



Geothermal Storage Integration into Supermarket's CO₂ Refrigeration System

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ABSTRACT

This paper investigates the integration of geothermal storage into the state-of-the-art CO₂ trans-critical booster systems. The objective is to evaluate the impact on energy efficiency of this integration. Three scenarios of integration are studied including stand-alone and integrated supermarket building systems. The results show that for a stand-alone supermarket, heat recovery from the CO₂ system should be prioritized over extracting heat from the ground, which can be done either by an extra evaporator in the CO₂ system or by a separate ground source heat pump. In the case of supermarket integration with a nearby district heating consumer, geothermal storage integration with extra evaporator in the CO₂ refrigeration system can reduce the total annual running cost of the two buildings by 20-30%. The determining factors on profitability of geothermal storage integration are the heating demand of the supermarket and possibilities of coupling its heating system to another nearby consumer. This integration is beneficial if the full efficient heat recovery capacity of the CO₂ system is not sufficient to provide the entire demands.

1. INTRODUCTION

Supermarkets are the most energy intensive commercial buildings where the refrigeration system is their largest energy user (Karampour et al., 2016). They are also the largest consumers in Europe of high GWP refrigerants; about 35% of Europe HFC consumption (SKM Enviros, 2012). These two factors put the environmentally-friendly and energy-efficient supermarket refrigeration solutions as one of the priorities on climate change mitigation policies. CO₂ trans-critical refrigeration systems for supermarkets are seen as a solution that fulfills the environmental requirements; therefore, they have been introduced, installed and spread in mainly the relatively cold regions of Europe and the world with more than 15,000 systems as of November 2017 (Chasserot, 2017).

A potential improvement which has been less covered in the literature is the integration of geothermal storage into the CO₂ state-of-the-art system. The potential advantage of this integration is that the ground can be used as a heat sink to provide sub-cooling for the CO₂ system in summer and as a heat source in the winter for the heat pumping function of the CO₂ refrigeration system or via a separate Ground Source Heat Pump (GSHP).

As the number of CO₂ systems and integration of geothermal storage are increasing in Scandinavian supermarkets, it is necessary to discuss the advantages and limitations of this integration more in details. In section 2 of this paper the studied systems are described and three different scenarios of geothermal storage integration are presented in section 3.

2. SYSTEM DESCRIPTION

The reference system in this study is state-of-the-art (SotA) CO₂ trans-critical booster system which is presented by the black lines in the schematic in Figure 1. This system is abbreviated as CO₂ SotA hereinafter. The features of this

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system have been discussed in details by the authors in previous research (Karampour and Sawalha, 2018). The CO₂ SotA system takes the advantage of flooded evaporation to run at high evaporation temperatures and uses parallel compression to compress the flash gas vapour. It has been shown that these features decrease the refrigeration annual energy use (AEU) of the standard CO₂ booster system by 15%. The CO₂ SotA system also integrates space heating, tap water heating, and air conditioning functions into the refrigeration system. The energy efficiency of providing heating and air conditioning demands by CO₂ SotA are either higher or comparable to efficient alternative solutions, which further decreases the overall AEU for refrigeration, heating, and air conditioning. The air conditioning and tap water heating are not included in this study, and heat recovery is done only for space heating, which is the major heating demand in supermarkets.

A feature which hasn't been evaluated in scientific publications but applied in some supermarkets, mainly in Scandinavia, is the 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 1-left. The geothermal integrated lines are highlighted by green colour. 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 during this season and an extra evaporator (Geothermal Heat Extractor in Figure 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.

As shown in Figure 1-left, 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 extractor evaporator is fully open and the exit line is connected to the parallel compressor. Both methods of extracting at P_{MT} or P_{rec} level have been applied in field installations in Sweden and studied in this paper.

