

Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry

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ABSTRACT

This study investigates the integrated heat pump system of a green-field dairy located in Bergen, Norway. The purpose of the study is to determine the energy consumption and system performance. The dairy features a novel and innovative solution of a fully integrated energy system, employing high temperature heat pumps such as the hybrid absorption-compression heat pump (HACHP) with natural refrigerants to provide all temperature levels of heating and cooling demands. To evaluate the performance an energy analysis has been performed based on available process data for a comparatively energy-intensive week in February. The results have shown that the integrated system is able to meet the occurring demands. Furthermore, the specific energy consumption with 0.22 kWh l^{-1} product can outperform the annual average value of the replaced dairy even under difficult conditions. However, it is expected that the specific energy consumption will be further reduced on an annual basis. Through measures such as the extensive use of waste heat recovery accounting for 32.7% of the energy used, energy consumption was reduced by 37.9% and greenhouse gas (GHG) emissions by up to 91.7% compared to conventional dairy systems. Simultaneous, the process achieves a waste heat recovery rate of over 95%. Furthermore, demand peaks were compensated and a system coefficient of performance (COP) of 4.1 was achieved along with the identification of existing potential for further improvements.

1. Introduction

Climate change is one of the most significant topics of modern society. The energy demand and thus greenhouse gas (GHG) emissions of industrial processes are continuously increasing, with a clear trend for the coming years [1]. To achieve environmentally friendly, cheap and sustainable energy systems, it is now globally recognized that there is a necessity to increase the energy efficiency of industrial processes and reduce direct GHG emissions, e.g. from the burning of fossil fuels [2]. Simultaneously, large amounts of low-grade waste heat are available for potential waste heat utilization in various industrial processes, which are not directly usable and therefore are not exploited [3–5]. Due to this situation, it is essential to develop more efficient and environmentally friendly ways to provide thermal energy as usable heat and cold for industrial applications.

A promising approach to achieve these goals, which has been increasingly investigated in recent years, is the integrated use of high temperature heat pumps in combination with thermal storage tanks for

combined heating and cooling demands in industrial applications [6–8]. Of special interest regarding environmental sustainability is the use of natural refrigerants with low global warming potential (GWP) and known effects on the atmosphere for the operation of heat pump and refrigeration systems to avoid undesirable side effects [2]. Food processing plants in particular offer great potential for initial improvement measures due to the simultaneous cooling and heating requirements in achievable temperature ranges for heat pump solutions that are currently ready for the market [9]. This observation corresponds with the results of comprehensive studies on the food industry, which state that a considerable amount of energy is required for evaporation and freezing processes [10]. Currently, most of this energy is generated using fossil fuels and the decarbonisation of these processes is key for a green transition of the industry [11].

Dairy plants were found to be very well suited for implementing high temperature heat pump systems due to the given process requirements. Processing of dairy products involves a combined application of product heating (thermal treatment) and cooling. In a conventional dairy the heating demand is traditionally covered by fossil fuel boilers, while the

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Nomenclature*Abbreviations*

CIP	Cleaning-in-place
DH	District heating
DHW	Domestic hot water
EB	Electric boiler
EU	European Union
GHG	Greenhouse gas
GWP	Global warming potential
HACHP	Hybrid absorption/compression heat pump
IHPS	Integrated heat pump system
NGB	Natural gas boiler
NH ₃ HP	Ammonia heat pump
NO	Norway
PV	Photovoltaic

Roman letters

COP	Coefficient of performance [-]
h	Specific enthalpy [kJ·kg ⁻¹]
\dot{m}	Mass flow rate [kg·s ⁻¹]
\dot{Q}	Thermal load [kW]
T	Temperature [°C]
\dot{W}	Power [kW]

Greek symbols

ρ	Density [kg·m ⁻³]
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Subscripts

el	Electrical
eq	Equivalent
i	Index
in	Inlet
out	Outlet

cooling demand is covered by a separate refrigeration system. By integrating an industrial heat pump that can deliver both process cooling and heating, the need for fossil fuel is eliminated. A large share of emissions from dairy products is emitted during processing within the dairy [12], meaning there is great potential for improvements [13]. Thereby varying developments can be observed in the various countries within the European Union (EU), both concerning the treatment methods used and the primary energy sources used [14,15]. Here, the Scandinavian countries in particular achieve the lowest values in product-specific energy consumption [16].

Published work in the literature shows that several approaches can be followed to improve energy efficiency and reduce GHG emissions of industrial processes. In recent years, many studies were conducted on food processing plants and the associated processes, aiming to improve energy efficiency and reducing the energy consumption with the associated reduction of GHG emissions. On one side, there is a great effort to increase the efficiency of certain processes in terms of the technology used and the operating conditions, such as dryers [17]. On the other side, the way energy is provided [18] and controlled [19] within the plant is extensively investigated, as even a minimum of energy consumption is necessary with improved processes. With a focus on optimising individual processes as well as the overall system, several scientific and engineering methods are employed and continuously improved [20]. These include the use of energy, exergy and pinch analyses, as well as the development and implementation of advanced mathematical approaches for the optimal design and integration of industrial heat pumps for a variety of industrial processes [21,22]. For many of the investigations carried out and methods used, primarily case studies of existing plants were employed to identify the potential for optimisation in the scope of improved process control and/or waste heat recovery.

The present work aims to support the described trend in the scientific field focusing on integrating high temperature heat pumps with a high degree of waste heat recovery to minimise external energy consumption and GHG emissions of food processing plants. Unlike previous work based on simulations and theoretical case studies, this study demonstrates the performance of a fully integrated energy system of a green-field dairy with real operational data. To authors' best knowledge, the new dairy is the first in the world to operate without fossil fuel or direct electric heating, for which it won the "Heat Pump City of the Year 2019 award" in the DecarbIndustry category [23]. The aim of this study is to demonstrate that high temperature heat pumps using natural refrigerants can provide further improvements even for comparatively good systems and thus substitute conventional fossil fuel-based solutions. Furthermore, the demonstration of possible applications and

operating data of integrated high temperature heat pumps in combination with thermal storage tanks increase confidence in such systems among plant owners and key decision makers. Moreover, the present work can reduce non-technical barriers due to uncertainties based on a lack of experience among the potential users.

