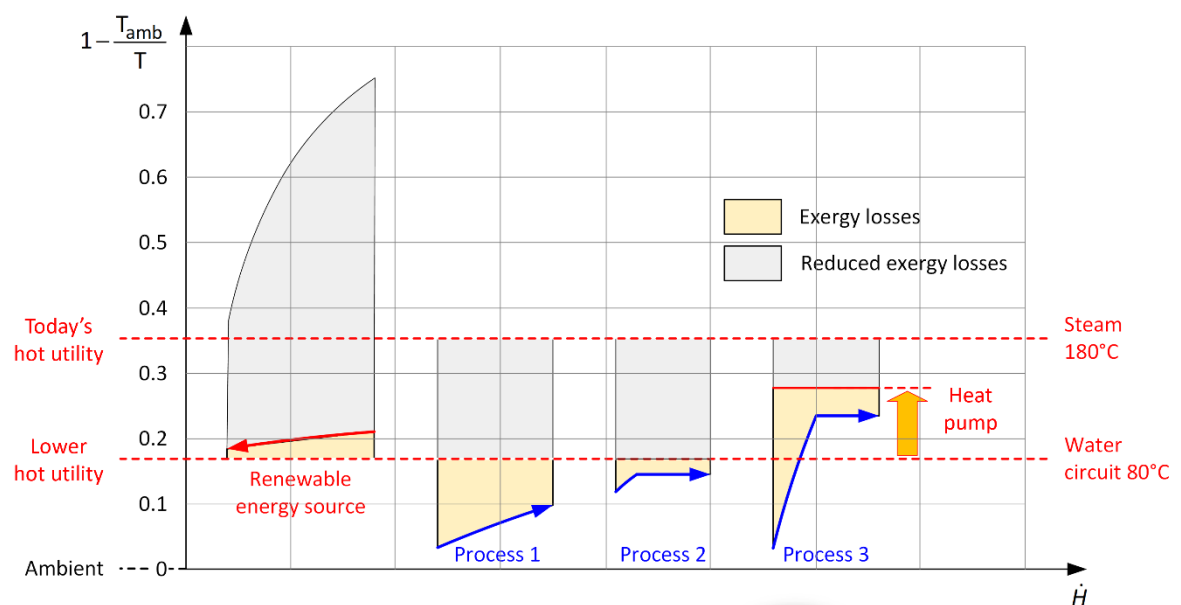




Final report from 31 March 2025

DeCarb-PUI Guideline

Decarbonization of industrial processes through redesign of the process-utility interface





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Summary

As industries strive toward decarbonization, process integration, energy conversion, and renewable technologies play a crucial role. However, relying solely on these technologies often falls short of achieving deep decarbonization due to inherent inefficiencies in conventional utility systems. In many industrial sectors, utility systems are designed to cater to the highest temperature demands, often leading to significant exergy losses. The SFOE co-funded project, “Decarbonization of industrial process through redesign of process-utility interface”, DeCarb-PUI, addresses these inefficiencies by rethinking utility supply temperatures and redesigning utility systems to achieve greater energy efficiency and decarbonization.

DeCarb-PUI is based on the principle that, in a resource-constrained world, exergy efficiency is more important than mere energy savings. This approach challenges the status quo of “standard” utility systems, such as medium-pressure steam, which frequently results in inefficient resource use across industrial processes. By focusing on the process-utility interface, DeCarb-PUI aims to optimize heat transfer, reduce energy waste, and promote sustainable energy use. This approach is set up by involving partners from both process industries and equipment manufacturers.

This document provides a framework to guide industrial stakeholders and equipment manufacturers through the decarbonization potential offered by redesigning the process-utility interface (PUI). It demonstrates how larger heat recovery, enhanced efficiency, and profitability can be achieved with optimized energy conversion technologies, like heat pumps, and renewable resources. It is especially relevant for process designers and energy engineers experienced in methodologies like Pinch Analysis. Pinch Analysis is integral to this approach, beginning with accurately defining the heating and cooling requirements of each process. By adhering to the principle of “Keep Hot Streams Hot, Keep Cold Streams Cold,” users can identify optimal opportunities for heat recovery and utility integration.

In addition, the guideline emphasizes solutions that incorporate heat pumps, as an example, which can be applied at various integration levels:

- Localized: Heat pumps operate within a single process.
- Cluster: A “cluster” of processes is served by a single intermediate loop, achieving a balanced solution that meets economic and practical needs.
- Total site: Heat pumps serve processes across the whole site.

Profitability and decarbonization potential are influenced by the electricity-to-gas price ratio (Spark Spread ratio), making it crucial to evaluate solutions using mid-term projections rather than current values alone. This guideline will help users incorporate economic considerations, including the Spark Spread and cost-benefit analysis, to ensure sustainable and profitable outcomes.



List of abbreviations

CAPEX	capital cost
CC	composite curves
CIP	cleaning-in-place
COP	coefficient of performance
EEM	energy efficiency measure
GB	grey box (model)
GCC	grand composite curve
HEN	heat exchanger network
HEX	heat exchanger
HP	heat pump
HR	heat recovery
LLCO ₂	Levelized Cost of CO ₂
MVR	mechanical vapor recompression
OPEX	operating cost
PA	pinch analysis
PUI	process-utility interface
RCC	residual composite curves
Tec	technology (model)
Thm	thermodynamic (model)
UF	Ultrafiltration
Uti	utility (model)
WB	white box (model)



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1 Introduction

1.1. Context and motivation

As the industrial sector advances toward decarbonizing operations by 2050, roadmaps are being developed to support this critical transition. In 2020, SwissEnergy contributed significantly with the publication of the brochure "Auf dem Weg zur klimaneutralen Produktion"/"Vers une production climatiquement neutre" which outlined essential pillars for industrial decarbonization: enhancing energy efficiency, expanding renewable energy use, and implementing technologies to reduce or replace fossil-based heat sources, such as biomass, biofuels, solar thermal, and heat pumps (HPs).

While integrating these technologies—like process electrification paired with renewables—can reduce greenhouse gas emissions in the near term, achieving comprehensive climate neutrality will require fundamental changes. This includes rethinking energy resources and redesigning utility systems to align with the true thermal requirements of industrial processes.

Certain industries, such as cement and metals, need high-temperature energy resources, but for many sectors, including Food & Beverages and Biotech & Pharmaceuticals, low-temperature heat (below 100 °C) suffices to a large extent. Yet, many processes still rely on fossil-fuel-based, low- or medium-pressure steam systems, which are often mismatched for their thermal needs. This leads to substantial exergy losses and unnecessary CO₂ emissions—issues that underscore the importance of considering both energy and exergy efficiency.

