

CASE STUDY

NOVEMBER 2025



Electrification and Thermal Energy Storage in the Dairy Industry

By Future Cleantech Architects

FCA Future
Cleantech
Architects

Executive Summary

The European dairy industry processes 150 million tonnes of raw milk per year, to produce a wide range of consumable products, including milks, cheeses, and yoghurts. Greenhouse gas emissions arise throughout the supply chain, including on-farm milk production, manufacturing operations, and the refrigeration and transportation of the final products. Among these, the processes necessary to pasteurize, standardize, and clarify the raw milk require significant amounts of heat, typically delivered at temperatures below 150°C. Currently, this heat is supplied by natural gas-fired boilers, and emits approximately 20 Mt CO₂e per year.

This report presents a case study on the decarbonization of the dairy processing industry and the associated business case of heat electrification. The focus is solely on the currently gas-fired manufacturing processes; energy demand for refrigerated storage and transport is not considered. A nominally sized dairy processing facility located in Germany, is used as the reference case and a range of electricity and gas prices are considered. The findings from this analysis are relevant to the broader European food and beverage sector, which has similar heat demands and process temperature requirements.

Main Findings

- ▶ **Decarbonization pathways focus on the transition of dairy processing facilities away from using fossil fuels for heat** - The decarbonization of dairy processing facilities primarily involves replacing gas-fired boilers with electric boilers or high-temperature heat pumps. Both technologies enable integration with thermal energy storage (TES), allowing plants to shift electricity consumption in response to fluctuating electricity prices. With a TES system providing five hours of discharge duration, it is shown facilities can perform twice-daily load shifting to reduce operational costs while maintaining continuous production.
- ▶ **Currently, natural gas combustion provides the majority of heat input in dairy operations** - Around 70% of a dairy facility's total energy input is supplied as heat from natural gas combustion, with the remainder provided as electricity for auxiliary equipment. The pasteurization process dominates thermal demand, requiring heating of milk from 4°C to 75°C and subsequent cooling. These systems minimize net heat input by recovering much of the thermal energy during cooling, resulting in relatively small temperature lifts that are well suited to electrification.
- ▶ **Thermal energy storage provides economic value by reducing electricity costs by around 10 €/MWh** - Integrating TES enables load shifting by storing heat when electricity prices are low and discharging it during high-price periods, unlike gas-fired systems which lack inter-

day price variability. Optimization of storage operation using hourly German electricity price data for 2024 showed that a TES system with five hours of capacity can reduce a facility's average electricity cost by approximately 10 €/MWh. This reduction can significantly improve the competitiveness of electrification.

- ▶ **The business case for heat electrification depends strongly on the price difference between natural gas and electricity** - For most heat-electrification business cases with TES, the average electricity cost must be within 10 €/MWh of the gas price to achieve breakeven within five years. This condition was not met in Germany in 2024, where wholesale electricity was approximately 40 €/MWh more expensive than gas. Retail electricity pricing structures often add a 40% premium to wholesale prices, extending breakeven periods and acting as barrier to electrification.
- ▶ **Selecting between an electric boiler and high-temperature heat pump requires balancing upfront cost against lifetime cost** - The electric boiler offers lower capital cost and a faster breakeven period, while the heat pump provides significantly lower lifetime costs. The breakeven year is largely independent of the discount rate, as in both cases the cost of energy input to the system (i.e., gas or electricity) is discounted similarly.
- ▶ **The main benefit of thermal energy storage is its ability to deliver major system flexibility at relatively low cost** - TES typically accounts for only 2-20% of total system capital cost, yet it can provide substantial operational benefits through load shifting. Per unit of stored energy, TES is five to ten times cheaper than lithium-ion batteries while offering comparable flexibility for short-term energy balancing. This makes TES a cost-effective enabler of heat electrification and a strategic lever for reducing overall energy costs in dairy processing and the wider food and beverage industry.

For citation purposes, the case study should be referenced as:
J. W. Lazenby, M. Tovar, and A. Koen, "Case Study: Electrification and Thermal Energy Storage in the Dairy Industry," Future Cleantech Architects, Remscheid, Germany, Nov. 2025.

Acknowledgments:

Future Cleantech Architects would like to acknowledge and thank the following external reviewer for kindly providing invaluable input for this report: Professor Antonio Marco Pantaleo, University of Bari Aldo Moro. The contents of this report represent the views of Future Cleantech Architects and should not be taken to represent those of the reviewers or the organizations to which they are affiliated.

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1. Introduction

1.1 Overview

The paper presents a case study on the integration of thermal energy storage (TES) with industry for the delivery of process heat. The purpose of this series is to assess the technical and economic value of electrifying industrial heat while using TES, and to compare the performance and cost with the existing heat generation systems (typically gas-fired boilers). The expected benefits of TES include reducing the average price of electricity and lowering carbon intensity by shifting demand to periods of high renewable generation.

In the European Union (EU) the food and beverage industry employs approximately 4.7 million people and has an annual turnover of €1.4 billion [1]. This sector is a promising candidate for early TES adoption due to its low-temperature steam requirements, with typical processes requiring steam at 100-150°C. This represents an immediate “low-hanging fruit” opportunity for the integration of TES.

1.2 Decarbonization Pathways

Food and beverage facilities require both heat and electricity. Heat is typically supplied by the combustion of fossil fuels and electricity is supplied from the grid. Both of these inputs are delivered on demand – i.e., the gas network and electricity grid “flex” to supply the facility as required. This business-as-usual case is shown in Figure 1(a). Figure 1(b) shows the most basic decarbonization pathway, in which the gas boiler is replaced with an electric boiler (e-boiler) or heat pump. This option can deliver immediate carbon reductions but may be costly to operate, depending on electricity prices. Figure 1(c) shows an alternative in which heating is electrified, and lithium-ion (Li-ion) batteries are installed “behind the meter”. This allows electricity to be stored when prices are low, typically during periods of high renewable generation,

thereby enabling greater decarbonization than in Figure 1(b). However, Li-ion batteries remain capital-intensive. Figure 1(d) shows another option where TES is installed behind the meter to provide flexibility. This approach can achieve greater carbon reductions than Figure 1(b) by consuming a greater proportion of clean electricity and will likely offer lower capital costs when compared with Figure 1(c). A key objective of this case study is to assess whether such cost savings are actually realizable.

1.3 Dairy Processing Industry

Dairy processing is one of the largest segments of the European food and beverage sector, processing approximately 150 million tonnes of milk annually and employing close to 300,000 [2], [3]. **Additionally, its thermal processes typically operate using steam below 150°C, making the findings of this case study readily transferable to other industries, such as breweries, bakeries, and confectionery production.** Beyond its industrial scale, the dairy processing sector is also a notable source of greenhouse gas emissions, with total annual emissions exceeding 20 Mt CO₂eq (around 0.5% of total annual EU emissions) which is comparable to the annual emissions of roughly 4-5 million passenger vehicles (a liter of milk has an embodied emission intensity of approximately 0.76 kg CO₂eq, of which 15% arises from processing, see Refs. [3], [4], [5], [6] for more details on carbon intensity). These statistics are summarized in Figure 2 which shows the scale and distribution of dairy processing across Europe, and the significance of its processing emissions.

Note that processing is only one part of the wider dairy supply chain. On-farm milk production and collection, as well as the “cold-chain” for refrigeration and transport to consumers, are also energy and emissions intensive [4]. These aspects of the dairy sector are not considered in this study, as the focus is solely on heat electrification within the manufacturing process.

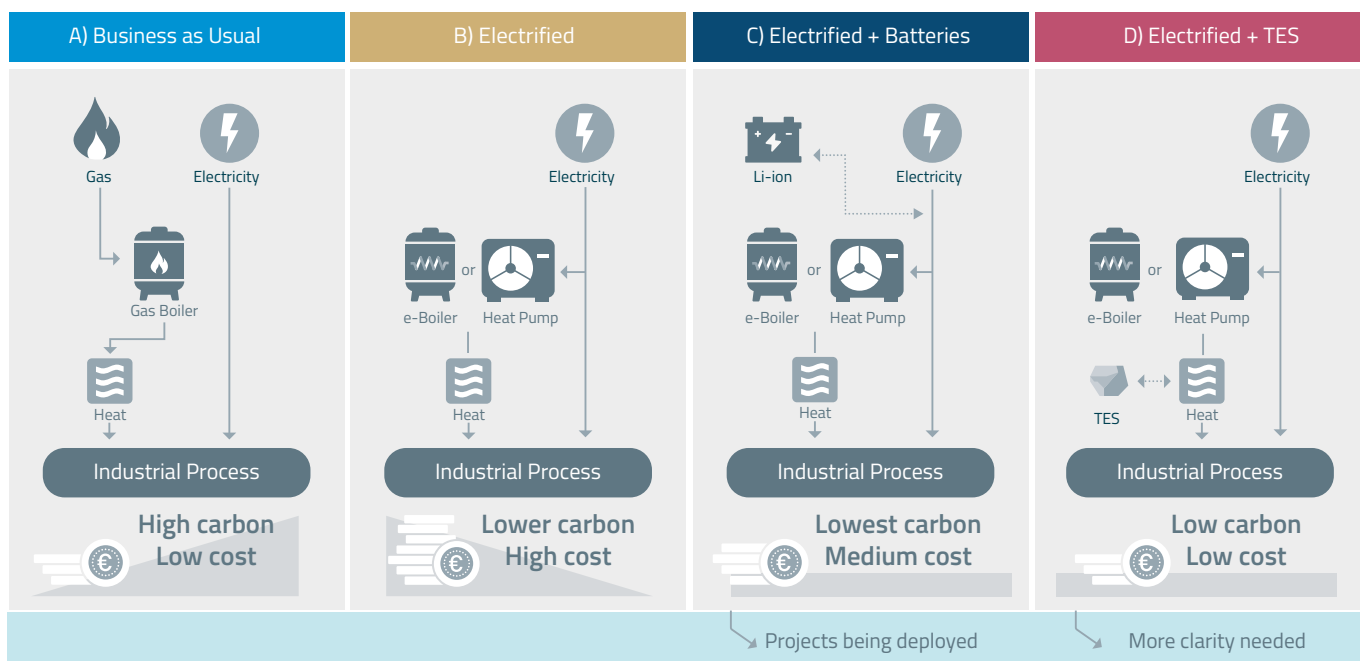


Figure 1: Strategies for decarbonization of industrial facilities: (a) business as usual; (b) direct electrification; (c) electrification with Li-ion batteries; (d) electrification with TES. Note that for higher-temperature industrial processes, other forms of electric heat generation can be used, such as electric resistance, induction, or plasma heating. TES = thermal energy storage; Li-ion = lithium-ion batteries.