For this reason, this study investigates the energy consumption and system performance of the fully integrated heat pump system of a new dairy in Bergen, Norway. At first, both the system configuration and the process parameters are presented. Subsequently, the data collection and evaluation methods used are described. By using available operational data for one energy-intensive production week from the process instrumentation, an energy analysis is performed to evaluate the performance. For an environmental analysis, the conducted results are evaluated and compared with conventional reference dairy systems. Based on the process integration and system performance, further optimisation potentials are identified and discussed.

2. System description

The following case study was conducted for a green-field dairy in Bergen, Norway, which was commissioned in 2018 with an innovative integrated heat pump system to provide cooling and heating at all temperature levels required for the production process. The dairy has a size of 20,000 m² and a forecasted annual production of 43.4 million litres, divided into fluid milk (83.1%), cream (3.7%) and juice (13.2%), with fluid milk dominating the production. On the roof 6000 m² of photovoltaic (PV) solar panels are installed, generating approximately 0.5 GWh of electricity annually. The dimensioning was based on a replaced dairy in Minde, Norway, with an annual energy consumption of 10.1 GWh (6.8 GWh electricity and 3.9 GWh district heating) resulting in a specific annual energy consumption of 0.24 kWh l⁻¹ product for the year 2015. The targeted specific energy consumption for the new dairy was defined at 0.15 kWh l⁻¹ product on an annual average, with production taking place only on weekdays and not at weekends. This value is a realistic target based on the experience of the plant owner on branch-typical energy demands. In the following, the specific energy consumption for the investigated dairy is calculated and benchmarked against the targeted and reference values.

Production processes within the dairy can be divided into several consumers at different temperature levels. The dairy uses the excess heat from cooling processes provided by ammonia chillers and upgrades this heat to supply usable process heat for heating demands. This enables process heat at different temperature levels of 40 °C, 67 °C and 95 °C. The integrated heating and cooling system of the dairy is visualized in Fig. 1, including three different heat pump systems and six temperature

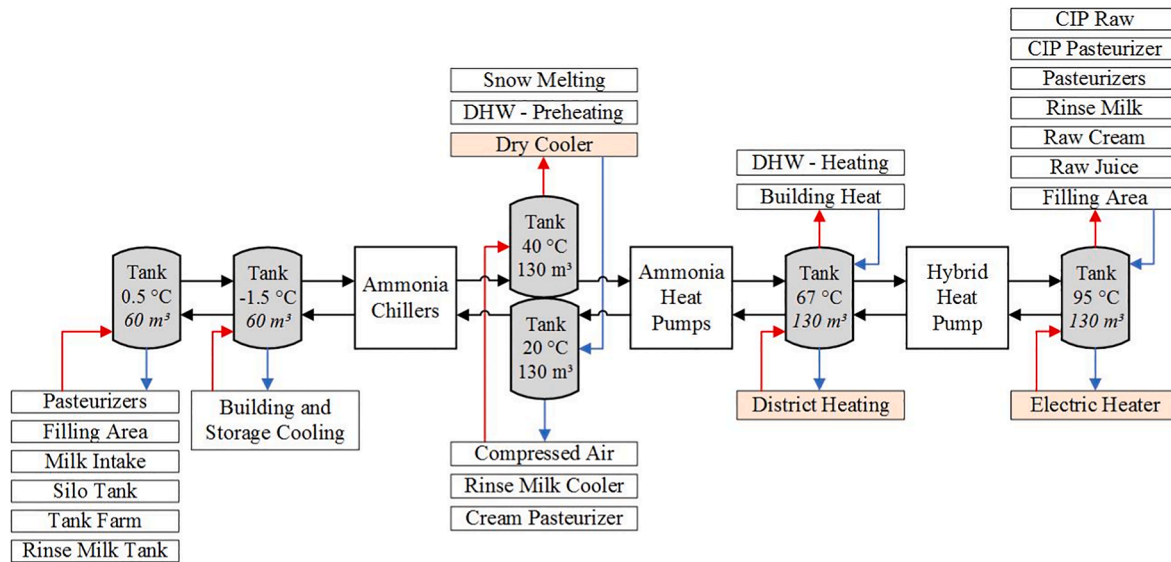


Fig. 1. Integrated energy supply system including heat pump systems and thermal storage tanks.

levels provided to the different consumers.

Ammonia chillers supply cold glycol at $-1.5\text{ }^{\circ}\text{C}$ to the building and storage cooling and via a heat exchanger to the ice water circuit at $0.5\text{ }^{\circ}\text{C}$, which provides cooling to different consumers, such as pasteurizers, filling area and milk intake. On the condenser side, the chillers produce hot water at $40\text{ }^{\circ}\text{C}$, which is accumulated in a storage tank. From the $40\text{ }^{\circ}\text{C}$ tank, the hot water is distributed to the snow melting, the preheating of domestic hot water (DHW) and to the ammonia heat pumps (NH_3 HPs). The return water enters another storage tank at $20\text{ }^{\circ}\text{C}$ before being heated by the condenser side of the chillers. From the $20\text{ }^{\circ}\text{C}$ tank, cooling is provided to the compressed air system, rinse milk cooler and cream pasteurizer. If the NH_3 HPs are unable to provide sufficient cooling for the $20\text{ }^{\circ}\text{C}/40\text{ }^{\circ}\text{C}$ circuit, the dry cooler ensures the required deficit.

