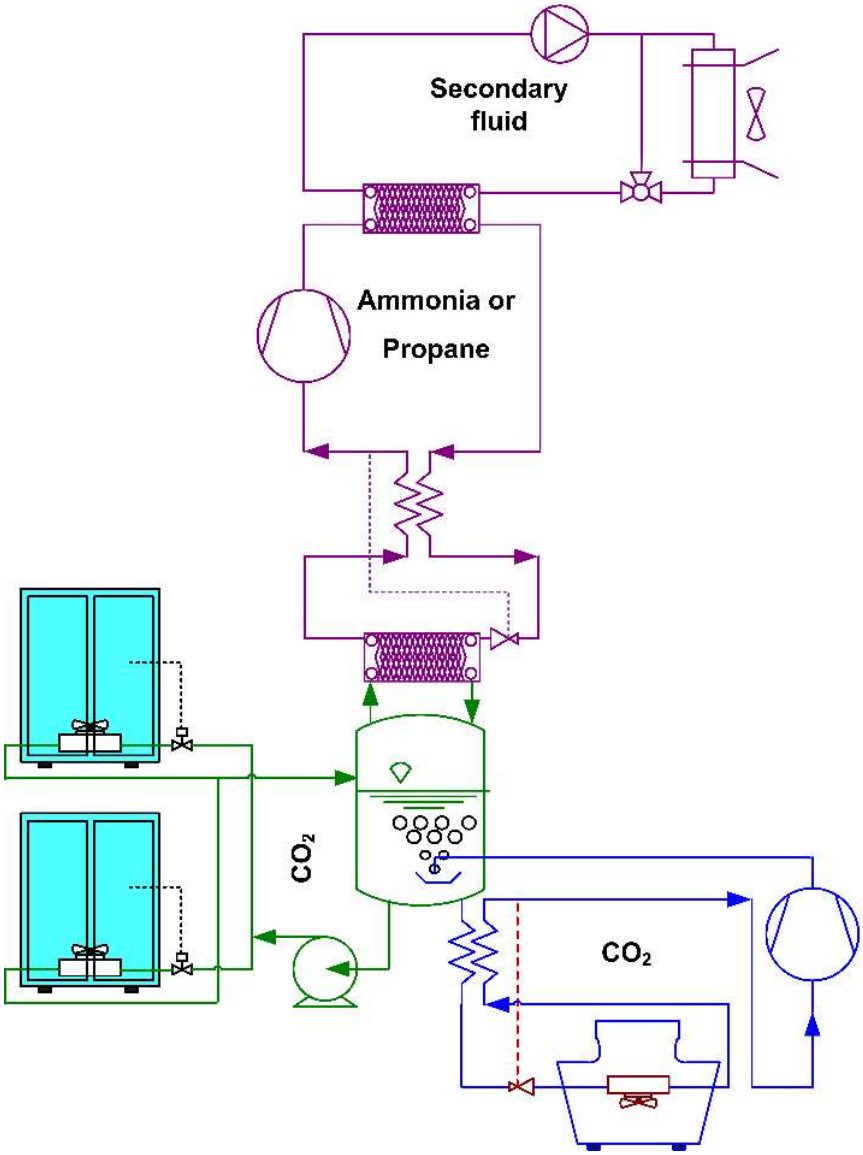


Figure 23: Schematic of an ammonia-CO2 or a propane-CO2 cascade system

3.4.2 Results and Discussion

Evaluation of the features of SotA CO2 system

Heat recovery

An essential feature of the SotA system is heat recovery. The heat is recovered in two de-superheaters to provide tap water heating and space heating. Usage of two de-superheaters instead of one gives better separated control of space heating and tap water heating functions.

The heat recovery from the CO2 system is compared with a separate HFC-based heat pump. In this comparison, an air source heat pump (ASHP) is considered, because ambient temperatures between 10 and -5 °C occur in 85 % of the winter time in Stockholm, where ASHP has comparable energy efficiency to a ground source heat pump (GSHP). This has been evaluated calculating the heating performance for ASHP and GSHP systems.

The evaporators of the CO2 system are assumed to be flooded, and the evaporation temperatures at MT and LT level are assumed to be 3-4 K higher than the CO2 standard system, -4.3 and -29 °C compared to -8 and -32 °C.

The modelled air-water ASHP uses R407C as the refrigerant and a compressor total efficiency correlation is developed based on a commercial product. 10 K of internal super-heating is assumed at the suction of the compressor. The approach temperature in the evaporator is 7 K, and the minimum evaporation temperature is -15 °C. For ambient temperature between -5 and -10 °C, the heating capacity of ASHP is fixed as a maximum, and the remaining heat required is provided by an auxiliary electric heater. Evaporator electric defrosting power is considered as 7% of compressor power in the below 0 °C region. When the ambient temperature is lower than -10 °C, ASHP is switched off and the auxiliary electric heater with 95% efficiency provides the required heating demand. The auxiliary heater is switched on at -5°C T_{amb}, and its capacity can increase up to 180 kW at -18°C T_{amb}.

Heating COPs and SPF of CO2 heat recovery and ASHP are shown in Figure 24. As can be seen in the graph, COP_{ASHP} is often higher than COP_{HR} at ambient temperatures above 0 °C. However, COP_{HR} has significantly higher values at ambient temperatures lower than 0 °C. These higher COP values are reflected in about 10% higher SPF_{HR} of CO2 system (SPF_{HR} = 3.9) compared to ASHP system (SPF_{ASHP} = 3.6). It is necessary to mention that if the system is located in warmer climates, for example Barcelona, or if the heat recovery is activated at higher ambient temperatures, for example 15 °C, the running situations is in favour of air source heat pumps and it is expected that they have higher SPF than CO2 heat recovery.

In addition to the 10% higher SPF_{HR} value, heat recovery from the CO2 system is significantly more compact heating solution; the only added components are one or two compact plate heat exchangers as de-superheater, compared to a stand-alone ASHP unit and an auxiliary electric heater. Furthermore, there is no limitation in low ambient temperature operation, and it uses a refrigerant with no environmental short- or long-term concerns. Compared to HFC heat pumps, the CO2 system can also provide a greater amount of high-grade heat proper for the high temperature demands of tap water heating.

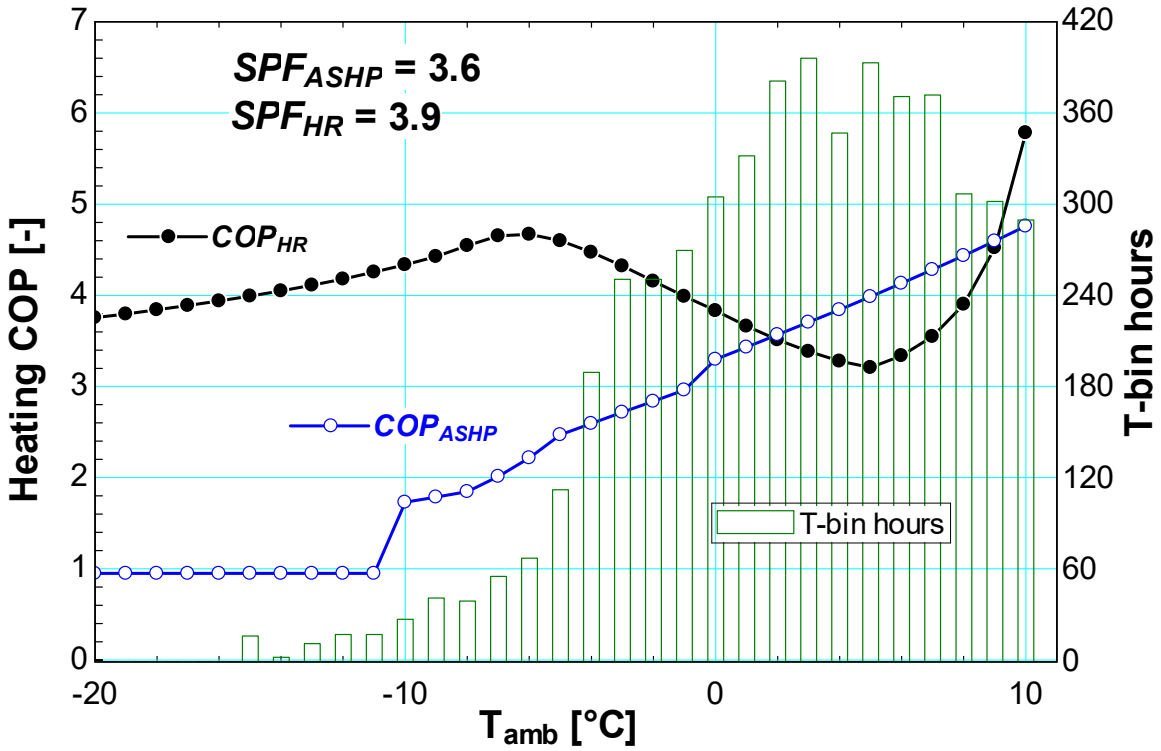


Figure 24: Heating COP and SPF of CO2 heat recovery and ASHP. On the right axis is Stockholm winter temperature-bin hour.

20-45% of the recovered heat from the CO2 system in +10 to -20 °C T_{amb} range is high-grade heat; i.e. it has CO2 temperatures higher than 65 °C, suitable to provide tap water heating demand with a temperature of 55-60 °C. Tap water heating demand is provided almost for free in summer time, due to high CO2 discharge temperatures in the floating condensing mode; i.e. there is no need to raise the discharge pressure. In order to calculate the tap water heating COP in winter, an hourly model is used instead of the temperature-bin model. Tap water heating demand is assumed as being 15 kW, supplied two hours early in the morning for food preparation and two hours late at night during supermarket cleaning. The assumptions regarding these operations are based on the observed hot water consumption pattern in a supermarket. The calculated average COP value for tap water heating is 5.4 which shows that the tap water heating function of the CO2 system is a very energy efficient solution for providing hot water.

The total energy costs of CO2 heat recovery and ASHP are compared to another conventional heating alternative, the district heating. The total space heating demand which is provided by any of these three systems is about 410 MWh, this number is based on the load assumptions presented before. It is assumed that district heating can provide

the entire space heating demand at the required temperature. The electricity price is assumed as 0.1 €.kWh^{-1} for electricity and 0.05 €.kWh^{-1} for district heating. As can be seen in Figure 25, the total energy cost of CO2 heat recovery is about 50% less than for district heating, and 20% less than ASHP.

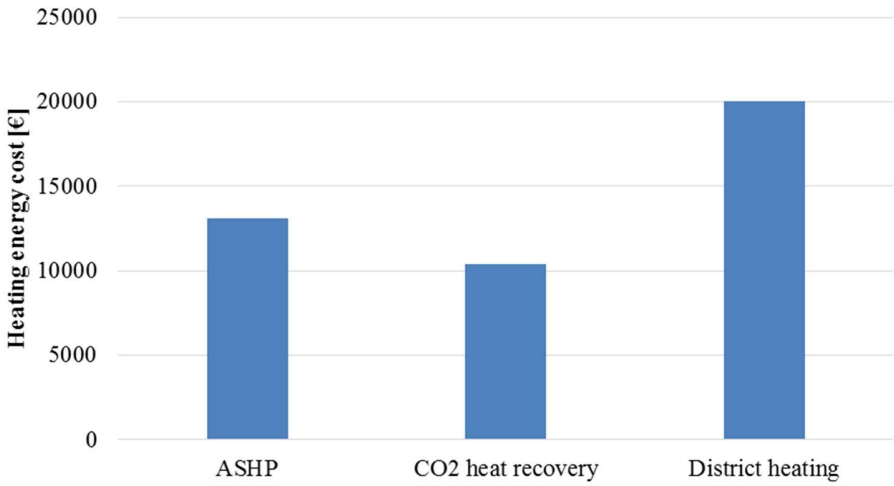


Figure 25: Annual heating energy cost of three heating systems [euros]

Flooded evaporation

In order to evaluate the impact of flooded evaporation in raising the evaporation temperature, the evaporators of an average size MT cabinet and an average size LT freezer are modelled. The MT cabinet size is assumed to have 5 kW capacity and it is supposed to cool the air from 8 °C to 3 °C, by a CO2 evaporation temperature of -8 °C and 10 K internal super-heating. By removing the 10 K super-heat and keeping evaporator capacity and air side temperatures constant, the evaporation temperature can be raised to -4.3 °C (3.7 K increase from -8 °C in the standard system). This way the CO2 leaves the evaporator at saturated vapour condition. The same procedure is carried out in order to model a 3.5 kW LT freezer cooling the air from -20 °C to -24 °C by CO2 evaporating at -32 °C and 10 K internal super-heating. The results show that the system can be run at -29 °C evaporation temperature (3 K increase from -32 °C in the standard system) and no super-heat. The higher evaporation temperature due to flooded evaporation results in less defrosting demand, compared to the standard system. This positive impact of the flooded evaporation is not considered in the annual energy use (AEU) comparison.

