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Integrated CO_2 refrigeration and heat pump system for a dairy plant: Energy analysis and potential for cold thermal energy storage

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ABSTRACT

Dairy processing is considered very energy-intensive due to significant thermal demands for both cooling and heating at different temperature levels. Conventional dairy plants have separate systems for supplying the various thermal loads, such as refrigeration systems for the cold side of the process and boilers for the heating requirements. In a previous study, a fully integrated CO_2 heat pump/refrigeration system installed in a dairy plant in central Norway was presented and theoretically evaluated. Recommendations for increasing the energy efficiency at the plant were suggested. This paper continues that work by analysing data collected by the recently installed energy data acquisition system at the dairy. The thermal energy demands on the hot and cold sides of the dairy process were monitored to increase the knowledge of the overall thermal requirements and distribution of load in various periods. Based on the analysed data from the plant, a concept for installing a latent cold thermal energy storage (CTES) into the refrigeration system to reduce the peak loads from process cooling is described. The results of this study will be used as a basis for the decision-making process concerning the installation of a CTES system at the dairy.

Keywords: Cold Thermal Energy Storage (CTES), CO_2 refrigeration, Energy efficiency, Food processing, Heat pump

1. INTRODUCTION

Consumption of milk and dairy products is the largest among all food sectors in Europe and is projected to be increased to over 220 kg per person per year in 2050 (Bruinsma, 2012). Dairy processing is considered very energy-intensive due to significant thermal demands for both cooling and heating at different temperature levels (Briam et al., 2015), using chillers for process cooling and steam boilers for heating processes. The growth of dairy production worldwide will cause considerable challenges concerning the increase in energy consumption and greenhouse gas (GHG) emissions. To reduce the environmental impact of dairy processing and increase energy efficiency, decarbonization of processes and increased system integration using heat pumps are considered promising solutions (Ahrens et al., 2021; Schlemminger et al., 2022).

To better understand and document the demand for refrigeration and process heating in the dairy industry, detailed measurements of the major consumers of thermal energy is crucial. The present study aims to investigate and map the thermal energy consumption of a Norwegian dairy plant. A previous investigation concerned the description of the thermal energy system at the dairy plant and proposing changes to reduce the energy consumption of the refrigeration system (Selvnes et al., 2022). The present study continues the previous work by analysis of process data gathered from recently installed measurement equipment at relevant locations of the dairy process. The dairy plant is a demonstrator in the EU Horizon 2020 project ENOUGH, aiming to demonstrate promising technological solutions applied within the main sectors of the European food chain. Logging the energy use at the demonstrators is therefore important for benchmarking system layouts and technical solutions across countries.

2. SYSTEM DESCRIPTION AND METHODS

2.1. Thermal energy system of the dairy

The energy system of the dairy plant was presented in detail in the previous work (Selvnes et al., 2022), but a brief description of the system is given here for reference. Recently, a new CO_2 heat pump/refrigeration system with a cooling capacity of 120 kW has been installed to replace the two 40 kW CO_2 prototype units installed in 2014. The two 40 kW units will be phased out from the refrigeration system when the next large maintenance requirement arises and are at present not actively used. A simplified overview of the thermal energy system is provided in Figure 1. The CO_2 refrigeration units are installed in parallel to provide cooling of propylene glycol (35 %) at a supply and return temperature of -7 °C and -2 °C, respectively. The cold glycol is collected in a 5 m^3 accumulation tank with a theoretical maximum thermal storage capacity of about 27 kWh. The glycol is supplied to the various cold consumers in the plant, such as cooling of the process water circuit, cooling rooms and air-conditioning (AC) in the facilities and offices. The process cooling water has a supply and return temperature of 0.6 °C and 2 °C, respectively. To reduce the required peak load for cooling, a buffer tank of 9 m^3 is installed between the cooling consumers and the process water/glycol heat exchanger. The tank provides a maximum thermal storage capacity of about 15 kWh due to the narrow temperature difference between supply and return.

The heat from the CO_2 refrigeration units is recovered and hot water at around 70 °C is produced in the gas coolers, which is further used for various heating purposes in the plant. The hot water is stored in two parallel packs of 12 x 400-litre tanks connected in series. The hot water storage has a total storage capacity of 9.6 m^3, equivalent to about 660 kWh considering fully charged at 70 °C and fully discharged at 10 °C. The hot process water is used for process heating, supplied to cleaning-in-place (CIP) systems and as boiler feedwater. The electric boiler is used for heating needs that require higher temperatures than those provided by the hot water heat pump system. If the hot water storage is fully charged while the CO_2 units still provide cooling, the excess hot water goes to the drain through a rejection valve. Furthermore, the local district heating system is used for heating the building, operating with a supply temperature in the range of 55-70 °C, depending on the outside temperature. The district heating supplies heat to an internal water circuit at the dairy that heats ventilation air in the air handling units (AHU), radiators in the offices and fan coil heaters.

