Combining High Temperature Heat Pumps with other Technologies to Maximize the Decarbonization of a Yogurt Production Plant

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Abstract:

Industrial process heat is essential in many industries, such as steel, chemicals, food processing, and paper manufacturing. However, at present this thermal need is mainly satisfied by burning fossil fuels, which makes these industries be responsible for a significant global warming contribution and leads high temperature heat pumps (HTHPs) to be identified as the most promising eco-friendly alternative.
In this work a comprehensive energy, economic and environmental analysis of a R601 HTHP combined with other technologies was performed to replace a natural gas-fueled boiler in a yogurt production plant needing saturated steam at 11.35 bar and 186 °C. The investigated technologies were an electrical boiler, a natural gas-fueled boiler and a biogas-fueled boiler. The results were obtained for both the European context and the Danish one. The outcomes for the European context suggested that the HTHP with the electrical boiler is a suitable replacement for the natural gas-fueled boiler for price ratios up to 1, whereas the electrical boiler should be replaced by a natural gas one for higher price ratios. As for the selected day in Denmark, switching from a natural gas-fueled boiler to an electrical one with respect to the price ratio was found to lead to an operating cost reduction of 26.9 %.

Keywords:

Boiler replacement; HTHP; Industrial Heat Decarbonization; Industrial Process Heat; R601.

1. Introduction

Industrial process heating represents about 18 % of the annual global greenhouse gas (GHG) emissions. Around 26 % of this thermal demand is based on temperature levels between 100 °C and 200 °C and mainly satisfied using fossil fuels [1]. As a consequence, in the attempt to significantly decarbonize this industry, a strong focus is being given to electrification and waste heat recovery, thus leading HTHPs to take centre stage in the green transition of process heating.

Among the natural refrigerants for HTHPs, R601 is a promising working fluid for HTHPs. Yin et al. [2] reported a coefficient of performance (COP) increase of 3.4 % and 3.8 % when using R601 in comparison with R245fa and R600 in a HTHP employing waste heat from a textile industry to generate steam at 160 °C, respectively. Sulaiman et al. [3] showed that R1233zd(E), R1336mzz(Z), and R601 can enhance the COP of HTHPs providing heat at 100-150 °C by up to 8.32 %, 11.68 % and 19.61% compared to R245fa, respectively. Shi et al. [4] evaluated that R601 offers higher COPs than R601a in two-stage systems supplying heat at 160-200 °C. The use of R601 in HTHPs was found to allow for higher COPs than R1336mzz(Z) HTHPs for supply temperatures between 100 °C and 150 °C [5] as well as at supply temperatures between 140 °C and 170 °C [6]. However, high supply temperatures further increase the technological challenges of HTHPs, such as the need for additional compression stages or uncommon and expensive compression techniques, high discharge temperatures and pressure, advanced and costly materials, which result in a considerable investment cost.

In order to decarbonize industrial process heating while limiting the technological issues of HTHPs, the present work aims at evaluating the economic and environmental benefits from replacing a natural gas-fueled boiler with a R601 HTHP combined with other technologies. At present, in fact, the available techno-economic evaluations have mostly focused on the use of one specific technology [7]. The investigated technologies combined with the HTHP were an electrical boiler, a natural gas-fueled boiler and a biogas-fueled boiler. The investigation was based on a yogurt production facility requiring saturated steam at 11.35 bar and 186 °C. In addition, the average natural gas price and emission factors in Europe as well as a representative day with the actual electricity price varying over 24 hours for Denmark were considered.

The work is organized as follows: the investigated case study and model system as well as the developed thermodynamic model are described in Section 2, while the results are presented in Section 3. Finally, the conclusions are summarized in Section 4.

2. Materials and methods

2.1. Investigated case study

The yogurt production facility investigated by Jokandan et al. [8] was used as the case study, which relied on a natural gas-fueled boiler to heat 6.3 kg/s of compressed liquid water from 95.2 °C (at 11.35 bar) up to superheated vapour at 186 °C (at 11.35 bar).

Firstly, the investigation was carried out considering the average conditions in Europe according to the parameters summarized in Table 1.

