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Cold thermal energy storage for air conditioning in a supermarket CO_2 booster refrigeration system

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ABSTRACT

Integrated supermarket refrigeration systems are based on transcritical CO_2 booster systems, supplying cooling and freezing of the products in the store and air conditioning (AC) of the shop area by cooling a glycol circuit supplied to the air handling unit (AHU). The design capacity of the refrigeration system must handle all the refrigeration load and the AC load during the warmest summer day, which results in overcapacity and part load operation for most of the year. In this paper, it is proposed to replace the glycol circuit to the AHU with a combination of a CO_2 circuit and a cold thermal energy storage (CTES). The CTES is using water/ice as the storage medium and can be used to store cold energy during the night and supply AC during the peak hours of the day. Numerical simulations of the proposed system demonstrate peak power reductions of 13-19% in four Norwegian locations.

Keywords: Supermarket Refrigeration, Carbon Dioxide, Cold Thermal Energy Storage, Energy Efficiency

1. INTRODUCTION

Carbon dioxide (CO2, R744) refrigeration systems are the preferred selection for commercial refrigeration and supermarket applications in many countries in Europe, including Norway. This refrigerant performs very efficiently in locations where the weather is mild or cold, but operation in warmer locations can be challenging due to its low critical temperature of approximately 31 °C (Bell et al., 2014), using transcritical operation. Even so, CO_2 refrigeration systems are spreading throughout the world thanks to several technological improvements that enhance their performance in the transcritical cycle, such as mechanical subcooling and ejector technology (Gullo et al., 2019; Llopis et al., 2018). Moreover, CO_2 is a safe choice legally and environmentally, while it is becoming competitive in cost (Gullo et al., 2018; Karampour and Sawalha, 2018). In addition, the integration of air conditioning (AC) and heat recovery in the same centralized CO_2 refrigeration system is a popular option, meeting all the demands in the shop with a single unit (Gullo et al., 2017). Several demonstration projects for CO_2 technology for heating and cooling in the southern European context were carried out in the EU project MultiPack. The performance of a fully integrated CO_2 supermarket system covering cooling, AC and heating was investigated in the project, proving the competitiveness of the technology also in warm climates (Pardiñas et al., 2021).

Cold thermal energy storage (CTES) with phase change materials (PCMs) utilising the latent storage principle has attracted a lot of attention in the latest years due to offering a more compact solution over conventional sensible storage technology. The possibility to select a PCM with a phase transition temperature well matched with near-isothermal evaporation and condensation process in refrigeration systems makes this technology particularly attractive. CTES technology with PCM for refrigeration systems has been investigated in almost the entire cold chain, spanning from industrial refrigeration in production/processing, transport refrigeration and packaging, commercial refrigeration in supermarkets and domestic refrigeration (Selvnes et al., 2020). CTES technology using water/ice and a PCM with a freezing point of -9.6 °C in a pillow-plate heat exchanger was experimentally demonstrated for a pump-circulated CO_2 refrigeration system (Selvnes et al., 2022, 2021). The technology has the potential to decouple the supply and demand of refrigeration, increase the flexibility of operation, achieve peak shaving of the refrigeration load and improve capacity utilisation of the installed equipment. In this paper, a concept for implementing a latent CTES using water/ice as the storage medium in a CO_2 supermarket refrigeration system is proposed. The potential for peak shaving and reduction of operating costs is investigated by numerical modelling.

