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DECARBONISATION THROUGH INNOVATION

Systematic industrial decarbonization through heat integration and high-temperature/steam-generating heat pump- A case study in agrochemical sector

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Abstract

This study demonstrates systematic decarbonization at a Swiss agrochemical site, combining pinch analysis with different temperature-lift technologies: mechanical vapor recompression (MVR), high-temperature heat pumps (HTHPs), and steam-generating heat pumps (SGHPs). The focus was placed on the site's largest steam consumer (29 % of total), where practical barriers (low source temperatures, capacities below commercial thresholds, chemical compatibility, and ATEX requirements) limited direct heat pumping potential. A networked solution was developed aggregating multiple low-capacity heat sources through an intermediate fluid circuit, creating a consolidated flow suitable for commercial-scale upgrading. The upgraded heat is redistributed to multiple sinks efficiently at varying temperatures through a second network. A mixed-function HTHP-SGHP configuration maximizing steam production (6 barg) and pressurized water (120 °C) emerged as optimal fit for this case-study, achieving 26 GWh thermal energy savings (13.3 GWh net), 67 % steam reduction in the analyzed plant (20 % site-wide), and 12 % total site CO_2 reduction with non-fossil electricity. This work advances industrial heat recovery through: (1) transforming scale mismatches into advantages via strategic networking; (2) prioritizing electrification-based heat pumping over direct integration; (3) enabling steam injection for operational independence; and (4) considering multiple heat output with flexible ratios to reduce exergy losses.

Keywords: Industrial heat pumps, MVR, HTHP, SGHP, Chemical industry decarbonization, Pinch analysis, Exergy optimization, Process integration, Waste heat recovery

1. Introduction

Large energy-intensive industries such as agrochemical production face mounting pressure to decarbonize, with process heating (often from fossil-fueled steam) driving high emissions and costs. Efficiency measures and electrification via heat pumps offer the most immediate paths to carbon reduction per McKinsey abatement curves [1], before resorting to more costly options such as carbon capture or low-carbon fuels. Yet real implementations are limited due to financial barriers, insufficient case studies, and installation complexity [2]. For chemical industry, site-specific challenges including mismatched scales between processes and commercial technologies, chemical incompatibilities (flammable material and ATEX zone), and operational constraints are additional obstacles.

Recent work demonstrates industrial heat pump viability. Arpagaus et al. [3] reviewed Swiss HTHP integration achieving coefficient of performances (COPs) of 3-4 and paybacks under 5 years. Bamigbetan et al. [4] reviewed vapor compression heat pumps enabling temperature lifts exceeding 100 °C. Babaei & Patel [5] showed that HTHPs can cover ~80 % of pulp and paper steam demand with 1.82–5.15 year paybacks. The role of HTHPs in Swiss climate pathways has been further explored by [6], identifying the chemical industry as a key target for heat pump deployment to meet national decarbonization goals. Combining pinch analysis with heat pumps optimizes integration [7], with Schlosser et al. [8] demonstrating 20 to 100 % energy cuts.

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Exergy analysis further refines heat pump integration; Wu et al. [9] showed cascaded heat recovery minimizes irreversibility. Building on multi-level data approach and total site integration [10-12], this work extends existing frameworks to prioritize electrification pathways aligned with net-zero objectives.

This study carried out at a Swiss agrochemical site addresses the gap for small-to-medium capacity industrial units where chemical complexity and scale limitations make conventional approaches unviable. It introduces novel solutions for: (1) aggregating multiple small-capacity heat sources to enable the application of commercial-scale heat pumps, (2) flexible steam and hot water co-production to reduce thermal exergy losses, and (3) steam network injection strategies enabling heat pump operational independence from production variability and schedule. The steps from pinch-based potentials to thermo-economic evaluation are presented, showing how these innovations can accelerate decarbonization. The methodology combined pinch analysis for identifying heat recovery potentials, multi-level data modeling for transition from theoretical target to realistic solution, different temperature-lift technologies, and a thermo-economic analysis to evaluate them.

