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Performance analysis of high temperature heat pumps and thermal energy storages for a dairy

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ABSTRACT

This paper analyses the performance of the integrated energy system of an existing dairy in Bergen, Norway. The investigated dairy has an innovative solution for the thermal process supply by using only heat pumps and thermal energy storage to cover all temperature levels of the existing heating and cooling demand. The aim of the study was to determine the energy consumption and system performance for one winter week and one summer week and compare these results against each other. To evaluate the performance, a comprehensive energy analysis was carried out based on the available process data. The results show for a comparatively energy-intensive week in February that the integrated energy system covers the existing demand and can compensate for demand peaks, with a waste heat recovery rate of over 95% for the process. The chillers and heat pumps achieved high COPs in the range of 4.2 to 5.9, while the overall system achieved a total COP of 4.1. A comparative week in June was then investigated and compared with the results of the operating week in February. Due to higher building cooling demands and lower building heating demands, the demand for dry cooling was significantly increased in the summer, whereas the need for electric heating and district heating was reduced. The achieved COPs in the range of 4.2 to 5.7 were similar in the summer week, meaning that the energy system functions well in different climatic conditions. Based on the results of this study, the performance of the system under different conditions was evaluated and the impact on power consumption and potential use for other climatic regions was discussed.

Keywords: High Temperature Heat Pump, Heat Recovery, Process Integration, Thermal Energy Storage, Dairy

1. INTRODUCTION

Climate change is one of modern society's most important challenges. For the present and the near future, there is a distinct trend showing a continuous increase in the energy demand and greenhouse gas (GHG) emissions of industrial processes (Conti et al., 2016). To achieve environmentally friendly and affordable energy systems, it is therefore necessary to improve the energy efficiency of industrial processes. It is especially important to reduce direct GHG emissions, e.g. from burning fossil fuels (Bamigbetan et al., 2017). In many industrial processes, large amounts of low quality waste heat are available for potential waste heat recovery (Forman et al., 2016). To utilize this potential for industrial applications it is therefore important to develop and implement efficient and environmentally friendly methods for providing thermal energy in the form of both heat and cold.

Historically, heat pumps were mostly developed and used for refrigeration applications. In the last two decades, it has become increasingly important to provide useful heat e.g., for heating buildings or for production of process water, as well as the active use of the capacity of the condensers in refrigeration systems. Industrial heat pump applications can use available waste heat at low temperature levels to provide

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useful heat at different process-relevant temperature levels, which consequently reduces the use of primary energy. Food processing plants such as dairies, for example, offer great potential for the use of heat pumps due to the simultaneous need for cooling and heating in the achievable temperature ranges for market-ready heat pump solutions. The area of application of market-ready industrial heat pumps for heat generation is currently in the temperature range from 30 °C to 70 °C for the heat source side and from 70 °C to a maximum of 100 °C for the heat sink side (Arpagaus et al., 2018).

Heat pumps that can reach temperatures above 100 °C are described in the literature as high temperature heat pumps (HTHP) and to date there are only a few industrial systems in operation. Furthermore, HTHPs with a possible temperature rise of more than 100 K have hardly been researched so far, despite the versatile application possibilities with simultaneous use of the heat source and heat sink side (Schlemminger et al., 2018). Due to the high condensation temperatures, the selection of suitable refrigerants for HTHPs is limited. In order to avoid undesirable effects on the environment, the use of natural refrigerants with low global warming potential and known effects on the atmosphere is of particular interest (Bamigbetan et al., 2017). Water (R718), ammonia (R717), pentane (R601) and n-butane (R600) (Bamigbetan et al., 2016), for example, have favourable properties for use at condensation temperatures above 100 °C. Schlemminger et al. (2018) have shown that a cascade with propane (R290) in the low-temperature circuit and R600 in the high-temperature circuit is promising.

In this study, the possibilities for the integration of HTHPs into industrial processes are examined using a case study for an existing dairy. The operation of a newly built and fully integrated dairy is analysed, with the entire process demand being covered by heat pumps. As part of the investigations, the performance parameters of the heat pump systems are analysed and evaluated.