2. METHOD AND SIMULATION

2.1. Presentation of the concept

The reference system for this study is a standardised transcritical CO_2 booster system installed by a leading supermarket chain in Norway. The booster cycle includes the integration of AC and heat reclaim. A simplified P&ID is included in Figure 1. It represents the MT and LT compressors, the heat reclaim heat exchanger downstream of the MT compressors and the AC solution. The AC system includes a heat exchanger with a 3-way valve downstream of the high-pressure valve (HPV) on the CO_2 side, and a pumped loop of monoethylene glycol (MEG) delivering to the AHU. The cooling of the MEG circuit is carried out by evaporating the two-phase mixture of refrigerant downstream of the high-pressure control valve at the receiver pressure. The heat absorbed by the refrigerant from cooling the MEG circuit results in an increased amount of vapour sent to the receiver, which is further throttled by the flash gas bypass valve (FGBV) to the MT compressor suction level. These units may not be the most efficient under those very specific warm conditions and for AC production but are simple and robust. This system is delivered to all the new shops covered by this supermarket chain, although the ambient conditions vary greatly across the country. The design capacity for the supermarket refrigeration system is presented in Table 1. Since the system is in a booster configuration, the MT compressor capacity has to be sufficient to handle the combined refrigeration load from the LT, MT and AC level and compress it to the gas cooler pressure for heat rejection. The cooling of the MEG circuit occurs at the receiver pressure but is later throttled to the MT suction, so the AC is in reality produced at -7 °C. In high-ambient conditions, the amount of flash gas formed and the AC load is higher, and a parallel compression configuration can be applied to improve the efficiency (Sarkar and Agrawal, 2010).

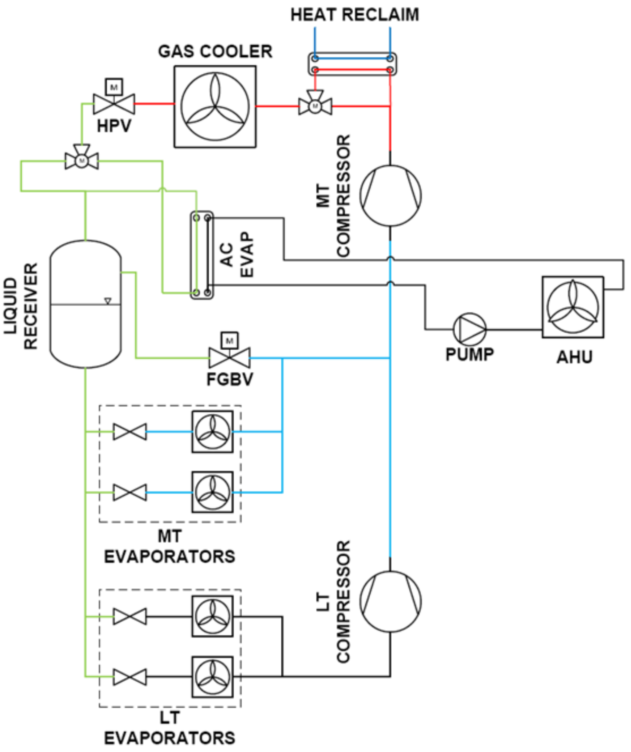

Figure 1: Reference system consisting of a standard transcritical CO2 booster system with air conditioning.

Table 1: Compressor capacity and refrigeration load for the reference CO2 system

Type of load	Temperature [°C]	Capacity [kW]	Comment
MT compressor capacity	-7	80	Temperature on the refrigerant side
LT compressor capacity	-30	10	Temperature on the refrigerant side
Air conditioning load	7	25	Temperature on the glycol side

This paper aims to improve the system solution described above by implementing a different approach to AC production which relies on CTES technology. The proposal is to design a system where the AC demand in the AHU is supplied from a CTES unit with PCM during the daytime when the load on the refrigeration system is already high. The cold accumulation to the CTES unit will be carried out by the CO_2 refrigeration system during the night to maintain a steady compressor load, avoid on-off cycling and benefit from lower ambient temperature to improve the COP. For supplying AC demands, water/ice is an excellent choice for a latent storage medium/PCM. Water is inexpensive, accessible and has well-documented thermo-physical properties. The MT evaporation level can be used during the charging process (cold accumulation) to solidify the water into ice, and there is a sufficient temperature difference to the supplied cold air in the AHUs from the phase transition temperature of water to carry out the discharging process. The proposed concept is based on the work presented by (Selvnes et al., 2021), where a CTES unit based on a pillow-plate heat exchanger and water/ice as a storage medium was experimentally investigated for a CO_2 system. Figure 2 shows a simplified P&ID of the proposed system in charging mode (left) and discharging mode (right). The rest of the CO_2

refrigeration system has not been changed, except for the removal of the AC heat exchanger and three-way valve downstream of the HPV.

