Potential for optimal operation of Industrial Heat Pumps with Thermal Energy Storage for emissions and cost reduction

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Abstract:

This paper presents an optimal control strategy for an industrial heat pump with thermal energy storage (TES) in a brewery. The objective of the study is to investigate the potential benefits of load shifting using the TES and the impact of the fluctuations of electricity price, solar radiation and carbon intensity of the grid on the system operating costs and CO_2 emissions. The study is conducted using a simulation model, and the results show that by utilizing the TES, the operating costs and CO_2 emissions of the heat pump can be reduced significantly. The optimal operation of the heat pump is found to be highly dependent on the electricity price and the efficiency of the heat pump. Furthermore, the study shows that cost-optimal operation leads to a reduction in CO_2 emissions and vice versa. The study highlights the potential benefits of implementing such an optimal control strategy in industrial settings, where energy demands are high and subject to electricity price fluctuations. However, accurately predicting parameters such as electricity price, solar radiation, and energy demand is crucial for the optimal control strategy to be effective. Implementing a predictive model that can accurately predict these parameters is necessary to exploit the potential of the optimal control strategy.

Keywords:

thermal energy storage, industrial heat pump, solar energy, heat recovery, energy efficiency, load shifting

1. Introduction

The transition from fossil fuels to renewable energy sources in the power sector presents a significant opportunity for the electrification of industry and the implementation of Power-to-Heat technologies, which would yield substantial environmental benefits. High Temperature Heat Pumps (HTHP) are capable of supplying heat up to 150 °C with high energy efficiency by upgrading industrial waste heat [1]. However, with the share of renewables in electricity production increasing, there is an emerging imbalance between energy production and consumption, necessitating new grid management approaches.

Thermal energy storage (TES) can play a vital role in enhancing grid flexibility by providing a means to balance the intermittent nature of renewable energy sources. TES systems enable excess thermal energy to be stored during times of high availability and used later during periods of low availability, such as during peak demand hours [2]. While TES have already been used for industrial waste heat recovery [3], the use of this technology may be key to help integrate HTHP and electrify industrial process heat.

While the combination of heat pumps and thermal energy storages to offer demand flexibility for domestic and district heating systems has been investigated in several papers [4]–[8], the industrial application is generally overlooked [9].

The objective of this study is to assess the capacity of an industrial heat pump system, when integrated with TES, to lower CO_2 emissions and operating expenses by optimizing its operating schedule. Additionally, this study examines the potential benefits of varying the system size, considering investment expenses, and conducts a sensitivity analysis of the parameters that mostly impact the results.

1.1 Case study

A brewery in Faxe, Denmark, previously described by Hansen et al.[10] is used as the case study throughout this work to evaluate the potential savings from the implementation of optimal heat pump operation. This industrial facility has an indirect heat recovery system that recovers heat from high-temperature processes and stores it in a 375 m^3 (V_{tank}) to later distribute it to various processes. The external heating is supplied by a

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natural gas boiler through a pressurized hot water loop with a forward temperature of 145 °C. The cooling system currently rejects heat to the ambient through cooling towers. Additionally, the brewery installed a 12 MW ($P_{\mathrm{PV,nom}}$) photovoltaic (PV) park to reduce its electricity consumption.

As a measure to reduce the consumption of natural gas and contribute to its carbon neutrality goals, the facility will install a 1.2 MW ($Q_{\mathrm{HP,max}}$) heat pump to upgrade the heat from the condensers of the refrigeration system to deliver it to the heat recovery tank. This heat pump is the focus of this study. The heat source of the heat pump is stable throughout the year and the heat recovery tank offers an opportunity to optimize its operation.

A schematic representation of the system to be studied is given in Figure 1:

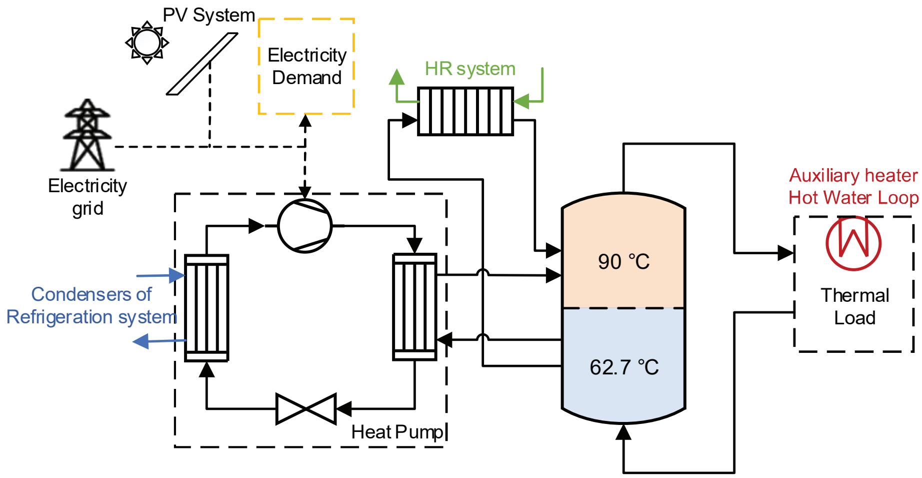

Figure 1:Schematic of the studied heat pump and TES system

Hourly data from the process demand ($Q_{\mathrm{Load},t}$), heat recovery system ($Q_{\mathrm{HR},t}$) and electricity consumption ($P_{\mathrm{load},t}$) is given by the brewery in order to calculate the potential savings from the optimal HP operation.