1.4 Approach of Case Study

The case study begins with an overview of the skimmed milk and cream production process and highlights possible locations for integrating TES. The main energy flows, which are driven by heating and cooling requirements, are then discussed. In Section 3, three distinct sets of analyses are performed to estimate the reduction in electricity costs that a facility can achieve by integrating five hours of TES. Germany is

selected as the case study location due to its large dairy industry and the daily “duck curve” of electricity prices, which creates opportunities for demand shifting. In Section 4, the estimated cost savings from TES are then combined with capital cost values from the literature to determine the breakeven year. Consideration is given to the distinction between e-boilers and heat pumps, the discount rate, ranges of electricity and gas prices, retail price increases, and total lifetime costs. The case study concludes by presenting lessons learned from deployed projects.

DAIRY INDUSTRY IN THE EU

Dairy Milk Processing



150 Mt
of raw milk per year



20 Mt
CO₂eq per year *



0.5%
of total EU emissions

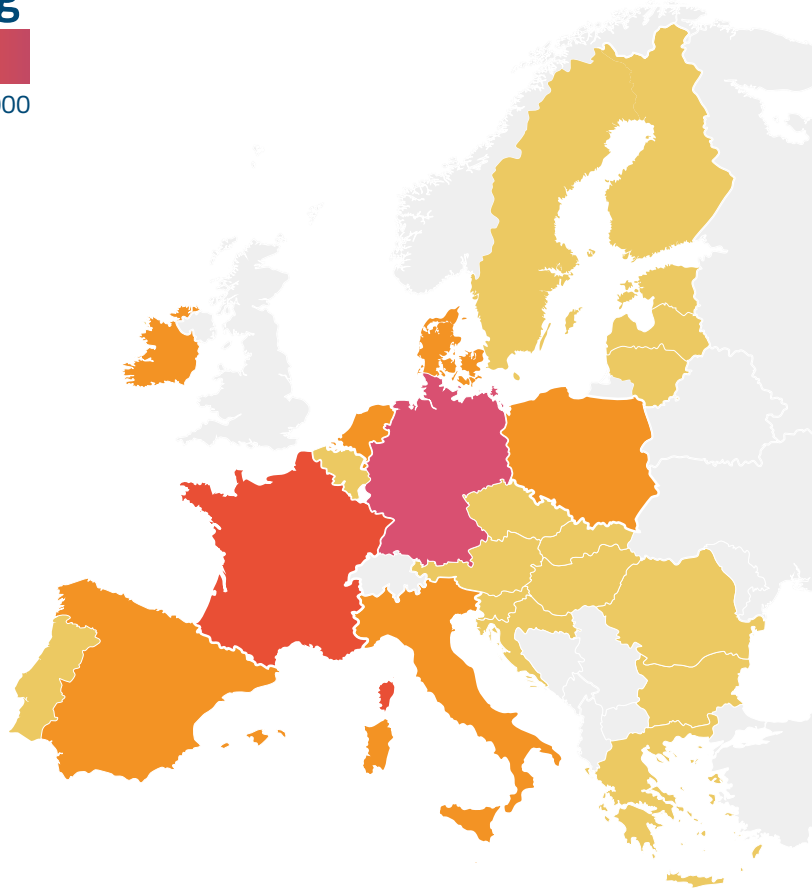


4-5 M.
Annual emissions
of 4-5 millions cars



300,000 jobs

* just processing



WHY USE DAIRY AS A CASE OF STUDY?

Heat currently
provided by
natural gas



100°C - 150°C range



1 MW scale

Figure 2: Overview of the European dairy processing industry. Data is for dairy production in 2024 [2]. Total carbon emission calculated from the carbon-intensities given in Refs. [4], [5], [6].

2. Dairy Plant: Layout, Energy Demand, and Integration Options

2.1 Process Overview

Dairy processing facilities have three main functions [7]:

- Clarification: removing unwanted solid matter (e.g., dirt and debris) from the raw milk.
- Standardization: modulating the fat content of the raw milk to create standardized products such as skimmed milk (0.5% fat), semi-skimmed milk (2% fat), whole milk (3.5% fat), and cream (40% fat).
- Pasteurization: heat treating the products to ensure safety and to extend the shelf life.

Figure 3 shows a simplified layout of a dairy facility producing both skimmed milk and cream. The process begins with whole milk entering the facility at 4°C, after transport from the milking system. The raw milk is first pumped through a recuperative heat exchanger (i.e., a recuperator), where its temperature is raised to approximately 54°C using heat recovered from the outgoing pasteurized product. The preheated raw whole milk then passes through a separation system, where the fat is mostly removed, producing streams of raw skimmed

The process described above and shown in Figure 3 is known as the High-Temperature Short-Time (HTST) pasteurization method. Although HTST is the industry standard, alternative methods with different temperatures and durations are used for specific product requirements (see Figure 6.1.2 in Ref. [7]). Note that dairy processing plants are highly optimized and make use of extensive recuperative heat exchangers. This significantly reduces the thermal energy demand, with heat only added from 63–75°C.

2.2 Thermal Energy Storage Integration Options

The pasteurization process presents several opportunities for integrating TES which is valuable because it (i) enables the displacement of gas consumption through electrification and (ii) allows consumers to access low-cost, low-carbon electricity by storing energy during off-peak periods for later use. Potential locations for TES integration are shown in Figure 3. The main options include:

- Steam System (>100°C): The gas boiler is replaced with an electric resistive boiler (e-boiler) or a high-temperature heat pump. A TES system stores thermal energy at temperatures above 100°C and

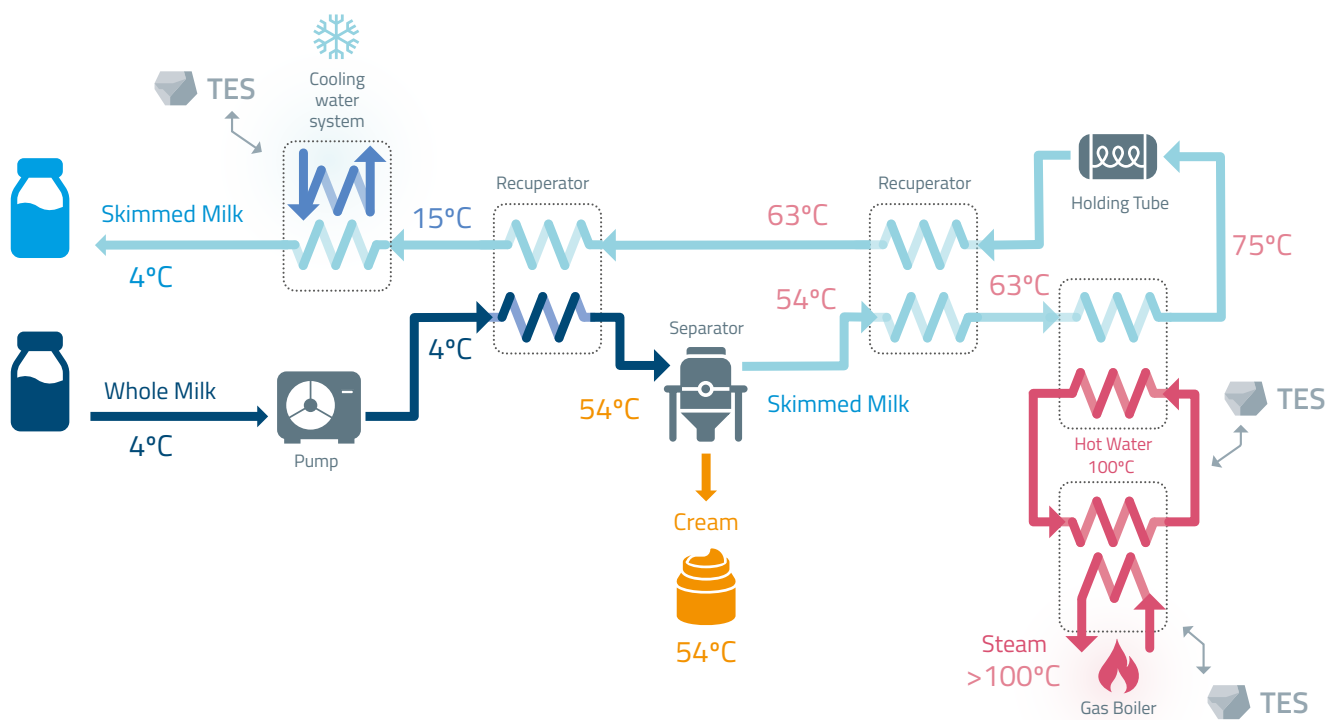


Figure 3: Process flow diagram for a dairy processing facility. System shown produces skimmed milk using the high-temperature short-time pasteurization method. Note: omission of storage tanks, valves, pumps, etc. for clarity. Based on system layouts from Ref. [8] and Ref. [7].

milk and raw cream. The raw skimmed milk undergoes a second stage of recuperative heating, raising its temperature to 63°C. Pasteurization is then completed by transferring heat from a hot water loop, which is typically supplied by a steam system. The milk is held at 75°C for 15 seconds in a holding tube, the length of which is designed based on the flow rate to ensure the correct holding time. The pasteurized milk is then cooled to 15°C using the other sides of the recuperative heat exchangers, and finally chilled to 4°C using a cold-water system. The skimmed milk leaves the system ready for packaging and transport. A similar process occurs to the cream product, noting that due to the increased fat content (40%), pasteurization occurs at 88°C for 15 seconds. Further details may be found in Refs.[7], [8].

discharges steam when required by the process. Storage media may include steam accumulators, high-pressure water (flashed on demand), solid media, or thermal oils, which exchange heat with the steam circuit. Care must be taken when implementing heat pumps across large temperature lifts, as the coefficient of performance (COP) decreases with increasing temperature difference. However, well-designed systems, including those which utilize waste heat recovery, can help maintain efficiency.

- Hot Water System (<100°C): The steam system is removed, and an e-boiler or high-temperature heat pump is connected directly to the hot water loop. A system of ambient pressure hot water storage tanks

is added, which allows thermal energy to be stored as surplus hot water below 100°C. However, this option is only feasible when the existing process already uses hot-water for heat distribution; otherwise, the full heat distribution system would require modification.

- ▶ **Cooling Water System (<4°C):** The existing electrically driven refrigeration system is integrated with a chilled-water TES system. This typically involves a chilled-water tank or a water mixture with ethylene glycol or salt solutions to allow sub-zero storage temperatures. Many dairy facilities already employ limited ice-slurry storage, which can be expanded for load shifting.

The hot water and steam system options are mutually exclusive, as both aim to replace the gas-fired system. However, hybridization with the existing gas boiler is possible during transition periods or to provide backup capacity. The cooling system is less likely to deliver the same level of emissions reduction as the first two “hot-side” options, since it is already electrically powered. However, it can still benefit from TES by reducing electricity costs and shifting consumption to periods of lower carbon intensity. The technical and economic considerations of the hot-side options are the focus of the rest of this case study.