Table 1. *Parameters considered for Europe.*

Parameter	Selected value
Natural gas cost	40 €/MWh
Biogas cost	54 €/MWh
Price ratio (i.e., household ratio of electricity price to natural gas price)	From 0.5 to 4.0
$CO_{2\ equivalent}$ emission factor for natural gas combustion	200 kg/MWh
$CO_{2\ equivalent}$ emission factor for electricity generation	231 kg/MWh

In addition, the study also considered the specific case of Denmark, for which the hourly average electricity rate for June 2025 (Figure 1) was considered and obtained from Ember [9]. All the other parameters used for Denmark are summarized in Table 2.

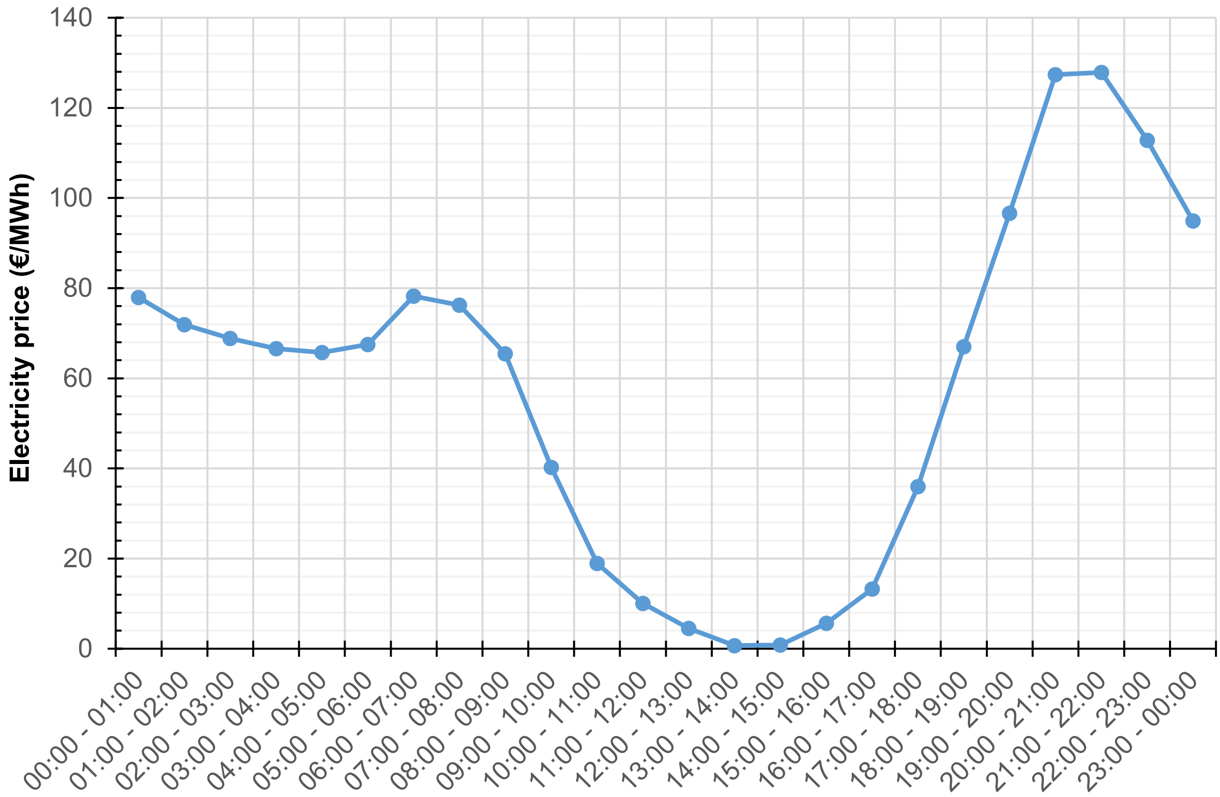

Figure. 1. *Hourly average electricity rate in Denmark in June 2025.*

Furthermore, the efficiency was selected to be equal to 0.90 for both the biogas- and the natural gas-fueled boilers and equal to 0.95 for the electrical boiler [10].

