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OVERVIEW ON TASK 6.3

1 GENERAL SUMMARY

Within this task, innovative solutions to increase the overall sustainability – especially to reduce the greenhouse gas (GHG) emissions - of dairies have been investigated in four demonstrators. Demos 2 to 4 consider measures in actual dairies located in Norway, Austria and the United Kingdom. Demo 1 treats the interconnection of different actors within the food supply chain, one of which is a dairy. The following four demonstrators are the subject of this task:

- **Demo 2 – Energy Smart Dairy (Norway):** This demonstrator maps and optimizes the CO_2-based thermal energy system at Rørosmeieriet to reduce specific energy consumption by ~36% and assess cold thermal energy storage for increased flexibility and robustness.
- **Demo 3 – High-Temperature Heat Pump (HTHP) Dairy (Austria):** An HTHP lifts waste-heat of a chiller to temperature levels of up to 90 °C mainly to preheat cleaning fluids in a Cleaning-In-Place (CIP) system.
- **Demo 4 – Heat Pump Integration Dairy (UK):** A new ammonia chiller reduces cooling energy use. The rejected heat from the chiller is used to preheat milk reducing natural gas use.
- **Demo 1 – Control:** A holistic control covers an instance of the supply chain to foster continuous improvement of all participating processes towards a shared goal, particularly the reduction of GHG emissions.

First, recommendations deduced from the findings of the demonstration campaigns are given. After an overview on the dairy sector, the technical solutions implemented at the demo sites are introduced in general. Based on this, demonstrator specific information is given with a focus on results and impacts.

2 RECOMMENDATIONS

- Industry
    - The analysis of (thermal) energy flows is key to efficiently cover the heating and cooling demand of dairies. Emphasis should be put on the system boundaries, interdependencies and relevant temperature levels.
    - For plants already in operation, production data can be a data source for this analysis. Attention should be paid regarding the availability of additional sensor data within control systems (e.g. SCADA) and possible data export.
    - If additional measurement data is needed, clearly define the scope of the analysis and needed measurement equipment, including the management of gathered measurement data. Details such as sensor placement should be given particular attention.
    - Regarding Demo 1: Lightweight interoperability – low technical and technological barriers for connecting to the system through the SDS technology – can facilitate SMEs (small medium enterprises) participation in complex food supply chain processes by lowering entry barriers, while enabling them to be guided and supported by other participants and decision-making tools for continuous improvement.

- Academia
    - The study of thermal energy flows in dairy processing provides valuable foundation for applied research on energy efficiency and decarbonisation. Research should aim to bridge theory and industrial practice by using real-world data and case studies. Collaboration with industry partners and transparency in data handling (cleaning, aggregation, interpolation etc.) is essential to ensure quality in analyses.
    - Model-based analysis using transient simulations can be used to analyse the demands. Depending on the complexity of the energy supply system (which can be drastically increased in case of preceding retrofits), certain simplifications are necessary. Strong involvement of experts of the specific plant can help identify relevant aspects.
    - Demo 1: New research frontiers for the food supply chain address key challenges such as: the development of a sustainable and democratic relationship among participants – every node in the communication is a peer and subject audits requiring the same quality and security rules; a new approach to using Blockchain technologies for the conscious mitigation of the impacts of new technologies and digitalization – against sustainability and social acceptance issues; formal control and correction of unexpected errors in shared and collaborative industrial processes; promotion of continuous improvement against complexity.
- Society
    - Public awareness of energy and environmental footprint of dairy products can drive demand for cleaner production methods.
    - Demo 1: Privacy and sustainability of the processes. A privacy preserving technology, as any participant is guaranteed privacy and safety depending on their choice on public commitment to the supply chain. Decision making relies on both collective and private decisions, which involve also societal and ethical issues by design.
- Policy makers
    - Support frameworks that incentivize energy monitoring and management systems in dairy production.
    - Demo 1: Support to sustainable value creation in food supply chains, promoting environmental and societal breakthroughs through flagships market niches.

3 DESCRIPTION OF THE SECTOR

In 2023, farms within the EU produced 160.8 million tons of raw milk. Out of these, 149.3 million tons (145 million tons of which are cows' milk) were processed in dairies to 106.6 million tons of products. Approximately 70 % of all whole milk available to dairies in the EU was used to produce cheese (10.6 million tons) and butter (2.3 million tons). (Eurostat, 2024)

According to Bakalis (2019), the EU was not only the world's largest producer of cows' milk in 2019, but also the largest exporter with 0.9 million tons. Vinci (2024) state, that there are around 12,000 processing facilities and 650,000 dairy farmers throughout Europe, 300,000 jobs are sustained within the milk processing sector with 45,000 positions directly associated with exporting dairy products to third countries.

Around 80 % of the energy demanded by dairies is thermal energy to generate steam and hot water, according to a report by the Joint Research Centre, the European Commission's in-house science service (Santoja et al, 2019). Besides this, diaries typically demand significant cooling. Thus, the focus of the involved demonstrators is on optimising the energy flows within dairies.

4 DESCRIPTION OF THE TECHNICAL SOLUTIONS

Dairies typically demand both heating and cooling during the involved processing steps. In case the temperature profiles of the involved media overlap (the medium to be cooled is hotter than the medium to be heated), exchange of thermal energy and thus heat recovery is possible.

A conventional system to supply process heat in a dairy usually utilizes a natural gas or biomass-fired steam boiler, while chillers are used to cover the cooling demand of the dairy, as shown in Figure 1 (a). The waste heat of the chillers is at too low a temperature to be used for process heating and is therefore dissipated to the ambient. Heat pumps, see Figure 1 (b) can be used to lift this waste heat to temperature levels suitable for process heat supply, which reduces the load of the steam boilers. As the waste heat from the chillers is recovered, the overall process energy demand is reduced. By reducing or replacing fossil-fuelled process heat supply, heat pumps can contribute to a decarbonisation of the supplied processes. The additional term “high temperature” refers to the temperature level of the heat supplied by the heat pump. Although no general definition exists, mostly temperature levels of above 80 °C (Arpagaus et al., 2018) or 100 °C (Zühlsdorf et al., 2023) are considered “high temperature” in the context of heat pumps. Thermal energy storages (TES), see Figure 1 (c), can be used to reduce thermal demand peaks and may be integrated into both the heating and cooling systems of a plant. TES systems are usually classified as either sensible or latent: sensible storages work by raising the temperature of the storage medium (e.g. liquid water), while latent storage relies on energy exchange during phase changes (e.g., water to ice, ice to water). A key difference is that latent storage provides nearly constant temperatures during charging and discharging and has high energy density, while sensible storages require larger volumes and exhibits varying temperatures dependent on state of charge.

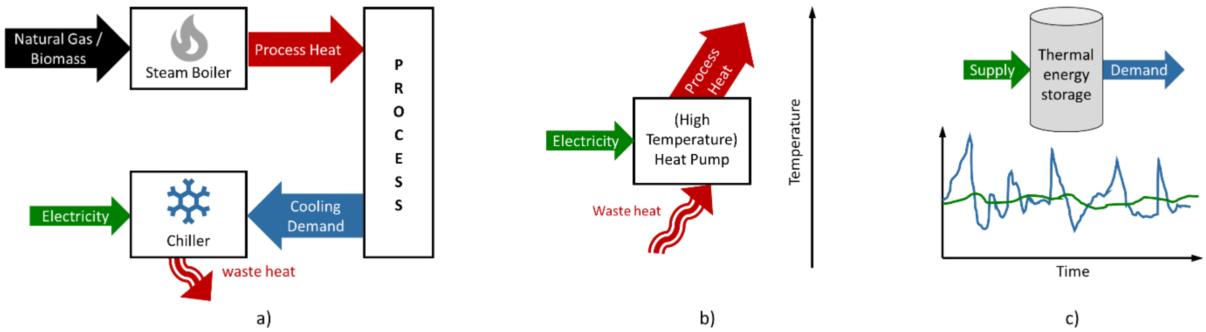

Figure 1: Schematic depictions of: a) Conventional gas-fired steam boiler and chiller to cover process heat and cooling demand, b) heat pump and c) thermal energy storage.

The demonstrators within this task use these technical solutions based on a thorough investigation of the concerning energy flows and temperature levels within the process heat supply and cooling system of the respective diaries. An example integration is given in Figure 2 with an HTHP recovering waste heat of a chiller to supply process heat and reduce the steam demand. Both hot and cold TES are used to even out demand peaks.

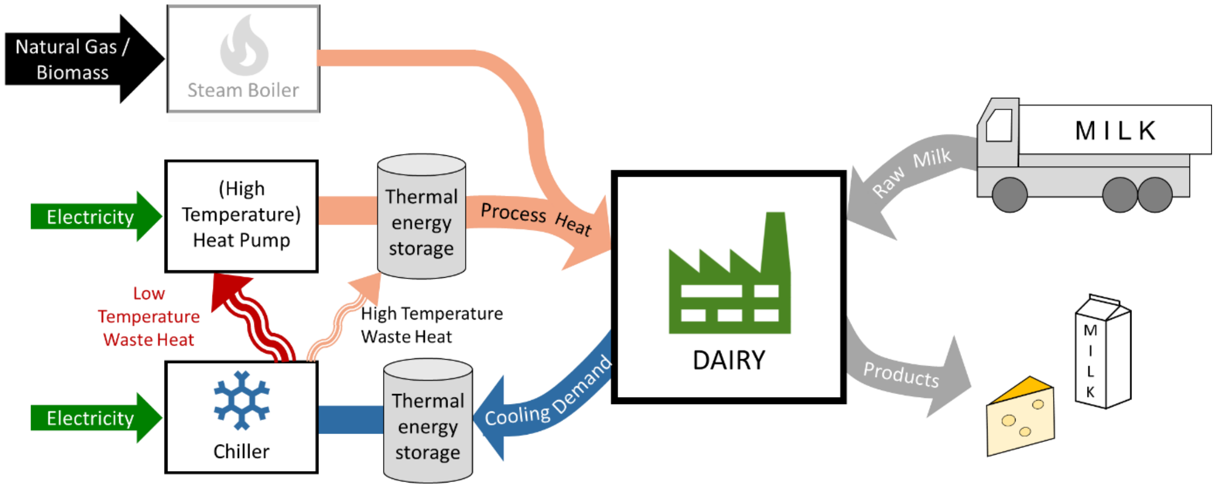

Figure 2: Schematic depiction of the integration of a (high temperature) heat pump and thermal storages in the energy system of a dairy.

More detailed information on the specific integration will be given in the chapters dedicated to each demonstrator below. For further information of the technologies HTHP, TES and waste heat recovery, the reader is referred to the Food processing road map published during the course of the ENOUGH project.

4.1 Definition of KPIs and benchmarks

As mentioned above, one focus of the presented Demos is on flows of thermal energy, specifically the cooling and heating capacities measured at certain system boundaries. In the following, a generalized approach to calculate heating and cooling capacities, the corresponding thermal energy and the CO_2 reduction when utilizing a low-emission substitute are presented.

