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Assessing Decision-Making Strategies for Cost-Optimal Brewery Electrification Pathways from 2025 to 2050

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Abstract

This work presents a method to evaluate how industrial decision-making strategies influence the decarbonization of breweries through energy-saving and electrification technologies. The approach builds on common practices from Pinch Analysis to identify a set of possible technology investments from 2025 to 2050. The considered options include wort cooling heat recovery, boil-off heat recovery (Pfaduko), a mechanical vapour recompression (MVR) system, a warm-water heat pump (80 °C), a high-temperature heat pump (110 °C), and an electric boiler.
After identifying feasible technologies and their expected savings, common industrial decision-making practices, based on payback period (PBP) thresholds, are simulated and compared to a cost-optimized strategy under uncertain future energy price developments. Through 5,000 Monte Carlo simulations, the results show that strategies allowing longer PBPs lead to lower expected total discounted costs (TDC) and higher levels of electrification by 2050. Under current market conditions, only 12 % of the scenarios achieve full electrification with a three-year PBP, whereas this share increases to 48 % with a ten-year PBP.
The cost-optimal implementation plan serves as a benchmark for ideal long-term investment behaviour, achieving 5 % lower TDC than the ten-year PBP strategy and 25 % lower than the three-year PBP strategy. The findings reveal that short-term decision-making strategies can create technological lock-in, limiting the adoption of efficient high-temperature heat pumps and delaying industrial decarbonization. Encouraging longer investment horizons could enable faster and more cost-effective electrification of industrial heat demand.

Keywords: Process integration; Techno-economic optimization; Heat Pumps; Electrification; Heat recovery

1. Introduction

The electrification of process heat is a key strategy to decarbonize breweries. Heat pumps offer an efficient solution for process heat supply, particularly within the typical temperature range of breweries (up to ~140 °C) [1]. However, trade-offs exist between system efficiency and investment costs [2]. In order to electrify process heat, breweries face multiple investment decisions. These decisions include improving the heat recovery system [3,4], electrifying the utility steam with a high temperature heat pump [5], partially electrifying by integrating heat pumps for lower temperature requirements [6] or installing an electric or a biomass boiler [7].

Most breweries, like many other industrial sectors, are reluctant to invest in projects with payback periods (PBP) exceeding 3–5 years [8]. However, considering longer investment strategies can accelerate heat electrification and decrease overall emissions [9]. Rethinking investment strategies in energy efficiency and electrification projects is key for reducing carbon emissions, aligning with climate goals for carbon neutrality by 2050 [10].

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Understanding how common industrial decision-making strategies can lead to technological lock-in, inefficient or delayed implementations, and ultimately additional carbon emissions is key to improving industrial transition planning. Providing tools that support investment planning while accounting for future developments in energy costs can help minimize these additional costs and manage investment risks [11]. Likewise, assessing whether existing frameworks and market signals can drive electrification without additional incentives is fundamental for both industry and policymakers [12]. In this context, this research aims to investigate three main questions:

- Are PBP-based decision-making strategies leading to inefficient or costly energy transitions in breweries?
- What characterizes an effective implementation plan that minimizes total transition costs?
- Are current policies, technology costs, and energy prices sufficient to enable cost-effective decarbonization?

To address these questions, this research has evaluated heat pump based decarbonization strategies for breweries by comparing conventional PBP-based strategies with an optimized long-term strategy to serve as a lower bound. The study used projections for gas, electricity and CO_2 prices, and grid carbon intensity from 2025 to 2050. The model simulated yearly investment decisions over this period, considering heat recovery, heat pump integration, and electric boiler installation, and then evaluated the total costs and outcomes of each resulting decarbonization pathway.

With the proposed methodology, this study aimed to bridge the gap between short-term industrial decision-making and long-term decarbonization objectives. It provides a structured way to evaluate how investment behaviour, technology development, and policy signals interact over time. Beyond the brewery case, the approach illustrates how uncertainty-aware planning can inform strategic electrification decisions across other energy-intensive industries.

2. Method

This section describes the analytical method used to identify and evaluate decarbonization pathways for the studied brewery. First, conventional Pinch Analysis [13] was applied to identify opportunities for heat recovery and heat pump integration. This involved mapping process energy demands and using Pinch principles to define feasible heat recovery solutions.

The novelty of this work lies on building upon this catalogue of energy recovery and electrification investment options to propose an implementation plan. This includes constructing energy price projections and estimating associated uncertainty distributions, which are then used to design and evaluate the performance of the proposed implementation plan.

An overview of the method is shown in Figure 1.