Finally, the specific total investment cost for the electrical boiler ($TIC_{spec\ EL}$), natural gas-fueled boiler ($TIC_{spec\ NG}$) and biogas-fueled boiled ($TIC_{spec\ BIOGAS}$) were taken as 210 €/kW, 103 €/kW and 103 €/kW [10], respectively. As for the HTHP, its specific total investment cost ($TIC_{spec\ HTHP}$) was estimated using Eq. (1) [11].

$$TCI_{spec\ HTHP} = 3157 \cdot \dot{Q}_{condenser}^{-0.322} \qquad (1)$$

Table 2. *Parameters considered for Denmark.*

Parameter	Selected value
Natural gas cost	40 €/MWh
Biogas cost	64 €/MWh
CO_2 equivalent emission factor for natural gas combustion	200 kg/MWh
CO_2 equivalent emission factor for electricity generation	120 kg/MWh

2.2. Investigated solution

The investigated solution, which is schematized in Figure 2, consisted of a R601 HTHP used for heating 6.3 kg/s of compressed liquid water from 95.2 °C to an intermediate temperature within the condenser before achieving the targeted temperature (i.e., 186 °C) with the aid of either an electrical boiler or a natural gas-fueled boiler or a biogas-fueled boiler. A natural gas-fueled boiler was used as the baseline.

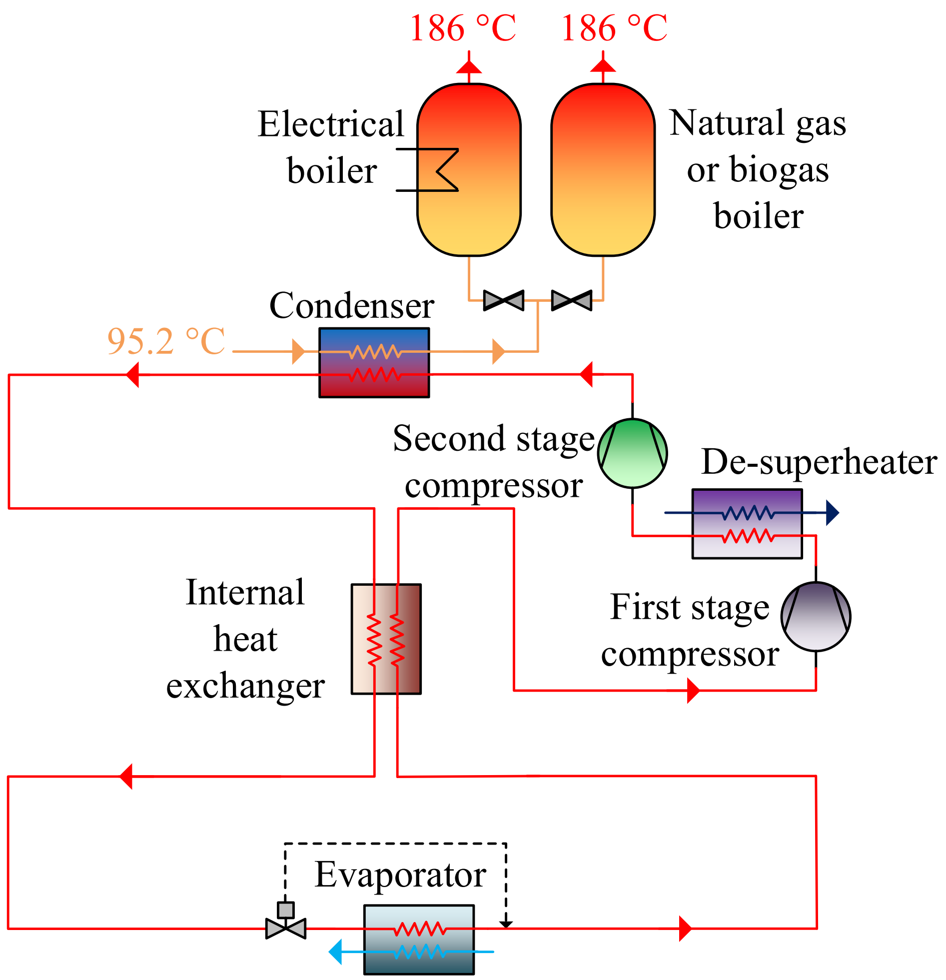

Figure. 2. *Schematics of the investigated solution.*

The subcooled liquid leaving the high pressure side of the internal heat exchanger is isenthalpically expanded in the expansion valve before it vaporizes in the evaporator. The resulting superheated vapour is further heat up in the low pressure side of the internal heat exchanger to avoid wet compression. Then, the refrigerant is compressed in the first stage compressor to an intermediate pressure and cooled down in the de-superheater before it is drawn by the second stage compressor. Finally, the required heating capacity is provided in the condenser where the refrigerant is turned into saturated liquid.