2.3 Energy Demands

Dairy facilities typically process 2,000-25,000 kg of raw milk per hour, in near continuous operation [7], [9]. This section focuses on the production of skimmed milk (as shown in Figure 3), although similar analyses may be performed for other dairy products. Table 1 shows the required heat and electricity inputs for the production of skimmed milk, which follow the High-Temperature Short-Time (HTST) pasteurization guidelines. The values in Table 1 represent lower-bound estimates for dairy processing, as products with higher fat content (e.g., butter, ghee, cream) or more refinement (e.g., whey, powdered milk) require greater energy input.

Table 1: Heat and electricity inputs for a high-temperature short-time (HTST) milk production process. Values are per kg of raw milk input.

Process	Heat Input (Wh/kg)	Electricity Input(Wh/kg)
Steam Generation	25- 35	0
Cooling System	0	5-10
Pumping	0	1-3
Separation	0	1-2
Other	10-15	5
Total	35-50	12-20

Steam generation is the dominant process, accounting for more than 50% of the total energy input. This is the heat input from the gas boiler. Thus, assuming a boiler efficiency of $\eta_b = 0.81$ and a natural gas lower heating value of 44 MJ/kg, the steam system requires the combustion of 3 g of natural gas per kilogram of raw milk. The cooling system is the second most energy intensive process and uses a vapor-

compression refrigeration system. The refrigerant is usually ammonia, which transfers heat with a water-glycol mixture, operating at 1°C with ice normally forming on the evaporator coils [7]. The category “Other” includes processes such as cleaning, lighting, and packaging. Note that without recuperative heat exchangers, the heating and cooling demands would increase by a factor of six. **While steam generation accounts for approximately 50% of total energy use, it is responsible for more than 70% of the associated CO₂eq emissions [9] (reference assumes grid intensity of 600 gCO₂eq/Wh).** One of the aims of this case study is to examine how this heat input can be electrified, and system cost reduced through the integration of TES.

Note the specific heat capacity and density of milk can be approximated as $c_p \approx 3.95$ kJ/kgK and $\rho \approx 1020$ kg/m³, respectively, with more detailed formulations available as functions of the fat, protein, ash, and water content [7], [8]. The electricity values in Table 1 were taken from Table 11 in Ref. [10]. The heat input for steam generation was calculated using the temperatures and flow rates from Table 4 in Ref. [10] and assuming a thermal loss of 15% between the hot water and steam systems as recommended in Ref. [7]. The electricity input for the chilled-water system was calculated in a similar manner, assuming a cooling coefficient of performance (COP) of 3.5 based on Equation 4.8 in Ref. [10]. However, note that reported values for heat input vary significantly in the literature. For example, estimates include 10 Wh/kg [11], 40 Wh/kg. [8], and 230 Wh/kg [9], reflecting the wide variation in dairy plant designs; at the higher end, recuperative heat exchangers are likely not employed. Nevertheless, the values used in this paper represent best estimates based on first-principles calculations.

2.4 Optimization of Dairy Processing: Recuperation, Waste Heat, and Heat Pumping

For most heat decarbonization pathways in the dairy sector, the gas-fired boiler is replaced with either an e-boiler or a high-temperature heat pump, both powered by electricity. While improving the efficiency of these components (e.g., by increasing the heat pump COP) is important, significant benefits can also be achieved by optimizing heat flows within the pasteurization process itself. The biggest opportunity is to maximize recuperation through heat exchangers, as shown in Figure 3. For example, instead of heating milk from 4°C to 75°C using only external heat, counter-current heat exchange with the outgoing hot product can preheat the incoming stream to approximately 60-65°C. This reduces the external heat requirement by around a factor of five.

In addition to recuperative heat exchange, further efficiency gains are possible by integrating heating and cooling demands. For instance, rather than pumping heat from the ambient environment temperature, a heat pump can utilize waste heat from the condenser of the refrigeration system [12] (typically 30-40°C) or from a waste hot water stream [13], thereby reducing the temperature lift and improving the COP. More advanced configurations combine the heating and cooling functions into a single dual-purpose heat pump that directly upgrades heat from the chilled milk stream to supply pasteurization temperatures [14], [15]. Effectively halving the amount of costly equipment required.

However, the challenge with these highly integrated solutions, is that they generally require modifications to existing process equipment and plant layouts, which can be capital-intensive and operationally complex. **In contrast, the electrification and TES options examined in this case study are selected because they are largely “drop-in” solutions which can be deployed across a wide range of existing facilities with minimal disruption.** In other words, process-level optimization remains desirable, but the focus here is on practical, near-term implementation pathways.

3. Economic Benefits of Thermal Energy Storage

3.1 Shifting Electricity Consumption

The integration of thermal energy storage (TES) will lower the average cost of electricity for dairy facilities. When electricity prices are low, electricity can be converted into stored thermal energy, and when prices are high, the stored thermal energy can be used instead of purchasing electricity from the grid. The purpose of this section is to quantify the extent to which TES can reduce electricity costs, and to use these results in the following section on total system cost. Three methods of analysis are performed, progressing from simple to detailed, to estimate the magnitude of cost reduction.

3.2 Yearly Thought-Experiment

Figure 4(a) shows a histogram of electricity spot-market prices in Germany during 2024, with a mean price of 78.5 €/MWh [16]. Germany was selected as it has an electricity to gas price ratio similar to other European countries. Additionally, its high solar deployment produces a pronounced “duck curve”, with frequent negative-price hours, meaning it is well suited to demand shifting. Assuming a storage system that replaces the most expensive 20% of hours with energy purchased during the cheapest 20% of hours, the histogram shifts to that of Figure 4(b). Here, the high-cost price bins are replaced by additional low-cost bins. This represents the theoretical upper bound for a five-hour storage system operating with perfect foresight - i.e. always charging at the lowest prices and discharging at the highest, with no seasonal constraints. In reality, however, low-price periods often extend over several consecutive days, meaning that such idealized shifting is impossible; this case, therefore, represents a strict upper limit. Under these assumptions, the mean electricity price is 52.2 €/MWh, a 33% reduction compared to the no-storage case.

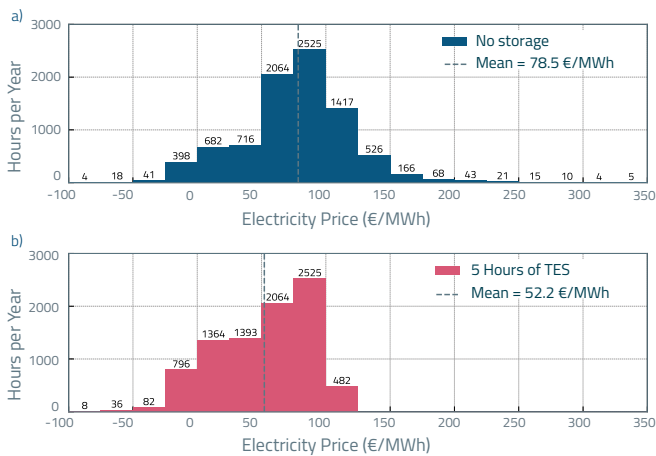


Figure 4: Histogram of electricity prices in Germany during 2024. (a) Nominal case without storage. (b) Idealized case in which the most expensive 20% of hours are replaced with the cheapest 20%. FCA analysis; Electricity price data from [16].

3.3 Analysis of the Average Daily Price Profile

While the yearly perspective provides an upper benchmark for the cost savings due to storage, analysis on a daily timescale offers a more realistic estimate of operational benefits. It reflects the fact that thermal storage is typically sized for only a few hours of discharge capacity. Figure 5 shows the average hourly wholesale electricity price profile in Germany during 2024. The average daily price is 78.5 €/MWh (blue dashed line). The red dashed line indicates a more realistic estimate of the average daily price if five hours of storage capacity is available, giving 66.1 €/MWh.

In this case, rather than shifting 20% of prices across the entire year (as in Figure 4), the storage shifts the most expensive 20% of hours within each day to the cheapest 20%. This results in a 15% reduction in average electricity cost compared to the no-storage case; it is significantly less than the 33% reduction from the yearly analysis. The comparison indicates the trade-off between daily flexibility and the additional capacity required to capture multi-day periods of price volatility.

3.4 Optimization Using Hourly Price Timeseries

To capture properly electricity price variations, and the true performance of a TES system, a linear optimization model was implemented using hourly electricity spot price data from the German grid in 2024. The optimizer determined for each hour whether to charge, discharge, or hold energy in storage, subject to a maximum capacity constraint of five hours. The objective was to minimize total electricity cost, and it was assumed the e-boiler had an efficiency of 99% and the TES had a round-trip efficiency of 82% (the rationale for selecting these values is discussed in the following section). Optimization was performed using the PuLP Python library with spot market data from ENTSO-E [16]. Figure 6 shows an example of the model results over a randomly selected five-day period, from midnight on 17 March to midnight on 23 March 2024, noting that the optimization was performed over the full year (with a five-day period only shown for ease of plotting).

As expected, the electricity spot price follows a daily bimodal pattern, with maximums typically occurring around 6 AM and 6 PM, and minimums around midnight and noon. The average price across the year is again 78.5 €/MWh. The optimization results are overlaid on the plot and show how “full” the storage is on the right-hand axis (a storage fraction of 1.0 corresponds to the full 5-hour capacity). Interestingly, the storage dispatch mirrors the daily price variations, as the TES system charges and discharges twice per day, typically shifted by 2.5 hours from the electricity price curve, to cover the 5-hour periods around the daily price peaks. **With 5 hours of TES integrated, the average electricity cost is reduced to 65.4 €/MWh.** Although this is only 0.7 €/MWh lower than the simpler daily analysis presented in the previous subsection, it should be remembered that storage efficiencies are no longer assumed to be perfect in this model.

Note that this optimization still assumes perfect foresight, i.e. it has access to the entire timeseries in advance. In reality TES operation would need to rely on predicted day-ahead prices.

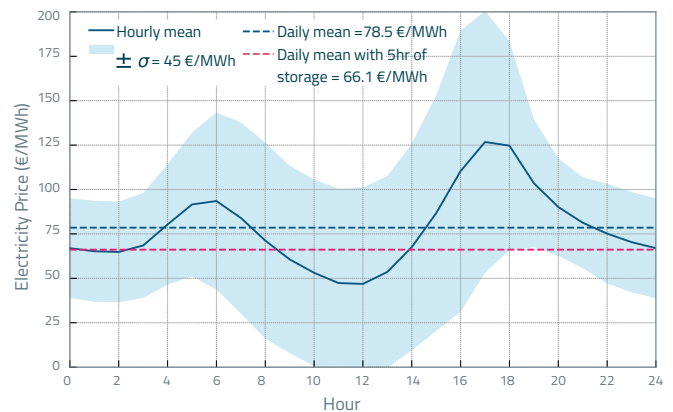


Figure 5: Average hourly price in Germany during 2024, and effect of TES on reducing costs. $\pm \sigma =$ one standard deviation above and below the hourly average. Price data from Ref. [16]; FCA analysis; Electricity price data from [16].