2. Methodology

This study applies the general methodology of [10] to a large-scale agrochemical site, with adaptations to prioritize electrification pathways for sustainability.

A site-wide steam mapping identified the largest steam-consuming plant as the primary target. Initial assessment revealed data gaps: no existing energy balance models and insufficient utility metering (notably missing steam flow measurement). A multi-level data extraction approach [11] combining black-box, grey-box, and process-level models was implemented using both top-down and bottom-up methods. This hybrid approach allowed cross-validation of results and gap-filling using mobile measurements and process simulations where necessary.

Enhanced pinch analysis was applied using multiple data representations [13,14] (thermodynamic, technology, and utility levels) instead of a single idealized model. This ensured that each unit's heat demand was represented in a way consistent with available data and operational constraints. Integration of exergy analysis with process limitations helped define realistic recovery targets. Constraints considered included: limited process access, chemical compatibility, temperature limits, safety and ATEX requirements, and minimal modification of existing equipment. The methodology prioritized the use of the lowest feasible temperature sources to minimize exergy destruction and maximize system efficiency. Additional factors such as space limitations, preference for proven technologies, organizational capacity, and long-term decarbonization strategies were integrated into solution screening.

All solutions were evaluated not only on energy savings but also on economic and carbon performance, with the cost per ton of CO_2 avoided serving as the primary decision metric. This allowed the study to remain focused on decarbonization impact rather than short-term profitability alone. Final selection balanced efficiency with practicality, considering fluctuating energy prices, source-temperature tolerance, technology maturity, and alignment with site evolution plans.

3. Heat Integration and Heat Pumping Potential Assessment

3.1. Direct Heat Integration (HI) Analysis

Plant A with five production lines accounting for 29 % of the site's steam consumption is selected as HI target. The ideal-target Composite Curve (CC) is built with only thermodynamic representations achieving 43% maximum energy recovery (MER) of the total plant A heat requirements (Figure 1-Left). Then applying the enhanced pinch analysis framework with multiple representations methodology and considering all constraints the MER potential is reduced to 29% (Figure 1-Right) but defining practical target.

Analysis of this realistic CC revealed that existing heat recovery exchangers were generally well-positioned. Nonetheless, this potential was not excluded from the subsequent heat pumping analysis. This strategic decision reflects the prioritization of electrification-based decarbonization over traditional heat exchange optimization.

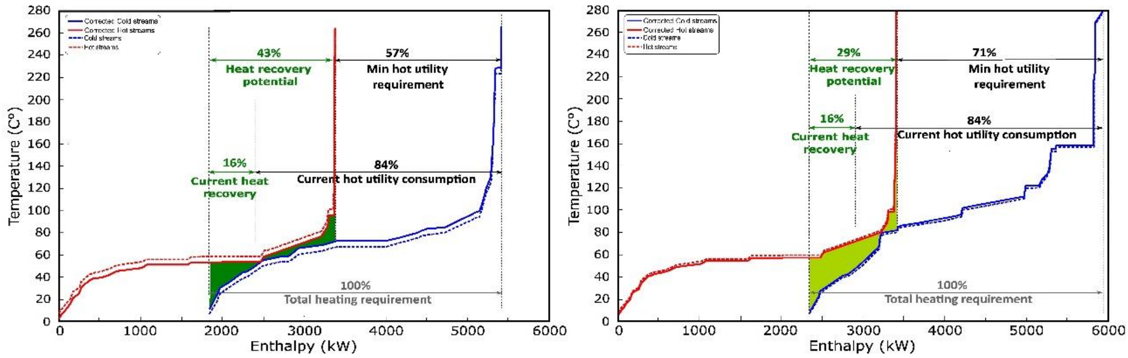

Figure 1. CC of base case (Left) with thermodynamic representation and (Right) with multiple representations

3.2. *Beyond Direct Integration: Operational and Advanced Solutions*

Grand Composite Curve (GCC) analysis revealed energy improvement opportunities beyond direct heat exchange, including operational modifications and advanced heat pumping.