Using the $20\text{ }^{\circ}\text{C}/40\text{ }^{\circ}\text{C}$ circuit as heat source, the NH_3 HPs produce hot water at $67\text{ }^{\circ}\text{C}$, which is then accumulated in a storage tank. The $67\text{ }^{\circ}\text{C}$ tank supplies heating for the building heat system, DHW heating and the high temperature heat pump. Eventual capacity deficits are compensated using district heating (DH). The installed hybrid absorption/compression heat pump (HACHP), operating as high temperature heat pump, produces hot water at $95\text{ }^{\circ}\text{C}$ for a further storage tank. The tank distributes the hot water to consumers, such as the cleaning-in-place (CIP) processes, pasteurizers and filling area. In case of a heat deficit in the $95\text{ }^{\circ}\text{C}$ circuit, an electric heater serves as reserve source.

The heat pump systems are designed to be able to provide nearly all required cooling and heating demands at the dairy, with the dry cooler, electric heater and DH as backup resources. Table 1 contains a detailed overview of the installed heat pump systems including refrigerant, number of units, heat source and sink temperatures and total capacities.

The chillers and NH_3 HPs are designed as single stage vapour compression heat pump systems with ammonia as refrigerant. Ammonia is a popular working fluid for both industrial refrigeration systems

(chillers) and large NH_3 HP systems due to excellent heat transfer properties and high volumetric heat capacity [24], which reduces the required compressor swept volume. The HACHP system uses the zeotropic ammonia/water mixture as refrigerant and is based on the Osenbrück cycle [25], which extends a vapour compression cycle with an additional solution circuit [26]. This extension offers the typical features of HACHP systems, such as high achievable sink temperatures at comparably low-pressure levels in combination with non-isothermal heat transfers [27]. The volumes of the storage tanks (see Fig. 1) were selected in relation to the required and available process demands and the objective of efficient operation with continuous supply to all process consumers.

3. Data collection and evaluation methods

The data used in this analysis were collected for one week in the period from February 10th (00:00 CET) to February 17th (00:00 CET) 2020. The period of one full week was selected to identify cross-production influences that would not be noticeable in a daily analysis. At the same time, due to the comparatively short time from commissioning and the resulting constant changes in the operation control, it was not meaningful to conduct an analysis of a longer period including different seasonal influences. This increases to a certain degree the uncertainty regarding the full-year values and reduces the possibility of a direct comparison with annual values. During the installation of the dairy, a significant number of sensors were installed, which made it possible to closely monitor the process. For all heat pump systems, thermal energy storages and consumers, the inlet and return temperatures were determined using PT100 temperature sensors (iTherm TM411, Class A, $\pm 0.15 + 0.002 \cdot T$ [$^{\circ}\text{C}$]). Volume flows measurements in each fluid line were conducted using Coriolis flow sensors (Promass F300 Hart, $\pm 0.1\%$) and electromagnetic flow sensors (Promag H300 ProfiNet, $\pm 0.2\%$). Values for total power consumption and specific power consumption for the various heat pumps and the electric heater were determined using power meters (PowerLogic PM3000, $\pm 0.5\%$). From 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 of Square method [28].

For size reduction of measurement data, the value at a certain time is only logged by the measurement system if it differs from the value in the

Table 1
Overview of installed heat pump systems.

System	Refrigerant	Units	Source	Sink	Total capacity
Chillers	NH_3	3	$4\text{ }^{\circ}\text{C}/$ $-1.5\text{ }^{\circ}\text{C}$	$20\text{ }^{\circ}\text{C}/$ $40\text{ }^{\circ}\text{C}$	2400 kW (cooling)
NH_3 HPs	NH_3	2	$40\text{ }^{\circ}\text{C}/20\text{ }^{\circ}\text{C}$	$60\text{ }^{\circ}\text{C}/$ $67\text{ }^{\circ}\text{C}$	1577 kW (heating)
HACHP	$\text{NH}_3\text{-H}_2\text{O}$	1	$67\text{ }^{\circ}\text{C}/60\text{ }^{\circ}\text{C}$	$73\text{ }^{\circ}\text{C}/$ $95\text{ }^{\circ}\text{C}$	940 kW (heating)

previous time step within a defined range. Since the time steps for the different measurements consisting of temperatures, flow rates, and power consumption were not the same, this led to many empty cells when merging the logged values. Linear interpolation between two known values was used to fill all empty cells. For the further use, the recorded data was resampled, and the average values were calculated on a minute basis. The programming language Python was used for data collection, data handling and energy balance calculations. Specifically, the data analysis library Pandas was used for data processing, while the CoolProp package was used to calculate energy balances.

3.1. Energy analysis

The conducted energy analysis is based on the logging values from the heating and cooling distribution system. It does therefore not consider any inefficiencies of the processing equipment itself, but merely studies how much energy is required to operate the dairy. Due to the absence of energy meters within the system, the specific thermal loads, \dot{Q}_i [kW], are determined using the specific energy balance for each consumer, i , as shown in Eq. (1).

$$\dot{Q}_i = \dot{m}_i \cdot (h_{out,i} - h_{in,i}) \pm 3.0\% \quad (1)$$

Pressures for water streams at all temperatures were assumed as 1 bara and glycol streams as 3.5 bara based on information from the dairy. Since flow measurements were volumetric, mass flow rates were calculated using the densities for constant temperatures based on the mean values of the respective temperature levels (see Table 1). The specific enthalpies at the inlet and outlet of each component or process were determined using the respective measured inlet and outlet temperatures and assumed pressures. The average value of the calculated measurement uncertainty [%] based on the measurement system used is presented in the equation [29].