Equation 1 is used to calculate the thermal capacity $\dot{Q}$ supplied to or removed from a liquid stream based on the measured volumetric flow rate $\dot{V}$, evaluated density ρ and specific heat capacity c of the medium as well as measured temperatures at inlet t_{in} and outlet t_{out} of a specific system boundary (e.g. a heat exchanger, or process facility). Heating up the stream requires the supply of the calculated heating capacity, while cooling down the stream requires the rejection of the required cooling capacity (thus a negative algebraic sign when evaluating Equation 1).

$$\dot{Q} = \dot{V} \cdot \rho \cdot c \cdot (t_{out} - t_{in}) \qquad \text{Eq. 1}$$

If the thermal energy is not directly measured using a thermal energy meter, evaluating Equation 1 for a time-series of measurement data allows to evaluate the thermal energy. Equation 2 lists this evaluation as multiplying the evaluated thermal capacity $\dot{Q}_i$ with the respective duration $\Delta\tau_i$ (or measurement interval) and summing these contributions over the considered time span τ.

$$Q = \sum_i \dot{Q}_i \cdot \Delta\tau_i \qquad \text{Eq. 2}$$

The evaluation of the GHG-emission reduction by substituting e.g. a fossil-fuelled heat supply with a low-emitting substitute is shown with Equation 3. The emission reduction $E_{reduction}$ is calculated by subtracting the emissions caused by utilizing the substitute technology $E_{substitute}$ from the emissions caused by the replaced technology $E_{replaced}$. This is done by multiplying specific carbon emission factors $e_{CO2,eq}$ (e.g. the emissions caused by supplying thermal energy through combusting natural gas, given in CO_2-equivalents) with the respective amount of supplied energy Q.

$$E_{reduction} = E_{replaced} - E_{substitute} = Q_{replaced} \cdot e_{CO2eq,replaced} - Q_{substitue} \cdot e_{CO2eq,substitute} \quad \text{Eq. 3}$$

The specific carbon emission factors used to evaluate the GHG emission reductions enabled through applying the proposed technologies in the Demos are listed in Table 1.

Table 1: Specific carbon emissions factors used to evaluate GHG-emission reductions.

Demo (country)	Energy Source	Specific carbon emissions [kg CO_2e/kWh]	Source
Demo 2 (Norway)	Electricity (consumption)	0.017	NVE (2020)
Demo 2 (Norway)	District heating	0.025	Ren Røros (2019)
Demo 3 (Austria)	Electricity (consumption)	0.156	OIB (2023)
Demo 3 (Austria)	Combustion of natural gas	0.201	OIB (2023)
Demo 4 (UK)	Electricity (consumption)	0.196	GOV.UK (2025)
Demo 4 (UK)	Combustion of natural gas	0.202	GOV.UK (2025)

PRESENTATION OF DEMONSTRATORS

5 DEMO 2 – ENERGY SMART DAIRY (NORWAY)

5.1 Description

Rørosmeieriet is Norway's largest organic dairy and a brown field site where the thermal energy system must continuously adapt to growing production and the merging of two sites. This presents challenges for a secure energy supply and compromises energy efficiency due to constant adjustments and redundant setups to keep production running. The current system includes four parallel refrigeration units, with excess heat recovered and stored as hot water for use in production. The project aims to enhance energy efficiency by identifying improvement opportunities. To achieve this, the thermal energy demand across seasons must be accurately assessed, necessitating the installation of energy flow meters at key points for long-term monitoring.

Since the demand for hot and cold thermal energy typically occurs at different times in dairies, integrating sufficient thermal energy storage (TES) on both sides is crucial for energy- and cost-efficient operations. With the dairy's increasing demand for products, space constraints make commonly used sensible energy storage impractical due to its large footprint. Therefore, the project is exploring the use of latent heat thermal energy storage.

Ice slurry technology presents an innovative approach to energy storage in dairy processing, particularly when temperatures around 0 °C are required. This technology is available in cooling capacity sizes of 240 – 880 kW but not inside Europe so far, and not in smaller sizes at all. A goal of the project is thus exploring the benefits of integrating the ice slurry technology in diary processes in the European market and in downscaling the technology. Together with our project partner Rørosmeieriet a small-scale demonstrator, as shown in Figure 3, is planned to show the advantages of such a system to increase product quality, system utilization, peak shaving and increased overall system efficiency.

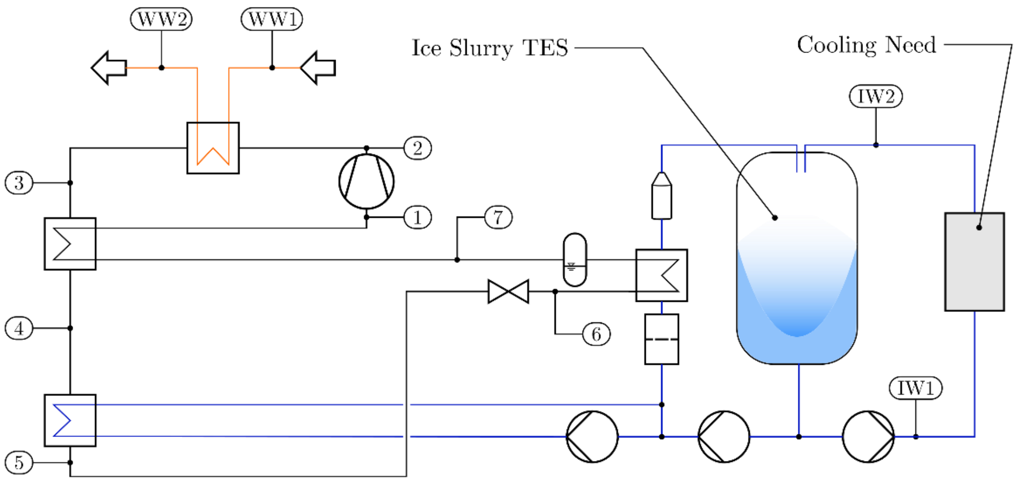

Figure 3: P&ID of an ice slurry TES system for Rørosmeieriet (WW=Warm water, IW=Ice water).

Another case study investigates the potential for integrating a high-temperature heat pump (HTHP) at Rørosmeieriet to improve energy efficiency by reusing internal low-grade heat instead of relying solely on electric steam boilers with relatively low efficiency. A significant amount of thermal energy is currently lost to drain, mainly through water discharged at elevated temperatures (assumed 35–40 °C) after being used as process water or in CIP operations. These streams have been identified as promising heat sources based on system mapping and sensor data. One challenge, however, is that they are not continuously available. To address this, the study also explores using waste heat from the CO_2 gas cooler of the planned ice slurry system as a heat source for the HTHP. Several HTHP concepts have been developed and evaluated, including single-stage compression, cascade systems, and a hybrid absorption–compression cycle (HACHP). The system is currently at TRL 4–5, with potential for upscaling to demonstration level (TRL 6 – 7).

5.2 Application methodology and assessment

As part of the project, a comprehensive energy monitoring system was established at the dairy's refrigeration units. While the physical installation was carried out by a third-party contractor, the project team was heavily involved in the specification and quality assurance of the setup. This included the strategic placement of sensors, but also detecting issues such as incorrect units or inverted signals which was corrected on coordination with the installer. In addition, to validate the system performance, the project team conducted a field measurement campaign using independent flow measurement equipment. The monitoring setup has evolved throughout the project, and current configuration is illustrated in Figure 4.

In parallel, a custom-built data processing pipeline to handle raw data streams from the monitoring system has been developed. The automated pipeline performs data cleaning, resampling, correction of unit mismatches and signal inversions, and feeds selected outputs into an interactive online energy dashboard. The dashboard, developed in Python using 'Streamlit' and hosted behind an authentication portal, displays live and historical energy analyses for selected periods, KPI tracking and tailored visualisations. The system has been operational since January 2023 but has undergone continuous refinement. Iterations have been driven by changes in the dairy's technical systems, but also due to new sensors and general improvement of reporting layouts.

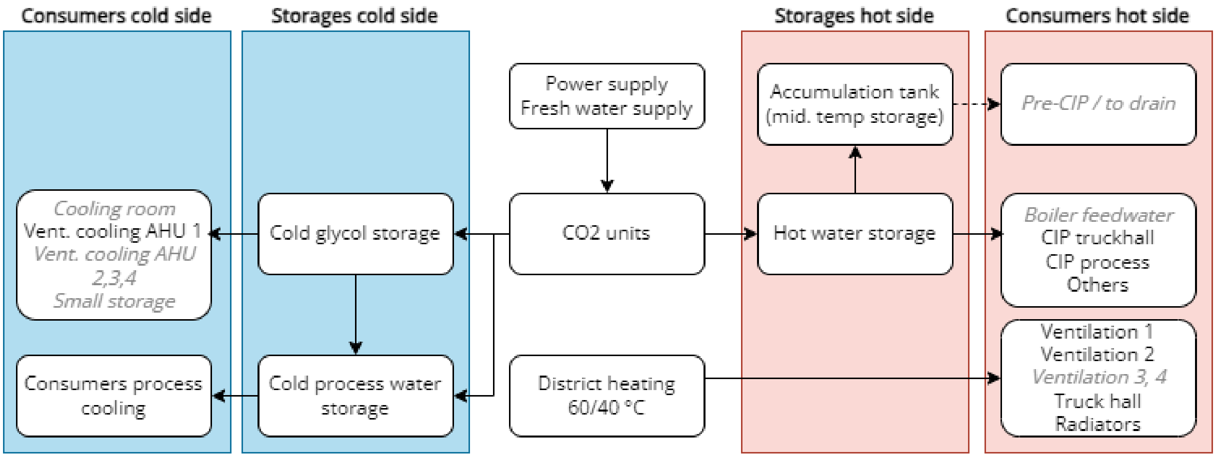

Figure 4: Overview of thermal energy flows and storage in the dairy. Italic grey text indicates subsystems where no dedicated energy metering is installed.

Data from the energy monitoring system has played a vital role in the assessment of both CTES (cold) and HTHP integration. These evaluations were carried out as desktop studies, using real-time operational data in combination with several technical meetings with personnel at Rørosmeieriet. For selected technologies, modelling and simulation methods were applied to estimate performance and impact under realistic operating conditions. Two master's theses—focused on CTES and HTHP integration, respectively—have been carried out as part of the project and are expected to be completed by August 2025.

The most important KPIs for Rørosmeieriet are:

- Specific energy use (per liter of produced milk): $\frac{E_{total}}{Milk\ production}$ [Wh/l]
- Specific freshwater use (per liter of produced milk): $\frac{Freshwater\ use}{Milk\ production}$ [-]
- Specific GHG emissions (per liter of milk): $\frac{Emissions\ assosiated\ to\ energy\ use}{Milk\ production}$ [gCO_2e/l]

The KPIs are compiled and reported on a monthly and annual basis and are benchmarked against both the previous period and the corresponding month of the previous year.