2. PRESENTATION OF THE FULLY INTEGRATED ENERGY SYSTEM OF A NEWLY BUILT DAIRY

In this case study, the plant operation of a newly built and fully integrated dairy was analysed. The dairy was put into operation in 2018 in Bergen, Norway and analysed in 2021 by Ahrens et al. (2021). The dairy has a size of 20,000 m² and a projected annual production of 43.4 million litres, divided into liquid milk (83.1%), cream (3.7%) and juice (13.2%), with liquid milk dominating the production. 6,000 m² of photovoltaic panels (PV) are installed on the roof, which generate around 0.5 GWh of electricity annually. In this system, the entire thermal process demands are supplied by heat pumps, and thermal energy storages are used to decouple the heat sources and sinks to buffer occurring demand peaks. A combination of NH_3 chillers (3 units, 2400 kW_{th}, -1.5 °C/40 °C), NH_3 heat pumps (2 units, 1577 kW_{th}, 20 °C/67 °C) and an NH_3-H_2O hybrid heat pump (1 unit, 940 kW_{th}, 60 °C/95 °C) is used.

The production processes in the dairy are divided among several consumers with different temperature levels. The fully integrated energy system uses the available waste heat from the cooling processes as a heat source and upgrades it to provide usable process heat for heating requirements. This enables the provision of process heat at different temperature levels of 40 °C, 67 °C and 95 °C.

The NH_3 chillers supply glycol at a temperature of -1.5 °C for cooling of the building and storage space. Via a heat exchanger, glycol at 0.5 °C is supplied to the other cooling processes. The NH_3 chillers deliver hot water at 40 °C from the condensers, which is collected in a thermal storage tank. Water from this tank is supplied to various process consumers and the evaporators of the NH_3 heat pumps. The return flow is collected in another tank at around 20 °C to cool further processes. If insufficient heat is demanded or extracted, the dry coolers can be used to assist in heat dissipation.

To provide the process heat, the NH_3 heat pumps use the 20 °C/40 °C circuit as a heat source and supply hot water at 67 °C for the building heating system, domestic hot water (DHW) heating and for the NH_3-H_2O hybrid heat pump. A connection to the district heating network can, if necessary, compensate for any deficits in the 67 °C tank. The NH_3-H_2O hybrid heat pump combines the functional principles of an absorption and compression heat pump and uses a NH_3-H_2O mixture as refrigerant. In the dairy, this acts as a HTHP and

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supplies consumers with process hot water at 95 °C via an additional thermal storage tank. If necessary, the HTHP is supported by an electric heater to ensure the required temperature for the process consumers.

Figure 1 shows the fully integrated heating and cooling system of the dairy, including the three heat pump systems and six temperature levels available to the various process consumers.

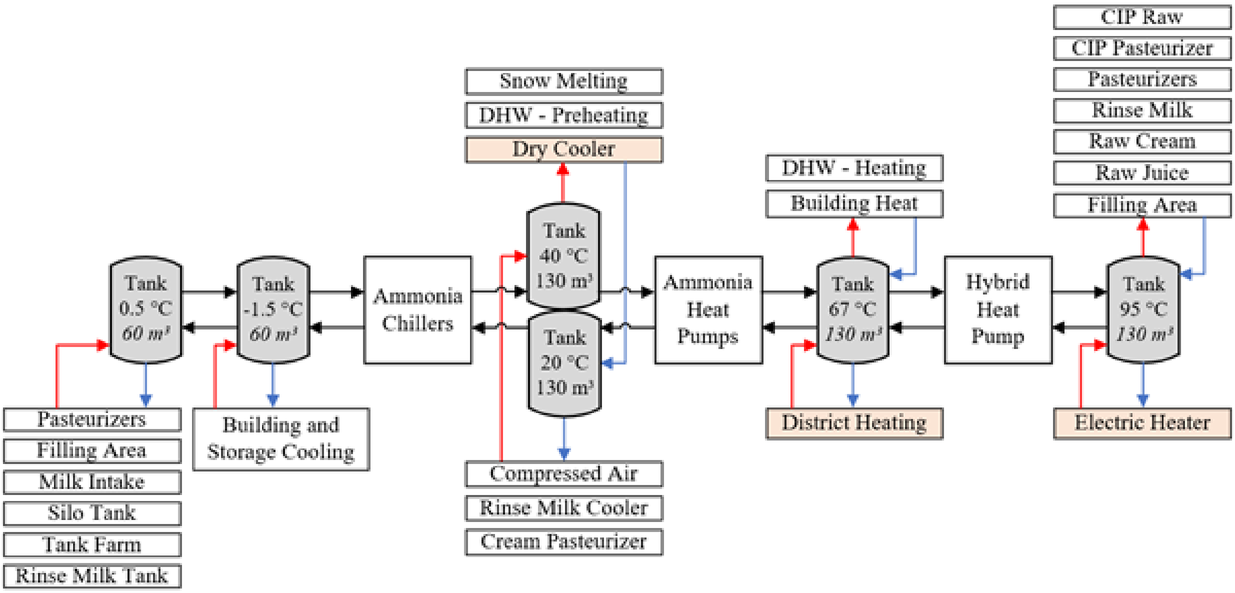

Figure 1: The energy system with consumers, heat pumps and thermal energy storage (Ahrens et al., 2021)