In the Swiss Food & Beverages sector, for example, while energy efficiency is relatively high, exergy efficiency is notably low due to the prevalent use of high-quality fuels for low-temperature heating. This highlights a significant opportunity: by aligning energy sources more closely with process needs, industries can reduce both resource waste and emissions, paving the way toward climate-neutral production.

DeCarb-PUI focuses on the context of future decarbonization efforts, where mitigating misallocation and waste becomes imperative due to the constrained availability and cost-efficiency challenges of renewable resources. Instead of a direct fuel substitution for deeper decarbonization, DeCarb-PUI recommends lowering the supply temperature first, to reduce the load of fuel substitution.

The following energy conversion and heat distribution technologies are relevant for the Swiss industry:

- Superheated water boiler
- Hot water boiler
- Electrical heater / boiler
- Solar heat (both $\leq 100^{\circ}\text{C}$ and $> 100^{\circ}\text{C}$)
- Heat pump (both $\leq 100^{\circ}\text{C}$ and $> 100^{\circ}\text{C}$)
- Internal combustion engine CHP
- Mechanical vapour recompression (MVR) and thermal vapour recompression technologies (to be integrated at the process level, to be analysed ahead of global utility integration)
- Heat storage.

The coefficient of performance (COP) of a heat pump is highly sensitive to temperature lift (ΔT_{lift}). Figure 1 illustrates this relationship, showing COP as a function of ΔT_{lift} for different second-law efficiencies, which represent the ratio of the practical COP to the theoretical Carnot COP (typically ranging from 0.45 to 0.55). The strong dependence on temperature lift highlights the importance of operating at temperatures as close as possible to process requirements. Consequently, the widespread and economically viable adoption of heat pump technologies relies heavily on their ability to operate efficiently within these temperature constraints. Similarly, the efficiency of solar thermal collectors decreases almost linearly as the collector temperature increases (more precisely as a function of $T_{\text{coll.}} - T_{\text{ambient}}$).

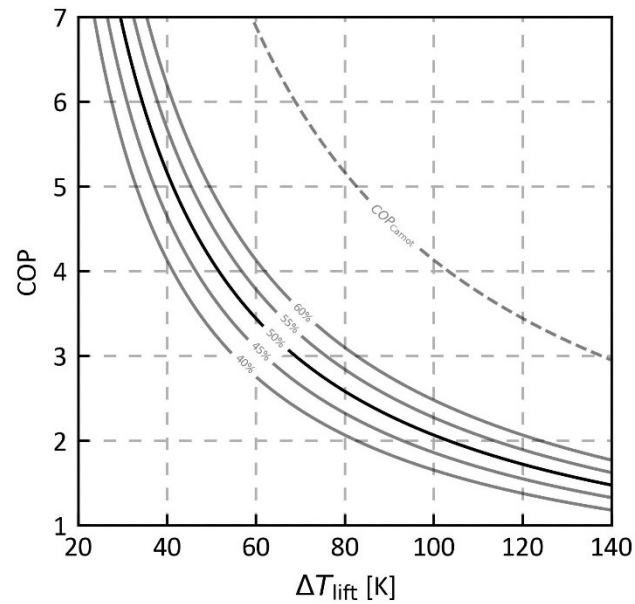


Figure 1: Efficacy of heat pump based on their temperature lift, based on a T_{sink} of 140 °C.

1.2. DeCarb-PUI objectives

The overarching aim of the project DeCarb-PUI is to “retrofit for cooler hot utility and hotter cold utility”. The project aims to achieve this by optimizing the PUI through exergy analysis, balancing costs and resource efficiency by addressing energy and exergy efficiencies, holistically, using Pinch Analysis (PA). It focuses on reducing exergy losses, especially at the PUI, to enhance heat integration and the efficiency of energy conversion technologies, e.g. HPs, as shown in Figure 2.

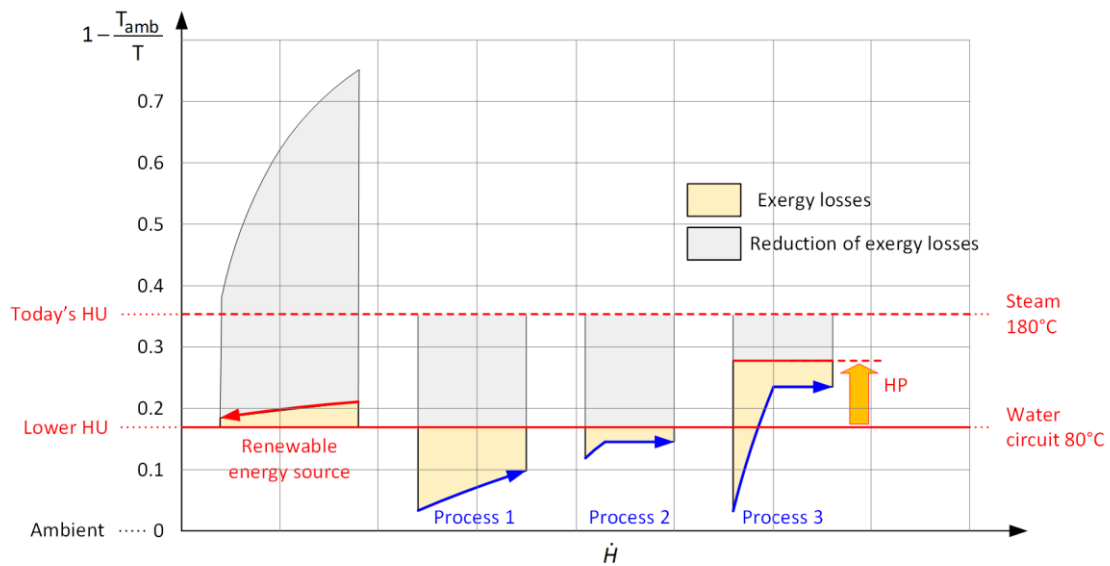


Figure 2: Illustration of the ideality of DeCarb-PUI

By lowering hot utility temperatures, it minimizes exergy losses but must consider the trade-offs between operational and capital expenses. Unlike complex academic approaches, DeCarb-PUI emphasizes practical tools and methodologies, drawing from real case studies to align industrial thermal equipment manufacturers' requirements with those of process industries.



The aim of this guideline is to guide industrial stakeholders to rethink the method to retrofit their PUI in a holistic manner, by using PA and Exergy Analysis. The guideline uses both methodologies to:

- Identify improvements in temperatures for heat supply using practical methods
- Identify the decarbonization potential
- Identify trade-offs between exergy loss reduction and energy conversion and renewable technologies integration concepts.