As part of Demo 2, equipment has been installed to enable more detailed monitoring of energy use, particularly for the heating and cooling systems. This allows the dairy to better understand where and how energy is consumed across different processes beyond just tracking total energy. The key benefit of this insight is that it enables identification of inefficiencies more easily and to implement targeted improvements. Ultimately, all the improvements that are suggested in the demo should be reflected in improved KPIs. Replacing the electrical boiler with a heat pump should improve both specific energy use (and emissions as a consequence) and freshwater use. Installing a TES system on the cold side does not directly impact the standard KPIs, as its primary purpose is to cover short-term peaks in cooling demand rather than reduce overall energy consumption. In a more conventional solution, such peaks would typically be met by upsizing the installed cooling capacity, which may lead to suboptimal part-load operation.

5.3 Results

Rørosmeieriet has undergone significant development since its establishment in 2001. As an organic dairy, it has maintained a strong focus on sustainability and continuous improvement in terms of environmental impact. The company originally operated two separate production sites, which were later merged into a single *brownfield* facility. Since then, both the thermal and production systems have been continuously developed and expanded.

A dedicated focus on energy use and the adoption of natural refrigerants began in 2014, marked by the installation of two 35 kW prototype CO_2 refrigeration systems. Systematic energy monitoring at a plant-wide level was introduced in 2018, and selected KPI values are presented in Table 2.

Table 2: KPI values for 2018, 2021 and 2024. Values in parentheses indicate the relative change (%) compared to the preceding year shown.

KPI	Unit	2018	2021	2024
Processed milk	m^3	13 149	16 300 (+24%)	20 546 (+26%)
Specific energy consumption	Wh/l	233	131 (-44%)	118 (-10%)
Specific water consumption	-	1.7	1.4 (-18%)	1.3 (-10%)
Specific CO_2 emissions	g CO_2e/l	5.5	2.3 (-59%)	2.1 (-10%)

2018-2021

During this period (predating the ENOUGH project) the dairy achieved several significant improvements in emission reduction, while simultaneously increasing overall milk production. Milk production rose by 24%, whereas specific energy consumption, specific water consumption and specific CO2 emissions all decreased. One of the most impactful measures was the phase-out of the fossil fuel burner, which was replaced by an electric steam boiler. In addition, the dairy was connected to the local district heating network and expanded its refrigeration system to include a total of five CO_2-based units with integrated heat recovery, supported by a number of hot water storage tanks. As a result, specific emissions were reduced from 5.5 to 2.3 g CO_2e per liter of milk during the period.

2021-2024

Following the initiation of the ENOUGH project, milk production rose by an additional 26% between 2021 and 2024, while KPI's continued to improve. The energy monitoring system was commissioned in January 2023 and has since played a central role in identifying and implementing energy efficiency measures (see Figure 5). One example is the reduction of thermal losses from hot water production. Due to limited storage capacity, surplus hot water was previously discharged to the drain. By re-allocating part of the medium-temperature hot water for pre-washing purposes, the dairy significantly reduced waste heat losses. Other examples include the detection of calcification in gas coolers through inspection of COP performance, and the identification of suboptimal unit control through analysis of compressor cycling. The latter negatively affects both efficiency and equipment lifespan and has prompted further investigation.

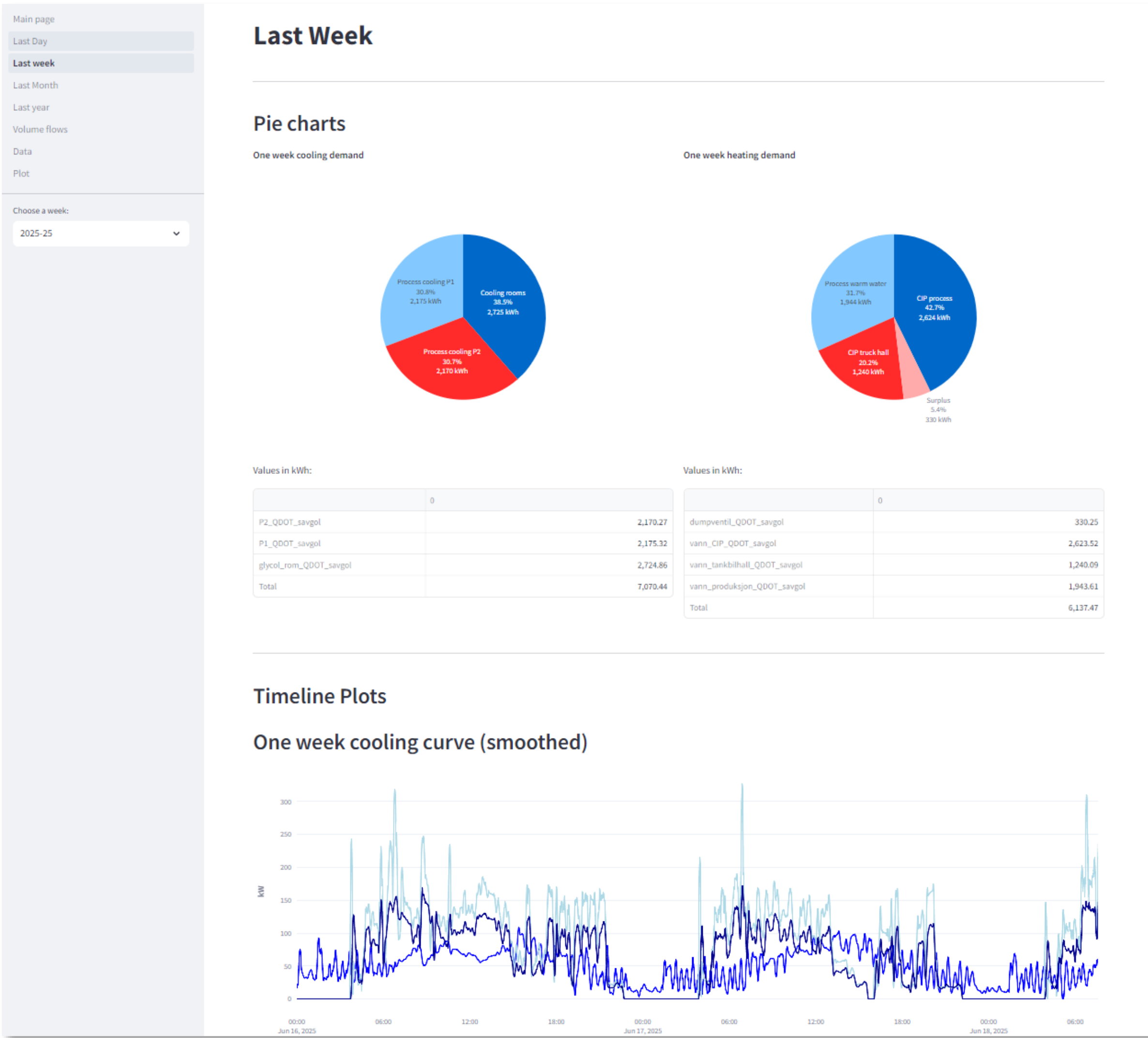

Figure 5: Snapshot from the energy monitoring dashboard.

CTES

Model-based analyses of the ice slurry supercooling system (not yet published) have demonstrated its potential to increase both energy efficiency and operational flexibility in the existing refrigeration setup at Rørosmeieriet. The system offers the advantage of simultaneous charging and discharging, while cooling the milk directly to the target temperature of 3 °C. Instead of meeting the daily 570 kWh cooling demand with peak loads of up to 185 kW, the technology enables a stable operation at 27 kW throughout the day. This allows the refrigeration system to operate continuously at its design point, which improves efficiency and reduces maintenance requirements. The constant production of cooling capacity, combined with the ability to discharge as needed, makes the system highly flexible and well-suited to the dairy's cooling needs.

Replacing electric boiler with heat pump

A key finding from energy analyses revealed that the electric steam boiler operates continuously at approximately 35 kW due to pressure and heat losses, resulting in a total energy loss of 20-22 MWh per month. A HTHP could be more efficient provided that suitable heat sources are available. Two such sources have been identified:

- Greywater, at 35-40 °C, with approximately 55 kW available for ~15 hours/day.
- Heat from the proposed ice slurry system: the CO_2 gas cooler could continuously offer up to 41 kW.

Multiple HTHP configurations have been evaluated, including single-stage, cascade and hybrid absorption-compression systems. The best-performing concept combined:

- Two evaporators in series: one at low pressure using greywater, and one at medium pressure using heat from ice slurry system.
- A two-stage compression cycle with flash tank.

Theoretical evaluation showed that this configuration achieves a COP of 3.16 to 3.79 and delivered between 131 and 154 kW of heat. Key parameters involved in the study were temperature requirement (based on varying consumer demands), the evaporation temperature (affecting COP) and intermediate temperature in the systems IHX. In addition to this system, a hybrid absorption-compression (HACHP) system showed potential, but was excluded from detailed evaluation due to limited data availability.

An extrapolation was also performed to assess how the implementation of a such a system could affect KPIs. The calculation assumed the same milk production volume as in 2024 but removed the contribution of the electric steam boiler ($W_{elboiler}$) from the overall electricity consumption (W_0) and instead covered the thermal steam demand using a high-temperature heat pump. This scenario has a substantial impact on the KPIs, primarily because the current electric steam boiler operates continuously at an output exceeding the actual thermal demand (Q_{steam}) (due to idle power as described earlier). By replacing it with a heat pump system operating at a COP of 2.5, the effective efficiency increases from 100% to 250%, significantly reducing the specific energy consumption per unit of product. The extrapolated total electricity consumption after implementing the heat pump can be estimated as:

$$W_1 = W_0 - W_{elboiler} + \frac{Q_{steam}}{COP}$$

Where subscripts 0 and 1 refer to values before and after implementation, respectively. Substituting the new electricity consumption (W_1) into the KPI calculations shows that specific energy consumption could decrease by 27% and specific emissions by 26%, resulting in projected values of 87 Wh/l and 1.54 g CO_2e/l milk, respectively.