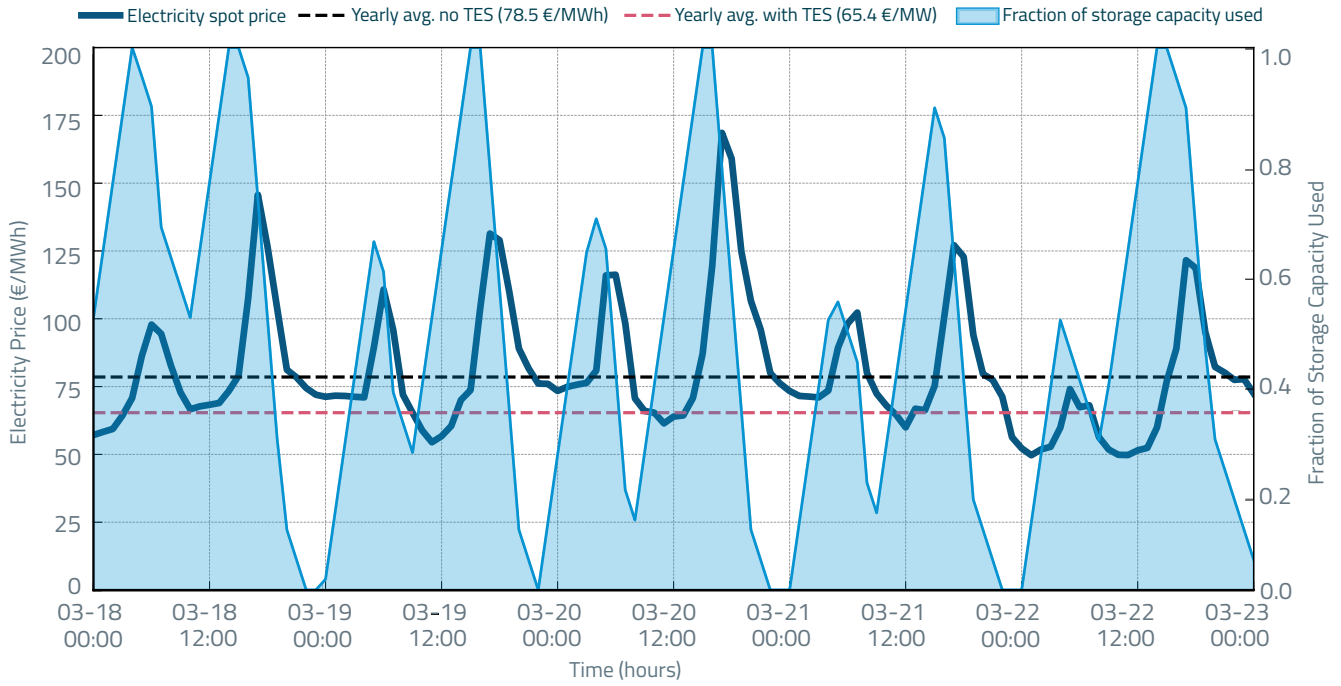


Figure 6: Results from TES dispatch optimization using hourly electricity price time series for Germany in 2024. FCA analysis; Electricity price data from [16].

4. System Cost Analysis

This section presents a detailed cost analysis of electrification, with and without TES, to evaluate the business case for a dairy facility under present-day conditions. The underlying cost equations and assumptions are introduced first, followed by a series of plots that calculate the breakeven year for a range of gas and electricity price combinations.

4.1 Costing Equations

The total cost to electrify an average-sized dairy production facility is given by,

$$\text{Net Present Cost} = \text{CAPEX} + \sum_{t=1}^{\eta} \frac{\text{OPEX}_t}{(1+r)^t} \quad (1)$$

where CAPEX is the capital expenditure, OPEX is the annual operational expenditure, η is the project lifetime (years), t is a specific year, and r is the discount rate.

The operational expenditure for a gas boiler or an electrified system is given by,

$$\begin{aligned} (\text{OPEX}_g)_t &= \left(\frac{c_g Q}{\eta_g} \right)_t \\ (\text{OPEX}_e)_t &= \left(\frac{c_e Q}{\eta_e} \right)_t \end{aligned} \quad (2)$$

where c_g is the unit cost of gas, Q is the total heat required by the process, and η_g is the gas boiler efficiency. For the electrified system, c_e is the unit cost of electricity and η_e is the efficiency of the electrified system.

During operation without storage, the efficiency of the electrified system is equal to either the e-boiler efficiency or the heat pump COP,

$$\eta_e = \eta_{eb}, \quad \eta_e = \text{COP}_{hp} \quad (3)$$

During operation with storage, an additional factor corresponding to the TES efficiency, η_{TES} , must be included,

$$\eta_e = \eta_{eb} \eta_{TES}, \quad \eta_e = \text{COP}_{hp} \eta_{TES} \quad (4)$$

4.2 Assumptions

All costs are reported in euros, referenced to January 1, 2024. A discount rate of $r=0.04$ was chosen, as recommended by the Danish Energy Agency [17], [18] and consistent with other published values [17],[18].

The analysis assumes a large dairy facility which processes a raw milk input of 20,000kg/h with a specific heat load of 40 Wh/kg (see Table 1). This corresponds to a total heat rate consumption of approximately 800 kW. Table 2 summarizes the technical performance parameters applied in the case study. Analysis is performed for two system configurations, where heat is generated by either (i) an electric boiler with TES, or (ii) a heat pump with TES. A storage discharge duration of 5 hours was assumed, corresponding to a total storage capacity of 4 MWh. For the electric boiler configuration, an average efficiency of 95% is applied, representing operation at 99% efficiency for 19 hours per day and 82% efficiency during the 5 hours of storage discharge.

Note in this analysis we attribute zero CAPEX to the existing gas-fired system. This represents a scenario where the electrification retrofit occurs early in the lifetime of the existing gas-fired system. If the retrofit instead occurs near end of life, or for a greenfield project, the gas-boiler CAPEX must be included, and would balance the comparison.

Table 2: Technical performance parameters.

Parameter	Value	Ref
Gas Boiler Efficiency	80%	[7], [19]
Electric Boiler Efficiency	99%	[19],[20]
Heat Pump COP	3	[13],[20], [21] [22]
TES Efficiency	70-95%	[23] [24]
Storage Discharge Duration	5 hours	

The capital costs for the electric boiler and heat pump systems are listed in Tables 3 and 4, respectively. They are based on a review of the literature and discussions with innovators in the TES and industrial heating space. Balance-of-plant costs include heat exchangers, insulation, and piping, and were estimated using a CAPEX multiplier of 0.33 [20]. **A main conclusion from these values is that the cost of including TES is relatively low compared to the e-boiler or heat pump, with a per-unit energy cost approximately five-ten times lower than that of a Li-ion battery [24].**

Table 3: Capital cost for an e-boiler system with TES. Balance of plant costs include heat exchangers, insulation, piping, etc., and were calculated using a CAPEX multiplier of 0.33. Values taken from the Danish Energy Agency technology data catalogue, academic literature, and discussions with innovators.

Component	CAPEX (€)	Unit cost	Ref.
Electric boiler	80,000-200,000	100-250 €/kW _{th}	[20]
Storage	8,000-60,000	2-15 €/kW _{th}	[24]
Balance of Plant	30,000-85,000	0.33 × CAPEX	[20]
Total	120,000-350,000 (average: 235,000)		

Table 4: Capital cost for a heat pump system with TES. Balance of plant costs include heat exchangers, insulation, piping, etc., and were calculated using a CAPEX multiplier of 0.33. Values taken from the Danish Energy Agency technology data catalogue, academic literature, and discussions with innovators.

Component	CAPEX (€)	Unit cost	Ref.
Heat Pump	800,000-1,600,000	1,000-2,000 €/kW _{th}	[20]
Storage	8,000-60,000	2-15 €/kW _{th}	[24]
Balance of Plant	270,000-550,000	0.33 × CAPEX	[20]
Total	1,100,000-2,200,000 (average: 1,700,000)		

4.3 Breakeven Year

The costing equations from Section 4.1 are now applied using the values from Section 4.2, to estimate the most likely costs associated with electrifying the dairy facility.

Figure 7(a) shows the number of years required for an e-boiler with TES system to breakeven with the existing gas-fired system, for a range of average electricity and gas prices. Note, the x-axis is expressed in terms of the wholesale electricity price. The corresponding electricity price when TES is included is shown above this, and is €10 less based on the analysis from Section 3. The effect of the higher retail electricity price compared with the wholesale is considered later. Each cell indicates the number of years after which the new electrified system achieves breakeven. Areas without numbers correspond to electricity and gas price combinations where the electrified system does not breakeven within a 30-year period.

It is immediately apparent that the electricity price must be lower than the gas price for the system to breakeven within a reasonable timeframe. The contours between breakeven year levels appear approximately linear. For example, for an e-boiler, if the gas price is 20-25€/MWh higher than the electricity price, the system breaks even within one year. If the gas price is 5-10 €/MWh higher, breakeven occurs in two years. This behavior arises because the efficiencies of the e-boiler with TES and the existing gas system are similar (81 % and 95 %, respectively). **The slope of the contour levels is proportional to the ratio of these efficiencies (0.80/0.95), meaning that for every €1 increase in electricity price, the gas price can increase by roughly €0.84 to maintain the same breakeven year. This highlights an important but obvious conclusion: when comparing system costs, what truly matters is not the absolute costs of electricity and gas, but the difference between them.**



Figure 7(b) presents the corresponding breakeven period for a system using a heat pump with TES. Since the heat pump has COP = 3, the slope of the contour levels between breakeven years decreases to 0.27 (0.81/3). This means that for every €1 increase in electricity price, the gas price can increase by approximately €0.27 to maintain the same breakeven year. Thus, even though the heat pump system achieves breakeven later in the project life compared with the e-boiler, it can do so at higher electricity prices.

Figure 7(c) and Figure 7(d) show the breakeven year when the system is electrified without TES. For these cases, the effective electricity price equals the wholesale electricity price, as the lack of storage prevents daily demand shifting. Overall, the lack of thermal energy storage increases operating costs and therefore lengthens the time to breakeven. This results in a wider combination of electricity and gas price scenarios where the system does not achieve breakeven within 30 years (i.e. more white space on the plots).