2. Methods

Hourly-based Time-series data of the electricity prices, carbon emission intensity and solar radiation, in combination with the thermal load, heat recovery and electricity consumption of the facility are used to optimize the operation of the heat pump delivering heat to the heat recovery tank. The optimization is performed in Python using Pyomo [11].

The study compares the CO_2-optimal and cost-optimal strategies with a base-case scenario that assumes no smart control. Additionally, an investigation is included to determine the optimal tank and heat pump size and to highlight the importance of thermal energy storage (TES) in the proper integration of the heat pump.

2.1. Preliminary calculations

In every case, the Coefficient of Performance (COP) of the heat pump is considered constant. It is calculated considering a fixed source temperature (T_{source}), which corresponds to the temperature of the condensers of the refrigeration system; fixed sink inlet ($T_{\mathrm{sink,in}}$) and outlet ($T_{\mathrm{sink,out}}$) temperatures corresponding to the temperatures in the tank; and a fixed Lorenz efficiency (η_{Lor}).

$$\mathrm{COP} = \eta_{\mathrm{Lor}} \cdot \frac{T_{\mathrm{sink,out}} - T_{\mathrm{sink,in}}}{T_{\mathrm{source}} \cdot \ln \frac{T_{\mathrm{sink,out}}}{T_{\mathrm{sink,in}}}} \tag{1}$$

The capacity of the tank ($E_{\mathrm{tank,max}}$) is also fixed for the entirety of the simulation. It is calculated as:

$$E_{\mathrm{tank,max}} = V_{\mathrm{tank}} \cdot \rho \cdot c_p \cdot \left(T_{\mathrm{sink,out}} - T_{\mathrm{sink,in}}\right) \tag{2}$$

The output from the PV system ($P_{\mathrm{PV},t}$) is calculated from the dataset representing a “Design Reference Year” on horizontal solar radiation ($G_{h,t}$) from the Danish Meteorological Institute [12] and the incidence angle (θ_t), dependant on the hour, day of the year, location, and tilt of the panels.

$$P_{\mathrm{PV},t} = P_{\mathrm{PV,nom}} \cdot \frac{G_{h,t}}{G_{\mathrm{STC}}} \cdot \cos(\theta_t) \tag{3}$$

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2.2. Model description

The calculation of the annual cost and carbon emissions is based on the energy balance on the tank for every timestep (*t*) as well as the balance on the electricity used and the electricity generated from the PV panels.

In this study, the tank is considered a perfectly stratified tank, with two distinct temperature levels ($T_{\text{sink,in}}$ and $T_{\text{sink,out}}$) without mixing or ambient losses. The energy on the tank on the following timestep ($E_{\text{tank},t+1}$) is calculated using Eq. (4) from the current energy level ($E_{\text{tank},t}$), the heat recovered ($Q_{\text{HR},t}$), the energy output of the HP ($Q_{\text{HP,max}} \cdot x_t$) and the thermal demand ($Q_{\text{Load},t}$).

$$E_{\text{tank},t+1} = \begin{cases} 0 & if \quad E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t - Q_{\text{Load},t} < 0 \\ E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t - Q_{\text{Load},t} & if \quad 0 < E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t - Q_{\text{Load},t} < E_{\text{tank,max}} \\ E_{\text{tank,max}} & if \quad E_{\text{tank,max}} < E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t - Q_{\text{Load,t}} \end{cases} \tag{4}$$

Therefore, the energy from the heat recovery system to be curtailed ($Q_{\text{curt},t}$) and the energy that must be supplied to the load using the auxiliary boiler ($Q_{\text{boiler},t}$) are also calculated using Eq. (5) and Eq. (6):

$$Q_{\text{curt},t} = \begin{cases} 0 & if \quad E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t - Q_{\text{Load},t} < E_{\text{tank,max}} \\ E_{\text{tank,max}} - E_{\text{tank,t}} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t - Q_{\text{Load},t} & if \quad E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t - Q_{\text{Load},t} > E_{\text{tank,max}} \end{cases} \tag{5}$$

$$Q_{boiler,t} = \begin{cases} 0 & if \quad E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t > Q_{\text{Load},t} \\ Q_{\text{Load},t} - E_{\text{tank},t} + Q_{\text{HR},t} + Q_{HP,\text{max}} \cdot x_t & if \quad E_{\text{tank},t} + Q_{\text{HR},t} + Q_{\text{HP,max}} \cdot x_t < Q_{\text{Load},t} \end{cases} \tag{6}$$

Finally, the operational costs and CO_2 emissions can be calculated. The price of electricity ($p_{\text{elec},t}$) and natural gas ($p_{\text{gas},t}$) in Denmark are found in Energinet [13] and the corresponding taxes as of 2021 are applied ($p_{\text{elec,taxes}}$). The data on the carbon intensity (CI_{elec}) is taken from ElectricityMaps database [14], and for the combustion of natural gas (CI_{gas}), a value of 200.8 g/kWh is considered [15].