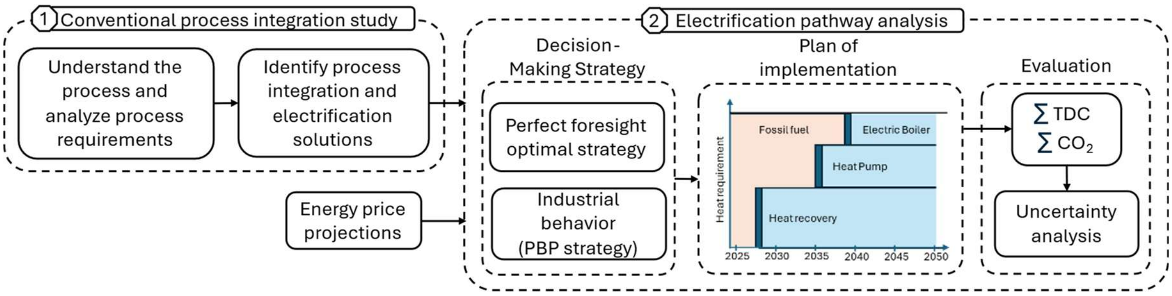

Figure 1: Overview of the proposed method for analysis of the heat electrification pathways

2.1. Identifying heat recovery and electrification solutions

The first step in energy efficiency analysis was to map the energy use within the facility. In this study, a representative brewery with typical heating and cooling requirements was considered. The processes in the brewery, required temperatures and time average heat demands are shown in Figure 2. The brewery had an annual production of 900,000 hl of beer and operated 6,000 hours per year.

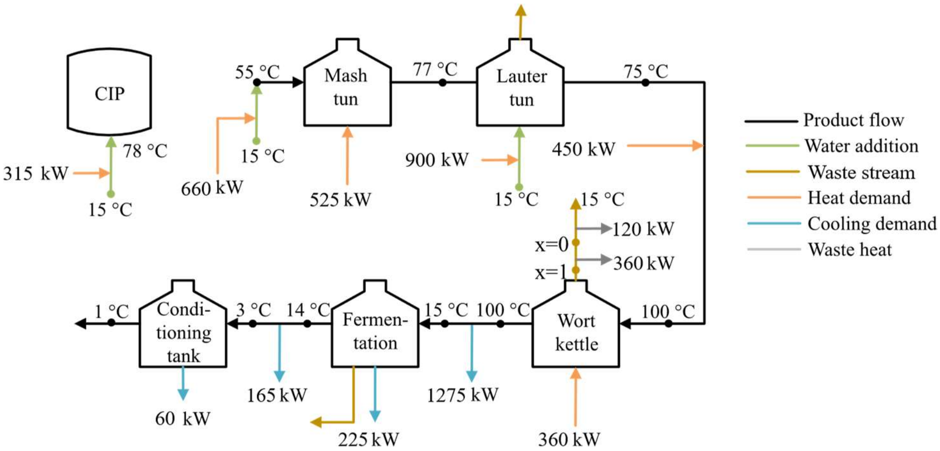

Figure 2: Processes and energy demands of the brewery

The heat recovery potential and feasible electrification solutions were identified using Pinch Analysis [13]. This method was used to visualise and analyse energy demands across different temperature levels and has been extensively applied in the design of heat exchanger networks [14]. It has since been extended to other applications [15], including (relevant to breweries) the integration of indirect heat recovery loops with hot water tanks[16] and integration of industrial heat pumps [17].

Based on the energy requirements summarized in Table 1, conventional Pinch Analysis assuming a global minimum approach temperature (ΔT_{min}) of 10 K was performed to construct the Composite Curves and the Grand Composite Curve (GCC), which are presented in Figure 3.

Table 1: Temperature and heat requirements of the brewery

Process	T_{start} (°C)	T_{target} (°C)	$\dot{Q}$ (kW)
Pre-mashing	15	55	660
Mashing	55	77	525
Lautering/filtering	15	75	900
Wortboiling (preheating)	75	100	450
Wortboiling (boiling)	100	101	360
Wortcooling	100	15	1,275
Boiloff condensation	101	100	360
Fermentation	15	14	225
Beer cooling	14	3	165
Cooling for filtration and centrifugation	3	1	60
CIP	15	77	315

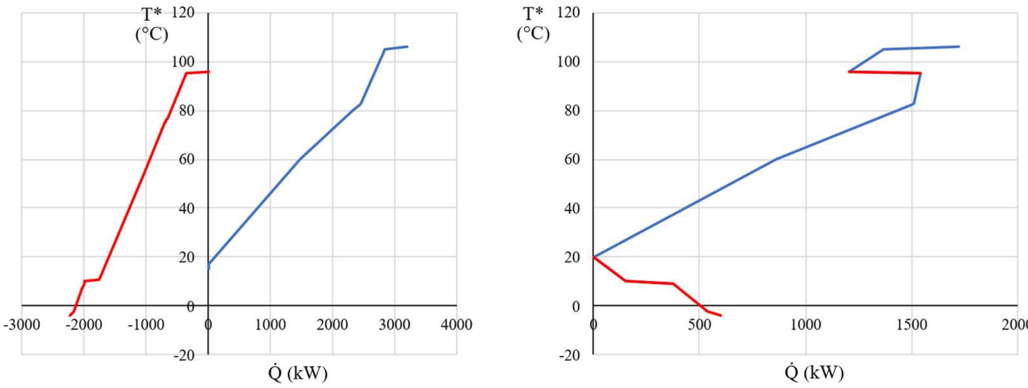

Figure 3: Resulting Composite Curves (left) and Grand Composite Curve (right) of the brewery