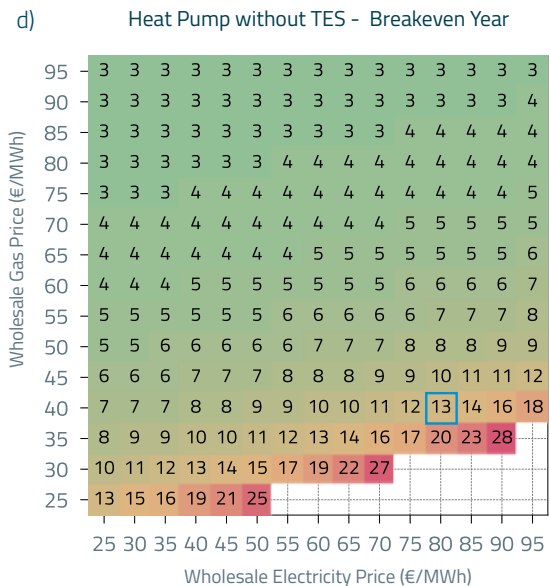
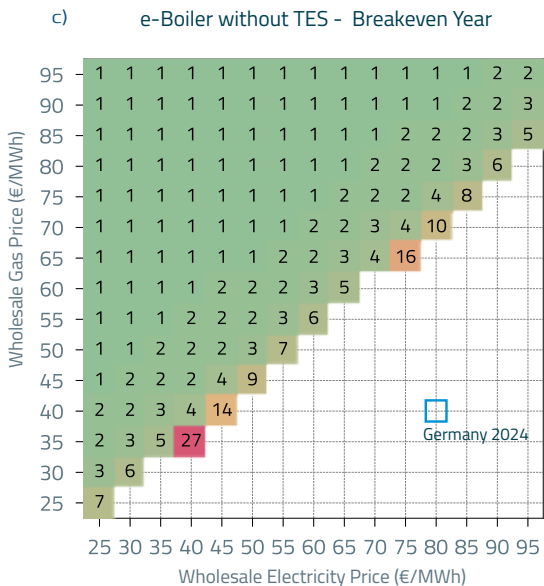
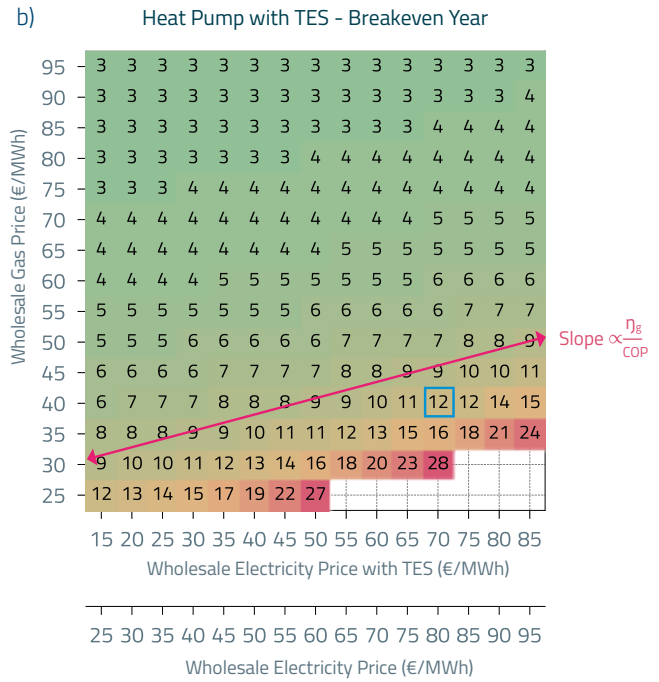
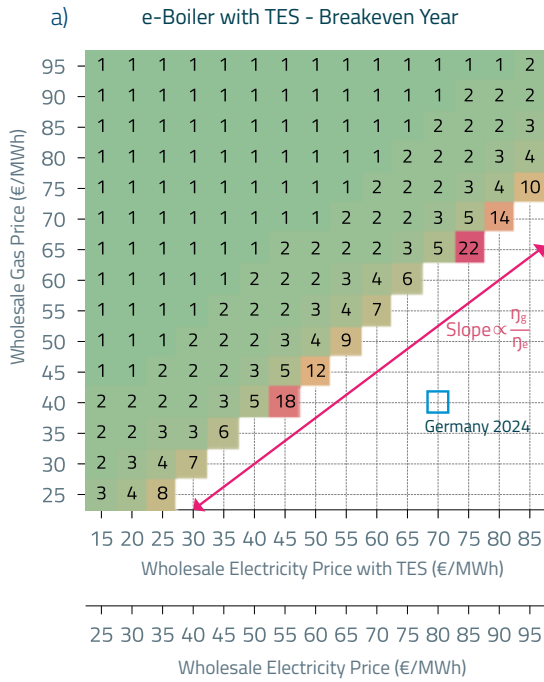


Figure 7: Breakeven year at which an electrified system becomes cheaper than the existing gas system. (a) e-boiler with TES; (b) heat pump with TES; (c) e-boiler without TES; (d) heat pump without TES. White areas indicate cases where the project does not breakeven within a 30-year period. FCA analysis.

4.4 Levelized Cost of Heat (LCOH)

Figure 8(a) shows the net present cost over the lifetime of the project for the specific case where the wholesale electricity price with TES is $c_e = 50$ €/MWh and the average gas price is $c_g = 50$ €/MWh. Note, the intersection of the cost curves for the nominal gas-fired system and the electrified system corresponds to the breakeven period. Figure 8(b) shows the levelized cost of heat (LCOH), which is calculated by,

$$\text{LCOH} = \frac{\text{Total Cost}}{\text{Total Heat Delivered}} = \frac{\text{CAPEX} + \sum_{t=1}^n \frac{\text{OPEX}_t}{(1+r)^t}}{\sum_{t=1}^n \frac{Q_t}{(1+r)^t}} \quad (5)$$

where the total present cost is divided by the total discounted heat delivered.

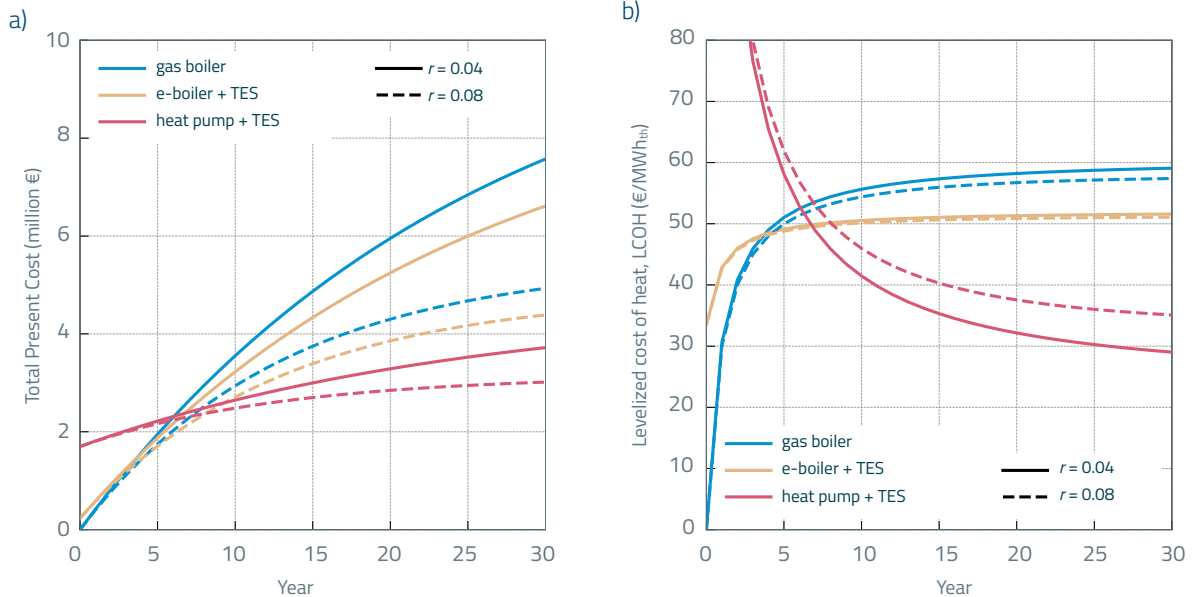


Figure 8: Comparison of heat generation systems over project lifetime. (a) Total present cost and (b) Levelized cost of heat. Solid lines are for a discount rate of 4% and dashed lines are for 8%. All curves are for a wholesale gas price of 50 €/MWh and a wholesale electricity price of 50 €/MWh. FCA analysis.

4.5 Effect of Grid Fees and Retail Tariffs

The analysis so far has considered electricity and natural gas prices in the range of 25–95 €/MWh. This range was selected because the average wholesale electricity spot price is around 78 €/MWh and is expected to decline over time due to learning effects and supportive policy, whereas the current natural gas price is about 40 €/MWh and is likely to rise due to carbon pricing.

An important additional consideration, however, is the retail electricity price. Retail prices are not simply equal to the wholesale spot-market price, but also include grid fees, levies, and taxes. Using Eurostat data for consumption band ID (annual consumption of 2000 MWh to 19999 MWh), it was determined that the total retail electricity price is approximately 40% higher than the corresponding wholesale price. Figures 9(a) and 9(b) therefore present scenarios where the spot-market electricity price has been increased by 40% to account for retail

fees, and then reduced by 10 €/MWh to approximate the TES cost reduction.

Figure 8 also shows cost curves for when the discount rate is doubled to $r = 0.08$ (dashed lines). A key result is that the discount rate does not significantly change the breakeven year for the e-boiler system. This is because the heat input for the e-boiler is similar in magnitude to the gas system (reflecting their comparable efficiencies), and both fuels (electricity and gas) are discounted at the same rate. The breakeven year for the heat pump increases slightly with higher discount rate, but not by much since the CAPEX is the dominating lifetime cost.

Although the e-boiler achieves breakeven much faster than the heat pump, its lifetime costs are 10% lower than the gas-fired system, whereas the heat pump is 50% lower. Consequently, food and beverage facilities considering electrified solutions with TES must balance the importance of earlier breakeven vs. maximizing lifetime savings.

As expected, the retail electricity price increases the OPEX of the selected systems and therefore lengthens the breakeven time. The slope of the contour lines between breakeven years (e.g. moving from 1 to 2 years, or 2 to 3 years) is no longer simply proportional to the ratio of the gas boiler efficiency and the electrified system efficiency (or COP), but is instead multiplied by a factor of approximately 1.4. This means that, for every 1 €/MWh increase in the grid electricity price, the gas price can rise by about 1.4 €/MWh while maintaining the same business case and breakeven year.

It should be noted that this analysis does not include carbon pricing, since dairy facilities are typically below the 20 MW threshold for inclusion in the EU ETS.

