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COLD THERMAL ENERGY STORAGE FOR SUPERMARKET APPLICATIONS: NUMERICAL INVESTIGATION

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ABSTRACT

The supermarket refrigeration sector has experienced significant transitions, with a strong focus on reducing energy demand, installation costs and environmental friendliness. Supermarket refrigeration systems typically operate at part load with lower efficiency than designed. In this context, application of cold thermal energy storage (CTES) technologies can provide cooling load during peak times, reducing the peak load demands. The Norwegian supermarket chain REMA1000 typically uses a glycol loop in CO_2 refrigeration systems to deliver both the refrigeration loads and air conditioning loads. The systems are designed for summer days, resulting in part load operation during most of the year. To address this issue, a CTES unit was designed and simulated to supply the air conditioning demand in a supermarket. Separate simulations of the existing system and CTES integrated into the existing system have been investigated. It was found that by integrating CTES into the existing supermarket refrigeration system, there could be electricity cost savings in the range of 4.5% to 14% based on the temperature of the day and different tariff structures applied.

Keywords: Phase Change Material, Latent Heat Storage, Ice Storage, Pillow-Plate Heat Exchanger, Carbon Dioxide, Dymola

1. INTRODUCTION

Cold thermal energy storage (CTES) is an innovative approach for storing nighttime off-peak energy for use during the daytime, mainly to serve the demand for electrical power during the summer. In certain areas, air conditioning (AC) is the main reason for summer peak demand which might account for more than half of the power demand during hot midday hours when electricity prices are the highest. Usually, a CTES uses a refrigeration system at night to create a reservoir of cold material which is utilised during daytime to provide the cooling capacity. In this way CTES provides advantages in the form of reducing the energy consumption of the refrigeration systems and reducing daytime peak demands for the electricity grid (Xu et al., 2021).

Phase change materials (PCMs) are a group of materials that are used in latent thermal energy storage systems since they have relatively large enthalpy of fusion during their solid-liquid transition. There have been many studies on different types of PCMs. However, only a few PCMs have been commercialised mainly due to problems associated with phase separation, supercooling, corrosion, thermal stability and low heat conductivity (Joybari et al., 2015). Among them, water/ice remains the most common PCM due to several inherent advantages including low cost, availability, nontoxicity, nonflammability, high storage density, and environmental friendliness.

Carbon dioxide is a naturally and abundantly available material. It is very commonly used as the refrigerant (R744) and benefits from relatively high latent heat capacity, low cost, molecular stability, noninflammability, low toxicity, noncorrosiveness (for most materials), zero ozone depletion potential (ODP) and low global warming potential (GWP). However, its operational pressure is relatively high, requiring specific heat exchangers and piping that can withstand such high pressures.

The most common type of heat exchangers encountered in industry are shell-and-tube heat exchangers and plate heat exchanges. Among the latter, pillow plate heat exchangers (PPHXs) have their own advantages in terms of high structural integrity, withstanding high pressures, hermitically sealed construction, and simple installation.

Hence, they are widely used in HVAC industry (Eldeeb et al., 2018), dairy industry, chocolate, wine, and paper and pulp industries (Zibart and Kenig, 2021). Specifically in HVAC industry, PPHXs provide compactness, better temperature approach, and less material and refrigerant requirements. PPHXs are made by superimposing two identically thick metal sheets followed by seam welding the edges except the edges considered for fluid flow. Then the seam welded structure is spot welded using either laser or resistance welding and subsequently hydroformed to create their pillow-like shape (Piper et al., 2014).