2.3. Thermodynamic model

All the simulation models were developed using Engineering Equation Solver (EES) [12] and based on the mass and energy balances at component level at steady state conditions. The following assumptions were made:

- negligible heat gains/losses from the components;
- negligible pressure drops in the heat exchangers and pipes;
- negligible kinetic and potential energy variations in the components;
- expansion process within the expansion valve was assumed to be isenthalpic;
- no subcooling at the outlet of the condenser;
- $T_{condensation} – T_{sink\ out}$ = 1 K within the condenser;
- $T_{evaporation}$ = 60 °C;
- compressor isentropic efficiency = 0.7;
- evaporator superheating degree = 10 K;
- superheating degree at the suction of the 2nd stage of compression = 15 K to avoid wet compression;
- effectiveness of the internal heat exchanger = 0.3 to avoid wet compression and too high discharge temperatures;
- maximum compression ratio = 4 to avoid unrealistic discharge temperatures;
- intermediate pressure = $(P_{evaporation} \cdot P_{condensation})^{\wedge 0.5}$.

3. Results and discussion

3.1. Results for Europe

The operating cost, the $CO_{2\ equivalent}$ emissions and the TIC obtained assuming that the whole hourly industrial process heating demand was covered by a natural gas-fueled boiler were equal to 667.4 €, 3854 $kg_{CO2\ equivalent}$ and 1718.6 k€ for the European context, respectively. The results related to the minimization of the operating costs for the three investigated solutions are summarized in Table 3. Considering a price ratio of 0.5 (e.g., Norway, Finland, Sweden), the results revealed that the HTHP integrated with a natural gas-fueled boiler needs to be operated to provide $T_{sink\ out}$ = 150 °C, resulting in a reduction of 7.7 % in the operating costs and 17.6 % in the $CO_{2\ equivalent}$ emissions, respectively. The low electricity price also led the HTHP to need to operate at $T_{sink\ out}$ = 150 °C when combined with the electrical boiler, reducing the operating costs by 55.2 % and the CO_2-equivalent emissions by 10.3 %. As for the price ratios between 1 (e.g., North Macedonia) and 3 (e.g., Romania, Denmark, Germany), the HTHP was forced to operate at lower condenser temperatures due to the increase in the electricity price, resulting in operating cost and $CO_{2\ equivalent}$ emission reductions from 1.1 % to 5.5 % and from 3.1 % to 4.9 % as integrated with a natural gas-fueled boiler. In order to reduce the operating costs the use of the HTHP with the electrical boiler was supposed to be used only for price ratios up to 1 (-10.3 %). Furthermore, for price ratios up to 1 the integration of both the natural gas-fueled boiler and the electrical boiler led to significant increases in the TIC. i.e., by 54.6 % and 138.7 %, suggesting the enormous need to decrease the cost of HTHPs (together with stricter GHG emission taxes). The combination of the HTHP with a natural gas boiler implied TIC increases ranging from 33.1 % to 48.1 % for price ratios from 1 to

3. If price ratios above 3 were considered, the results showed that the HTHP with the natural gas-fueled boiler can provide similar operating costs to the baseline with $CO_{2\ equivalent}$ emission reductions by 3.1 %, whereas the use of the electrical boiler with the HTHP was found to be unsuitable. Finally, it is worth remarking that on the one hand, the HTHP integrated with the biogas-fueled boiler was found to increase the operating costs by up to 33.5 % for all the considered price ratios as a consequence of the high biogas price. On the other hand, these technologies were able to provide the highest $CO_{2\ equivalent}$ emission reductions (by up to 95.2 %) as no $CO_{2\ equivalent}$ releases were associated with the biogas combustion.

