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Optimizing Industrial Heat Electrification: Balancing Cost and Emissions

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ABSTRACT

The electrification of industrial heat is a promising pathway for decarbonization, yet challenges persist in balancing capital costs, operating costs, and emissions reduction. While previous studies have assessed electrification through heat integration and graphical methods, these approaches do not inherently determine the optimal hybrid technology configuration. This study introduces an optimization-based framework that systematically evaluates the cost-optimal allocation of electrified and conventional heating technologies. Formulated as a Mixed-Integer Linear Programming (MILP) model and implemented in Gurobi, the framework minimizes Total Annualized Cost (TAC) while satisfying heat demand, technology constraints, and emissions targets. Applied to an industrial case study, the model compares three scenarios: a fully conventional system relying on steam boilers and fired heaters, a fully electrified system utilizing high-temperature heat pumps, electrode boilers, and electric heaters, and an optimized hybrid system that strategically integrates both conventional and electrified technologies. The results demonstrate that the optimized hybrid system achieves a 75% electrification rate, reducing TAC by 7% compared to previous graphical electrification assessments. The model selects a combination of a high-temperature heat pump and a steam boiler, highlighting the importance of accounting for heat pump cost savings in economic evaluations. Additionally, a comparison with Carbon Capture and Storage (CCS) reveals that partial electrification results in a lower CO_2 abatement cost of 131 \$/tCO_2, compared to 140 \$/tCO_2 for CCS, reinforcing the economic viability of industrial heat electrification. This study provides a systematic optimization framework for guiding industrial electrification decisions and emphasizes the role of carbon taxation, electricity pricing, and renewable energy incentives in shaping cost-effectiveness. The findings underscore the importance of integrating process optimization with techno-economic analysis to accelerate industrial decarbonization.

Keywords: Optimization, Renewable and Sustainable Energy, Energy Systems, Technoeconomic Analysis

INTRODUCTION

The industrial sector is a major contributor to global energy consumption and greenhouse gas (GHG) emissions, with process heat accounting for over half of industrial energy use [1]. Traditionally, industrial heat has been generated using fossil fuel-based technologies, leading to significant CO_2 emissions. Decarbonizing industrial heat generation is therefore essential for achieving sustainability targets and reducing reliance on fossil fuels. One of the most promising pathways for industrial decarbonization is electrification, where technologies such as high-temperature heat pumps (HTHPs), electrode boilers (EBs), and electric heaters (EHs) replace conventional systems.

A comprehensive analysis has shown that 78% of industrial energy demand is electrifiable, with potential CO_2 reductions of up to 78% as the power sector decarbonizes [3]. Industrial process heating, particularly electrifying industrial boilers, has been identified as a high-impact application, potentially reducing emissions by 19 million metric tons of CO_2 equivalent (MMmtCO_2e) under a high-renewables energy grid scenario [4]. Gaps remain in developing systematic, cost-effective electrification processes tailored to specific industries, particularly in chemical sectors and high-temperature heat pump applications [5].

Beyond technological feasibility, policies and economic incentives play a critical role in accelerating industrial electrification [7]. However, transitioning to electrified heat generation presents several key challenges. Matching electrical heating technologies to specific temperature requirements and industrial applications remains complex, as different processes require different heating profiles [6]. Additionally, electrified heating systems often have higher capital and operating costs compared to conventional fossil-fuel-based technologies, making economic feasibility highly dependent on electricity prices and carbon taxation policies [2]. At the same time, there is a pressing need for a systematic framework that optimizes hybrid heat system configurations while leveraging renewable electricity sources to minimize CO_2 emissions and enhance sustainability.