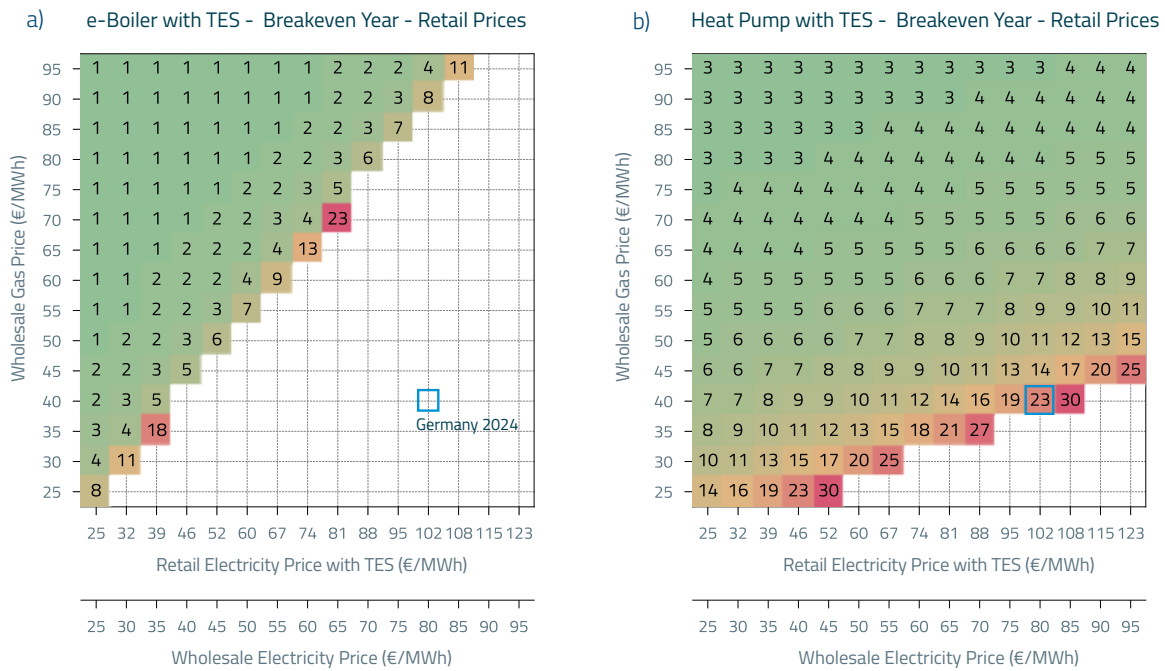


Figure 9: Impact of retail electricity costs on the breakeven year for (a) an e-boiler with TES and (b) a heat pump with TES. Retail costs include taxes, levies, and grid charges. The blue box indicates 2024 German price levels. FCA analysis.

4.6 CAPEX Targets for Industry

In the previous sections, the most likely capital costs were assumed from literature and used to calculate the breakeven year. In this section, however, a fixed breakeven period of five years is assumed, and the maximum allowable CAPEX is "back-calculated" for the e-boiler and heat pump systems with TES. This provides a target CAPEX for industry and innovators.

Figure 10(a) shows the maximum CAPEX target for the e-boiler and TES system. The values in each cell represent the maximum CAPEX in euros per unit of thermal power that can be spent while still achieving breakeven within five years. **When electricity and gas prices are close in value, the maximum CAPEX is low because the only mechanism to achieve faster breakeven is the slightly higher efficiency of the e-boiler, which lowers OPEX.** Conversely, when gas prices are significantly

higher, the allowable CAPEX increases, as electricity OPEX is much lower than that of gas. Across all price scenarios, a key conclusion is that electricity must be cheap for electrification to be economically viable. To put this into perspective for an 800 kW dairy facility, a total CAPEX of €0.3 million (0.38 €/W) requires the cost of electricity consumed to be roughly 0-10 €/MWh lower than the gas price.

Figure 10(b) shows the corresponding maximum CAPEX values for the heat pump with TES system. **The main difference compared to the e-boiler case is that the heat pump can achieve breakeven across a wider range of gas and electricity prices, due to its coefficient of performance (COP=3).** However, for an 800 kW dairy facility, a total CAPEX of €2 million (2.5 €/W) means the electricity cost can be up to 15 €/MWh higher than the gas price and the project still breakeven. The drawback, however, is that heat pump systems are generally more expensive, even though the maximum CAPEX target is higher.

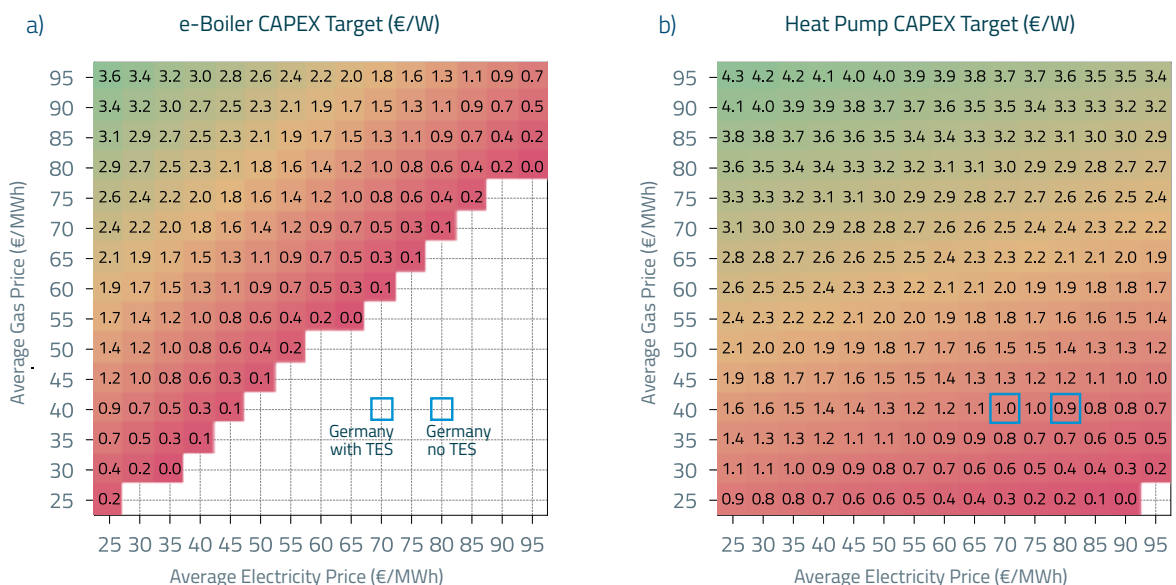


Figure 10: Industry CAPEX targets for (a) e-boiler and TES and (b) e-boiler and TES, to achieve a 5-year breakeven period, with a discount rate of 4%. FCA Analysis.

5. Lessons Learned from Existing Projects

The integration of thermal energy storage (TES) in dairy facilities remains limited, despite high technology readiness levels (TRL) [25]. Nevertheless, a small number of commercial systems have been implemented. Example systems are described below with summaries of the main lessons learned.



5.1 California Dairies Inc. (Turlock) Zero-Emissions Thermal Energy

In 2022, California Dairies received funding from the California Energy Commission to install a solar thermal system with TES to provide renewable heat to the plant [26]. The system has since been discontinued, but several lessons were identified:

- ▶ The solar thermal system experienced significant downtime and added cost. Challenges arose from strict locational requirements and the extensive insulation needed to transport heat across the facility.
- ▶ A steam-generating heat pump is recommended as a more suitable option for heat generation.
- ▶ Poor contractor performance hindered the project (e.g., a heat exchanger was installed backwards).
- ▶ The storage system itself, consisting of insulated hot-water tanks, operated effectively.



5.2 New South Wales On-Farm Energy Pilot Projects

The government of New South Wales funded pilot projects which use excess renewable electricity from a co-located solar PV array to produce chilled water for milk storage [27].

- ▶ Project costs were 33-50% higher than expected due to underestimating the cost of electrical components.
- ▶ Thermal storage should maintain separation of cold and hot water in dedicated tanks. If this is not possible, stratification should be used, with cold supply drawn from the bottom and warm return directed to the top.
- ▶ “Waste” heat from the chiller (heat pump) can be effectively utilized for heating hot water.



5.3 Alberta Energy Efficiency on Dairy Farms

The Alberta government commissioned a study into general energy efficiency measures that could be deployed on dairy farms [28].

- ▶ System upgrades should be implemented when existing equipment reaches end-of-life, or when new capacity is required.
- ▶ Higher CAPEX is justified for more efficient systems, as operating costs dominate lifetime expenses.
- ▶ The study is cautious about using instantaneous electric water heating (without storage) due to high power demand.
- ▶ Using waste heat from refrigeration units (heat pumps) is recommended for water heating.



5.4 Deployed Electric Boiler Systems

Mataura Valley Milk in New Zealand has installed an electric boiler to provide process heat [29], [30].

- ▶ Regarding the business case: Over a ten-year period, the electrified system is estimated to be twice as expensive as the existing coal system. However, this premium was justified in anticipation of higher carbon costs over the same period.
- ▶ The facility uses an advanced electrode boiler capable of generating steam on demand.
- ▶ The system is rated for 6 MW, with capacity to upgrade to 12 MW. System required upgrades to the local grid connection.



5.5 FrieslandCampina’s Advanced Heat Pump System

FrieslandCampina in Maasdam, Netherlands has installed a high-temperature heat pump to decarbonize part of its production process [31], [32], [33].

- ▶ The system was installed in 2024 and uses Olvondo’s Highlift heat pump which can achieve temperature lifts of up to 150°C.
- ▶ The heat pump utilizes waste heat which would otherwise be rejected through cooling towers, with a likely COP of 2.
- ▶ So far, the plant’s emissions have been reduced by 36%, equivalent to removing 1,100 tonnes of CO₂eq per year.

6. Conclusions

Dairy processing facilities typically use fossil-fired boilers to generate process steam for pasteurization and other operations, in the range of 100-150°C. A case study exploring heat electrification options and the inclusion of TES has been presented to better understand decarbonization in the wider food and beverage industry in the EU.

Currently, the difference in price between natural gas and electricity makes electrification mostly uneconomic. TES designed to manage twice daily fluctuations in electricity price (5 hours of storage) can reduce the average cost by around 10 €/MWh. However, this reduction is generally insufficient to change the business case. **A central conclusion, therefore, is that policy efforts should focus on narrowing the gap between gas and electricity costs.** Additionally, technical solutions such

as increasing storage capacity and discharge duration could help bridge this gap, since the capital costs of TES are relatively low.

The results of the case study indicate that high-temperature heat pumps can currently breakeven with gas systems over very long timeframes (15-30 years). Their higher efficiency ($COP > 3$) substantially reduces lifetime OPEX costs. On the other hand, electric boilers cannot breakeven at current prices. However, if the gap between gas and electricity price closes, they offer the potential to breakeven more quickly than heat pumps (due to lower CAPEX). Nevertheless, this quicker breakeven is a trade-off with lifetime cost which remains close to that of existing gas-fired systems (due to similar boiler efficiencies).