The calculations show that the MT evaporation temperature increase results in 9% AEU saving in Stockholm and 10% in Barcelona. Raising the LT evaporation by 3 K will save about 2-3% AEU in both cities. The savings for flooded LT is insignificant due to the large

load ratio LR ($\dot{Q}_{MT}/\dot{Q}_{LT}$). The AEU savings for flooded LT will be higher in systems with lower load ratio.

The combined effect of running MT and LT in flooded case is an AEU saving of about 12% in Stockholm and Barcelona, compared to the standard CO2 booster system with heat recovery. These results are summarized among other features in Figure 28.

Three methods which can be implemented in order to flood the MT and/or LT evaporators are discussed in the following paragraphs.

The first method to run the system with flooded evaporators is to use a single or a set of ejectors. A simple schematic of such a system is shown in Figure 26a. The ejector is used to return the liquid collected after the MT evaporators, from the liquid accumulator to the receiver. The cabinet expansion valve is controlled by the air return temperature instead of the super-heating amount. Ejectors have the possibility of running both MT and LT levels in flooded evaporation mode with a set of ejectors.

The second method is using a pump circulation unit, as shown in Figure 26b. The pump directs the accumulated liquid after the MT evaporators back to the receiver. The pump should be actuated by a liquid switch in the accumulator tank. The CO2 pump electricity use is calculated and added to the compressors and gas cooler fans electricity use. It is assumed that the pump compensates for 70 kPa pressure drop, its efficiency is equal to 70% and the circulation ratio is 2. The latter means that the mass flow rate of refrigerant in the evaporators is twice as much the rate needed to achieve full evaporation. The calculations show this AEU saving is about 1% lower compared to the ejector solution for an efficient pump with 70% efficiency and low pressure drop of 70 kPa. The AEU saving is about 2% lower compared to the ejector solution for an inefficient pump with 40% efficiency and high pressure drop of 400 kPa. The CO2 pump power is in both cases insignificant compared to the compressor power.

The third method which can be applied is by using internal heat exchangers (IHX) inside the cabinets, and the way how this is done in LT cabinets is shown in Figure 26c. The signal to the expansion valve is sent from the CO2 stream exiting the IHX, instead of the traditional internal super-heating control. In this case, all, or most, of the super-heating is achieved inside the IHX instead of inside the evaporator.

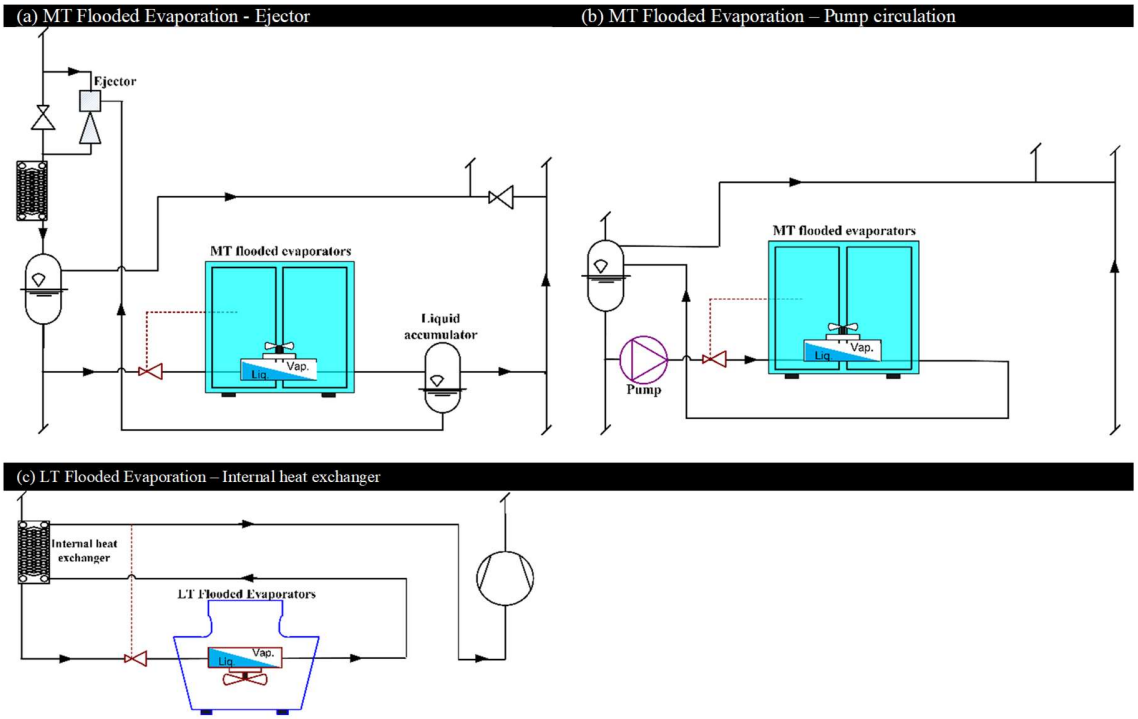


Figure 26: Schematic diagram of methods of providing flooded evaporation: a) Ejector b) Pump circulation c) IHX

Parallel compression and air conditioning

Parallel compression (PC), as shown in Figure 22-right, is an alternative method to direct the vapour formed in the receiver back to the high-pressure side. It is more efficient than the standard flash gas by-pass applied in standard systems since it compresses the vapour from higher suction pressures compared to MT compressors. The main limitation to using PC is the minimum flow rate restriction of the parallel compressors. There should be a minimum vapour content in the receiver to actuate the parallel compression and more vapour in the receiver is a more favourable condition to run PC. The minimum flow rate which the parallel compression unit can handle is equal to the smallest flow rate corresponding to the PC lowest capacity in part load operation.

The set point for PC activation in this paper is assumed to be 13 °C. The calculations show that using PC can save about 3% AEU in Stockholm and about 7 % in Barcelona compared to a standard CO2 system with flash gas by-pass.

Air conditioning (AC) integration into the CO2 system is another feature of the SotA system. It is a compact solution that requires the addition of few extra components in contrast to a stand-alone AC unit. The AC performance of a CO2 SotA system is compared to a conventional stand-alone AC system using R410A (GWP = 2088) as the refrigerant. The R410A system has an evaporation temperature of 0 °C, and the approach

temperature difference on the condenser side is 7 K, similar to CO2 sub-critical air-cooled condensation. The AC seasonal energy efficiency ratio SEER [-] of these two systems is calculated. The comparison result is shown in Figure 27. As can be observed, $SEER_{AC,CO2}$ is comparable to $SEER_{AC,R410A}$ in Stockholm (about 4.5) and in Barcelona (about 4.0). Other economic factors worth mentioning include: saving space, being an environmentally friendly long-term solution, requiring fewer components and less refrigerant (compared to a complete stand-alone system).

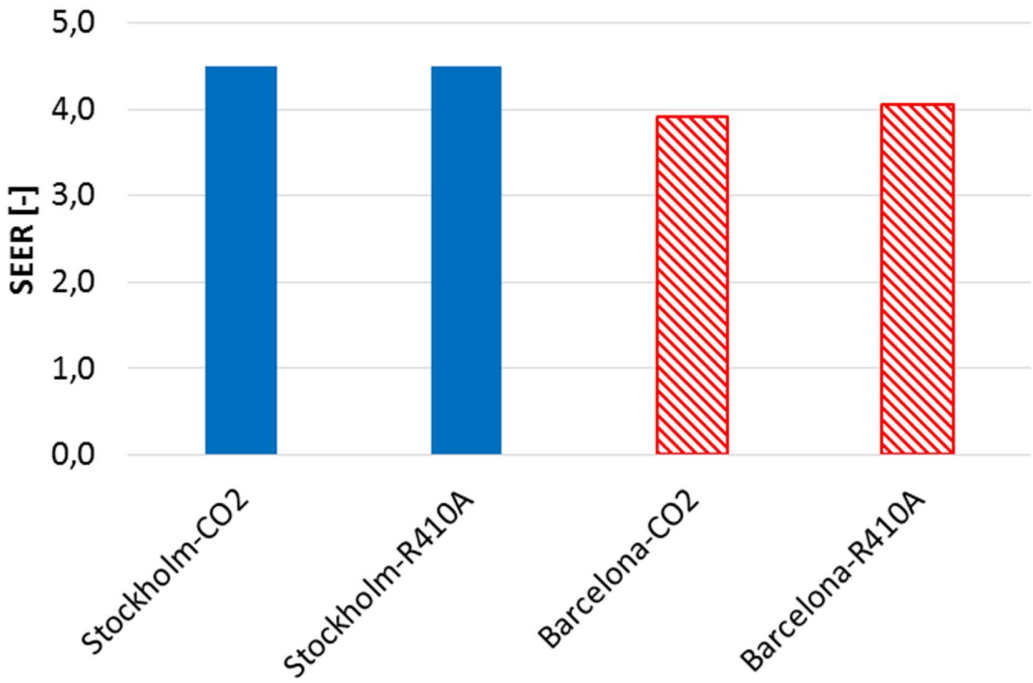


Figure 27: Seasonal Energy Efficiency Ratio $SEER_{AC}$ of CO2 and R410A AC solutions in Stockholm and Barcelona

Other SotA features

There are other modifications which have less significant impacts (as the analysis following will show) or more application limitations compared to the key features of the SotA system, which are analysed in the previous sub-sections.

Mechanical sub-cooling: sub-cooling has a positive impact on the refrigeration performance. A propane mechanical sub-cooler is modelled and designed to increase its capacity linearly between 30-60 kW in sub-critical conditions of ambient temperatures between 15-23°C. It is run with full capacity, i.e. 60 kW, in trans-critical conditions. These capacity values are based on a calculation to size a sub-cooler to provide a reasonable 15-20 K sub- /further-cooling. The propane sub-cooler cycle operates as a simple

refrigeration cycle with no sub-cooling and 5 K internal super-heating. Propane evaporation temperature is set to 0° C, and the condensing temperature has 7 K approach difference with T_{amb}. Condenser fan power use is set to be 3% of the condenser heat rejection amount.

AEU saving has been studied for 15° C T_{amb} starting set point of mechanical sub-cooling, and it is found that about 3% in Stockholm and 7.6% in Barcelona can be saved. The investment cost of a 60 kW propane sub-cooling unit should be taken into account which might be a strong factor in limiting the application of this feature.