3.2.1. Pressure Modification Potential

GCC identified one attractive modification: reducing falling film evaporator pressure to create a heat recovery pocket with another column's evaporator. Process simulations indicated that a 0.7–0.9 bar reduction (i.e. atmospheric to approximately 100 mbar vacuum) was needed. Laboratory tests confirmed feasibility. This increased theoretical recovery from 29 % to 43 %, representing 4.1 GWh additional annual savings with minimal capital and no additional electricity consumption.

3.2.2. Advanced heat pumping integration

GCC interpretation identified multiple units with upgrading potential. However, a market screening revealed commercial systems were incompatible due to: (1) capacity below commercial thresholds at the source temperatures, (2) chemical compatibility issues (flammability, toxicity, fouling), and (3) ATEX requirements. Closed-cycle systems theoretically addressed chemical compatibility, but the capacity mismatch persisted.

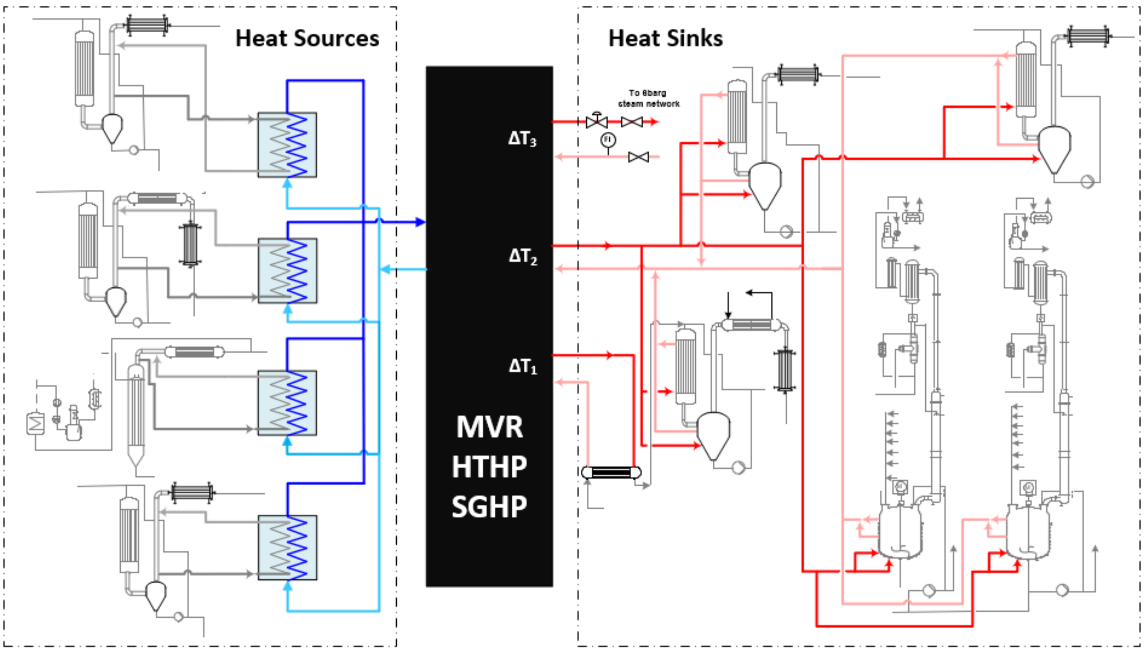

Figure 2. Heat sources and heat sinks networks connected to a temperature-lift technology

An innovative network-based approach was developed to aggregate multiple small-capacity sources through an intermediate fluid collection network, generating a consolidated waste heat stream upgradable through commercial-scale technology, then redistribute to multiple sinks at various temperatures through a second network (Figure 2). This bridges the gap between small-scale sources and commercial technologies.

The heat source aggregation network was designed to recover the full waste heat potential while respecting pinch constraints, thermodynamic feasibility, and heat pump operational limits. The design aimed to: maximize source temperature to improve COP, minimize heat exchanger count and surface area, reduce piping complexity and maintain operational flexibility in a chemically complex environment.