3. MEASUREMENT DATA AQUASITION AND EVALUATION

For the case study examined, two full weeks were analysed to identify cross-production influences and to take them into account in the evaluation. When recording measurement data, a value at a specific point in time is only logged by the measurement system if it differs from the value of the previous time step by a defined amount. Because the time steps for the different measurements were not consistent, merging the logged values resulted in numerous blank cells. To fill all empty cells, a linear interpolation between two known values was performed. For further use, the recorded data was resampled, and the average values were calculated on a minute basis. The Python programming language was used for data acquisition and processing, specifically the Pandas data analysis library and the CoolProp material data library. For the measurement data analysis and calculation of energy balances, Microsoft Excel was used with the REFPROP 10.0 library to access thermophysical properties.

In the measuring system of the investigated dairy, the supply and return temperatures were determined for all consumers, heat pump systems and thermal energy storage tanks with PT100 temperature sensors (iTHERM TM411, class A, ± 0.15 + 0.002 - T [°C]). The volume flow measurements were carried out with Coriolis (Promass F300 Hart, ± 0.1%) or electromagnetic (Promag H300 ProfiNet, ± 0.2%) flow meters. The total power consumption and the specific power consumption of the various heat pumps and the electric heater were determined using power meters (PowerLogic PM3000, ± 0.5%).

Based on this information, an average relative uncertainty was determined for each measurement point. These values were then used to determine the combined relative measurement uncertainty of the various system parameters including all contributing variables by applying the root sum method. The measured values were averaged over 60 minutes. The standard deviation of the measured values was calculated as a quality control. The performance of the heat pumps is measured directly on the secondary side of the evaporator and condenser. The coefficient of performance (COP) for the heat pumps and chillers are calculated using Eq. (1) and (2), respectively (Ahrens et al., 2021).

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$$COP_{heating} = \frac{\sum|\dot{Q}_{heating}|}{\sum \dot{W}_{el}} \pm 3.6\% \qquad \text{Eq. (1)}$$

$$COP_{cooling} = \frac{\sum|\dot{Q}_{cooling}|}{\sum \dot{W}_{el}} \pm 3.6\% \qquad \text{Eq. (2)}$$

where $\dot{Q}_{heating}$ is the amount of heat supplied to a system and $\dot{Q}_{cooling}$ is the heat extracted from a system, both in W. $\dot{W}_{el}$ is the required input power in W. Eq. (3) and (4) were used to determine the Carnot COP, i.e. the theoretical maximum COP, for heating and cooling, respectively.

$$COP_{Carnot,\,heating} = \frac{T_{sink}}{T_{sink} - T_{source}} \qquad \text{Eq. (3)}$$

$$COP_{Carnot,\,cooling} = \frac{T_{source}}{T_{sink} - T_{source}} \qquad \text{Eq. (4)}$$

where T_{source} and T_{sink} are the heat exchanger outlet temperatures in K for the heat source and sink, respectively. Further, the Carnot efficiency in Eq. (5) can be used to evaluate the COP of the system.

$$\eta_{Carnot} = \frac{COP}{COP_{Carnot}} \qquad \text{Eq. (5)}$$

When considering the performance of the whole energy system, it can be useful to calculate an overall COP for the provision of cooling and heating to all process consumers according to Eq. (6). This is the ratio between the useful heating and cooling delivered by the system and the required energy input in terms of electricity.

$$COP_{system} = \frac{\sum|\dot{Q}_{heating}| + \sum|\dot{Q}_{cooling}|}{\sum \dot{W}_{el}} \pm 8.7\% \qquad \text{Eq. (6)}$$

4. RESULTS

This section presents and evaluates the determined results for the weeks under investigation. In the first part, the focus is on the system analysis and process integration based on the energy flows and utilization of the energy systems. Subsequently, a performance analysis of the used heat pump systems is conducted.