Further results and detailed analyses are available in several published studies and master's theses related to this demo:

- Bengsch, Jan., Köster, Lukas., Svendsen, Eirik S., Selvnes, Håkon., Widell, Kristina N., 2024. Sizing and optimization of a cold thermal energy storage (CTES) for a dairy: A case study. Presented at the 8th IIR International Conference on Sustainability and the Cold Chain (http://dx.doi.org/10.18462/iir.iccc2024.1060)
- Köster, Lukas., Bengsch, Jan., Svendsen, Eirik S., Widell, Kristina N., Jenssen, Sigmund., 2024. Increasing the energy efficiency of a dairy by implementing a high temperature heat pump – a theoretical evaluation. Presented at the 8th IIR International Conference on Sustainability and the Cold Chain. (http://dx.doi.org/10.18462/iir.iccc2024.1061)
- Bengsch, Jan; Svendsen, Eirik Starheim; Selvnes, Håkon; Köster, Lukas; Hafner, Armin; Widell, Kristina Marianne Norne; Jenssen, Sigmund. Integriertes CO_2- Kälteanlagensystem einer Molkerei: Energieflussanalyse und Potenzial für einen kalten thermischen Energiespeicher. I: Proceedings of DKV Conference 2023 in Hanover, Germany. German refrigeration and air conditioning technology 2023 ISBN 978-3-932715-56-3.
- Selvnes, Håkon; Jenssen, Sigmund; Sevault, Alexis Gerard Edouard; Bengsch, Jan; Widell, Kristina Marianne Norne; Ahrens, Marcel Ulrich; Ren, Shuai; Hafner, Armin. Integrated CO2 refrigeration and heat pump system for a dairy plant: Energy analysis and potential for cold thermal energy storage. I: Proceedings of the 26th IIR International Congress of Refrigeration: Paris, France, August 21-25, 2023 – volume 2. International Institute of Refrigeration 2023 ISBN 978-2-36215-056-2. s. 1546-1555.
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- Bless, Marco, Model-Based Investigation of Upgraded Thermal Energy System Designs of the Organic Dairy in Røros – with PCM-Storage Integration and Experimental Pressure Drop Analysis of Pillow Plates; 2023 (https://hdl.handle.net/11250/3094653)
- Dahl, Cecilie Torp, Utilization of surplus heat from the organic dairy at Røros, 2023, Utilization of surplus heat from the organic dairy at Røros. (https://hdl.handle.net/11250/3096561)

5.4 Impacts

While the results presented reflect specific improvements achieved at Rørosmeieriet, many of the methods and technologies applied in the demonstration are not unique to this site. Consequently, there is a broader potential for replication across the dairy sector. Many of the challenges addressed are likely common to other small and medium-sized dairies, even though the specific technical solutions may vary. The approach taken in this demonstration illustrates a practical pathway for reducing environmental impact through continuous improvement and collaboration with R&D partners.

One of the most transferable elements is the establishment of an energy monitoring system. This is an immediately actionable measure that forms the foundation for any systematic energy efficiency effort.

Without reliable energy data, it is difficult to identify inefficiencies, quantify savings, or evaluate the effect of implemented measures. This demonstration confirms that such a system can quickly deliver actionable insights. There are no major barriers preventing replication. Technology is readily available, and several commercial solutions exist. However, care should be taken to validate measurements and ensure that the reporting structure provides actionable insights.

The integration of CTES is another promising approach for reducing peak cooling loads and increasing the operational flexibility of refrigeration systems. The ability to decouple cooling production from demand allows refrigeration units to operate under more stable and efficient conditions and enables load shifting in response to energy pricing or grid constraints. These benefits must be considered in relation to local conditions (i.e., different countries) and system configurations. For dairies in hot climates, where condensing heat is rejected to the ambient, CTES may also contribute to increased energy efficiency by leveraging reduced ambient temperatures during night. For the temperature ranges relevant for dairy applications, mature CTES technologies are available.

Many dairies require process heat at temperatures above 100 °C for applications such as CIP and pasteurisation. Traditionally, this demand has been met using fossil-fuelled boilers, and more recently, electric steam boilers. However, technological developments in HTHPs now make it possible to cover this demand using electricity far more efficiently. Replacing fossil-fuelled boilers with HTHPs represents a significant opportunity to eliminate direct emissions, while replacing electric boilers can improve system efficiency substantially depending on configuration and operating conditions.

5.5 Business potential

The dairy industry offers substantial business opportunities related to energy efficiency. The deployment of energy monitoring systems enables the identification of inefficiencies and supports targeted improvement measures—creating demand for specialised installation, maintenance, and energy auditing services.

Given that dairies typically require both cooling (above freezing) and moderate-temperature heat (up to ~100 °C), the growing maturity of technologies such as CTES and high-temperature heat pumps represents a clear market opportunity. This applies both to traditional sales and after-sales services, as well as emerging business models such as *heat-as-a-service*.

6 DEMO 3 – HTHP INTEGRATION IN AN AUSTRIAN DAIRY

6.1 Description

Demo 3 covers the integration of a HTHP into the chiller of the dairy Ennstalmilch in Stainach (Austria). The HTHP lifts waste heat of the chiller to a temperature level of up to 90 °C to heat up the cleaning fluids lye and acid for the CIP systems of the dairy which is used to clean process equipment such as tanks, filling machines, pasteurisers, milk collecting trucks, etc. Fresh and rinse water used in the CIP System are not heated by the HTHP. Recently, the system was upgraded to supply parts of the cheese dairy as well.

One peculiarity of this system is that the HTHP was directly installed into the refrigerant circuit of the existing chiller, as can be seen from

Figure 6. Thus, both the chiller and the HTHP use the natural working fluid ammonia (R717). While the chiller operates continuously, the HTHP is activated on demand, depending on the temperature levels within the TES. Closing the valves $V_{HP,13}$ and $V_{HP,10}$ enables operation of the chiller without the HTHP. Using these valves as “interfaces” helped to keep the down-time of the chiller as short as possible during construction of the HTHP.

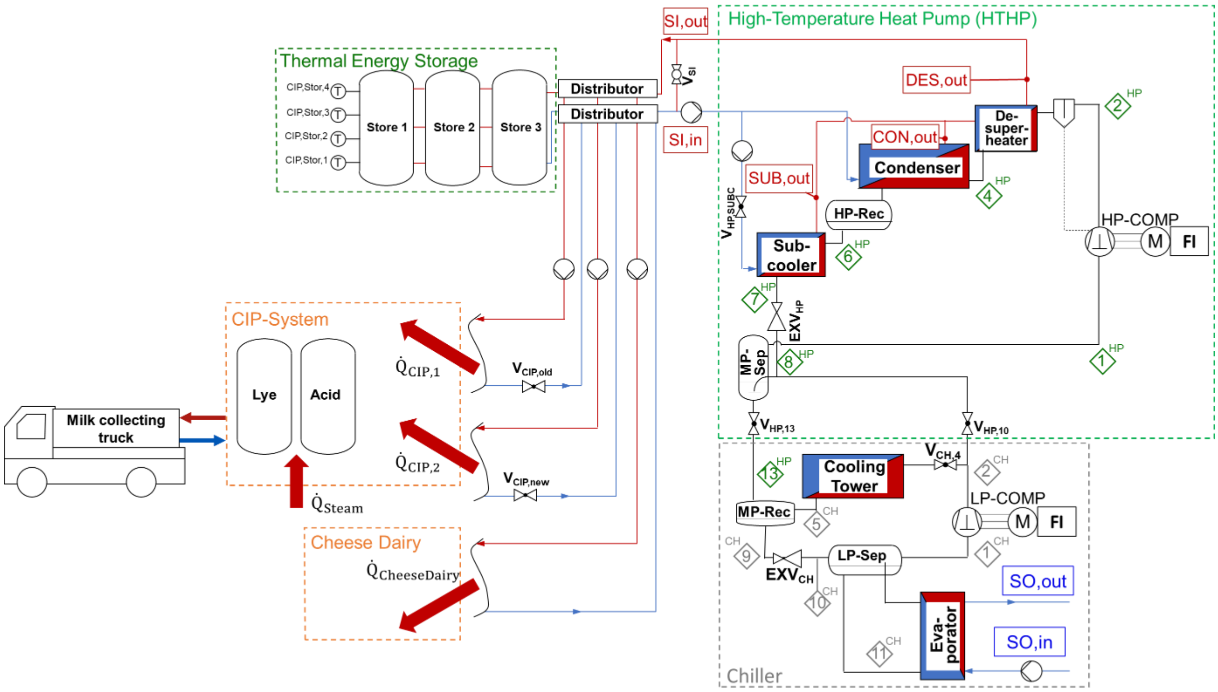
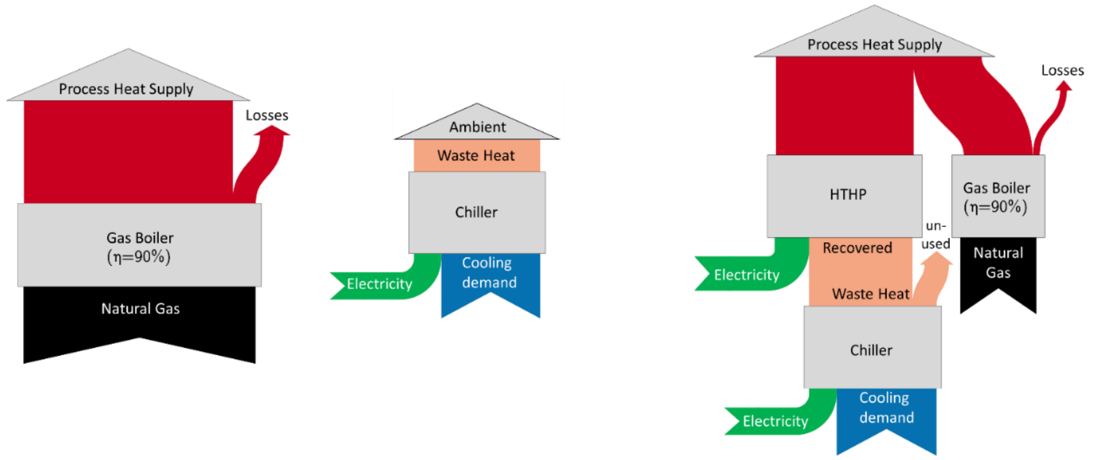


Figure 6: Schematic of Demo 3 at Ennstal Milch, consisting of a Chiller, directly integrated HTHP, TES and heat supply to the CIP-System and cheese dairy.

The chiller covers parts of the cooling demand of the dairy by cooling water from ca. $t_{SO,in}$ = 4 °C to ca. $t_{SO,out}$ = 1 °C using the flooded evaporator, connected to the low-pressure separator (LP-Sep). The low-pressure compressor (LP-COMP) compresses the refrigerant vapour to the medium-pressure level. If the HTHP is not in operation, all of the waste heat is rejected to the ambient via the cooling tower. If the HTHP is in operation, refrigerant from the discharge port of the low-pressure compressor is fed to the medium pressure separator (MP-Sep) from where the high-pressure compressor (HP-COMP) draws saturated refrigerant vapour and compresses it to high pressure. Through de-superheating, condensation and sub-cooling of the refrigerant, water (heat sink) is heated to a maximum temperature of 90 °C. This hot water circuit connects the HTHP with a TES of in total 12 m³ and the process heat consumers (two CIP-systems and the cheese dairy). In both CIP-systems, water heated with the HTHP and steam is used to heat the cleaning fluids lye and acid.

In contrast to a conventional process heat supply using a steam boiler only and a chiller covering the cooling demand, see Figure 7(a), recovering parts of the waste heat from the chiller using the HTHP, see Figure 7(b), reduces the load of the gas boiler. Besides a significant reduction of the system's final energy demand as schematically shown in Figure 7, substantial CO_2-savings are possible. The specific CO_2-savings may depend significantly on the type of fuel saved and the carbon intensity of the electricity used for the chiller and HTHP.



(a) (b)

Figure 7: Energy flow diagram of: a) conventional process using a gas boiler and chiller; b) waste heat recovery of a chiller utilizing an HTHP (right).

At the start of the project, this system was an early commercial installation and during the course of the project, ongoing optimisation and improvements lead to a fully qualified product at the end of the project, being commercialised by the project partner EQUANS.