The problem resembles a Heat Exchanger Network (HEN) design challenge, a multi-objective, non-linear optimization problem [16] where the same cold stream passes through multiple exchangers, and heat pump specifications impose additional constraints. Two heuristic-based configurations were developed for this study phase (Figure 3):

- Parallel configuration maximizes outlet temperature for each exchanger while recovering 100 % of available heat; simple and low-CAPEX, but may incur higher exergy losses due to non-isothermal mixing.
- Hybrid parallel-series configuration increases source temperature by splitting into multiple loops feeding separate heat pumps; reduces exergy losses and can improve individual loop COP, but requires additional loops, more complex controls, and higher initial investment.

Both configurations recover the full available waste heat. The parallel configuration offers simplicity and easier integration, whereas the hybrid design can achieve higher source temperatures and marginally better COP at the loop level. However, in this case study the overall COP values were comparable between the two designs, as shown by the calculated Lorenz COPs (reference hot temperature = 165 °C) in Figure 3.

A full multi-objective optimization could be pursued in the implementation phase. For this study, a deterministic heuristic model was applied to ensure feasibility and comparability across scenarios, with the optimum design retained as a potential upgrade option for future capacity expansion.

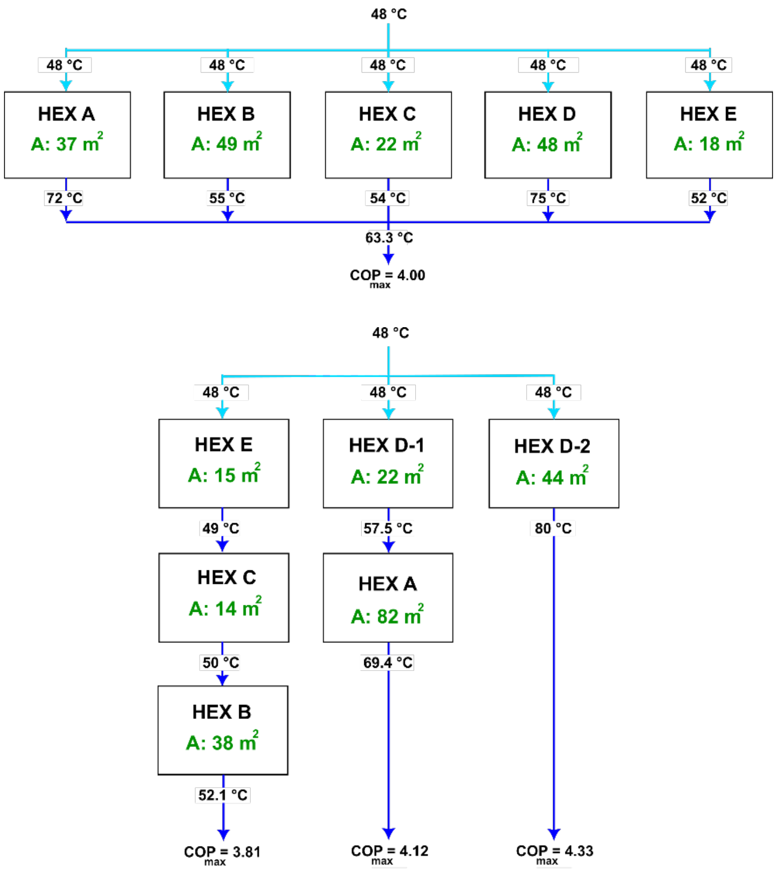

Figure 3. Comparison of two heat source integration network configurations: parallel (top) and hybrid parallel-series (bottom)

For each developed scenario, we secured viable commercial offers from established heat pump suppliers confirming both the technical, and economic, feasibility. While introducing operational complexity through centralized interdependence, it enables significant efficiency gains applicable across industrial sectors facing similar challenges.

3.2.2.1. Closed-Cycle MVR with Pressurized Water Output

This configuration employs a closed-cycle mechanical vapor recompression system collecting waste heat from three falling-film evaporators and one wiped-film evaporator as saturated steam at approximately 48 °C. The system delivers pressurized water at five different temperature levels (90 to 120 °C) to three falling-film evaporators, two reactors, and one rotary dryer, with temperature lifts ranging from 42 °C to 72 °C depending on sink requirements. A COP of 3.6 is estimated and thermal energy savings of approximately 13 GWh. This configuration achieves the highest COP among selected options.

