International Journal of Refrigeration xxx (xxxx) xxx

Contents lists available at ScienceDirect

International Journal of Refrigeration

journal homepage: www.elsevier.com/locate/ijrefrig

Geothermal storage integration into a supermarket's CO_2 refrigeration system

Mazyar Karampour[a,*], Carlos Mateu-Royo[b], Jörgen Rogstam[c], Samer Sawalha[a]

[a] Energy Technology Department, Royal Institute of Technology (KTH), Brinellvägen 68, SE-100 44 Stockholm, Sweden
[b] Department of Mechanical Engineering and Construction, ISTENER Research Group, Universitat Jaume I, Campus de Riu Sec s/n, E12071 Castelló de la Plana, Spain
[c] Energi & Kylanalys AB, Varuvägen 9, Älvsjö 125 30, Sweden

ARTICLE INFO

Article history:
Available online xxx

Keywords:
State-of-the-art CO_2 system
Supermarket
Geothermal energy storage

ABSTRACT

This paper investigates the integration of geothermal storage into state-of-the-art CO_2 trans-critical booster systems. The objective is to evaluate the impact of this integration on energy efficiency. Three scenarios of integration are studied including stand-alone and integrated supermarket building systems.

The results show that for a stand-alone average size supermarket, heat recovery from the CO_2 system should be prioritized over a separate ground source heat pump. Extracting heat from the ground by an extra evaporator in the CO_2 system has also little impact on this supermarket annual energy use. However, in the case of supermarket integration with a neighboring building where the supermarket provides heat to the neighbor, geothermal storage integration can reduce the total annual running cost of the two non-integrated buildings by 20–30% with a payback time of less than 3.5 years. The results also show there is no need for a separate ground source heat pump.

Intégration du stockage géothermique dans le système frigorifique au CO_2 d'un supermarché

Mots-clés: Système au CO_2 de pointe; Supermarché; Stockage d'énergie géothermique

1. Introduction

Supermarkets are the most energy intensive commercial buildings where the refrigeration system is their largest energy user (Karampour et al., 2016). Supermarkets are also the largest consumers in Europe of high global warming potential (GWP) refrigerants; about 35% of Europe hydrofluorocarbons (HFC) consumption (SKM Enviros, 2012). The latter resulted in adopting the EU F-gas regulation; the European supermarkets are banned to use any refrigerant with GWP higher than 150 for centralized systems larger than 40 kW from year 2022, with exception for primary cycle in cascade configurations to use refrigerants with GWP up to 1500 (EU 517/2014, 2014).

These two factors place environmentally-friendly and energy-efficient supermarket refrigeration solutions as one of the priorities on climate change mitigation policies. CO_2 trans-critical refrigeration systems for supermarkets are viewed as a solution that are more environmentally-friendly and more/as efficient as advanced conventional solutions (Gullo et al., 2018a; Karampour and Sawalha, 2018); therefore, they have been introduced, installed, and spread in mainly the relatively cold regions of Europe and the world with more than 20,000 systems as of November 2018 (Skačanová, 2018).

CO_2 refrigeration systems have become standard in some relatively cold climate countries. Integrating other thermal functions, including space/water heating, and air conditioning, and their performance in warmer climates have been subject to research and optimization. The latter is due to the fact that standard CO_2 systems loses efficiency more rapidly than other conventional HFC cycles in warm climates. Various modifications to increase the

* Corresponding author.
E-mail addresses: mazyar.karampour@energy.kth.se, mazyar@kth.se (M. Karampour).

https://doi.org/10.1016/j.ijrefrig.2019.05.026
0140-7007/

Nomenclature

AC	Air Conditioning
AEU	Annual Energy Use
COP	Coefficient of performance
DH	District heating
EED	Earth Energy Designer
El	Electricity
EES	Engineering Equation Solver
GSHP	Ground source heat pump
GWP	Global warming potential
HFC	Hydrofluorocarbons
HP	Heat pump
HR	Heat recovery
LT	Low temperature level
MT	Medium temperature level
NPV	Net present value
PC	Parallel compression
PR	Pressure ratio
Ref	Refrigeration/refrigerant
S	Scenario
SC	Sub-cooling
SotA	State-of-the-art

Variables

a	coefficient for compressor efficiency
AEU	annual energy use, MWh
b	coefficient for compressor efficiency
c	coefficient for compressor efficiency
COP	coefficient of performance
f	frequency of operation, h
$\dot{E}$	electric power, kW
h	enthalpy per unit mass, kJ kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
n	number of temperature-bins
P	pressure, bar
Q	cooling or heating energy, MWh
$\dot{Q}$	cooling or heating load, kW
T	temperature, °C

Greek variables

Δ	difference
η	efficiency of compressor

Subscripts

AC	air conditioning
amb	ambient
comp	compressor
dsh	de-superheater
El	electricity
ex	heat extraction
f	secondary fluid
fan	gas cooler/condenser fans
fc	floating condensing
gc	gas cooler
gc exit	gas cooler exit
GEO	geothermal, geothermal storage
HR	heat recovery
is	isentropic
LT	low temperature level
MT	medium temperature level
opt	optimal
PC	parallel compression
max	maximum
rec	receiver
ref	refrigeration/refrigerant
tot	total

energy efficiency of CO_2 systems have been evaluated by researchers (Gullo et al., 2018a2018b; Hafner and Banasiak; 2016, Llopis et al., 2015; Javerschek et al., 2016; Minetto et al., 2014a; Karampour and Sawalha, 2017; Pardiñas et al., 2018; Purohit et al., 2018). Based on evaluation and review of these modifications, the definition of the state-of-the-art (SotA) CO_2 system has been introduced (Karampour and Sawalha, 2018). This CO_2 SotA system is presented in Section 2.

A potential improvement, which was not covered in the authors' previous research and is less studied comprehensively in the literature to the best of authors' knowledge is the integration of geothermal storage into the CO_2 state-of-the-art (SotA) system. The potential advantage of this integration is that the ground can be used as a heat sink to provide sub-cooling for the CO_2 system in summer and as a heat source in the winter for the heat pumping function of the CO_2 refrigeration system or via a separate Ground Source Heat Pump (GSHP).

Geothermal storage has good complementary characteristics with the CO_2 refrigeration system function. It is a well-known fact that CO_2 system efficiency drops more rapidly than other conventional refrigerants at high ambient temperatures. This efficiency reduction has been shown in a field performance analysis of CO_2 and HFC systems (Sawalha et al., 2017). The ground is typically colder than the ambient air in these time periods; therefore, it can be used as a heat sink for sub-cooling of the CO_2 refrigeration system and thereby increase system efficiency. In winter, the cooling demand of the supermarket decreases typically to 50% or less of the average summer demand (Polzot et al., 2017; Karampour and Sawalha, 2017; Freléchox, 2009). This means that about half or more of the compressors' installed capacity is not used in winter time. This unused capacity can be applied to extract heat from the ground and provide heating either for the supermarket or a neighboring facility. Heat extraction during the winter cools the ground and prepares it for the following summer season sub-cooling.

The literature on the concept of geothermal storage integration into supermarket energy systems can be classified into two categories: (1) a major number of oral and written publications present the concept design with less deeper study on the geothermal integration impact. (2) Few publications evaluate the energy efficiency impact of this integration more in detail.

Of the first category, a number of supermarkets using geothermal storage have been introduced in a review of eco-friendly supermarkets (Karampour et al., 2016). Some examples of Swedish supermarkets applying this technology and the lack of proper/adequate measurements for detailed studies are presented and discussed by Mateu-Royo (2017). The design concept of integrating various energy systems in a supermarket and taking advantage of ground storage is also presented by Hafner et al. (2014). In a Norwegian Rema 1000 supermarket four boreholes each 170 m deep have been installed to sub-cool a CO_2 system, and provide free cooling for air conditioning and de-humidification in summer. The stored heat is extracted and used for various heating demands in winter. This extra heat source for the CO_2 system has made the supermarket independent of any auxiliary heating supply. The ground storage is mentioned as one the reasons the electricity use is 30% lower compared to four other similar supermarkets (Sintef, 2016).

Of the more detailed studies, Rehault and Kalz (2012) evaluated the impacts of geothermal storage integration in a German supermarket using a CO_2 trans-critical booster system. The supermarket targeted a 30% energy reduction compared to the average energy

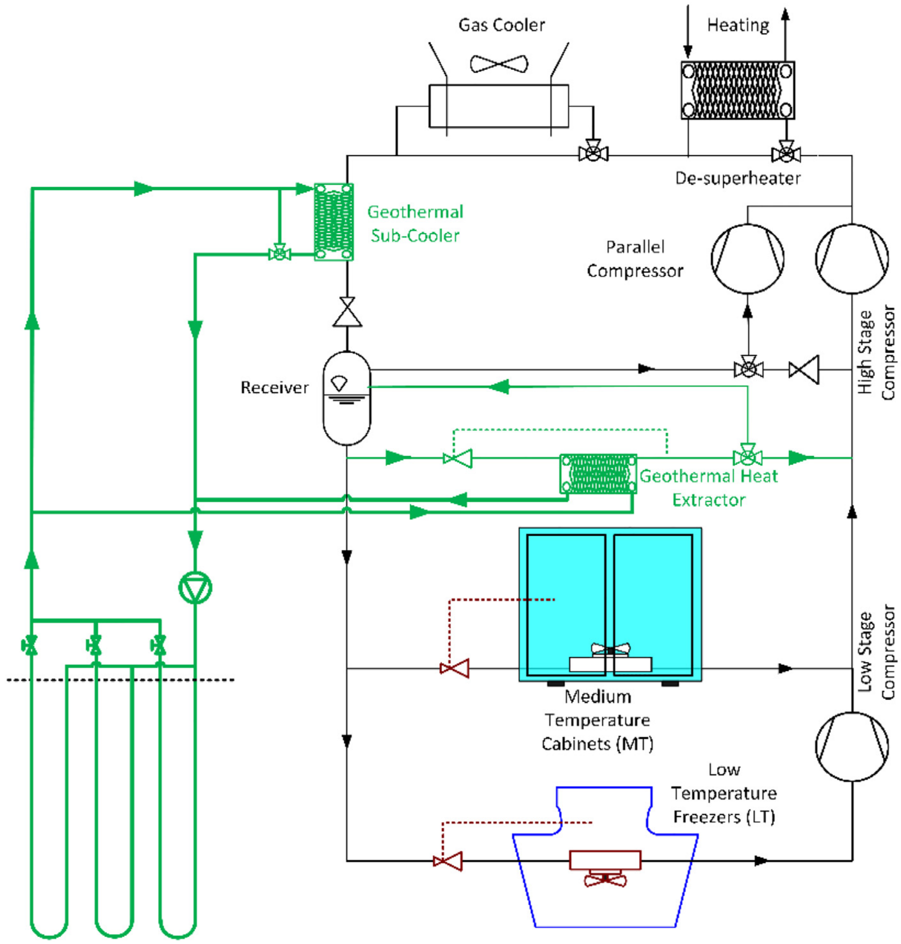


Fig. 1. Schematic of a SotA CO_2 booster system (black) and integrated geothermal storage (green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

use of 300 benchmarked German supermarkets. Among other innovative solutions, the CO_2 system with 250 kW refrigeration capacity uses six 100 m-deep boreholes for sub-cooling in summer time. An extra heat exchanger connected to the air handling unit provides also free cooling from the ground, whenever possible. The stored heat is used in winter time as an extra heat source. A parallel compressor is used as the “heat pump compressor” to extract and upgrade the heat in winter. Heat recovery from the CO_2 system is considered as the primary heating source. The study showed that energy use is 23% less than the average energy use of the 300 benchmarked supermarkets after two years of operation, and it was noted that optimization of the geothermal storage usage is a key to achieve the target in the coming years.