Several studies have been conducted on PPHXs for thermal storage purposes. For instance, a comprehensive literature review was conducted on the advancements up to date and challenges ahead of the widespread application of PPHXs (Joybari et al., 2022). Besides, recent developments and latest research studies on CTES using PCMs applied to refrigeration systems was reviewed by Selvnes et al. (2021b). The study included a classification of different types of PCMs applied for AC systems (20 °C) to low-temperature freezing of food (−60 °C). In another study, a parametric study was conducted on the design and operational parameters of an industrial-scale PPHX with CO_2 as the PCM (Joybari et al., 2023). The storage size over the phase change time (kWh/h) and cost over the storage size (USD/kWh) were selected as the parameters to evaluate under a constant heat transfer area. The temperature difference between the refrigerant and CO_2 phase change had the highest significance among these parameters. The design and performance of a CTES unit consisting of a PPHX immersed in a low temperature PCM as the storage medium was investigated by Selvnes et al. (2022). The charging and discharging performance of the CTES unit was extensively tested using CO_2 as the refrigerant and a commercial PCM with the phase change temperature of -9.6 °C.

Specifically using water/ice as the PCM, a mathematical model of CTES (consisting of PPHXs) was developed based on 2D transient Navier-Stokes equations in ANSYS Fluent for a poultry processing plant (Selvnes et al., 2019a). The phase change of PCM was evaluated based on enthalpy-porosity formulations. The results showed that the melting/solidification time and heat transfer rates are higher with PPHXs when compared to flat wall models. In a later study, Selvnes et al. (2019b) described the design and development of a CTES unit and associated experimental test rig with PPHXs in a steel tank using water as the PCM. The design, development, and experimental performance was investigated for a novel plates-in-tank CTES unit design intended to integrate into pump-circulated CO_2 industrial refrigeration systems (Selvnes et al., 2021a). The results showed that the evaporation and condensation temperatures of the refrigerant were the most critical parameters influencing the performance of the charging and discharging cycles, respectively.

In this study, a numerical investigation was carried out on the existing and novel (i.e., existing + CTES) system. To this end, several models were developed in Dymola considering different operational modes of the integrated system.

2. DESIGN OF THE COLD THERMAL ENERGY STORAGE UNIT

2.1. Cold thermal energy storage unit description

The existing refrigeration system in REMA1000 is a conventional CO_2 booster system. In the gas cooler, some heat is recovered for space heating through the air handling unit (AHU). During summer, the space cooling requirement is met by the same system utilising a water-glycol loop where part of the refrigerant after the high-pressure valve (HPV) is directed to a heat exchanger, in which CO_2 evaporates, cooling down the water-glycol mixture. Subsequently, the refrigerant is sent to a liquid receiver and the formed vapour is flashed to the medium temperature (MT) compressor which also receives vapour through a flash gas bypass valve (FGBV) and to the low temperature (LT) compressor.

A CTES unit (shown in Figure 1) was considered for the AC system which can store cold energy to release when there is a cooling demand. The CTES used water/ice as the PCM using PPHXs in a stainless-steel container. During summer, the supermarket requires cooling, and AC starts if a threshold ambient temperature (i.e., 20 °C) is exceeded. In this section, different operational modes of the CTES are presented.