The costs and emissions related to the combustion of natural gas are calculated using Eq. (7) and Eq. (8) respectively:

$$\text{Cost}_{\text{gas}} = \frac{1}{\eta_{\text{boiler}}} \cdot \sum_{t=0}^{t=n} Q_{\text{boiler},t} \cdot p_{\text{gas},t} \tag{7}$$

$$\text{CO}_{2\,\text{gas}} = \frac{\text{CI}_{\text{gas}}}{\eta_{\text{boiler}}} \cdot \sum_{t=0}^{t=n} Q_{\text{boiler},t} \tag{8}$$

For the electricity, the production from the PV panels is considered. The cost and emissions from the purchased electricity is calculated using Eq. (9) and Eq. (10) respectively:

$$Cost_{\text{elec}} = \sum_{t=0}^{t=n} \begin{cases} \left(p_{\text{elec},t} + p_{\text{elec,taxes}}\right) \cdot \left(\frac{Q_{\text{HP,max}} \cdot x_t}{COP} + P_{\text{load},t} - P_{PV,t}\right) & if \quad \frac{Q_{\text{HP,max}} \cdot x_t}{COP} + P_{\text{load},t} > P_{\text{PV},t} \\ p_{\text{elec},t} \cdot \left(\frac{Q_{HP,\text{max}} \cdot x_t}{COP} + P_{\text{load},t} - P_{PV,t}\right) & if \quad \frac{Q_{\text{HP,max}} \cdot x_t}{COP} + P_{\text{load},t} < P_{\text{PV},t} \end{cases} \tag{9}$$

$$CO_{2\,\text{elec}} = \sum_{t=0}^{t=n} \begin{cases} CI_{\text{elec},t} \cdot \left(\frac{Q_{\text{HP,max}} \cdot x_t}{COP} + P_{\text{load},t} - P_{\text{PV},t}\right) & if \quad \frac{Q_{\text{HP,max}} \cdot x_t}{COP} + P_{\text{load},t} > P_{\text{PV},t} \\ 0 & if \quad \frac{Q_{\text{HP,max}} \cdot x_t}{COP} + P_{\text{load},t} < P_{\text{PV},t} \end{cases} \tag{10}$$

2.3. Heat Pump operation

2.3.1. Base case operation

The basic control strategy of the heat pump does not consider fluctuations on electricity price or CO_2 emission intensity, nor the power produced by the PV system. In this case, the operation of the heat pump is solely regulated by the energy level stored in the tank.

When the state of charge of the tank ($E_{\text{tank},t}$ / $E_{\text{tank,max}}$) is below 50 %, the HP is working at its maximum capacity ($x_t = 1$). As the energy level in the tank approaches the 50 % threshold, the power output of the HP is proportionally reduced. In order to avoid curtailing energy from the HR system, the HP is deactivated ($x_t = 0$) when the tank level reaches 80 % of its maximum capacity. To avoid curtailment of energy from the heat recovery system, the HP is turned off when the level on the tank is at 80 % of its maximum capacity. This straightforward control strategy is intended to prevent energy wastage while maximizing the use of the heat pump. The control of the HP as function of the energy level on the tank can be shown in Figure 2:

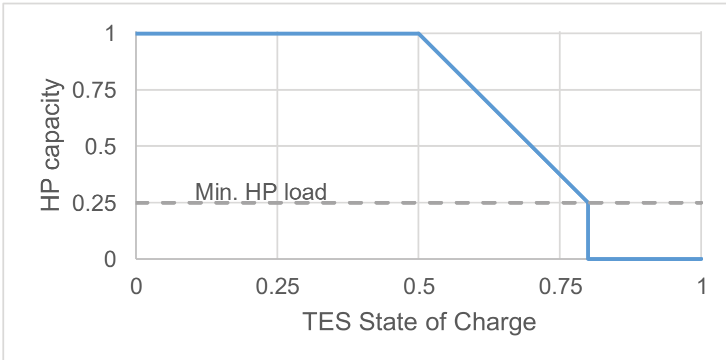

Figure 2: HP control strategy for the base case

2.3.2. CO_2 and cost-optimal heat pump operation

In contrast to the previous section, the CO_2 and the cost-optimal operation strategies consider the fluctuations on the electricity price or carbon intensity as well as the fluctuation of the power output of the PV panels. The model described previously is implemented in Pyomo, with the capacity of the HP at each timestep (x_t) as the optimization variable.

Two distinct optimizations are performed with two different objective functions: a cost-optimal operation ($\text{Cost}_{\text{gas}} + \text{Cost}_{\text{elec}}$) and a CO_2-optimal operation (${\text{CO}_2}_{\text{gas}} + {\text{CO}_2}_{\text{elec}}$).

Additional constraints are included to limit the maximum ramp-up ($x_{\text{ramp-up}}$) and ramp-down ($x_{\text{ramp-down}}$) of the heat pump capacity between consecutive timesteps.

2.4. Uncertainty and sensitivity analysis

Throughout this analysis, certain parameter values have been assumed, and while some of these assumptions are reasonable, others, especially those related to the efficiency of the heat pump, are subject to significant uncertainty.

To investigate the robustness of the study's conclusions under different scenarios and to put the potential benefits of the optimal operation schedule into perspective relative to other sources of uncertainty, an uncertainty analysis is conducted. Table 1 shows the parameters that will be investigated.