BACKGROUND AND RELATED WORK

Industrial heat electrification has gained significant attention as a key strategy for reducing greenhouse gas emissions and improving energy efficiency in industrial processes. Several studies have explored the techno-economic feasibility of electrification technologies, particularly high-temperature heat pumps (HTHPs), electrode boilers, and electrochemical processes. HTHPs have demonstrated high efficiencies, with coefficient of performance (COP) values ranging from 2.5 to 7 for low-to-medium temperature applications (≤160°C) [8]. However, their adoption remains limited by temperature constraints and high capital costs, restricting their widespread application in high-temperature industrial processes. Recognizing these limitations, Zühlsdorf et al. analyzed the potential for heat pump-based process heat supply at large capacities and temperatures exceeding 150°C, assessing the technical and economic feasibility of integrating heat pumps into industrial systems [9].

Beyond conventional electrification technologies, innovative electrochemical processes are also being explored for cleaner and more energy-efficient industrial applications. Electrochemical synthesis has shown promise in producing ethylene and propylene oxides, providing a cleaner alternative to conventional petrochemical production methods [11]. However, despite their selectivity and efficiency, technical bottlenecks remain, particularly in scaling up these processes for widespread industrial adoption [10]. The integration of electrochemical pathways into industrial heat systems requires further research to address these challenges and enhance their feasibility for large-scale operations.

Several studies have examined the broader implications of industrial electrification on energy systems. Lechtenböhmer et al. found that a fully electrified industry would create significant demand for electricity, which could place major strains on existing power infrastructure [12]. Similarly, Kosmadakis) estimated that high-temperature heat pumps (above 150°C) could meet only 1.5% of industrial heat demand in Europe, underscoring the limitations of single-technology solutions[13]. Bühler et al. investigated the electrification potential in Danish industries, concluding that while up to 80% of heat demand could technically be electrified, economic feasibility remains a major challenge due to high upfront costs and fluctuating electricity prices [14]. These studies highlight the varying degrees of electrification potential across industries but emphasize the need for a more holistic approach that integrates flexibility, cost analysis, and system-level impacts.

Techno-economic analysis (TEA) is commonly employed to evaluate Total Annualized Cost (TAC), Levelized Cost of Heat (LCOH), and CO_2 abatement costs, with studies showing that low electricity prices and high carbon taxes are essential for making electrification competitive with fossil-fuel-based systems [16].
Furthermore, individual electrification technologies, optimization-based frameworks have been proposed to evaluate the electrification of industrial heating systems. A multi-period graph-theoretical (P-graph) approach has been applied to assess refinery electrification, optimizing technology selection under different economic and environmental scenarios [18]. Similarly, a deterministic global optimization model has been developed to evaluate solar thermal and photovoltaic (PV) hybridization for industrial process heat, identifying parabolic trough collectors with thermal energy storage as the most cost-effective solution [19]. While these studies provide valuable insights into electrification strategies, they primarily focus on energy sourcing and hybridization, rather than optimizing the allocation of electrified heating technologies within an integrated process heat system.

This study develops an optimized electrification framework for hybrid industrial heat system, integrating heat integration techniques with Mixed-Integer Linear Programming (MILP) optimization. The framework systematically evaluates and allocates heat generation technologies based on TAC, emissions constraints, and technical feasibility. A key contribution is the comparison between previous graphical electrification assessments and an optimization-based approach, demonstrating improvements in hybrid system allocation and cost-effectiveness. The model is applied to an industrial case study, enabling a comparative analysis of full electrification, hybrid heating systems, and conventional fossil-based technologies. By integrating process integration, techno-economic analysis, and carbon taxes, this research provides a comprehensive and practical roadmap for achieving cost-effective and sustainable industrial heat systems.

OPTIMIZATION FRAMEWORK

Industrial heat electrification presents significant economic and technical challenges, necessitating a systematic approach to determine the most cost-effective integration of electrified and conventional heat generation technologies. While graphical heat integration techniques can provide initial insights, they do not inherently identify the optimal hybrid system allocation that balances cost and emissions reduction. This study introduces an optimization-based framework formulated as a Mixed-Integer Linear Programming (MILP) model, implemented using Gurobi, to achieve a cost-optimal hybrid heat system configuration.