Skelton (2011) studied the impacts of geothermal storage on the energy efficiency in a British supermarket. The supermarket uses three identical CO_2 systems with 250 kW medium temperature level (MT) and 25 kW low temperature level (LT) cooling capacity each, and in total about 1.1 MW rejected heat in summer including compressor power. The author claimed that in order to increase the energy efficiency of the system, the trans-critical operation should be avoided or shortened since it is not an efficient operation mode. To shorten the operating hours of the systems in trans-critical mode, fifteen 200 m-deep boreholes and 4 plate heat exchangers are used to reject the heat to the ground in warm climate conditions. A large air-cooled gas cooler is also installed in parallel to the plate heat exchangers to ensure smooth performance of the systems. The ground stored heat is used by five heat pumps to provide tap water and space heating demands. However, heat pumps are considered as the primary and only heating system even though it is a widely-accepted fact that CO_2 systems have excellent performance in heat recovery mode. The cost of two parallel and enormous heat rejection systems is another drawback of this solution. However, it is claimed that the annual energy use is 55% less compared to a benchmark supermarket. The benchmark is a similar sized store utilizing UK standard systems, i.e. air-cooled CO_2 refrigeration packs and gas boilers for heating.

The idea of “preventing trans-critical operation by using the ground as heat sink” is also discussed by Leiper et al. (2014). However, to prove the benefits of this idea, only cold-months operation has been discussed, instead of warm climate operation. The benefits of heat recovery from the refrigeration system is also neglected in this paper.

Ohannessian and Sawalha (2014) compared five cases of geothermal storage and/or heat recovery implementation in CO_2 systems, with a reference system comprised of a CO_2 refrigeration system and a separate heat pump. The authors concluded that a CO_2 system with heat recovery uses 8.1% less energy compared to the reference energy solution. This saving increases to 11.4% for a system with both heat recovery and thermal storage.

Mands and Sauer (2008) investigated an integrated system of a refrigeration system, ground storage, and a reversible heat pump/AC system. The heat pump is used to provide heating in winter and air conditioning in summer, replacing separate air conditioner and boiler systems. The ground in summer is used as a “full heat sink” for the heat pump/AC and as a “partial heat sink” for the refrigeration system. The refrigeration system uses a

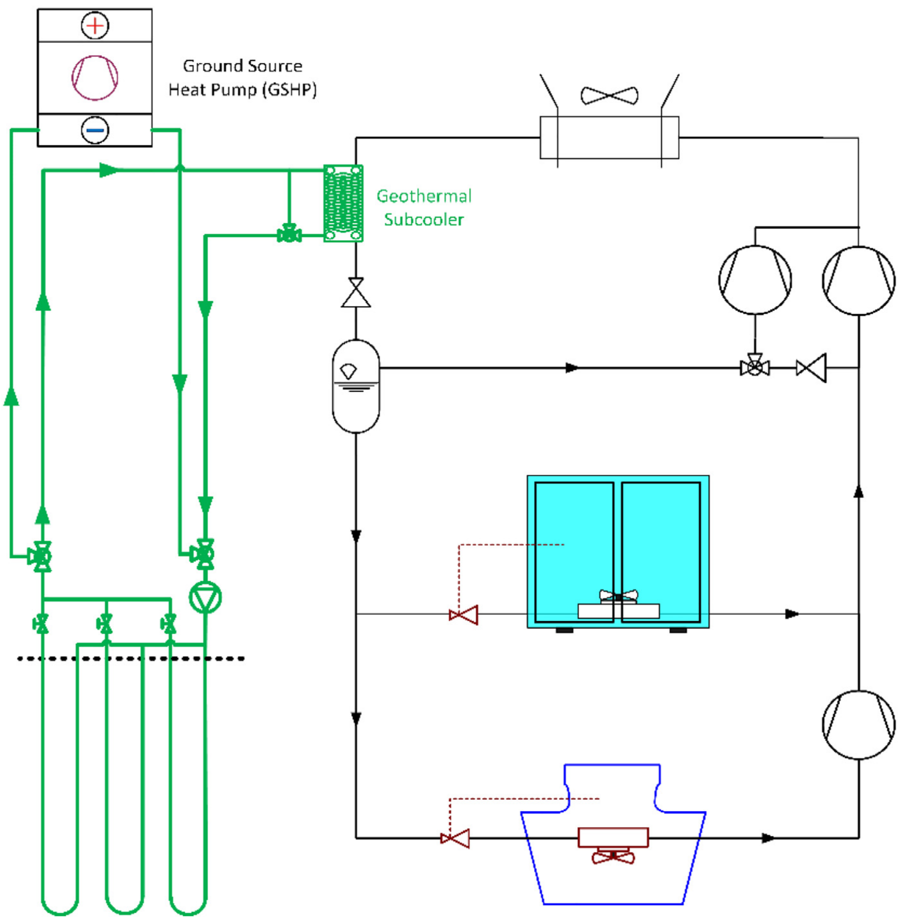


Fig. 2. Hybrid geothermal solution: refrigeration system sub-cooling in summer, heat source for GSHP in winter.

parallel air cooler as the condenser to cover the rest of waste heat rejection. The stored heat is used as the heat pump heat source in winter. Three ground covering scenarios of 65%, 30%, and 15% "partial heat sink" are studied. It was determined that 16, 10, and 7 boreholes each 100 m deep are required, respectively. The payback period of using this concept for three other scenarios has been calculated using a conventional system as reference. The conventional system is composed of separate refrigeration, air conditioning, gas boiler space heating, and electric water heating systems. The studied three scenarios were "full heat rejection coverage by ground", "balanced stored energy in the ground" and "maximum heat recovery". The payback periods are calculated as 23, 16, and 18 years, respectively, which are not reasonable values for energy efficiency investments in supermarkets.

A Wahlgreens Store in USA is designed to be the first net zero store in the country. The main source of power is solar panels on the roof. Among other innovations, the store has implemented eight 150 m-deep boreholes to use in winter as heat source and in summer as heat sink for sub-cooling a CO_2 trans-critical booster system (Cyclone, 2013). The CO_2 system is an integral solution providing all the thermal demands of the supermarket. The benchmarking of the supermarket in Energy Star software showed 60% reduction in annual energy use, about 200 MWh, compared to 450 MWh in conventional Chicago Wahlgreens stores. However, the energy use has been reported to be about 290 MWh in the first year of operation (Robbins et al., 2015).

The number of CO_2 systems with integrated geothermal storage is increasing in Swedish supermarkets; this is according to communications with the project partners, participation in Nordic refrigeration events, and distant access to web monitoring of recent system installations. The impact of this integration on energy efficiency and the ground energy balance needs to be investigated in details to ensure that these advantages are maintained during the lifetime of the system. Using computer simulations, this paper evaluates the integration of geothermal storage into supermarket CO_2 trans-critical booster systems. In Section 2 of this paper, the evaluated systems are described and three different scenarios of geothermal storage integration are presented in Section 3.

2. Systems description

The reference system in this study is a state-of-the-art (SotA) CO_2 trans-critical booster system. This system is abbreviated as CO_2 SotA hereafter. The features of this system have been discussed in detail by the authors in a previous research (Karampour and Sawalha, 2018). In brief, a CO_2 SotA system provides all or a major part of thermal demands in supermarkets. The CO_2 SotA system uses parallel compression to compress the flash gas vapour. This system takes the advantage of flooded evaporation to run at high evaporation temperatures. As described in the previous research, flooded evaporation can be provided by liquid ejectors, pump circulation, or internal heat exchangers. It has been shown that these features decrease the refrigeration annual energy use (AEU) of the standard CO_2 booster system by 15% both in cold and warm climates (Karampour and Sawalha, 2018).

The CO_2 SotA is represented by the black lines in Fig. 1. To simplify and generalize, the specific method of flooded evaporation is not shown. The signal to the valves before the evaporators is measured at cabinet air return temperature, unlike the standard superheat control. The CO_2 SotA system presented in the previous

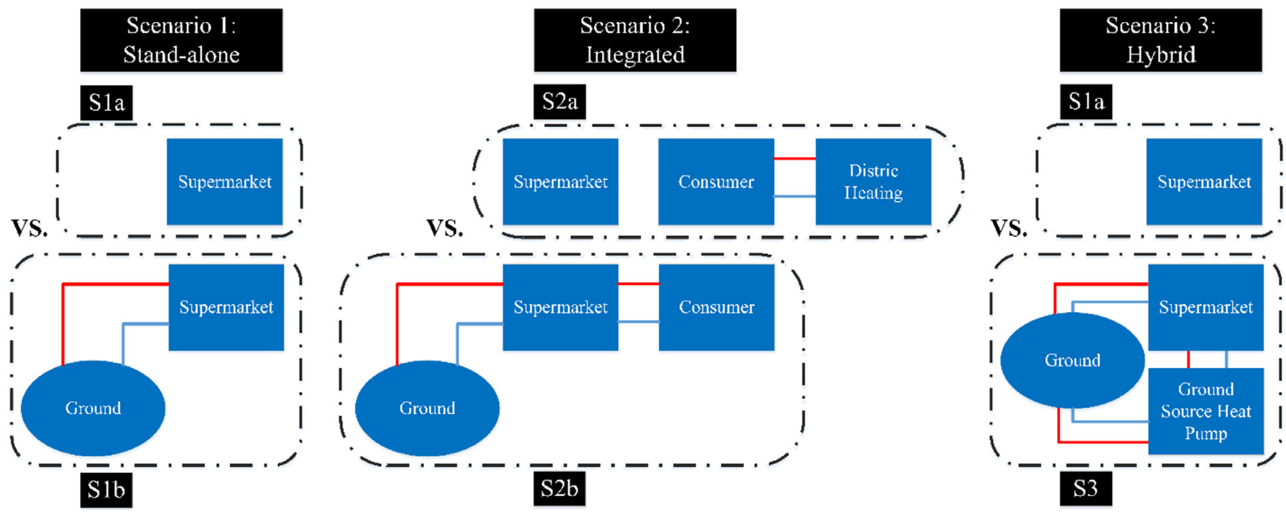


Fig. 3. The three research scenarios.

research integrates space heating, tap water heating, and air conditioning functions into the refrigeration system. The energy efficiency of providing both heating and air conditioning demands by CO_2 SotA are either higher or comparable to efficient alternative solutions, which further decreases the overall AEU for refrigeration, heating, and air conditioning (Karampour and Sawalha, 2018). However, air conditioning and tap water heating are not included in this study, and not shown in Fig. 1. The heat recovery is used only for space heating, which is the major heating demand in supermarkets (Polzot et al., 2017; Karampour and Sawalha, 2017).

