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Energy saving potential of high temperature heat pumps in the UK Food and Drink sector

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Abstract

Addressing GHG emissions from industry is vital to achieving decarbonisation targets. However, finding alternatives to many industrial energy requirements remains a challenge. Many processes in the food sector require heat at relatively low temperatures (i.e. 80°C to 200°C). High temperature heat pumps under development present a heat source that is efficient (especially if coupled with waste heat sources) and low carbon (especially if powered by decarbonised electricity). This study analysed their potential in the UK Dairy sub-sector and extrapolates this to the wider Food and Drink sector. There is potential to save approximately 164 kt-CO₂/yr in the modelled processes. Applied to similar processes across the Food and Drink sector, there is scope to save 2.6 Mt-CO₂/yr with projected 2030 grid electricity emissions factors. High temperature heat pumps have the potential to save energy and reduce GHG emissions. These GHG savings will increase further as the electrical grid continues to be decarbonised. While fuel cost savings are possible, these depend upon the processes and become more significant with projected fuel prices.

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1. Introduction

The Food and Drink sector is a significant source of Greenhouse Gas (GHG) emissions, accounting for over 11% of UK industrial emissions in 2015 (Fig. 1a) [1]. A large proportion of these emissions relate to the provision of low temperature heat (i.e. below 200°C) and so it is a clear target for the application of High Temperature Heat Pumps (HTHPs), [2] (also see Fig. 1b).

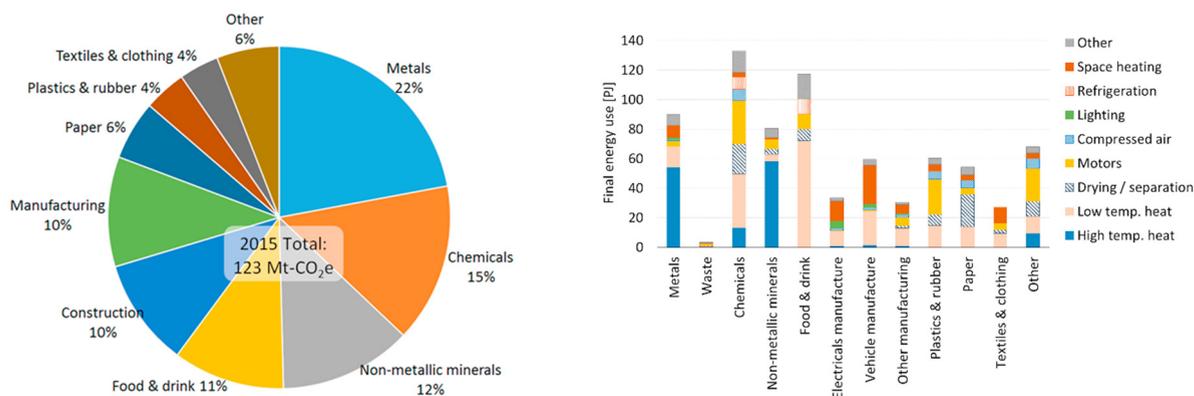


Fig. 1.(a): UK industrial GHG emissions; (b): Energy use in UK industrial sectors (source: [3])

The wide potential applicability of HTHPs and the opportunity that they present to save energy and (especially in conjunction with a decarbonised electricity supply) to reduce GHG emissions, means that they are the subject of extensive research and development efforts [4][5] (see section 2). With maximum supply temperatures of well over 140°C now possible, steam generation has been suggested as a good application for them [6].

Previous research has indicated that the use of industrial heat pumps might reduce non-Energy Intensive industry GHG emissions by 9% but also that financial incentives may be necessary to ensure their widespread use [7]. Other studies suggest high capital expenditure as a barrier to their uptake [8] and propose potential synergies with energy storage [9]. However, these studies tend to focus on the larger picture rather than the specific operating parameters (most significantly temperatures) that characterise processes. These temperatures are carefully considered in the present work as they are key to heat pump performance [5][10].

In this paper, we first present background and recent developments relating to HTHPs. A general overview of the use of heat in the UK Dairy sector is provided along with specific considerations regarding key processes. A concise methodology section explains the approach taken to estimate the GHG and financial energy cost savings that are available before these results are presented and conclusions drawn.

2. High temperature heat pump development

High Temperature Heat Pumps (HTHP) are undergoing active research and development. This section gives an overview of some of the HTHPs currently available.