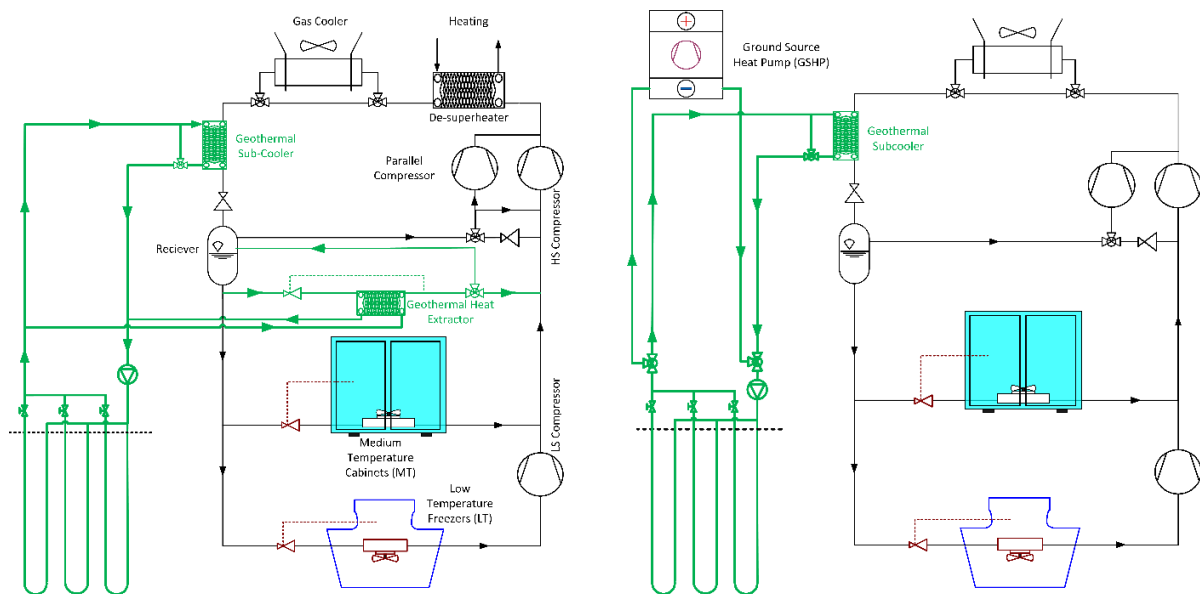


Figure 1: Schematic of a state-of-the-art CO₂ booster system and integrated geothermal storage, the later is highlighted by green (left), Hybrid geothermal solution, refrigeration system sub-cooling in summer, heat source for GSHP in winter (right)

Another option to extract and use the stored heat from the ground in winter is by running the CO₂ system in floating condensing mode, i.e. lowest pressure possible, and use a separate ground source heat pump (GSHP) to provide the supermarket's heating demands. Schematic of this system, called "hybrid" in this paper, is shown in Figure 1-right. This system is also studied in this paper.

3. RESEARCH SCENARIOS

The objective of the paper is to study three research scenarios, these are visualized in Figure 2:

S1- Comparing the annual energy use (AEU) of a stand-alone supermarket using CO₂ system (S1a) versus geothermal storage integrated CO₂ system (S1b).

S2- Comparing AEU of “separate systems of supermarket and a neighbor consumer of district heating energy” (S2a) versus “integrated systems of supermarket, the neighbor consumer and geothermal storage” (S2b). In the later, the entire heating demand of the neighbor is provided by heat recovery from the CO₂ system in winter. Ground also provides sub-cooling for CO₂ system in summer.

S3- Comparing AEU of a stand-alone supermarket using CO₂ system (S3a) versus a “hybrid solution of sub-cooling CO₂ system by ground in summer, and extracting heat from the ground by GSHP in winter (S3b).