3.2. Environmental analysis

To provide an environmental perspective of the benefits of the integrated energy system, energy savings and GHG emissions were investigated. Based on the energy analysis a comparison between the energy system of the investigated dairy and a reference system with separated cooling and heating systems has been made, using the same energy requirement for each process. Here, cooling is provided using the chillers and dry cooler against the ambient temperature. It can be assumed that the power demand for a refrigeration system rejecting all its heat to the ambient will be lower than for a system rejecting heat to an integrated heat pump system (IHPS) due to lower condensing temperatures [30]. The supply of the heating demand was divided into two scenarios: 1. EB + DH scenario with electric boiler (EB) for 95 °C consumers and DH for the remaining heating demands; 2. NGB scenario with natural gas boiler (NGB) for all heating demands. A thermal efficiency of 95% was assumed for the heat transfer to process heat from electricity, gas and DH. For a comprehensive consideration of the GHG emissions savings, these have been determined for Norwegian (NO) and EU emission cases. For electricity, an equivalent CO₂ emission factor of 17 g CO_{2,eq} kWh⁻¹ is assumed in the NO case, based on the Norwegian energy mix for electricity consumption in 2019 [31]. In the EU case, the emission factor for electricity is 295.8 g CO_{2,eq} kWh⁻¹, based on the EU energy consumption in 2016 [32]. For DH, the emissions factor is 23.4 g CO_{2,eq} kWh⁻¹, based on the energy mix of the local district heating provider BKK in 2019 [33]. This value does not include CO₂ emissions associated with the combustion of bio waste, which in most cases can be justified as it is part of the natural carbon cycle. The emission factor associated with natural gas consumption is 205 g CO_{2,eq} kWh⁻¹ [34].

3.3. Performance analysis

The performance of the individual heat pump systems is evaluated through the respective coefficient of performance (COP). It relates the total amount of heat supplied to (for heating) or extracted from (for cooling) a system to the total amount of work required to achieve that effect, hence indicating the efficiency of the heat pump or refrigeration system:

$$COP_{Heating} = \frac{\sum |\dot{Q}_{Heating}|}{\sum \dot{W}_{el}} \pm 3.6\% \quad (2)$$

$$COP_{Cooling} = \frac{\sum |\dot{Q}_{Cooling}|}{\sum \dot{W}_{el}} \pm 3.6\% \quad (3)$$

where $\dot{Q}_{Heating}$ is the useful heat supplied to the system and $\dot{Q}_{Cooling}$ is the useful heat removed from the system. For the work required, the value determined by the power meters is used, which includes losses in the inverter, motor, and compressor. Other values for auxiliary equipment such as pumps are not included. The theoretical maximum for the COP of a heat pump or refrigeration system operating between heat source and sink with constant temperatures is defined by the Carnot process, which is given by

$$COP_{Carnot\ Heating} = \frac{T_{sink}}{T_{sink} - T_{source}} \quad (4)$$

$$COP_{Carnot\ Cooling} = \frac{T_{source}}{T_{sink} - T_{source}} \quad (5)$$

where T_{sink} and T_{source} are in [K], respectively. In this case there is a small temperature difference between the input and output of the heat source and heat sink, and the temperatures are not constant, so the average output temperatures are used for the calculation. To evaluate the system performance, the Carnot efficiency, η_{Carnot} , is determined as the ratio of the COP to the theoretically achievable Carnot COP, as shown in Eq. (6) [35].

$$\eta_{Carnot} = \frac{COP}{COP_{Carnot}} \quad (6)$$

The overall system COP is defined as the ratio of the sum of the useable thermal heating and cooling loads to the total electricity consumption of the heat pump systems, using Eq. (7):

$$COP_{system} = \frac{\sum |\dot{Q}_{Heating}| + \sum |\dot{Q}_{Cooling}|}{\sum \dot{W}_{el}} \pm 8.7\% \quad (7)$$

4. Results and discussion

The results of the conducted analysis are based on the investigated production week in February. The total amount of product was 733,957 L, corresponding to a production capacity of 88%, divided into 589,399 L of fluid milk (80.2%), 26,045 L of cream (3.5%) and 119,513 L of juice (16.3%). When comparing this amount to the total energy consumption of electricity (138.6 MWh) and DH (26.6 MWh), excluding the electricity generated by PV solar panels (0.8 MWh), this results in a specific energy consumption of 0.22 kWh l⁻¹ product. The period studied covers one week in winter with temperatures below zero degree and snowfall, when energy consumption is generally higher than in summer. Therefore, it is expected that specific energy consumption will be reduced on an annual basis and full production volume. And despite the difficult conditions, the investigation already indicates a reduction of about 10% compared to the specific energy consumption of the replaced dairy, which was 0.24 kWh l⁻¹ product on an annual basis. As

the operational experience with this dairy is new, it is also expected that with increasing knowledge of process equipment and optimization techniques, the specific energy consumption will continue to decrease over time, thus reaching the targeted 0.15 kWh l^{-1} product on an annual basis. To identify potential improvements for the further reduction of the energy consumption, an energy and environmental analysis were performed, and the process integration and system performance investigated.

4.1. Energy analysis

Table 2 gives an overview of the energy demands with amount [MWh] and share [%] of the various process consumers. The list includes only end consumers of energy and intermediate consumers of heat and electricity, such as the heat pump systems, are not included.

The process consumer labelled "Other" has the largest single share (33.7%) and consists of a collection of consumers which includes electrical consumption from building lighting, the air compressor and fans, pumps and other auxiliary processing equipment, DH not used directly in the dairy process and waste heat, where individual values were not available. This value was obtained from subtracting the known consumers of electricity and DH from the total consumption. The second and third biggest energy consumers are the heat consumers at 95°C (22.3%) and 67°C (17.3%). Overall, heating processes thus account for the largest share of energy demand (41.6%).

To provide the required energy demands, electricity and DH were used as external energy sources, and waste heat recovery was utilized by the heat pump systems. Energy sources used in the dairy with their respective amounts [MWh] and shares [%] are shown in Table 3.