For low- to medium-pressure steam replacement, the Kobelco Steam Grow double screw compressor heat pump (70–660 kW) with a capacity of 70kW–660kW has a Coefficient of Performance (COP) of 3.2 at 120°C and a COP of 2.5 at 165°C when upgrading waste heat at from 65°C and 70°C respectively [9]. The latter performance is achieved by an additional flash tank to generate low pressure steam and a steam compressor to raise the steam temperature to 165°C. R245fa used in this unit will need to be replaced due to its high Global Warming Potential (GWP) and R1233zd would increase performance by 7% in the heat pump element (Fig. 2b). Alternatively, a Viking Heat Engine heat pump (28–188 kW) utilising R133mzz(Z) can deliver heat up to 150°C has a COP of 2.5 when upgrading heat from 80°C to 140°C [11].

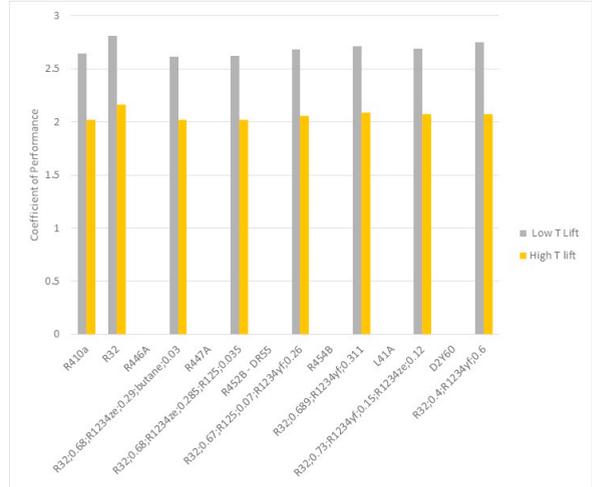


Figure 2. (a) Ulster University High Temperature Heat Pump Test Facility; (b) Performance of R410a Alternatives.

Milk processing applications and hot water provision see a number of candidate heat pumps in addition to those mentioned above. Ammonia units can be the Hybrid Energy, Star Refrigeration NeatPump and the GEA Refrigeration Grasso system. The NeatPump [12] (350 kW-15000 kW) delivering 90°C hot water from fjord water at 8°C to the Drammen district heating network has a COP of 3.05 when heating water from 60°C to 90°C.

Lower temperature units at <50°C hot water/air can utilise traditional heat pump technologies, although R410a is under pressure for its GWP. R32 has been proposed although it is flammable. Its performance is like that of R410a with COP’s of R32 and other alternatives [13], [14] are shown in Fig. 2b.

However, the overriding concern with the integration of heat pumps for upgrading waste heat in the UK food industry is the lack of access to higher grade heat sources. Food hygiene is a primary concern and therefore refrigeration condenser waste heat is often the most suitable to use. However, this then leads to process integration which again is under-utilised.

3. UK Dairy Industry

3.1. Overview

The Dairy subsector is responsible for approximately 10% of the Food and Drink sector’s direct GHG emissions in the UK and 12 PJ/yr of final energy use (9% of the Food and Drink total). In contrast to some of the Food and Drink subsectors, it is relatively concentrated with around 100 dairy sites in the UK, together processing almost 14 billion litres of milk annually. Approximately 48% of raw milk is consumed as liquid milk, 31% is used in cheese production and 21% is used for powder, yogurt and other products, as shown in Figure 3 [15]. These have several steps in common (e.g. pasteurisation, standardisation, homogenisation) and use several ancillary processes such as refrigeration and cleaning in place (CIP) [8].

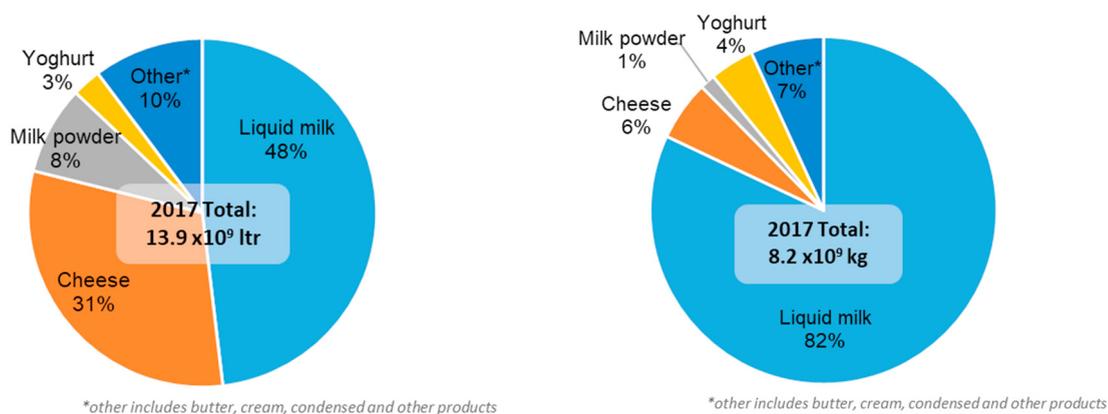


Fig. 3: UK dairy output in 2017 (a) by raw milk volume; (b) by mass of products (data from [15])