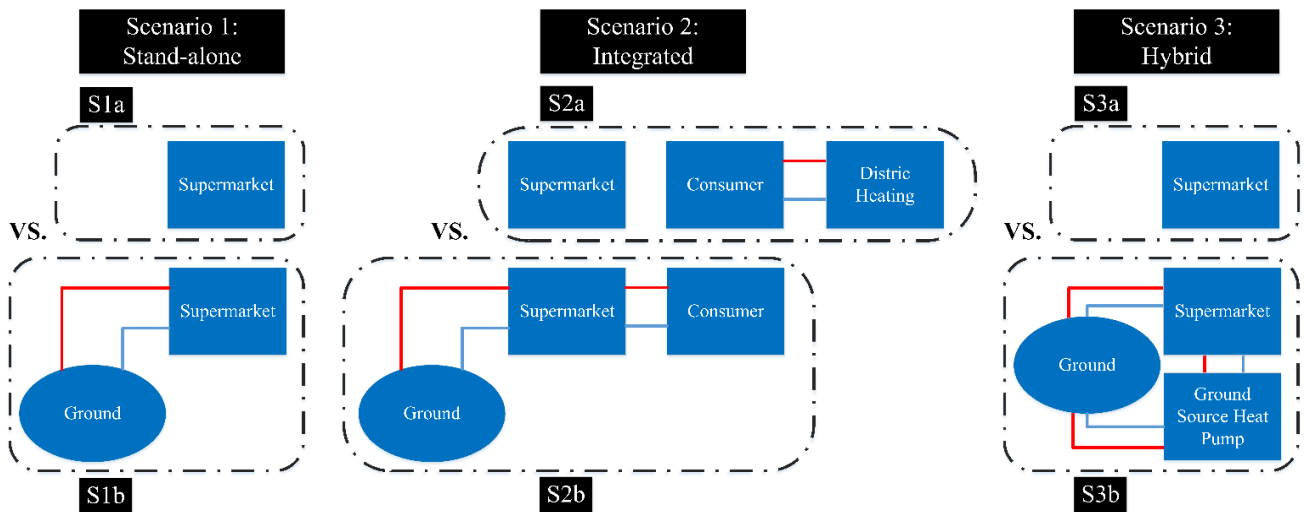


Figure 2: An illustration of the studied scenarios

4. MODELLING DETAILS

4.1 Boundary conditions and assumptions

4.1.1 Thermal Loads

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 rather constant through the entire year and assumed to be 35 kW. Medium and low stage evaporation temperatures of the CO₂ SotA are -4°C and -29°C, respectively.

The heating demand is obtained by the program CyberMart for a medium-sized supermarket in Sweden. CyberMart is a tool to calculate the annual energy demand and use of different refrigeration, heating and air conditioning systems in supermarkets. Detailed description and calculation procedure of the program can be found in the Doctoral Thesis by Arias (Arias, 2005).

The main heating demand in supermarkets is space heating and it starts at the set-point of 10°C ambient temperature. 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. 5K approach temperature is assumed between the water return temperature and the refrigerant in the condenser of the separate GSHP, or the de-superheater..

4.1.2 Control strategy

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

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

The heat recovery control strategy in winter follows the recommendations presented by Sawalha (2013). In brief, the recommendation consists of a stepwise control strategy; the first step is to regulate the gas cooler pressure P_{gc} and run the gas cooler fans with highest speed to maintain gas cooler exit temperature $T_{gc,exit}$ as low as possible with a minimum value of 5°C. The second step is to fix the gas cooler pressure at a maximum value for high efficiency P_{gc} and decrease the gas cooler capacity by reducing the fans speed. The third step is to fully by-pass the gas cooler. Due to the sharp drop in system efficiency the system should never go beyond the third step. If more heat is required, the fourth step is to extract the heat from the ground.

The heating season is called winter operation mode and it starts at ambient temperatures lower than 10°C. The rest is called summer operation mode. Temperature-bin hours of Stockholm is used as the studied climate.

4.1.3 Geothermal storage and GSHP hybrid solution

Modelling simulations for the ground heat exchanger have been done for Stockholm conditions, therefore the ground properties used for the borehole design are rock thermal conductivity of 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 geothermal loops. It has a freezing temperature of -14.6 °C; however, its operating temperature T_f [°C] is restricted to be within the range of -5°C and +20°C. The flow rate is 0.5 l/s per borehole, which is constant during all the operation time. The borehole uses single U-tube heat exchangers and their depth is selected to vary within the 150-200m range. The pump power is assumed to be 5% of the GSHP compressor electricity use. The GSHP uses R07C as the working fluid, with a heating capacity of 200 kW. The evaporator has a capacity of 80 kW. Both evaporator and condenser have 5K 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 similar boundary conditions to CO₂ heat recovery de-superheater. The evaporator has an approach temperature of 5K with the secondary fluid and 10K internal super-heating.

4.2 Energy efficiency calculations

A computer model in EES (Engineering Equation Solver) software (Klein, 2015) is used to analyze the performance of the CO₂ SotA and GSHP systems. The calculations of cooling and heating loads have been explained comprehensive in authors previous research (Karampour and Sawalha, 2018) (Karampour and Sawalha, 2017).