Gas cooler evaporative cooling: in order to avoid operating the refrigeration system at high trans-critical pressures, water can be sprayed in the inlet air stream to the gas cooler. The evaporative cooling is activated when the outdoor temperature is relatively high. In this modelling work, the evaporative cooling is activated at an ambient temperature of 25 °C and above. The evaporative cooling process is assumed to be 80% efficient. 100% evaporative cooling efficiency means the dry bulb temperature reaches the wet bulb temperature. This evaporative cooling process results in lowering the dry bulb temperature by about 3 K.

It is calculated that the AEU saving is 1% in Stockholm and 3% in Barcelona. The main reason for this negligible impact is the running hours of evaporative cooling; it is active only for 2% of the year in Stockholm and 14% in Barcelona. Barcelona has relatively humid summer season. Evaporative cooling could result in higher annual savings in cities with drier summer periods. However, availability of water, water treatment, and components corrosion are some other factors which could limit the feasibility and wide spread usage of this choice.

LT de-superheater: a de-superheater after the LT booster compressor can be used for heat recovery in winter time and heat rejection in summer time. In both seasons, a simple assumption is used where the de-superheater is assumed to cool CO2 down to 35°C. The annual calculations of the system performance show that AEU saving is insignificant, less than 2% in case of using LT de-superheater. The reason for this insignificant saving is that the low stage mass flow rate in the LT is considerably smaller compared with high stage mass flow rate. This is due to the higher refrigeration load at MT than LT. In winter, the heat recovery ratio of low stage unit (the recovered heat in the low stage de-superheater divided by the LT refrigeration load) is about 7%, corresponding to 3 kW only.

Comparison results of modification features

The results of all the discussed modifications impact on AEU saving [%] are summarized in Figure 28. The reference system is a standard CO2 booster system with heat recovery. Heat recovery is included in all the modified solutions while air conditioning is not included. According to the results, the combined effect of flooded evaporation in MT and

LT levels and parallel compression shows the most promising solution which saves 13 and 17% of AEU in Stockholm and Barcelona, respectively.

Considering the discussed results in these five sub-sections, the SotA CO2 refrigeration system (SotA) can be defined as a system integrating heating and air conditioning functions. It uses flooded evaporation in MT and LT level, and parallel compression due to the significant combined effects of these features on energy efficiency. Mechanical sub-cooling, gas cooler evaporative cooling and LT de-superheater are not considered as essential features of this SotA system. However, for the regions with much warmer and drier climate conditions than Barcelona, mechanical sub-cooling and evaporative cooling are worth to be evaluated in the system design procedure.

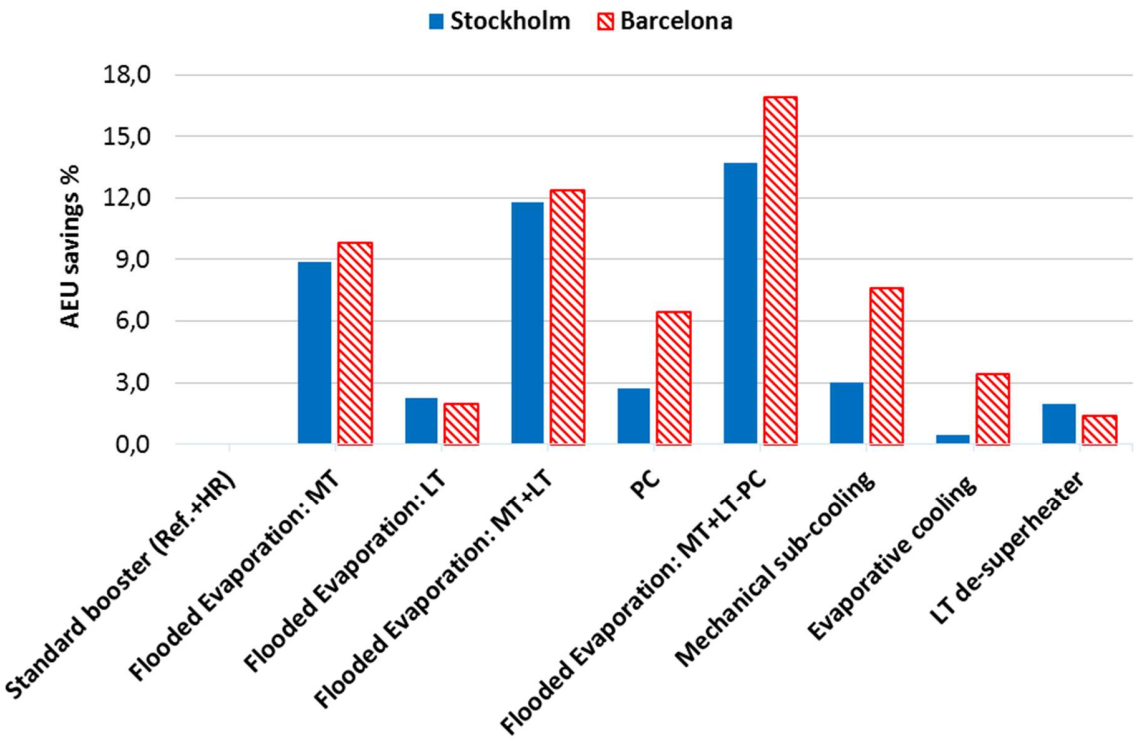


Figure abbreviations:

PC: Parallel compression, MT: medium temperature, LT: low temperature, HR: heat recovery, Ref: refrigeration

Figure 28: Impacts of modifications on AEU compared to a "standard CO2 booster with heat recovery"

In addition to the energy saving comparisons, an economic calculation is done to find out how much would it be justified to pay for each modified feature in order to get higher system efficiency. The lifetime of the system is assumed 15 years and the electricity price 0.1 €.kWh^{-1}. The results of this "justified cost" economic calculation is shown in Figure 29. As can be seen, the most efficient solution, combined flooded MT-LT and PC, justifies the payment of 104 thousand euros in Stockholm and 156 thousand euros in Barcelona.

Integration of heat recovery and air conditioning in the SotA system are other important features when comparing the installation cost of CO2 and other alternative cooling-heating solutions. These functions integration into the CO2 refrigeration system has much less installation cost comparing to conventional stand-alone heating and air conditioning systems.

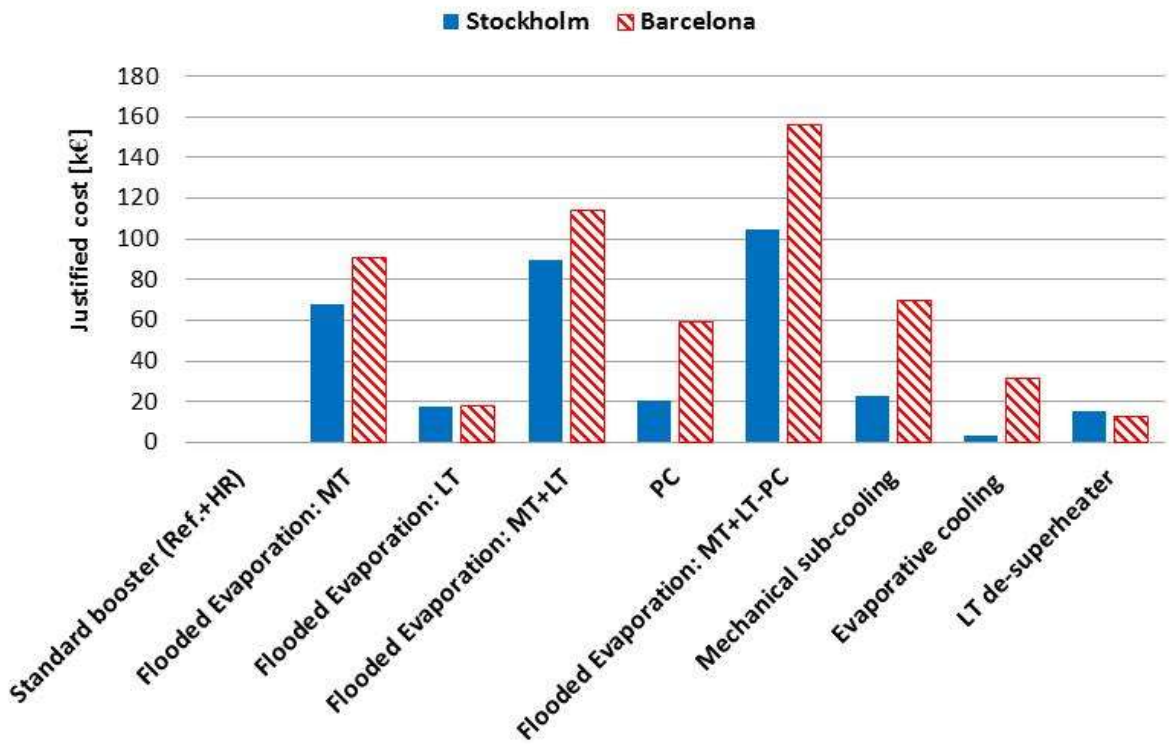


Figure abbreviations:

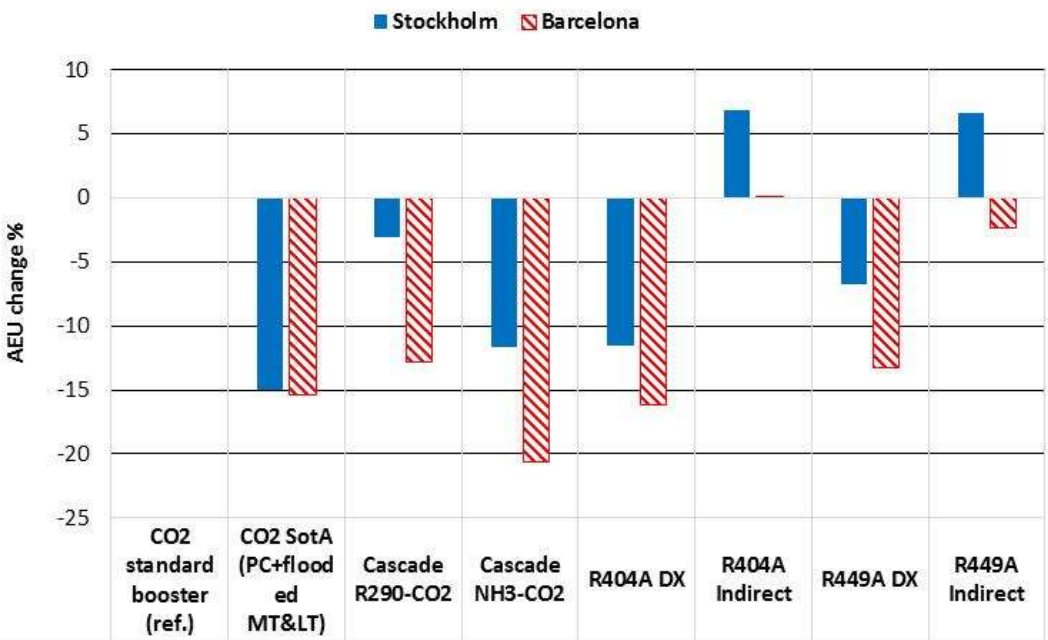
PC: Parallel compression, MT: medium temperature, LT: low temperature, HR: heat recovery, Ref: refrigeration

Figure 29: Justified cost [thousand Euros] for implemented modifications

Comparison of the SotA system with alternative refrigeration systems

The performance of SotA CO2 system is compared to standard CO2 and key alternative refrigeration solutions. These alternative systems include: conventional direct expansion DX, indirect synthetic refrigerant-based systems, and natural refrigerant-based cascade solutions. These systems are described earlier in this chapter.

The annual electricity use AEU of the refrigeration systems are compared to the reference standard CO2 trans-critical booster system in Stockholm and Barcelona. Only refrigeration load is included in this comparison. The annual electricity use of this system is 425 MWh in Stockholm and 612 MWh in Barcelona. The results of the comparison are shown in Figure 30. The negative values indicate the percentage of energy saving compared to the reference system.