The Grand Composite Curve (GCC) is central to Pinch Analysis. In this case, the pinch point was located at 20 °C, corresponding to the inlet temperature of fresh water into the brewery. Further, the minimum heating target was 1.725 MW. Above the pinch temperature, there was significant potential for heat recovery in the wort cooling process and during the condensation of boil-off vapours from the wort boiling. Both wort-cooling and boil-off heat recovery are common practices in industrial breweries [18]. Due to the batch nature of the brewing process, these solutions typically involve heat recovery tanks used to preheat water for processes operating below 80 °C [19].

In the brewery used for the case study, wortcooling heat recovery had a potential of 1,125 kW using a warm water tank operated at 82 °C. In addition, the boil-off heat recovery (also known in breweries as Pfaduko system) recovered 360 kW in total, of which 270 kW were used for wort preheating and 90 kW could supply warm water. The combination of these two systems met the heat recovery targets identified through Pinch Analysis. The implemented heat recovery configuration is illustrated in Figure 4.

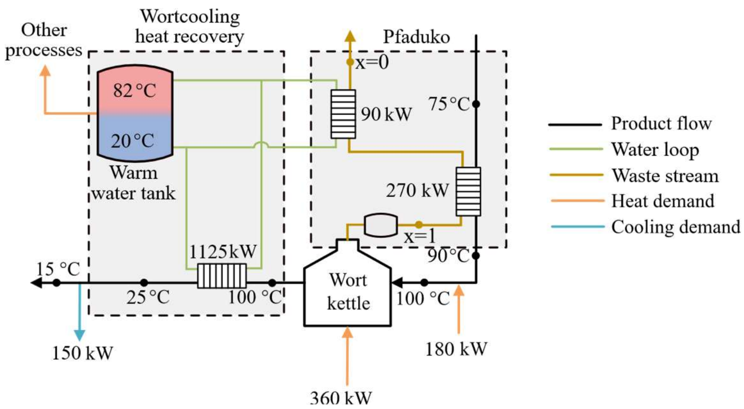

Figure 4: Diagram of the heat recovery solutions: Wort cooling heat recovery and boil-off heat recovery (Pfaduko)

The cost of each heat recovery option was estimated using the cost functions provided in the technology catalogue of the Danish Energy Agency[20], assuming the use of heat recovery tanks. The investment cost was calculated according to Eq. (1):

$$C_{HR} = \alpha_{HR} \cdot V^{\gamma} \quad (1)$$

where α_{HR} and γ were cost coefficients obtained from the catalogue, shown in Table 2, and V was the tank volume. The volume of each tank was determined based on the process-side temperature levels and a required storage capacity equivalent to 24 hours of operation.

For heat pump integration, the GCC was used to identify potential integration points. According to conventional heat pump integration rules, heat should be extracted below the pinch temperature and delivered above it [21]. Recent investigations, however, show that integrating heat pumps into the heat pockets of the GCC increases the total heat that must be supplied by the heat pumps. Nevertheless, under specific conditions (particularly when multiple heat pumps are integrated) the lower temperature lift can compensate for this effect by improving heat pump efficiency and thereby reducing overall electricity consumption [22].

In this case, a mechanical vapour recompression (MVR) system installed at the wort kettle, a common solution in industrial breweries, would be integrated within these heat pockets. While this configuration limits heat recovery and represents an inefficient heat integration from a heat demand perspective, it was modelled and included as a potential investment option; as it had the potential to improve the efficiency of the system when combined with other technologies.

To optimize the MVR integration, the wort-cooling heat recovery could be adjusted to utilize the high-temperature heat available after wort boiling for wort preheating. The configuration of the MVR system and the corresponding modifications to the wort-cooling heat recovery are shown in Figure 5. Note that any additional investment cost from the modification of the heat recovery system required for this configuration was not included in this study.

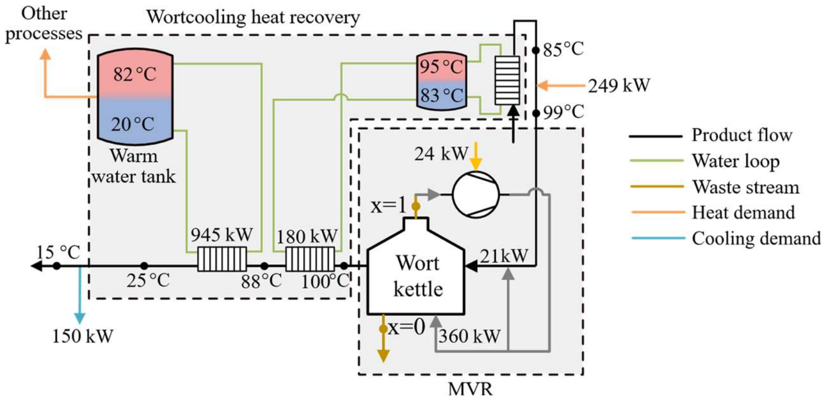

Figure 5: MVR integration and required optimization of the wortcooling heat recovery system

A common option for heat pump integration is a Warm Water Heat Pump (WWHP) that supports the warm water system, particularly when combined with wort-cooling heat recovery [5]. In this case, the WWHP heated water to 82 °C to supply the processes operating below 77 °C.