Table 1: Parameters and uncertainties used in the analysis

Parameter	Mean value	Type of deviation	Deviation
T_{source}	15 °C	Uniform, absolute	3 K
$T_{\text{sink,in}}$	62.7 °C	Uniform, absolute	1 K
$T_{\text{sink,out}}$	90 °C	Uniform, absolute	1 K
η_{Lor}	50 %	Normal, absolute	5 %
η_{Boiler}	95 %	Normal, absolute	5 %
$x_{\text{min.load}}$	25 %	Uniform, absolute	5 %
$x_{\text{ramp-up}}$	90 %	Uniform, absolute	10 %
$x_{\text{ramp-down}}$	90 %	Uniform, absolute	10 %

The parameters related to the efficiency of the HP have high uncertainty. The value of 50 % is reasonable approach to the calculation of the efficiency of the HP and is taken from a recent market overview [1]. The other parameters including the ramp-up, ramp-down and minimum load are taken from the technology catalogue [16].

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The values for the temperatures and the efficiency of the boiler are given by the brewery. For these parameters, less conservative approach to its uncertainty has been taken.

Among the possible techniques, the Monte Carlo analysis is chosen for the present study [17]. This method is chosen for its usefulness not only for uncertainty but for the sensitivity analysis by linear regression techniques. After defining the parameters and their uncertainties, a sampling number of N=2000 is defined, and a sampling matrix is generated by means of Latin hypercube sampling. Finally, N number of simulations are performed using this matrix, and the results are retrieved to analyse their uncertainties.

A sensitivity analysis is also performed for the economic savings and CO_2 reduction when using a cost-optimal operation schedule. For the sensitivity analysis on the model, the Standardized Regression Coefficient (SRC) method is used. The SRC method provides a measure of the sensitivity of the model output to each input parameter. It does this by quantifying the magnitude and direction of the effect of each input parameter on the output, while controlling for the effects of the other input parameters. This method quantifies the sensitivity of the results on input parameters by constructing a linear model based on the outputs from the Monte Carlo simulation [18].

2.5. Optimal heat pump and tank size

The optimized operation schedule of the HP may result in an improved business case for the HP and TES system. To explore this further, this work includes a small investigation on the investment costs of the system and compares the optimal sizing of the HP and TES to the base case operation.

The investment cost ($\mathrm{Cost_{inv,tank}}$ and $\mathrm{Cost_{inv,HP}}$) functions are found in the Technology Catalogue from the Danish Energy Agency [16]:

$$\mathrm{Cost_{inv,tank}} = 7450 \cdot {V_{\mathrm{tank}}}^{0.53} \tag{11}$$

$$\mathrm{Cost_{inv,HP}} = 0.73 \cdot Q_{\mathrm{HP,max}} \tag{12}$$

The investment cost is annualized by annualization factor considering a discount rate of i=5% and a lifetime of LT_{HP}=25 years and LT_{tank}=40 years.

$$\mathrm{Cost} = Cost_{\mathrm{inv}} \cdot i \frac{(1+i)^{\mathrm{LT}}}{(1+i)^{\mathrm{LT}} - 1} + \mathrm{Cost}_{op} \tag{13}$$

Note that, in this part of the analysis, an uncertainty analysis is not performed, as such an optimization would have been much more time-consuming and computationally demanding. The average values of the parameters presented in Table 1 are used.

3. Results

3.1. Energy use

The annual thermal energy demand of the facility is 16,815 MWh, with 8,587 MWh provided by the heat recovery system. The amount of heat delivered by the HP and the boiler, however, differ for every case. Table 2 shows the annual thermal energy use in the facility in all of the three cases:

Table 2: Results on heat use

	Base case operation	Cost-optimal operation	CO_2-optimal operation
Heat Pump	8,017.5 ± 0.2 MWh	8,166.4 ± 0.2 MWh	8,107 ± 4 MWh
Boiler	210.1 ± 0.2 MWh	61.3 ± 0.2 MWh	119 ± 4 MWh
Heat Recovery	8,587.3 MWh	8,587.3 MWh	8,587.3 MWh
Curtailment	0 MWh	0 MWh	0 MWh
Total load	16,815.0 MWh	16,815.0 MWh	16,815.0 MWh

In every case, the entirety of the energy from the HR system is utilized, and the curtailment of energy is avoided. From the three scenarios, the cost-optimal operation avoids utilizing the boiler as much as possible, even more than the CO_2-optimal operation. This implies that, with a sufficiently low HP efficiency and a very unfavourable electricity mix, the natural gas boiler is in fact avoiding CO_2 emissions. There is, however, a high degree of uncertainty in this aspect, and this strategy seems to be the most sensitive to the uncertainties of the inputs.

As for the electricity use, the electricity demand of the brewery before considering the HP is 28,063 MWh and the solar panels produce 8,074 MWh annually. Table 3 shows the main results on the electricity use on the three cases:

Table 3: Results on electricity use

	Base case operation	Cost-optimal operation	CO_2-optimal operation
Elec. Purchase	24,110 ± 12 MWh	24,120 ± 12 MWh	24,097 ± 10 MWh
Elec. Sold	1,283 ± 1 MWh	1,241 ± 1 MWh	1,241 ± 1 MWh
HP consumption	2,839 ± 13 MWh	2,891 ± 13 MWh	2,867 ± 12 MWh
PV production	8,074.4 MWh	8,074.4 MWh	8,074.4 MWh
Demand (without HP)	28,061.7 MWh	28,061.7 MWh	28,061.7 MWh

In both cost and CO_2 optimal operation schedules, the selling electricity from the PV power is avoided compared to the base case operation. The uncertainties in the results, especially in the electricity consumption of the HP, seem to be larger than the uncertainties presented in Table 2.