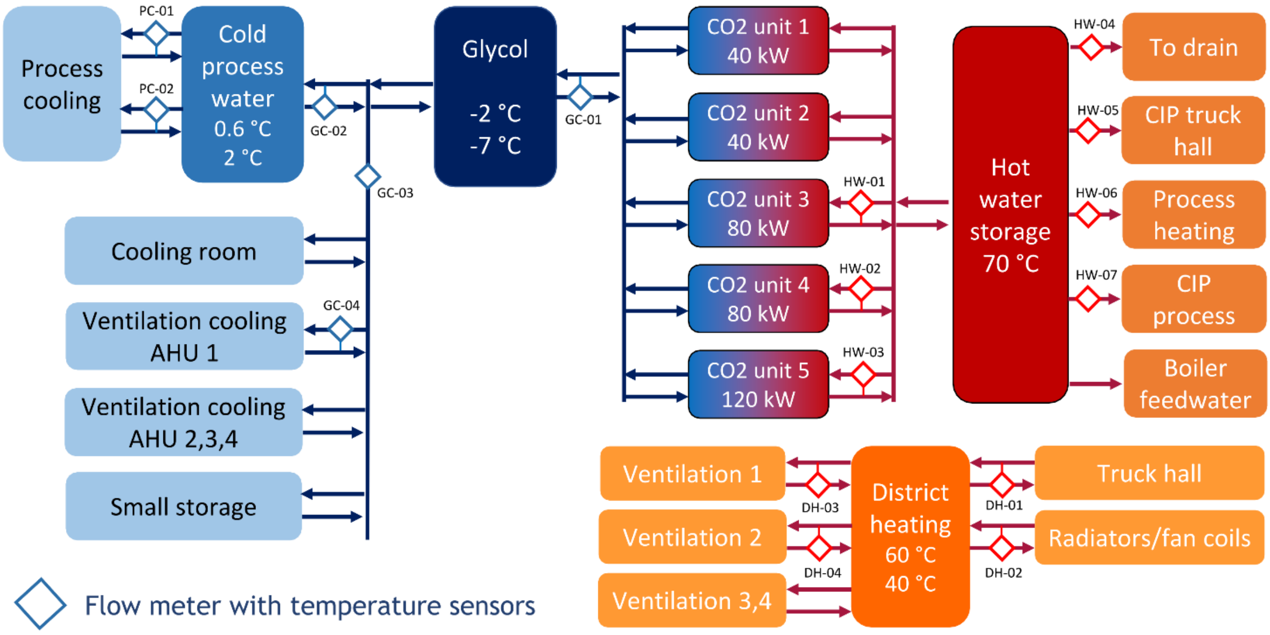

Figure 1: Simplified overview of the thermal energy system at the dairy plant with ID tags of the installed flow sensors.

2.2. Measurement equipment and data acquisition system

A selection of flow sensors paired with energy calculators has recently been installed and commissioned at the plant. The energy calculators are transmitters that read the signal from the flow meters which are paired with two temperature sensors (supply and return pipes). Table 1 shows an overview of the location and subsystems where the flow meters have been installed. The ID tag in column 2 reflects the location indicated on the simplified system overview in Figure 1.

Table 1: List of flow meters installed at the plant.

Subsystem - Measurement point	ID tag	Medium	Sensor type
Process cooling – Circuit 1 and 2	PC-01, PC-02	Water	Badger M1000
Glycol –supplied by CO_2 units, process water cooling, other cooling consumers, AHU 1	GC-01, GC-02, GC-03, GC-04	Propylene glycol 35%	KROHNE Optisomic 3400
Hot water – CO_2 unit 3, CO_2 unit 4, CO_2 unit 5, To drain, CIP truck hall, process heating, CIP process	HW-01, HW-02, HW-03, HW-04, HW-05, HW-06, HW-07	Water	Kamstrup Ultraflow 54/24
District heating – truck hall, radiators/fan coils, AHU 1, AHU 2	DH-01, DH-02, DH-03, DH-04	Water	Kamstrup Ultraflow 24

The measurement points were selected to document the largest consumers of thermal energy at the plant, and the selection was made as a compromise between completeness and the cost of purchasing and installation. On the cold side, the highest demands are the process cooling, where both circuits were monitored. The flow of cold glycol provided by the CO_2 heat pump units was monitored, and the distribution of load between the process cooling and the other consumers such as cold storage rooms and AC demands in the AHUs was made. Furthermore, the cooling demand for one of the AHUs was monitored in detail. The sampling of the process data was carried out from the energy meters by a centralized data acquisition system. A log file containing all the data points from all the sensors is created and sent every week. The selected period for analysis was week 8 of 2023 (From Monday 30.01.2023 to Sunday 05.02.2023).