6.2 Application methodology and assessment

The integration of the HTHP into the existing refrigerant circuit of a chiller which was in operation demonstrates the application of HTHP-technology in a brown-field approach. During the construction and installation of the HTHP, emphasis was put on keeping the down-time of the chiller as short as possible.

To monitor and optimize the system, the HTHP and the CIP system was equipped with extensive measurement equipment. Besides analysing the daily operation, special measurement campaigns were conducted to experimentally investigate the influence of certain operating parameters such as the medium pressure level, for example.

As the installation in an operating plant poses certain limitations on the measurement campaigns and to get detailed insight, simulations of the system were carried out in addition. One focus of these simulations was to further investigate one part of the CIP-system in more detail with the aim to reproduce the heating demand of the CIP system, reflecting changes in operation of the system such as altered temperatures in the fluid tanks caused by different operating strategies of the HTHP.

The supplied energy was evaluated at the heat exchangers supplying the CIP system ($\dot{Q}_{CIP,1}$ and $\dot{Q}_{CIP,2}$ in Figure 6), according to Equations 1 and 2. The GHG emissions reduction are calculated compared to a natural gas boiler with an efficiency of 90% by applying Equation 3. The specific GHG emission factors used for these calculations are listed in Table 1.

6.3 Results

Figure 8 shows the thermal energy supplied by the HTHP to the CIP systems 1 and 2 and the cheese dairy, as well as the resulting CO_2e reduction compared to the usage of a natural gas boiler to cover the whole heating demand during an example week of operation.

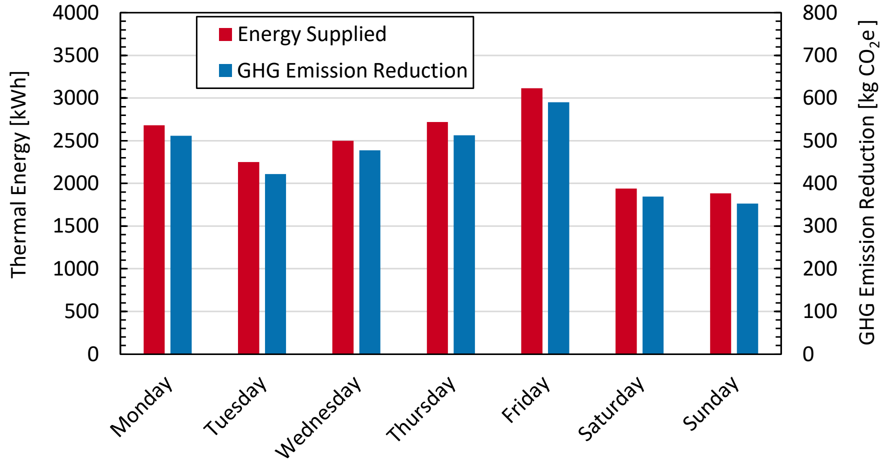


Figure 8: Thermal Energy supplied by the HTHP to CIP System 1, 2 and the cheese dairy, and resulting GHG-emissions saved compared to a gas boiler.

Within the investigated week, the thermal energy supplied by the HTHP per day varied between 1.8 and 3.1 MWh with an average of 2.4 MWh. The resulting reduction of GHG emissions when using the HTHP instead of an gas boiler is in the range of 0.35 to 0.59 t CO_2e per day with an average of 0.46 t per day. Projecting this average to a whole year of operation leads to a GHG emission reduction of 170 t CO_2e. The yearly emissions from a natural gas boiler would add up to 200 t CO_2e.

A further look into the process heat supply of CIP-System 1, the part of the CIP system investigated in more detail, is shown in Figure 9. During the investigated day, 1.18 MWh of heat is supplied by the HTHP, while 2.57 MWh is supplied via steam. This means that 31 % of the process heat demand of CIP-System 1 is covered by the HTHP. Further investigations carried out during the course of the project, including simulations, helped to better understand how the operation of the CIP system influences the energy demand and how to increase HTHP-based process heat supply. This in particular includes ways to increase the share of heat supplied by the HTHP, such as changes to the CIP operation enabling to use more cleaning liquid from storage tanks that were heated up using the HTHP rather than utilizing steam to heat the cleaning fluids.

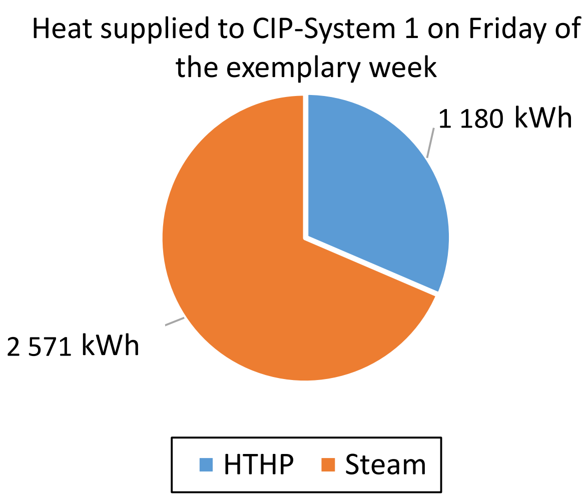


Figure 9: Share of thermal energy supplied by the HTHP and by steam to CIP System 1.

More in-depth information on the system and model-based analysis is provided in the following publications:

Verdnik, M.; Wagner, P.; Rieberer, R. (2023): Operating Strategies of an Industrial R717 Heat Pump Recovering Waste Heat of a Chiller. In: Proc. 26th IIR International Congress of Refrigeration (ICR 2023). Paper 696. Paris, France, August 24-30. International Institute of Refrigeration.

Wernhart, M.; Verdnik, M.; Pertiller, G.; Rieberer, R. (2024): A comparison of simplified modeling approaches and simulation quality of an industrial R717-HTHP. In: Proc. 16th IIR-Gustav Lorentzen Conference on Natural Refrigerants (GL2024). Paper 1277. College Park, Maryland, USA, August 11-14. International Institute of Refrigeration.

6.4 Impacts

The integration of an HTHP into the existing ammonia chiller at a dairy can serve as an example installation applicable to other dairies or production facilities that operate an ammonia chiller to cover a cooling demand (at temperatures around 0 to 5 °C), while demand for process heat supply (at temperature levels of up to 95 °C) exists. As the HTHP was installed directly into the refrigerant circuit of an existing chiller, this solution can be applied for brown-field retrofits, significantly decreasing the primary energy demand for process heat supply.

Specifically, the demonstrator with a nominal heating capacity of 500 kW displayed that 2-3 MWh of process heat could be supplied by the HTHP per day. Reducing natural gas fired process heat supply by this amount leads to an annual GHG emission reduction of ca. 170 t CO_2e.

Additional investigations of measurement data, supported by simulation models, helped to get a better understanding of the energy demand of certain processes within the CIP system. The experimental investigations are of particular interest, as an allocation of energy demands within a steam-supplied system is challenging. Conducted simulation studies enabled to investigate different scenarios including changes to the operation of the CIP system and changes to the relevant supply temperature levels of the HTHP. While conducting these investigations experimentally would either be not possible or risky during production, simulation models enabled to investigate different scenarios based on actual measurement data independent of the plant operation. The applied methodology could be used for other CIP-facilities as well.

6.5 Business potential

The concept to install an HTHP as an “Add on” to a previously existing chiller can serve as an example retrofit solution suitable for other applications and industries. This solution has a broad market across dairies and food processing industries. The ability to recover waste heat for reuse is especially attractive for large operations with significant heating needs, offering high ROI through reduced energy costs. Accordingly, there is a general business potential for suppliers of heat pump technology in various industries, including long-term maintenance contracts. Additionally, performance-based contracts can be established, where fees are based on achieved energy savings. More specific to this demo is the direct integration of the HTHP into the refrigerant circuit of the existing ammonia chiller. Potential further application of similar scale are basically production sites with a cooling demand of ca. 1000 kW at around 1 °C with a process heat demand in the range of 500 kW at temperatures of up to 90 °C.

Another business potential concerns consulting services, starting from the analysis of energy flows and energy demand at the investigated production site and the deduction of possible measures. This could be further expanded to formulating requirements and preparing tender documents and even include the commissioning and monitoring phase of realised measures.

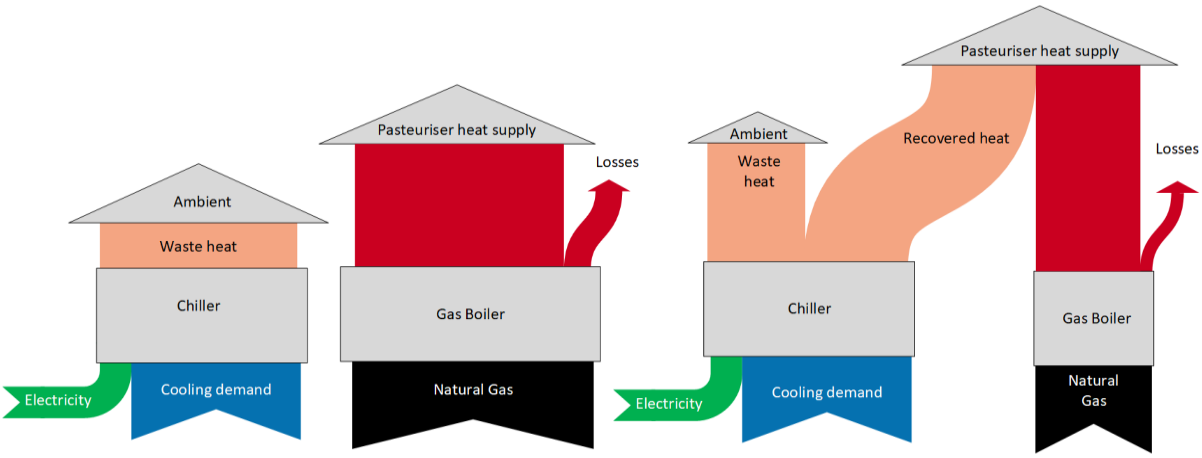
7 DEMO 4 – THERMAL INTEGRATION AT A YOGHURT DAIRY (UK)

7.1 Description

Demo 4 has delivered a new chilled water system at Yeo Valley's Blagdon site. The ammonia chiller replaces HFC chillers. The rejected heat from the chiller is used to preheat milk prior to pasteurisation, reducing natural gas use. The rejected heat is stored in a 40m^3 tank allowing for future expansion to the rejected heat use. The new chiller system installation is shown in Figure 10.

Figure 10: New ammonia chiller system with integrated heat recovery

The energy flow diagram in Figure 11 shows the savings available in this application.



(a) (b) (c)

Figure 11: Energy flow diagram of existing chiller (a), existing pasteuriser heat supply (b), and pasteuriser heat supply with heat recovery from chiller (c) which is phase 1

7.2 Application methodology and assessment

The integration of the new chilled water system demonstrates the application of heat recovery within a yoghurt dairy.

A four-stage roadmap was developed to eliminate all gas from the Blagdon Site.