It is important to note that the electricity consumption of the heat pump, and therefore the focus of this optimization represents only between 9.1 and 9.3 % of the total electricity demand.

3.2. Potential for cost and CO_2 emission reduction

While the difference in annual energy consumption is not substantial, the cost and emissions reduction achieved through smart operation of the system is, given that the HP only represents a fraction of the energy consumption of the brewery, quite significant. Specifically, the total operation cost including natural gas and purchased electricity is 2,934,900 ± 1,500 € in the base case, but it is reduced to 2,901,700 ± 1,400 € and 2,918,800 ± 1,500 € in the cost- and CO_2-optimal cases, respectively. Additionally, the annual CO_2 emissions are 7,021 ± 3 kgCO_2eq. in the base case and are reduced to 6,964 ± 3 kgCO_2eq. and 6,922 ± 3 kgCO_2eq. in the cost- and CO_2-optimal cases, respectively.

The potential for reduction of costs and emissions is shown in Figure 3:

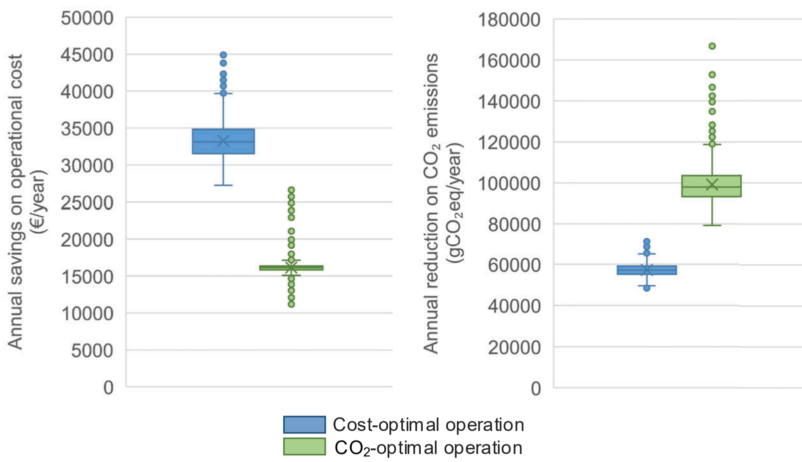

Figure 3: Potential for cost and emission reduction using a cost-optimal and CO_2-optimal HP operation

The average cost reduction is 33,286 ± 108 €/year and 16,148 ± 38 €/year for the cost- and CO_2-optimal operation, respectively. Similarly, the reduction in CO_2 emissions is 57.27 ± 0.13 kgCO_2eq. and 99.19 ± 0.38 kgCO_2eq. for cost- and CO_2-optimal operation, respectively. These results show that the cost-optimal smart operation of the heat pump not only would imply economic savings but also reduce CO_2 emissions and vice versa, as the CO_2-optimal operation would imply a reduction in the operational cost.

3.3. Sensitivity analysis

The sensitivity of the results shown in Figure 3 on the input parameters from Table 1 is measured using SCR method. The Standardized Regression Coefficients for each input with respect to each of the four model outputs are shown in Table 4:

Table 4: SRC of the input parameters for each of the outputs

	Cost reduction (Cost-optimal)	Cost reduction (CO_2-optimal)	Emissions reduction (Cost-optimal)	Emissions reduction (CO_2-optimal)
T_{source}	-0.126	-0.041	-0.106	-0.120
$T_{\text{sink,in}}$	-0.031	-0.070	-0.097	-0.041

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$T_{\text{sink,out}}$	0.067	0.084	0.128	0.071
η_{Lor}	-0.947	-0.368	-0.798	-0.930
η_{Boiler}	0.217	-0.130	-0.564	-0.119
$x_{\text{min.load}}$	-0.140	-0.043	-0.117	-0.109
$x_{\text{ramp-up}}$	-0.001	0.002	-0.003	-0.007
$x_{\text{ramp-down}}$	-0.006	-0.005	-0.004	-0.013
R^2	0.981	0.165	0.985	0.900

The linear fit is good for the cost and emissions reduction on the cost-optimal operation case and for the reduction in emissions for the CO_2-optimal case, having a coefficient of determination (R^2) of 0.981, 0.985 and 0.900 respectively. On the other hand, a linear model cannot describe the variance of the reduction in cost on the CO_2-optimal case, with an R^2 that is 0.165, a value way below the acceptable threshold [19]. In this case, the SRC method does not capture all the interactions between the inputs and the non-linear behaviour of the system. Therefore, some sources of uncertainty may remain unaccounted for. It is possible that this uncertainty can be attributed to the non-linear relationship between the electricity price and the CO_2 intensity of the grid, which may not be fully captured by the linear model used in this study.

The Lorenz efficiency of the HP is in any case the main source of uncertainty. A negative, high SRC value indicates that an increase in the Lorenz efficiency will decrease the savings relative to the basic operation. This is an expected outcome, since the COP improvement will decrease the costs and CO_2 emissions, the absolute difference in the savings is diminished.