2.3. Calculation procedure

The measurement data was included in a file with a comma-separated values format (.csv), which was imported into Excel for further analysis. Each energy sensor has five output values: supply temperature, return temperature, volumetric flow rate, calculated heat transfer rate and the accumulated exchanged thermal energy. The energy calculator on the flow sensor uses the in-built property data on heat capacity and density of the measured fluid to calculate the heat flow (in kW) and thereby the accumulated thermal energy (in kWh). A comparison was done to detect any issues regarding the measurement equipment. The instantaneous heat flow was calculated based on the following equation:

$$\dot{E} = \dot{V} \cdot \rho \cdot c_p \cdot \left(T_{supply} - T_{return}\right). \qquad \text{Eq. (1)}$$

Here $\dot{E}$ is the heat flow, $\dot{V}$ is the volumetric flow rate, ρ is the density, c_p is the specific heat capacity at constant pressure and $\left(T_{supply} - T_{return}\right)$ is the temperature difference between the supply and return of the measured stream. The thermodynamic properties of the fluids were retrieved using the REFPROP 10 thermodynamic library (Lemmon et al., 2018). The accumulated thermal energy for every 15 minutes was calculated using the obtained heat flow, multiplied by 15 x 60 seconds and converted to the correct unit (kWh). The data was then compared to the accumulated thermal energy reported by the internal calculation of the flow meters themselves, which was updated at a much higher frequency than 15 minutes. Some of the flow sensors do not have temperature sensors and only report the volumetric flow rate and the accumulated volume of fluid that has passed the sensor. These are sensors HW-04 to HW-07, due to the hot water being used at these consumers and then returned to the drain. For calculating the heat rate and accumulated energy use for these heat consumers, the difference between the cold city water temperature and the hot water supply temperature delivered by the CO_2 units was used.

3. RESULTS

3.1. Energy analysis of cooling load

This section presents the results of the energy analysis of week 8 of 2023 at the dairy plant. The cooling loads for the process water circuit, the cooling rooms and AC are presented in Figure 2. The cooling rooms and the AC are shown together as they represent a minor load compared to the process water cooling. Furthermore, the cooling load for AC is currently only monitored for one of the four AHUs. However, the remaining cooling load in addition to the process water cooling can be observed by sensor GC-03 (see Table 1 and Figure 1). It can be observed that the demand for process cooling starts at approximately 05:00 during the production day and represents a peak lasting for 6-8 hours. The magnitude of the maximum daily peak demand is within the range of 140-160 kW and is relatively uniform for production days. The supply of glycol cooling for the cooling rooms and AHUs is less significant and more constant throughout the week with a mean value of about 12.3 kW. The process cooling circuit constitutes about 75 % of the total cooling demand at the plant during the week.