4.1. System Analysis

For the examined week in February 2020, the total energy demand of the various process consumers for the entire dairy was 325.8 MWh. The largest process consumers were hot water at 95 °C and warm water at 67 °C for the provision of building heat, with 22.3% and 17.3%, respectively. This resulted in a total energy consumption of 245.5 MWh, of which 56.5% was covered with electricity, 10.8% with district heating and 32.7% with the recovery of waste heat from the NH_3 chillers and cooling processes. The contribution from PV panels was 0.3%. The large amount of usable waste heat in the energy system gives a considerable potential for saving primary energy or externally sourced energy. The dimensioning of the heat pump systems and thermal energy storage is important for efficient operation of the system and optimal supply to all process consumers. The aim is to even out production-related load peaks and temporal fluctuations between the available heat supply and demand, as well as the temperature differences.

For the week in June 2021, the total energy demand for the dairy was 300.2 MWh, representing a 7.8% decrease compared to the winter week. Now, the largest process consumers were hot water at 95 °C and cooling at 1.5 °C, with 23.4 % and 21.6%, respectively. This change from a large building heating demand to a large building cooling demand as second biggest consumer was expected due to the warmer weather and ambient temperatures in June compared to February. The overall value for the available energy sources was 251.9 MWh, which represents an increase of 2.6% compared to February. In proportion, the consumed

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electricity remains almost constant at 56.4%, whereby during the summer week 10.3% of this energy was supplied by the installed PV solar panels. Furthermore, it is important to mention that no district heating was required for the supply of the heating demands. Thus, the remaining 43.6% of the available energy was provided by the waste heat from NH_3 chiller and cooling processes, whereby this energy source was only partly utilized within the process. Consequently, a large part of the available waste heat was released through the dry coolers without being exploited. However, the overall energy consumption from external sources was reduced by 29.3%, thus reducing the dependency of the facility on the power and heat grid.

Figure 2 shows the energy flows (in MWh) in the dairy in the form of a Sankey diagram for the winter week. The energy flows from left to right, with heat sources on the left and heat sinks on the right. Deviations between the energy going into and out of a component are mainly caused by occasionally low measurement resolution, as well as measurement uncertainties related to rapid changes in temperature and volume flow (Ahrens et al., 2021). Only the district heating used directly in the dairy processes has been included here, excluding district heating for snow melting. The utilization rate of available waste heat from cooling is over 95% for the production process, with only a small amount of heat leaving the system through the dry cooler.