3.4. Optimal heat pump and tank size

The reduction of operational cost derived from the use of the TES for load-shifting affects the business case of the HP and the TES. The optimal size of the HP and TES system using an optimized operation schedule differs from the optimal size using the base case operation. Figure 4 shows the annualized costs (from Eq. 13) for different configurations of HP and TES for both the base-case and the cost-optimal operation:

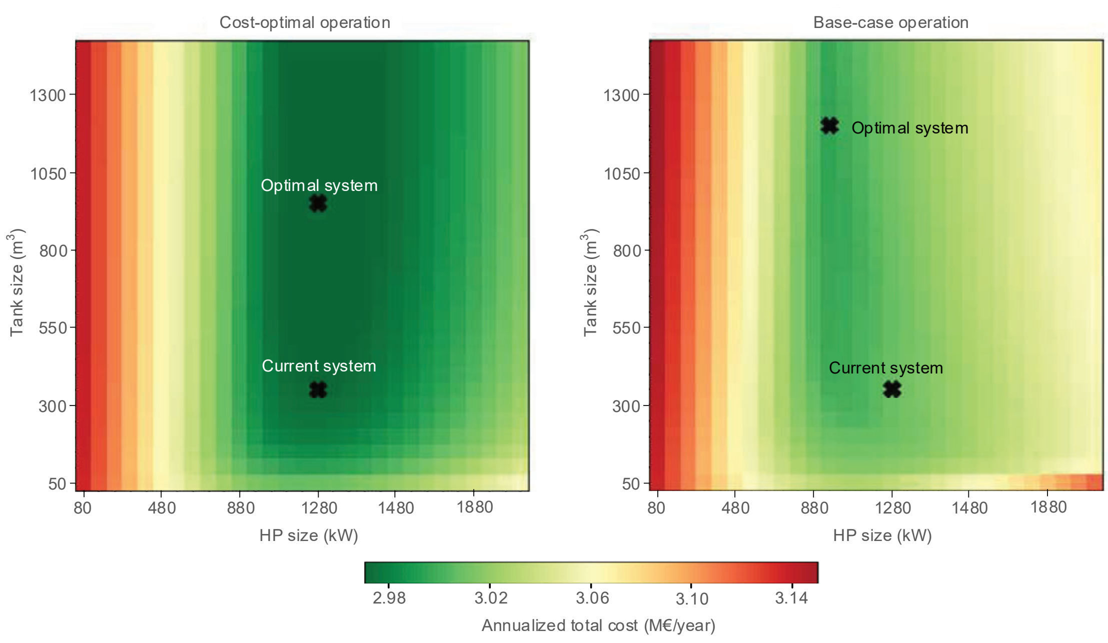

Figure 4: Annualized total costs of different HP and TES sizes using cost-optimal and base-case operation schedules

The optimal size of the system is a 960 kW HP with a 1,200 m^3 tank for the base case and a 1,280 kW HP with a 950 m^3 tank for the case with an optimized operation schedule.

As shown, the optimal size of the system is dependant on the operation strategy used. When the optimized operation is implemented, the HP size can be much larger, completely avoiding any combustion of natural gas and being able to supply more heat during the hours with high solar output or low electricity prices. Additionally, the tank size much smaller, as its operation is optimized to take advantage of the entirety of its capacity.

Note that, due to space constraints, the current TES system installed in the brewery is largely undersized. With the current HP system projected, an additional 375 m³ of storage capacity (doubling the size of the current tank) would reduce the annual operation costs of the facility by 8,300 € for the base case and 12,300 € for the cost-optimal case.

4. Discussion

The results show a big potential for savings with the smart operation of the Heat Pump. These reductions on cost and emission, however, do not necessarily come from a reduction on the energy use (as shown in Table 1 and Table 2) but from an optimal scheduling of the HP.

To visualize this effect, the consumption of electricity for three normal days of operation is shown in Figure 5 for the cost-optimal schedule. Note that, in this figure, the electricity has been normalized to the electricity demand of the brewery and does not represent absolute values.

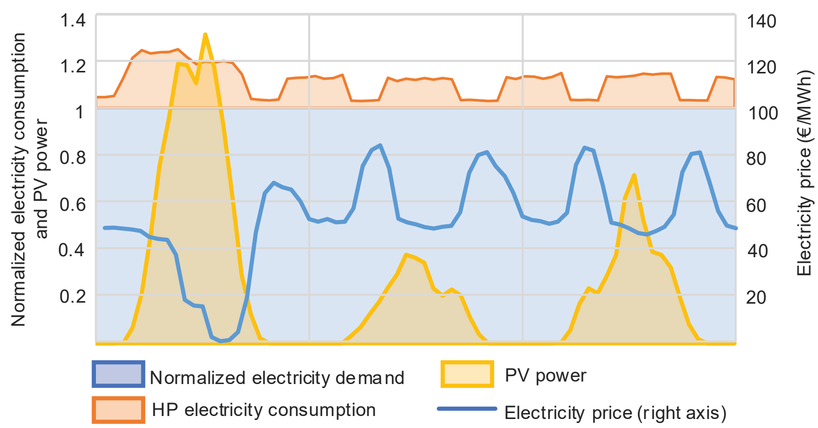

Figure 5: Normalized electricity consumption and electricity price for the Cost-optimal operation schedule for three days of operation

The electricity consumption of the HP represents, at most, less than 30 % of the rest of the brewery's electricity demand. This relatively small flexibility, however, is exploited in order to avoid an excess on the PV power production to be sold to the grid. It is also noticeable that, during the hours with peak electricity price (right axis in Figure 5), the HP is working at minimum load when possible.