3.2.2.2. HTHP with Pressurized Water Output

This high-temperature heat pump configuration collects waste heat from two falling-film evaporators and one wiped-film evaporator as hot water at approximately 50 °C, delivering pressurized water at 120 °C to three falling-film evaporators, two reactors, and partial heat demand for one wiped-film evaporator. A COP of 2.8 (ΔT=70 °C) is estimated with thermal energy savings of 13 GWh.

3.2.2.3. HTHP-SGHP Hybrid with Dual Output

This hybrid configuration combines a high-temperature heat pump and steam-generating heat pump technologies, collecting waste heat from two falling-film evaporators and one wiped-film evaporator at approximately 50 °C. The system delivers both pressurized water at 120 °C and steam at 6 barg, to provide the heat requirement for the defined units on the composite curve (CC). A combined HTHP-SGHP configuration is used with a COP of 2 (ΔT = 115 °C) to 2.81 (ΔT = 70 °C) to deliver thermal energy of approximately 17 GWh. This configuration introduces operational flexibility through dual-output capability, enabling optimization between sensible and latent heat delivery based on instantaneous demand profiles.

3.2.2.4. Maximum Capacity HTHP-SGHP with Steam Network Injection

This advanced configuration represents a major change in integration strategy, utilizing the full waste heat capacity, including portions suitable for direct heat recovery or already in place, to maximize steam production. The system collects waste heat from three falling-film evaporators and one wiped-film evaporator at approximately 54 °C. An optimized HTHP-SGHP system can deliver thermal energy of approximately 26 GWh with a COP of 3.1 for ΔT = 36 °C; 2.78 for ΔT = 66 °C and 2.05 for 6 barg ΔT = 111 °C. The system delivers pressurized water at two temperature levels (90 °C and 120 °C) to three falling-film evaporators and two reactors, while producing steam at 6 barg for direct injection into the plant steam network. The production ratio between pressurized water and steam is dynamically adjustable, enabling real-time optimization to minimize exergy destruction and maximize carbon reduction based on process requirements.

4. Result & discussion

Table 1 summarizes the results of all scenarios studied. The composite curves of the base case and the scenario with SGHP integrated at its maximum capacity are shown in Figure 4-left and their exergy GCC on right. The color variation of the maximum energy recovery (MER) area shows how the heat recovery potential changes for each scenario, improving from 29 % by only direct heat integration to 97 % with the SGHP scenario (100 % basis is the total heat requirement represented in the analysis from this plant). From the direct heat recovery potential, selected options for fast implementation bring approximately 1.7 GWh energy savings. This potential for saving is independent of other solutions and can be pursued separately. Pressure modification is the simplest scenario, with an estimated 4.1 GWh annual energy savings. It requires minimal capital and operational expenditure, as it avoids significant electricity consumption and uses only modest additional equipment. Both closed-cycle MVR and HTHP solutions improve the MER further to 78 % compared to the base case. Although the CO_2 abatement cost is slightly higher in the MVR system, it represents a better decarbonization solution than a HTHP with saving higher energy (8.8 GWh) and thermal exergy due to better efficiency (COP=3.6).