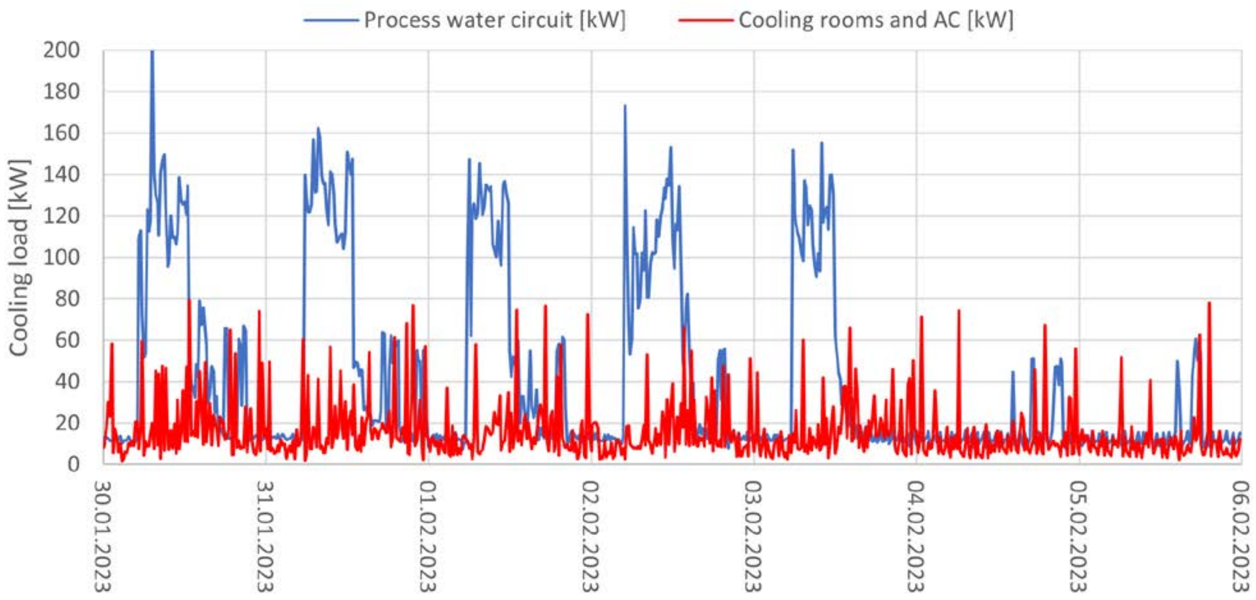

Figure 2: Distribution of cooling load in the glycol circuit for the process cooling circuit, cooling rooms and air-conditioning (AC) during the analysed week.

The total cooling to the glycol circuit provided by the CO_2 refrigeration units throughout the week is presented in Figure 3. The provided cooling fluctuates, and a curve showing the hourly average cooling (red) is included in the figure for clarity. The hourly average cooling load follows the same pattern as the process cooling load since it is the major driver of the cooling demand in the plant. The peaks are in the same order as for the process cooling demand, confirming that the buffer storage in the process water circuit and glycol circuit are only present to dampen short-term fluctuations. Furthermore, significant cycling of the CO_2 units is observed during the weekend. The provided cooling rate varies from 0 kW to 100 kW at least every 30 minutes to maintain the glycol temperature at the correct setpoint. A quite large discrepancy in the accumulated cooling demand over the week was found between the total process water cooling load measured from the glycol side and the water side (PC-01 + PC-02 vs GC-02). The measurements on the water side were about 35 % higher than on the glycol side. The total cooling produced by the CO_2 units measured on the glycol side corresponded well with the hot water produced. This indicates the flow and/or temperature sensors on the process cooling water side should be checked. For this reason, the glycol sensors GC-01 to GC-04 were used for further analysis.