	CO2 standard booster (ref.)	CO2 SotA (PC+flooded MT&LT)	Cascade R290-CO2	Cascade NH3-CO2	R404A DX	R404A Indirect	R449A DX	R449A Indirect
Stockholm	0,0	-15,0	-3,1	-11,7	-11,6	6,9	-6,8	6,6
Barcelona	0,0	-15,4	-12,8	-20,6	-16,2	0,0	-13,3	-2,3

Figure abbreviations:

PC: Parallel compression, MT: medium temperature, LT: low temperature, Ref: refrigeration, DX: direct expansion

Figure 30: Annual Electricity Use (AEU) change % compared to reference CO2 standard system (only refrigeration load is included, no heat recovery)

SotA CO2 system is the most energy efficient refrigeration solution in Stockholm, saves 15% of AEU compared to the standard CO2 system. Ammonia-CO2 cascade and R404A DX have comparable savings of about 12% in Stockholm and R449AA DX system saves about 7% of AEU.

The most energy efficient solution in Barcelona is ammonia-CO2 cascade with 21% AEU saving. CO2 SotA and R404A DX have comparable savings of 15-16% and R449AA DX system saves about 13% of AEU. The CO2 SotA system is still a strong solution considering the limitations of other alternative refrigeration system, discussed later in this section.

Propane-CO2 cascade solution has about 9% less saving compared to ammonia-CO2 cascade solution in both cities. The main reason for this difference is compressors efficiencies. The selected commercial propane compressor has about 5% less efficiency compared to the ammonia compressor. With a more efficient propane compressor this gap will decrease.

The HFC/HFO indirect solutions have the least efficiency in both cities. Standard CO2 refrigeration system is about 7% more efficient than HFC/HFO indirect system.

A common practice in some European countries is to have the condenser of this HFC/HFO indirect system in direct contact with the air (air cooled). If the condenser of the HFC/HFO indirect systems were assumed direct (air cooled), their energy efficiency could be increased by about 13%, compared to full indirect systems. This means these solutions would have rather comparable energy efficiency to full DX systems.

According to the results, the CO2 SotA system is the most energy efficient solution in cold climates. Ammonia-CO2 cascade solution has higher, R404A DX system has comparable, and R449A DX system has lower energy efficiency compared to the CO2 SotA system in warm climates. However, these systems have some operation limitations.

Usage of ammonia or propane requires taking safety precautions. Compact designs and limiting the refrigerant charge will facilitate the application of this refrigeration solution. The relatively high GWP (about 1400 for R448A and R449A, and 1500 for R407H) and the amount of refrigerant charge in the HFC/HFO DX systems make this solution vulnerable to present and probable future environmental regulations. The high cost of these refrigerants and non-regulated price changes, similar to what is happening for R404A in its phase-out period, is another problem that these systems will face. Considering these environmental and economic restrictions, the HFC/HFO DX solution may not be considered a long-lasting solution, specifically for new installations.

The refrigeration COP of CO2 SotA and three solutions presenting cascade, DX and indirect are shown in Figure 31. As can be seen in the figure, COP_{ref} of CO2 SotA system is higher than cascade NH_3-CO2 and R404A DX system in ambient temperatures lower than about 13 and 18 °C, respectively. The COP of the HFC indirect system is the lowest compared to all the other three options. The crossover temperature for standard CO2-R404A was about 23 °C in the authors' previous studies while this temperature for SotA CO2 is about 33 °C, as shown in Figure 31.

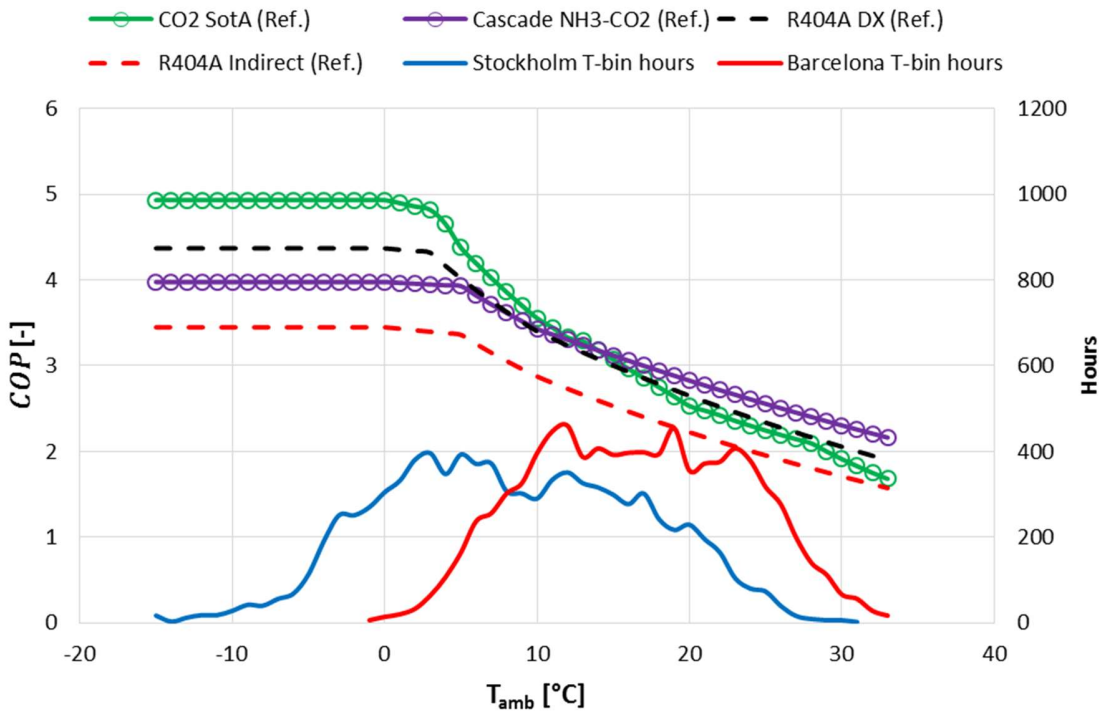


Figure 31: Total refrigeration COP (COP_{ref}) – right and temperature-bin hours - left

COP_{MT} and COP_{LT} are calculated to compare the systems' performance at two refrigeration temperature levels separately. In this way, the system is treated as two separate units for MT and LT, and can be compared to other system solutions. COP_{MT} and COP_{LT} values are presented in Figure 32.

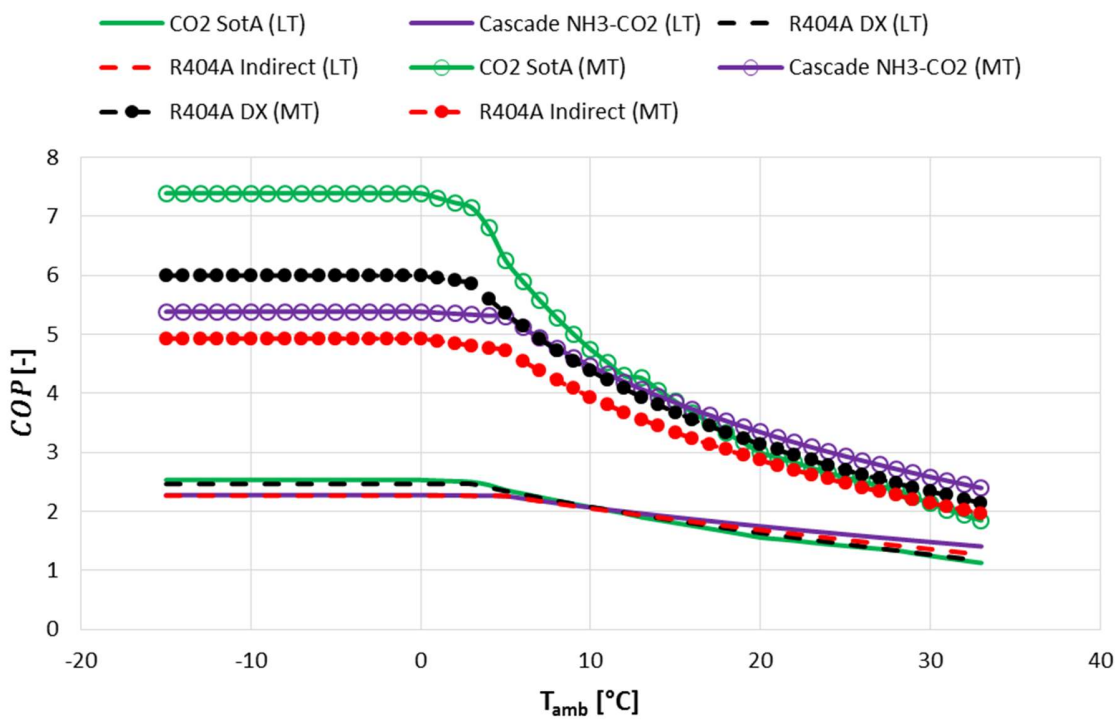


Figure 32: Medium temperature COP (COP_{MT}) and low temperature COP (COP_{LT})

TEWI Comparison

The Total Equivalent Warming Impact (TEWI) is a greenhouse gas emissions (i.e. global warming impact) measure used to assess the direct and indirect global warming impacts of refrigeration systems. The direct impact originates from the refrigerant leakage and end-of-life disposal. The indirect impact is associated with the CO2 emission content of the generated electricity, used by the refrigeration system. TEWI comparison provides a clear image of these impacts in the service lifetime of the refrigeration system.

The results of the TEWI analysis are shown in Figure 33. What can be observed is that the synthetic refrigerant-based refrigeration systems emit 2-7 times more greenhouse gases than the natural refrigerant-based refrigeration solutions during their lifetime in Stockholm. This enormous difference is clearly due to the leakage of high GWP synthetic refrigerants. Direct emissions are also high in Barcelona for the synthetic systems, however, it is not the major and only reason behind high GHG emissions of the systems.

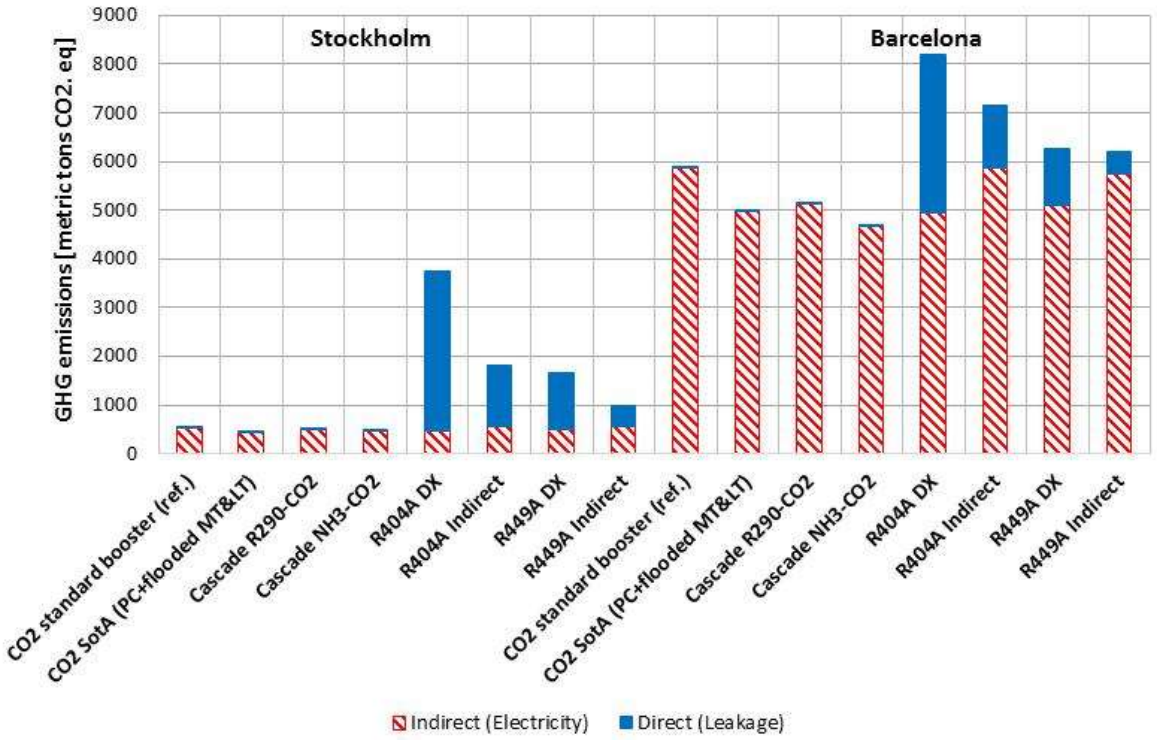


Figure 33: TEWI comparison of refrigeration systems in Stockholm and Barcelona

This TEWI analysis compared different "refrigeration system" solutions. If heat recovery/heating and air conditioning are added to have "energy systems" TEWI analysis, the integrated CO2 system would outperform the other cooling-heating alternatives more significantly in terms of being environmentally friendly.