1. Replace icebank chillers with water cooled chiller. Use recovered heat to preheat milk prior to pasteurisation.
2. Increase pasteuriser efficiency by changing plate configuration. Replace old blast chillers, allowing rejected heat to be used.
3. Install HTHP. This will allow all CIP operations to be heated without steam.
4. Install HTHP to replace remaining gas heating for pasteurisation.

Yeo Valley has an energy monitoring system which has detailed historical data. Parameters monitored include

- Gas Consumption
- Submetered electricity consumption for individual refrigeration systems and pumps
- Steam flow rate, temperature and pressure
- Chilled water flow rate, flow and return temperatures

The base line performance is taken from the monitoring system data for 2022.

Phase 1 takes the monitored 2022 chilled water use and electricity consumption and recalculates the electricity required based on a new chiller with an average COP of 4.2. The existing icebank system had a measured COP of 2. Further savings are calculated based on recovered heat from the chiller being used to preheat milk from 5°C to 25°C prior to entering the pasteuriser.

Currently the milk is heated in the pasteurisers from 80°C to 98°C. Phase 2 savings were calculated based on reducing the milk heating requirement to 93°C to 98°C Further savings in phase 2 were proposed based on heat recovery from new blast chilling equipment, the recovered heat to be used to preheat water for the clean in place systems.

A high temperature heat pump delivering water at 86°C is proposed in phase 3 to replace gas heating for the CIP processes. The heat pump source is rejected heat from the blast chilling equipment installed in phase 2.

A second high temperature heat pump is proposed in phase 4 to deliver high pressure hot water at 110°C to replace the remaining steam heating in the pasteurisation process.

The estimated savings from these measures are shown in Figure 12. The gas use shown is the full site gas use, as it is all used to raise steam. The electricity use includes the electricity used by the blast chillers on site, as their replacement forms part of phase 2 of the plan. The savings are based on measured 2022 operating data (“As Is” case). Energy costs are based on £0.1/kWh for gas and £0.3 for electricity. GHG emissions have been calculated using the specific carbon emission factors in table 1.

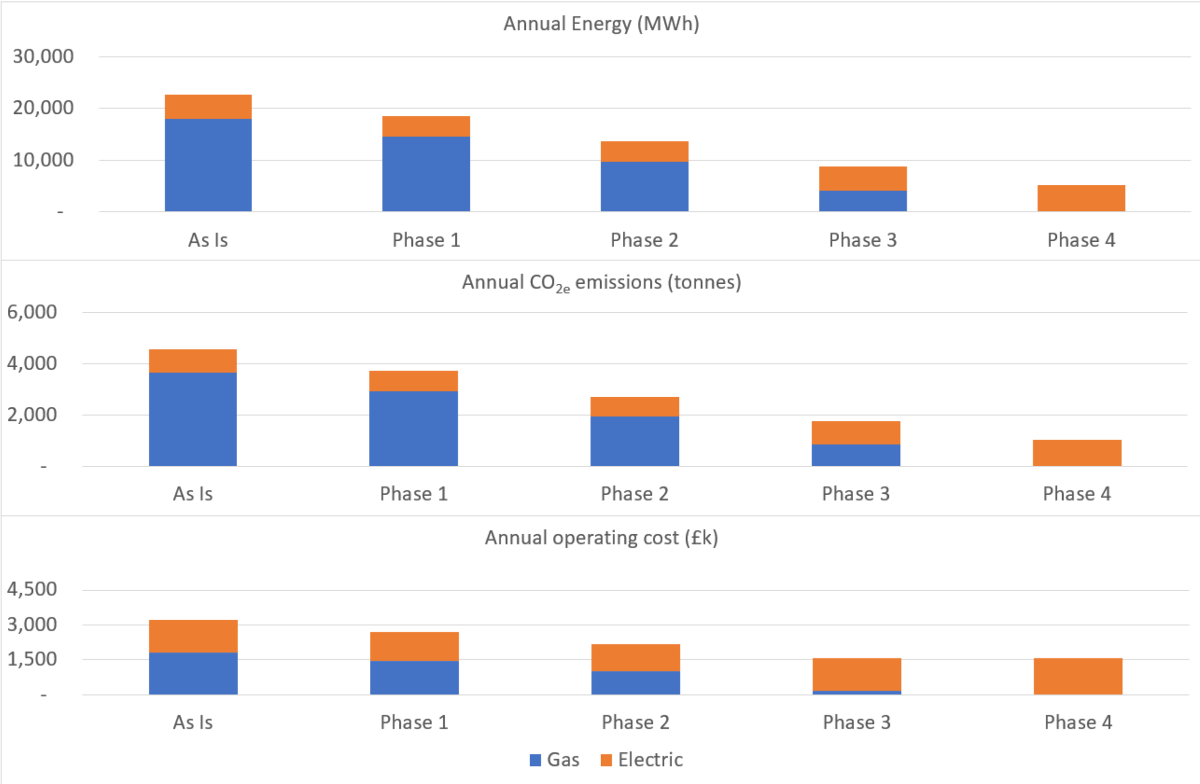


Figure 12: Savings estimated for the phases of the roadmap.

The dairy already has extensive process monitoring in place. The new chiller has been equipped with instrumentation to allow the operational savings to be measured.

7.3 Results

Phase 1 has been constructed and is currently being commissioned. As well as phase 1 a new additional pasteuriser has been installed which has improved effectiveness, requiring the milk to be heated from 86°C to 95°C, halving the high temperature heat required. This saving only applies to part of the production as the older pasteurisers are still in use. The remaining phases will be considered at a later date.

Table 3 shows KPIs that have been calculated from 12 months before phase 1 was constructed between April 2024 and April 2025. Predicted figures based on the actual equipment installed are also included for comparison.

Table 3: Current and predicted KPIs for demo 4.

	Current weekly average	Current specific usage	Predicted specific usage
Production	2,800 t		
Cooling from Chilled water	77,000 kWh	27 kWh/t	27 kWh/t

Chilled water electricity use	33,000 kWh 6,500 $kgCO_{2e}$	12 kWh/t 2.4 $kgCO_{2e}$/t	9 kWh/t 1.8 $kgCO_{2e}$/t
Site gas use	370,000 kWh 75,000 $kgCO_{2e}$	130 kWh/t 27 $kgCO_{2e}$/t	110 kWh/t 22 $kgCO_{2e}$/t

The commissioning of the system is still ongoing. The plant should be fully operational by October 2025. At that point data will be collected to provide a performance comparison which will be presented in a conference paper.

7.4 Impacts

As a result of the ENOUGH project, a £200,000 UK government backed KTP project has been approved to expand the work done within ENOUGH to other sites within Yeo Valley.

8 DEMO 1 – HOLISTIC SUPPLY CHAIN MANAGEMENT AND CONTROL

8.1 Description

Demo 1 is the place where researchers from the different demos get together to search and experiment new possibilities for holistic and systemic value creation, beyond their independent breakthroughs. Demo 3 (“HTHP Dairy Austria”), 5 (“Energy- efficient dynamic controlled atmosphere (DCA)”), and 11 (“Thermal storage unit for refrigeration cycle”) are participating to provide an example and a feasibility study.

Demo 1 serves as the testing ground for the technological and business framework developed within WP5 (Smart Data Systems - SDS). For further technical details and wider explanation on its concept and functioning, please refer to the final deliverable of WP5, deliverable D5.7. Here, we provide the strictly necessary information to describe how the SDS system selected three of the existing case studies on project demonstrators to showcase how the SDS methodology has the potential to make any supply chain system stakeholder an active and collaborative participant in a continuous, systemic, and holistic improvement process.

The main concept proposed by Demo 1 is the systematization of the full variety of actors that make up a supply chain. By using the SDS framework and related platform, a set of stakeholders commit themselves to become participants into a supply chain business. The platform creates a new Supply chain Entity (SCE) that will become a digital twin of the supply chain along its whole life cycle. The participants are digitally connected and allowed to the set of tools for communication of information and monitoring provided by the SDS and other third parties in a marketplace. The goal is to create a continuous decision-making and feedback loop, both at the individual and group level, which drives performance improvement of the SCE on two levels, private and operational, public and collaborative.

The first level is the local one. An actor (the human or artificial entity delegated by the stakeholder to act on the SCE on their behalf) is enabled to exchange information and data, and to access informational and technological services provided by both consortium stakeholders and third parties through a process of connection to the SDS infrastructure. Thanks to this connection, both at the operational (OT) and information technology (IT) levels, a supply chain actor is able to detect the actual impact of their technological and process solutions in relation to the global effects these have on the supply chain as a whole. This is achieved through the informational and process interactions organized within the complexity of a real-world supply chain. At this first level, the actor is encouraged to improve their processes and assess the actual effectiveness of their technological innovations in a complex operational context.

The second level concerns active participation in a group that establishes a branding associated with a specific supply chain instance to which they belong. In SDS terminology, this instance is called a SCE. A participant can be connected to one or more SCEs. Each SCE has its own specific market and associated target, which can express — simultaneously and in a differentiated way — the impact of a participant's innovation in relation to the unique characteristics of the SCE. At this level, the focus shifts from local objectives to the global operational and market context of the SCE in which the actor is involved, with a more strategic and policy-driven level of decision-making.

For the execution of an initial experiment, here referred to as Demo 1, a virtual SCE was designed and implemented. This virtual SCE brought together the specific innovations and independently validated results of three project demonstrators, in order to challenge them against the complexities of deployment within a supply chain context that featured its own, as realistic as possible, goals.

Specifically, Demo 3 "HTHP Dairy Austria", Demo 5 "Energy Efficient DCA", and Demo 11 "Thermal storage unit for refrigeration cycle" (and partially Demo 7 "Fresh and green delivery") were involved as actors in a virtual SCE intended to showcase the additional value and group-level effects that arise when technologies—each proven effective in reducing GHG emissions in entirely different contexts—are aligned into a coordinated and unified supply chain action, rather than remaining as isolated components.

The goal is to address the recognized complexities of supply chains in real-world contexts, so as not to nullify the individually achieved results of each technology through unexpected losses (such as mutual cancellation of technological benefits), but rather to amplify these advantages through a self-reinforcing leverage effect. This is achieved by enabling each actor to contribute their technological, process, and service improvements to the supply chain as a whole.

In Figure 13 a concept of the information interactions between the SDS actors is pictorially rendered in an abstract scheme.