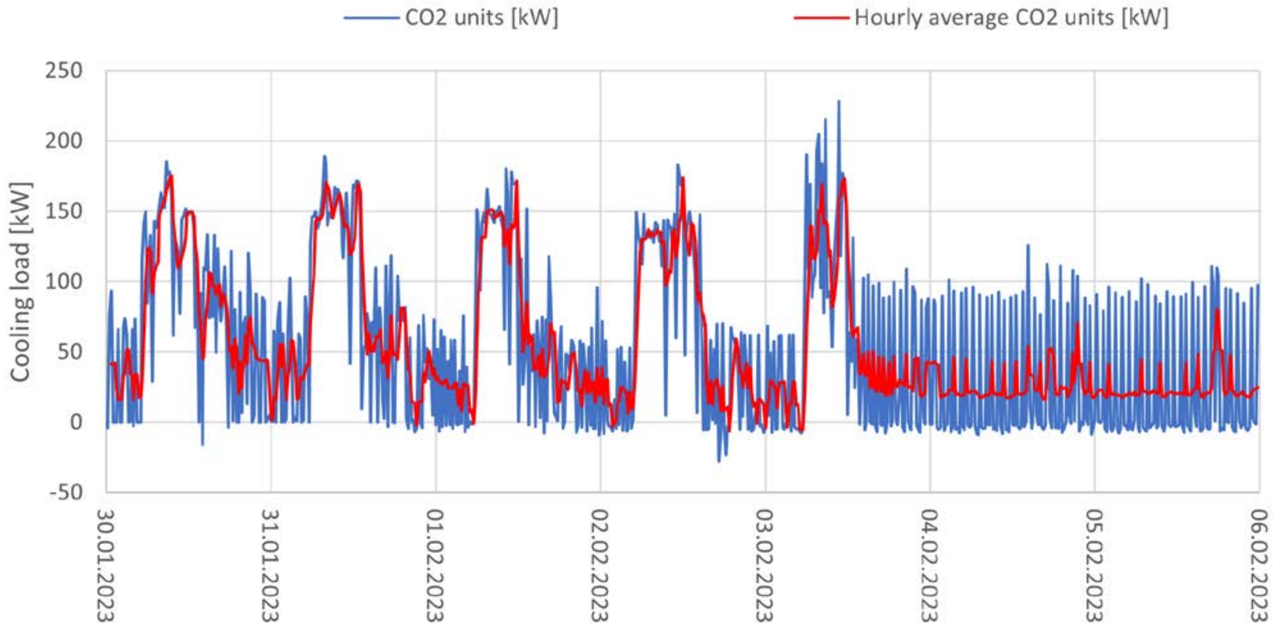

Figure 3: Total cooling produced from the CO_2 refrigeration units during the analysed week. CO_2 units 3-5 were active during the week (80 kW, 80 kW and 120 kW capacity).

3.2. Energy analysis of heating load

On the warm side of the dairy process, hot water is produced by heat recovery from the CO_2 refrigeration units and stored in the hot water accumulation tank system. The hot water is used for several purposes around the dairy plant, and the distribution of the heating load of various consumers is presented in Figure 4 and Figure 5. In Figure 4, the required heat load for the CIP processes in the truck hall and the dairy process is shown together with the cumulative thermal energy demand throughout the week. The CIP in the truck hall is utilised for cleaning/sterilising the pipes and equipment after milk has been delivered from the milk trucks. The CIP processes require significant heating over relatively short periods, with peaks exceeding 350 kW. This means that the hot water tanks serve their purpose of providing a short-term buffer of heat between the CO_2 units and the heat consumers. The CIP system in the dairy process is used to clean and sanitise pipes, vessels and equipment between different products in the production.

A major part of the process heating goes to the pasteurisation process and hence depends on the quantity of milk processed. The process heating follows closely the production schedule of five days. The amount of the produced hot water from the heat recovery of the CO_2 units which was not utilised (goes to the drain) was investigated by installing a flow sensor on the pipe going to the drain from the hot water tank system. As mentioned before, the rejection valve is opened whenever the CO_2 units are operating to provide cooling and the hot water storage tanks are fully charged. Figure 5 shows that the opening of the rejection valve occurs during two periods: during the daytime operation and the weekend. During the daytime, the cooling load could be higher than the required heating. The order of cooling and heating demand in the dairy process can also affect the utilisation of the recovered heat, and a larger hot water storage system could increase the heat recovery utilisation. During the weekend, the CO_2 unit cycle on-off to maintain the glycol setpoint temperature satisfying the cooling demand e.g., for the cooling rooms. During this period, there is not any need for heat except when milk is delivered. From the cumulative curve of the rejection valve, about half of the thermal energy loss occurs during the weekend.