3.4.3 Conclusions of Paper IV

This paper investigated the SotA modifications of a CO2 trans-critical booster system so as to identify the most promising features in terms of energy efficiency. The impacts and limitations of these features are compared to the standard CO2 system in Stockholm and Barcelona.

The results indicate that two-stage heat recovery, parallel compression, AC integration, and flooded evaporation are the important features of SotA integrated CO2 systems. Some other modifications including mechanical sub-cooling and gas cooler evaporative cooling are considered as arbitrary options considering their impact and limitations.

According to the calculation results, heat recovery in two stages is an energy efficient solution to provide tap water heating and space heating demands. Space heating SPF_{HR} of the CO2 system is about 10% higher than a stand-alone air source heat pump. Tap water heating is also provided by the CO2 system with high average COP_{TWH} values of

5.4. The heating provided by CO2 is about 50% cheaper than purchasing the heat from district heating network, and 20% cheaper than providing the heat by air source heat pump.

The air conditioning integration into CO2 system is compared with a stand-alone AC system. $SEER_{AC}$ of the CO2 system is comparable to stand-alone HFC-based AC system; about 4.5 in Stockholm and about 4 in Barcelona. Moreover, other factors including compactness and environmental considerations motivate the AC integration into CO2 system. Parallel compression activation matches well with air conditioning.

Flooded evaporation and the methods to provide it are discussed. An evaporation temperature increase of 3-4 K in MT and LT levels results in energy saving of about 12% in Stockholm and Barcelona. Evaporation side modifications seem to be more consistent and promising compared to high pressure side modifications including mechanical sub-cooling and gas cooler evaporative cooling. Flooded evaporation is considered as a promising solution in warm and cold climates. The combined impact of using flooded evaporation at MT and LT levels, and parallel compression is about 13% in Stockholm and 17% in Barcelona.

The refrigeration performance of the SotA CO2 system is compared to alternative refrigeration system solutions. These include cascade ammonia-CO2 and propane-CO2 solutions, and DX or indirect HFC/HFO solutions. Standard CO2 refrigeration system is considered as the reference system. Comparison of annual energy use (AEU) in Stockholm shows that the SotA CO2 system is the most energy efficient solution (15% AEU saving). Cascade ammonia-CO2 and HFO/HFC DX systems are other energy efficient choices. The AEU comparison in Barcelona indicates that ammonia-CO2 cascade has energy savings of about 20%, and the SotA CO2 system and R404A DX follow these systems with about 15-16% AEU saving. R449A DX system is less efficient than the SotA CO2 system both in warm and cold climates. This shows that the CO2 system is even an efficient solution for warm climates.

The safety limitations of cascade solutions and the environmental-economic limitations of HFC/HFO systems might be some factors which make the SotA CO2 system a favourable solution in both cold and warm climates. Furthermore, the integration of heating and AC makes this system a favourable all-in-one energy system. The cascade solutions can be considered as an alternative in warmer climates in case of satisfying the safety and risk issues. Using compact and low charge chillers facilitates this application. The synthetic refrigerant-based solutions have reasonable efficiency in warm climates, but are constantly subject to limitations of environmental regulations and long-term economic instabilities.

To conclude, the SotA integrated CO2 system is an energy efficient, environmentally friendly and compact solution able to provide the entire thermal demands of supermarkets efficiently in cold and warm climates.

3.5 Paper V - Investigate the potential for geothermal storage

This paper investigates the integration of geothermal storage into the SotA CO2 trans-critical booster systems. The objective is to evaluate the energy efficiency impact of this integration. Different scenarios of integration are studied including stand-alone and integrated supermarket building systems.

3.5.1 System Description of CO2 SotA with geothermal connections

The reference system in this study is SotA CO2 trans-critical booster system. This system is abbreviated as CO2 SotA hereinafter. The features of this system have been discussed in Paper IV.

A feature which hasn't been evaluated widely but applied in some supermarkets, mainly Scandinavians, is geothermal storage integration. The design concept is to use the ground as a heat sink in summer and a heat source in winter. The schematic of a CO2 SotA system and its integrated geothermal storage is shown in Figure 34. The geothermal integrated lines are highlighted by green color. The geothermal sub-cooler is located after the gas cooler and provides sub-cooling in the warm summertime. The heat is stored in the ground in this season and an extra evaporator is used to extract the heat from the ground in winter. The extracted heat is then "pumped" by the compressors to provide some extra heat in the heat recovery de-superheater.

As shown in Figure 34, the extracted heat can be added at P_{MT} level and compressed by high stage compressors or it can be added at P_{rec} level and processed by parallel compressors. In the case of heat extraction at P_{rec} level, the expansion valve before the extra evaporator is fully open. Both methods have been applied in field installations. Since there is not a significant difference between these two pressure levels in CO2 SotA system, it is expected that heat recovery is not strongly influenced by this choice.

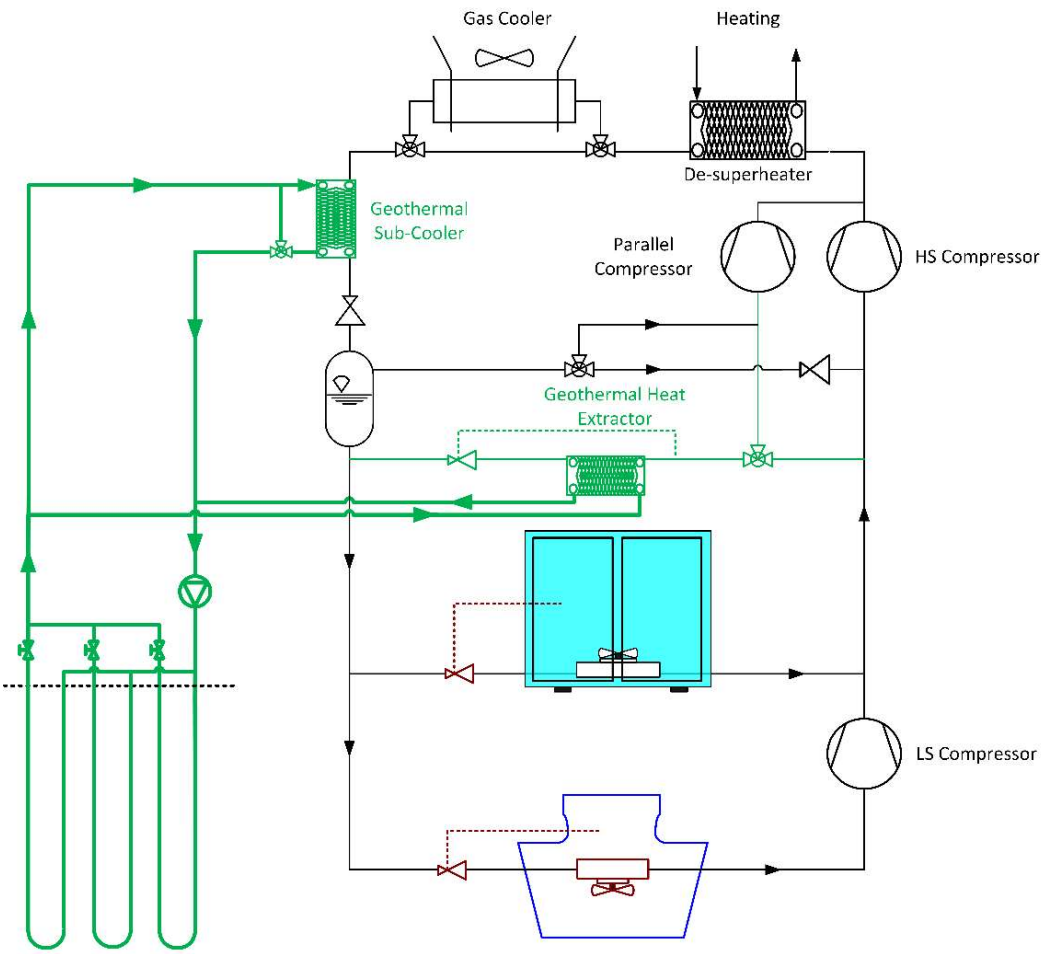


Figure 34: Schematic of a SotA CO2 booster system and integrated geothermal storage, the later highlighted by green

There is another option to extract and use the stored heat from the ground in winter. The solution is to run the CO2 system in floating condensing mode, i.e. lowest pressure possible, and a separate ground source heat pump (GSHP) extracts the heat from the ground, and provides the supermarket heating demands, as it is shown in Figure 35. This solution is called “hybrid” in this paper. The reason this system discussed is that some supermarkets use this solution, preferring to have separate operation and control of heating and refrigeration systems. The solution can also be applied to other non-CO2 refrigeration solutions where their heat recovery is not as efficient as CO2 heat recovery performance.