A feature which is evaluated less comprehensively in scientific publications to the best of authors' knowledge, but is applied in some supermarkets, 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 CO_2 SotA system and its integrated geothermal storage system (represented by green lines) is shown in Fig. 1. The geothermal sub-cooler is located after the gas cooler and provides sub-cooling in the warm summertime. Heat is stored in the ground during this season and an extra evaporator (Geothermal Heat Extractor in Fig. 1) is used to extract the heat from the ground during winter. The extracted heat is then "pumped" by the compressors to provide heat in the heat recovery de-superheater.

The extracted heat can be added at either the P_{MT} level and compressed by high stage compressors or at P_{rec} level and processed by parallel compressors. In the case of heat extraction at P_{rec} level, the expansion valve before the geothermal heat extractor is fully open and the exit line is connected to the receiver. Both methods have been applied in field installations in Sweden (Mateu-Royo, 2017) and are evaluated in this paper.

Another option to extract and use the stored heat from the ground in winter is by running the CO_2 system in floating condensing mode with minimum condensing temperature of 10 °C, i.e. lowest pressure possible, and use a separate ground source heat pump (GSHP) to provide the supermarket's heating demand. A schematic of this system, designated as "hybrid" in this paper, is shown in Fig. 2.

3. Research scenarios

The integration of geothermal storage into a CO_2 system is evaluated for three integration scenarios. The research questions for each scenario are:

S1(S is short for Scenario) – Does geothermal storage integration decrease the annual energy use (AEU) of the CO_2 refrigeration system in a stand-alone average size supermarket? In this scenario, the AEU of the CO_2 systems with full heat recovery and without geothermal storage (referred to as S1a) and with geothermal storage (S1b) are compared. S1a and S1b are visualized in Fig. 3, where all the integration scenarios are also visualized.

S2 – Does geothermal storage integration decrease the total running cost of a coupled system of a supermarket and a neighboring consumer of space heating energy? The first case in this scenario (S2a) is the reference without coupling, it consists of two separate energy systems of a supermarket that recover all its heating needs and a neighboring facility that buys its heating needs from district heating network. The second case (S2b) couples the supermarket and neighbor energy systems by integrating the geothermal storage, and providing the entire heating demands of the two buildings by heat recovery from the refrigeration system.

S3 – Does geothermal storage integration and usage of a separate ground source heat pump (GSHP) decrease the AEU compared to a stand-alone supermarket with CO_2 refrigeration system (compared to S1a)? In the third scenario of geothermal integration (S3), the ground is used for summer sub-cooling of the refrigeration system and a separate ground source heat pump (GSHP) is used in winter to extract the stored heat and provide the supermarket heating demand.

Summary of the research scenarios is the following:

S1a: Stand-alone supermarket with full heat recovery and without geothermal storage

S1b: Stand-alone supermarket with full heat recovery and with geothermal storage

S2a: Stand-alone supermarket with full heat recovery and stand-alone neighboring building buying heat from district heating (i.e. no coupling)

S2b: Supermarket with geothermal storage coupled to neighboring building where all heating needs of the supermarket and the neighboring building are recovered from the refrigeration system

S3: Stand-alone supermarket with ground source heat pump and geothermal storage; i.e. no heat recovery from the refrigeration system

While studying these three scenarios, the proper heat recovery control strategy and sizing of the required borehole field have been addressed, as well.

4. Modeling details

4.1. Boundary conditions and assumptions

4.1.1. Thermal loads

The cooling demands and refrigeration boundary conditions are based on field measurements of five Swedish supermarkets using CO_2 as the refrigerant (Sawalha et al., 2015). Some parameters are updated according to a previous research study on the characteristics of the SotA CO_2 systems (Karampour and Sawalha, 2018).

Medium temperature cooling demand is assumed to be 200 kW at 35 °C and decreases linearly to 100 kW at 10 °C, below which the demand remains constant. Low temperature cooling demand is approximately constant through the entire year and assumed to be 35 kW. Medium and low stage evaporation temperatures of the CO_2 SotA are −4 °C and −29 °C, respectively. These temperatures are about 3–4 °C higher than the typical evaporation temperatures in standard CO_2 systems, according to the modeling (Karampour and Sawalha, 2018) and field observations (Minetto et al., 2014b). As discussed in the introduction section, the reason is taking advantage of the flooded evaporation.

Heating demand is obtained by the program CyberMart for a medium-sized supermarket in Sweden. CyberMart is a tool to calculate energy demands and use in supermarket buildings. Detailed descriptions and the calculation procedure of the program can be found in Arias (2005).

The main heating demand in supermarkets is space heating, which starts at the ambient-temperature set-point of 10 °C. Based on CyberMart calculations, the heating demand is estimated to be 40 kW at 10 °C ambient temperature and increases linearly to 190 kW at −20 °C ambient temperature. Water return temperature from the heating system is assumed to be 30 °C. 5 K approach temperature is assumed between the water return temperature and the refrigerant in the condenser of the separate GSHP, or the de-superheater in the case of heat recovery from the refrigeration system. The heating demand and temperature requirements of the neighboring building are assumed to be the same as the supermarket.

As space heating is the major heating demand in supermarkets, the tap water heating demand is neglected in this study.

4.1.2. Control strategy

The system runs in the floating condensing mode in the summer. The discharge pressure (condensation temperature) follows the ambient temperature in sub-critical condition with an approach temperature of 7 K. The discharge pressure follows an optimum discharge pressure control for max *COP* in super-critical conditions with an approach temperature of 3 K. The optimum pressure $P_{opt,\,gc}$ [bar] is a function of the gas cooler exit temperature $T_{gc,\,exit}$ [°C], as follows (Sawalha, 2008):

$$P_{opt,gc} = 2.7 * T_{gc,exit} - 6 \quad (1)$$

The standard CO_2 system uses a flash gas by-pass expansion valve to direct the vapour from the receiver to the suction line of the high-stage compressors. The standard CO_2 system schematic is similar to that of CO_2 SotA in Fig. 2 but without the parallel compressor. The CO_2 SotA system uses parallel compression (PC) to remove this vapour at higher pressure than that of the medium temperature cabinets; about 3 bar higher (Karampour and Sawalha, 2017). It is assumed that PC is activated for ambient temperatures higher than 13 °C. This value is selected based on field measurement observations where PC is activated in the range of 10–15 °C.

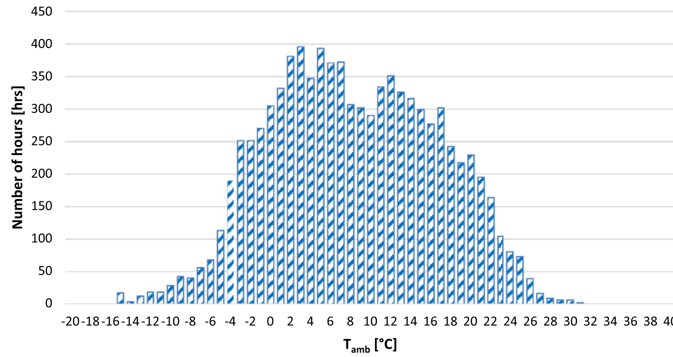


Fig. 4. Stockholm temperature-bin hour profile, extract from Meteonorm (Meteotest, 2016).

Heating starts at an ambient temperature of 10 °C and continues for ambient temperatures lower than this set-point. The heating season is called winter mode in this paper and the rest is summer mode. Stockholm climate is used for the climate in this paper; Stockholm ambient temperature-bin hours are applied to represent this climate condition and is shown in Fig. 4.

The heat recovery control strategy in winter follows the recommendations presented by Sawalha (2013). In brief, the recommendation consists of a stepwise control strategy, as shown in Fig. 5. In the first step, the gas cooler pressure P_{gc} is regulated and the gas cooler fans are operated at their highest speed to maintain a gas cooler exit temperature ($T_{gc,\,exit}$) as low as possible, with a minimum value of 5 °C. In the second step, the gas cooler pressure P_{gc} is fixed at a maximum value for high efficiency $P_{opt,gc,\max}$ and the gas cooler capacity is decreased by reducing the fans' speed. This pressure value is based on the following correlation, similar to Eq. (1) but with the de-superheater exit temperature $T_{dsh,\,exit}$ as the independent variable.

$$P_{opt,gc,max} = 2.7 * T_{dsh,exit} - 6 \quad (2)$$

$T_{dsh,\,exit}$ is equal to 35 °C in this paper. During step 2 the fan speeds are reduced, which causes $T_{gc,\,exit}$ to increase.

Step 3 is the last efficient heat recovery step; all fans are switched off, the gas cooler is by-passed (in order to avoid even natural convection), and the gas cooler exit temperature is equal to the de-superheater exit temperature; 35 °C.

An inefficient method of harvesting more heat from the CO_2 system is accomplished by increasing P_{gc} to higher pressures (step 4 in Fig. 5), but this results in a sharp decrease in COP_{HR}, as discussed by Sawalha (2013). The reason for reaching this step at very low outdoor temperatures (about −23 °C here) is the relatively low heating demand in an average size supermarket. In case of a supermarket with heating demand larger than the one used in this study (for example, for a hypermarket), the outdoor temperature at which step 4 will be reached will be higher than in this plot.

4.1.3. Geothermal storage and GSHP hybrid solution

Simulations for the ground heat exchanger have been performed for Stockholm conditions; therefore, the ground properties used for the borehole design are rock thermal conductivity = 3.1 W m^{-1} K^{-1}, volumetric heat capacity = 2.16 MJ m^{-3} K^{-1}, and ground surface temperature = 6.6 °C (Acuña, 2013).