The targeted audience of this work aims at engineers, industrial and manufacturing partners, and researchers interested in improving the process-utility interface. This guideline requires audiences to have basic knowledge on Pinch Analysis, and exergy analysis, which they are fully described in the final report of DeCarb-PUI.

As a reminder, the Swiss Federal Office of Energy (SFOE) supports the analyses of thermal processes within the framework of the SwissEnergy programme in industrial and commercial enterprises. Swiss Energy's promotion and financial support over the last decade have allowed the establishment of the PA as an essential practical method to optimize heat recovery (HR) and achieve heat integration of industrial processes. There are two categories of PA in Switzerland, rough and detailed PA. However, in DeCarb-PUI, detailed PA is essential. Detailed PA requires comprehensive data collection and data evaluation with the aim of gaining a clear overview of the energy flows and the energy balance of the whole site (production and infrastructure facilities). Rough PA does not provide enough sources and sinks information to consistently apply the approach and properly evaluate the solutions proposed by DeCarb-PUI.

2 Guideline steps

DeCarb-PUI combines three established engineering techniques to create a practical framework for improving utility supply, as shown in Figure 3. The DeCarb-PUI framework primarily leverages Pinch Analysis. In addition, Exergy requirements and heat transfer exergy losses are estimated for different system boundaries for three different utility retrofit levels, (i) localized (process level), (ii) cluster of processes, and (iii) total site. Finally, an economic analysis is done to compare the economic performance of the alternative designs. Section 5.1 provides a brief summary of the basics of Pinch Analysis.

The localized process refers to a single operating unit, a cluster refers to the integration of multiple operating units, and the total site refers to all operating units of the industrial process. The retrofit designs can include different measures like heat pumps or renewable energy technologies. After following the DeCarb-PUI methodology, it can be extended by looking at other decarbonization options, e.g., fuel substitutions. Although fuel substitution involves renewable energy as well, contrary to measures addressed by DeCarb-PUI, its efficiency does not (or only slightly) depend on the temperature level of the utility system. The numbering of steps described below follows the sequence depicted in Figure 3.

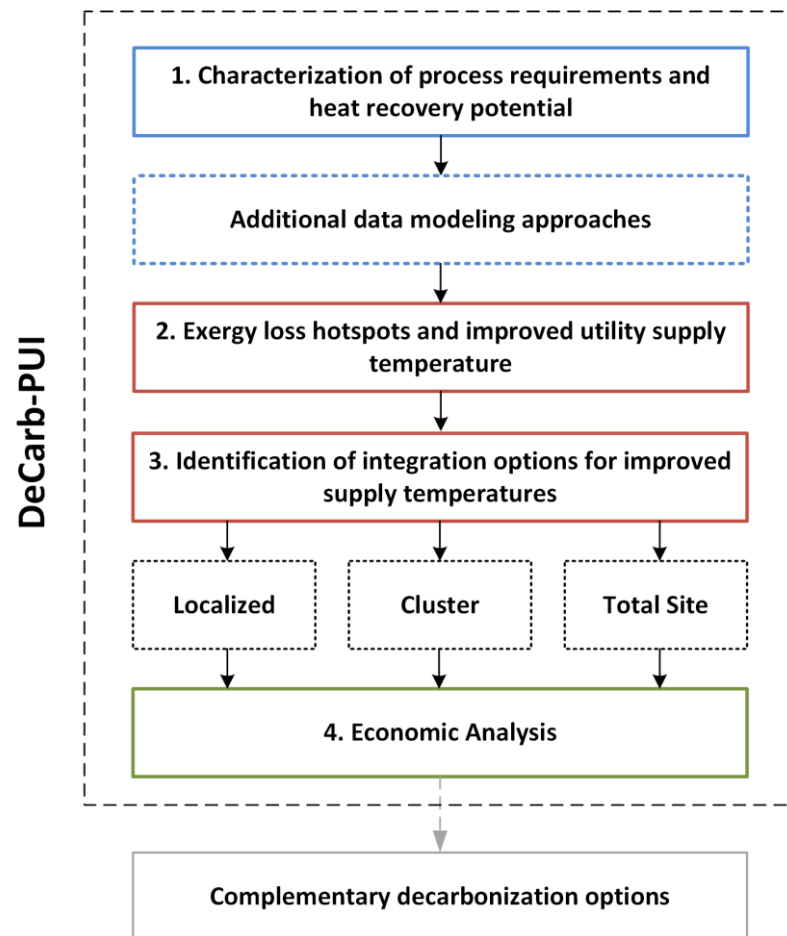


Figure 3: Overall methodology for retrofit of process-utility interface.

Step 1: Process data extraction and estimation of heat recovery potential

The appropriate definition of process heating and cooling requirements (also called “process data extraction”) is a key step for a successful and meaningful PA, which forms the foundation of the DeCarb-PUI framework. PA relies on several key principles, among which:

1. **Keep hot streams hot and cold streams cold:** to maximize the heat recovery potential, define the heating requirements (cold stream) at their lowest temperature possible (i.e., as close as possible to the actual process requirement); likewise, for the cooling requirements.
2. **Do not carry over features of the existing solution:** this means 1) do not take existing operating conditions for granted, but challenge them to identify the real process requirements (e.g., prevent non-isothermal mixing, very large driving forces, etc.), and 2) ignore (in a first stage at least) non-critical heat transfer and solution features to extract actual problem data.
3. **Golden Rules of heat transfer:**
 - a. Do not cool hot streams above the pinch temperature using cold utility.
 - b. Do not heat cold streams below the pinch temperature with hot utility.
 - c. Avoid heat transfer across the pinch point from hot to cold streams.

Any violation of these Golden Rules decreases the heat recovery potential and entails an increase of operating cost (OPEX) or a reduced HR for a given capital cost (CAPEX).



In DeCarb-PUI, we distinguish between two typical process data modelling alternatives:

- **White box (WB):** the heating and cooling requirements included in the process stream table are defined as "as close as possible" to the process. According to data extraction principles, features of any previous HR solution are ignored when extracting heating and cooling requirements for the WB model. Thus, proposed energy efficiency measure (EEM) solutions are not constrained by pre-existing process features.
- **Grey box (GB):** defined by a restricted list of heating and cooling requirements after excluding the requirements achieved by the existing HR heat exchangers (HR HEXs). These processes usually have a small scope for additional heat exchange between the process streams but have significant utility use. GB model typically depicts "residual heating and cooling requirements".

The appropriate modelling alternative depends on the location of the boundary between the part where heat transfer can be modified (and process data are known or can be determined) and the part where no change can be made (and/or process data are unknown). The WB model offers the greatest flexibility and the highest HR potential. Hence, the WB or GB models refer to various boundaries of possible modifications of the considered process.