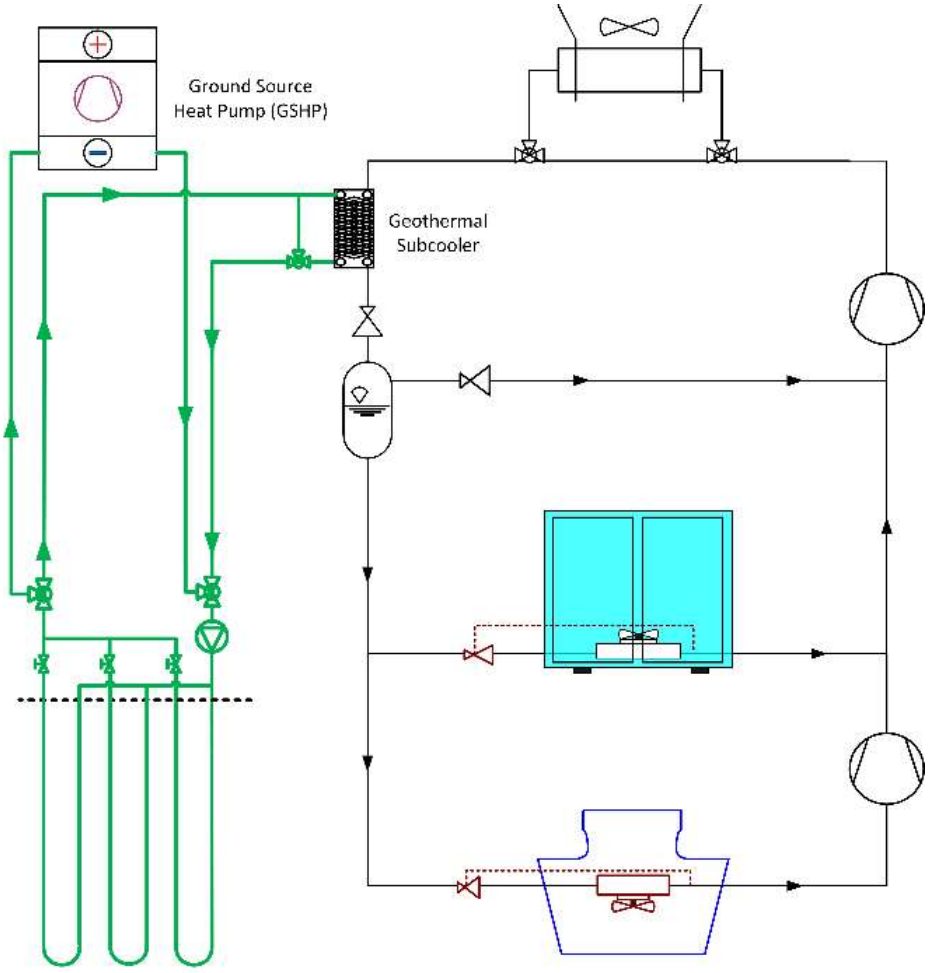


Figure 35: Hybrid geothermal solution, refrigeration system sub-cooling in summer, heat source for GSHP in winter

3.5.2 Results and Discussion

The refrigeration systems with geothermal connection possibilities have been modelled. The energy use and efficiencies of the refrigeration systems have been calculated in three different operation scenarios which have been referred to as research questions 1-3. The research questions are schematically sketched in Figure 36 and explained in the following paragraphs.

Question 1: in a stand-alone supermarket two systems are compared which are; the CO2 SotA system with heat recovery and without the geothermal connection (reference) Vs. CO2 SotA system with heat recovery and sub-cooling from the ground during summer, during winter heat is extracted from the ground by extra evaporator (i.e. geothermal heat extractor in Figure 34).

Question 2: In an integrated solution the supermarket is part of a larger building, such as shopping center (i.e. referred to as consumer in Figure 36), where the supermarket has the possibility to provide heat to the shopping center. The shopping center has also the possibility to buy heat from the district heating. In this question two systems are compared; “separate supermarket and district heating consumer” Vs. “integrated supermarket providing heat to the consumer by utilizing the geothermal connection; i.e. the refrigeration system recovers heat and acts as a ground source heat pump”.

Question 3: In a stand-alone supermarket two systems are compared which are; the CO2 SotA system with heat recovery and without the geothermal connection (reference) Vs. CO2 SotA system with heat recovery and with the hybrid geothermal connection presented in Figure 35.

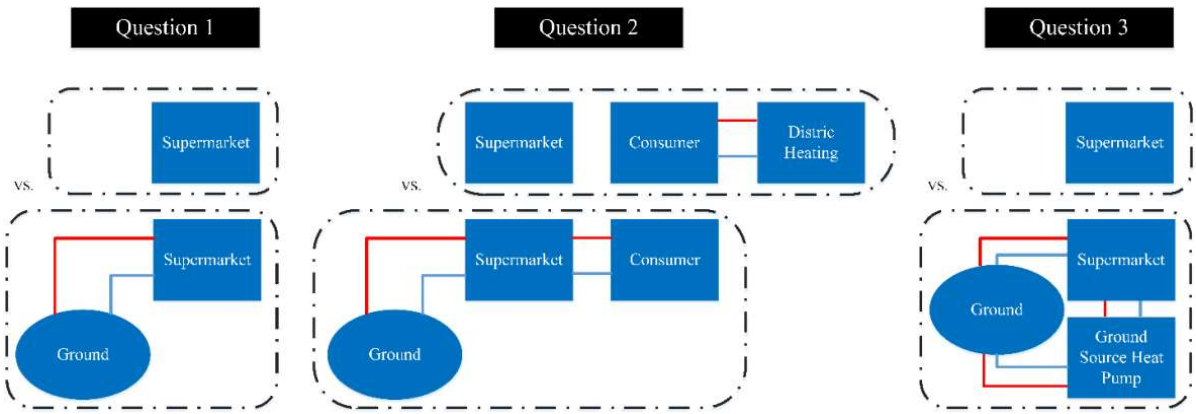


Figure 36: The three different operation scenarios (i.e. research questions 1-3)

Question 1: Stand-alone Supermarket

The first research question is to compare “CO2” and “CO2+geothermal” systems in a stand-alone supermarket. The annual energy use of CO2 SotA system without geothermal storage, and seven other geo-coupled cases are compared and the results are shown in Figure 37. The studied cases include only summer sub-cooling, three cases of heat extraction at P_{MT} level, and three cases of heat extraction at P_{rec} level. The extra evaporator $\dot{Q}_{ex}$ [kW] is studied for sizes of 40, 80 and 120 kW, in the later six cases. These values are selected to be a reasonable capacity able to be provided by the installed compressors. Summer sub-cooling is also studied for a reasonable range of up to 15K sub-cooling, this results in a sub-cooling design capacity of about 60kW.

As it can be seen in Figure 37, geothermal sub-cooling can provide about 4% AEU saving. However, this is most likely not a sustainable solution since the ground is used only as heat sink, and the stored heat is not used in winter.

The savings for the later six cases are less than 3%, this implies that heat recovery in the integrated CO2 plus geothermal system is less efficient than the stand-alone CO2 system. The heat pumping in these cases are activated for ambient temperatures lower than -5°C since heating efficiency is low at higher ambient temperatures than -5°C.

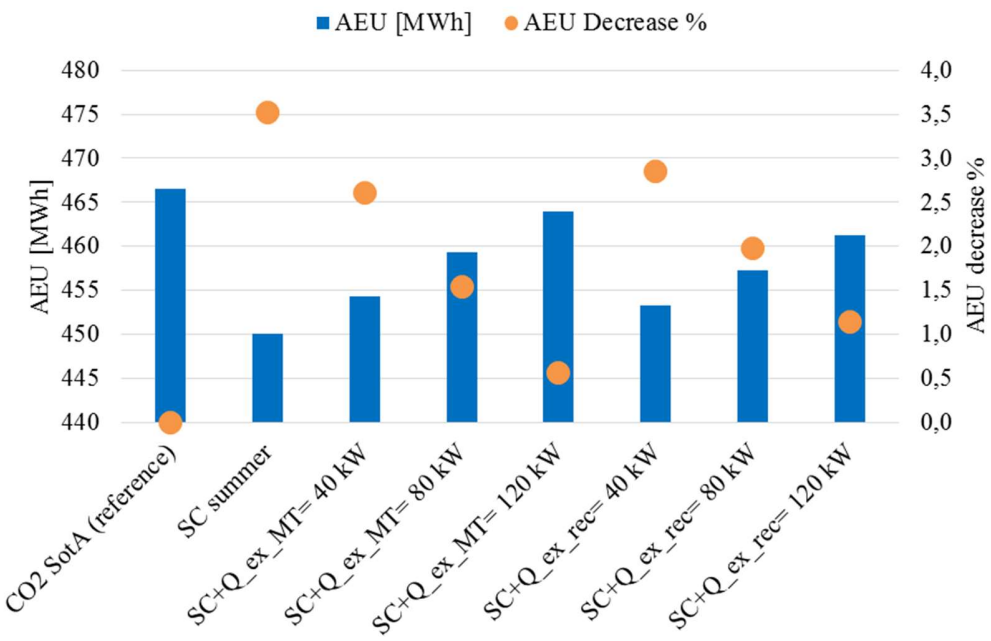


Figure abbreviations:

SotA: State-of-the-art, SC: sub-cooling, ex: extra evaporator, rec: receiver, MT: medium temperature

Figure 37: Annual Energy Use and Savings in AEU comparison

To justify why heat recovery in the integrated solution is less efficient than the stand-alone CO2 system, COP_{HR} of the CO2 system is compared to the heating COP of geothermal heat extraction $COP_{HR,ex}$. As it is shown in the figure, COP_{HR} of the CO2 system is higher than $COP_{HR,ex}$ for a wide range of ambient temperatures. This is more apparent in ambient temperatures higher than -5°C. As it is shown, $COP_{HR,ex}$ is only higher than COP_{HR} when the gas cooler is fully by-passed. This is the point that increase in the discharge pressure results in sharp drops in COP_{HR}. This means that the heat recovery from the stand-alone CO2 system should be prioritized and heat extraction from the ground should be activated only when the gas cooler is fully by-passed.

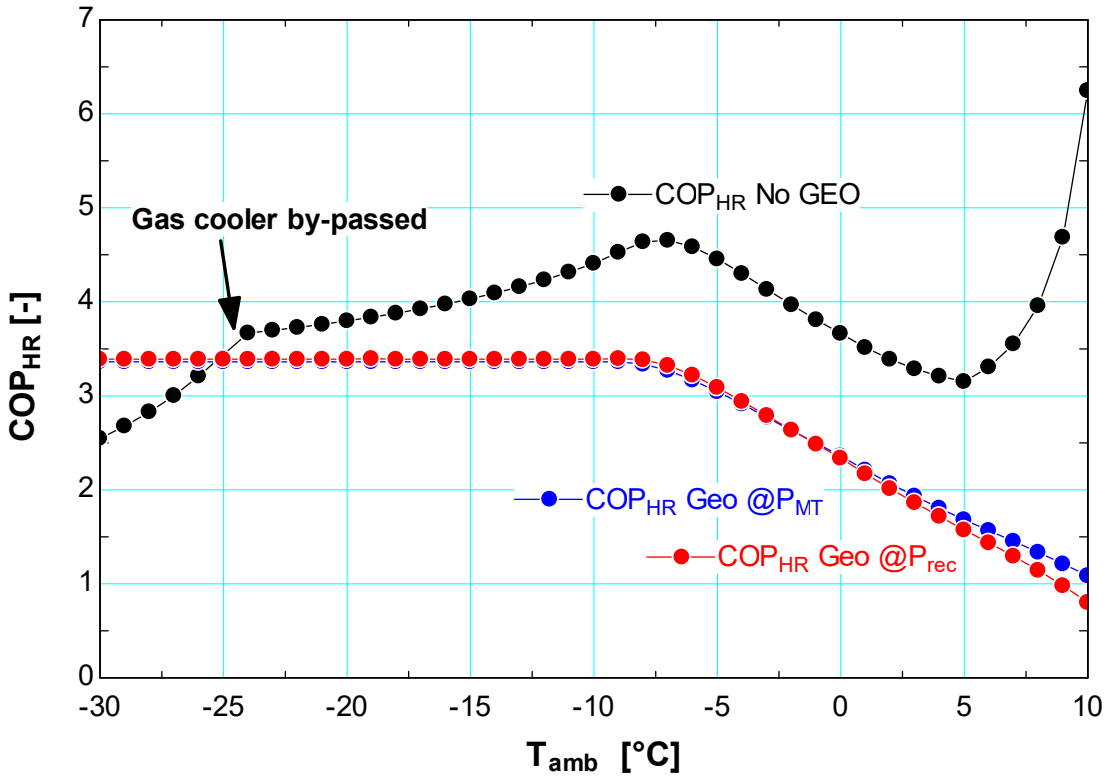


Figure 38: Heat recovery COPs for CO2 stand-alone and CO2 ground-coupled systems

Question 2: Integrated Supermarket

The second research question is to compare "separate supermarket and district heating consumer" systems with "integrated supermarket+consumer+geothermal" systems in two nearby supermarket and consumer buildings or facilities. This case is seen frequently, for example, when the supermarket is located inside a larger shopping mall. The consumer is assumed to have the same heating demand profile as the supermarket. Since the nature of heating and electricity are different, the separate and integrated solutions are compared based on the annual running cost spent on purchasing energy carriers. Two scenarios for energy prices are compared: rather high electricity price and low district heating price, and low electricity price and high district heating price. The numbers are based on prices on the Swedish market.