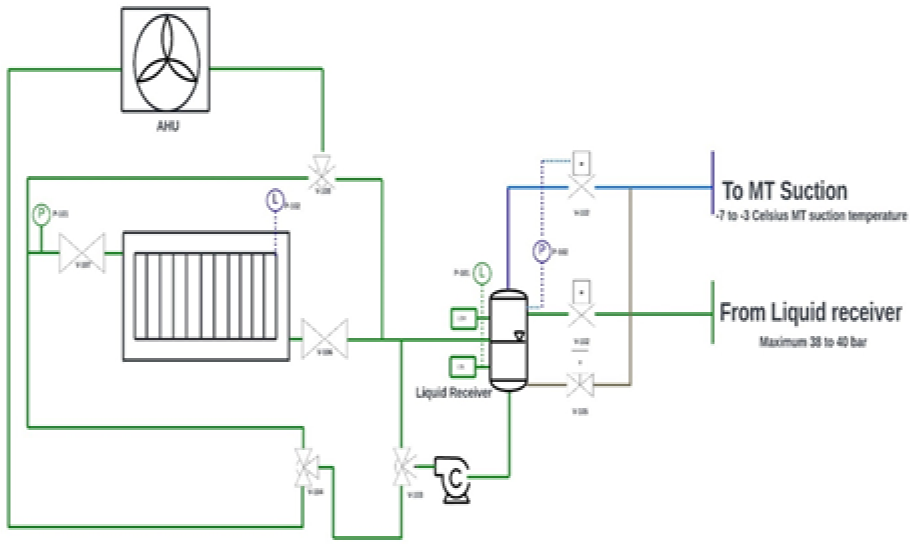

Figure 1: P&ID of the AC system integrated with CTES

2.1.1. Standby mode

This is the mode used when the CTES is fully charged and there is no AC requirement. Therefore, the pump remains off. The liquid receiver is open to the suction of MT compressors (through V-102) to allow the formed flash gas to flow to the MT compressors. The recirculation line from the pump back to the CTES liquid receiver is open and the rest of the system is closed.

2.1.2. Charging mode

The charging mode helps freeze the water in the CTES which is caried out in either off-peak periods or when there is a low refrigeration load. The CTES controller sends a signal to the main controller of the supermarket, requesting the lowest possible suction pressure for charging. Charging mode is activated either at a specific time or when a higher temperature is forecast for the next day.

2.1.3. Direct AC mode

This mode is activated if the storage is empty (from L-102) and if there is a request for cooling from the AHU. Further, if the CTES becomes empty while operating in discharging mode, then also direct AC mode is activated. The three-way valve V-108 is open to bypass the storage and supply CO_2 directly to the liquid receiver to remove the heat load from the AHU.

2.1.4. Discharging mode

The AHU controller sends an analogue signal to the CTES controller requesting cooling. To avoid frost formation on the AHU coils, a temperature greater than 0 °C is maintained at the CO_2 side such that the desired pressure in the CTES system is closer to the receiver pressure of the main system. If the AHU requests higher loads than the CTES can deliver, then the storage is fully discharged.

2.1.5. Safety mode

If L-102 measures a level lower than a certain minimum value, the receiver must be refilled as it indicates that there has been a leakage. A low priority alarm needs to be activated. If the liquid level inside the CTES receiver is activating high- or low-level alarm, the pump will be stopped requiring a manual reset. Therefore, the main unit will need to activate the glycol-based cooling loop for the AHU.

2.2. Component selection

2.2.1. Pillow plate heat exchanger

The geometrical design parameters of PPHXs include the wall thickness (t), spot weld diameter (d_{ws}), longitudinal pitch (s_L), transversal pitch (s_T), channel inflation height (h_i), and distance between neighbouring plates (h_o). In the current study, the spot welds are 10 mm in diameter with longitudinal and transversal pitch values of 50 mm and 30 mm, respectively. Each plate is 1 mm thick, with maximum inflation hight of 4 mm. 26 plates are installed in the thermal storage unit with a distance of 30 mm which creates the space where water can freeze/melt. Each plate has overall dimensions of 2500 mm × 1250 mm (L × H).

2.2.2. Air handling unit

The AHU acts as an evaporator which is a finned tube heat exchanger where only the liquid CO_2 enters. The AHU design conditions can be summarised as volumetric air flow rate of 15,000 m^3/hr, air inlet temperature of 23 °C, air inlet relative humidity of 60%, cooling capacity of 30 kW, and evaporating temperature of 5.3 °C.

2.2.3. Pump

The CTES had a pump installed after a liquid receiver so that it is ensured that the pump can function without cavitation. The pump is supplied by Witt, Germany. It is a hermitic radial refrigerant pump. A small portion of the refrigerant flows through the pump for cooling purposes and is returned to the liquid receiver placed 0.5 m above the pump. The pump was designed to achieve minimum volumetric flow rate of 0.6 m^3/hr, maximum speed of 2,900 RPM, maximum current of 2.1 A (with CO_2) and maximum head of 25 m.