References

- [1] Eurostat, "Businesses in the manufacturing sector." Accessed: Sept. 15, 2025. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Businesses_in_the_manufacturing_sector
- [2] E. C.-D.-G. for A. and R. Development, "European Commission | Dairy production." Accessed: Oct. 20, 2025. [Online]. Available: <https://agridata.ec.europa.eu/extensions/DashboardDairy/DairyProduction.html>
- [3] Eurostat, "Milk and milk product statistics." Accessed: Sept. 15, 2025. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Milk_and_milk_product_statistics
- [4] M. I. Malliaroudaki, N. J. Watson, R. Ferrari, L. N. Nchari, and R. L. Gomes, "Energy management for a net zero dairy supply chain under climate change," *Trends Food Sci. Technol.*, vol. 126, pp. 153–167, Aug. 2022, doi: 10.1016/j.tifs.2022.01.015.
- [5] G. Thoma et al., "Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008," *Int. Dairy J.*, vol. 31, pp. S3–S14, Apr. 2013, doi: 10.1016/j.idairyj.2012.08.013.
- [6] S. J. Cooper, G. P. Hammond, N. Hewitt, J. B. Norman, S. A. Tassou, and W. Youssef, "Energy saving potential of high temperature heat pumps in the UK Food and Drink sector," *Energy Procedia*, vol. 161, pp. 142–149, Mar. 2019, doi: 10.1016/j.egypro.2019.02.073.
- [7] Tetra Pak, *Dairy Processing Handbook*. [Online]. Available: <https://www.tetrapak.com/en-anz/insights/handbooks/tetra-pak-dairy-processing-handbook>
- [8] M. I. Malliaroudaki, N. J. Watson, Z. J. Glover, L. N. Nchari, and R. L. Gomes, "Net zero roadmap modelling for sustainable dairy manufacturing and distribution," *Chem. Eng. J.*, vol. 475, p. 145734, Nov. 2023, doi: 10.1016/j.cej.2023.145734.
- [9] N. Jungbluth, R. Keller, G. Doublet, A. König, and S. Eggenberger, "Re-design of the dairy industry for sustainable milk processing - Deliverable 7.3 Report on life cycle assessment, economic assessment, potential employment effects and exergy-based analysis."
- [10] M. I. Malliaroudaki, "Modelling energy consumption in the dairy supply chain Single and Multi-product Manufacturing and Distribution." Horizon 2020 PROTECT-ITN.
- [11] J. Upton, J. Humphreys, P. W. G. Groot Koerkamp, P. French, P. Dillon, and I. J. M. De Boer, "Energy demand on dairy farms in Ireland," *J. Dairy Sci.*, vol. 96, no. 10, pp. 6489–6498, Oct. 2013, doi: 10.3168/jds.2013-6874.
- [12] M. U. Ahrens, S. S. Foslie, O. M. Moen, M. Bantle, and T. M. Eikevik, "Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry," *Appl. Therm. Eng.*, vol. 189, p. 116731, May 2021, doi: 10.1016/j.applthermaleng.2021.116731.
- [13] J. Cox, S. Belding, and T. Lowder, "Application of a novel heat pump model for estimating economic viability and barriers of heat pumps in dairy applications in the United States," *Appl. Energy*, vol. 310, p. 118499, Mar. 2022, doi: 10.1016/j.apenergy.2021.118499.
- [14] D. S. Ayou, R. Hargiyanto, and A. Coronas, "Ammonia-based compression heat pumps for simultaneous heating and cooling applications in milk pasteurization processes: Performance evaluation," *Appl. Therm. Eng.*, vol. 217, p. 119168, Nov. 2022, doi: 10.1016/j.applthermaleng.2022.119168.
- [15] D. K. E. C. B.V., "Pasteurization," *Industrialheatpumps.nl*. Accessed: Oct. 28, 2025. [Online]. Available: <https://industrialheatpumps.nl/english/applications/pasteurization/>
- [16] ENTSO-E, "Day-ahead Prices - DE-LU." [Online]. Available: <https://transparency.entsoe.eu/dashboard/show>
- [17] Danish Energy Agency, "FINDING YOUR CHEAPEST WAY TO A LOW CARBON FUTURE The Danish Levelized Cost of Energy Calculator." 2020. [Online]. Available: <https://ens.dk/en/global-cooperation/tools-and-publications>
- [18] Trinomics, *Cost of energy (LCOE): energy costs, taxes and the impact of government interventions on investments*. Publications Office, 2020. Accessed: Aug. 19, 2025. [Online]. Available: <https://data.europa.eu/doi/10.2833/779528>
- [19] ERM, "Future opportunities for electrification to decarbonise UK industry," *Rep. Dep. Energy Secur. Net Zero*, Oct. 2023.
- [20] Danish Energy Agency, "Generation of Electricity and District Heating - Technology Data Catalogue." 2025. [Online]. Available: <https://ens.dk/en/analyses-and-statistics/technology-data-generation-electricity-and-district-heating>
- [21] S. Klute, M. Budt, M. Van Beek, and C. Doetsch, "Steam generating heat pumps – Overview, classification, economics, and basic modeling principles," *Energy Convers. Manag.*, vol. 299, p. 117882, Jan. 2024, doi: 10.1016/j.enconman.2023.117882.
- [22] F. Schlosser, S. Zysk, T. G. Walmsley, L. Kong, B. Zühlsdorf, and H. Meschede, "Break-even of high-temperature heat pump integration for milk spray drying," *Energy Convers. Manag.*, vol. 291, p. 117304, Sept. 2023, doi: 10.1016/j.enconman.2023.117304.
- [23] LDES Council and McKinsey and Company, "Net-zero heat: Long duration energy storage to accelerate energy system decarbonization," Nov. 2022, [Online]. Available: <https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-power-long-duration-energy-storage-for-a-renewable-grid>
- [24] Danish Energy Agency, "Technology Data Catalogue for Energy Storage." May 2025. [Online]. Available: <https://ens.dk/en/analyses-and-statistics/technology-data-energy-storage>
- [25] L. Vallese et al., "A comprehensive review of thermal energy storage technologies and their applications: Creation of a database," *Renew. Sustain. Energy Rev.*, vol. 225, p. 116133, Jan. 2026, doi: 10.1016/j.rser.2025.116133.
- [26] Skyven Technologies and California Energy Commission, "California Dairies Inc. (Turlock) Zero Emissions Thermal Energy," May 2025, [Online]. Available: <https://www.energy.ca.gov/publications/2025/california-dairies-inc-turlock-zero-emissions-thermal-energy>
- [27] J. O'Connor, "On-farm Energy Pilot Case Study – Boondabah Holsteins, Jones Island and Manning Valley Dairy, Wingham," [Online]. Available: <https://www.dpi.nsw.gov.au/dpi/climate/about-dpi-climate/climate-change-research-strategy/project-2-energy-efficiency-solutions/on-farm-energy-pilot-projects>

References

[28] Alberta Government, "Energy Efficiency on Dairy Farms." Accessed: Sept. 16, 2025. [Online]. Available: <https://open.alberta.ca/publications/energy-efficiency-on-dairy-farms>

[29] B. Akers, "Electric boiler now fully operational at Mataura Valley Milk, New Zealand's first all-electric dairy processor." Accessed: Sept. 16, 2025. [Online]. Available: <https://thea2milkcompany.com/latest-company-news/electric-boiler-now-fully-operational-at-mataura-valley-milk-new-zealand-s-first-all-electric-dairy-processor>

[30] Synlait, "Electrode Boiler Fact Sheet." Accessed: Sept. 16, 2025. [Online]. Available: https://www.synlait.com/wp-content/uploads/2019/03/Synlait-Electrode-Boiler-fact-sheet_March-2019.pdf

[31] European Heat Pump Association, "Pioneering a low-carbon future: transforming dairy with heat pump innovation," European Heat Pump Association. Accessed: Oct. 27, 2025. [Online]. Available: <https://ehpa.org/news-and-resources/news/pioneering-a-low-carbon-future-transforming-dairy-with-heat-pump-innovation/>

[32] European Heat Pump Association, "Cool cows: how a dairy plant's embracing the future with a heat pump," European Heat Pump Association. Accessed: Oct. 27, 2025. [Online]. Available: <https://ehpa.org/news-and-resources/news/cool-cows-how-a-dairy-plants-embracing-the-future-with-a-heat-pump/>

[33] "HighLift heat pump by Olvondo TechnologyTM." Accessed: Oct. 28, 2025. [Online]. Available: <https://www.tetrapak.com/en-gb/solutions/integrated-solutions-equipment/processing-equipment/heat-pumps/highlift-heat-pump>

[34] Crane Co, Ed., Flow of fluids: through valves, fittings and pipe, Repr. in Technical paper, no. No. 410. Stamford, Conn: Crane, 2009.

[35] Eastman Chemical Company, "THERMINOL VP-1 Heat Transfer Fluid - Ultrahigh-temperature, vapor/liquid phase fluid." Accessed: Sept. 16, 2025. [Online]. Available: https://www.therminol.com/sites/therminol/files/documents/TF09A_Therminol_VP1.pdf

[36] J. Macnaghten, "Engineering challenges for affordable, scaleable thermal storage," presented at the IMechE Mini-Symposium Cambridge, Mar. 17, 2025.

[37] P. M. Gerhart, A. L. Gerhart, and J. I. Hochstein, Munson, Young and Okiishi's fundamentals of fluid mechanics, Eighth edition. Hoboken: John Wiley & Sons Inc, 2016.

Appendix: Review of Energy Balances and Pipe Sizing

The body of this case study focused on identifying locations within the pasteurization process where thermal energy storage could be integrated, and quantifying the extent to which storage could reduce the average price of consumed electricity. A detailed analysis of the business cases for a range of gas and electricity price combinations was then provided. However, an important aspect of thermal storage, and indeed electrification of industry in general, is the technical modifications required at the plant level. The intent of this Appendix is to review the method for performing a basic energy balance for a heat exchanger component, and to explain how this should inform design of the system. An example is then provided comparing the required pipe diameters for a range of heat transfer fluids.

Energy Balance and Thermal Losses

Thermal losses in heat transfer systems typically manifest as a reduction in temperature of a fluid. If the reduction is small, the fluid can still deliver sufficient heat transfer for the process. However, if the reduction is too large, the process requirements cannot be met. There are two main mechanisms of thermal loss:

- ▶ **Heat leakage** – thermal energy is removed from the system through heat transfer with the environment, typically mitigated with insulation.
- ▶ **Irreversibilities** – entropy is generated due to imperfect heat transfer across temperature gradients or frictional pressure drops, typically mitigated through heat exchanger design, selection of heat transfer fluid, and optimization of flow rates.

Figure 11 shows a standard counter-flow heat exchanger, where heat is transferred from a hot fluid entering at temperature T_{hi} to a cold fluid entering at temperature T_{ci} . The goal of such a heat exchanger is to raise the outlet temperature of the cold stream, T_{co} , above the required process temperature.

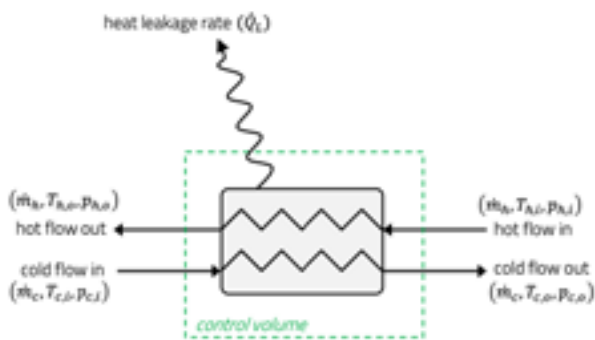


Figure 11: Energy balance for a counter-flow heat exchanger. Work input is zero and therefore omitted from the diagram.