3.2. Pasteurisation and Cleaning in Place

The greatest heat requirements for liquid milk production are for pasteurisation and CIP. Pasteurisation is also the first stage of most dairy processes. These are illustrated in a flow diagram in the Supporting Information.

The type of pasteurisation determines the shelf life of the processed milk. There are three types of pasteurisation: low-temperature long time (LTLT), high-temperature short time (HTST) and Ultra pasteurisation, where the milk is heated to 63°C for 30 min, 72-75°C for 15-25s and 125-138°C for 2-4s respectively [16]. Most pasteurisation in the UK uses the HTST process [8].

In the HTST process, milk enters the pasteurisation heat exchanger (HX) at approximately 5°C before being raised to approximately 72°C and then cooled to 4-5°C. The majority (up to 95%, [16]) of the heat is regenerated; i.e. heat to warm the incoming milk is taken from the outgoing milk as it is cooled. This requires a temperature differential (or ‘heating approach’) of approximately 5-8°C [8], so additional cooling is required for the final cooling of the outgoing milk and additional heating is required at the highest temperature heating of the incoming milk. If heat is supplied in the form of steam, then this additional heat can be at a significantly higher temperature to aid heat transfer (e.g. 144°C). However, it is possible to supply this heat at a lower temperature (e.g. a realistic 10°C temperature differential would give 82°C) if a more effective HX were warranted by the resulting efficiency improvement [17].

The heat rejected by the refrigeration that supplies the additional cooling should be sufficient to supply a heat pump providing the top-up heating. This heat transfer could be indirectly coupled – if rejected to air, the heat from the refrigeration will typically be around 10°C higher than ambient air. Alternatively, a direct coupling is possible (e.g. using ammonia as refrigerant [9][17]) and may offer system integration advantages but will not be analysed in this study. It is not clear, however, that the heat rejected by the refrigeration stage would be sufficient to supply heat for other demands such as CIP – this is far more dependent upon specifics of the plant and site.

Cleaning in place (CIP) is also a major energy consuming process in the Dairy industry. The main purpose is to ensure hygiene and prevent fouling; cleaning the inside of process equipment without dismantling it. There is typically an initial rinse followed by a hot detergent (caustic or acid) wash and a final rinse [8]. Water for CIP is typically raised to 65-75°C [16] though sources differ slightly and in some cases the temperature may be higher.

While the CIP water temperature requirements are similar to those for pasteurisation (i.e. up to 80°C), this heat is used to warm water from its cold water supply temperature (around 12°C) and so the heat supply temperature can cover a range (rather than being at a constant temperature). This may make alternative heat pump cycles more effective (notably CO₂ / R744 in a transcritical cycle). However, the nature of the CIP process means that it may be unfeasible to recover this thermal energy from the equipment and waste water after cleaning.

3.3. Alternative heat regenerator options – Cheese and Yogurt

In cheese production, the pasteurisation, standardisation and separation processes are followed by coagulation, moulding or cheddaring and pressing. The milk can leave the pasteurisation process at a higher temperature (e.g. 34°C) to facilitate the further processes. A simple “drop in” replacement heat pump would need to supply heat at around 95°C. However, it should be possible to improve on the performance of this arrangement by using two heat pumps. An initial heat pump would provide initial low-temperature heating up to the maximum temperature at which outgoing milk could start to heat incoming milk (i.e. around 30°C). The regenerator would then heat this incoming milk from around 30°C to around 63°C. A second heat pump would finally take over to provide the highest temperature heat required in order to complete the pasteurisation process.

In yogurt production, the initial pasteurisation / standardisation process is similar to that for liquid milk. This is followed by a heating and culture stage that has similar temperature and heat requirements to the cheese pasteurisation process. Finally, a heating and homogenisation stage has similar requirements to the liquid milk process. Flow diagrams of typical processes are supplied in the Supplementary Information.