Usually, GB modelling is recommended by the company and chosen by the Pinch engineer as a reasonable and easier approach. Except in particularly constrained cases, it is also worth building the Composites Curves (CCs) and the HR targets with the WB model. In this way, the improvement of the HR potential and/or the decrease of the required exergy can be checked and quantified. It can then be decided whether the resulting potential savings are worth the modifications of the existing heat recovery, or not.

The WB model itself may either be set up for the process as presently operated with the existing technology (**Tec** variant), or assuming modifications in order to tend towards the thermodynamically ideal (**Thm** variant) according to the above 1. and 2. rules for process data extraction.

Step 1.2: Identification of heat recovery potential and energy savings

Once the list of heat transfer requirements of the different processes has been set up through the step of process data extraction, the simplified workflow presented in Figure 4 can be followed to identify heat recovery potentials for individual processes and inter-process potentials (e.g., through the integration of HPs). The workflow presented aims to guide the search for promising heat integration solutions, assessing them and selecting the most appropriate one(s), apply the analysis to each relevant alternative model (WB-Thm, WB-Tec, GB), and check for differences in targets, especially at Actions 1 and 5.

For a clearer understanding, heat recovery and heat upgrading are distinguished in the context of DeCarb-PUI:

- **Heat recovery** means heat transfer from a heat source to a heat sink at lower temperature (whether the transfer occurs directly, or through an intermediate media/loop). Here, the heat sink is not an evaporator stream of a heat pump, but a process stream to be heated up;
- **Heat upgrading** involves the increase of the temperature of the heat source to supply a heat sink at a higher temperature. It is complementary to heat recovery as defined above.

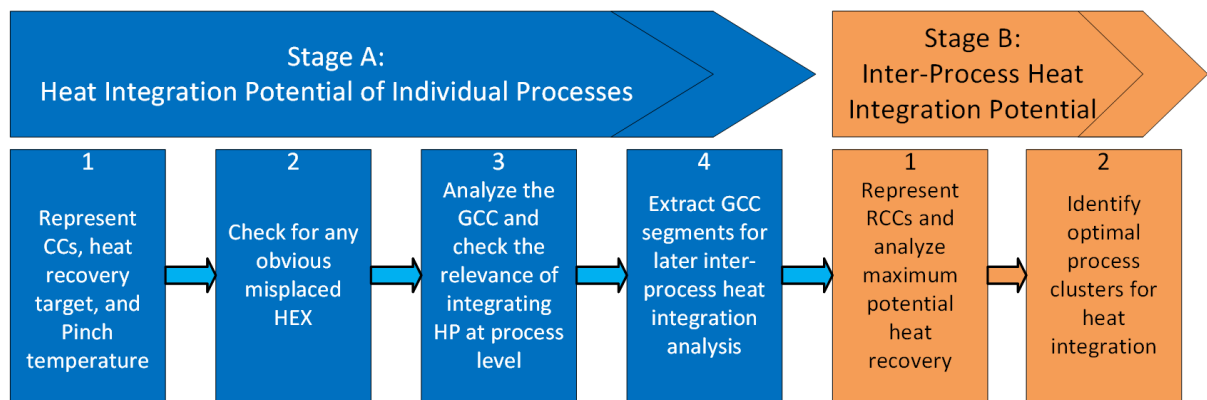


Figure 4: Simplified workflow for targeting and optimizing an industrial site's heat recovery and upgrading via HP(s), including several processes (excerpt from *HTHP Guidelines* document from the SFOE co-funded *HTHP-CH – Integration of High-Temperature Heat Pumps (HTHPs) in Swiss Industrial Processes*)

Note that HR and heat upgrading can be targeted and designed in two ways:

- **Simultaneously:** during targeting, the heat pump is “defined” (i.e. by selecting the appropriate heat duty, the condenser and evaporator temperatures) against the profile of the Grand Composite Curve (GCC). In this way, the optimum operation conditions of the HP (minimum temperature lift, maximum COP) can be obtained. This is done prior to the design of the heat exchanger network (HEN), which shall be developed to achieve both heat recovery and heat upgrading.
- **Or Sequentially:** in this case, the heat recovery HEN is designed first (without bothering about the heat upgrading). Then, the remaining heating and cooling requirements of streams left over by the heat recovery HEN can be listed and the remaining heat integration problem can be defined. The GCC of this remaining problem is then used to “define” the HP. This means heat upgrading is considered as an afterthought, resulting in most cases in poorer performances of the HP. However, the design of the HEN in two phases (first the heat recovery HEN, then the heat upgrading HEN with the HP) makes the job and the HEN simpler (i.e. containing fewer heat exchangers).

Stage A: Heat Integration Potential of Individual Processes

The first stage focuses on heat integration within individual processes, prioritizing direct heat recovery as it is typically more cost-effective than inter-process integration. Each process is analyzed in isolation before considering broader site-wide optimization.

1. The analysis begins with the representation of CCs in kilowatts, defining the heat recovery target and identifying the Pinch temperature. This step determines whether there is potential for internal heat recovery, considering a single process in isolation.
2. Once the Pinch temperature is known, HEXs are evaluated for misplacement. Any HEX that violates fundamental heat transfer principles—such as transferring heat across the Pinch—must be identified. Additionally, HEXs with large temperature driving forces are flagged, as they may compromise total site HR potential. While these units may not necessarily violate heat transfer rules, they must be assessed further in Stage B, where inter-process integration is considered.
3. After identifying misplaced HEXs, the GCC is analyzed to assess whether a HP could be effectively integrated at the process level. This involves evaluating its potential profitability, although final placement decisions must account for the overall Pinch temperature, which will be determined in the inter-process integration stage.
4. The final step in Stage A is the extraction of GCC segments for use in inter-process integration. These extracted heat surplus and deficit segments, measured in kilowatt-hours over a reference duration, provide a basis for broader heat recovery strategies. Selecting an appropriate reference duration is critical—if set too broadly (e.g., a full year), it may mix process contributions



that never overlap in real-time. Conversely, if the timeframe is too short, potential heat recovery opportunities may be overlooked. Multiple operating cases may need to be considered to account for seasonal variations and scheduling differences between processes.

With Stage A complete, individual process efficiencies have been optimized, and the extracted GCC data is ready for inter-process integration in Stage B.

Stage B: Inter-Process Heat Integration Potential

While Stage A maximizes heat recovery for individual processes, this stage expands the scope to identify additional savings through inter-process heat recovery and HP integration at either the utility or process-cluster level.