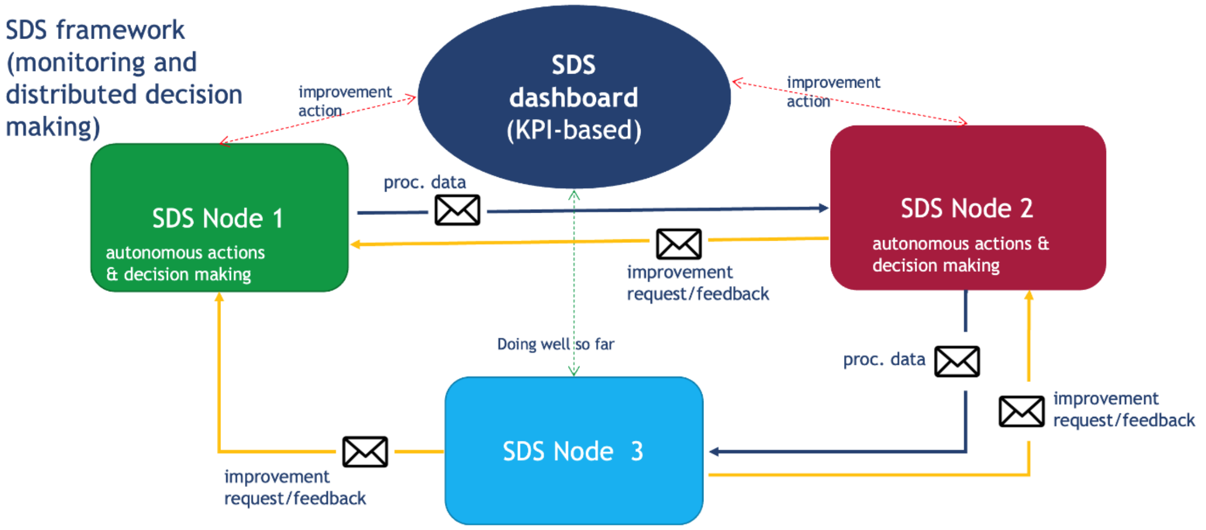


Figure 13: Schematic representation of the information interactions that happen between the different actors in the SDS infrastructure for the goal of collaboration towards continuous improvement.

Figure 13 expresses the major concept that the SCE is monitored and controlled by actors by means of digital public messages. The information exchanges by these messages determine the events that advance and declare the operations that each of the actors committed to perform in the SCE. However, the conceptual view of Figure 13 cannot express the details that are needed from the actors to make correct decisions. To this end, a language that all the participants can easily try to use to unify their process has to be used. One the most used and standardized open specification language is BPMN (Business Process Model and Notation), a globally recognized standard for graphically representing business processes. Among the different BPMN sub languages, the one that best encapsulates the concepts of message exchanges of SDS—although it cannot fully display all operational aspects and the multitude of integration and interoperability services of the infrastructure—is typically that of a so-called BPMN choreography. A BPMN choreography is a diagram that models the interactions (message exchanges) between participants in a business process, focusing on who communicates with whom and in what order, without showing internal workflows.

The primary view of collaboration within an SCE is based on a standard representation of the process that is reasonably easy to understand and access by all actors, each with their own multidisciplinary expertise. This view is the result of a collaboration agreement and a shared instance of the supply chain. It also represents the main responsibilities and opportunities associated with participating in the SCE.

In Figure 14, we show the final design and implementation of the SCE for Demo 1. It depicts a small supply chain in which all the key interacting actors originate from their respective actions on the selected case studies and through global informational interaction within the SCE.

Figure 15 shows a detail of the initial steps of the whole BPMN choreography in general. This diagram shows how a retailer coordinates orders with two suppliers: a coolstore and a dairy plant. It starts when the retailer issues new orders to both the coolstore and the dairy plant, essentially telling each supplier what it needs, by means of messages *msg_01* and *msg_14*. After sending these initial orders, the process continues with separate negotiations. The retailer and the coolstore discuss and agree on the specific order requirements, such as quantities, delivery dates, or other conditions, by means of the message contents. At the same time (or alternatively), the retailer negotiates the details with the dairy plant to make sure they can meet the order needs. The process ends once these negotiations are complete with both suppliers. Overall, the diagram represents the sequence of communication steps between the retailer and its suppliers to successfully place and confirm orders.

In general, a BPMN choreography is a flow of activities that involve a message sent from a sender (Initiator) to a recipient.

All the solutions that make up the SDS business are then layered onto this basic representation, acting on a case-by-case basis and at different levels. The solutions conveyed in the SDS concept come from previous research experience and result in different domains and have been renewed into a new and stronger set of tools for interoperability, control, and decision making. While the separate starting levels of TRL of these separate components were ranging from 4 to 5, here the experiment of composing and orchestrating into the new purposeful Demo 1 can realistically be acknowledged to be as a whole at the level of TRL 7.

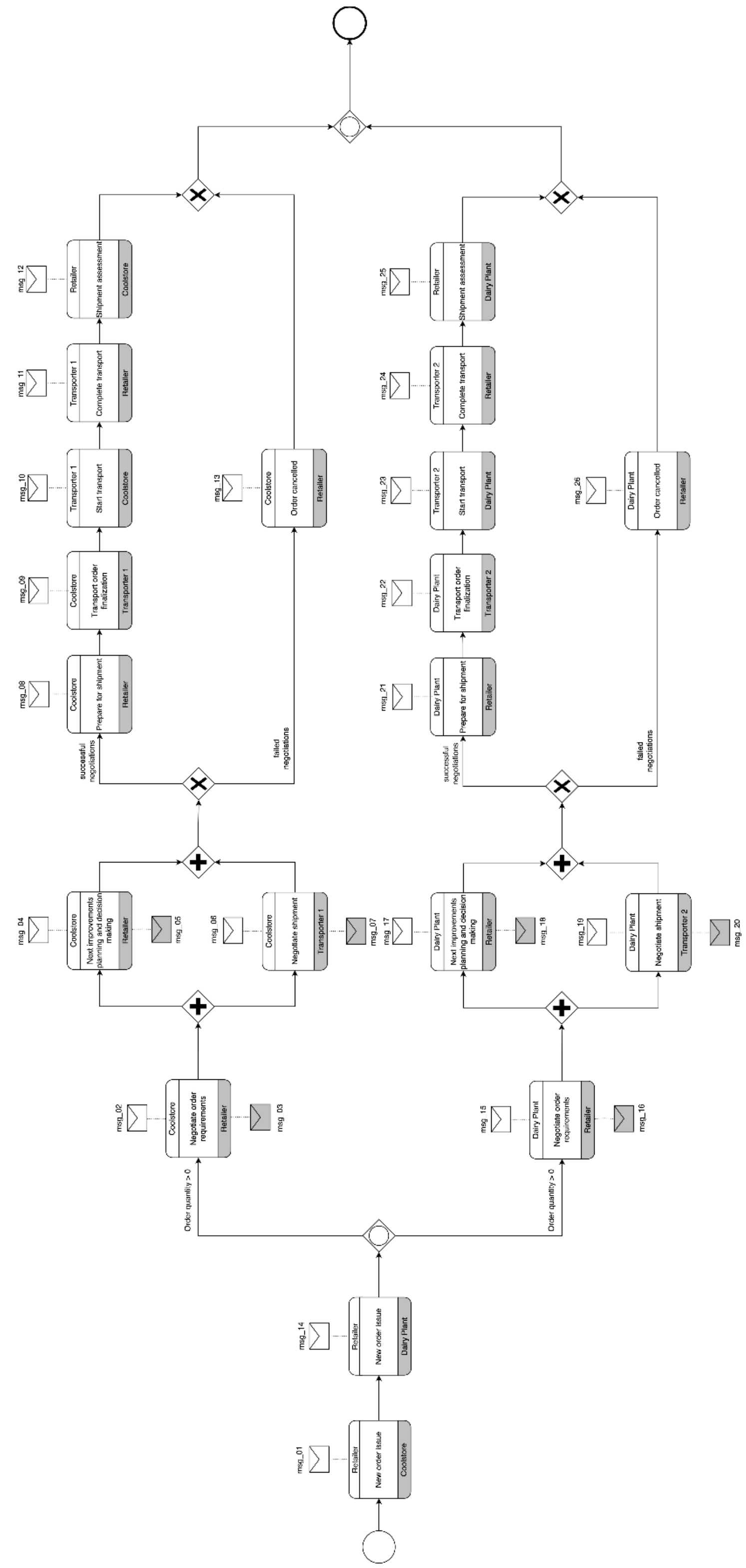


Figure 14: Main view of the SCE, with Demo 3 as the "Dairy Plant" actor, Demo 5 as the "Coolstore" actor, and the Demo 11 as the "Retailer" actor. Other actors (Transporter 1 and 2) in this SCE are virtual and automated, due to the lack of suitable and realistic components usable for this experiment.

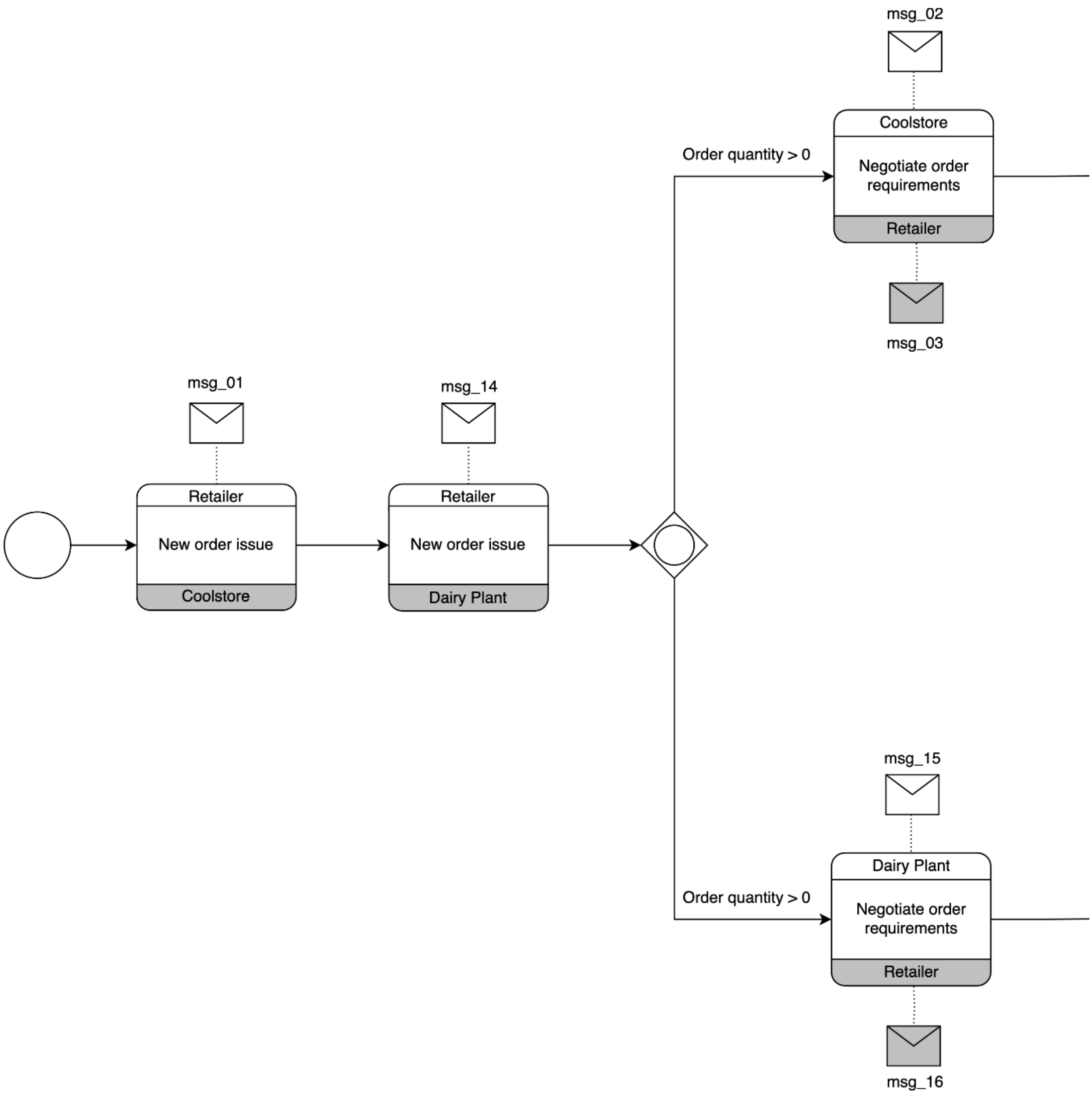


Figure 15: Detail of the BPMN choreography showing the first activities in the flow of the SCE.