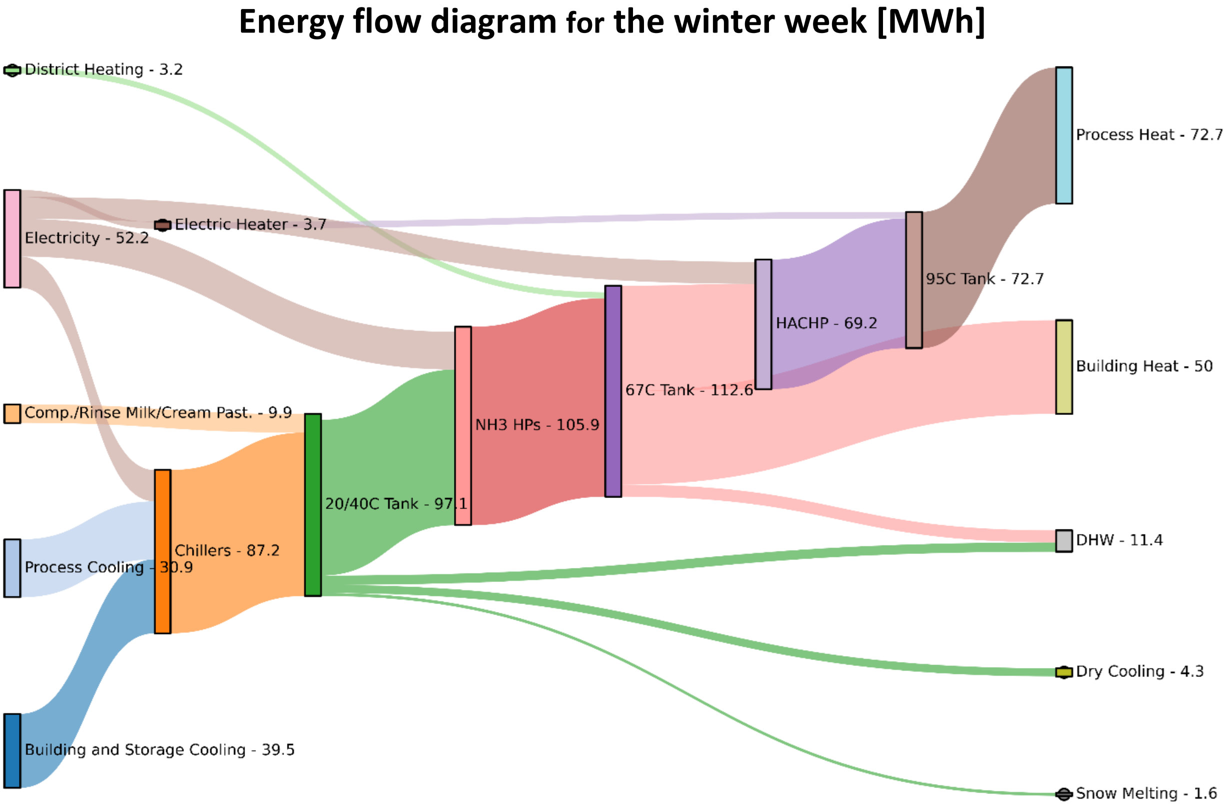

Figure 2: Sankey diagram showing the energy flows in the dairy in MWh for the winter week (Ahrens et al., 2021)

The representation of the energy flows demonstrates that the energy system is well designed for the occurring process demands of the investigated dairy. From the supply of the cooling consumers, the energy is transferred through the heat pump systems and thermal energy storage tanks to the heating consumers without large in- or outflows, except for consumed electricity. District heating as an external energy source or the auxiliary systems such as the dry cooler and electric heater are only used to a very small extent compared to the main consumer energy flows.

Figure 3 illustrates the determined energy flows (in MWh) for the investigated summer week in June. Again, almost all heating demands were covered through the recovery of available waste heat from the cooling processes. Compared to the utilisation rate achieved in February, however, the heat recovery rate was almost halved. This was caused by a larger building cooling demand in the summer leading to a larger amount of recovered heat, as seen in the diagram. However, due to a much lower building heating demand in the

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summer months, much of this heat will not be utilised and simply released to the ambient through the dry cooler. Due to these low heating demands, there was no need for external heat in the form of district heating.