2.2.4. Liquid receiver

As mentioned, the liquid receiver is used to prevent cavitation in the pump. The liquid receiver has a height of 1.7 m and a volume of 190 L. The receiver is designed tall to avoid vortex generation. A DN100 pipe is welded from the liquid receiver to the pump inlet.

3. NUMERICAL MODEL DEVELOPMENT

3.1. Simulations strategy

First, the existing refrigeration system at REMA1000 was modelled in Dymola. Then, the CTES system with its charging, discharging and direct AC modes were introduced. Finally, a comparison for the existing system and system integrated with the CTES was conducted for the hottest and average summer day.

3.1.1. Existing system with CTES-AC charging load

This model (shown in Figure 2a) was developed based on an existing study conducted at NTNU on a similar small-scale CTES with PPHXs using ice (Selvnes et al., 2023). The system functions as a booster CO_2 refrigeration cycle with separate LT evaporators, MT evaporators, two LT compressors, four MT compressors, gas cooler, high pressure valve, liquid receiver and internal heat exchanger, assuming (1) The CTES system is used as an evaporator operating at the MT pressure to simulate the TES charging process from 11 PM until 8 AM. The CTES charging capacity is 30 kW. (2) When the AC works during the daytime, it works with the aid of the CTES discharging mode. (3) From 9 AM until 11 PM the AC system works with the charged CTES while the load on the refrigeration system rises. The AC system load depends on the outside temperature.

3.1.2. Charging/discharging of CTES and direct AC charging

The CTES was simulated separately for the charging, discharging and direct AC modes (Figure 2b-d). Subsequently, all these three modes were integrated into a single simulation using three-way valves.

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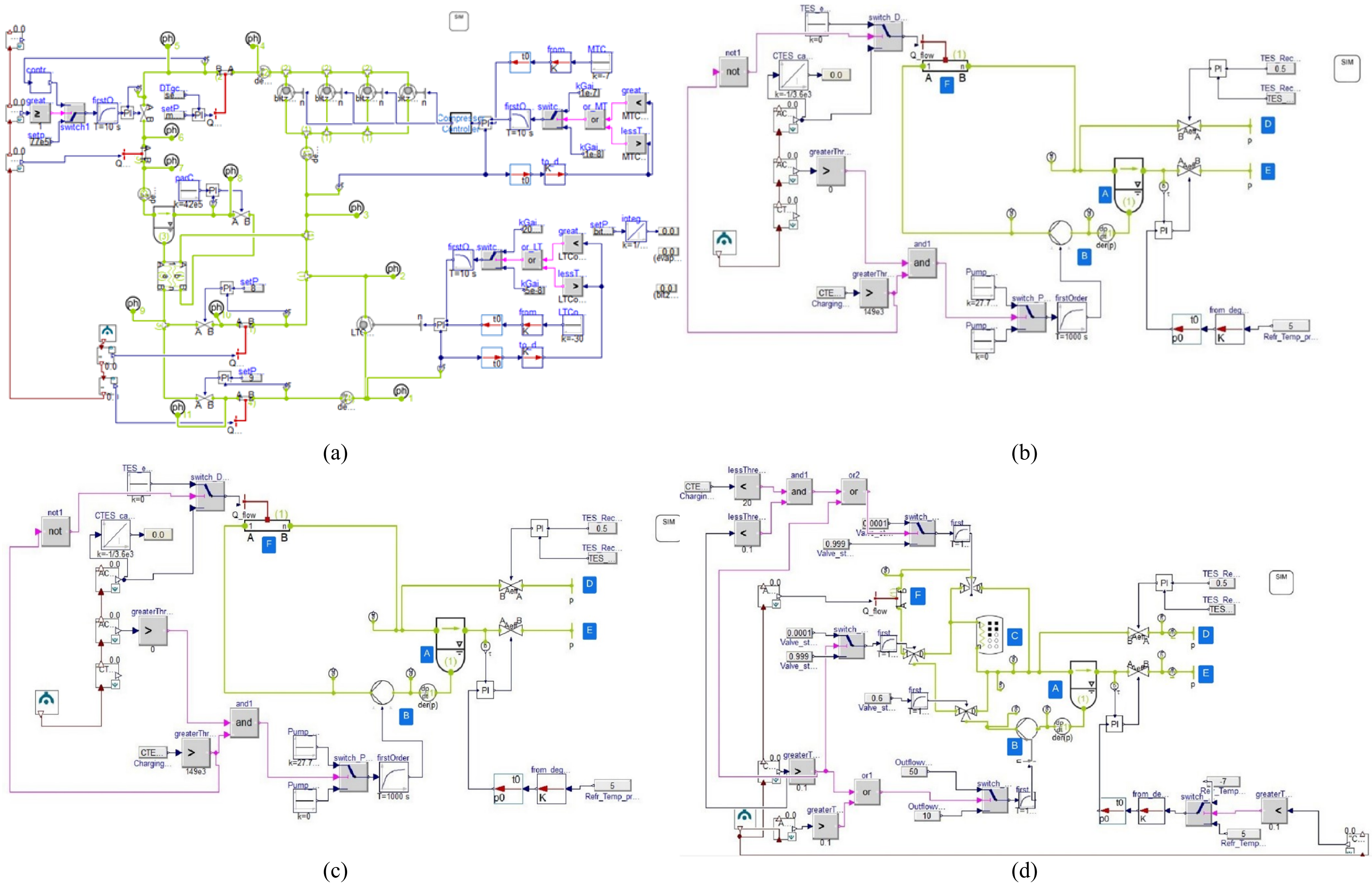