The results of the comparison are shown in Figure 39. As can be seen in the figure, depending on the energy prices, the integrated solution can offer about 20-30% of annual running cost savings. This integrated solution can offer lower heating prices for the consumer and provides some profits to the supermarket due to the winter time heating sale and summer time sub-cooling.

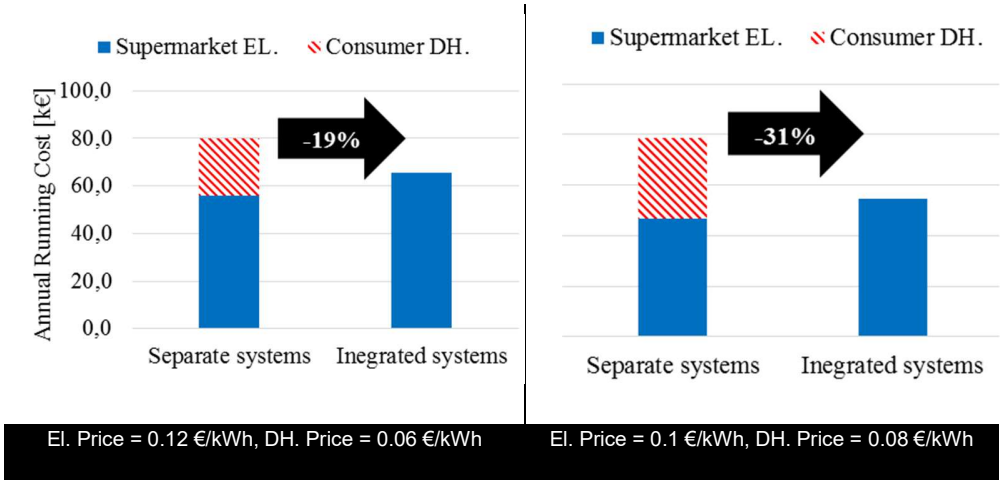


Figure 39: Separate and integrated systems annual running cost [thousand Euros]

Question 3: Hybrid solution

The third research question is to compare "CO2" and "hybrid CO2 + GSHP" systems. As mentioned earlier, the entire supermarket heating demand is provided by heat recovery from the CO2 system in a stand-alone supermarket. However, the heat demand in the supermarket with the hybrid solution is provided by the GSHP. The ground is the heat source for GSHP in winter and heat sink for CO2 sub-cooler in summer.

The results of the comparison are shown in Figure 40. The hybrid system consumes about 8% less electricity than the stand-alone CO2 system in summer, thanks to the geothermal sub-cooling. On the other hand, the winter energy use of the stand-alone system is 5% less than the hybrid system. These energy use decrease in summer and increase in winter counter balance, and the hybrid system is only 2% more efficient than the stand-alone CO2 system annually.

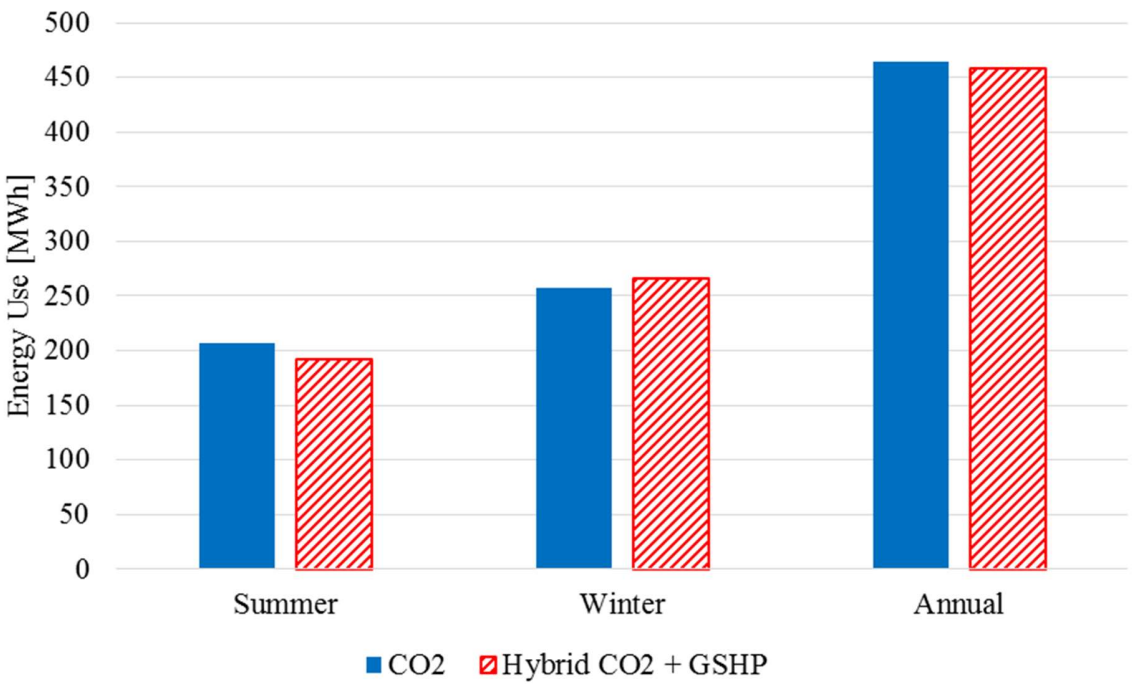


Figure 40: Energy use of stand-alone CO2 vs hybrid system solutions

In order to understand why heat supply by GSHP is less efficient than CO2 heat recovery, the heating COP of the GSHP has been added to Figure 38 and is presented in Figure 41. As can be seen in the figure, the heating COP of the GSHP is lower than heat recovery COP of the CO2 system in below zero ambient temperatures. This COP is even lower than the heating COP of the “CO2 system with extra evaporator” for very cold ambient temperatures. This means that if heat extraction from the ground is required in winter, it is more efficient to pump the heat through the CO2 system, rather than GSHP.

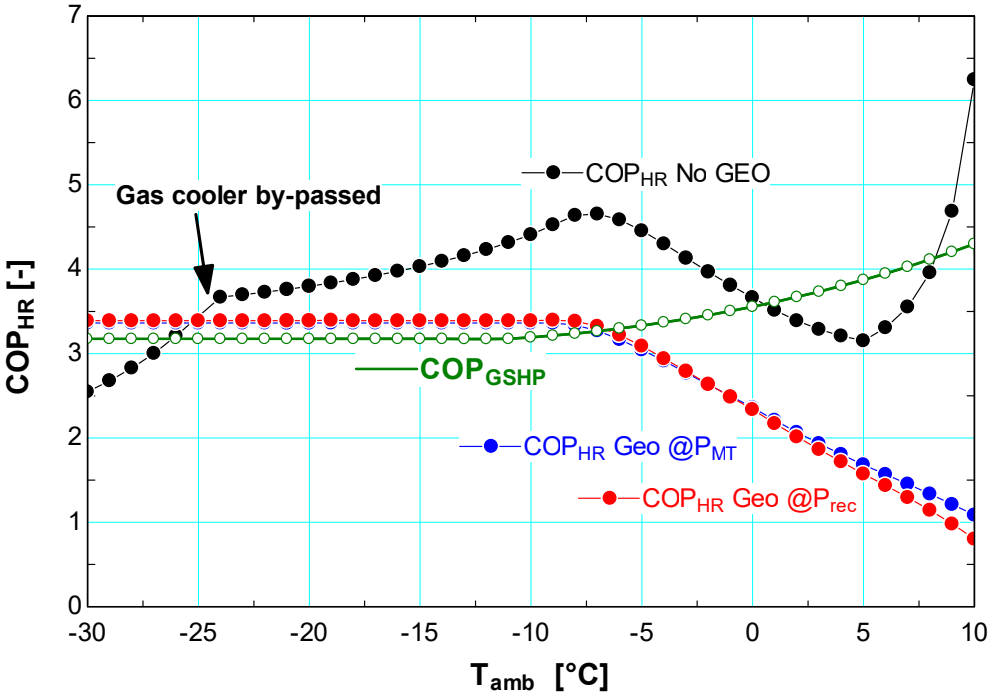


Figure 41: Heating COPs for stand-alone CO2 and ground-coupled CO2 systems, including GSHP

Since the entire heat is provided by GSHP, the calculations show that the winter load on the ground has a higher order of magnitude than the summer heat injection load. This results in a total number of 24 boreholes required which is much higher compared to a CO2 system, where heat recovery is prioritized to heat extraction. This large number of boreholes are required to guarantee thermally balanced ground over the lifetime of the system. The payback time for such a large bore field is estimated to be more than 7-8 years since, in addition to the borehole drilling and pipe heat exchanger costs, a large heat pump is required to be purchased. To sum up, integration of ground source heat pump and CO2 system does is not economically favorable over the stand-alone CO2 system.

3.5.3 Conclusions of paper V

This paper investigated the advantages and challenges of geothermal storage integration into a SotA CO2 supermarket refrigeration system. Three different research questions on integration scenarios are studied. The first scenario is to integrate geothermal storage and CO2 system in a stand-alone supermarket. The second scenario is to supply the heat from a ground-coupled CO2 system to a nearby consumer buying heat from the district heating network. The third research question is to have an integration of CO2, geothermal storage, and a ground source heat pump (GSHP).

The results indicate that heat recovery from a stand-alone CO2 SotA system is more efficient than providing part of the heating demand by using an extra heat source, here, the ground. It has been shown that using this option is beneficial only when the gas cooler is fully by-passed. This is added as the ultimate step in a previously-presented stepwise heat recovery control strategy. However, it is shown that in the summer sub-cooling the CO2 system with the ground can save about 4% of the AEU.

The second research question results show that annual running cost of two separate supermarkets and district heating consumer can be decreased by 20-30% if the systems are coupled; i.e. geothermal storage is applied and supermarket provides heating for the consumer. A parametric study shows that with the current energy prices, the integrated solution can be applied with a payback time of less than 3 years.

Study on the hybrid solution, CO2 system and a separate GSHP, shows that about 2% of the AEU can be saved compared to stand-alone CO2 system. However, the demand for a large borehole field makes the payback time very long and the solution not economically feasible.

To conclude, geothermal storage integration into CO2 supermarket refrigeration system doesn't have a significant impact in the case of a stand-alone supermarket. In the case of an integrated supermarket with a neighboring building/facility the heating demand is much higher than a stand-alone supermarket where geothermal storage integration can contribute to significant running cost savings. The application of a separate GSHP is also not recommended since heat can be recovered from the CO2 system efficiently.

4 Discussions

This project started the research work by connecting to early research work on field measurements where old and newer CO2 refrigeration systems where analyzed and compared to the conventional solution in Sweden. The field measurements results have been complemented with modelling analysis and have been published in two journal papers.

The results show that the newer CO2 refrigeration systems (installed in 2010) has 35-40% higher total COP compared to older exampled of 2007. The newer CO2 refrigeration systems have also been compared to conventional HFC solutions and showed higher COP values from the field measurements. Modelling the performance of CO2 and HFC conventional refrigeration systems for Stockholm region shows that about 20% lower AEU is expected when using CO2 refrigeration system.

The studies in the first two papers showed that the newer CO2 refrigeration system solution, which is a booster system with flash gas by-pass at intermediate pressure level, has the highest COP among the compared solutions; therefore, it has been used as the reference CO2 system solution that is well characterized in performance and to be improved by the research in this project.