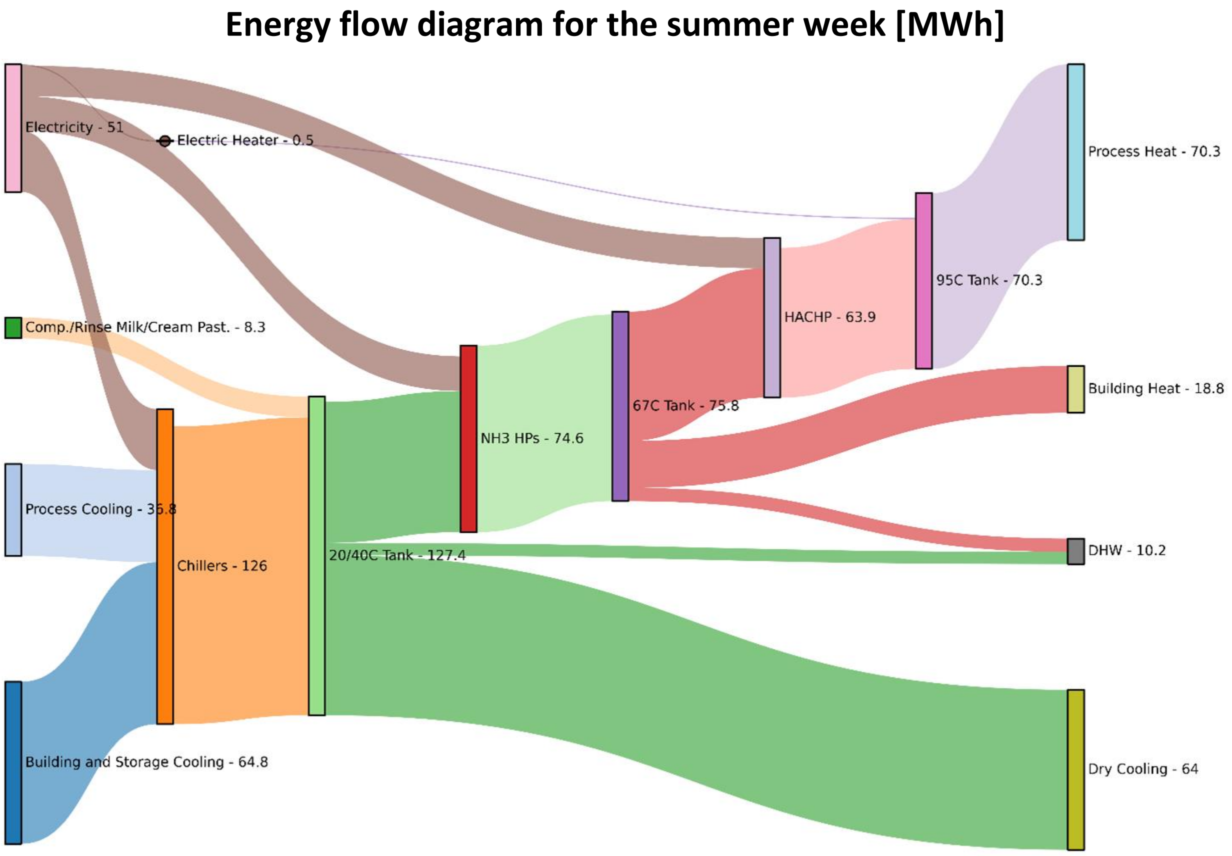

Figure 3: Sankey diagram showing the energy flows in the dairy in MWh for the summer week

The illustration of the energy flows for the operation of the plant during the summer demonstrates the capacity reserves of the energy system. The core process from process cooling to process heat is relatively identical to winter operation. Despite the large increase in the required cooling load with a simultaneous decrease in building heat demand, the energy system can handle this through the NH_3 chillers and installed dry cooler. In comparison of the two investigated weeks, it appears that the use of multiple units for the NH_3 chillers and NH_3 HPs is reasonable to efficiently adjust the capacity to the large changes in the demands. When operating outside the design point of the system in the part load range, there will most likely be a reduction in the COP. The use of several units in combination allows to react more precisely to changing load conditions by shutting down individual units while maintaining high efficiency of the overall heat pump stage.

4.2. Process Integration

In addition to the determined energy flows for the entire week, the temporal occurrence of the various demands and supplies as well as the use of the auxiliary systems are investigated in more detail for the evaluation of the process integration. Figure 4 illustrates the hourly thermal load profiles for the various process consumers at the different temperature levels and suppliers throughout the winter week. The stacked chart area shows the sum of the thermal load profiles for all heat consumers, while the solid line represents the heat supply from the recovered waste heat from cooling processes, including the heat generated from the electricity for the heat pumps. The different dashed lines show the utilization of the respective auxiliary systems. The illustration shows that heat demand and supply match well for most of the time. Surpluses and deficits, represented by the deviation of the stacked area and the solid line, are mostly bridged without using the auxiliary systems. This suggests that the thermal storage systems provide adequate compensation for the imbalance between the process heat required and the heat supplied by the heat pump systems.

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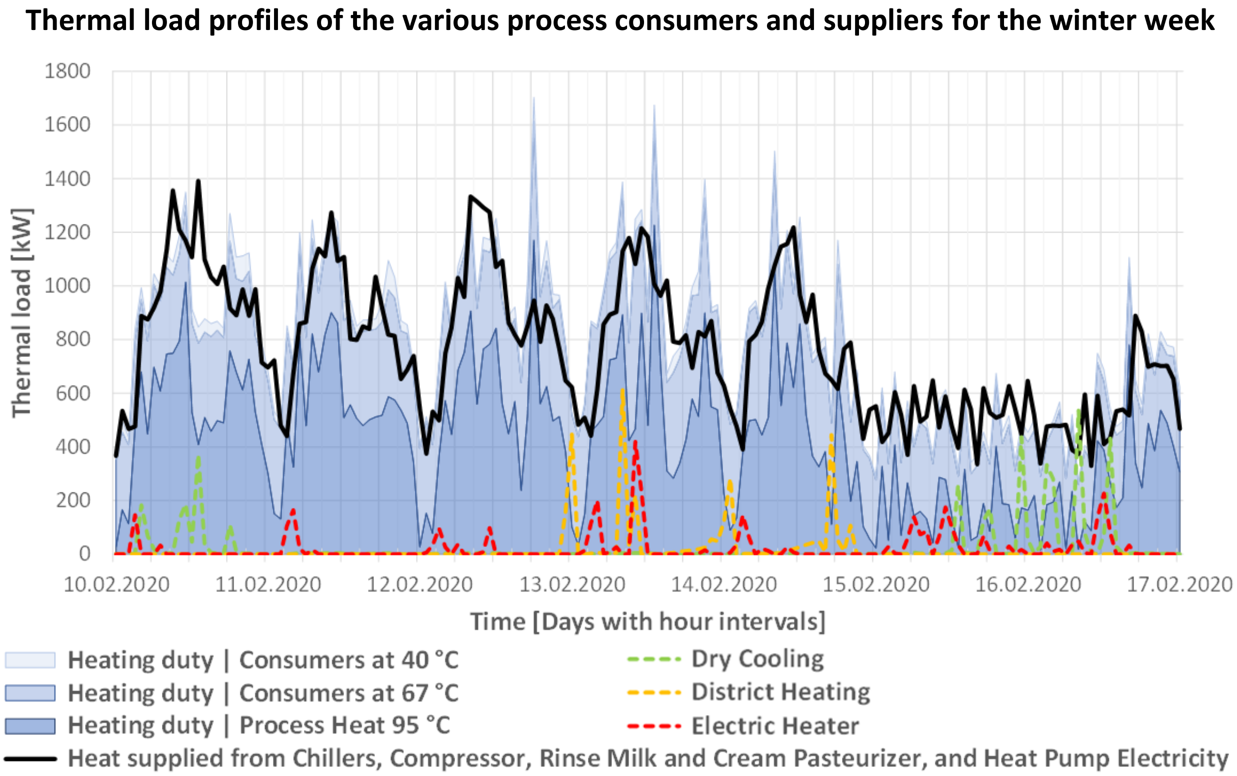