The total electricity use \dot{E}_{tot} [kW] of the system is calculated based on Eq. (2):

$$\dot{E}_{tot} = \dot{E}_{MT} + \dot{E}_{LT} + \dot{E}_{PC} + \dot{E}_{fan} + \dot{E}_{geo,pump} \quad (2)$$

where \dot{E}_{MT} , \dot{E}_{LT} , and \dot{E}_{PC} [kW] are the electricity use of three compressor units. These are calculated based on overall efficiency of the compressors, extracted from manufacturer's data. \dot{E}_{fan} [kW] is the electricity use of gas cooler fans. \dot{E}_{fan} is estimated to be 3% of the heat rejected in the gas cooler \dot{Q}_{gc} [kW]. $\dot{E}_{geo,pump}$ is the pump electricity use to circulate the secondary fluid. It is estimated that it is about 5% of the extra evaporator capacity in winter or geo sub-cooler in summer.

Heat recovery COP (COP_{HR}) of the CO₂ SotA system is defined as:

$$COP_{HR} = \frac{\dot{Q}_{HR}}{(\dot{E}_{tot} - \dot{E}_{tot,fc})} \quad (3)$$

\dot{Q}_{HR} [kW] is the amount of recovered heat, \dot{E}_{tot} [kW] is the total electricity use calculated from equation (2), and $\dot{E}_{tot,fc}$ [kW] is the amount of electricity use if the system was not controlled for heat recovery and was run in floating condensing mode with minimum condensing pressure in winter.

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

$$AEU = \sum_{i=1}^n (\dot{E}_{tot,i} \cdot f_i) \quad (4)$$

where \dot{E}_{tot} [kW] is the total electricity use calculated from equation (2), n is the number of temperature-bin hours, and f is the frequency, i.e. number of hours, of each temperature bin.

The calculations on the geothermal storage and its borehole field design are done using Earth Energy Designer (EED) software (Hellström and Sanner, 1994).

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 software calculates the optimized geometry and fluid temperature as a function of time of the year. This function is correlated to ambient temperature and used as a new variable sub-cooling amount in the EES code. EES calculates again the amount of ground loads in winter and summer. This iterative calculation between EES and EED is repeated to find a good match between EES and EED results.

5. RESULTS AND DISCUSSIONS

5.1 S1-Stand-alone Supermarket

The 1st scenario is to compare CO₂ refrigeration system without (S1a) and with (S1b) geothermal connection in a stand-alone supermarket. Eight system design cases have been calculated in this scenario:

- CO₂ SotA (reference): the system has no geothermal connection and heat recovery from its de-superheater is used to provide the space heating demand in the supermarket building.
- Sub-cooling in the summer (SC summer): the CO₂ system uses ground as heat sink in summer to sub-cool the refrigerant exiting the gas cooler.
- Sub-cooling in the summer (SC summer) and heat extraction in winter: The studied six cases include three cases of heat extraction at P_{MT} level, and three at P_{rc} level. The extra evaporator \dot{Q}_{ex} [kW] is studied for sizes of 40, 80 and 120 kW. These values are selected to be a reasonable capacity able to be provided by the installed compressors; no additional compressors are needed. Summer sub-cooling is also studied in all these six cases for a reasonable range of up to 15K sub-cooling, this results in a sub-cooling design capacity of about 60 kW.

The AEU and AEU decrease, compared to the reference case (CO₂ SotA – no geothermal), of these eight cases are shown in Figure 3. As can be seen in Figure 3, geothermal sub-cooling can provide about 3.5% AEU saving. However, this is not an economically feasible solution since there is no heat extraction in winter time; no earth thermal de-charging, and a large number of boreholes are required to keep the earth energy balance. The savings for the later six cases are less than 3%, the reason that AEU saving changes from 3.5% (only sub-cooling) to less than 3% (sub-cooling and heat extraction) is that winter heat recovery in the geothermally integrated CO₂ system is less efficient than the stand-alone CO₂ system.