The following is a description of the operational strategy of the proposed system. During charging mode, the liquid level valve (V level) supplies refrigerant from the liquid receiver by throttling it to the liquid receiver in the CTES system. The FGBV2 is fully open so that the formed refrigerant can be handled by the MT compressors in parallel to other loads. The liquid refrigerant is supplied from the receiver in the CTES system to a refrigerant pump and pumped to the inlet of the CTES unit (Ice storage). The charging valve (V charge) is open and the valve to the AHU (V AC) is closed. The refrigerant (at MT evaporation temperature) evaporates inside the pillow plates while the water is solidified to ice inside the CTES unit, with an outlet vapour fraction of about 0.9. The two-phase refrigerant mixture is returned to the receiver in the CTES system, where vapour is taken by the MT compressors to maintain the pressure. During the discharging mode (daytime, AC needed), FGBV2 is operated as the FGBV in the standard system, i.e., maintaining a pressure in the receiver of the CTES system to the selected operating temperature (approximately 5 °C). The liquid refrigerant is pumped from the CTES receiver through valve V AC to supply cooling of the ventilation air in a CO_2 coil in the AHU. The CO_2 is evaporated upon absorbing the heat from the air, and the returning vapour is passed through the CTES unit. The CO_2 vapour is condensed in the pillow plates while the ice is melting in the process. The resulting liquid is returned to the CTES receiver. The system also allows for operating without the CTES unit by opening the V AC direct valve, bypassing the CTES unit. The vapour is then throttled by the FGBV2 to the MT evaporation level and handled by the MT compressors.

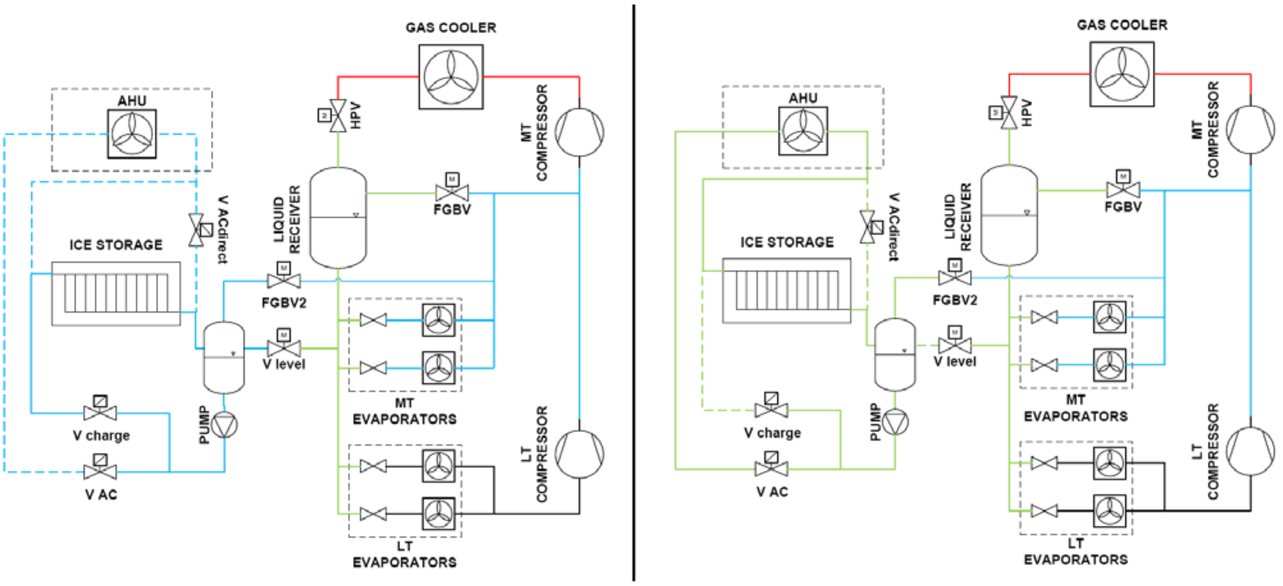

Figure 2: The novel concept for supplying AC by CTES unit based on water/ice as the storage medium. The left shows the system in charging mode, the right shows the system in discharging mode.

2.2. Assumptions and simulation model

The reference CO_2 refrigeration system was modelled with the Modelica programming language in Dymola 2022x[1] (Dassault Systems, Vélizy-Villacoublay, France), TIL 3.11.0 and TIL Media 3.11.0 libraries for components and working fluid properties[2], respectively (TLK-Thermo GmbH, Braunschweig, Germany). The compressor models were parametrized according to the dimensioning provided by the technical department of the supermarket operator, based on the correlations from Bitzer's software[3].