1. The first step in this stage is the representation of Residual Composite Curves (RCCs) to evaluate the maximum potential for inter-process heat recovery. These RCCs are constructed using the GCC segments extracted in Stage A, with surplus heat shifted by $-\Delta T_{\min}/2$ and deficit heat shifted by $+\Delta T_{\min}/2$. This provides an upper-bound estimate of the total heat recovery potential. Additionally, different RCC extraction scenarios—including those that consider or exclude deep or wide pockets—are analyzed to determine their impact on heat integration.
2. Once RCCs are established, optimal process clusters are formed, grouping processes that offer the best synergy for heat integration. Several factors influence the clustering strategy, including short piping distances, large energy flows, simultaneous operation schedules, and minimal temperature lifts. The goal is to balance technical feasibility with economic practicality, ensuring that capital investments in heat transfer loops or utility networks are justified by energy savings.

With inter-process heat recovery opportunities identified, the **most efficient heat pump integration strategy** can be selected. In some cases, **HP integration at the process level** may remain the best option, while in others, a **site-wide or utility-level HP** may offer greater cost-effectiveness due to **economies of scale**.

Key Considerations for Implementation

Beyond the structured workflow, several technical considerations influence the effectiveness of heat integration:

- **Process Scheduling & Synchronization:** Unlike CCs in continuous processes, RCCs represent residual heat flows that may not always coexist in time. If process schedules do not align, heat storage may be required to facilitate effective heat recovery.
- **Heat transfer Loops & Utility Networks:** Inter-process heat recovery requires dedicated heat transfer loops or shared utility networks, introducing capital and operational costs. The number of loops required depends on process temperatures, network configurations (parallel vs. series), and whether excluding certain processes could optimize cost-effectiveness.
- **Overall Pinch Temperature for HP Placement:** To ensure optimal efficiency, a heat pump's placement must be validated against the overall Pinch temperature of the process cluster, rather than the individual process. Additionally, HEXs flagged in Stage A must be reassessed in this stage to confirm compliance with efficiency targets.

By following this systematic, multi-stage approach, the DeCarb-PUI methodology ensures that heat recovery and heat upgrading solutions are not only technically viable but also economically optimized, providing a pathway toward cost-effective industrial decarbonization.

Step 2: Identify exergy loss hotspots and optimum utility supply temperatures



To complement PA with the estimation of exergy losses, a new representation of the composite curves named exergy GCC, i.e. using the Carnot factor instead of the temperature for the vertical axis¹ (Figure 5). In the Energy Availability Diagram (Figure 5 (a)), the process part of hot and cold CCs provide a quantified and direct view of exergy requirements, whereas the utility part of the curves provides the measure of exergy supplied. A cumulative net process exergy demand can then be estimated and plotted with the exergy supplied by the utilities (Figure 5 (b)). The exergy losses of the different processes can then be identified based on the difference between the net process exergy demand and exergy supplied by constructing EGCCs for different processes or groups of processes. In addition to exergy losses caused by heat transfer at the process-utility interface, the exergy losses due to different technological implementations are also estimated in a similar fashion, but the exergy losses due to exergy destruction (e.g., through combustion) are not included in this study. This step aims to identify inefficiencies, such as temperature mismatches between process requirements and the current utility supply, thus leading to the identification of exergy loss hotspots.

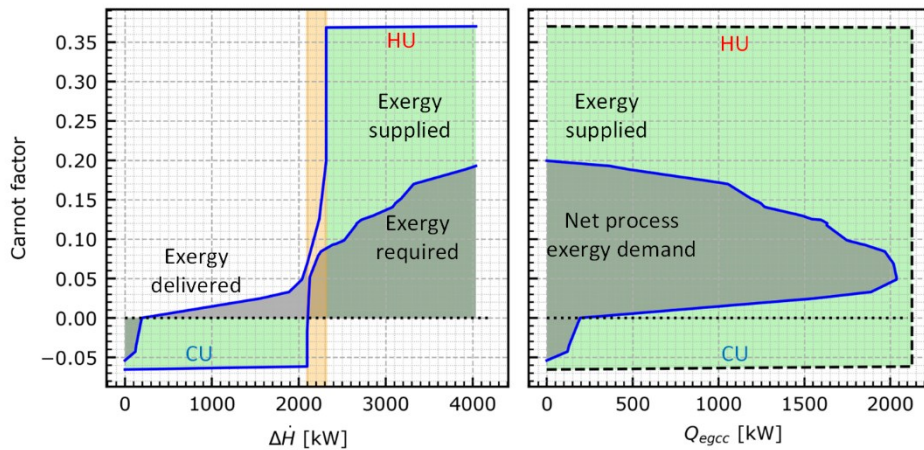


Figure 5. (a) Energy availability diagram (b) Exergy GCC

In DeCarb-PUI, Exergy Analysis is used to assess the efficiency of utility retrofit at three different levels, (i) localized, (ii) cluster of processes, and (iii) total site. Localized solutions are measures for individual processing unit. When deciding which processes to cluster in an industrial process, the main criteria focus on maximizing energy efficiency, cost-effectiveness, and operational compatibility, especially when energy conversion technologies (HPs) are considered. The critical criteria are:

- 1) Temperature level compatibility:
 - Source Temperature: The process providing the heat to the heat pump should have a waste heat temperature within the effective operating range of the heat pump's evaporator.
 - Sink Temperature: The process requiring heat should need it at a temperature achievable by the heat pump's condenser. Higher temperature lifts generally result in higher energy costs, so the temperature difference between source and sink should be minimized for efficiency.
- 2) Energy demand and supply compatibility
 - Energy Demand Requirements: The demand from the receiving process should be compatible with the energy output characteristics of the conversion technology. A stable or predictable demand helps optimize technology performance.

¹ For more information on the exergetic GCC, the explanation of the representation can be found in the final report.



- Supply Availability: Ensure a consistent and adequate supply of the energy source, whether it's waste heat, steam, or mechanical energy, to avoid underutilization or cycling issues in the conversion technology.
- 3) Operational schedule compatibility
- Alignment of Operating Times: Processes with matching or complementary operating schedules are ideal. Energy conversion technologies perform optimally when they operate continuously, so matching continuous processes or complementary batch operations is beneficial.
 - Downtime and Maintenance Schedule: Processes that align in maintenance schedules with the energy conversion technology can minimize disruptions and improve reliability.
- 4) Physical proximity
- Physical Distance: Closer proximity between the processes reduces energy loss and transportation costs, especially critical for thermal energy. This also impacts installation costs, as shorter piping or wiring distances are cheaper and more efficient.
 - Integration with Existing Infrastructure: Look for processes located near existing energy distribution infrastructure (e.g., steam lines, electrical connections) to reduce capital costs and simplify integration.
- 5) Energy conversion and renewable technologies compatibility:
- Energy conversion technologies: capacity ranges, design and performance data, economic data (capex, maintenance costs, depreciation, etc.), and free space requirements.
 - Solar heat: availability of suitable area, design and performance data, economic data (capex, maintenance costs, depreciation, etc.) constraints (required load-bearing capacity of roof, where applicable)
- 6) Reliability and process compatibility
- Operational Stability: Connect to processes with stable energy outputs to avoid frequent shut-downs or variability in conversion efficiency. Technologies like turbines and heat pumps often require steady inputs for efficient operation.
 - Contaminant and Fouling Potential: Processes that provide clean energy sources are more compatible with energy conversion systems, as contaminants may damage or reduce the efficiency of the technology.