The model is designed to minimize the Total Annualized Cost (TAC) while ensuring compliance with industrial heat demand, technology constraints, and emissions targets. The technologies included are both electrified (High-Temperature Heat Pumps, Electric Boilers, Electric Heaters) and conevtional ones (Steam Boilers and Fired Heaters).

To assess the optimization framework, the model is applied to an industrial case study, generating an optimized hybrid heating system. This system identifies the most cost-effective mix of conventional and electrified technologies for an industrial plant. The optimized system is then compared to scenarios using only conventional technologies (steam boilers and fired heaters) and a fully electrified system (relying solely on HTHPs, EBs, and EHs).

The comparison highlights the trade-offs between capital costs, electricity prices, and carbon taxation policies.

METHODOLOGY

Overview

To evaluate the electrification potential of an industrial heating system, a two-stage approach is employed:

- Graphical Analysis Using Heat Integration – Heat recovery is maximized using Pinch Technology, and the Grand Composite Curve (GCC) is generated to determine minimum heating and cooling demands. This step establishes a benchmark for heating utility selection and technology placement.
- Optimization via MILP Model – An MILP-based framework is developed to determine the optimal technology mix that minimizes cost while meeting emissions constraints.

While graphical methods provide valuable initial insights, they do not yield an optimal solution. The MILP optimization model builds upon heat integration findings, ensuring that the electrification strategy is both technically feasible and economically optimal.

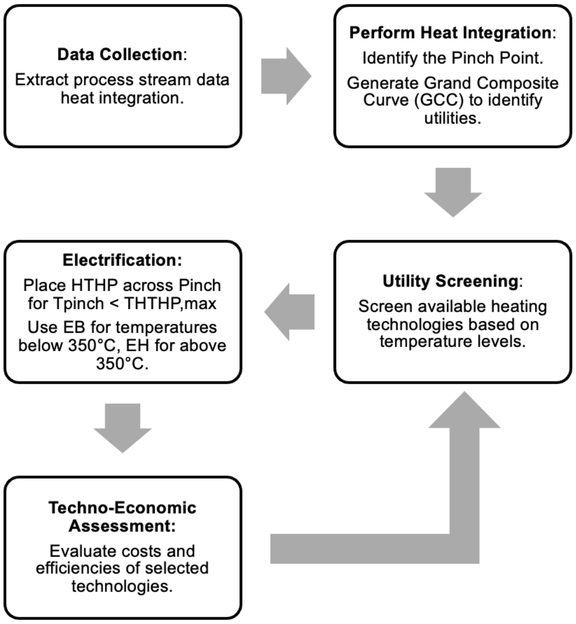

Figure 1. Electrification framework.

To evaluate the electrification potential of an industrial heating system, heat integration is first performed to maximize heat recovery and establish a baseline for assessing various heating technologies. Process stream data is extracted, and Pinch Technology is applied to determine minimum heating and cooling demands. The Grand Composite Curve (GCC) is generated, which helps identify utility requirements and guides the selection of suitable utilities based on the required heat load and corresponding temperatures. The GCC also informs the placement of available heat-supplying technologies. By integrating a heat pump and utilizing heat integration, the placement of the heat pump further reduces the minimum utility requirements. Once the technologies are placed and a final system design is achieved, a techno-economic assessment compares the costs and efficiencies of each option, and Technology Readiness Levels (TRL) ensure the feasibility of implementing electrification.

While this approach uses graphical methods to provide insights, it does not yield the optimal solution. Therefore, once the framework is established, it becomes clear that an optimization model, utilizing heat integration as a benchmark, is necessary to achieve the desired optimal outcome.

The MILP optimization model developed in this study determines the optimal allocation of heat generation technologies while ensuring compliance with technical constraints, economic feasibility, and emissions reduction goals.