Figure 2: Simulation details of (a) the existing system, (b) CTES charging mode, (c) CTES discharging mode, (d) direct AC charging mode

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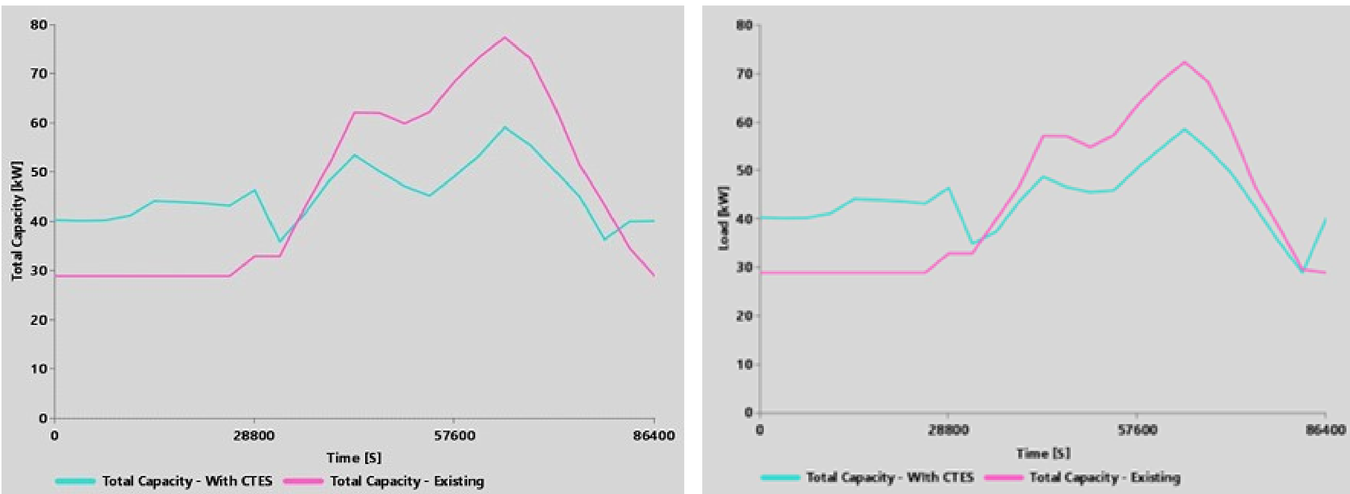
3.2. Simulation results

3.2.1. Load profile

The load profile of the existing system and the system integrated with the CTES are depicted in Figure 3a and b for the hottest and average days, respectively. The highest temperature on the hottest day is 33.2 °C (only 5 days above 30 °C in 2023). Hence, this load profile is an indicative load profile to depict that the simulated design also caters to very high load scenarios. Regarding the average day, the highest temperature is 25 °C (encountered in 40 days in 2023).

