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A SCENARIO-BASED ASSESSMENT OF COMPETING TECHNOLOGIES FOR INDUSTRIAL DECARBONIZATION

Summary

The integration of energy efficiency measures, energy conversion technologies, renewable technologies, and sustainable fuels into industrial processes is a key technological lever for decarbonizing process heat. However, the cost-effectiveness of the chosen technologies, or a combination of technologies, depends on the type of process and exogenous resource constraints. Process integration is a systematic framework for identifying and exploiting opportunities for decarbonizing process heat. Pinch Analysis provides a proven framework to support process integration efforts. The present work demonstrates an application of a framework developed by leveraging Pinch Analysis, Life Cycle Analysis, and Multi-Objective Optimization. The framework identifies optimal configurations of heat recovery measures, heat pumps, solar thermal, and biomass under various resource constraints, including solar irradiance, grid emissions factor, and energy prices.

Keywords: Process Integration, Heat pumps, Solar thermal, multi-objective optimization, Pareto Front

Field of application for the findings: Decision-making framework for industrial decarbonization

Addressed audience: Industrial decision-makers, engineering consultants

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1. Background and Aim

Industrial process heat is responsible for generating approximately a quarter of global CO_2 emissions (IEA, 2025). Several technological pathways can be pursued to achieve deep decarbonization of industrial process heat, including direct heat recovery via heat exchanger networks, heat valorization via heat pumps (HPs), renewable energy via solar thermal systems (ST), and sustainable fuels such as biomass (BM). However, the cost-effectiveness and environmental impact of these pathways depend heavily on the type of industrial process and regional resource constraints. Moreover, despite these technologies being effective at reducing Scope 1 emissions, as the degree of integration increases, electricity consumption for their operation and the manufacturing of technology components results in additional Scope 2 and Scope 3 emissions, respectively. To achieve holistic decarbonization cost-effectively, it is important to have a robust, systematic, and flexible decision-making framework to identify the optimal configuration of decarbonization technologies for the given industrial process within the given resource constraints. The current work leverages Pinch Analysis (PA) to identify technically feasible configurations of decarbonization technologies, Life Cycle Analysis (LCA) to estimate environmental impacts, and combines these with economic analysis to identify optimal configurations using Multi-Objective Optimization (MOO).

Process integration serves as a systematic framework for identifying decarbonization opportunities and is facilitated by techniques such as PA. Traditionally, PA implements tools such as composite curves (CCs) and grand composite curves (GCCs) to identify direct heat recovery (DHR), utility targets, and optimal utility placements (Linhoff and Vredeveld, 1983). The PA-based methods have been adopted to evaluate the integration potentials of various technologies into industrial processes, such as HPs (Olsen et al., 2017a), ST (Walmesly et al., 2013), geothermal (Barkaoui et al., 2016), and combined heat and power (CHPs) (Olsen et al.,2017b). Several studies have explored the economic optimization of HENs (Yee and Grossmann, 1990), HPs (Wallerand et al., 2018), and HPs and thermal energy storage (Stampfli et al., 2019). In addition to the economic-optimal integration of energy efficiency measures and energy conversion technologies, the existing literature includes MOO frameworks that simultaneously minimize economic costs and environmental impacts associated with HEN implementation, formulated as mixed-integer nonlinear programming (MINLP) (Wen and Sonnard, 2003). Despite these advancements, a robust and flexible decision-making framework remains needed. As a result, the current work aims to develop and apply a decision-making framework to identify optimal integration regimes for HPs, STs, and BM for various industrial processes under regional resource constraints.