To understand why heat recovery in the integrated solution is less efficient than the stand-alone CO₂ system, COP_{HR} of the CO₂ refrigeration system without geothermal connection (COP_{HR}) is compared to the heating COP of the geothermal heat extraction only ($COP_{HR,ex}$) and shown in Figure 4. $COP_{HR,ex}$ is defined as the amount of recovered heat (by the addition of extra heat source) over the amount of extra electricity use in compressors. In COP_{HR} the geothermal heat extraction is assumed to be switched off while in $COP_{HR,ex}$ the heating demand is provide primarily by heat extraction from the ground, and the remaining demand is provided by heat recovery from the refrigeration system. For $COP_{HR,ex}$ the sole effect of the geothermal heat extraction is calculated.

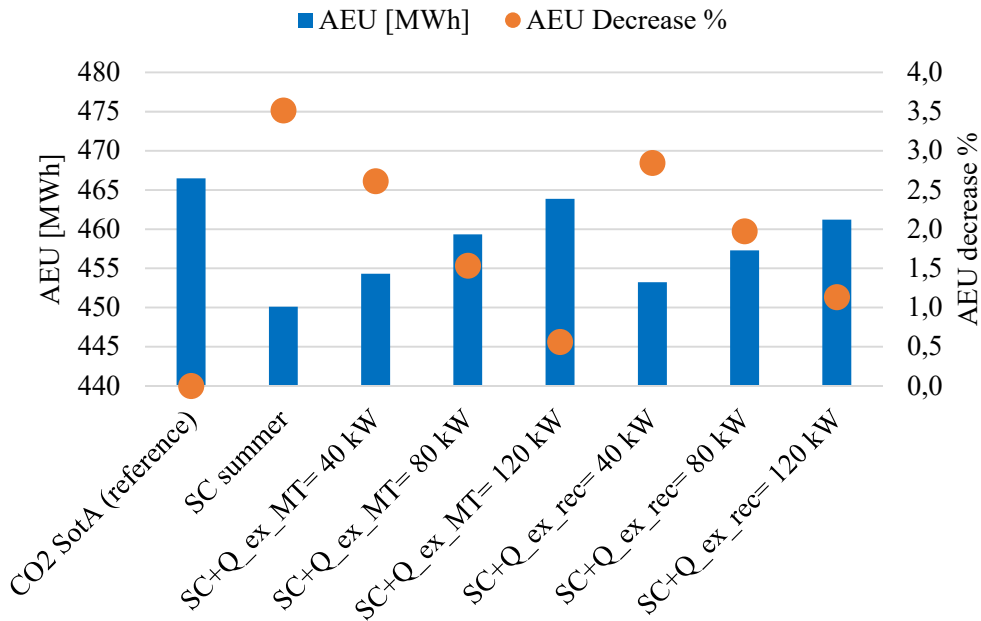


Figure 3: Annual Energy Use and Savings for S1 design cases

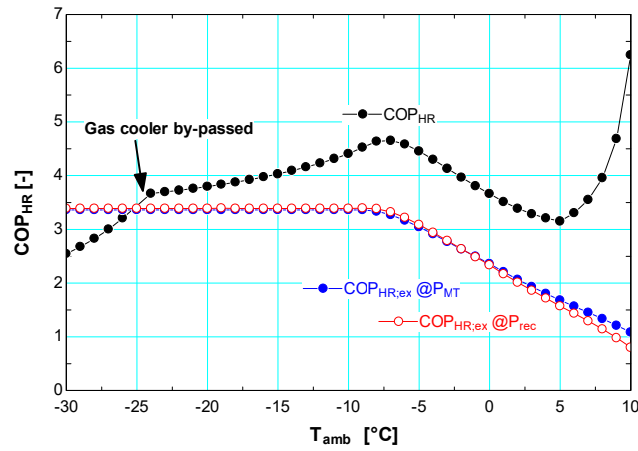


Figure 4: Heat recovery COPs for CO₂ stand-alone and CO₂ ground-coupled systems

It can be observed that $COP_{HR,ex}$ is low at relatively high outdoor temperatures (i.e. heating loads) where the system operates in the sub-critical region and small amount of heat is recovered from the de-superheater. COP_{HR} is higher than $COP_{HR,ex}$ for most of the calculated range of ambient temperatures. It should be pointed out that the system is not expected to operate for many hours at very low outdoor temperatures; however, the range has been extended in this analysis to quite low outdoor temperatures in order to increase the heating demand in the building and show the limits of the refrigeration system to recover heat. $COP_{HR,ex}$ is only higher than COP_{HR} 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 sharp drop in COP_{HR} (i.e. fourth step in the control strategy explain in section 4.1.2).