Objective Function

The objective function minimizes the Total Annualized Cost (TAC), incorporating:

$$TAC = = \sum(\text{Capital Costs}) + \sum(\text{Operating Costs}) - \mathit{Cost\ Savings\ from\ Heat\ Recovery} \quad (1)$$

where capital costs (CAPEX) account for the investment cost of each technology, and operating costs (OPEX) include electricity and fuel expenditures. CO_2 taxes are incorporated to penalize emissions, incentivizing a transition toward low-carbon heat sources.

The decision variables in the model represent the heat supplied by each technology across different temperature levels. Additionally, a binary variable is introduced to govern the usage of HTHPs, ensuring that the heat pump can only operate when its temperature constraints are satisfied.

Constraints

Heat Balance Constraint

At each temperature level iii, the total heat supplied by all technologies must satisfy the corresponding heat demand:

$$\sum Qtech, i = Di, \forall \mathrm{i} \quad (2)$$

where $Q_{tech,i}$ is the heat provided by each technology at interval i, and Di represents the industrial process heat demand at the same interval.

Technology Operating Temperature Constraints

Each heat generation technology is restricted to operate within its maximum allowable temperature range to ensure technical feasibility:

$$Tmax, i \geq Ti, \forall \mathrm{i} \quad (3)$$

where $T_{max,tech}$ is the maximum operating temperature of a given technology, and T_i is the required process temperature at interval i.

Emissions Constraint

To ensure emissions reduction, the total CO_2 emissions fossil fueled technologies must be below a predefined threshold:

$$\sum Econventional \leq \mathrm{Ethreshold} \quad (4)$$

where $E_{conventional}$ represent the CO_2 emissions from conventional technologies. And $E_{threshold}$ enforces a cap on total emissions, encouraging greater electrification.

Piecewise Linearization of Heat Pump COP

The Coefficient of Performance (COP) of heat pumps is a nonlinear function of the heat load and temperature lift, requiring piecewise linearization for integration into the MILP model:

$$COPhthp = f(Qhthp, Tlift) \quad (5)$$

This approximation ensures computational efficiency while capturing nonlinear COP behavior.

The COP curve was approximated using 13 breakpoints, placed at 5 (K) increments across the 0–70 (K) temperature lift range. At the identified optimal solution, the linearization error was 0.6%. A sensitivity analysis was conducted by varying the number of breakpoints (7–13). The results showed that the Total Annualized Cost (TAC) varied by less than 5% across different configurations, while the hybrid technology mix, such as the combination of high-temperature heat pumps (HTHPs) and steam boilers, remained stable. Only minor shifts in heat allocation were observed, with HTHP utilization varying by approximately ±3%. These findings confirm that the model's conclusions are robust to reasonable changes in linearization parameters, reinforcing the validity of the approach.

Cost Modeling

Conventional equipment cost estimation followed guidelines by Smith (2016) [17]. Cost data is represented through charts showing costs relative to equipment capacity or expressed as a power law of capacity:

$$C_E = C_B(\frac{Q}{Q_B})^M \quad (6)$$

Where C_E is the equipment cost at Q capacity, C_B is the base cost for equipment of Q_B capacity, and M is an equipment type dependent constant.

Capital costs of electrified technologies are estimated using CAPEX factors from the literature.

$$\mathit{Capital\ Cost} = \mathit{Capacity}\ (MW) \times \mathit{CAPEX\ factor}\ (\$ /MW) \quad (7)$$

The operating cost includes electricity cost for electric technologies and fuel cost for steam boilers and fired heaters.

The optimization model is solved using Gurobi, and the output includes the optimal technology mix, representing the megawatts of heat supplied by each technology at eachtemperature level, along with the Total Annualized Cost (TAC), total CO_2 emissions, and the percentage of electrification achieved.