Total site on the other hand considers all processing units in the industrial plant. *However, the criteria above can be used to eliminate processes from the total site solution.*

Step 2.1: Identifying optimum utility supply temperature

The exergy GCCs for different local solutions and clusters provide the basis for finding an optimum utility supply temperature that minimizes the total annual cost. In this case, it is conducted for multiple design variants, localized, cluster, and total site.

NOTE: PA typically precedes improvements identified for PUI, providing a comprehensive assessment of potential heat recovery. WB modelling is ideal for this stage as it defines requirements without current heat recovery constraints, maximizing the flexibility of solutions. Once PA is completed, PUI improvements can be targeted using residual heating and cooling requirements, which account for existing heat recovery infrastructure.

Step 3: Identification of measures for improved supply temperature

Once the utility supply temperatures closer to the process requirements are identified, various measures and technologies that can provide these temperatures can be identified based on the range of their typical operating temperatures. The information on the integration of the different technologies can be found in various SFOE reports ([1, 2]) and SWEET project [3]. The correct integration of technologies is



crucial. For example, the position of the pinch point and the shape of the GCC indicate whether it makes sense to integrate a HP or whether an existing HP is correctly integrated into the process. With a correctly integrated HP, the heating and cooling requirements and the associated energy costs can be reduced simultaneously (note that if waste heat (“soft streams”) is used as a heat source, only the heating requirements and associated costs are reduced).

Step 4: Economic Analysis

Once the improved utility temperatures and the measures to achieve those temperatures are identified, the total costs of technology options for the PUI improvements are estimated using cost functions derived from historical data. The total cost of technologies implemented to improve the PUI consists of CAPEX and OPEX for implementing the HPs, piping, and installation. The total CAPEX is converted to annualized CAPEX using the annuity factor, which in turn is a function of the discount rate and the lifetime of the technology. Use the Levelized Cost of CO₂ Abatement (LCCO₂) to evaluate the financial feasibility. To conduct an economic analysis of energy integration technologies in an industrial context, certain key considerations and data points are essential:

1) Economic Parameters

- CAPEX: Investment costs for equipment, installation, and infrastructure adjustments. Break-down CAPEX by equipment type, piping, instrumentation, and installation costs.
- OPEX: Include maintenance costs, labour, and the costs of utilities (e.g., electricity or fuel).
- Energy Savings and Cost Reduction: Calculate potential reductions in energy consumption and their impact on OPEX. Account for potential energy savings from HR/conversion technologies.
- Carbon Costs and Savings: Estimate CO₂ savings and any financial implications based on carbon credits or regulatory requirements (if applicable).

2) Technical and Performance Data

- Energy Profiles: Gather data on temperature levels, flow rates, and heat loads for all sources and sinks.
- Performance Metrics: For each technology (e.g., HPs, turbines), collect data on performance indicators like efficiency, COP, or capacity factor.
- Lifetime and Depreciation: Define the expected lifetime of equipment and depreciation rate, which affects profitability and return on investment calculations.
- Operating Hours: Estimate the number of annual operating hours to ensure accurate calculation of energy savings and equipment utilization.

3 Example

To show the concept and steps of reducing the temperature of the PUI, it is presented using a dairy plant as a case study (simplified schema present in Figure 6). The chosen dairy plant produces cheese, cream, and milk powder. Due to the campaign-driven operating schedule, a typical winter day is used to represent the heating and cooling demands. To simplify the example, the following assumptions are made:

- 1) CO₂ contribution of electricity: Assume electricity is CO₂-free to directly correlate energy savings with CO₂ savings. This assumption simplifies the CO₂ reduction calculation, which could otherwise be impacted by the carbon intensity of electricity.
- 2) Process Continuity: Assume continuous processes to avoid the need for complex scheduling or storage considerations, thus making it simpler to analyze heat recovery and energy flows.



- 3) Simplified COP calculation for HPs: Exclude intermediate loops in the COP calculation for heat pumps, focusing only on direct heat source and sink connections.
- 4) Market conditions and prices: Set assumptions for energy prices, CO₂ pricing, and any relevant subsidies or incentives.
- 5) Capital cost: In the cost analysis, different generalized factors adopted from widely available literature (e.g., Smith, 2005) are used for piping for localized, clusters, total site variants.²

The example included in this document demonstrates the application of the methodological framework developed in this project. The results and discussions presented in this section follow the same sequence as that of the steps introduced in the methodology section (Figure 3). However, it should be noted that the results obtained by applying this methodology presented in the example below are site-specific and cannot be generalized for the Dairy industry.