As the most conventional GSHP secondary fluid in Europe (Ignatowicz et al., 2017), an aqueous ethanol solution of 24% weight concentration is used as the heat-carrier fluid for the geothermal loops. It has a freezing temperature of −14.6 °C; however, its operating temperature T_f is restricted to the range of −5 °C to +20 °C. The flow rate is 0.5 l s^{-1} per borehole, which is constant during the entire operation. The boreholes uses single U-tube heat exchangers and their depth varies in the 150–200 m range. The

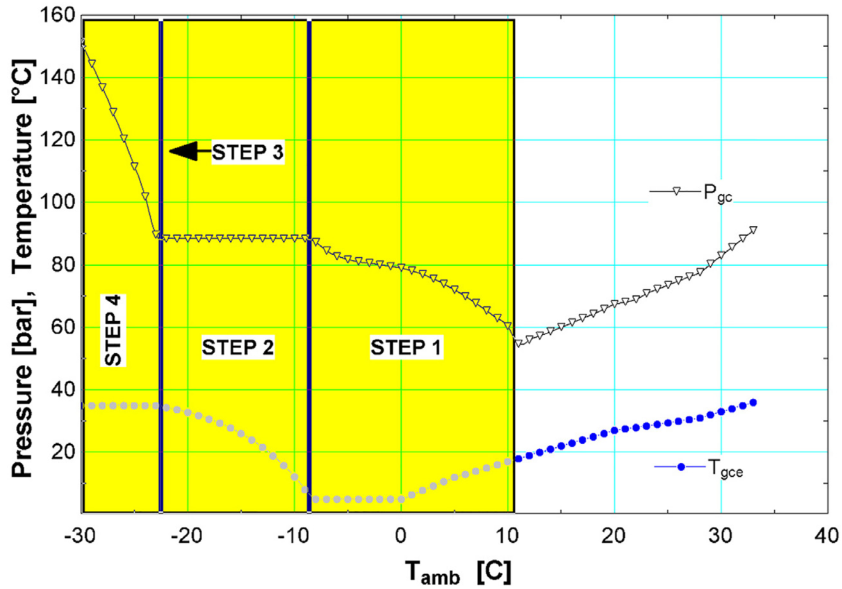


Fig. 5. Standard heat recovery control strategy.

pump power is assumed to be 5% of the GSHP compressor electricity use. This is roughly in the same order of magnitude as presented by Kavanaugh and Kavanaugh (2012).

The GSHP uses R407C as the working fluid, with a heating capacity of 200 kW. The evaporator has a capacity of 150 kW. Both the evaporator and the condenser have a 5 K approach temperature with their heat exchanging fluids. The condensation temperature is fixed to 35 °C (i.e. fixed 30 °C water return temperature from the heating system), which is a similar condition for a CO_2 heat recovery de-superheater. The evaporator has an approach temperature of 5 K with the secondary fluid and 10 K internal super-heating.

4.2. Energy efficiency calculations

A computer model developed using EES (Engineering Equation Solver) software (Klein, 2015) is used to analyze the performance of the CO_2 SotA and GSHP systems.

Mass flow rates in the MT cabinets and LT freezers are calculated using equation below:

$$\dot{Q} \ = \ \dot{m}_{ref} \ . \ \Delta h_{heat \ exchanger} \tag{3}$$

where $\dot{Q}$ [kW] is the cooling load in the MT cabinets ($\dot{Q}_{MT}$) or LT freezers ($\dot{Q}_{LT}$). $\dot{m}_{ref}$ [kg s^{-1}] is the refrigerant mass flow rate and $\Delta h_{heat\,exchanger}$ [kJ kg^{-1}] is the enthalpy difference across the heat exchangers.

Knowing the mass flow rates in the different lines of the system, compressor electricity use $\dot{E}_{\ comp}$ [kW] in MT, LT, and parallel compressors are calculated using equation below:

$$\dot{E}_{\ comp} = \left(\dot{m}_{ref}.\ \Delta h_{is}\right)/\eta_{tot} \tag{4}$$

where η_{tot} is the overall efficiency of the compressors, and Δh_{is} [kJ kg^{-1}] is the isentropic enthalpy difference over each compressor unit. Compressor commercial datasheets are used to obtain the total efficiency of the compressors as a quadratic function of discharge to suction pressure ratios (PR); "a.PR^2 + b.PR + c" (BITZER, 2017). The coefficients a, b, and c are equal to −0.079, 0.346, and 0.204, respectively, for LT compressors. These coefficients are −0.0065, −0.003, and 0.726 for MT and parallel compressors.

The calculation method is described in authors' previous research (Sawalha et al., 2015). In brief, mass flow rate is calculated according to Eq. (3) as the cooling capacity and thermodynamic cycle boundaries are known. Subsequently, Eq. (4) is used to calculate the total efficiency.

The total electricity use $\dot{E}_{tot}$ [kW] of the system is calculated based on Eq. (5):

$$\dot{E}_{tot} \ = \ \dot{E}_{MT} + \dot{E}_{LT} + \dot{E}_{PC} + \dot{E}_{fan} \ + \dot{E}_{GEO,pump} \tag{5}$$

where $\dot{E}_{MT}$, $\dot{E}_{LT}$, and $\dot{E}_{PC}$ [kW] are the electricity use of the three compressor units. $\dot{E}_{fan}$ [kW] is the electricity use of the gas cooler fans. $\dot{E}_{fan}$ is estimated to be 3% of the heat rejected in the gas cooler $\dot{Q}_{gc}$ [kW], according to communication with a major CO_2 gas cooler manufacturer. This assumption has the same order of magnitude as in some other research works including Tsamos et al. (2017) and Lozza et al. (2007). $\dot{E}_{GEO,pump}$ is the pump electricity used to circulate the secondary fluid, which is estimated to be approximately 5% of the extra evaporator capacity in winter or geo sub-cooler capacity in summer. This assumption is an estimation based on indirect loops presented by Sawalha et al. (2017).

Heat recovery COP (COP_{HR}) of the CO_2 SotA system is defined as:

$$COP_{HR} \ = \ \frac{\dot{Q}_{HR}}{\left(\dot{E}_{tot} \ - \ \dot{E}_{tot,fc}\right)} \tag{6}$$

$\dot{Q}_{HR}$ [kW] is the amount of recovered heat, $\dot{E}_{tot}$ [kW] is the total electricity use calculated from Eq. (5), and $\dot{E}_{tot,fc}$ [kW] is the amount of electricity use if the system is not controlled for heat recovery and is operated in floating condensing mode with minimum condensing pressure in winter.

Annual energy use AEU [MWh] is calculated using the following equation:

$$AEU = \sum_{i=1}^{n} \ \left(\dot{E}_{tot,i} \ . \ f_i\right) \tag{7}$$

where $\dot{E}_{tot}$ [kW] is the total electricity use calculated from Eq. (5), n is the number of temperature-bin hours, and f is the frequency, i.e. number of hours, of each temperature bin.

The calculations for the geothermal storage and its borehole field design are performed using Earth Energy Designer (EED) software (Blomberg et al., 2017; Hellström and Sanner, 1994). EED evaluates the secondary fluid temperature evolution in a specific borehole arrangement based on imposed heating and cooling loads. Two major options are available in this software:

ARTICLE IN PRESS
JID: JIJR [m5G;July 10, 2019;16:40]

1) Loads and secondary fluid temperature constraints are defined, and the optimized borehole heat exchanger geometry, array, and configuration which satisfy these constraints in the lifetime period of the system are determined.
2) Loads and borehole geometry are defined, and the evolution of the secondary fluid temperature in the lifetime of the system is calculated.

The first option has been adopted in this study. The monthly heat stored (summer sub-cooling) and heat extracted (winter heat pumping) are input to the EED software. The first estimation in EED is based on an assumed constant amount of sub-cooling in EES. Using the defined secondary fluid temperature range, the optimized geometry and fluid temperature as a function of time of the year are calculated in EED. This function is correlated to ambient temperature and used as a new variable sub-cooling amount in the EES code. The ground loads in winter and summer are then calculated again in EES. This iterative process between EES and EED is repeated to find an accurate match between EES and EED results.

5. Results and discussion

The following sections include results for different geothermal storage arrangements for the three research scenarios presented in Section 3 and Fig. 3.

5.1. S1-stand-alone supermarket

The first research scenario compares a CO_2 refrigeration system without (S1a) and with (S1b) geothermal storage in a stand-alone supermarket. The performance of eight system arrangements, or designs, have been calculated in this research scenario.

1. S1a (reference): the system has no geothermal storage and heat recovery through its de-superheater is used to provide the space heating demand in the supermarket building.
2. Sub-cooling in the summer (SC summer): The system is similar to the reference case in winter (i.e. no heat extraction from the ground) but uses geothermal sub-cooling in summer. This case is shown as "S1b: SC summer" in Fig. 6. The method to calculate the amount of sub-cooling is described further in the text.
3. Sub-cooling in summer and heat extraction from the ground in winter (SC summer + winter $\dot{Q}_{ex}$, as presented in Fig. 1): six cases are studied; three cases of heat extraction at P_{MT} level, and three cases of heat extraction at P_{rec} level. System performance is examined for three levels of extra evaporator capacity $\dot{Q}_{ex}$: 40, 80, and 120 kW. These values are based on the reasonable capacity that could be provided by the installed compressors; no additional compressors are needed. The high stage compressors are designed to provide 250 kW capacity in the warmest summer days for MT and LT refrigeration, while in winter about half of this capacity is assumed to be required, based on field observations. This is because the compressors typically run in the summer time to extract vapor from the receiver but are switched off partly during the winter. The control strategy to extract the heat from the ground is explained later in this section.

The amount of sub-cooling for cases S1(b) is calculated based on an iterative calculation process between EES and EED. First, a constant amount of 5 K sub-cooling is assumed. The amount of monthly stored heat in the ground due to this sub-cooling is calculated in EES. These monthly load profiles are input to EED. The annual evolution of secondary fluid temperature is calculated in EED. In the second round of EES calculations, sub-cooling is variable and a function of variable secondary fluid temperature out from the ground, with 3 K approach temperature. This iteration is repeated until the difference between two rounds of secondary fluid temperature calculation gets minimal, less than 0.2 K. The calculated amount of sub-cooling is up to 15 K; this results in a sub-cooler design capacity of about 60 kW at warmest summer outdoor temperature.