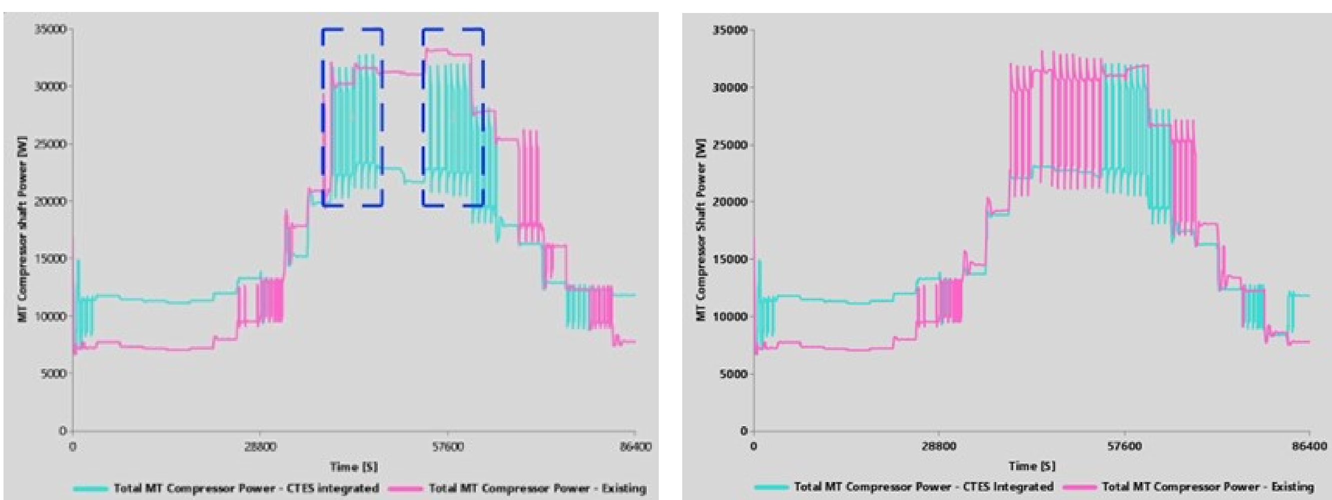


(a) (b)

Figure 3: Load profile of the system for (a) hottest day, (b) average day

3.2.2. MT compressor power

The MT compressor power variation for the hottest and average days are shown in Figure 4. The total MT compressor power of the system integrated with CTES is higher during the early hours of the day. However, during the daytime, the MT power for the system with CTES is lower than that for the existing system. Note that there are a few spikes in Figure 4 which is resulting from the compressor controller switching procedure. Although several attempts were made to rectify this issue by changing the compressor controller, this issue was not resolved to a satisfactory level.