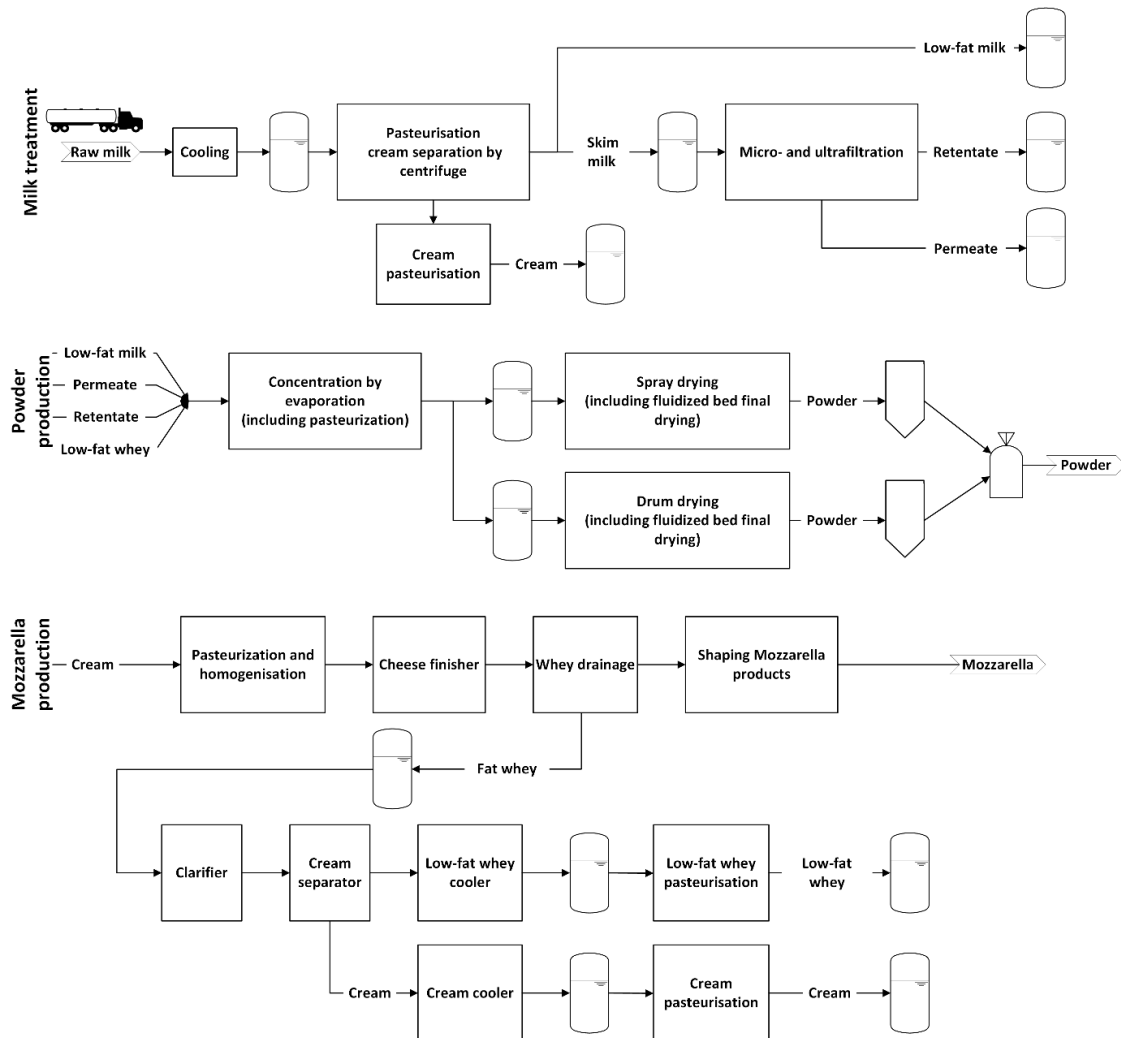


Figure 6. Simplified production route at Dairy plant considered.

3.1.1.Characterization of process requirements and heat recovery potential

² The initial economic analysis following the PA is conducted during the conceptual phase, using widely available generic cost factors for preliminary estimates. As the project progresses to the detailed design phase, these factors are refined based on site-specific considerations such as material selection, insulation requirements, drilling through walls, and space constraints at the plant. Since these adjustments are tailored to individual projects, their inclusion is beyond the scope of this document.



Representing almost a quarter of the total annual heating demand, spray drying is the largest heat-consuming process in the plant, followed by drum drying, which is responsible for about 13% of the total final heat demand (see Figure 7). The process stream table consists of data for 52 process streams. In order to keep the example concise, an abridged version of the process stream table is presented in Table 1. However, the results include detailed heating and cooling requirements of selected process streams.

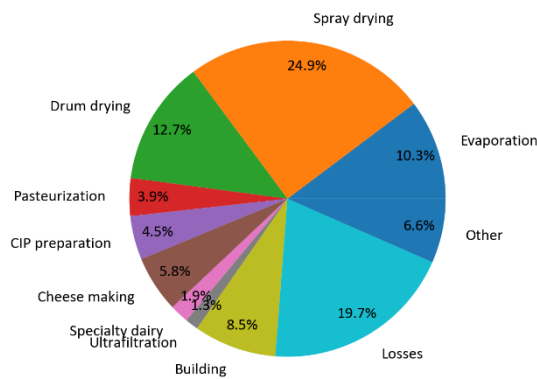


Figure 7. Share of energy demand by end-use [4].

Table 1: Typical process requirements for a dairy plant.

Process*	Hot/cold	T _{in} (°C)	T _{out} (°C)
Separation	Cold	90	95
Spray drying	Cold	46	195
Roller ventilation (RV)	Cold	4	18
Pasteurization heating	Cold	53	82
Compressor	Cold	40	60
Cheese production melting water (CP)	Cold	15	81
Cleaning in place (CIP)	Cold	15	75
Ultrafiltration heating (UF1 & UF2)	Cold	36	72
Domestic hot water	Cold	50	60
Pasteurization cooling	Hot	62	5
UF cooling	Hot	42	15
Chiller recooling	Hot	30	20
Wastewater	Hot	27	20

*Since the PUI improvement, in this case, is analyzed after PA-related improvements, the grey box modeling approach is implemented for the PUI analysis, i.e., only the residual heating and cooling requirements are considered.



3.1.2. Exergy loss hotspots and optimum utility supply temperatures

Based on the methodology presented in the previous section, heat transfer exergy losses are estimated for all major processes based on the current utility design (see Figure 8). The heating requirement for the majority of processes is below 100 °C. However, because the drying process requires heating at 190 °C, the current hot utility is provided as 18 bar (g) and 13 bar (g) steam. Based on the exergy analysis, the current utility system results in 1'707 kW (approx. 25% of total annual heating demand) of heat transfer exergy losses across the entire plant, with drying, pasteurization, and ultrafiltration contributing the largest share towards overall exergy losses as well as CO₂ emissions.

The exergy analysis helps identify the optimum temperature for the utility supply. Lowering the hot utility supply temperature reveals opportunities for internal heat recovery and HP integration. The process-level exergy analysis (Figure 8) shows a significant difference between the temperature of hot utility and real process requirements for many processes. The exergy analysis of all processes reveals about 75% of heating requirements are between 50 °C and 100 °C. Thus, reducing the current utility supply temperature can potentially result in a reduction of steam demand (if energy conversion technologies are used) and the corresponding CO₂ emissions.