The total value of 245.5 MWh includes all energy consumed in the dairy, with electricity covering most of the energy demand (56.5%). Except for the electricity generated from the installed PV solar panels (0.3%), this energy is supplied together with DH (10.8%) from external sources and contribute to GHG emissions. With a share of 0.3%, PV solar panels contribute little to reducing total external energy consumption. However, as the data collection period was in February, a week with cloudy weather and regular snowfall, their contribution is expected to be significantly higher on average over a whole year. Waste heat recovery is accountable for 32.7% of the energy supplied and is provided by two main sources, the chillers (28.7%) and cooling of the compressor, the rinse milk and cream pasteurizer (4.0%). With the integration of the waste heat from the chillers into the dairy process being by far the largest contribution to waste heat recovery. For further utilization in the process, the waste heat recovered from the chillers is increased by the electricity consumption, as the electricity required for cooling is unavoidable. In contrast, cooling of the compressor, the rinse milk and cream pasteurizer can take place above the ambient temperature and

Table 2
Energy demands of the various process consumers.

Energy consumers	Amount [MWh]	Share [%]
Heating processes at 95°C	72.7	22.3
– Process Heat	72.7	22.3
Heating processes at 67°C	56.4	17.3
– Building Heat	50.0	15.3
– DHW – Heating	6.4	2.0
Heating processes at 40°C	6.6	2.0
– DHW – Preheating	5.0	1.5
– Snow Melting	1.6	0.5
Cooling processes at 20°C	9.9	3.0
– Comp. /Rinse Milk/Cream Past.	9.9	3.0
Cooling processes at 0.5°C	30.9	9.5
– Process Cooling	30.9	9.5
Cooling processes at -1.5°C	39.5	12.1
– Building and Storage Cooling	39.5	12.1
Other	109.8	33.7
Total	325.8	100.0

Table 3
Energy sources with amount and share.

Energy sources	Amount [MWh]	Share [%]
Electricity	138.6	56.5
– From grid	137.8	56.2
– From PV solar panels	0.8	0.3
District heating	26.6	10.8
Waste heat recovery	80.3	32.7
– Chillers	70.4	28.7
– Comp./Rinse Milk/Cream Past.	9.9	4.0
Total	245.5	100.0

therefore do not require additional energy. However, in this case the heat is used within the process via heat recovery. These results show that despite the modest reduction in specific energy consumption, without waste heat utilization, the consumption of electricity and DH would be considerably higher. The contradictory results indicate that this was a week where energy demands per litre product were higher than average.

4.2. Environmental analysis

Based on the energy demands presented in Table 2, a comparison was made between the IHPS and a reference system with separated cooling and heating system, as described in Chapter 3.2. When using dry cooling in the IHPS, the return temperature after cooling was on average about 7°C lower than the return temperature of the other cooling sources, making it clear that the cooling efficiency was to some extent sacrificed to achieve the utilization of surplus heat. The cooling system for the reference system can achieve a higher COP due to the reduced condensing temperature, resulting in lower power consumption. For the calculation of the electricity demand for the chillers in the reference scenarios, it was therefore assumed that the exclusive use of dry cooling leads to 7°C lower condensing temperatures. This results in a Carnot COP of 9.5, which with an expected Carnot efficiency of 60% gives a COP of 5.7. Cooling requirements at 20°C are not included as energy demand since it requires no additional energy input from either system. Data including additional power consumption from auxiliary equipment related to the heat pumps and thermal storage tanks was not available, so that this part has been neglected. Table 4 shows the comparison of the investigated energy systems based on the determined energy input values.

Based on the values in Table 2 and by excluding the 20°C processes,

Table 4
Comparison between the IPHS and a reference energy system.

Process	Required [MWh]	IHPS		Reference	
		Source	Amount [MWh]	Source	Amount [MWh]
Heating at 95°C	72.7	HHP	11.7	EB/ NGB	76.5
		EB	3.7		
Heating at 67°C	56.4	NH3	20.1	DH/ NGB	59.4
		HP	3.2		
Heating at 40°C	6.6	Chillers	0.0	DH/ NGB	6.9
Cooling at $0.5^\circ\text{C}/$ -1.5°C	70.4	Chillers	16.7	Chillers	12.3
Other	109.8	El. Grid	85.6	El. Grid	86.4
		EL	0.8		
		Solar	23.4	DH/ NGB	23.4
Total	315.9		164.4		264.9

the total energy demand of the dairy is 315.9 MWh. The IHPS requires an external energy input of 164.4 MWh to cover this demand, reduced by the 0.8 MWh of energy generated by the PV solar panels. For the reference system, the total energy consumption is 264.9 MWh, resulting in a total external energy saving for the IHPS of 100.5 MWh (37.9%). Compared to the EB + DH scenario (using electric boiler and DH), this corresponds to electricity savings of 37.4 MWh (21.3%) and DH savings of 63.1 MWh (70.4%). In the NGB scenario, 98.7 MWh were provided by electricity and 166.1 MWh by the NGB. For the investigation of the GHG emissions, the determined external energy consumption was projected over a period of one year and multiplied by the corresponding equivalent CO₂ emission factors. Fig. 2 shows the calculated GHG emissions in tons CO₂ equivalent projected for the period of one year [t CO_{2,eq} year⁻¹] of the investigated scenarios for the NO and EU case, respectively.

The reduction in GHG emissions for the IHPS in the NO case is 41.6% compared to the EB + DH scenario and 91.7% compared to the NGB scenario. The relatively low emission factor for electricity is responsible for the large GHG emission savings compared to the energy savings. A reduction in GHG emissions will also be achieved in the EU case, even though the savings are proportionally lower with 23.2% (EB + DH) and 34.3% (NGB) respectively. These results are consistent with the findings of [36] and [37], which stated that the use of high temperature heat pumps and EB can substitute conventional NGB and lead to large savings in primary energy consumption and GHG emissions, especially in countries with a high share of renewable energy sources in their energy mix.