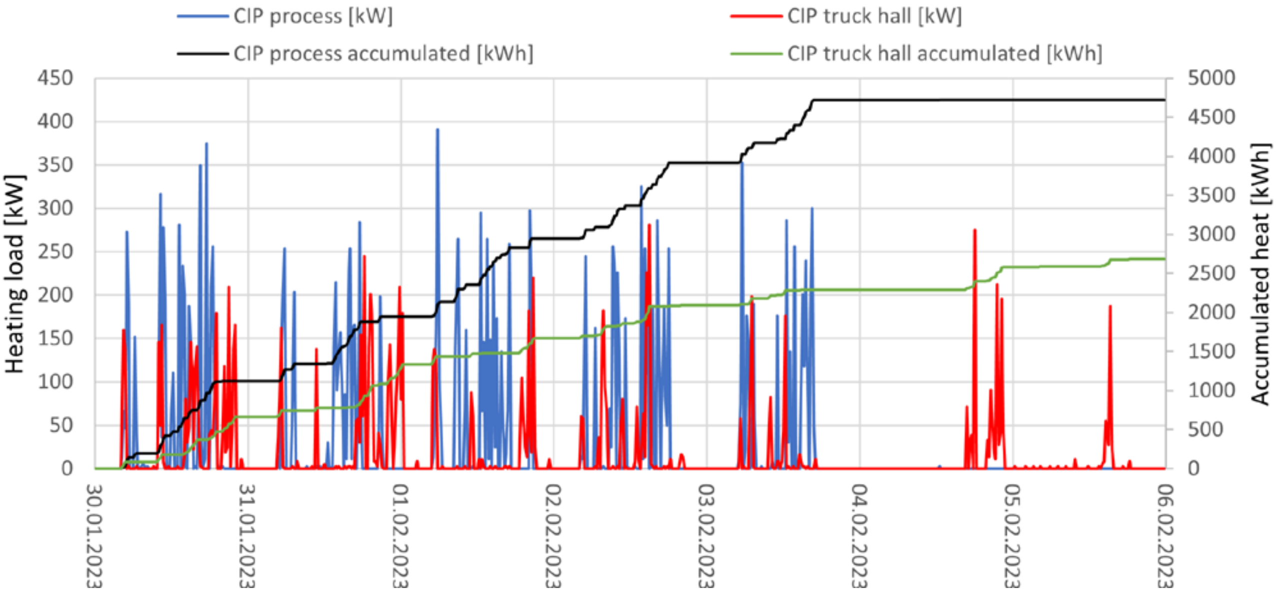

Figure 4: Heating load and accumulated heat used for the cleaning in place (CIP) in the dairy processing and the truck hall.

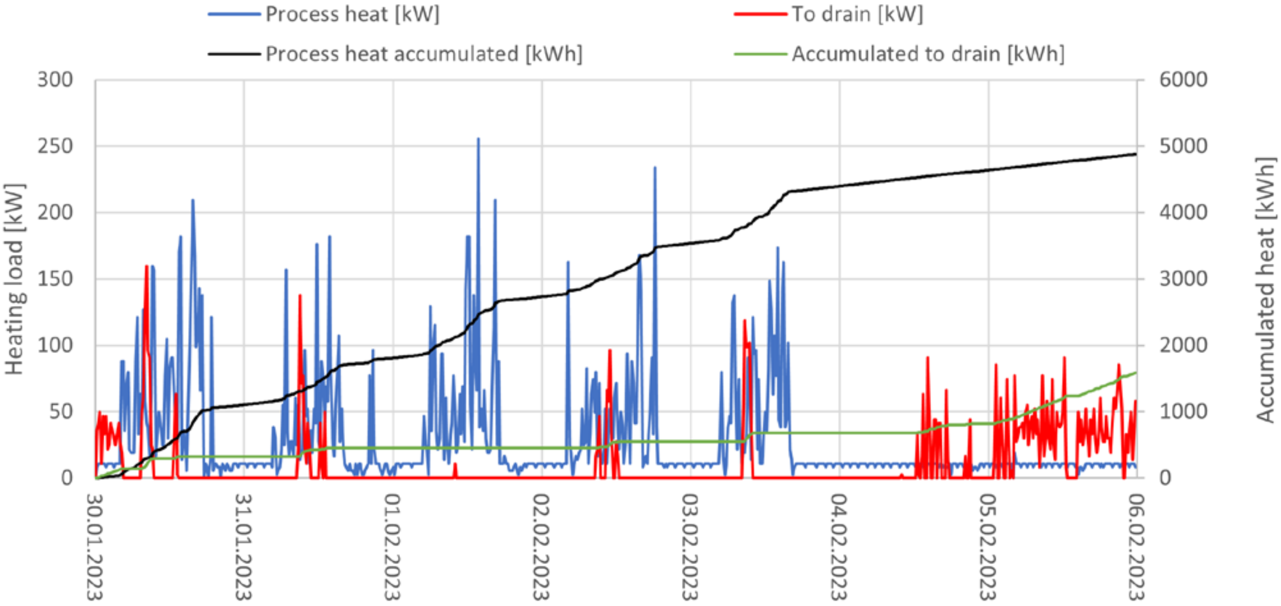

Figure 5: Heating load and accumulated heat used for process heating, as well as the equivalent heat of hot water going to the drain when the hot water storage is fully charged.

3.3. District heating

The local district heating network is used for heating the building and the ventilation air during the heating season. The district heating system is a low-temperature grid with a supply temperature of about 50-70 °C depending on the ambient temperature. During the analysed week the mean ambient outside temperature at the dairy was -11.2 °C with a minimum temperature of -25.6 °C and a maximum of -0.2 °C. The distribution of heating loads of the various consumers in the dairy is presented in Figure 6. Only the heating load of one out of four AHUs are monitored at present together with the heating of the truck hall and the radiators and fan coil units. The heating of ventilation air is mostly active during the daytime, requiring about 5-10 kW heating capacity. The highest heating demand is required in the truck hall with peaks exceeding 25 kW. The hall is not well insulated and needs to be kept above freezing point due to the water pipes and other process equipment located there. The average heat demand during the week for the consumers listed here is about 20.8 kW.