Figure 4: Thermal hourly load profiles of process consumers and suppliers, February 2020 (Ahrens et al., 2021)

Figure 5 shows the hourly thermal load profiles for the process consumers and suppliers throughout the summer week. Compared with the winter week in Figure 4, there is now a much larger deviation between the heat demand and supply, leading to large amounts of dry cooling throughout the whole week. Use of the electric heater is significantly reduced and there is no need for district heating.

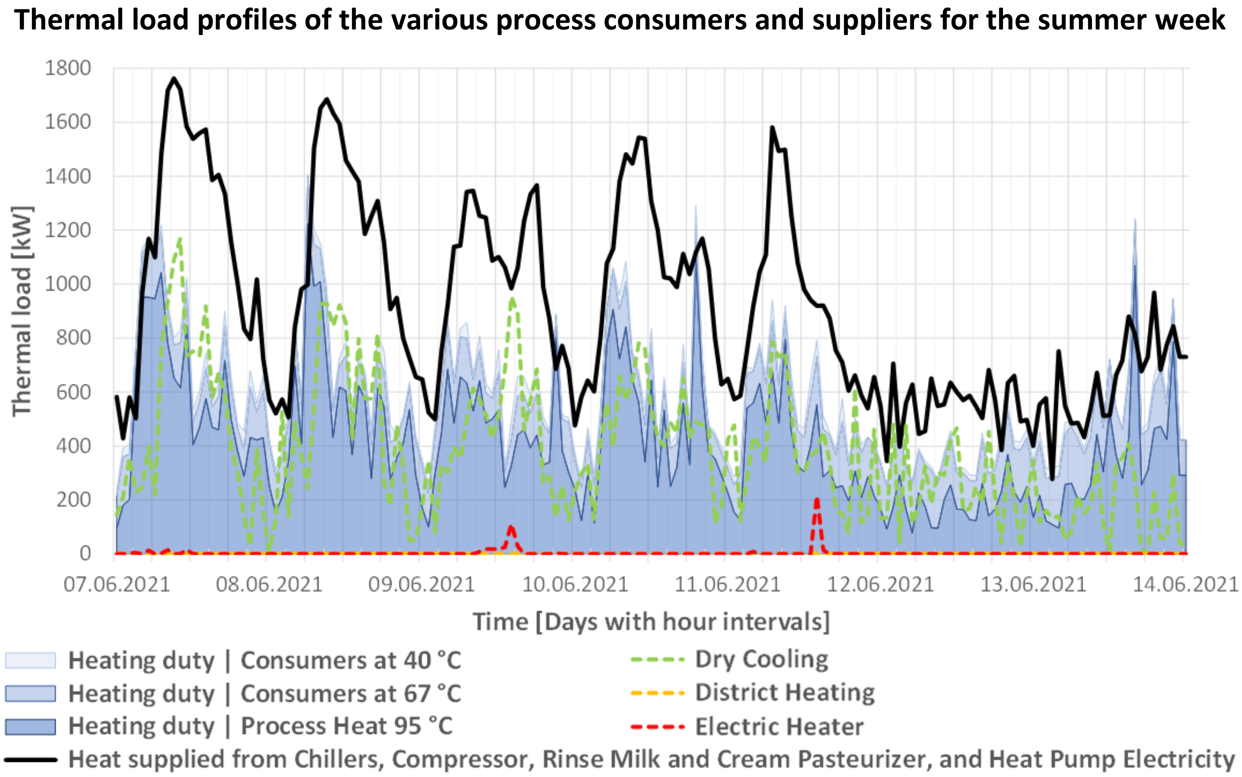

Figure 5: Thermal hourly load profiles of process consumers and suppliers, June 2021