Lastly, a High-Temperature Heat Pump (HTHP) could directly replace the central utility system, operating at the highest process temperature (110 °C) to cover all heating demands. Similarly, an electric boiler (EB) represents a lower-cost electrification option capable of supplying heat at any temperature required in the brewery.

The COPs of the MVR, WWHP and HTHP were calculated using the logarithmic mean temperature of the sink ($\bar{T}_{\text{sink}}$) and source ($\bar{T}_{\text{source}}$), applying the Lorenz efficiency (η_{Lor}) [23], which was assumed to be 0.55 for all heat pumps [24], as expressed in Eq.(2).

$$COP = \eta_{Lor} \cdot \frac{\bar{T}_{sink}}{\bar{T}_{sink} - \bar{T}_{source}} \tag{2}$$

The resulting COP values were 17.4 for the MVR, 4.5 for the WWHP, and 2.2 for the HTHP. The capacity of the MVR if installed is shown in Figure 5, whereas the capacities of the remaining electrification technologies depended on the level of heat recovery already implemented.

The WWHP capacity corresponded to the remaining heating demand below 77 °C, which varied between 2,400 kW (no heat recovery), 1,455 kW (wort-cooling heat recovery), 2,310 kW (Pfaduko), and 1,185 kW (combined wort-cooling and Pfaduko heat recovery). Similarly, the HTHP and EB capacities supplied the remaining heating demand, ranging from 3,215 kW (no heat recovery and no WWHP) down to 249 kW (with wort-cooling HR, WWHP, and MVR) or 540 kW (with wort-cooling HR, Pfaduko, and WWHP).

The cost of the electrification technologies were calculated with the cost function shown in Eq. 3. [25]. The values for α and β are shown in Table 2.

$$C = \alpha \cdot \dot{Q} + \beta \tag{3}$$

Table 2: Parameters for the cost functions of each of the technologies

	α (Mean ± SD)	β (Mean ± SD)	γ (Mode ± range)
HR (Wortcooling or Pfaduko)	7450 ± 500	-	0.65 ± 0.05
MVR	350 ± 70	280,000 ± 56,000	-
HP (WWHP or HTHP)	600 ± 120	520,000 ± 104,000	-
EB	210 ± 50	-	-

2.2. Simulation and evaluation of electrification pathways

In order to simulate the implementation of the investigated technologies from 2025 to 2050, projections for the Emissions Trading System (EU-ETS), natural gas, and electricity prices were considered. The projected prices from the IEA *World Energy Outlook* reports for 2022 [26], 2023 [27] and 2024 [28], together with the

Danish *Klimafremskrivning* (KF) 2021–2024 [29] , were used as references to define a probability distribution for the price evolution until 2050. The projected prices applied in this study are shown in Figure 6.