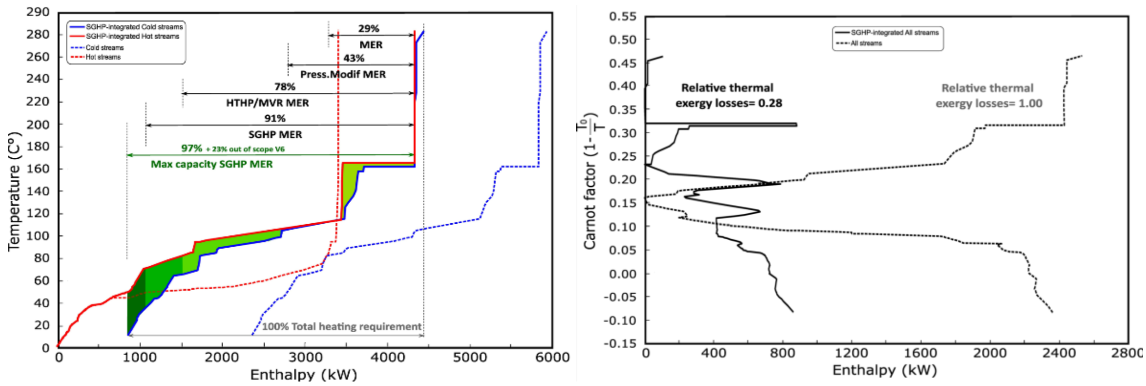

Figure 4. Composite curves (left) and exergy grand composite curves (right) for base case and SGHP integrated at maximum capacity.

The SGHP model producing steam and pressurized water performs even better with less cost per ton CO_2 savings while increasing both MER and steam saving as well as reducing the exergy destruction. This is mainly due to the advantage of latent heat in comparison to the solution with only pressurized water (sensible heat).

Here, not only is the full capacity of waste heat used but the potential for direct heat exchange and already implemented waste heat recovery is also reconsidered. A notable example is the waste heat recovery exchangers that used good-quality heat to preheat process at low temperature. While in this solution those heat sources are used to generate steam and improve the system COP has higher temperature available at heat source. It shows 97 % potential of MER with further 23 % through steam generation that is not visible in the curve, bringing the total waste heat recovery to 120% of the plant's heat demand. This apparent over-100% recovery is achieved because steam generation adds an additional usable energy stream beyond the originally targeted heat demand, effectively delivering more recoverable heat than the baseline requirement. Without SGHP and by applying only traditional methods, this efficiency level and waste heat utilization were not possible. The SGHP solution at maximum capacity, while it has the best cost rate among heat pumping technologies, reduces dramatically the exergy destruction and can save 26 GWh thermal energy and net, 13.3 GWh energy, which corresponds to a 67 % reduction in steam consumption for this plant and 20 % for the site overall. The savings from previously implemented preheating heat exchangers were already deducted from this potential. This solution has a higher cost for saving a ton of CO_2 than traditional solutions for direct heat recovery, however it has a 5 to 13 times higher steam saving capacity and consequently decarbonization potential in the presence of non-fossil electricity sources. Also, the steam network injection strategy provides several operational advantages: (1) Flexible distribution: Steam can be consumed by any production line based on instantaneous demand, (2) Inter-plant potential: Creates opportunity for steam sharing across multiple plants, (3) Production independence: Heat pump operation decouples from specific unit production rates, and (4) Infrastructure optimization: Eliminates complex dedicated piping to individual consumers.

Table 1. Summary of all scenarios

Integrated option	MER (%)*	Relative thermal exergy destruction (T_0=298k) (-)⁑	Thermal energy saving (GWh)	Net energy saving (GWh)	Price of a ton of CO_2 saving in system lifetime (CHF/ton CO_2) ⁂	Heat supply type & Solution characteristics
Direct HI	29	1.0	1.7	1.7	51.0	Process flow
Pressure modification	43	0.87	4	4.1	12.4	Process flow, ΔP=0.9 bar
Closed-cycle-MVR	78	0.48	13	8.8	90.1	Pressurized water 90 to 120 °C, COP=3.6
HTHP	78	0.56	13	8.1	82.4	Pressurized water 120 °C, COP=2.81
HTHP-SGHP	91	0.42	17	10.5	74.2	Pressurized water 120 °C and steam at 6barg, $COP_{overall}$=2.68
HTHP-SGHP at max capacity	97 (120)	0.28	26	13.3	69.4	Pressurized water 90 to 120 °C and steam at 6barg, $COP_{overall}$=2.43

* The 100 % basis is the total heat requirement represented in the CC.
⁑ The used steam as a utility is from cogeneration unit.
⁂ Levelized cost of CO_2 abatement (CAPEX) over the system's expected lifetime (25 years for MVR and 20 years for others).