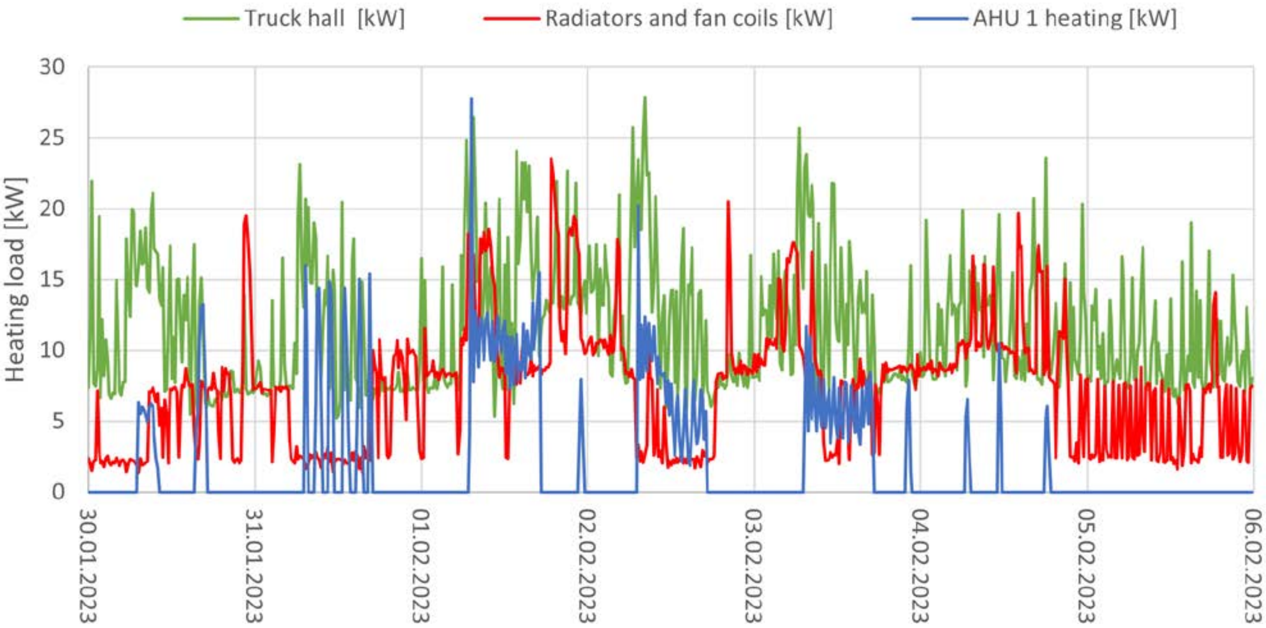

Figure 6: Heating load from the district heating system used for various heat consumers in the dairy. There are three additional air handling units (AHUs) currently not monitored.

3.4. Summary of heating and cooling demand

To summarise the demand for heating and cooling, a pie chart of all thermal demands is presented in Figure 7. The heating provided by the electrical boiler is estimated based on a monthly report of the electricity consumption extrapolating to one week of operation. The boiler provides heating for the highest temperature requirements for the CIP and process heating. The boiler load is linked to the weekly production schedule, which is similar from one week to the other. An efficiency of 0.98 is assumed for the boiler. About 20 % of the thermal demands in the dairy plant come from refrigeration processes, while about 12 % of the demands are due to the heating of the building (district heating). Since the heating demand of two AHUs is not known, the total ventilation heating demand was estimated. The total use of district heating per month is known and the heating demand of the analysed week was for the sake of completeness estimated assuming an even distribution during the month. The heat demand for radiators/fan coils and heating of the truck hall was subtracted from the overall amount to indicate the total contribution from ventilation heating. The remaining 2/3 of the thermal demand is due to process heating and CIP processes. The use of district heating is highly dependent on the ambient temperature, and the distribution of the thermal loads is expected to be slightly different during a summer week. The need for heating will be negligible, but the cooling requirement from cooling rooms and AC can increase significantly. The measurement campaign will continue to document the seasonal variations at the dairy plant.