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[1] https://www.3ds.com/products-services/catia/products/dymola/
[2] https://www.tlk-thermo.com/index.php/en/software/38-til-suite
[3] https://www.bitzer.de/websoftware/

The following is a description of the constraints that were considered during the preparation of the model. The MT refrigeration demands are based on the hour of the day as represented in Figure 3. The LT demand was constant at 8 kW. The MT and LT evaporation temperatures had a setpoint at -7 °C and -30 °C, respectively. The expansion valves were controlled according to superheat, setpoint at 8 K. The AC demand profile was based on the outdoor temperature (linearly dependent). Dimensioning load for the AC demand was 25 kW (from the specifications of the system drawings) at 30 °C, with no demand at 15 °C. The heat reclaim was disregarded in this analysis. The temperature approach at the gas cooler outlet (the difference between CO_2 temperature at the outlet and air temperature at the inlet) was equal to 3 K.

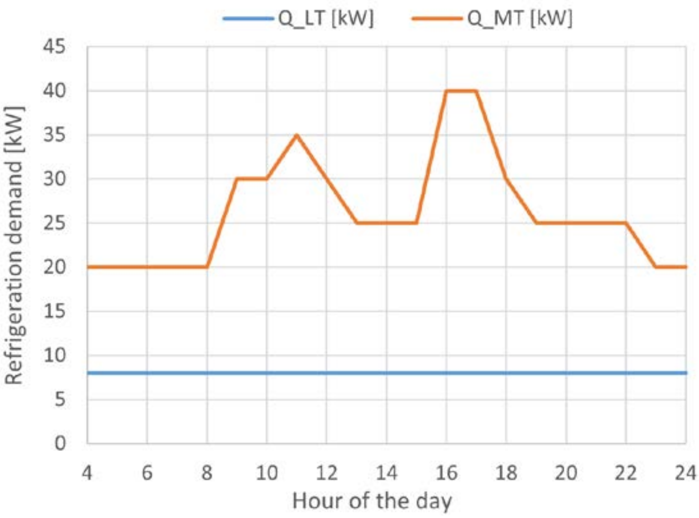

Figure 3: Assumed daily load profile for MT and LT refrigeration in the supermarket.

Simulations were performed to determine the COP of the reference CO_2 unit without storage at the different operating conditions and refrigeration and AC loads. The simulation matrix was created based on varying the outdoor temperature from 10 °C to 34 °C (2 K steps), varying the MT loads from 20 kW to 50 kW (10 kW steps) and varying the AC loads from 0 kW to 25 kW (5 kW steps), in total 24 cases. The value taken for each combination of parameters was that corresponding to the steady state. These values were then used to define a COP correlation that could be used in a simple manner in further analysis, presented in Eq. (1). This correlation has a coefficient of determination R2 = 0.954, and the parameters are defined in Table 2.

$$COP = a \cdot (Q_{MT} + Q_{AC}) + b \cdot T_{amb} + c \cdot {T_{amb}}^{2} + d \cdot (Q_{MT} + Q_{AC}) \cdot T_{amb} + e \qquad \text{Eq.(1)}$$

Table 2: Values of parameters used in Eq.(1)

Parameter	Value	Observations
a	2.38·10-5	Loads in W
b	-1.87·10-1	Temperatures in °C
c	2.24·10-3	Temperatures in °C
d	$-5.06\cdot10^{-7}$	Loads in W, temperature in °C
e	5.02	

This correlation was utilized in a numerical evaluation to determine the impact of substituting the current AC integration with the proposed CTES system as described in the previous section. To do so, weather data and electricity prices for week 28 in 2022 (July 11th to 17th) were considered. Weather data were taken from Norsk klimaservicesenter[4], representing relevant climates in Norway (station number in parentheses): Oslo (SN18210), Kristiansand (SN39150), Trondheim (SN68860) and Tromsø (SN90490). Electricity prices for the given week were extracted from the Nordpool electricity market database[5]. The ambient temperature and the electricity prices of the four locations are presented in Figure 4.