The results plotted in Figure 4 means that heat extraction from the ground should be activated only when the gas cooler is fully by-passed; quite low outdoor temperatures and/or very high heating demand. In an average size

supermarket in Sweden, which has been assumed in this study, the refrigeration load in the supermarket is able to cover the space heating demand with relatively high COP for outdoor temperatures higher than -24°C ; i.e. no need for heat extraction from the ground.

5.2 S2-Integrated Supermarket

The 2nd scenario is to compare “separate supermarket and district heating consumer” systems (S2a) with “integrated supermarket, consumer, and geothermal storage” systems (S2b) in two nearby supermarket and consumer buildings. 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: (I) rather high electricity price and low district heating price, and (II) 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 5.

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. This saving is the justified cost which should be compared with the cost of geothermal storage and systems integration. In the following subsection, first, the borehole heat exchanger is designed for this integrated solution. Second, based on the energy and geothermal storage costs, the payback time for this integration concept is calculated.

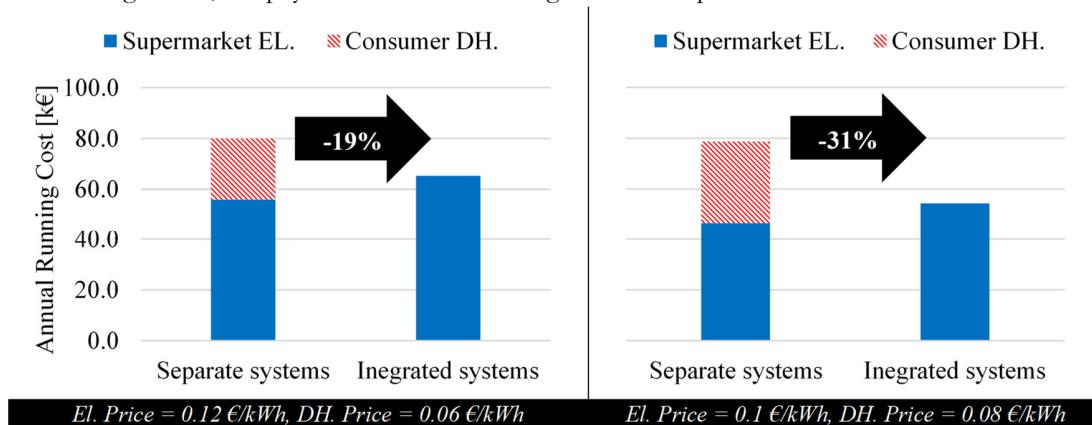


Figure 5: Separate and integrated systems annual running cost [thousand Euros]

Borehole design

In this section, the borehole field for the above-mentioned integrated solution is designed. The results of secondary fluid temperature T_f [$^{\circ}\text{C}$] and specific heat extraction rate [$\text{W}\cdot\text{m}^{-1}$] fluctuations for a 15-year lifetime of the energy system solution are shown in Figure 6-left. The minus values for the extraction rate means 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 seen, T_f varies within the design criteria of -5°C to $+20^{\circ}\text{C}$. This has been achieved by optimizing the geometry of the borehole field. The calculated number of boreholes to have reasonable ground energy balance is 12, in a 3×4 rectangular arrangement, with 10m spacing and about 159m deep. This results in a total length of 1908 meters. The total cost of borehole drilling and the U-tube heat exchanger is about 25 €/m in Sweden. This means that the total cost for the desired borehole heat exchanger is 47.700 €. This value can be compared with the amount of annual running cost saving, presented in the previous section, to calculate the payback time.

The payback time for different energy price ratios (electricity to heating) compared to the geothermal storage cost is shown in Figure 6-right. The three electricity prices considered are 0.1, 0.12 and 0.14 $\text{€}\cdot\text{kWh}^{-1}$ and the three heating

prices are 0.06, 0.08 and 0.1 €/kWh⁻¹. This forms nine combinations. According to some communications with supermarkets owners, a payback time of three years is a reasonable value for investments like the proposed solution. The energy price “ratios” for Sweden is presently within the range of 1.2-1.7. This implies that geothermal storage integration is a solution with reasonable payback time for present energy prices.