3.2. Results for Denmark

The operating cost, the $CO_{2\ equivalent}$ emissions and the TIC obtained assuming that the whole daily industrial process heating demand was covered by a natural gas-fueled boiler were equal to 16017.6 €, 80088.0 $kg_{CO2\ equivalent}$ and 1718.6 k€ in Denmark, respectively. The combination of the HTHP with the natural gas-fueled boiler (Figure 3) was found to reduce the operating cost and the environmental impact by 4.6 % and 5.8 %, respectively. However, the total cost investment would have increased by 60 % due to current very high cost of HTHPs. On the one hand, integrating an electrical boiler or a biogas-fueled boiler would have allowed an enormous decrease in emissions (by 46.2 % and 97.7 %, respectively). On the other hand, both the operating cost (by 30.4 % and 50.3 %) and the total investment cost (by 138.7 % and 60.0 %, respectively) would have increased. The best combination was using the HTHP and the natural gas-based boiler from 0:00 to 9:00 and again from 18:00 to 0:00 and switching to the electrical boiler from 9:00 to 18:00. Consistently with the results obtained in the previous subsection, this was due to the fact that the electrical boiler is more convenient than the natural gas-fueled boiler when the price ratio is below 1. This combination was found to lead to energy savings and emission reductions by 26.9 % and 20.4 %, respectively. However, the total investment cost would have been 234.3 % higher.

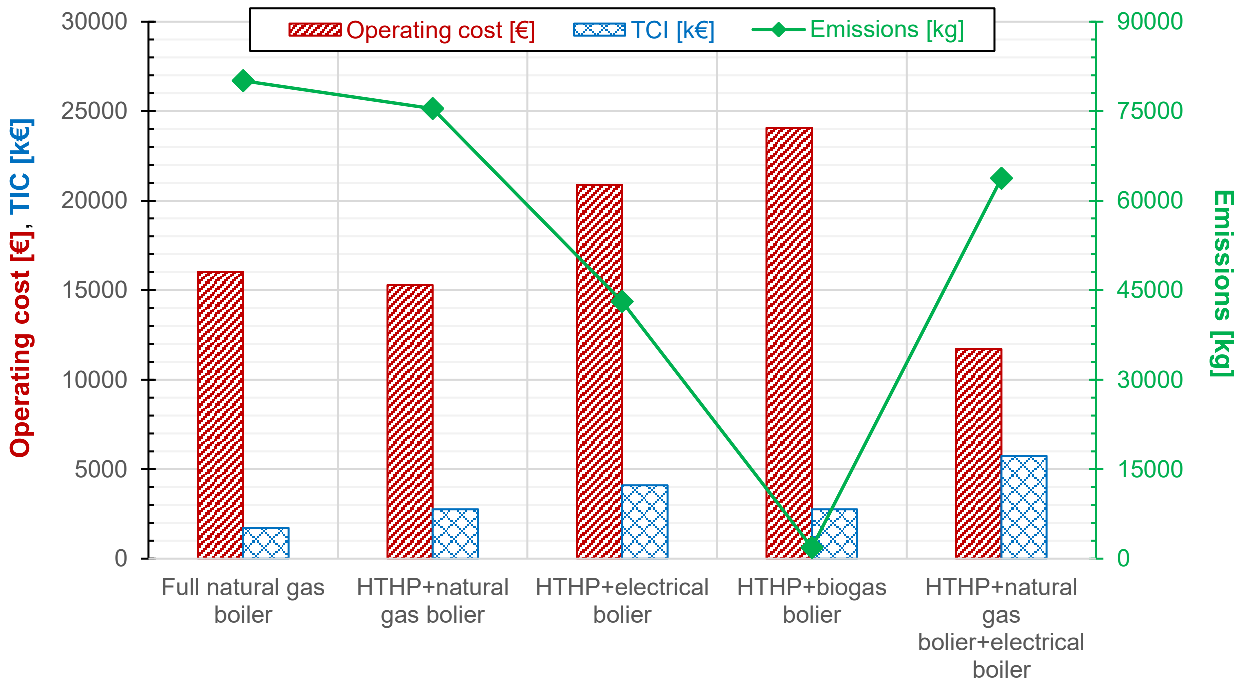

Figure. 3. *Lowest operating costs over the considered 24 h for the investigated solutions in Denmark.*

It is worth remarking that assuming $T_{condensation} – T_{sink\ out}$ = 1 K affected the results of both Subsection 3.1 and Subsection 3.2 negatively. In fact, a proper pinch point analysis would have led to a lower condensation temperature and thus to higher energy savings. Also, in order to have more reliable results, the study should have involved an assessment on an annual basis and a proper refrigerant and HTHP layout selection. It is also important to highlight the need to decrease the total cost investment (together with stricter GHG emission taxes) to make HTHPs competitive.