The cases considered in the evaluation were:

- Scenario 1. AC is produced following the needs equal to the reference system (Figure 1). Electricity cost during the week according to the market price presented in Figure 4.
- Scenario 2. AC demand for the following day is produced the preceding night, distributed in the 8-hour period corresponding to closed shop, and stored as ice in the CTES unit. AC needs are met by the discharging of the CTES unit during the day. It is assumed that the CTES storage is dimensioned to cover the AC load in terms of delivered cooling and capacity. Electricity cost as in Scenario 1.

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[4] https://klimaservicesenter.no/

[5] https://www.nordpoolgroup.com/en/Market-data1/#/nordic/table

- Scenario 3. AC produced as in Scenario 1. The cost of electricity is assumed as fixed day and fixed night prices. Based on the average market electricity price per location, it was considered that the day price (09:00 to 24:00) would be 50% above the average, while the night price (24:00 to 09:00) 50% below the average. This pricing scheme was assumed to illustrate the effect of a transition step from the fixed electricity price scheme applicable to many larger customers today to a scheme where the end user is fully following the market price equivalent to private consumers. This assumes that the demand for electricity in the grid is lowest at night, and consequently, the prices are reduced.

- Scenario 4. AC is produced as in Scenario 2 using the CTES unit. Electricity cost as in Scenario 3.

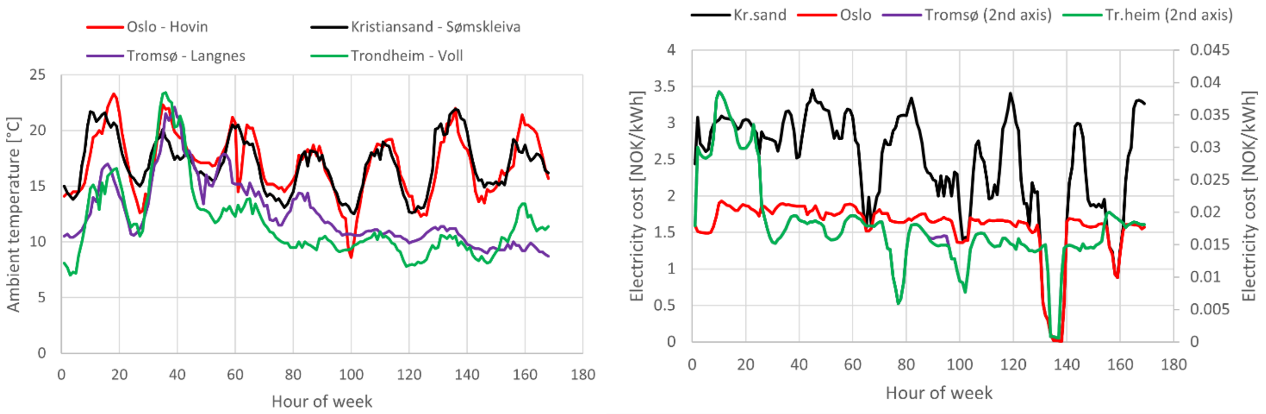

Figure 4: Input to calculations in the study; ambient temperature (left) and electricity price (right)

3. RESULTS

The ambient conditions in Oslo are selected to present the impact on the system operation of implementing a CTES unit for supplying the AC demand. Figure 5 depicts the COP of the CO_2 refrigeration system per hour for the city of Oslo during the given week, as well as the evolution of the ambient temperature. Both scenarios present very similar results, with small differences between them. The difference originates mainly from the electricity consumption of the compressor pack, where different compressors might be active (in operation) during the various hours of the week. For example, during Scenario 2 more load is put on the MT suction group during the night compared to Scenario 1 due to the charging of the CTES unit. The refrigeration load ratio (MT/LT load) is then increased, and the system COP is improved. To start with, the first MT compressor is inverter driven, and such compressors were modelled with overall efficiency function also of the frequency (as indicated by the manufacturer). Thus, their overall efficiency will be lower the further they are operated from the 50-60 Hz frequency range.