These six cases are shown as following in Fig. 6:

- S1b: SC+40 kW Q_ex_MT
- S1b: SC+80 kW Q_ex_MT
- S1b: SC+120 kW Q_ex_MT
- S1b: SC+40 kW Q_ex_rec
- S1b: SC+80 kW Q_ex_rec
- S1b: SC+120 kW Q_ex_rec

System performance in terms of AEU [MWh] (presented as bars) and AEU decrease [%] (presented as dots) for the eight arrangements is presented in Fig. 6.

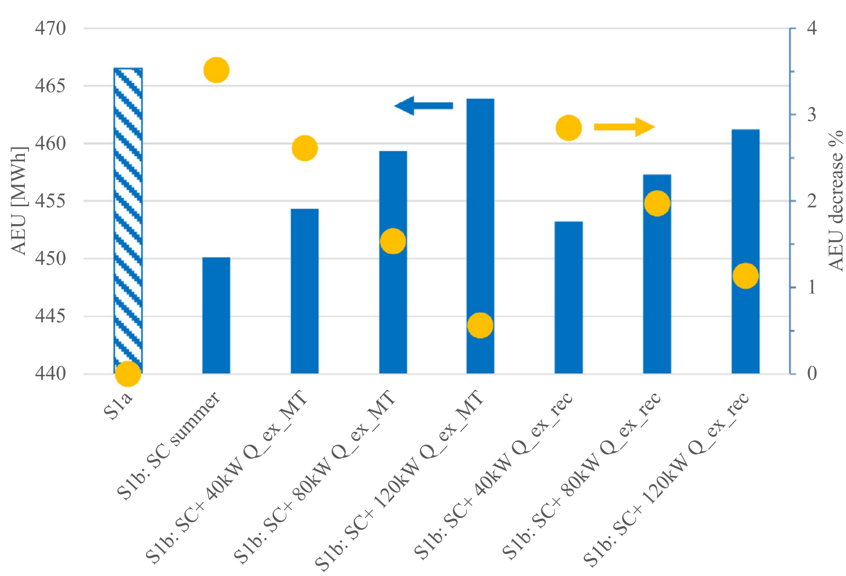


Fig. 6. Annual energy use [bars-left y-axis] and savings [dots-right y-axis] compared to the reference case for S1 cases.

Please cite this article as: M. Karampour, C. Mateu-Royo and J. Rogstam et al., Geothermal storage integration into a supermarket's CO2 refrigeration system, International Journal of Refrigeration, https://doi.org/10.1016/j.ijrefrig.2019.05.026

Table 1
Monthly sub-cooling loads [MWh] and secondary fluid mean temperature T_f [°C].

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Load [MWh]	0.00	0.00	0.21	2.12	8.19	14.94	22.92	20.86	9.37	2.48	0.26	0.00
T_f –Year 1	8.55	8.55	8.58	8.89	9.91	11.1	12.5	12.4	10.6	9.51	9.1	9.01
T_f –Year 5	9.65	9.63	9.63	9.91	10.9	12.1	13.5	13.3	11.6	10.4	9.98	9.86
T_f –Year 10	10.2	10.2	10.2	10.5	11.5	12.6	14	13.9	12.1	10.9	10.5	10.4
T_f –Year 15	10.6	10.5	10.5	10.8	11.8	13	14.4	14.2	12.4	11.3	10.8	10.7

Table 2
Annual energy use AEU [MWh] and annual ground thermal balance [MWh] as functions of heat extraction activation temperature.

Heat extraction activation when T_{amb} is lower than	AEU [MWh]	Annual ground thermal balance [MWh]	Winter heat extraction [MWh]	Summer sub-cooling [MWh]
10	546.6	327.4	413.8	−86.4
5	520.1	196.1	282.5	−86.4
0	485.8	48.2	134.6	−86.4
−5	459.4	−53.2	33.2	−86.4
−10	449.8	−78.7	7.7	−86.4

As shown in Fig. 6, geothermal sub-cooling in summer can provide about 3.5% AEU saving compared to the reference system. However, if the number of boreholes is not sufficient, the ground will not be cold enough after few summers to be used as an efficient heat sink. For instance, the results of modeling in EED shows that 12 boreholes each 200 m deep are required to keep the secondary fluid temperature lower than 15 °C during a 15-year lifetime of the system. The sub-cooling loads (for ambient temperatures higher than 10 °C) and the secondary fluid mean temperature T_f [°C] are shown in Table 1.

To study the winter heat extraction effect on AEU saving in the latter six cases, various heat extraction starting points have been studied by computer simulations; i.e. the ambient temperature at which the heat extraction from the ground should be started. The results indicate that only at ambient temperatures below 0 °C is it beneficial to extract heat from the ground. “Beneficial” is a compromise between energy efficiency and ground thermal energy balance in summer-winter. A comparison of annual energy use and ground thermal balance for different heat extraction ambient temperatures is summarized in Table 2. The ground thermal balance is the absolute difference between winter heat extraction (positive values) and summer sub-cooling (negative values), and it is preferred to be minimum. Based on these calculations, in scenario S1, the ground heat extraction is set to be activated for ambient temperatures lower than −5 °C.

The savings for these six cases that employ geothermal storage the entire year are less than 3%, as shown in Fig. 6. Compared to the “SC summer” case (3.5%), this implies that heat recovery in the geothermally integrated CO_2 systems has negative impact on energy saving; i.e. not as efficient as heat recovery in the standalone CO_2 system, referred to as S1a in this paper. The reason that these six cases are annually 0.5–3% more efficient than S1a, according to Fig. 6, is the sub-cooling in summertime.

To understand why heat recovery in the integrated solution is not as efficient as the stand-alone CO_2 system S1a, COP_{HR} of the CO_2 refrigeration system without geothermal connection ($COP_{HR,\,S1a}$) is compared to the heating COP of the geothermal heat extraction only ($COP_{HR,\,GEO}$) system. In $COP_{HR,\,S1a}$ there is no geothermal connection and the only heat source is the refrigeration load. In $COP_{HR,\,GEO}$ the extracted heat is added to the refrigeration load while the system control is the same as in S1a; thus, the sole effect of the geothermal heat extraction is calculated. In this way the system is seen as a heat pump extracting heat from the ground and supplying heat via the de-superheater. $COP_{HR,\,S1a}$ is calculated using Eq. (6). As shown in Eq. (8), $COP_{HR,\,GEO}$ is defined as the ratio of the amount of recovered heat $\dot{Q}_{HR,ex}$ [kW] (by the addition of the extra heat source) to the amount of extra electricity use in compressors, pumps, and gas cooler fans $\dot{E}_{tot,ex}$ [kW]. Heat is recovered from the de-superheater as demonstrated by the processes shown in the P–h diagram in Fig. 7.

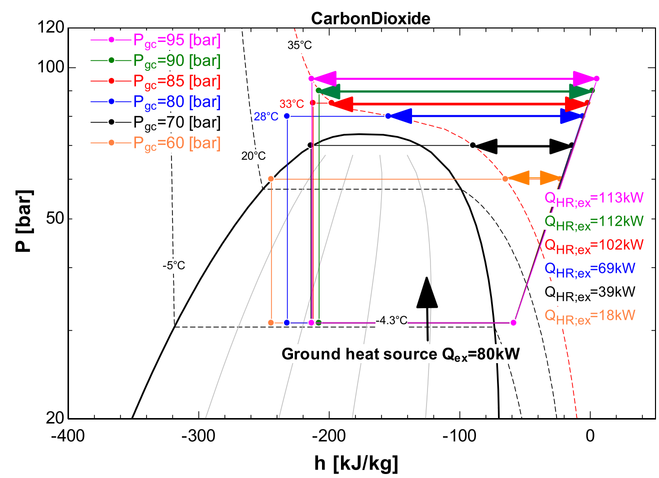


Fig. 7. Recovered heat as a function of increased pressure, 80 kW heat extraction capacity.

$$COP_{HR,GEO} = \frac{\dot{Q}_{HR,ex}}{\dot{E}_{tot,ex}} \quad (8)$$

Fig. 7 shows an example of 80 kW ground heat extraction and the recovered heat for different operating gas cooler pressures P_{gc}. It can be observed in the process plot in Fig. 7 that only a small part of the heat added in the geothermal heat extractor is available as useful heat recovery from the de-superheater and the rest is rejected through condenser/gas cooler to the ambient. This results in low $COP_{HR,GEO}$ at relatively low discharge pressures (high T_{amb}, low heating demands), which can be observed in the COP comparison plot in Fig. 8.

Geothermal heat extraction can be executed at two pressure levels, either at the pressure level of the medium temperature cabinets (P_{MT}) or at the receiver pressure (P_{rec}). $COP_{HR,GEO}$ data at both pressure levels are presented in Fig. 8. The difference in $COP_{HR,GEO}$ at P_{MT} and P_{rec} is negligible due to high MT evaporation temperatures in CO_2 SotA systems. As mentioned earlier, $COP_{HR,\,S1a}$ in Fig. 8 is the heat recovery COP of S1a calculated according to Eq. (6).

Looking at the values in Fig. 8 it should be pointed out that the system is not expected to operate for many hours at very low outdoor temperatures; however, the temperature range has been ex-

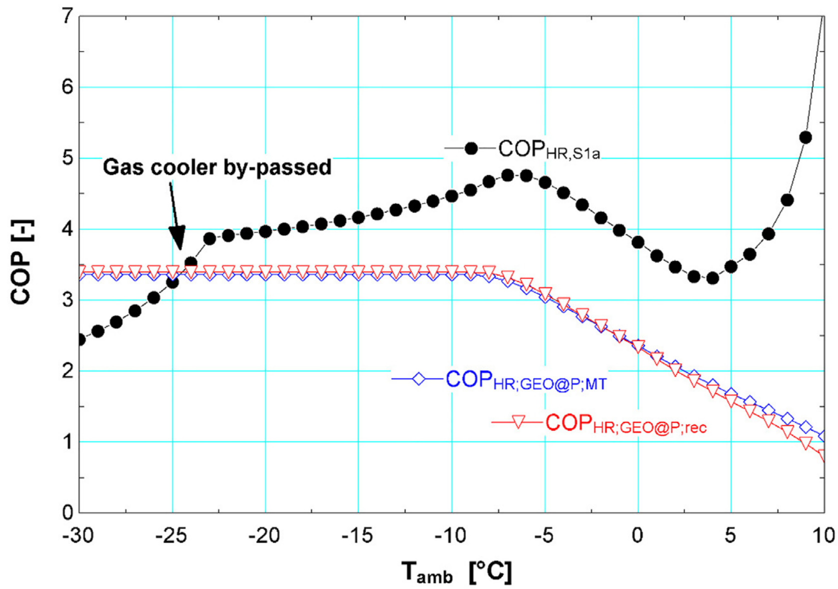


Fig. 8. Heat recovery COP for CO_2 stand-alone $COP_{HR,\ S1a}$ and CO_2 ground-coupled systems at MT pressure level $COP_{HR,\ GEO}@P_{MT}$, and receiver pressure level $COP_{HR,\ GEO}@P_{rec}$.