The analysis is sensitive to key assumptions, particularly the electricity-to-gas price ratio and achievable COP. A sensitivity analysis was performed to determine the minimum COP required for positive operational savings under various price scenarios:

$$COP_{min} = \frac{Electricity\_price\ [\frac{MU}{kWh}] \times Steam\_specific\ enthalpy\ [\frac{KJ}{Kg}]}{3600\ [sec] \times Steam\_price\ [\frac{MU}{Kg}]} \quad (1)$$

Where MU is the monetary unit. Only technologies exceeding COP_{min} in all tested scenarios were considered viable.

The optimal solution is therefore not universal; it depends on the specific weighting of factors in each organization's decision framework. For example, if electricity prices were to double, the SGHP-at-maximum-capacity scenario might lose its economic advantage, making a closed-cycle MVR more attractive despite lower decarbonization potential.

5. Conclusion

The study employed a systematic methodology based on process integration to evaluate all possible heat recovery solutions through integration of heat pumping technologies families. A real-life case was studied, and different models were developed using the available parameters from commercial equipment, including closed cycle MVR, HTHP and SGHP. The results of each technology are presented and compared. The analysis shows that short-term financial optimization may differ from optimal carbon reduction, but both converge when considering long-term net-zero objectives. Analysis of the different possibilities shows that the best decarbonization strategy is to think into long term solutions. In this specific case study, a combined HTHP-SGHP stands as the best decarbonization choice that fits the defined decision criteria, despite its higher price implication in the short term.

To overcome the waste heat source limitation by its low temperature and capacity, an intermediate waste heat recovery network is developed to connect several low-capacity heat sources via closed circuit, generating a single consolidated waste heat stream of greater capacity. This stream is then upgraded using temperature-lift technology and redistributed to multiple heat sinks at different temperature levels through a second network by minimizing exergy destruction and maximizing carbon reduction. This method allows to turn a limitation, the mismatch in scale between small industrial processes and commercial heat recovery technologies, into an advantage, enabling considerable carbon reduction.

The first focus of industrial heat decarbonization should be on efficiency and low-to-medium-temperature process heat electrification, then filling the remaining needs with low-carbon fuels or applying carbon capture, utilization and storage (CCUS) methods. Here, it is proposed to prioritize advanced-technologies integration rather than direct heat integration to increase carbon reduction. This is different from traditional heat integration, where non-penalizing heat exchangers are generally accepted and the possible direct heat recovery in the MER zone of PA is preferred, i.e. performing heat recovery for the same amount of heat without consuming any extra electricity and with simple infrastructure (normally only heat exchangers and pumps). Therefore, to decarbonize and achieve net-zero, heat pumping solutions can be prioritized over direct heat recovery through heat exchanger installation or process operating condition modification, particularly when non-fossil electricity and favorable electricity-to-gas price ratio is available. Its advantage is two-fold: 1) increasing the potential of decarbonization, in proportion to the heat pump's COP, and 2) satisfying higher-temperature-requirement heat sinks, which, if not satisfied, would use gas today and later require to be decarbonized using more complex approaches such as CCUS [1]. Therefore, to decarbonize and arrive to net zero, the heat pumping solutions sometimes take priority over direct heat recovery through heat exchanger installation or process operating condition modification.

When the potential of heat pumping and heat sinks requirement are identified, the choice of heat pumping technology should be studied wisely. The optimum solution among different types of MVR, HTHP and SGHP or their combination available in the market differs case by case and depends on the characteristics of each case-study, the organization's internal criteria and set objectives, and electricity-to-gas price ratio.

The idea of generating variable and flexible amounts of heat output (pressurized hot water and steam) allows to reduce the exergy destruction at any moment, so that optimizing on CAPEX and OPEX cost.

The idea of generating maximum potential of steam and its injection into available steam network, allows the heat pump technologies to be independent of the specific production line or unit, providing heat for a wider range of sink. This gives significant flexibility into the dynamics of production and avoids at the same time any limitation on both the product quantity and decarbonization potential by the heat pump technology.

Beyond the specific case studied, the proposed approach can be applied to a wide range of industrial sectors, offering a replicable pathway for accelerating industrial decarbonization worldwide.

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