8.2 Application methodology and assessment

As previously mentioned, the objective of Demo 1 is to demonstrate the feasibility of the SDS framework concept. Since no real supply chain was available for testing within the project, the adopted methodology followed a best-effort approach based on the components already present in the project and involved in the specific Demo 1.

Therefore, as shown in the view in Figure 14, the criterion used here is the grounding of simulations and virtualizations of the SDS infrastructure through the participation of three case studies that refer to physical and real-world experimentation, each with their own individual objectives, within the scope of this WP6.

This grounding with specific case studies has multiple implications. The first is a direct comparison with the real needs and acceptance of the SDS concept and technologies by heterogeneous users, forming a minimal test sample for the results. The second is the opportunity to demonstrate how the SCE concept developed for Demo 1 is entirely generic and universal, ready to be instantiated in even larger and more complex supply chains.

The third implication is the demonstration that the SCE essentially constitutes a digital twin of a supply chain — specifically, a fourth- and fifth-level digital twin (according to the classification by Saracco, 2022), where the digital and physical parts become intertwined and inseparable as a single, functioning and symbiotic whole.

The lack of real case studies to cover all roles shown in Figure 14 — particularly transportation — offered the opportunity to also understand this important role of the SDS concept, in which the core of the reality and phenomenon to be managed is information, which unifies the physical and digital parts.

The fourth implication is the growing involvement and awareness of the project partners in what was initially a very abstract concept of SDS. By its nature, SDS is a business and an industrial platform (but predominantly a software platform). It is therefore a mostly intangible and protean object, which takes the shape of the supply chain instantiated each time. Only through the collective and continuous work carried out for the development of Demo 1 has it been possible to give a materialized form to the SDS concept, useful for the development of the business case foreseen among the project’s objectives.

8.3 Results

The results of the activities for Demo 1 occurred at multiple levels, given the variety of aspects that needed to be tested within the SDS framework. We summarize them below:

1 - The multi-part and multisided business model of SDS follows a flow of activities that begins with the collection of requirements from stakeholders. Through these requirements gathering, the contract that underpins the configuration and creation of the specific instance of the SCE is defined. This is a fundamental part of the process underlying the SCE business model and was tested with the leaders of the case studies and Demos 3, 5, and 11 involved here.

2 - Some stakeholders who become participants in SCE interactions require integration through an adapter to send and receive data from their processes. The so-called SDS connector was specifically developed for Demo 3 (and preliminarily for Demo 6). Another example of OT-level connection was provided for Demo 7.

3 - While all actors need access to the monitoring dashboard for overall SCE performance, some actors require an interaction application hosted by the infrastructure for negotiations. This is implemented with custom-developed web interfaces as part of the SDS business activity flow.

4 - In the specific case of Demo 3, it was possible to apply a decision-making module based on the Holonic Management Tree and Mixed Reality methodology (called HMT+MR). This implementation demonstrated both the feasibility for a stakeholder to use a tailored decision-making product (ideally different for each stakeholder based on their local needs and provided by third parties through the SDS platform), and the potential of the specific module developed by UNIVPM, which is the result of multi-year innovative research conducted across two H2020 projects.

8.4 Impacts

The immediate technical impacts directly related to the specific implementation of the SCE for Demo 1 can essentially be classified as follows:

1 - A push toward further improvement of local performance for each case study, as an add-on compared to the use of technologies in a separate and independent way from the specific supply chain. This impact is generally difficult to measure because it depends on the dynamics and specific context. It is highly influenced by the feedback received and the awareness of participating in a challenging collective goal for each SCE. However, in the case of Demo 3 (identified as the Dairy Plant actor), the use of the localized decision-making module in its vertical implementation provided an example of how, while considering the global effects of decisions, it is possible to achieve detailed local insights into the performance levels of different parts of the process and thus intervene on bottlenecks with specific actions to improve performance. In the case study, the objective was to further reduce GHG emissions by paying attention to the context in which the technological solution (described in Section 6) is embedded.

2 - An increase in the use of renewable energy within the SCE, achieved as a configuration possibility of the SCE itself, through multidimensional choices based on economic performance, sustainability, and lower GHG emissions, guided by a collective decision-making and ranking process for a given supply chain.

3 - A continuous push towards improvement and overall reduction of emissions in an SCE, through the self-organizing mechanism that is generated within the SCE.

Beyond the technical and technological impacts, the implementation of the Demo 1 experimentation has driven scientific research that itself forms the basis for future studies. This applies to two main areas and research directions:

The first concerns the inclusion of SDS among the enabling technologies of Industry 4.0/5.0, with particular emphasis on interoperability, accessibility to technology transfer for SMEs, and—very significantly—on new frontiers regarding cybersecurity and the sustainability of information processing within the SDS system.

The second involves the improvement of decision-making capabilities in the context of operational and process complexity.

These research efforts have a scientific impact expressed with the following publications during the period:

- Spegni, F., Fratini, L., Pirani, M., & Spalazzi, L. (2023, March). Choen: A smart contract based choreography enforcer. In *2023 IEEE international conference on pervasive computing and communications workshops and other affiliated events (PERCOM workshops)* (pp. 86-91). IEEE.
- Pirani, M., Cacopardo, A., Cucchiarelli, A., & Spalazzi, L. (2023, December). A soulbound token-based reputation system in sustainable supply chains. In *Proceedings of the 2023 international conference on embedded wireless systems and networks* (pp. 363-368).
- Raikov, A., Giretti, A., Pirani, M., Spalazzi, L., & Guo, M. (2024). Accelerating human–computer interaction through convergent conditions for LLM explanation. *Frontiers in Artificial Intelligence*, *7*, 1406773.
- Pirani, M., Cucchiarelli, A., & Spalazzi, L. (2024, November). A Role of RMAS, Blockchain, and Zero-Knowledge Proof in Sustainable Supply Chains. In *IECON 2024-50th Annual Conference of the IEEE Industrial Electronics Society* (pp. 1-4). IEEE.
- Pirani, M., Carbonari, A., Cucchiarelli, A., Giretti, A., & Spalazzi, L. (2024). The Meta Holonic Management Tree: review, steps, and roadmap to industrial Cybernetics 5.0. *Journal of Intelligent Manufacturing*, 1-42.
- Pirani, M., Cucchiarelli, A., Naeem, T., & Spalazzi, L. (2025). A Blockchain-Driven Cyber-Systemic Approach to Hybrid Reality. *Systems*, *13*(4), 294.

8.5 Business potential

In synergy with the exploitation activities supported by WP8, a business model plan has been developed for Demo 1. The plan is based on two major pillars of the SDS business:

1. There is an action for exploitation that aims to collect the services and the competencies of the partners in the ENOUGH project that would be conveyed in the platform for the creation of the SCEs, which is currently at TRL 8 to arrive at TRL 9 with appropriate market actions and funding.
2. A fork of the SDS project is destined to remain as a continuous technology and a living lab transfer between the academic partners that will continue to use SDS as a test bench for research primarily on decision-making in complexity and formal methods and technologies for sustainable cybersecurity of supply chains and their digital counterparts. This part is considered an incubator for follow up projects in the field.

GENERAL CONCLUSIONS

9 GENERAL KPIS/IMPACT

This deliverable presented the application of waste heat recovery, lifting of waste heat to higher temperatures through HTHPs, the integration of cold and hot thermal storages in different dairies. Although the presented integrations are tailored to the needs of the specific dairies, the information presented can serve as a starting point for investigating possible efficiency improvements, energy savings and emission reductions.

Implementation of ice slurry technology at Rørosmeieriet (Demo 2) could enable stable cooling production at 27 kW throughout the day, alleviating peak loads up to 185 kW, thus improving overall system efficiency and reducing compressor cycling. Replacing the electric steam boiler with a HTHP indicate potential reductions in SEC and emissions by 27% and 26%, respectively.

The recovery of waste heat of an existing ammonia chiller to supply process heat (up to 90 °C) to the CIP system presented in Demo 3 (see Chapter 6) showed an reduction in daily thermal energy demand in the range of 2 to 3 MWh, resulting in an annual GHG-emission reduction of ca. 170 t CO_2e.

The replacement of the chiller system with an ammonia chiller with heat recovery to preheat milk ahead of pasteurisation as shown in Demo 4 is expected to show an annual saving of 4,400 MWh gas use and 400 MWh electricity use, resulting in annual GHG emission reduction of ca. 950 t CO_2e.

10 DISSEMINATION AND COMMUNICATION

Relevant scientific contributions related to the presented Demos are listed at the respective sections of the demos (see Section 8.4 for Demo 1, Section 5.3 for Demo 2 and Section 6.3 for Demo 3).

11 GENERAL FUTURE OUTLOOK

From Demo 1, the major takeaway is that the future food supply chain must look into its inherent complexity to find a systemic new ground for breakthroughs. This involved a new integration, perspective, and harmonization of the digital transformation technologies and related business processes that must keep the pace with the continuously moving constraints and targets coming from the real field and its actual needs. These challenges are already well framed in the challenges of Industry 5.0, but the solutions are currently lagging due to a lack of interdisciplinary and more holistic endeavour is needed. The research and the practice conducted in the context of Demo 1 have determined a scientific and business roadmap in this sense.

Demo 2 demonstrates how long-term energy monitoring can serve as a foundation for innovation in thermal energy systems. Continuous data collection and analysis enabled the identification of inefficiencies, supported targeted improvements and provided operation insight needed to pursue studies into HTHP and CTES.

The waste heat recovery from a chiller using an HTHP to supply process heating demand within Demo 3 showed that the steam demand of the CIP-system could be significantly reduced. Analysing the CIP processes in details allows for a further optimisation of the system. Possible supply of additional processes, especially in the cheese dairy, have the potential to increase the heat supplied by the heat pump and by that reduce the steam demand even further.

Demo 4 shows that there is both scope and appetite in industry for energy and emission reducing upgrades to existing plant. Engaging with industry has helped identify commercially viable opportunities and delivered significant reductions in gas fuelled process heating.

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