4.3. Process integration

A well-integrated process is necessary to compensate for peak energy loads, time differences between available heat surplus and demand, and temperature differences. Fig. 3 presents an overview of the energy flows [MWh] in the dairy processing plant using a Sankey diagram [38]. The diagram shows the integration of energy consumers, heat pump systems and thermal storage tanks at different temperature levels. Individual energy consumers of the corresponding temperature levels were summarized. The diagram does not include an overview of the power consumption of auxiliary equipment such as lighting, air compressors, fans, and other devices, as these were not provided individually. Energy flows are directed from left to right and the line width represents the respective quantity. Therefore, it is visible for each stage which energy flows enter and exit. Discrepancies between entering and leaving energy flows for single components in the diagram are caused by differences between the calculated values on both sides. Reasons for these discrepancies may be based on several factors, such as measurement uncertainties and data processing methods. The largest differences were observed where cyclical processes with rapid changes in temperatures and volume flows occur. It is therefore assumed that these, in combination with a periodically low measurement resolution, are the main causes for discrepancies between the determined results.

The analysis of the energy flows indicates that the amounts of energy

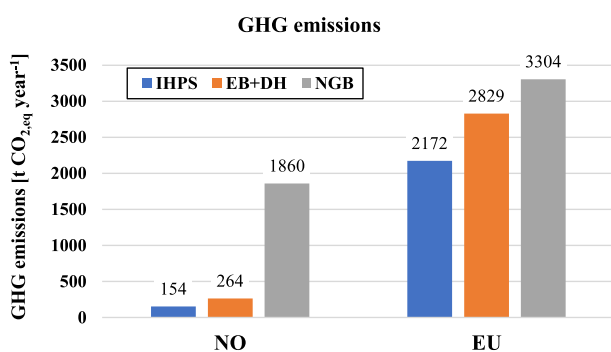


Fig. 2. GHG emissions of the investigated scenarios for the NO and EU case.

from the use of DH (3.2 MWh) and the electric heater (3.7 MWh) to cover the peak heat demand at 67 °C and 95 °C are small compared to the heat supplied by the heat pumps (105.9 MWh and 69.2 MWh). Likewise, the use of dry cooling (4.3 MWh) is limited compared to the amount of surplus heat provided by the chillers (87.2 MWh). This results in a waste heat recovery rate for the entire process of more than 95%. This indicates that the utilization of heat pump systems and thermal storage tanks are well integrated into the dairy process and sufficiently dimensioned. An investigation of hourly heat demands was made to further evaluate this integration. Fig. 4 shows the hourly thermal load profiles for the process consumers and suppliers over the period of the investigated week. The stacked chart area represents the sum of the thermal load for all consumers of heat, while the solid line represents the supply of heat from the recovered waste heat from cooling processes, including the heat generated from the electrical power to the heat pumps and the various dashed lines represent the use of the respective backup sources.

The illustration indicates a good match between heat supply and demand for most of the time. Occurring demand peaks and associated heat deficits are often managed without use of DH or electrical heater as backup sources. On the other hand, surplus heat is usually handled without the use of dry cooling. This indicates that the thermal storage tanks provide a reasonable compensation for the imbalance between the required process heat and the heat supplied by the heat pump systems.

During weekdays, the dairy processing is performed during daytime, resulting in the highest thermal peak loads. The cyclical behaviour of the load is highly affected by the load variations from the 95 °C processes. Peak loads from the 95 °C processes exceed the high-temperature heat pump capacity of 940 kW on a daily basis, proving again that the thermal storage tanks are used to overcome peak loads. The use of the electric heater is mainly limited to the start-up of the process, which is caused by the support of the high temperature heat pump start in the morning. Load variations in the 67 °C circuit are smaller than in the 95 °C circuit, as many of the consumers such as building heating and DHW require a continuous heat supply. Peak loads are usually well within the total heat pump capacity of 1577 kW. The increasing use of DH during the week therefore indicates a shortage of available waste heat from cooling processes.

During the weekend, the heat demand is reduced by more than half and remains more constant compared to weekdays. In particular, the heat demand for the 95 °C circuit is reduced and yet the electric heater is used more extensively. On the other hand, dry cooling is also being used more frequently in the same period. The backup source is thus used to cover a heat deficit with a simultaneous available heat surplus. The integration and evaluation of the data for the weekend indicates that by using the dry cooler, a total of 2.9 MWh of surplus heat was not utilized, which was almost twice as much as the amount of heat generated by the electric heater at 1.5 MWh. An explanation for this behaviour requires more insight into the process control system. In any case, these findings indicate that there is improvement potential for the energy utilization. For a more detailed analysis, the load profiles of HACHP and electric heater are plotted together with the temperatures from and to the 95 °C tank over the weekend (see Fig. 5). The solid lines represent the supplied heat load from both HACHP, and electric heater and the dotted lines represent the inlet and return temperatures before and after the systems.

With closer examination it becomes clear that the HACHP works in a cyclic manner together with the electric heater, but not at the same time. These systems are operated to maintain a certain temperature level in the thermal storage tank. If the temperature in the tank drops (indicated by the blue dotted line), the HACHP is operated until a defined set point temperature is reached and then stops operating. When the return temperature (orange dotted line) is too low or the required capacity is too small, the electric heater is used to raise the temperature. The missing ability of the HACHP to further reduce capacity could lead to this cyclical behaviour until it improves with increasing demand towards the end of the weekend. This is an indication that the system is not

Energy flow diagram [MWh]