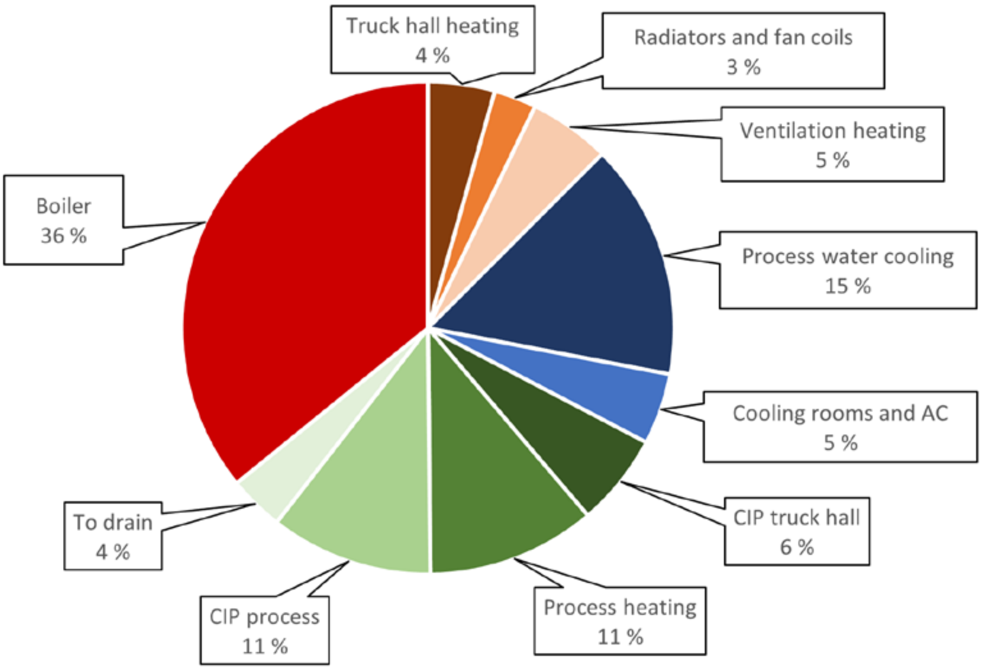

Figure 7: Distribution of heating and cooling demands at the dairy plant during the analysed week.

3.5. Integrating a cold thermal energy storage

Compared to the warm side of the dairy energy system, the thermal storage capacity on the cold side is very limited when observing the magnitude of the cooling demands. In particular, the process cooling circuit has been identified as the main driver of the cooling demands at the plant. One solution to achieve peak shaving and load shifting of the refrigeration demand at this temperature level is to implement a latent cold thermal energy storage (CTES) using ice as the storage medium. CTES units using pillow plate heat exchangers have recently been demonstrated using CO_2 as the refrigerant (Selvnes et al., 2021). For the implementation at the dairy plant, using the existing capacity of the CO_2 refrigeration systems to charge the CTES during off-peak periods (nights and weekends) is an attractive strategy. The resulting ice bank CTES will then supply cooling of the return stream of process water during the peak hours. The return flow of the process water has a temperature in the range of 3-5 °C.

The process cooling load during the peak period (05:00 to 13:00) over the five production days was analysed and averaged to one representative day. The average value for maximum peak cooling load (kW), average cooling load (kW) and cumulative cooling requirement (kWh) were found to be 880 kWh, 168 kW and 107 kW. Table 2 presents the preliminary design specifications of a CTES system providing 100 % to 25 % of the process cooling demand during peak hours. Further work will include detailed dimensioning of the CTES storage and a techno-economic assessment of the storage size.

Table 2: Preliminary sizing of a CTES system for various coverage of the process cooling load.

Coverage	100 %	75 %	50 %	25 %
Storage capacity [kWh]	880	660	440	220
Peak cooling rate [kW]	168	126	84	42
Mean cooling rate [kW]	107	80	53	27
Ice mass required [kg]	9501	7125	4750	2375

4. CONCLUSIONS

This paper has presented a thermal energy analysis of a Norwegian dairy plant applying integrated CO_2 refrigeration units supplying both cooling and heating. The analysis has shown that the cooling demands are strongly driven by the production schedule with distinct peaks in cooling demand of 140-160 kW lasting 6-8 hours. On the cold side, the process cooling constitutes about 75 % of the cooling demand, the rest is for cooling rooms and AC. On the warm side of the process, the process heating and CIP processes required about 1/3 of the total thermal energy at the plant. The boiler supplies slightly more than 1/3 of the total thermal energy by boosting the process water temperature for pasteurisation and CIP processes in the plant. A non-negligible amount of district heating was used for building heating purposes during the analysed week, contributing to about 12 % of the total thermal energy requirement.

To address the peak cooling demands originating from the process cooling circuit, a proposal for implementing a cold thermal energy storage system into the refrigeration system was made. Further work will include a more detailed analysis and dimensioning of the proposed CTES unit, followed by an implementation to measure the effect of the thermal storage related to peak power demand shifting and stabilizing the operation of the heat pump units.

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DATA AVAILABILITY STATEMENT

The data supporting reported results can be found in a public repository under the following DOI: 10.5281/zenodo.7632139

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