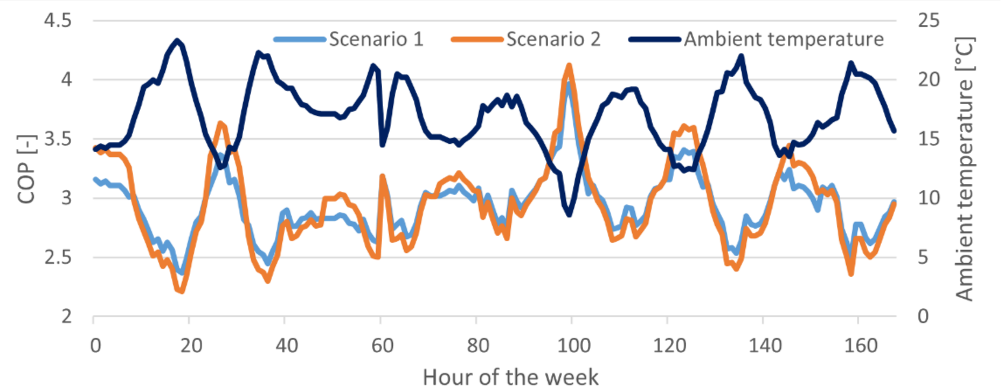

Figure 5: Comparison of COP between the reference case (Scenario 1) and the case with CTES (Scenario 2) for the Oslo conditions

The combined MT and AC load on the CO_2 refrigeration system for Scenarios 1 and 2 is shown in Figure 6 with the ambient conditions representing Oslo. In Scenario 1, the peak consumptions in MT load and AC load typically coincide or are very close in time, i.e. around the middle of the day, which is also the warmest period in the supermarkets. It can therefore be seen that the maximum peak cooling load during these periods are significant. In Scenario 2, due to the support of the CTES unit that transfers the AC production to the night period, peak shaving of the cooling load is achieved. The cooling load for AC is shifted to the night, and the refrigeration system operates more continuously during that period.

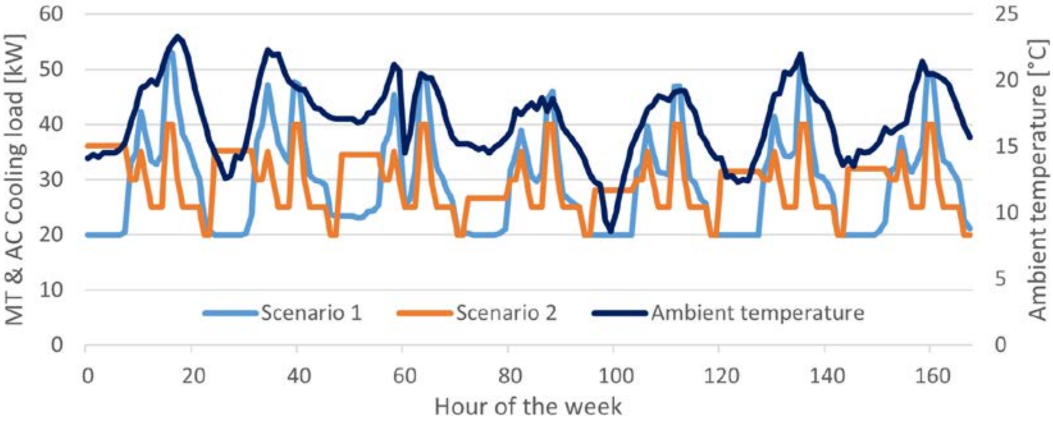

Figure 6: Sum of MT and AC load profile per hour for Oslo during the given week, comparing Scenario 1 (reference case) and Scenario 2 (CTES case)

The result of combining Figure 5 and Figure 6 is presented in Figure 7, which depicts the electricity consumption pattern of the refrigeration unit for Oslo for Scenario 1 and Scenario 2. It is clear that implementing the CTES system into the supermarket CO_2 systems allows for a more even electricity consumption throughout the week, with much lower peaks in the central hours of the day while maintaining a higher electricity use during the night. Thus, the operation of the refrigeration system is more stable and with much lower peak power consumption. The reduction in the maximum peak power demand comparing Scenario 1 and Scenario 2 was found to be 13 % in Trømsø, 15 % in Kristiansand, 16 % in Oslo and 19 % in Trondheim. Even higher values would be expected for a more representative week of a Norwegian summer, at least for the warmest cities.