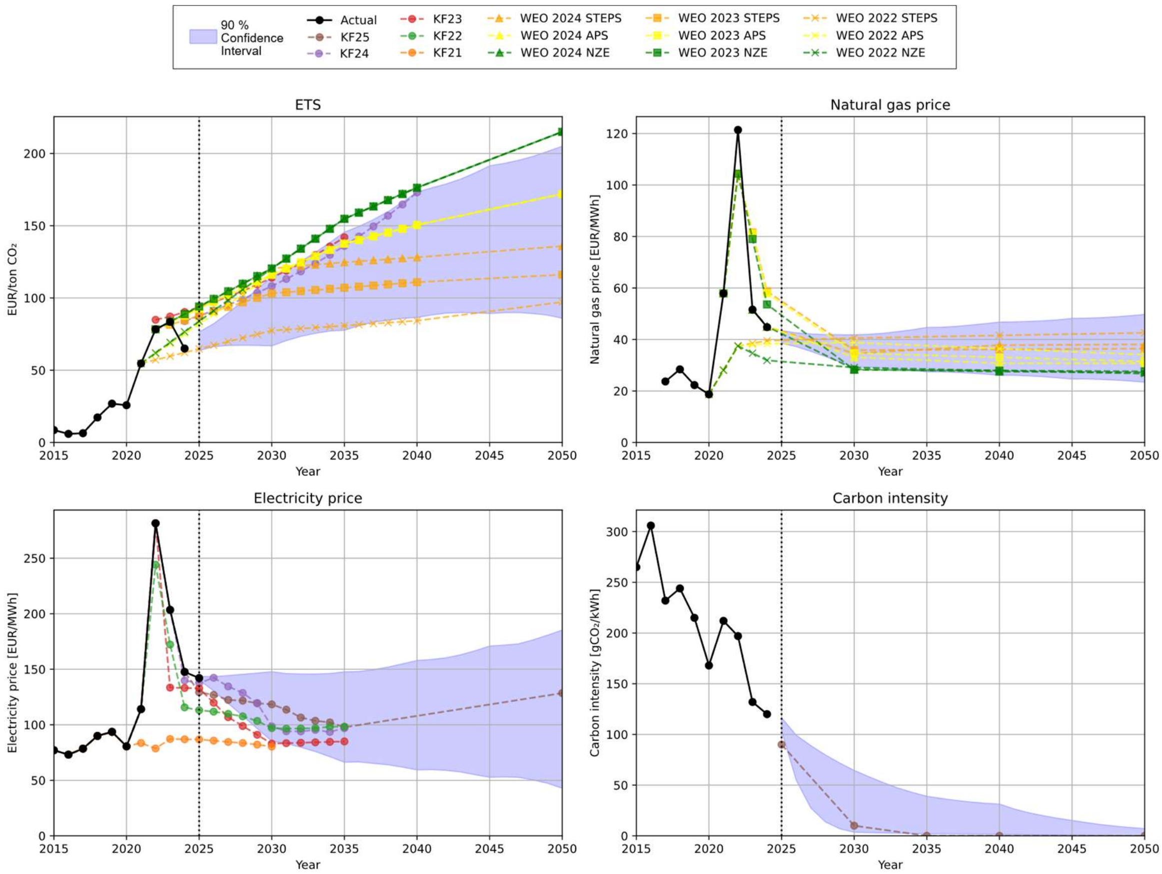

Figure 6: Projected ETS, natural gas and electricity price and carbon intensity of the grid.

Given the costs of the energy saving solutions investigated and the energy price developments from Figure 6, it was possible to simulate how the current industrial decision-making strategies, based on a maximum PBP threshold, lead to investments in these solutions.

For each year y, the simple PBP of all potential investments i was calculated from the expected savings and the corresponding capital investment, as expressed in Eq. (4):

$$PBP_{y,i} = \frac{C_{inv,i}}{OH\cdot\left(\frac{\dot{Q}_{NG,y,0}-\dot{Q}_{NG,y,i}}{\eta_{NG}}\cdot(p_{NG,y}+e_{NG}\cdot p_{ETS,y})+(\dot{W}_{y,0}-\dot{W}_{y,i})\cdot p_{elec,y}\right)} \quad (4)$$

where $C_{\text{inv},i}$ is the capital cost of investment i; OH the annual operating hours; $\dot{Q}_{\text{NG},y,0}$ and $\dot{Q}_{\text{NG},y,i}$ the natural gas consumption before and after the investment; η_{NG} the boiler efficiency; $p_{\text{NG},y}$ the natural gas price; e_{NG} the CO_2 emission factor; $p_{\text{ETS},y}$ the EU-ETS price; $\dot{W}_{y,0}$ and $\dot{W}_{y,i}$ the electricity consumption before and after the investment; and $p_{\text{elec},y}$ the electricity price in year y.

If the lowest PBP among all potential investments in a given year was below the specified threshold (PBP_{max}), the corresponding technology was implemented. This procedure was repeated for each year from 2025 to 2050, sequentially updating the remaining heating demand and electricity consumption after each investment. The result was a plan of implementation, specifying which technologies were adopted in each year and how the cumulative investments evolved over time.

The implementation plan resulting from a PBP-based decision-making strategy that considers only current energy prices can lead to sub-optimal investments, as it does not consider future price developments or interactions among the technologies. To illustrate the potential for improvement, an optimization model was developed to minimize the total discounted cost (TDC) from 2025 to 2050. In this model, the year of integration for each energy-saving solution was treated as an optimization variable, and only one investment per year was allowed. The corresponding objective function of this optimization was expressed as Eq. (5).

$$TDC_{opt} = min \sum_{y=2025}^{2050} \frac{C_{inv} + \frac{\dot{Q}_{NG,y}}{\eta_{NG}} \cdot (p_{NG,y} + e_{NG} \cdot p_{ETS,y}) + \dot{W}_y \cdot p_{elec,y}}{(1+d)^{y-2025}} \quad (5)$$

Where d was the discount rate, set to 7 %. The optimization problem was formulated in Pyomo [30] and solved using GLPK [31].

The resulting optimized plan of implementation serves as a lower bound for comparing the economic performance of different strategies, as it assumes perfect foresight of future energy prices. To investigate the effects of uncertainties in energy price projections and investment costs on the resulting implementation plans and their performance, 5,000 Monte Carlo simulations were performed. In each simulation, the projected gas, electricity, and carbon prices, as well as the capital costs of the technologies, were randomly sampled from their respective probability distributions. The plan of implementation was then recalculated for each realization, allowing the assessment of variability in investment timing, technology adoption, and total discounted costs under uncertainty.