3.4. Powder milk

While the initial stages of powder milk production are similar to those for liquid milk / cheese, the majority of heat is required for the drying process due to the high latent heat of evaporation of the water to be removed. There are examples of successful implementations in similar applications (e.g. fryers [9], paper [5]) but the mixed phase / phase change involved in extracting the majority of latent heat poses some challenges [18] and alternatives such as liquid sorption may offer promise [19]. However, calculations in this study assume that heat is extracted at a sufficiently lower temperature such that full condensation is achieved.

4. Methodology

The analysis was conducted in three stages. (i) The liquid milk, cheese, yogurt and powder processes within the Dairy subsector were analysed individually to determine the potential energy saving that could be achieved. (ii) These potential efficiency improvements were used with data regarding the total uses of energy within the Dairy sector in order to estimate the financial energy cost and GHG savings that are possible across the sector. (iii) Appropriate process-level improvements were then extrapolated to similar uses in the rest of the UK Food and Drink sector in order to estimate the possible savings across the entire sector. These steps are described below but a spreadsheet containing details of the calculations is also available (see Supporting Information).

4.1. Heat pump performance

For each product process, the potential for relative improvement was determined by comparing an estimate of the current efficiency of heat delivery with the efficiency that could be achieved with a HTHP. The latter efficiency was determined as its coefficient of performance (COP) under the relevant temperature conditions. Heat supply temperatures were taken from data on the relevant sub-processes, on the basis of (a) the current heat supply temperature (typically a steam system) and (b) an optimised heat supply temperature (as suggested, for example, in [9] and referred to in Section 3). The heat source temperatures for the heat pumps were based on modelled UK climate data [20] that was allocated to 5K ‘bins’ with an additional 10K rise in the cases where sufficient heat is rejected from a co-located refrigeration system.

Where several heating sub-processes were involved, the weighted harmonic mean of the COPs that could be achieved for each sub-process was used. As heating sub-processes are typically in series with each other (e.g. milk is pasteurised, then fed to a culture tank), the weighting could be performed on the basis of each kg of raw milk passing through the plant. The temperature difference between the milk entering and leaving each sub-process was used with typical regenerator efficiency data [16] to determine the relative heat input requirements.

To map from the known COP data at specific temperature conditions (see Section 2) to the relevant temperature conditions for each process, the exergy efficiency of the heat pump at the known conditions was calculated and it was

assumed that this could be achieved at the alternative conditions (see [21] for details and discussion of this approach).

4.2. Aggregation to Dairy sector

The proportion of the total Dairy sector heating energy demand that relates to each of the four product processes was calculated using relative specific energy demands (per kg raw milk) [8], [18], [22] and the proportion of milk consumption relating to each [15]. These proportions were used to weight the estimated efficiency improvements possible for each product process and calculate total figures for the Dairy sector.

The fuel composition used to supply this heat (primarily through gas heating steam) was taken from the industrial *Useable Energy Database* (UED) [23], commissioned by the *UK Energy Research Centre*. This was used together with BEIS (UK government) data for GHG intensity [24] and reference / baseline projections for fuel prices and future electricity generation mix [25] to calculate the impacts of the improved energy efficiency.

4.3. Aggregation to Food and Drink sector

The efficiency improvements relating to the first (conservative) option for steam generation in milk pasteurisation were considered to be the most conservative and appropriate results to extrapolate to the wider Food and Drink sector's general use of steam. The efficiency improvements relating to drying for milk powder were considered most appropriate where the steam is used to achieve drying. These figures were used with data on steam and cleaning used in the Food and Drink sector [23] to scale up the estimates of potential savings.

5. Results

Pasteurisation of liquid milk could be performed with a HTHP achieving a COP of 1.9 if supply temperatures are maintained at present levels or 2.6 if they are better optimised to the process requirements. CIP water could be heated with a COP of 2.9 if heat is supplied at the highest temperature or 4.8 if it is matched to a temperature glide. For cheese production, a COP of around 2.0 could be improved to over 6 by rearranging the regenerator to better suit heat pump characteristics (see Section 3.3).

Across the Dairy sector, these COPs relate to a total electrical energy inputs to the milk-heating processes of 43% of the current corresponding fuel energy input if HTHPs supply heat at the same temperature as the boilers they replace. If the optimisations referred to above are made, the electrical energy input to processes could be 25% of current fuel energy input. Additionally, the electrical energy input required for CIP could be as low as 20% of the current corresponding fuel energy input.