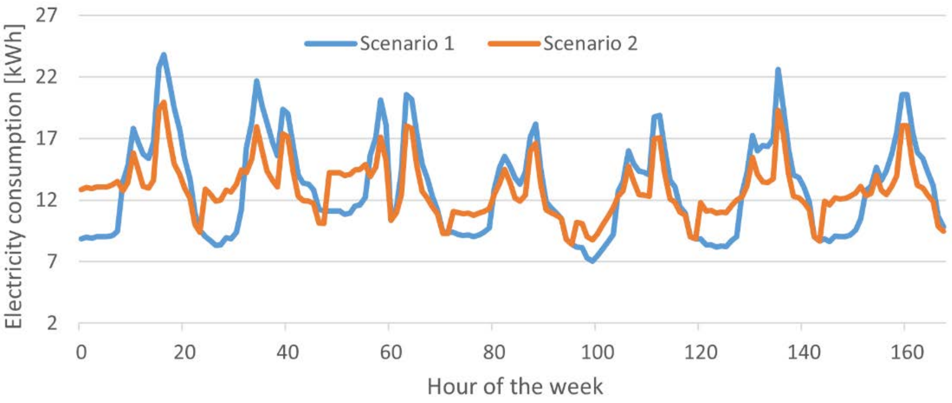

Figure 7: Electricity consumption profile per hour for Oslo during the given week, comparing Scenario 1 (reference case) and Scenario 2 (CTES case)

The potential cost reduction for electricity was calculated per location expressed as a percentage of the reference case. Two possibilities were investigated, Scenarios 1 and 2 using the dynamic pricing of the electricity market as presented in Figure 4, and Scenarios 3 and 4 which have clear day/night pricing of electricity. The results from the comparison of the reference CO_2 system and the proposed CTES-integrated CO_2 system yielded a negligible cost reduction for all locations (0-2%). The reason is that the dynamic market price of electricity was not always the lowest during the night or other off-peak periods (see Figure 4). In general, the intraday price variations were relatively small in the week considered for the present analysis. To adapt to such dynamic pricing, a predictive approach would be needed with a controller to initiate a charging process of the CTES if the price is low and the refrigeration load in the supermarket is moderate.

The electricity cost analysis comparing Scenarios 3 and 4 utilising day/night pricing is presented in Figure 8. It is observed that a larger cost reduction could be obtained following this pricing scheme, assuming 50 % higher than average electricity price during the daytime and 50 % lower during the night. The cost savings was calculated to be 2.0 % in Tromsø, 2.2 % in Trondheim, 6.8 % in Kristiansand and 7.3 % in Oslo. It is important to highlight that in the calculation of the cost reduction, the impact of reducing the maximum peak power demand is not evaluated. Reducing the maximum peak power demand required by the supermarket during the month will directly influence the consumption tariff paid to the grid operator. Furthermore, several grid operators now offer larger customers a reduction in the consumption tariff if they can offer flexibility in the power demand upon request on short notice. CTES technology integrated into refrigeration systems can allow system owners to decouple the supply and demand of refrigeration, and can thereby adapt their systems to the future electricity market.

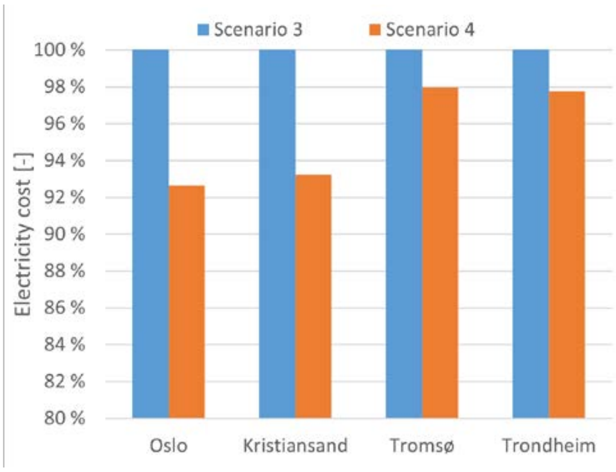

Figure 8: Electricity cost analysis for Scenario 3 and 4 at the various locations considered in the study