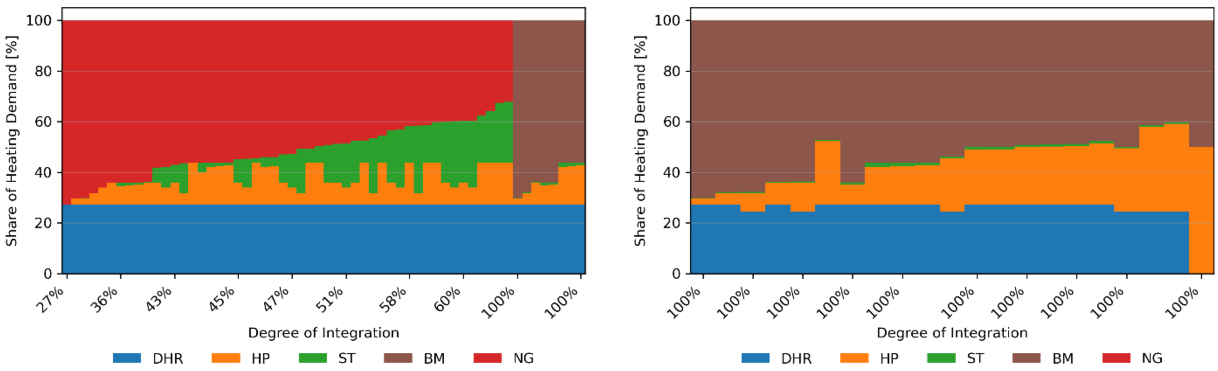
2. Methods and Data

The methodology integrates Pinch Analysis (PA), Life Cycle Assessment (LCA), and multi-objective optimization to systematically evaluate decarbonization strategies for industrial process heat systems. PA is used to generate all technically feasible configurations of direct heat recovery (DHR), heat pumps (HPs), solar thermal (ST), and fuels by identifying thermodynamic limits and integration points based on composite curves and source–sink profiles. Both conventional (EEM → ECT → RT) and non-conventional integration sequences are considered to ensure a comprehensive solution space. For non-continuous processes, indirect heat recovery (IHR) via thermal energy storage is modeled using time-averaged approaches. Scenario analysis is incorporated to capture the influence of external factors such as solar irradiance, electricity prices, and biomass availability, yielding a broad set of feasible configurations across process types and boundary conditions.

The generated configurations are evaluated using economic and environmental models. Total annual cost (TAC) includes amortized capital expenditure and operating costs, derived using technology-specific scaling laws and standard financial assumptions. Environmental impacts are quantified using a cradle-to-end-use LCA approach, capturing Scope 1, 2, and 3 emissions using parameterized models implemented in Brightway, based on Ecoinvent data and the IPCC 2021 GWP100 method. The resulting performance metrics are used in a multi-objective optimization framework to identify Pareto-optimal solutions, revealing trade-offs between cost and emissions. This approach enables the identification of economically and environmentally optimal integration strategies under varying industrial and regional conditions, while maintaining computational tractability through a sequential optimization structure.

3. Case Study and Results

The developed framework is applied to a variety of industrial processes to derive optimal decarbonization pathways that account for regional resource constraints. The chosen case studies represent continuous dairy production processes. The framework is implemented for two extreme scenarios. To simulate the most adverse conditions in Europe in terms of regional resources, the average annual solar irradiance is set to the lowest observed value, the highest grid emission factor is used, and biomass prices and spark gap ratio are set to their highest observed values. Similarly, a hypothetical, most favorable scenario is created using all favorable values for regional resources. The Pareto Front obtained by applying the developed framework comprises configurations that trade off cost and environmental impact. The configurations with a lower degree of integration represent lower cost (left of Figure 1), whereas the configurations with a higher degree of integration represent lower environmental impact (Right of Figure 1). Figure 1 (a) represents the share of heating demand covered by various technologies for Pareto-optimal solutions under most adverse conditions, whereas Figure 1 (b) presents the share of technologies for Pareto-optimal configurations under the favorable conditions. Based on the preliminary results so far, for a continuous process with a medium-temperature heat demand (70% below 100 °C), direct heat recovery is always a cost-effective baseline in both scenarios. In the more resource-constrained scenario, solar thermal plays a larger role, covering up to 30% of annual heating demand. Under more favorable conditions, on the other hand, the heat pumps and biomass integration appear more in the set of Pareto-optimal solutions. Based on the economic analysis, the Pareto-optimal configurations in the favorable scenario have an average payback time of 2 years, whereas those in the adverse scenario have a payback time of 8 years.



(a) (b)

Figure 1: Technology share of Pareto-optimal configuration for dairy processing under (a) adverse conditions and (b) Favorable conditions

4. Conclusions and outlook

The current framework provides a pathway for determining optimal integration strategies for various types of processes under different regional resource constraints for two objectives. The results presented in the extended abstract represent only two scenarios and a medium-temperature continuous process. Ongoing work focuses on extending the results to include more types of processes, such as non-continuous processes, high temperature processes, and more realistic scenarios to demonstrate the robustness and flexibility of this decision-making framework.

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