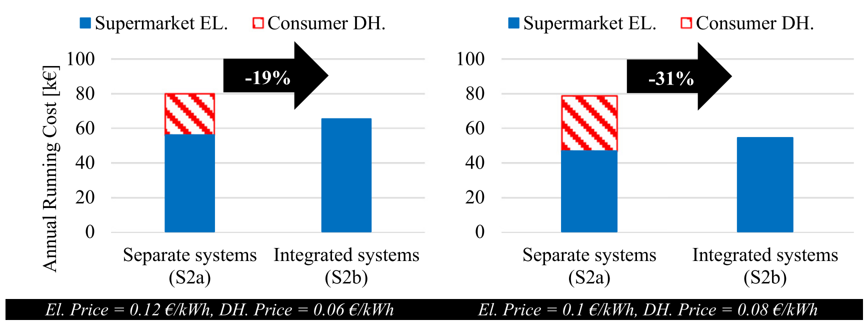


Fig. 9. Separate (S2a) and integrated (S2b) systems annual running cost [k€].

tended in this analysis to unexpectedly low outdoor temperatures in order to increase the heating demand in the building and show the limits of the refrigeration system to recover heat.

It can be observed in Fig. 8 that $COP_{HR,\ GEO}$ exceeds $COP_{HR,\ S1a}$ when the gas cooler is fully by-passed. This is the point where further increase in the discharge pressure beyond the maximum value for high efficiency results in a sharp decrease in COP_{HR} (i.e., the fourth step in the control strategy explained in Section 4.1.2). It can be concluded from the COP_{HR} data in Fig. 8 that heat extraction from the ground is great advantage to the system when the gas cooler is fully by-passed at relatively low outdoor temperatures; i.e. high heating demand.

In an average size supermarket in Sweden, which has been assumed in this study, the refrigeration load is able to cover the space heating demand with relatively high COP for outdoor temperatures higher than −24 °C, the only need for heat extraction from the ground at higher temperatures is to reduce the ground temperature to allow for sub-cooling of the refrigeration system during the summer. However, in supermarkets/hypermarkets with larger heating demands compared to the studied supermarket, the gas cooler is fully bypassed at higher ambient temperatures.

This step of extracting heat from the ground can replace less efficient step 4 in the heat recovery control strategy, discussed in Section 4.1.2 and Fig. 5. The efficient way to reclaim more heat is achieved by activating the heat extraction from the ground while keeping P_{gc} and $T_{gc,\ exit}$ at their maximum values, as in step 3.

5.2. S2-integrated supermarket

A comparison of “separate supermarket and district heating consumer” systems (S2a) with “integrated supermarket, geothermal system and district heating consumer” (S2b) is considered in the second research question. This case of close distance between these two facilities (a supermarket and a district heat consumer) is quite common, 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 heat and electric energies are of different types, separate and integrated solutions are compared based on the annual cost for purchasing the two types of energies to cover the refrigeration and heating demands. Two scenarios for energy prices are compared: (1) relatively high electricity price and low district heating price, and (2) low electricity price and high district heating price. Price values are based on the Swedish market (SCB, 2017; Energimyndigheten, 2018).

For case S2b the heat is extracted at P_{MT} level through an 80 kW heat exchanger. The heat extraction is activated for ambient temperatures lower than −5 °C. The sub-cooling in summer time is assumed variable and as a function of secondary fluid temperature. The difference between case S2b and case “S1b: SC+80 kW Q_ex_MT” is that heating demand is twice for S2b since the CO_2 system provides heating both to the supermarket and the adjacent building.

A comparison of the annual running cost for the two different scenarios is shown in Fig. 9. Depending on energy prices, the integrated solution produces annual running cost savings of 19–31%. The integrated solution offers lower heating cost for the consumer and provides some profits to the supermarket due to the winter time heating sale and summer time sub-cooling. Considering the present energy prices and heating COP of the CO_2 system, there is a good margin of savings where the supermarket can charge the neighboring building for heat and still be profitable for both supermarket and the neighboring building. This can be considered as a good business opportunity for the supermarket owners.

In the overall system design phase, this savings should be compared with the cost of geothermal storage and systems integration. In the following sub-section, the borehole heat exchanger is designed for this integrated solution. In addition, the payback time for the integrated concept is calculated based on the energy and geothermal storage costs.

5.2.1. Borehole design

The borehole field for the above-mentioned integrated solution can be designed based on the assumed system configuration, sizing, and performance. The configuration of the CO_2 system is depicted in Fig. 2. The extra evaporator is assumed to have 80 kW capacity, and heat is extracted at P_{MT} level. The sub-cooling in summer is provided by a 60 kW sub-cooler (design capacity), and the variable amount of sub-cooling, which depends on the ambient and ground temperatures, is considered in the design.

The monthly extracted heat from the ground (blue) and injected heat to the ground (red) are shown in Fig. 10. As mentioned earlier, these energies are iteratively calculated using EES and EED.

The secondary fluid mean temperature T_f [°C] and specific heat extraction rate [W m^{-1}] fluctuations for a 15-year lifetime of the energy system are shown in Fig. 11. Negative values for the extraction rate indicate heat injection to the ground in summer. In addition to these variables, the secondary fluid temperatures at peak maximum and minimum loads are shown. As shown, T_f varies between −1 °C and 19 °C within the design criteria of −5 °C to +20 °C. This performance has been achieved by optimizing the geometry of the borehole field.

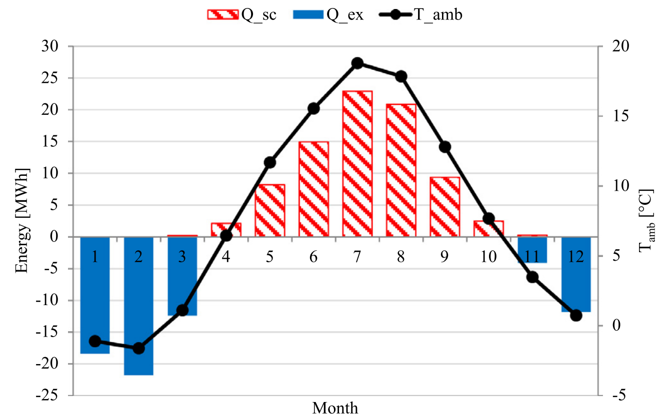


Fig. 10. Monthly heat extraction Q_{ex}, sub-cooling Q_{sc}, and average ambient temperature. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The number of boreholes to have reasonable ground energy balance is calculated to be 12, in a 3 × 4 rectangular arrangement, with 10 m spacing, and an approximate depth of 159 m. This design results in a total length of 1908 m. This design is based on optimizing the borehole array for the shortest total length; a list of the designs with shortest total length is summarized in Table 3. The total cost of borehole drilling and the U-tube heat exchanger is approximately 25 €/m in Sweden, according to personal communications with industrial experts and the weblog (Kostnadguiden, 2017). Thus, the total cost for the desired borehole heat exchanger is 47.700 €. This cost can be compared with the amount of annual running cost saving, presented in the previous section, to calculate the payback time.

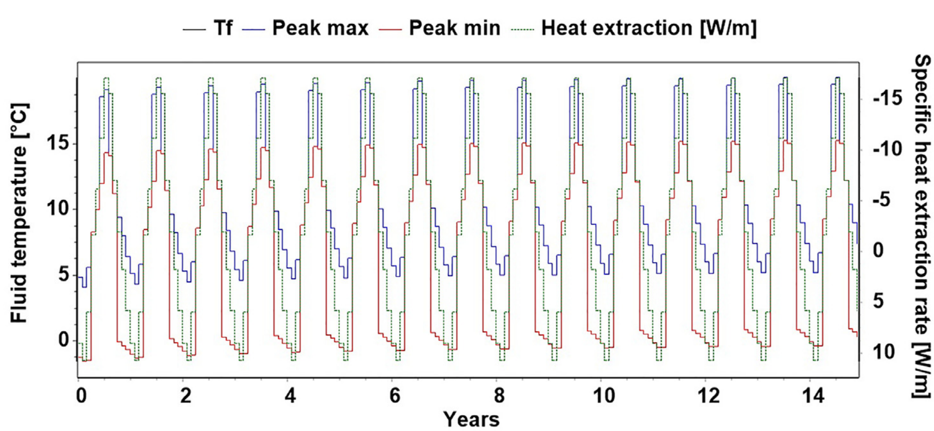
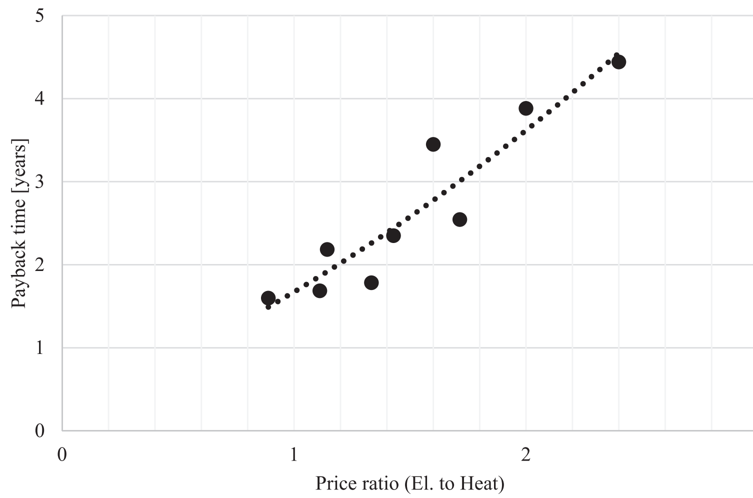


Fig. 11. Secondary fluid temperature and heat extraction fluctuations for a 15 year period.

Table 3
Design optimization for shortest total length of boreholes.