CASE STUDY AND RESULTS

This case study builds upon previous work in which heat integration techniques were applied and the assessment of electrification in an industrial plant heating system was performed graphically, following the developed framework shown in Figure 1. The analysis demonstrated a significant reduction in minimum heating and cooling utilities, with the heating utility for the plant after heat integration, Qhmin, at 16.5 MW and the minimum cooling utility, Qcmin, at 26.1 MW. The application of a high-temperature heat pump (HTHP) further lowered the minimum heating and cooling demands by utilizing waste heat. The study evaluated several scenarios, including partial and full electrification with renewable and conventional electricity, comparing the impacts on operating costs, capital costs, and CO_2 emissions.

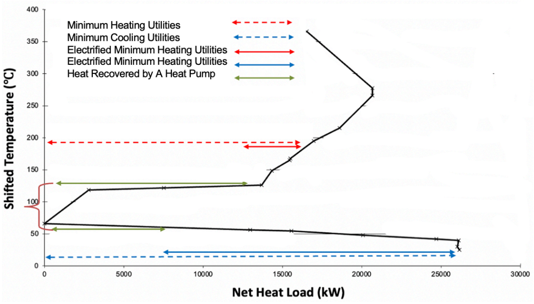

Figure 2. GCC of Case Study.

The Partial Electrification with Renewable Electricity scenario is used here as the case study for the optimization model, as it was the best-performing scenario when combining both emissions reduction and economic viability. In this scenario, the integration of an HTHP reduced heating demand by over 83%, resulting in an 80% reduction in emissions and lower annualized costs compared to conventional technologies. This scenario serves as the baseline for the optimization approach in the current study, which aims to evaluate and compare the performance of hybrid heat systems using a multi-criteria optimization model.

Table 1: Summary of scenarios results.

Scenario	**CO_2 reduction (%)**	**TAC (MM$/y)**
100 % electrified	100	7.9
Partial electrification	83	6.1
Partial electrification (Optimized)	75	5.8

DISCUSSION

The The optimization results revealed an optimal hybrid heat system configuration, where 75% of the heating demand was met using electrified technologies. The model selected a combination of a high-temperature heat pump (HTHP) and a steam boiler (SB) as the most cost-effective solution. The preference for a steam boiler over a fired heater was expected, as the steam boiler provides a more economical alternative, particularly when the temperature levels within the case study allowed for full coverage using steam. Similarly, the selection of an HTHP instead of an electrode boiler (EB) was largely influenced by the model's ability to account for heat pump cost savings within the objective function.

Interestingly, previous studies have not explicitly accounted for the cost savings associated with heat pump integration, which may have led to underestimations of electrification's economic feasibility. This omission may explain why electrification has often been perceived as less competitive compared to other decarbonization strategies. In this study, while the reduction in Total Annualized Cost (TAC) was modest (~7%), the computational efficiency and ease of implementation of the optimization model indicate that the trade-off is worthwhile. The limited TAC reduction aligns with expectations, as the capital investment required for electrified technologies remains fixed regardless of optimization. Once a technology falls within a certain capacity range, its investment cost remains relatively unchanged between the optimized and non-optimized cases.

In addition to evaluating full and partial electrification, this study also compared Carbon Capture and Storage (CCS) as an alternative decarbonization strategy. While CCS is a well-established technology, it is capital-intensive and raises concerns regarding the long-term environmental impacts of CO_2 sequestration. The results indicate that partial electrification achieved the lowest CO_2 abatement cost at 131 $/t$CO_2$, compared to CCS at 140 $/t$CO_2$. However, after optimization, the abatement cost increased to 133 $/t$CO_2$, which can be attributed to the nonlinear relationship between cost and the percentage of electrification. Unlike the trade-off between emissions reduction and electrification percentage, which is relatively linear, the cost vs. electrification percentage relationship is more complex.

Since the optimized scenario resulted in a lower percentage of electrification, it also incurred lower overall costs, but at the expense of higher emissions compared to the non-optimized case. This, in turn, led to a higher abatement cost due to the increased cost per unit of CO_2 reduction. Nevertheless, electrification remains a more attractive decarbonization strategy than CCS in this case study, as it offers a lower abatement cost and avoids uncertainties associated with long-term carbon sequestration.

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