A similar behaviour can be observed in the CO_2-optimal schedule. Figure 6 shows the electricity consumption in the CO_2-optimal case during the same three days of operation:

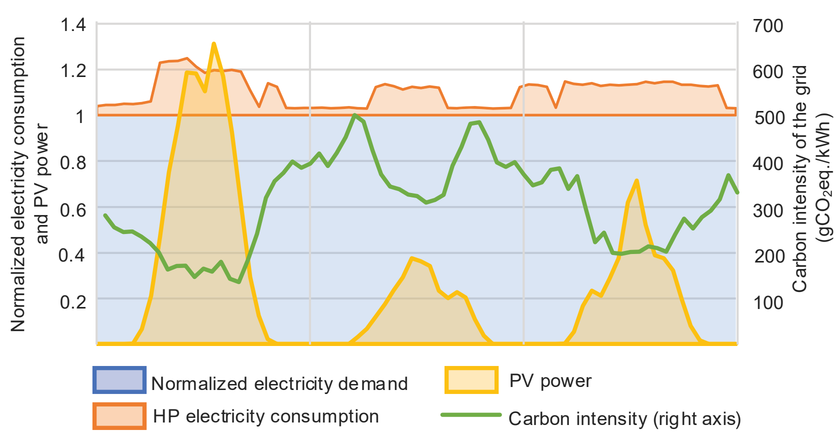

Figure 6: Normalized electricity consumption and carbon intensity of the grid for the CO_2-optimal operation schedule for three days of operation

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In this case, the electricity from the PV park is used as much as possible, and the fluctuations in the carbon intensity of the grid also affect the operation of the HP. During high carbon intensity hours, the HP is working at minimum load.

The effects observed in Figure 5 and Figure 6 are, as shown in the results from Figure 3, not exclusive. The electricity cost is closely related to the electricity mix and therefore its carbon intensity. As the most carbon-intense are also the most expensive energy sources, the cost-optimal schedule is also reducing CO_2 emissions.

4.1. Heat pump operation

As shown in Figure 5 and Figure 6, both the fluctuations of the energy price or carbon intensity and the generation from the PV park increase the impact of the optimal HP operation. Figure 7 compares the operation of the HP in base case with the cost-optimal and CO_2-optimal operation for one day:

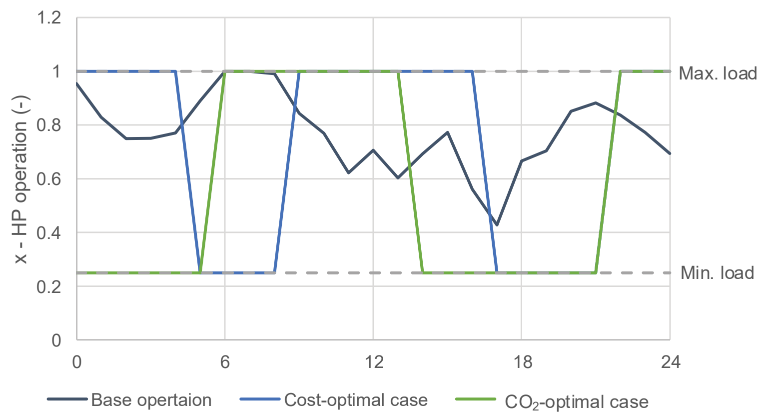

Figure 7: Heat pump operation for one day

In the optimal operation strategy, the HP operates almost independently of the energy level in the tank and instead follows a pattern that inversely corresponds to the electricity price. The HP operates intermittently between maximum and minimum loads, without operating at part-load. While this approach can improve the cost and emissions efficiency of the system, it may also cause more extreme and less smooth operation, potentially reducing the HP's lifetime and limiting its implementation [20]. Nevertheless, the maximum ramp-up and ramp-down speeds are already included in this work, with no significant impact observed.

The efficiency of the HP has the largest impact on results on absolute savings when comparing the optimal operation to the base case operation. While a heat pump with a given efficiency is a reasonable approximation for a preliminary study, a more detailed calculation of the COP and an actual dynamic HP model would be necessary to assess the potential savings in more detail.

4.2. Thermal energy storage operation

In the base case, the operation of the HP is determined by the energy level in the TES. It is designed to maintain an energy level that would avoid energy curtailment from the HR system and avoid emptying the tank as much as possible.

On the other hand, the optimized schedules take advantage of the flexibility given by the tank to optimize the schedule of the HP. In this case, the tank is charged and discharged more frequently, instead of being maintained at a certain energy level. An example of the TES operation is given in for the same day of operation in Figure 8:

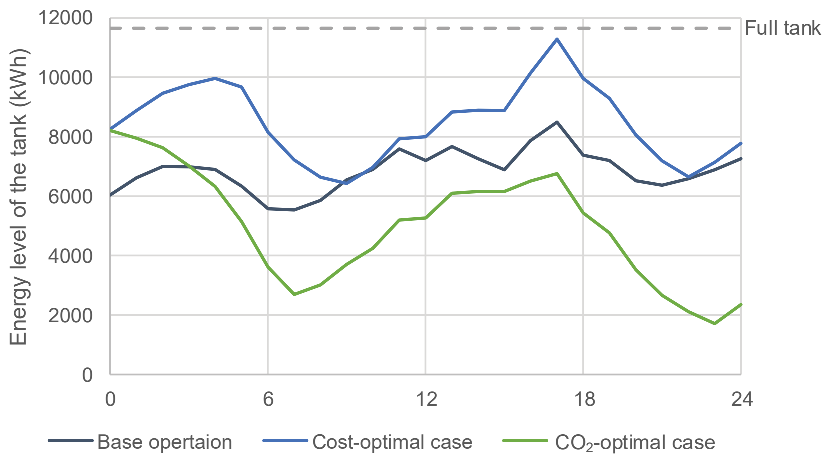

Figure 8:Thermal Energy Storage operation for one day

The model used in this research for the tank is very simple and does not take into account heat losses or mixing in the tank. Although assuming no mixing losses in the tank may seem unrealistic, it is reasonable only when the charging and discharging times are large. In the case of optimal operation, the heat pump (as shown in Figure 7), is working at its maximum or minimum load. Therefore, the tank is charged and discharged at faster speeds, which could lead to an increase in mixing losses of the tank [21].

The synergy of the TES and HP system is highlighted by the investment cost results. The existing tank in the facility was originally intended to be used for heat recovery. However, the investigation on investment costs shows that is largely undersized when it is used as a heat sink of the HP. A larger tank would allow the HP to deliver more heat to the load, and the use of natural gas could be avoided.

4.3. Directions for future research

While the sensitivity analysis demonstrated the significant impact of uncertainty on some parameters, particularly the efficiency of the HP, this study utilized fixed time datasets for the load, electricity consumption, PV power, heat recovery, and electricity price to evaluate the potential of the proposed smart operation. However, uncertainties associated with the accuracy of these parameter predictions must be taken into account when implementing this operational strategy.

To evaluate the actual system performance, it is necessary to incorporate a predictive model for these factors. Predictions on variables such as electricity price, solar radiation, or energy consumption within the brewery are typically only valid over a 24-hour time period. It would be interesting to investigate how such a predictive model would affect the results obtained in this study, thereby assessing the viability of implementing this approach in practice.

Furthermore, the heat pump and TES system considered in this study could be expanded to include more complex features, such as multiple heat sources or loads, and other possible energy storage systems (e.g., batteries) that could be used in conjunction with the TES. In addition, the use of a more detailed model for the heat pump, such as a dynamic model, would provide a more detailed assessment of the system's performance.

Finally, the investment cost analysis showed that a larger TES tank would be more cost-effective, which suggests that the sizing of the TES tank should be a consideration when designing a system of this kind. Further investigation into optimal tank sizing and operation could yield additional insights into system performance and cost-effectiveness.

Overall, this study provides a starting point for the development and implementation of smart energy management strategies and integration of HP with TES. However, additional research is needed to optimize and validate these strategies in practice.

5. Conclusion

The results of this study demonstrate the significant potential for reducing the cost of operation and CO_2 emissions of an industrial heat pump with thermal energy storage. By using an optimal control strategy that takes advantage of the thermal energy storage, load shifting can be achieved, which significantly improves the business case of the heat pump. The results show a significant correlation between the cost-optimal and CO_2-optimal operations of the HP. Optimal scheduling for cost reduction also leads to a reduction in CO_2 emissions

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and vice versa. Therefore, regardless of the CO_2 emission policies or electricity purchase agreements, smart operation of the system is both economically and environmentally beneficial.

It is important, however, to carefully evaluate the performance of the system, especially the COP of the heat pump, in order to assess the potential savings. The smart operation of the HP should be investigated further, as its synergy with the TES could change the optimal system configuration and benefit the business case for the overall system.

While the potential of the optimal control strategy has been shown, implementing such a strategy in practice can be challenging. One challenge is making accurate predictions on parameters such as electricity price, solar radiation, and energy demand, especially in complicated industrial settings. The results of this study were based on fixed time datasets, and the actual performance of the system will depend on the accuracy of these predictions. Therefore, implementing a predictive model that can accurately predict these parameters is key to exploiting the potential of the optimal control strategy.

Another challenge is the impact of the optimal control strategy on the lifetime of the heat pump. The results of this study showed that the optimal control strategy resulted in less smooth, more extreme operation of the heat pump. While the maximum ramp-up and ramp-down speed was included in the analysis, the impact of this type of operation on the lifetime of the heat pump is still an open question.

Despite these challenges, the potential benefits of the optimal control strategy cannot be ignored. This study has shown that by using thermal energy storage and load shifting, significant cost and emission reductions can be achieved. These benefits are especially important for industries that have high energy demands and are subject to fluctuating electricity prices.

In summary, the potential of an optimal control strategy for an industrial heat pump with thermal energy storage has been shown to be a promising approach for reducing costs and emissions. However, implementing this strategy in practice requires accurate predictive models and careful consideration of the impact on the lifetime of the heat pump. Nonetheless, this study provides valuable insights into the potential benefits of this approach and sets the stage for further research in this area.

Nomenclature

COP	Coefficient of Performance (-)	Q	Heat (kWh)
CI	Carbon Intensity (gCO_2eq./kWh)	T	Temperature (°C)
c_p	Heat capacity (kWh/kg K)	V	Volume (m^3)
E	Energy (kWh)	x	Capacity factor (-)
G	Irradiance (W/m^2)	η	Efficiency (-)
LT	Lifetime of investment (years)	θ	Incidence angle (°)
P	Electrical power (kWh)	ρ	Density (kg/m^3)
p	Price (€/kWh)		

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