To isolate the effect of decision-making strategies from uncertainties in energy prices or investment costs, the TDC were normalized. For each Monte Carlo simulation, the ratio of the TDC of strategy j over the cost-optimal plan was computed as Eq. (6).

$$r_j = \frac{TD\ _{opt}}{TDC_j} \quad (6)$$

This approach guarantees that the optimal plan always has a ratio of 1 and prevents misleading interpretations due to uncertainty of the inputs.

3. Results

The implementation plans resulting from the simulation of PBP-based strategies with thresholds of 3, 5, and 10 years, together with the optimized plan of implementation, can be visualized for the 5,000 Monte Carlo simulations, as shown in Figure 7. Figure 7 shows, for each year on the x-axis, the number of simulations on the y-axis in which each technology is present.

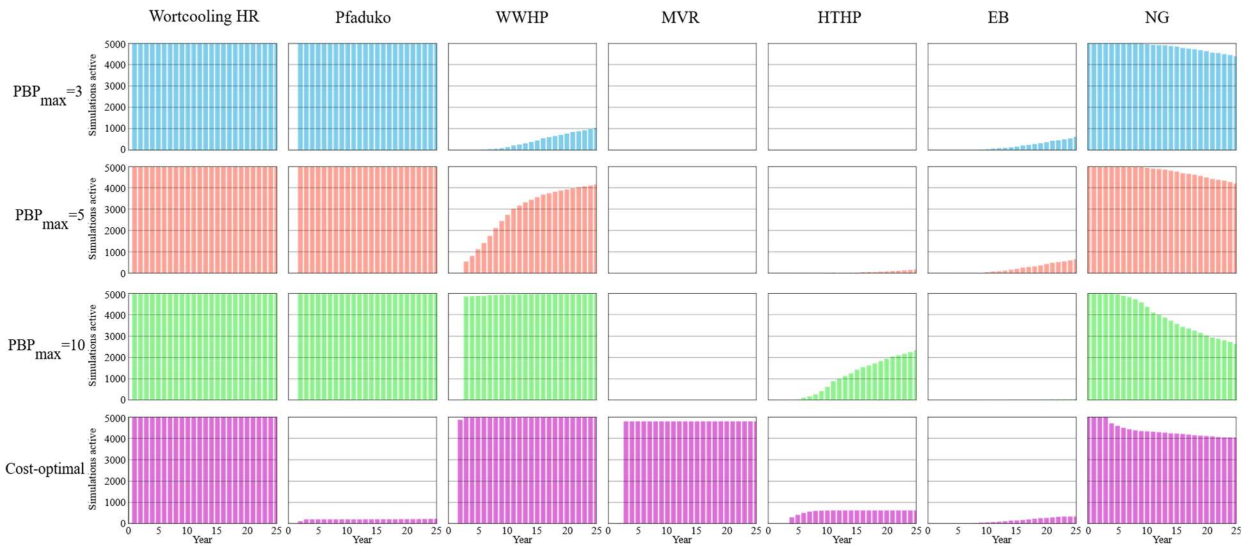

Figure 7: Resulting plan of implementation for the 5,000 Monte Carlo simulations for each decision -making strategy: allowed PBPs of 3, 5 and 10 years and optimized plan.

The differences in the technologies adopted under each decision-making strategy are significant. The Wortcooling heat recovery system was a priority in all cases, with 100 % of the simulations choosing to invest in it as early as possible, regardless of the strategy followed. Under PBP-based strategies, the Pfaduko heat recovery system was also consistently preferred over the MVR.

As longer PBPs were allowed, a higher share of simulations resulted in the adoption of heat pumps. With a PBP threshold of three years, there was only a 20 % probability that a WWHP would be installed in the brewery by 2050, whereas allowing PBPs of up to ten years led to the adoption of this technology in all simulations, by 2030 at the latest. In this case, HTHPs were also adopted, and the brewery became electrified in nearly 50 % of the simulations. In contrast, with the shorter PBP threshold, electrification occurred in fewer than 15 % of the simulations, and primarily through the less efficient EB technology.

Interestingly, the optimized plan favors investment in the MVR over the Pfaduko. While this solution was not optimal on its own according to the principles of process integration, it enables a larger share of the heating demand to be supplied by the WWHP instead of the HTHP or EB, leading to a more efficient overall system. The optimized strategy invested heavily in the WWHP but includes HTHP adoption only before 2030 and in about 12 % of the simulations, resulting in a lower degree of electrification than in the PBP_{max} = 10 years case.

The performance on the aggregated present cost and CO_2 emissions of each strategy is summarized in Table 3.

Table 3: Total Discounted Costs and Total emissions for the investigated decision-making strategies.