Number of boreholes	Type	Spacing [m]	Depth [m]	Total length [m]	Land area [m^2]	Length [m]	Width [m]
12	3 × 4 rectangle	10	159	1908	600	30	20
12	3 × 4 rectangle	9	160	1920	486	27	18
12	6 × 4 U-configuration	6	161	1932	540	30	18
15	7 × 5 U-configuration	5	131	1965	600	30	20
14	4 × 6 U-configuration	6	139	1946	540	30	18
15	7 × 5 U-configuration	5	130	1950	600	30	20
12	3 × 5 open rectangle	7	161	1932	392	28	14
14	4 × 6 U-configuration	6	139	1946	540	30	18



El. Price [SEK/kWh]	0.8	1	1.2	0.8	1	1.2	0.8	1	1.2
Heating Price [SEK/kWh]	0.5	0.5	0.5	0.7	0.7	0.7	0.9	0.9	0.9
Ratio	1.6	2	2.4	1.1	1.4	1.7	0.9	1.1	1.3

Fig. 12. Payback time for different energy price ratios.

The payback time for nine different energy price ratios (electricity to heating) compared to the geothermal storage cost is shown in Fig. 12. The three electricity prices considered are 0.1, 0.12, and 0.14 € kWh^{-1} and the three heating prices are 0.06, 0.08, and 0.1 € kWh^{-1}, resulting in nine combinations/points in Fig. 12. The energy price ratios for Sweden are presently in the range of 1.2–1.7 (SCB, 2017) (Energimyndigheten, 2018) where the payback period ranges between 1.7 and 3.5 years. This is the payback time to return the installation investment of geothermal storage borehole array. The short payback time over a wide range of electric to heat energy price ratios makes the geothermal storage integration a viable solution for efficient supermarkets with reasonable payback time for present energy prices.

To conclude this section, it should be noted that the integrated concept is beneficial both for the supermarket owner and the neighboring consumer facility. The extra heat from the supermarket can also be sold to a district heating network; these benefits and limitations of this design concept are studied by Adrianto et al. (2018).

5.3. S3-hybrid solution

The third research question compares stand-alone CO_2 (S1a) and "hybrid CO_2 + GSHP" (S3) systems. As mentioned earlier, the entire supermarket heating demand is provided by heat recovery from the CO_2 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 the GSHP in winter while the refrigeration system runs at floating condensing mode (i.e. no heat recovery), the ground is also the heat sink for the CO_2 sub-cooler in summer. The sub-cooling variable amount in the hybrid system is assumed to be similar to case "S1b: SC summer" in the first scenario S1. The heat extraction from the ground is activated for ambient temperatures lower than 10 °C as the entire heating is provided by GSHP.

Similar to Section 5.2, EED and EES calculations are used to evaluate AEU and to size the borehole field. Performance comparisons of the two systems in terms of AEU on a seasonal and annual basis are shown in Fig. 13. The hybrid system consumes about 8%

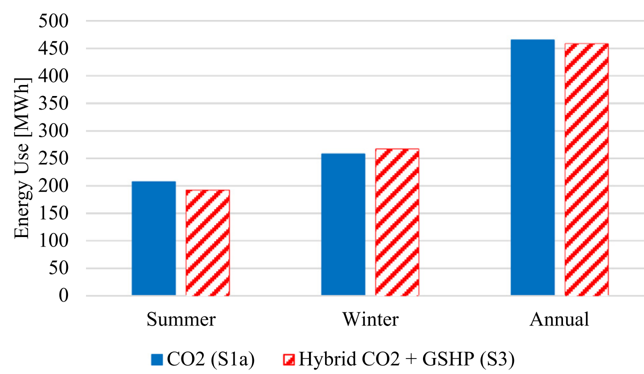


Fig. 13. Energy use of stand-alone CO_2 (S1a) vs hybrid system (S3) solutions.

less electricity than the stand-alone CO_2 system in summer, thanks to the geothermal sub-cooling. On the other hand, the winter energy use of the stand-alone system is approximately 5% less than the hybrid system. These seasonal energy use effects counterbalance, and the hybrid system is only 2% more efficient than the stand-alone CO_2 system annually.

To understand why the GSHP heat supply is less efficient than CO_2 heat recovery, the heating COP of the GSHP has been added to Fig. 8 and is presented in Fig. 14. The heating COP of the GSHP ($COP_{1,\ GSHP}$) is shown to be less than the heat recovery COP of the CO_2 system ($COP_{HR,S1a}$) at ambient temperatures below 0 °C.

The borehole field design for the GSHP has been conducted in a manner similar to Section 5.2.1 procedure. Since the entire heat demand is provided by the GSHP, the winter load on the ground has a higher order of magnitude than the summer heat injection load. This imbalance results in a 24-borehole 160 m-deep field design, which is much higher compared to a CO_2 system where heat recovery is prioritized to heat extraction. This large number of boreholes is required to guarantee a thermally balanced borehole field over the lifetime of the system. The payback time for such a large bore field is estimated to be more than 7–8 years, which is due, in part, to the expense of a required large heat pump of about 200 kW heating capacity, in ad-

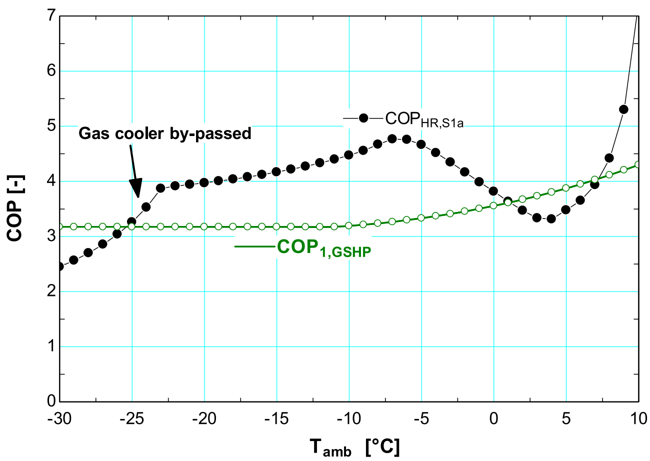


Fig. 14. Heating COPs for stand-alone CO_2 (S1a) and GSHP.

dition to the borehole drilling and pipe heat exchanger installation. To sum up, an integrated ground source heat pump and CO_2 system is not economically favorable over the stand-alone CO_2 system.

6. Conclusions

The effect on energy use due to geothermal storage integration into a SotA CO_2 supermarket refrigeration system has been investigated, using Stockholm climate conditions. Three different research questions related to different integration scenarios are studied. The first scenario, S1, considers integration of geothermal storage and CO_2 systems in a stand-alone supermarket. In the second scenario, S2, the heat from a ground-coupled CO_2 system is supplied to a nearby consumer who is buying heat from the district heating network. The third scenario, S3, considers an integration of CO_2, geothermal storage, and a ground source heat pump (GSHP). In cases where savings in annual energy use (AEU) can be achieved, the borehole field design is also discussed. Considering borehole field installation and energy costs, a basic economic analysis of this technology payback time is also performed.

The results show that heat recovery from a stand-alone CO_2 SotA system, S1a, is more efficient than providing part of the heating demand from the ground at medium or receiver pressure level, S1b. The results in this scenario also show that the addition of heat from the ground is especially beneficial when the gas cooler is fully by-passed, which is the ultimate step in the heat recovery control strategy where the heating demand is very high. However, sub-cooling the CO_2 system in the summer with the ground can save approximately 4% of the AEU.

The analysis of the second scenario, S2, indicates that annual running cost of a separate supermarket and district heating consumer (S2a) can be decreased by 19–31% if the systems are coupled, geothermal storage is applied, and the supermarket provides heating for the consumer (S2b). The parametric study shows that with current energy prices, the integrated solution can produce a payback time of less than 3.5 years.

The investigation of the hybrid solution, S3, which couples a CO_2 system, geothermal storage, and a separate GSHP, shows that approximately 2% of the AEU can be saved compared to a stand-alone CO_2 system. The savings are due to summer sub-cooling, the system uses more energy in the winter compared to the reference S1a system with heat recovery. However, the demand for a large borehole field and a large heat pump makes the payback time unreasonably long and the solution is not economically feasible.

In summary, geothermal storage integration into a CO_2 supermarket refrigeration system does not have a significant impact on energy use in the case of a stand-alone average size supermarket. For a supermarket combined with a neighboring building/facility, geothermal storage integration can contribute to significant running cost savings compared to separate systems running costs. The application of a separate GSHP is also not recommended as heat recovery from the CO_2 system is more efficient than this system. The CO_2 SotA is an efficient heat pump, with built in large heat source, i.e. refrigeration load. This load is the primary heat source and if more heat is required the ground storage can be used as the secondary heat source for the CO_2 SotA as a heat pump.

7. Limitation and future work

This paper evaluates the impact of geothermal storage integration into supermarket CO_2 refrigeration system. The study is fulfilled using computer simulations. The inputs to the model are partly based on field measurements analysis presented in authors previous research works. However, access to valid and sufficient measurements and processing this data is a time-consuming and challenging work; a report of insufficient instrumentations in 10 geothermal-integrated supermarkets reflects this challenge (Mateu-Royo, 2017). Proper instrumentation will help adopting more field-based assumptions input to the simulations, and also performing comprehensive field measurement analysis.

As part of an ongoing project started 2019, this research team will be involved in design, instrumentation, data collection and measurements analysis of a CO_2 state-of-the-art system. Depending on size and heating demands of the supermarket, geothermal storage integration will be studied.

Acknowledgment

The authors would like to acknowledge the Swedish Energy Agency funding this research through the Effsys Expand programme, grant number 40338-1. The authors would also like to thank project industrial partners Advansor, Alfa Laval, Cupori, Energi & Kylanalys, Friginor, Green & Cool, Huurre, ICA, Industri & Laboratoriekyl, and IWMAC. Finally, Carlos Mateu-Royo would like to acknowledge the Universitat Jaume I (Castelló de la Plana, Spain) for the financial support for his PhD studies under the Ph.D. grant PREDOC/2017/41.

References

Acuña, J., 2013. Distributed Thermal Response Tests: New Insights on U-pipe and Coaxial Heat Exchangers in Groundwater-filled Borehole Doctoral Thesis. Royal institute of technology (KTH), Stockholm, Sweden.
Adrianto, L.R., Grandjean, P.-A., Sawalha, S., 2018. Heat recovery from CO_2 refrigeration system in supermarkets to district heating network. In: Proceedings of the13th IIR Gustav Lorentzen Conference, IIR/IIF. Valencia, Spain.
Arias, J., 2005. Energy Usage in Supermarkets-Modelling and Field Measurements Doctoral Thesis. Royal Institute of Technology (KTH), Stockholm, Sweden.
BITZER, 2017. Bitzer Semi-Hermetic Reciprocating Compressors, Selection software, Retrieved 2017.04.15 from https://www.bitzer.de/websoftware/.
Blomberg, T., Claesson, J., Eskilson, P., Hellström, G., Sanner, B., 2017. Earth Energy Designer: EED, Software available at https://buildingphysics.com/eed-2/.
Cyclone, 2013. Walgreens Opens First Net-Zero Energy Retail Store, Retrieved 2016.04.15 from https://www.cyclone.energy/news/walgreens-opens-first-net-zero-energy-retail-store/.
Energimyndigheten, 2018. Energy in Sweden 2017, Retrieved 05.06.2018 from Swedish Energy Agency: http://www.energimyndigheten.se/en/ (Annual report).
EU 517/2014, 2014. Regulation (EU) No 517/2014 of the European Parliament and of the Council, of 16 April 2014 on Fluorinated Greenhouse Gases, and Repealing Regulation (EC) No 842/2006.
Freléchox, D., 2009. Field Measurements and Simulations of Supermarkets with CO_2 Refrigeration Systems Master Thesis. Royal Institute of Technology (KTH), Stockholm, Sweden.
Gullo, P., Hafner, A., Banasiak, K., 2018a. Transcritical R744 refrigeration systems for supermarket applications: current status and future perspectives. Int. J. Refrig. 93, 269–310. doi:10.1016/j.ijrefrig.2018.07.001.