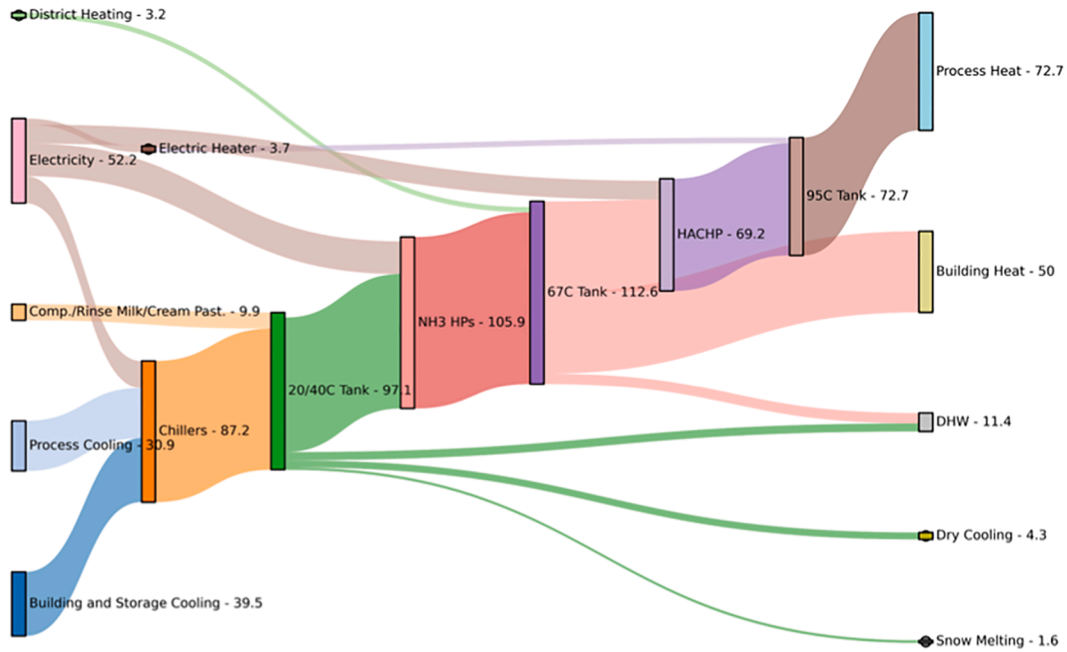


Fig. 3. Sankey diagram of energy flows in the dairy process.

Thermal load profiles of the various process consumers and suppliers

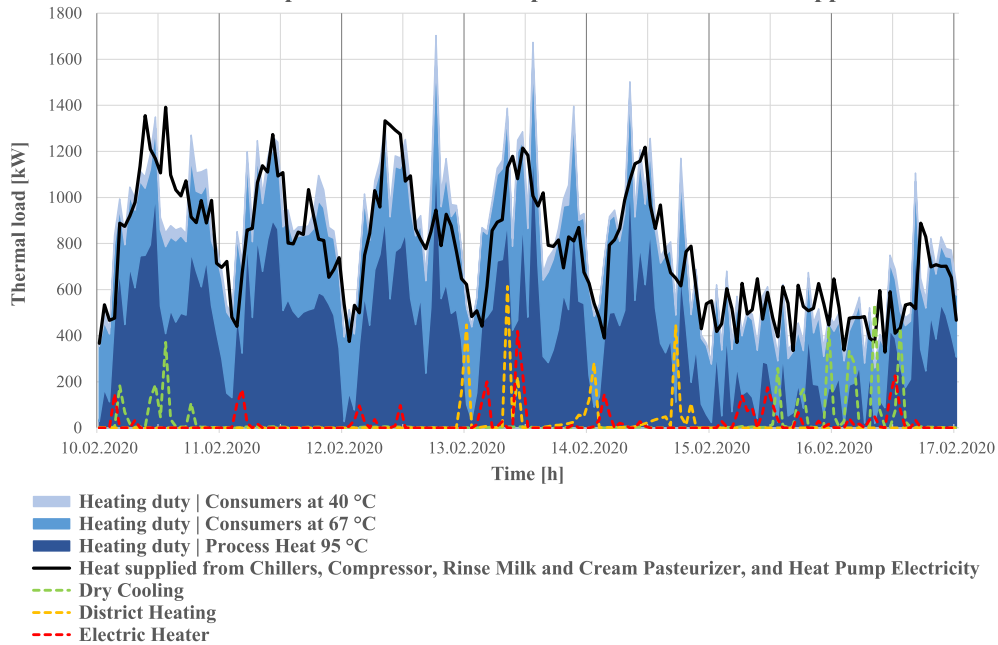


Fig. 4. Hourly thermal load profiles of the various process consumers and suppliers.

tuned for operation at half thermal load and further potential for improvement is available here. Possible approaches are the adaptation of the selected temperature set points. Thereby the temperature for the start of the electric heater could be reduced to limit the usage. In addition, if feasible, the minimum temperature level for the tank could be lowered on weekends to extend the charging times of the HACHP.

4.4. Performance analysis

In this section, the results of the performance analysis of the specific

heat pump systems as well as the overall system are presented. Fig. 6 shows the thermal load profiles of the heat pump systems during the investigated week.

The thermal loads for all heat pump systems were mostly well below the installed total capacity. As previously discussed, thermal loads for both heating and cooling are mainly affected by the high temperature processes at 95 °C, causing the cyclic heat demand during weekdays at daytime. The demand for building and storage cooling ensures that the chillers are in continuous operation throughout the week. The building heat and DHW ensure a stable heat demand in the 67 °C circuit, while

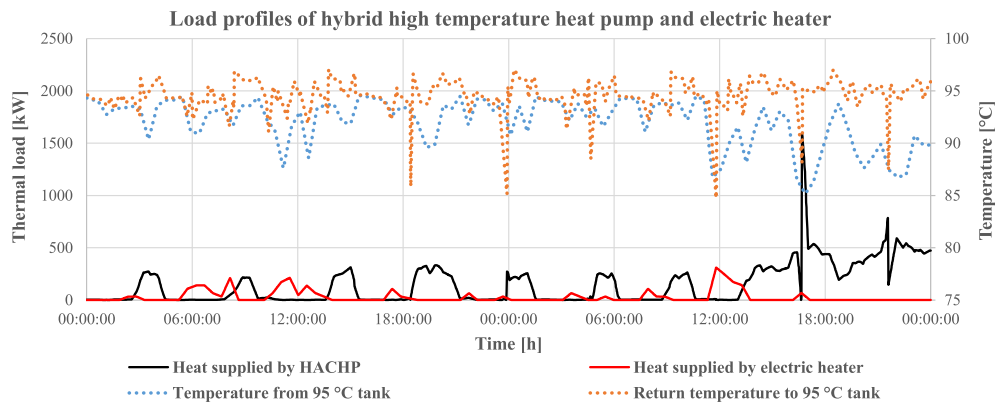


Fig. 5. Load profiles of high temperature heat pump and electric heater over the weekend.