	TDC (Mean ± SD)	Total Emissions (Mean ± SD)
PBP_{max}=3	12.6 ± 1.2 M€	57.5 ± 9.0 tonCO_2eq.
PBP_{max}=5	11.2 ± 1.3 M€	39.6 ± 13.1 tonCO_2eq.
PBP_{max}=10	10.0 ± 1.0 M€	22.9 ± 5.5 tonCO_2eq.
Cost-optimal	9.5 ± 1.0 M€	15.6 ± 3.8 tonCO_2eq.

The results show that the expected TDC was lower as the allowed PBP increases, and, similarly, the CO_2 emissions also decreased due to a larger share of the energy demand being electrified.

To better compare the performance of each decision-making strategy, Figure 8 presents the distribution of the performance ratios $r_{\text{PBPmax}=3}$, $r_{\text{PBPmax}=5}$, and $r_{\text{PBPmax}=10}$ obtained from the 5,000 Monte Carlo simulations.

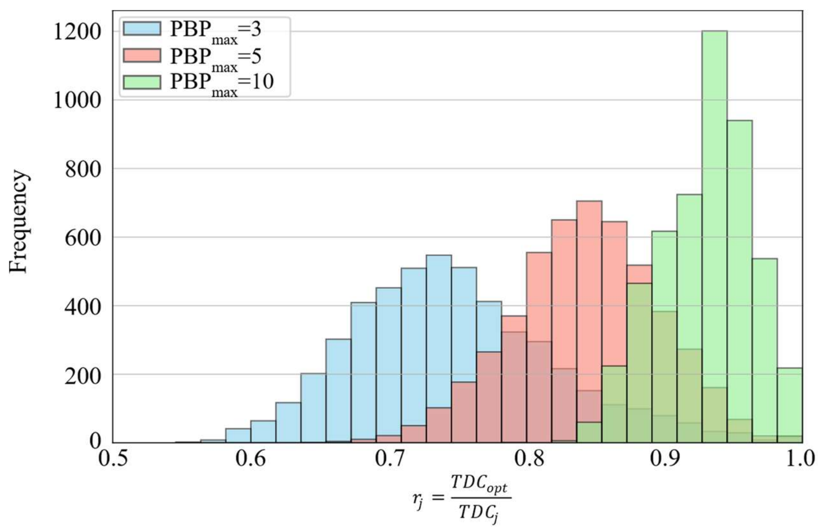

Figure 8: Histogram of the ratios of the minimum TDC (optimal) over the resulting TDC following the PBP-based strategies in all 5,000 Monte Carlo simulations.

The values of $r_{\text{PBPmax}=10}$ close to 1 indicated that the long PBP strategy performs near the ideal, with an expected value of 0.94. In contrast, shorter PBP thresholds led to less efficient technology adoption, with expected values of 0.75 for $r_{\text{PBPmax}=3}$ and 0.85 for $r_{\text{PBPmax}=5}$.

4. Discussion

The method presented in this work builds on common practices and techniques from Pinch Analysis for heat recovery and heat pump integration. After the initial study and the definition of investment options and possible energy-saving and electrification solutions, typical industrial decision-making strategies were simulated and compared with a cost-optimal implementation. This comparison was carried out using a Monte Carlo analysis that accounts for uncertainties in energy price developments and investment costs.

The results show that the expected TDC was lower when following strategies with longer allowed PBPs. Moreover, longer PBPs enable a larger share of the heat demand to be electrified by 2050, with a probability of full decarbonization of 48 % when following a PBP_{max} = 10 years strategy. The proposed approach not only illustrates how each strategy led to different implementation pathways but also allowed comparison with a perfectly optimized strategy acting as a lower bound. This comparison helps identify how the industry could realistically progress in the coming decades and what types of policies could accelerate the adoption of electrification technologies.

4.1. Optimal plan of implementation and technological lock-in in PBP-based strategies

The results showed that the optimal investment plan into energy-saving and electrification technologies in the brewery differed significantly from those derived from PBP-based strategies. A key observation was that, in a large portion of the Monte Carlo simulations, the MVR system was preferred over the Pfaduko, which never occurs under PBP-based strategies. By itself, the MVR was not an efficient energy-saving option, as it used electricity to recover heat that the Pfaduko could otherwise recover directly. This aligns with the rules of Pinch Analysis, which discourage integrating heat pumps such as the MVR within the heat pockets of the GCC. However, when the brewery was considered holistically, the MVR enabled heat recovery at a higher temperature, rather than cascading it to lower temperature levels. This increased the load on the WWHP, but simultaneously reduces the load on less efficient technologies such as the HTHP, natural gas boiler, or EB that would otherwise have supplied heat at the highest temperatures.

PBP-based strategies did not capture this long-term system effect, instead favoring immediate, less capital-intensive investments. This example clearly illustrates the phenomenon of technological lock-in, where technologies are chosen for their short-term economic advantage but subsequently limit future options, leading to higher overall costs and slower decarbonization.