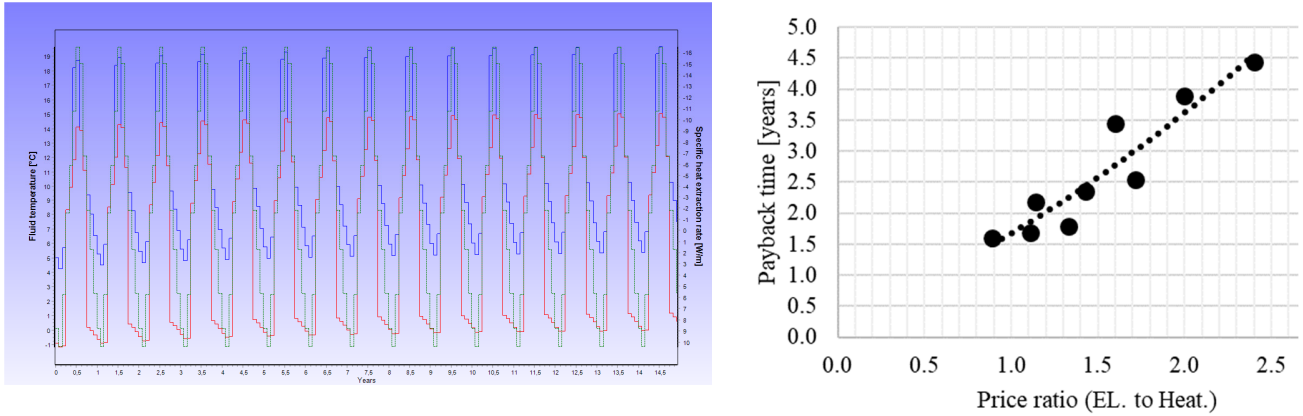


Figure 6: Secondary fluid temperature and heat extraction fluctuations (left), Payback time for different energy price ratios (right)

5.3 S3-Hybrid solution

The 3rd research scenario is to compare “CO₂” (S3a) and “hybrid CO₂ + GSHP” (S3b) 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. Similar to section 5.2, EED and EES calculations are used to evaluate AEU and to size borehole field. The results of the comparison are shown in Figure 7. 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.

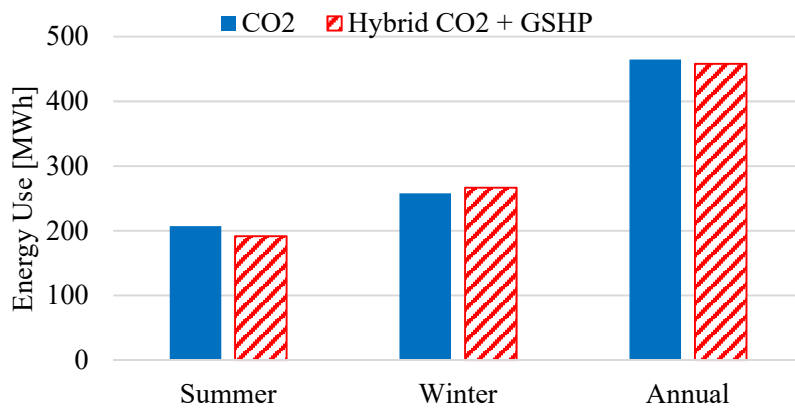


Figure 7: Energy use of stand-alone CO₂ vs hybrid system solutions

Borehole field design for GSHP has been done similar to section 5.2 procedure. 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 not seem economically favorable over the stand-alone CO₂ system.

6. CONCLUSION

This paper investigates the advantages and challenges of geothermal storage integration into a state-of-the-art CO₂ supermarket refrigeration system. Three different integration scenarios are studied.

The 1st scenario study 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.

The 2nd scenario study results show that annual running cost of two separate supermarket and district heating consumer can be decreased by 20-30% if the systems are coupled, geothermal storage is applied and supermarket provides heating for the consumer. A parametric study shows that with the current energy and borehole drilling prices, the integrated solution can be applied with a payback time of less than 3 years.

The 3rd scenario study on the hybrid solution of the 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. However, in the case of an integrated supermarket with a neighbor 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 long as heat can be recovered from the CO₂ system efficiently.

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