The GHG emissions and fuel cost savings that these reductions in energy requirements relate to, depend upon the emissions factors and prices of the respective fuels and electricity. These will vary with time. Figure 4 shows the likely progression of the relative CO₂ emissions and financial energy costs, assuming BEIS (UK government) projections. The reduction in the CO₂ emissions associated with the operation of the HTHPs between 2015 and 2017 is notable. There has been a significant reduction in the UK grid carbon intensity over this period and it is possible that earlier estimates of potential CO₂ emissions savings may underestimate the opportunity. Our calculated potential savings are higher than those estimated by the Carbon Trust (82 kt-CO₂e/yr) [8] but this may also relate to alternative constraints.

Across the broader UK Food and Drink sector, the aggregation in this analysis resulted in a slightly more conservative estimate than for the Dairy sector. A reduction of 2.1 to 2.2 Mt-CO₂/yr (69% to 72% of present) should be possible with current electrical generation mix (the higher saving relates to an alternative in which development of alternative refrigerants results in a 10% improvement in HTHP COPs). This reduction would increase to 2.6 to 2.7 Mt-CO₂/yr (85% to 86%) with the projected 2030 grid carbon intensity.

Initially, the overall effect on financial energy costs is negative. It is estimated that across the Food and Drink sector, the electricity to operate the HTHPs would cost around £88M to £148M (23% to 38%) more per year than the current fuels with 2017 prices. However, this cost penalty would reverse to a saving of £53M/yr to £11M/yr (9% to 19%) with projected 2030 energy prices.

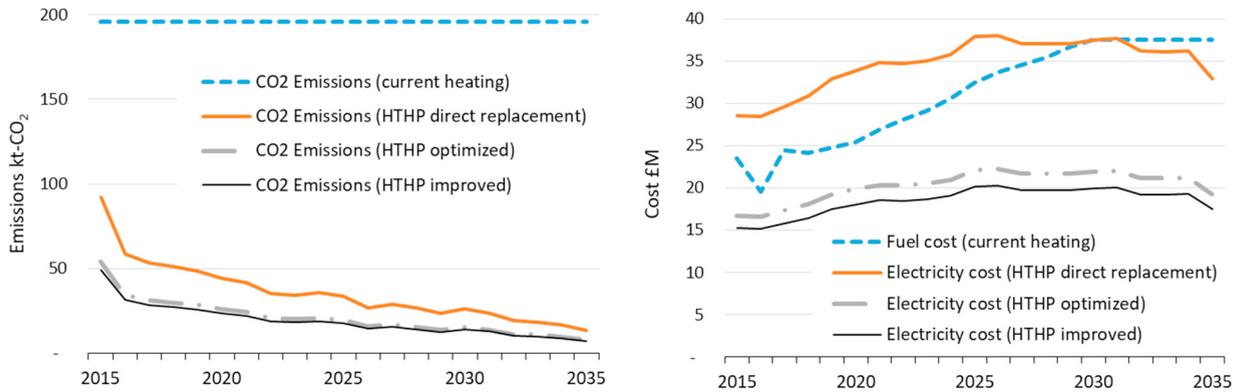


Fig. 4: Future impacts due to provision of process heat and CIP to UK Dairy sector (a) CO₂ emissions; (b) Fuel / electricity cost

6. Conclusions

High temperature heat pumps have the potential to reduce the energy requirements of the Dairy and wider Food and Drink industries. Their use is a very effective option for reducing GHG emissions. The rapid rate of decarbonisation in the UK grid since 2015 means that the potential for savings has significantly increased since then. The increase of their potential savings should continue with the projected grid carbon intensity to the 2030s.

While savings in financial energy costs can be achieved, these vary between processes. Financial support may be necessary to encourage the wider adoption of HTHPs.

The use of refrigeration condensers as a heat source helps the performance of the HTHPs, however it is not clear that a similarly suitable source will be available in the majority of applications. It is likely that development of HTHPs that can operate from an ambient temperature source will increase their scope for applications.

The sensitivity of their performance to the temperature lift that they operate between means that optimising the installation of HTHPs and the design of the related balance of plant is key to achieving maximum savings.

This research clearly supports the case for continued research to improve HTHP performance, given the potential advantages of their use. However, it also illustrates that research to increase the temperature range that they operate between and to optimise practical aspects of their operation and integration with balance of plant is warranted.

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Data access: All data produced during this study are freely available in the Supporting Information. This includes calculation steps, background data and detailed results in an Excel workbook, available at <https://doi.org/10.15125/BATH-00555>.

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