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When comparing the demand patterns, the previously discussed changes between winter and summer operations become visible. The demand for process heat at 95 °C proceeds very identically, whereas the areas for 67 °C and 40 °C decrease significantly in summer. Furthermore, in summer the supply line is almost always at a significant distance above the demand areas, which requires the increased use of the dry cooler. Based on Figure 5, the use of the electric heater does not really seem necessary and might be eliminated entirely by adjusting the control system.

4.3. Performance Analysis

For the analysis of the applied heat pump systems, the determined performance parameters were evaluated. Table 1 shows the determined COPs of the heat pump systems and resulting Carnot efficiency for the winter and summer weeks, as well as the achieved temperature lifts based on the averaged measurement values.

Table 1: COPs, Carnot efficiencies and temperature lifts for the chillers and heat pumps in the investigated weeks

	February			June		
	COP [-]	Carnot efficiency [-]	Temperature lift [K]	COP [-]	Carnot efficiency [-]	Temperature lift [K]
NH_3 Chillers	4.2	0.55	35.5	4.2	0.59	38.3
NH_3 HPs	5.3	0.65	42.1	5.4	0.64	40.9
NH_3-H_2O HP	5.9	0.53	33.4	5.7	0.51	33.5

The determined results were overall very similar in the winter and summer. The COP of the NH_3-H_2O heat pump was slightly lower in the summer, which could be caused by part load operation due to a somewhat lower process heating demand. For the NH_3 heat pumps was the achieved COP slightly higher, even though the delivered heat was significantly lower here. This can be explained by the multiple NH_3 heat pump units leading to easier adjustments at part load operation. Furthermore. there were small differences in the Carnot COPs and Carnot efficiencies due to variations in the measured average sink and source outlet temperatures and the associated temperature lifts.

Using Eq. (6), the overall COPs were calculated for the dairy process considering the total thermal energy delivered in the form of heating and cooling in relation to the electricity consumed. This results in overall COPs of 4.1 for both the winter and the summer week. It is important to note that due to the definition of the calculation method (see Eq. (6)), the small share of district heating used in the winter operation is not considered. In summer operation, however, the reduced heat demand eliminates the need for district heating, which reduces the dependency on the power and heat grid and can be considered positive in terms of independent system operation.

5. CONCLUSIONS

In this study, the energy system consisting of heat pumps and thermal energy storage tanks of an existing dairy was investigated during the operation of one week in winter and one in summer. Process cooling for various consumers is provided at a temperature level of -1.5 °C to 0.5 °C, while the highest supply temperature of the system for process heat is 95 °C. The operation of the dairy including all process consumers was characterized by high volatility of the thermal energy consumption. This is valid both within a production day and in the comparison between winter and summer operation. Depending on the season and the climatic conditions, large fluctuations in the demand for building cooling and heating were determined. Here, the installed auxiliary systems support the operation with additional heat in winter and

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with heat rejection to the ambient in summer. The results of the case study showed that an energy system based exclusively on heat pump systems and thermal energy storage tanks can be successfully implemented.

The energy system can provide the required cooling and heating demands for both winter and summer operation. With changing demands throughout the year, the achieved COPs remain almost constant in a range from 4.2 to 5.9 with Carnot efficiencies between 51% and 65%. The overall COP defined as the delivered cooling and heating output in relation to the electricity consumed was determined to be 4.1 in both cases. It can be concluded that the heat pumps are properly designed for the varying demands. Moreover, the investigated operation in the winter and summer week can be considered as a proof of concept for the application of fully integrated energy systems using high temperature heat pumps and thermal energy storage tanks. Occurring demand peaks and fluctuations can be buffered by the thermal energy storage tanks and the dependence on the power grid and district heating network can be decreased by the reduced energy consumption of the heat pump systems. It can further be argued that this type of energy system is suitable for sites with different environmental conditions and resulting demands than the current location in Norway.

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NOMENCLATURE

DHW	Domestic hot water	*GHG*	Greenhouse gas
HACHP	Hybrid absorption-compression heat pump	*HTHP*	High temperature heat pump

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