Please cite this article as: M. Karampour, C. Mateu-Royo and J. Rogstam et al., Geothermal storage integration into a supermarket's CO2 refrigeration system, International Journal of Refrigeration, https://doi.org/10.1016/j.ijrefrig.2019.05.026

Gullo, P., Tsamos, K.M., Hafner, A., Banasiak, K., Ge, Y.T., Tassou, S.A., 2018b. Crossing CO_2 equator with the aid of multi-ejector concept: a comprehensive energy and environmental comparative study. Energy 164, 236–263. doi:10.1016/j.energy.2018.08.205.

Hafner, A., Banasiak, K., 2016. Full scale supermarket laboratory R744 ejector supported & AC integrated parallel compression unit. In: Proceedings of the 12th IIR Gustav Lorentzen Conference on Natural Refrigerants. Edinburgh, Scotland.

Hafner, A., Claussen, I., Schmidt, F., Olsson, R., Fredslund, K., Eriksen, P., Madsen, K.., 2014. Efficient and integrated energy systems for supermarkets. In: Proceedings of the 11th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIR/IIF, Hangzhou, China.

Hellström, G., Sanner, B., 1994. Earth energy designer: software for dimensioning of deep bore holes for heat extraction, in: calorstock. In: Proceedings of the 6th International Conference on Thermal Energy Storage, Espoo, Finland, pp. 195–202.

Ignatowicz, M., Melinder, Å., Palm, B., 2017. Properties of different ethyl alcohol based secondary fluids used for GSHP in Europe and USA. In: Proceedings of the IGSHPA Technical/Research Conference and Expo. Denver, USA.

Javerschek, O., Reichle, M., Karbiner, J., 2016. Optimization of parallel compression systems. In: Proceedings of the 12th IIR Gustav Lorentzen Conference on Natural Refrigerants. IIR/IIF, Edinburgh, Scotland.

Karampour, M., Sawalha, S., 2018. State-of-the-art integrated CO_2 refrigeration system for supermarkets: a comparative analysis. Int. J. Refrig. 86, 239–257. doi:10.1016/j.ijrefrig.2017.11.006.

Karampour, M., Sawalha, S., 2017. Energy efficiency evaluation of integrated CO_2 trans-critical system in supermarkets: a field measurements and modelling analysis. Int. J. Refrig. 82, 470–486. doi:10.1016/j.ijrefrig.2017.06.002.

Karampour, M., Sawalha, S., Arias, J., 2016. D2.2 Eco-Friendly Supermarkets – An Overview, H2020 Project SuperSmart, Grant Agreement No 696076, Retrieved 11.11.2016 from: http://www.supersmart-supermarket.info/downloads/.

Kavanaugh, S., Kavanaugh, J., 2012. Long-term commercial GSHP performance. Part 2: ground loops, pumps, ventilation air and controls. ASHRAE J. July 2012 54 (7), 26–34.

Klein, S.A., 2015. Engineering Equation Solver (EES) V9, F-chart Software, Madison, USA, www.fchart.com.

Kostnadsguiden, 2017. Bergvärme, Pris för Installation och Borrhål, Retrieved 8.10.2018 from https://kostnadsguiden.se/bergvarme-pris-installation-och-borrhal/.

Leiper, A., Skelton, J., Rivers, N., Zaynulin, D., 2014. Preventing trans-critical operation of co_2 refrigeration systems with ground coupling. In: Proceedings of 3rd IIR International Conference on Sustainability and the Cold Chain. IIF/IIR, London, UK.

Llopis, R., Cabello, R., Sánchez, D., Torrella, E., 2015. Energy improvements of CO_2 transcritical refrigeration cycles using dedicated mechanical subcooling. Int. J. Refrig. 55, 129–141. doi:10.1016/j.ijrefrig.2015.03.016.

Lozza, G., Filippini, S., Zoggia, F., 2007. Using "Water-Spray" techniques for CO_2 gas coolers. In: Presented at the XII European Conference on "Technological Innovations in Air Conditioning and Refrigeration Industry,". Milan, Italy.

Mands, E., Sauer, M., 2008. Feasibility Study: Ggeothermal Heat Pump for Standardized Supermarket, Retrieved 12.11.2018 from http://ubeg.de/IGEIA/IGEIA-D10-feasibility-study-supermarket-Germany.pdf. UBeG.

Mateu-Royo, C., 2017. Field Measurements and Modelling Analysis of CO_2 Refrigeration Systems with Integrated Geothermal Storage Master Thesis. Royal Institute of Technology (KTH), Stockholm, Sweden.

Meteotest, 2016. Meteonorm Software V7. Bern, Switzerland, www.meteonorm.com.

Minetto, S., Brignoli, R., Zilio, C., Marinetti, S., 2014a. Experimental analysis of a new method for overfeeding multiple evaporators in refrigeration systems. Int. J. Refrig. 38, 1–9. doi:10.1016/j.ijrefrig.2013.09.044.

Minetto, S., Girotto, S., Salvatore, M., Rossetti, A., Marinetti, S., 2014b. Recent Installations of CO_2 supermarket refrigeration system for warm climates: data from the field. In: Proceedings of the 3rd IIR International Conference on Sustainability and the Cold Chain. IIR/IIF, London, UK.

Ohannessian, R., Sawalha, S., 2014. Thermal energy storage potential in supermarkets. In: Proceedings of the 3rd IIR International Conference on Sustainability and the Cold Chain. IIF/IIR, London, UK.

Pardiñas, Á.Á., Hafner, A., Banasiak, K., 2018. Novel integrated CO_2 vapour compression racks for supermarkets. Thermodynamic analysis of possible system configurations and influence of operational conditions. Appl. Therm. Eng. 131, 1008–1025. doi:10.1016/j.applthermaleng.2017.12.015.

Polzot, A., D'Agaro, P., Cortella, G., 2017. Energy analysis of a transcritical CO_2 supermarket refrigeration system with heat recovery. Energy Procedia 111, 648–657. doi:10.1016/j.egypro.2017.03.227, 8th International Conference on Sustainability in Energy and Buildings, SEB-16, 11-13 September 2016, Turin, Italy.

Purohit, N., Sharma, V., Sawalha, S., Fricke, B., Llopis, R., Dasgupta, M.S., 2018. Integrated supermarket refrigeration for very high ambient temperature. Energy 165, 572–590. doi:10.1016/j.energy.2018.09.097.

Rehault, N., Kalz, D., 2012. Ongoing Commissioning of a high efficiency supermarket with a ground coupled carbon dioxide refrigeration plant. In: Proceedings of International Conference for Enhanced Building Operations (ICEBO). Manchester, England.

Robbins, J., Skelton, B., Olden, R., 2015. Revealing Net Zero, Wahgreens Case Study. High Perform. Build., Fall 2015 30–36.

Sawalha, S., 2013. Investigation of heat recovery in CO_2 trans-critical solution for supermarket refrigeration. Int. J. Refrig. 36, 145–156. doi:10.1016/j.ijrefrig.2012.10.020.

Sawalha, S., 2008. Carbon Dioxide in Supermarket Refrigeration Doctoral Thesis. Royal Institute of Technology (KTH), Stockholm, Sweden.

Sawalha, S., Karampour, M., Rogstam, J., 2015. Field measurements of supermarket refrigeration systems. Part I: analysis of CO_2 trans-critical refrigeration systems. Appl. Therm. Eng. 87, 633–647. doi:10.1016/j.applthermaleng.2015.05.052.

Sawalha, S., Piscopiello, S., Karampour, M., Manickam, L., Rogstam, J., 2017. Field measurements of supermarket refrigeration systems. Part II: analysis of HFC refrigeration systems and comparison to CO_2 trans-critical. Appl. Therm. Eng. 111, 170–182. doi:10.1016/j.applthermaleng.2016.09.07.

SCB, 2017. Prisutveckling på Energi Samt Leverantörsbyten, Andrakvartalet 2017, Retrieved 13.09.2018 from https://www.scb.se/contentassets/1329c0634a734b01ae643071c5c3f6aa/en0304_2017k02_sm_en24sm1703.pdf (Quarterly report). Statistics Sweden, Stockholm, Sweden.

Sintef, 2016. Drastic Cut in Electricity Bill for Supermarket, Retrieved 20.07.2018 from https://www.sintef.no/en/latest-news/drastic-cut-in-electricity-bill-for-supermarket/.

Skačanová, K.Z., 2018. Natural Refrigerant Market Trends, Presented at ATMOsphere Italy 2018, Retrieved 20.01.2019 from http://www.atmo.org/media.presentation.php?id=1467.

Skelton, J., 2011. Closed Loop Geothermal Heating and Cooling for Supermarkets, Retrieved 15.05.2018 from http://fridgehub.com/News/geothermal-ground-source-heat-pumps-a-case-study, in: IOR. UK Institute of Refrigeration.

SKM Enviros, 2012. Phase down of HFC Consumption in the EU-Assessment of Implications for the RAC Sector, Retrieved from: http://www.epeeglobal.org/refrigerants/epee-studies/skm-enviros-study/.

Tsamos, K.M., Ge, Y.T., Santosa, I.d., Tassou, S.A., Bianchi, G., Mylona, Z., 2017. Energy analysis of alternative CO_2 refrigeration system configurations for retail food applications in moderate and warm climates. Energy Convers. Manag. doi:10.1016/j.enconman.2017.03.020.

Please cite this article as: M. Karampour, C. Mateu-Royo and J. Rogstam et al., Geothermal storage integration into a supermarket's CO2 refrigeration system, International Journal of Refrigeration, https://doi.org/10.1016/j.ijrefrig.2019.05.026