CO2 refrigeration system can be controlled to recover heat to provide space and domestic hot water heating during the winter. It can also provide air conditioning during the summer by applying parallel compression at the high stage. The system is called the integrated CO2 trans-critical system.

Field measurements and modelling of the integrated CO2 trans-critical system running in Stockholm show that air conditioning can be provided by the refrigeration system with parallel compression at efficiencies (COP_{AC} is about 4,5) comparable or higher than stand-alone HFC conventional alternatives.

The system is also able to cover all the space heating demand in an average size supermarket in Sweden with heating COP (or heat recovery COP) of 4-6 which is higher than, or comparable to, the majority of the efficient commercial heat pumps in the market. The additional installation cost required to recovery heat from the refrigeration system is negligible when compared to costly ground source heat pumps.

Further modifications to the integrated system solution have been studied in order to define the SotA energy system for supermarkets. SotA system is the most efficient and cost effective system that can be installed in supermarkets today. The analysis of several possible features of the SotA system showed that such system should have two-stage

heat recovery for space and tap water heating, parallel compression, AC integration, and flooded evaporation at medium and low temperature levels.

The refrigeration performance of the SotA CO2 system is compared to the reference CO2 solution and to alternative refrigeration system. These include cascade ammonia-CO2, cascade propane-CO2, DX HFC/HFO, and indirect HFC/HFO solutions. Comparison of AEU in Stockholm shows that the SotA CO2 system is the most energy efficient solution with about 15% AEU saving compared to the reference CO2 system.

The performances of the SotA system and the other alternatives have also been studied in warmer climate represented by Barcelona where SotA CO2 system and R404A DX have comparable energy use. However, ammonia-CO2 cascade has the highest energy savings of about 20% compared to CO2 reference.

An additional feature that can potentially improve the efficiency of the SotA system is the connection to the ground to provide heating in the winter and provide sub-cooling to the refrigeration system in the summer. The results show that heat recovery from SotA CO2 system is more efficient than extracting heat from the ground. Extracting heat from the ground is only beneficial when the gas cooler of the refrigeration system is fully by-passed; i.e. the refrigeration system cannot recover more heat at high efficiency.

However, if the supermarket has the possibility to provide heat to neighboring building (i.e. the heating demand is high) then it is beneficial to use the refrigeration system as heat pump to extract heat from the ground. This will save 20-30% of the annual running cost when compared to buying heat from the district heating network.

The summary of the results is that the SotA integrated CO2 system is energy efficient, environmentally friendly all-in-one compact solution able to provide the entire thermal demands of supermarkets efficiently in cold and warm climates. The system offers at least 15% annual energy savings compared to standard CO2 system and at least 25% compared to conventional systems with HFC's; making the system the most efficient and cost effective that can be installed today in Sweden. An average size supermarket in Sweden is expected to consume about 500MWh electricity for refrigeration, heating and air conditioning, which means that the SotA system will result in savings of at least 75 to 100MWh/year/system. The energy savings are especially important since the EU F-gas regulations means that the installation of CO2 based refrigeration systems for supermarkets will further accelerate due to the ban on installing systems with HFC's, which will practically be phased out from supermarket application starting from 2020.

Besides being the commercial building with the highest energy use intensity, supermarkets are also the largest consumers in Europe of high GWP refrigerants. Therefore, the use of CO2 (GWP=1) to replace the HFC-R404A (GWP=3922) will have significant contribution to better environment in the future with more and more installation

of the efficient CO2 systems. The environmental impact can be observed in the Total Environmental Warming Impact (TEWI) which is three times higher for conventional HFC system compared to SotA CO2 system.

The research activities conducted in this project have been done in close cooperation with our industrial partners with continuous dialogue and feedback. The analysis in this project has been expanded to cover other alternative systems and warmer climates which are expected to strengthen the competence of Swedish companies in providing several energy solutions for local and international markets.

The detailed and documented results in this project will give more attention to environmentally friendly technologies and will put more pressure on the future systems to be more efficient and environmentally friendly.

Recommendations for future work focuses on demonstrating the performance of the SotA energy system. The system does not exist yet in a supermarket installation. Some newly installed systems may have some common features with the SotA system but they are not necessarily to be optimized in design and cost. A demonstration project will offer great opportunity where researchers can be involved at early stage of designing the SotA system and gather all needed information on the case study. The researchers can make sure that the system is instrumented, monitored and evaluated as if it would be a test rig running in a laboratory.

Focus should also be directed towards the possibility of integrating the supermarket energy system into the district heating and cooling networks. In such arrangement the supermarket system can recovery (i.e. sell) heat to the district heating network when the conditions are right for high efficiency and good price. The reserve compressor capacity can also be used to provide cooling to the district cooling network; i.e. selling cold.

All the new features and the integration possibilities of the supermarket's energy system require careful control strategies so the system operates at the highest efficiency possible at all times. This aspect should further be investigated.

5 Publications list

One of the conference papers won two prizes in major international conference and one of the MSc thesis reports won prize from regional association in Spain. Details are in the list below.

The project publications are listed below. The contribution of the key publications to the project activities and objectives is clear in the results chapter.

Journal papers

4 published and 1 to be submitted to International Journal of Refrigeration:

1. Sawalha, S., Karampour M., and Rogstam J., Field measurements of supermarket refrigeration systems. Part I: Analysis of CO2 Trans-critical Refrigeration Systems, Applied Thermal Engineering, 2015. 87 (8), pp. 633-647.
2. Sawalha, S., Piscopiello S., Karampour K., Manickam L., and Rogstam J., Field measurements of supermarket refrigeration systems. Part II: Analysis of HFC refrigeration systems and comparison to CO2 trans-critical, Applied Thermal Engineering, 2017. 111 (1), pp. 170-182.
3. Karampour, M., Sawalha, S., Energy efficiency evaluation of integrated CO2 trans-critical system in supermarkets: A field measurements and modelling analysis, International Journal of Refrigeration. 2017. 82(10), pp. 470-486
4. Karampour, M., Sawalha, S., State-of-the-Art Integrated CO2 Refrigeration System for Supermarkets: a Comparative Analysis, International Journal of Refrigeration. 2018. 86(2), pp. 239-257
5. Draft to be submitted in the near future:
   Karampour, M., Sawalha, S., Mateo-Royo C., and Rogstam J., Geothermal Storage Integration into Supermarket's CO2 Refrigeration System. Planned for the International Journal of Refrigeration in April 2018

Conference papers:

8 in total: 4 published, 1 accepted to be published in June, 2 submitted to be published in June, and 1 to be submitted in two weeks:

1. Karampour M., Sawalha, S., Abdi A., Arias J., and Rogstam J., Review of Supermarket Refrigeration and Heat Recovery Research at KTH-Sweden. IIR Ammonia and CO2 Refrigeration Technologies Conference. 2015: Ohrid, Republic of Macedonia.
2. Karampour M. and Sawalha, S.,Theoretical Analysis of CO2 Trans-critical System with Parallel Compression for Heat Recovery and Air Conditioning in

Supermarkets, the 24th IIR International Congress of Refrigeration (ICR). 2015: Yokohama, Japan.

3. Karampour M. and Sawalha, S., Integration of Heating and Air Conditioning into a CO2 Trans-Critical Booster System with Parallel Compression. Part I: Evaluation of key operating parameters using field measurements. 2016: 12th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIF/IIR, Edinburgh, Scotland.
4. Karampour M. and Sawalha, S., Integration of Heating and Air Conditioning into a CO2 Trans-Critical Booster System with Parallel Compression. Part II: Performance analysis based on field measurements. 2016: 12th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIF/IIR, Edinburgh, Scotland.
   The paper won two prizes in the conference:
   - Prize for the best student paper on the theme of sustainability
   - and prize of the best overall student paper
5. Mateu-Royo C., Karampour M., Rogstam J., and Sawalha S. Integration of Geothermal Storage in CO2 Refrigeration Systems for Supermarkets. 2018: 13th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIF/IIR, Valencia, Spain.
6. Karampour M. and Sawalha S. Integration of Geothermal Storage in CO2 Refrigeration Systems for Supermarkets. 2018: 13th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIF/IIR, Valencia, Spain.
7. Piscopiello S., Karampour M., Michele Pressiani M., and Sawalha S. Guidelines of How to Instrument, Measure and Evaluate Refrigeration Systems in Supermarkets; With Focus On CO2 Trans-Critical Booster Systems. 2018: 13th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIF/IIR, Valencia, Spain.
8. Karampour, M., Sawalha, S., Mateo-Royo C., and Rogstam J., Geothermal Storage Integration into Supermarket's CO2 Refrigeration System. To be submitted to International Ground Source Heat Pump Association-Sweden Second Biennial Conference, September 2018.

Master thesis:

1. Mateu-Royo C., Field Measurements and Modelling Analysis of CO2 Refrigeration Systems with Integrated Geothermal Storage, 2017.
   1st prize winner of the Spanish Association of Refrigeration and Air Conditioning (ATECYR) competition for best MSc thesis work. Currently the thesis is nominated to the European student competition. This competition will be in Brussels (Belgium) and is organized by Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA). Results expected in April 2018.
2. Adnan R., Energy Efficienty of CO2 Trans-critical booster systems, 2015

Technical magazine:

1. Karampour, M., Sawalha, S., 2017. Morgondagens energieffektiva livsmedelsbutik. Kyla & Värme NR 3, 18–19.

2. Karampour, M., Sawalha, S., 2015. Morgondagens energieffektiva livsmedelsbutik. Kyla + Värmepumpar NR 7, 39.

Presentations and conference presentations:

- Participating in ATMOsphere Europe, September 2017, Berlin
- Participating in ATMOsphere Europe, April 2016, Barcelona
- Poster presentation oral presentations at:
    - Svenska Kyl & Värmepumpdagen 2017- 20 October 2017, Stockholm
    - Svenska Kyl & Värmepumpdagen 2016- 21 October 2016, Göteborg
    - Svenska Kyl & Värmepumpdagen 2015- 16 October 2016, Göteborg
    - KTH Energy Dialogue day - 24 Nov 2017, KTH, Stockholm, Sweden
    - KTH Energy Dialogue day - 24 Nov 2016, KTH, Stockholm, Sweden
    - KTH Energy Dialogue day - 26 Nov 2015, KTH, Stockholm, Sweden
    - Effsys Expand forskardagar, 16 May 2016, Tranås, Sweden
    - Norwegian refrigeration association meeting, 19 April 2017, Trondhiem, Nowray

PhD thesis:

It is expected to be published in September 2018.

Contribution to publications and research work

Mazyar Karampour has been the principal researcher in this project and responsible for most of its publications. The project leader and principal supervisor has been Samer Sawalha. Jaime Arias is an associate professor at the Energy Technology department who provided key calculations for energy load profiles using in-house calculation tool. Jörgen Rogstam from our partner Energi & Kylanalys supported in communicating with the partners to provide access to key installations, especially for the geothermal analysis.

All the industrial partners in the project helped in providing access to field installations, they provided information about existing installations and their features and helped contacting the store owners. In some cases missing instrumentations had to be installed which was accomplished by the industrial partners. Also the industrial partners helped explaining the logic behind some of the control techniques applied and they provided information on the components installed; compressor models for example.

The industrial partners engaged in discussing the results during the periodical project meeting and in individual discussions whenever was necessary. The feedback and the open atmosphere during project meetings facilitated the progress in the project work.

Students working on their graduation projects also contributed to the project, Carlos Mateu-Royo is an exchange student who did his master thesis on the geothermal integration into supermarket's energy system. Adnan Ribic is another exchange student who did his master thesis studying the first CO2 system with ejector in Sweden.

6 References

Detailed references can be found in the project publications.

7 Appendix

1. Journal paper I
2. Journal paper II
3. Journal paper III
4. Journal paper IV
5. Journal paper V