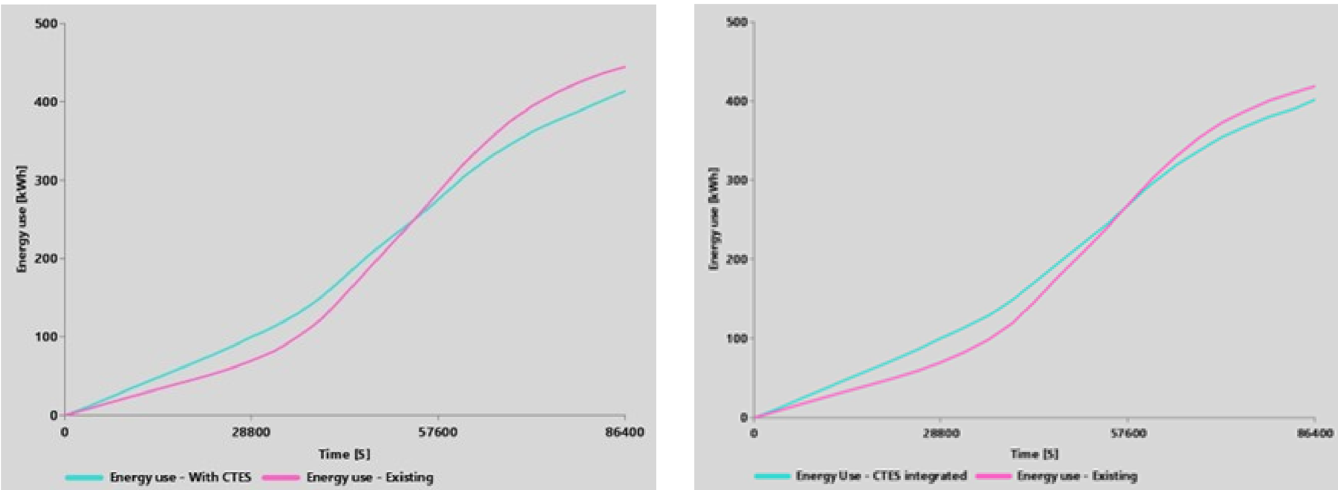


(a) (b)

Figure 4: MT compressor power profile for (a) hottest day, (b) average day

3.2.3. Energy consumption

The energy consumption of the two systems during the hottest and average days are depicted in Figure 5. In both cases, during the early hours of the day, the system integrated with CTES utilises more energy. However, as the day progresses the existing system utilises more energy.

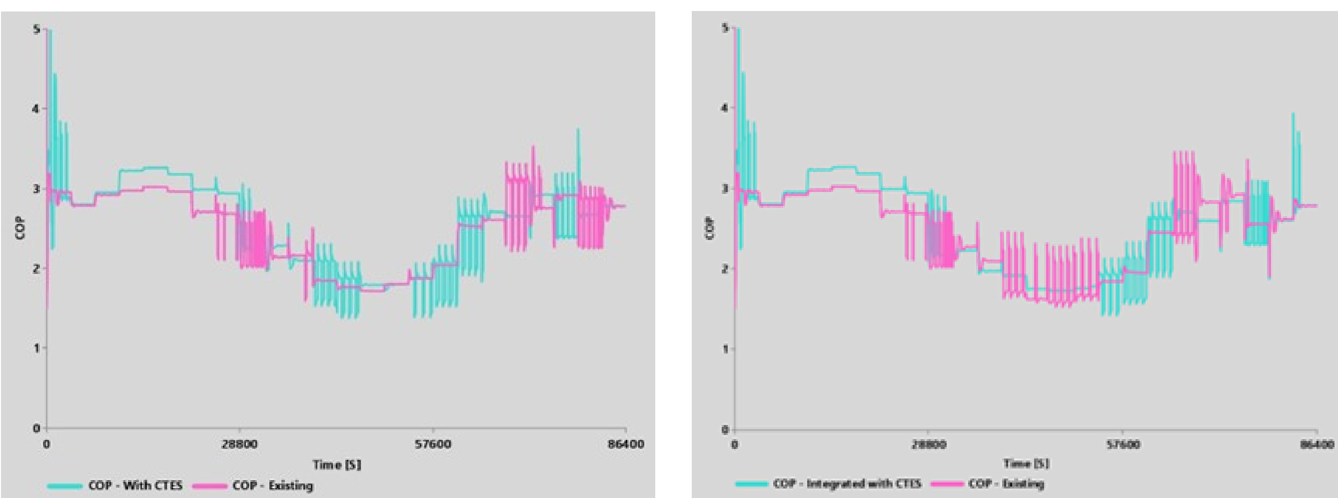


(a) (b)

Figure 5: Energy consumption profile for (a) hottest day, (b) average day

3.2.4. Coefficient of performance

The COP profiles of the two systems during the hottest and average days are presented in Figure 6. For both cases, the COP of the system integrated with CTES remains above that of the existing system in many instances. However, there are a few sudden fluctuations. During the early hours of the day, both systems have a COP of around 3. However, during the daytime, the COP of both systems reduces to around 2.5. There are certain spikes noted in the COP of the system integrated with CTES which coincide with the power variations noted earlier in Figure 4.