4. CONCLUSIONS

This paper describes the preliminary study to evaluate the feasibility of implementing a water/ice cold thermal energy storage (CTES) unit into a CO_2 transcritical supermarket booster system to substitute the current glycol-based AC production system and decouple AC production and demand. Numerical simulations of the reference supermarket system were carried out by using ambient conditions from four Norwegian cities. The results show that even if the week chosen for the analysis was not too demanding in terms of the outdoor temperature or AC demand, the implementation of the CTES unit could reduce the peak power consumption from 13 % and 19 %, depending on the location. A much more relevant effect on energy (and on peak power) consumption could be expected during warmer weeks which occur in southern (and even central) locations in Norway. However, due to the low cost of electricity in some parts of Norway, implementing the CTES is not always cost-effective. Nevertheless, following the recent European energy crisis, the cost of electricity has increased significantly all over the country. The economic attractiveness of this technology will be very dependent on the location and applicable peak power fees and electricity pricing scheme. CTES presents interesting flexibility options for the stakeholders in the refrigeration industry.

Based on the findings in the present study, the following activities are proposed as future work to develop the concept to the next phase: i) a deeper analysis of the performance of the proposed technology with more information on the system operation, alternative electricity contracts/energy pricing schemes and better load profiles ii) cost saving analysis over one year of operation at various locations in Norway, ranging from cold to mild climate conditions iii) investigate the possibility to implement a pilot CTES unit in a supermarket store to demonstrate the potential of this technology under real conditions.

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REFERENCES

Bell, I.H., Wronski, J., Quoilin, S., Lemort, V., 2014. Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp. Ind. Eng. Chem. Res. 53, 2498–2508. https://doi.org/10.1021/ie4033999

Gullo, P., Hafner, A., Banasiak, K., 2018. Transcritical R744 refrigeration systems for supermarket applications: Current status and future perspectives. International Journal of Refrigeration 93, 269–310. https://doi.org/10.1016/j.ijrefrig.2018.07.001

Gullo, P., Hafner, A., Banasiak, K., Minetto, S., Kriezi, E., 2019. Multi-Ejector Concept: A Comprehensive Review on its Latest Technological Developments. Energies 12, 406. https://doi.org/10.3390/en12030406

Gullo, P., Hafner, A., Cortella, G., 2017. Multi-ejector R744 booster refrigerating plant and air conditioning system integration – A theoretical evaluation of energy benefits for supermarket applications. International Journal of Refrigeration 75, 164–176. https://doi.org/10.1016/j.ijrefrig.2016.12.009

Karampour, M., Sawalha, S., 2018. State-of-the-art integrated CO2 refrigeration system for supermarkets: A comparative analysis. International Journal of Refrigeration 86, 239–257. https://doi.org/10.1016/j.ijrefrig.2017.11.006

Llopis, R., Nebot-Andrés, L., Sánchez, D., Catalán-Gil, J., Cabello, R., 2018. Subcooling methods for CO2 refrigeration cycles: A review. International Journal of Refrigeration 93, 85–107. https://doi.org/10.1016/j.ijrefrig.2018.06.010

Pardiñas, Á.Á., Jokiel, M., Schlemminger, C., Selvnes, H., Hafner, A., 2021. Modeling of a co2-based integrated refrigeration system for supermarkets. Energies 14. https://doi.org/10.3390/en14216926

Sarkar, J., Agrawal, N., 2010. Performance optimization of transcritical CO2 cycle with parallel compression economization. International Journal of Thermal Sciences 49, 838–843. https://doi.org/10.1016/j.ijthermalsci.2009.12.001

Selvnes, H., Allouche, Y., Hafner, A., 2021. Experimental characterisation of a cold thermal energy storage unit with a pillow-plate heat exchanger design. Applied Thermal Engineering 199, 117507. https://doi.org/10.1016/j.applthermaleng.2021.117507

Selvnes, H., Allouche, Y., Hafner, A., Schlemminger, C., Tolstorebrov, I., 2022. Cold thermal energy storage for industrial CO 2 refrigeration systems using phase change material: An experimental study. Applied Thermal Engineering 212, 118543. https://doi.org/10.1016/j.applthermaleng.2022.118543

Selvnes, H., Allouche, Y., Manescu, R.I., Hafner, A., 2020. Review on cold thermal energy storage applied to refrigeration systems using phase change materials. Thermal Science and Engineering Progress 22, 100807. https://doi.org/10.1016/j.tsep.2020.100807