Table 3. *Lowest operating costs with respect to the price ratios for the investigated solutions in Europe.*

Price ratio [-]	*R601 HTHP + natural gas boiler*				*R601 HTHP + electrical boiler*				*R601 HTHP + biogas boiler*			
	$T_{sink\ out}$ [°C]	*Operating cost [€]*	*Emission [kg]*	*TIC [k€]*	*$T_{sink\ out}$ [°C]*	*Operating cost [€]*	*Emission [kg]*	*TIC [k€]*	*$T_{sink\ out}$ [°C]*	*Operating cost [€]*	*Emission [kg]*	*TIC [k€]*
0.5	150	616.3	3174	2657.4	150	299.3	3457	4102.0	150	827.0	162.7	2657.4
1.0	150	630.4	3174	2657.4	150	598.7	3457	4102.0	150	841.1	162.7	2657.4
1.5	140	643.1	3182	2545.8	150	898.0	3457	4102.0	150	855.2	162.7	2657.4
2.0	130	651.1	3203	2423.5	150	1197.0	3457	4102.0	140	867.7	111.1	2545.8
2.5	120	656.4	3233	2287.0	150	1497.0	3457	4102.0	130	876.4	71.9	2423.5
3.0	120	660.0	3233	2287.0	150	1796.0	3457	4102.0	130	882.7	71.9	2423.5
3.5	120	663.7	3233	2287.0	150	2095.0	3457	4102.0	120	887.0	42.3	2287.0
4.0	120	667.3	3233	2287.0	150	2395.0	3457	4102.0	120	890.7	42.3	2287.0

4. Conclusions

The decarbonization of industrial process heat represents one of the most pressing challenges in the transition toward climate-neutral energy systems. Among food processing industries, yogurt production is particularly energy-intensive due to its reliance on multiple thermal processes. These processes typically require heat at temperatures ranging from 60 °C to over 180 °C, which is conventionally supplied by natural gas-fueled boilers. As a result, dairy plants contribute significantly to GHG emissions, highlighting the need for efficient and sustainable alternatives.

HTHPs have recently gained attention as a promising solution for electrifying industrial heat demand with high efficiencies while reducing global warming contribution. Yet, achieving high supply temperatures significantly intensifies the technological challenges associated with HTHPs, such as need for multi-stage compression or specialized and costly compression technologies, elevated discharge temperatures and pressures and the use of advanced and expensive materials. As a result, these factors contribute to substantially higher capital investment costs.

To support the decarbonization of industrial process heating while overcoming the technical constraints of HTHPs, this study has evaluated the energy, economic and environmental performance of a R601 HTHP combined with other technologies to replace a natural gas-fueled boiler in a yogurt production plant needing saturated steam at 11.35 bar and 186 °C. The studied technologies are an electrical boiler, a natural gas-fueled boiler and a biogas-fueled boiler. The investigation has been performed for both the European context and the Danish one (over a selected 24 hours).

As for the European context, the HTHP with the electrical boiler has been found to be a suitable replacement for the natural gas boiler for price ratios up to 1, whereas the electrical boiler should be replaced by a natural gas boiler for higher price ratios. As for the selected day in Denmark, switching from a natural gas-fueled boiler to an electrical one with respect to the price ratio resulted in an operating cost and environmental impact reduction of 26.9 % and 20.4 %, respectively.

To conclude, the combination of HTHPs with other technologies can be an appropriate replacement for natural gas-fueled boilers. However, the total cost investment of HTHPs needs to be significantly reduced, while stricter GHG emission taxes are implemented.

Nomenclature

COP	coefficient of performance,
GHG	greenhouse gas
HTHP	high temperature heat pump
T	temperature, °C
TIC	total investment cost, k€

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