(a) (b)

Figure 6: COP profile for (a) hottest day, (b) average day

4. CONCLUSIONS

This study presented a comprehensive analysis of the simulation results of the existing refrigeration system and the system integrated with CTES (denoted by the novel system) for a supermarket in Norway during the hottest day and an average day of the summer. Both the existing and novel refrigeration systems consume a total of 425 and 400 kWh on the hottest and average days, respectively. In terms of COP, for both systems, the COP is about 3.0 during the early hours of the day while hovering around 2.5 during the daytime. The MT power is expected to about 25 kW during the peak load periods of the day. However, there are spikes noted in the power due to the compressor switching. This issue is suggested to be addressed by resolving the compressor controller algorithm as a future work. The results of the existing and novel systems depict similar patterns to the results noted for respective systems during the hottest day.

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REFERENCES

Eldeeb, R., Ling, J., Aute, V.C., Radermacher, R., 2018. Heat transfer enhancement using approximation assisted optimization for pillow plate heat exchangers.

Joybari, M.M., Haghighat, F., Moffat, J., Sra, P., 2015. Heat and cold storage using phase change materials in domestic refrigeration systems: The state-of-the-art review. Energy and Buildings 106, 111-124.

Joybari, M.M., Selvnes, H., Sevault, A., Hafner, A., 2022. Potentials and challenges for pillow-plate heat exchangers: State-of-the-art review. Applied Thermal Engineering 214, 118739.

Joybari, M.M., Selvnes, H., Vingelsgård, E., Sevault, A., Hafner, A., 2023. Parametric study of low-temperature thermal energy storage using carbon dioxide as the phase change material in pillow plate heat exchangers. Applied Thermal Engineering 221, 119796.

Piper, M., Zibart, A., Tran, J., Kenig, E.Y., 2014. A numerical study on turbulent single-phase flow and heat transfer in pillow plates, International Heat Transfer Conference Digital Library. Begel House Inc.

Selvnes, H., Allouche, Y., Hafner, A., 2021a. Experimental characterisation of a cold thermal energy storage unit with a pillow-plate heat exchanger design. Applied Thermal Engineering 199, 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.

Selvnes, H., Allouche, Y., Manescu, R.I., Hafner, A., 2021b. Review on cold thermal energy storage applied to refrigeration systems using phase change materials. Thermal Science and Engineering Progress 22, 100807.

Selvnes, H., Allouche, Y., Sevault, A., Hafner, A., 2019a. A CFD analysis for the performance assessment of a novel design of plates-in-tank latent storage unit for freezing applications, 8th Conference on Ammonia and CO_2 Refrigeration Technologies, Proceedings. IIR.

Selvnes, H., Alvarez Pardinas, A., Hafner, A., 2023. Cold thermal energy storage for air conditioning in a supermarket CO_2 booster refrigeration system, 10th Conference on Ammonia and CO_2 Refrigeration Technologies. International Institute of Refrigeration.

Selvnes, H., Hafner, A., Kauko, H., 2019b. Design of a cold thermal energy storage unit for industrial applications using CO_2 as refrigerant, 25th IIR International Congress of Refrigeration Proceedings. IIR.

Xu, T., Humire, E.N., Chiu, J.N., Sawalha, S., 2021. Latent heat storage integration into heat pump based heating systems for energy-efficient load shifting. Energy Conversion and Management 236, 114042.

Zibart, A., Kenig, E., 2021. Numerical investigation of conjugate heat transfer in a pillow-plate heat exchanger. International Journal of Heat and Mass Transfer 165, 120567.