Applying the steady-flow energy balance to the control volume (i.e. the energy entering must equal the energy leaving), the expression for the cold outlet temperature, may be derived

$$\dot{m}_h h_{h,i} + \dot{m}_c h_{c,i} = \dot{m}_h h_{h,o} + \dot{m}_c h_{c,o} + \dot{Q}_L \quad (6)$$

$$\dot{m}_h (h_{h,i} - h_{h,o}) - \dot{m}_c (h_{c,o} - h_{c,i}) = \dot{Q}_L \quad (7)$$

$$\dot{m}_h c_{p,h} (T_{h,i} - T_{h,o}) - \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i}) = \dot{Q}_L \quad (8)$$

$$T_{c,o} = T_{c,i} + \frac{\dot{m}_h c_{p,h} (T_{h,i} - T_{h,o})}{\dot{m}_c c_{p,c}} - \frac{\dot{Q}_L}{\dot{m}_c c_{p,c}} \quad (9)$$

where h is the specific enthalpy and c_p is the specific heat capacity. Other variables and subscripts are defined in Figure 11.

From Equation 9, it is clear that maximising the temperature rise of the cold fluid requires:

- ▶ Minimising heat leakage (the final term).
- ▶ Maximising the temperature drop of the hot stream (the middle term).

However, it is not immediately clear whether the mass flow rates and specific heat capacities of the fluids should be minimized or maximized. This requires a more nuanced analysis of the heat transfer process within the heat exchanger, particularly by calculating the rate of entropy generation via application of the steady-flow entropy balance to the same control volume (i.e., application of the second law of thermodynamics to the system). Note, a similar energy balance may also be applied to a control volume around a single pipe, in which case the middle term of Equation 9 disappears, and losses are driven by heat leakage.

The following section considers various heat transfer fluids and their implications for pipe sizing, and qualitatively, for the amount of insulation required. It should be noted that thermal losses are not always detrimental. Provided the process temperature requirements are satisfied, thermal losses are a trade-off with equipment cost.

Heat Transfer Fluid Comparison

The electrification and integration of TES requires consideration of components required for the “balance-of-plant” - i.e. additional equipment other than the heat generation and TES systems. One specific aspect is the size and specification of piping needed to transfer heat throughout the plant.

Figure 12 shows a comparison of the pipe cross-sectional areas required to transfer 2 MW of thermal power, for a variety of common heat transfer fluids. The pipe cross sections are drawn to scale. (Note: the 2 MW reference was calculated using a reference state of 25 °C and 1 bar.) For each case, fluid velocities were set to industry-standard reference values: 2.5 m/s for liquids, 40 m/s for steam, and 10 m/s for air [34]. Each case is summarized as follows:

- ▶ **Case (a): Water at 100 °C** - Water is transported slightly above atmospheric pressure at 1.5 bar to ensure it remains in the liquid phase. At this temperature, the required pipe diameter is relatively small.
- ▶ **Case (b): Water at 170 °C** - As the water temperature increases, the specific enthalpy increases approximately linearly with temperature ($\Delta h \approx c_p \Delta T$). This reduces the mass flow required and thus the pipe cross-section. However, to remain in the liquid phase, the pressure must be increased to around 10 bar, which adds cost due to thicker pipe walls and higher-pressure fittings.
- ▶ **Case (c): Saturated steam at 170 °C** - At the saturation pressure of 7.9 bar, water exists as dry saturated steam. Although the density is far lower than liquid water, steam systems can carry significant thermal energy due to higher flow velocities and the energy contained in the latent heat of vaporization. As a result, the required pipe diameter is similar in magnitude to that of liquid water.
- ▶ **Case (d): Thermal oil at 170 °C** - Synthetic oils such as Therminol or Dowtherm have specific heat capacities of roughly half that of

Appendix: Review of Energy Balances and Pipe Sizing

water [36]. However, they can operate at much higher temperatures without pressurization (boiling points of 257°C at 1 bar). At 170°C, this means pressurization is not required, allowing thinner piping and lower costs.

- ▶ Case (e): Air at 170°C - Air has both low density and low specific heat capacity. Consequently, the required pipe diameter is two orders of magnitude larger than for the other fluids. At these scales, ductwork is typically used instead of pressurized piping.

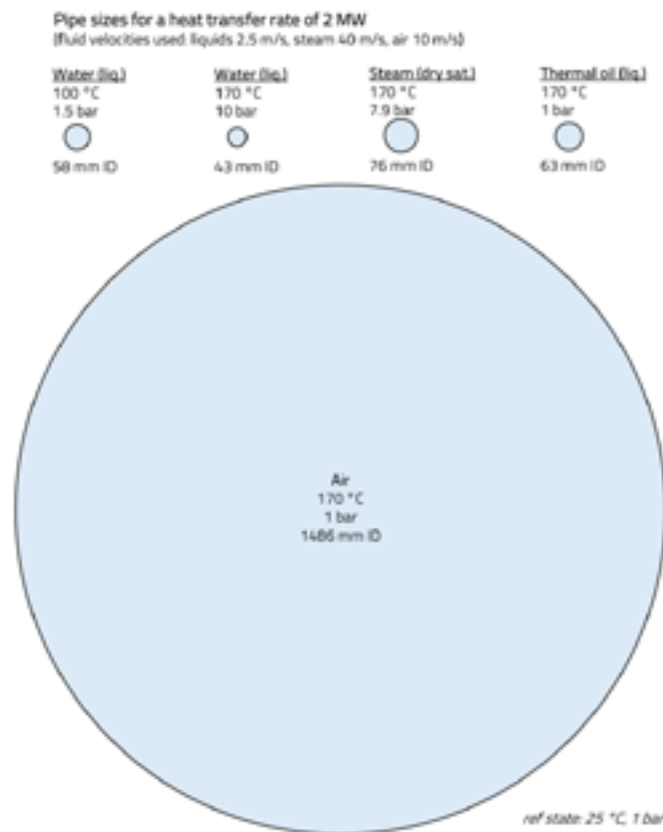


Figure 12: Pipe size comparison for a heat transfer rate of 2MW, for various heat transfer fluids. Cross-sections are shown to scale. Figure is roughly based on Ref.[36]. ID = internal diameter. FCA analysis.

Requirements for High Process Temperatures

The key conclusion from Figure 12 is that water and steam are effective heat transfer fluids (for low-temperature applications) due to their favorable thermo-physical properties, while air is more impractical for high-power transfer because of the excessive duct sizes required.

From Figure 12 it can be concluded that liquid water is the most effective heat transfer medium for low to medium temperature applications (typically below 200°C). However, at higher temperatures the pressure required to maintain water in the liquid phase increases substantially, necessitating thicker pipework and higher-cost components. In such cases, steam becomes the more practical option, as it can transfer large amounts of thermal energy without the need for excessive pressurization. At very high process temperatures, superheated steam may be used as well as other fluids such as air. (Note: the critical point of water is 374°C at 221 bar, above which distinct liquid and vapor phases no longer exist.)

Insulation Considerations

The pipe diameter required to transport a given thermal power is a key design parameter, as it directly determines the amount of insulation needed. The rate of heat leakage from the pipe can be estimated from Fourier’s law of heat conduction:

$$\dot{Q}_L = \frac{2\pi Lk(T_A - T_{env})}{\ln(r_o/r_i)} \quad (10)$$

where L is the pipe length, k is the thermal conductivity of the insulation, T_{env} is the temperature of the fluid inside the pipe, T_{amb} is the ambient temperature, and r_o and r_i are the outer and inner radii of the insulation, respectively. Therefore, larger pipe diameters require a greater quantity of insulation to maintain the same rate of heat leakage.

As an example, in the case of Figure 12(a), if glass wool insulation with a thermal conductivity of $k=0.038\text{W/m}\cdot\text{K}$ is used to limit the heat leakage rate to 0.025%/m, the required insulation thickness is 2.15 mm (i.e., a 2.5% thermal power loss over 100 m). However, for air in Figure 12(e), an insulation thickness of approximately 10 cm would be required to maintain the same loss rate. This demonstrates that the choice of heat transfer fluid is an important factor in pipe sizing and insulation design.

Pressure Losses

Figure 13 shows the pressure drop per unit length of pipe for each heat transfer fluid case. The pressure losses were calculated using the Darcy-Weisbach equation, with friction factors obtained from a Moody chart, assuming a pipe roughness of $\epsilon = 0.05\text{mm}$ (based on charts from pg. 431 in Ref. [37]). Under the operating conditions considered, all flows lie in the turbulent regime, and the pressure drop is strongly inversely correlated with pipe diameter and fluid density. This means that when air is used as the heat transfer fluid, the pressure loss per unit length is the lowest (and basically negligible). Note this analysis covers only major pipe losses and does not include so-called minor losses such as bends, tees, and valves.

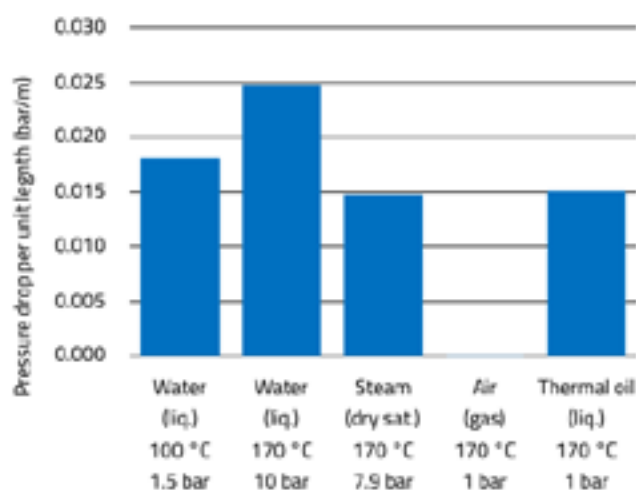


Figure 13: Pressure drop per unit length of pipe, for various heat transfer fluids. FCA analysis.

About Future Cleantech Architects:

We are a climate innovation think tank. We exist to close the remaining innovation gaps to reach net-zero emissions by 2050. To reach this objective, we accelerate innovation in critical industries where sustainable solutions are still in very early stages.



Further Information:

Magnolia Tovar
Director of Technologies and Impact
magnolia.tovar@fcarchitects.org

Or Contact Us:

Team:
mail@fcarchitects.org

Dr. James Lazenby
Cleantech Analyst
james.lazenby@fcarchitects.org

Address: Martin-Luther-Straße 29, D – 42853 Remscheid, Germany
e-mail: mail@fcarchitects.org



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