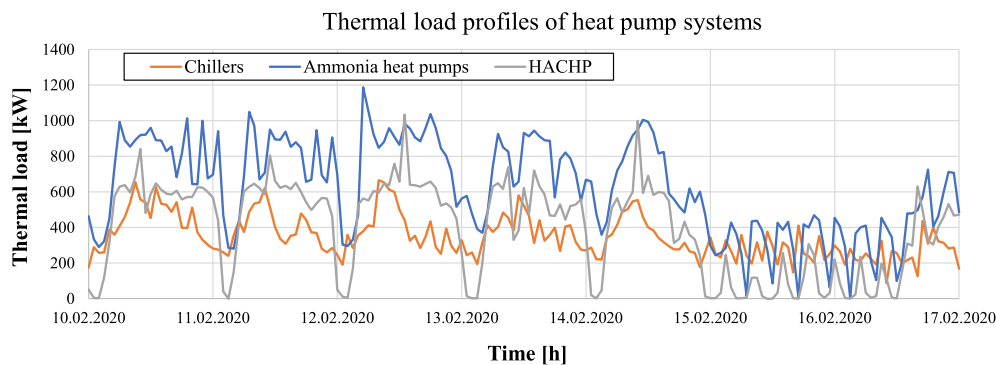


Fig. 6. Thermal load profiles of the heat pump system.

the total heat load is significantly reduced at weekends and the NH_3 HPs are operated cyclically. The HACHP system operates in the most cyclical way, as it only supplies heat to the 95 °C processes and is not in operation during the night on weekdays. This is also due to the fact of having only one unit which restricts the possible capacity control. Table 5 shows the results of the conducted performance analysis for the different heat pump systems.

During the investigated period, the average COP for the chillers was 4.2 with a Carnot efficiency of 55%. As already discussed in chapter 4.2, the use of dry cooling was minimal compared to the total amount of waste heat used for snow melting, DHW and the NH_3 HPs. However, when dry cooling was used, the return temperature after cooling was about 7 °C lower than the return temperature of the other cooling sources. This suggests that cooling efficiency has to some extent been sacrificed to achieve utilization of surplus heat. The average COP for NH_3 HP was 5.3, resulting in a Carnot efficiency of 65%, which is in the upper range for large scale industrial heat pumps [39]. The HACHP achieved an average COP of 5.9, resulting in a Carnot efficiency of 53%, which is within the expected range for state-of-the-art high temperature heat pumps on the market [9]. For the calculation of the overall system performance, all provided cooling and heating loads were summed up based on Table 2, excluding “Others”, resulting in a value of 216.0 MWh.

Table 5
Performance data of the heat pump systems.

System	Heat supply [MWh]	Power consumption [MWh]	COP [-]	COP_{Carnot} [-]	η_{Carnot} [%]
Chillers	70.4	16.7	4.2	7.7	55
NH_3 HPs	105.9	20.1	5.3	8.1	65
HACHP	69.2	11.7	5.9	11.2	53

The required work was determined to be 52.2 MWh based on the electricity consumption in Fig. 3. This results in a total system COP of 4.1 for the examined week in February. The presented performance values were achieved during an energy-intensive week, so it can be stated that the IHPS can certainly compete with conventional solutions.

5. Conclusion

This study investigates the energy consumption and system performance of an integrated energy system of a green-field dairy located in Bergen, Norway. The dairy features a novel and innovative solution of a fully integrated energy system. The system features high temperature heat pumps using natural refrigerants to provide all temperature levels of heating and cooling demands, enabling significant energy savings compared to the replaced dairy and other conventional dairy systems. By using available operation data for an energy-intensive week, an energy analysis has been performed to evaluate the system performance. The results were compared against reference dairy scenarios using conventional methods for providing the heating and cooling demands.

The results obtained show a specific energy consumption of 0.22 kWh l⁻¹ product for the investigated week, allowing the integrated dairy to outperform the annual average of the replaced dairy despite challenging conditions. The energy analysis indicated that 33.0% of all energy sources in the new dairy already come from either waste heat recovery or solar energy, while the process achieves a waste heat recovery rate of over 95%.

By using the determined energy demand of the dairy for the week, the external energy consumption and GHG emissions for a corresponding reference system were calculated. The integrated dairy achieved external energy savings of up to 37.9%, while GHG emission reductions of 23.2% to 91.7% are achievable, depending on the respective scenario and case. The continuing trend towards an increasing share of renewable

energy in the electricity mix has a positive effect on the competitiveness of the integrated system.

The detailed evaluation of the process integration revealed a good match between the heat supply from cooling processes and the heat demand from heating processes both in terms of overall load and the simultaneousness between supply and demand. Thermal storage tanks cover peak loads and provide useful heat storage, especially for the 95 °C circuit. A very modest use of backup resources in the process supports these findings, while further improvement potential was identified for the operation of these.

The results obtained clearly demonstrate that the integrated energy system with high temperature heat pumps and thermal storage tanks is suitable for providing all cooling and heating demands of the investigated dairy. The achieved performance values with a total system COP of 4.1 despite an energy-intensive operation period can certainly compete with conventional solutions. Thus, a further reduction of the specific energy consumption to the target value of 0.15 kWh l⁻¹ product on an annual average appears feasible. To support the conclusions of this paper, further work should include an analysis over a longer period, considering various seasonal influences.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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