4.2. Implications for industrial decision-makers and policymakers

The study showed that, under current policies and projected energy price developments, full electrification of the studied brewery was unlikely to be achieved cost-effectively. The cost-optimal implementation plan resulted in full electrification in only 19 % of the simulated scenarios, and only up to 2050. Under current industrial practices requiring PBPs of 3 years, complete decarbonization occurred in just 12 % of the simulations, with industries often preferring electric boilers over more efficient HTHPs.

Allowing longer PBPs substantially increased the probability of electrification, reaching 48 % of the cases when the maximum PBP was 10 years. This suggested that achieving carbon neutrality in industry would require either policy intervention or a shift in investment behavior. Policies should aim to reduce perceived risk and build confidence in future energy prices, or directly target capital investment costs for energy-efficient technologies. Doing so would allow industries to consider longer investment horizons, avoid risk-averse strategies, and prevent the adoption of less efficient technologies that delay decarbonization.

4.3. Limitations and future work

This study focused on how decision-making strategies influence the implementation pathway of electrification technologies. While uncertainties in projected energy prices were a central element of the proposed methodology, these uncertainties have not been analyzed in detail. A Variance-Based Global Sensitivity Analysis[32] would be necessary to better understand and quantify the influence of uncertain parameters on the results. Such analysis would help identify which input variables most strongly affect model outcomes and where additional data or model refinement would be most beneficial.

It is also important to note that the brewery model used in this work was a simplified representation, particularly regarding investment costs and process integration details. A more detailed process integration study, including the uncertainties in heating demand and temperature requirements, could improve the validity of the results and guide further work in measurement, modelling, cost estimation, and long-term projection improvements [33]. In addition, other energy saving technologies such as biodigesters [34], compression filters [35] and solar thermal systems [36] could be considered in future work to provide a more comprehensive view of brewery decarbonization options.

The current model assumed a fixed heating demand, representing the average load over 6,000 annual operating hours, and sizes the heat recovery tanks for 24 hours of storage. Including a more detailed batch scheduling model would allow for a more accurate and optimized sizing of the heat storage systems. It would also enable the implementation of smart control strategies for the WWHP, avoiding operation during peak electricity price hours and thus significantly reducing operating costs [37].

Finally, potential extensions of the method include the development of risk-aware implementation plans using stochastic programming, simulation of how external events, policy changes, and energy price fluctuations affect technology adoption, and expansion of the framework to other sectors such as dairy or paper production [38,39].

5. Conclusion

This study focused on the decarbonization pathway of a brewery, introducing a method to simulate and evaluate investment planning strategies for energy-saving and electrification solutions. Pinch Analysis was first used to identify suitable heat recovery and heat pump integration options, including wort cooling heat recovery, Pfaduko, MVR, WWHP, HTHP, and EB. Projections of energy price developments from 2025 to 2050 were then used to generate probabilistic scenarios for a Monte Carlo analysis, simulating how PBP-based decision-making strategies drive investments in these technologies and how their outcomes compare to a cost-optimal strategy.

The results showed that:

- PBP-based decision-making strategies led to inefficient and costly transitions by prioritizing low-cost, short-term investments and discouraging the adoption of efficient technologies such as HTHP. In all cases, Wort cooling heat recovery and Pfaduko were adopted, but only when long PBPs were accepted, WWHPs were integrated. This behaviour resulted in an average of 25 % (in the case of PBP_{max}=3) higher TDC compared to the cost-optimal plan.
- The cost-optimal plan minimized TDC between 2025 and 2050, investing in wort cooling heat recovery but preferring the MVR over the Pfaduko. Although the MVR was not an efficient technology on its own, it lowered the overall electricity consumption by enabling a larger share of the heating demand to be covered by the WWHP rather than the higher-temperature utilities.
- Under current policies, technology costs, and projected energy prices, full electrification of breweries was unlikely to be achieved cost-effectively by 2050. Policy support to reduce investment risk, extend acceptable payback periods, and lower capital costs of efficient technologies is essential to enable faster and more cost-effective industrial decarbonization.

Nomenclature

Abbreviations		**Symbols**	
EU-ETS	European Emission Trading System	COP	Coefficient of Performance (-)
HR	Heat Recovery	T	Temperature (K or °C)
EB	Electric Boiler	d	Discount rate (-)
NG	Natural Gas	$\dot{Q}$	Heat duty (kW)
WWHP	Warm Water Heat Pump	$\dot{W}$	Work (kW)
HTHP	High Temperature Heat Pump	η	Efficiency (-)
MVR	Mechanical Vapour Recompression	V	Volume
PBP	Pay-Back Period	α, β, γ	Cost function Coefficients (-)
TDC	Total Discounted Cost	C	Cost (€)
SD	Standard Deviation	p	Price (€/kWh or €/kgCO_2eq.)
OH	Yearly operating hours	e	Unit emissions (kgCO_2eq./kWh)

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