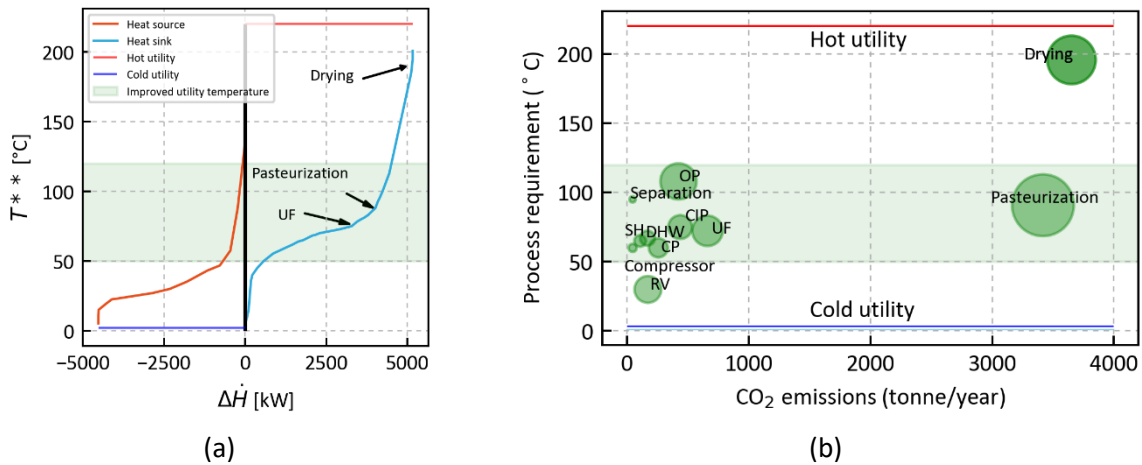


Figure 8: (a) Source-sink profile³ for the dairy process on a typical winter day, with global $\Delta T_{\min}$ of 10 °C (b) Exergy analysis for all processes (size of bubbles represent process-level exergy losses due to supplying heat at current utility temperatures).

However, due to spatial constraints for constructing plant-wide heat distribution networks at intermediate temperatures, the processes showing significant exergy losses (size of the bubble in Figure 8 (b)) and CO₂ emissions are selected for further analysis in this work and presented in Table 2. The exergy losses include the losses within the process and the supply of hot and cold utilities. Process optimization and the identification of opportunities for local networks can improve the heat supply to the selected processes.

³ The y-axis on the source-sink profile is T^{**} which shifts the streams by $\Delta T_{\min}$ instead of $\Delta T_{\min}/2$, more info can be found from literature. By using the Source-sink profile, it is possible to develop a heat recovery that maximizes efficiency across the entire site rather than optimizing each process individually (as in GCC). This holistic approach leads to a more integrated and energy-efficient site design.



Table 2: Exergy losses and CO₂ emissions for selected processes

Process	Exergy losses (kW)	CO ₂ emissions (tonne/year)	Operating hours (hr/year)
Pasteurization	663	3'417	4'250
Drying	454	3'651	5'000
Ultrafiltration (UF)	154	662	3'750
Cleaning in place (CIP)	96	43	8'250

Based on the exergy analysis of the selected processes, represented using the exergy GCC, the current utility supply results in 1'367 kW of exergy losses and 8'170 tonnes of CO₂ emissions per annum (86% of total annual CO₂ emissions from the plant). The exergy losses can be reduced by supplying heat closer to the process requirements, thus leading to a reduction in CO₂ emissions, if the energy conversion technologies use CO₂-free energy sources. Based on the exergy analysis, several lower utility supply temperatures between the range of 68 °C and 100 °C are identified for the selected processes.

3.1.3. Identification of integration options

Following the identification of improved utility temperatures, four variants of different HP integration concepts for local improvements, clusters, and total site improvements (heat networks at intermediate temperatures) are evaluated. Each variant represents a different system boundary. The localized HP integration concept (V1a, V1b) considers only a single process for the identification of heat sinks, whereas clusters and total site HP integration concepts consider multiple processes for the identification of heat sinks. The cluster HP solutions can be further categorized into small (two processes), medium (two to four processes), and large (more than four processes) clusters based on the number of processes considered to identify the heat sinks.

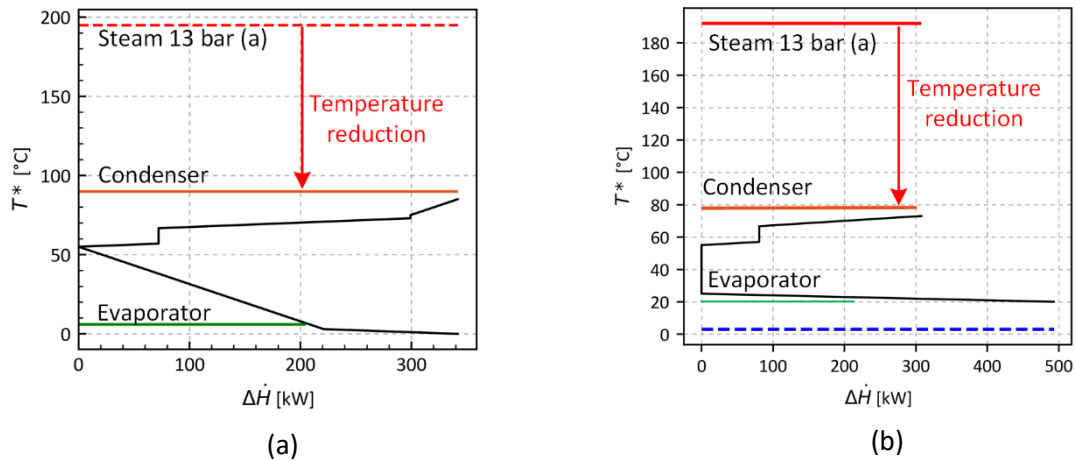


Figure 9: GCC with potential temperature reduction for (a) Fully-localized and (b) Semi-localized heat pump solutions.

Since the PUI improvement, in this case, is analyzed after the implementation of PA-related improvements, the grey box modeling approach is implemented for the PUI analysis, i.e., only the residual heating and cooling requirements are considered.



Variant 1a: Heat pump solution for fully localized process

Based on the residual requirements of the pasteurizer only, a HP with a thermal capacity of 350 kW can be integrated locally at 85 °C, potentially resulting in 1'853 MWh of natural gas savings and a 440-tonne reduction in the annual CO₂ emissions compared to current utility supply system. Identified heat sinks and sources for the fully localized HP integration concept are presented in the schematic in Figure 10.

The principles of PA recommend that direct HR measures be implemented before the other measures for energy efficiency improvement, such as HP integration. However, in praxis, technical complexities often impede the implementation of direct HR measures, as demonstrated by the present case study. Despite the theoretical HR potential displayed by the process streams “pasteurized cream cooling” and “raw milk heating”, its implementation requires stream splitting, which in turn results in complexity and additional costs. Thus, impeding the implementation of direct HR. As a result, the PUI improvement analysis for all variants considered in this work is only focused on HP integration.

Variant 1b: Heat pump solution for semi-localized process

The second variant for the pasteurizer is evaluated for lower heat sink temperatures and higher source temperatures that are not local. This configuration results in a slightly smaller heat pump with lower potentials (390 t-CO₂/year for CO₂ abatement and 1'589 MWh of natural gas savings) but better COP (3.4) than a fully localized solution.

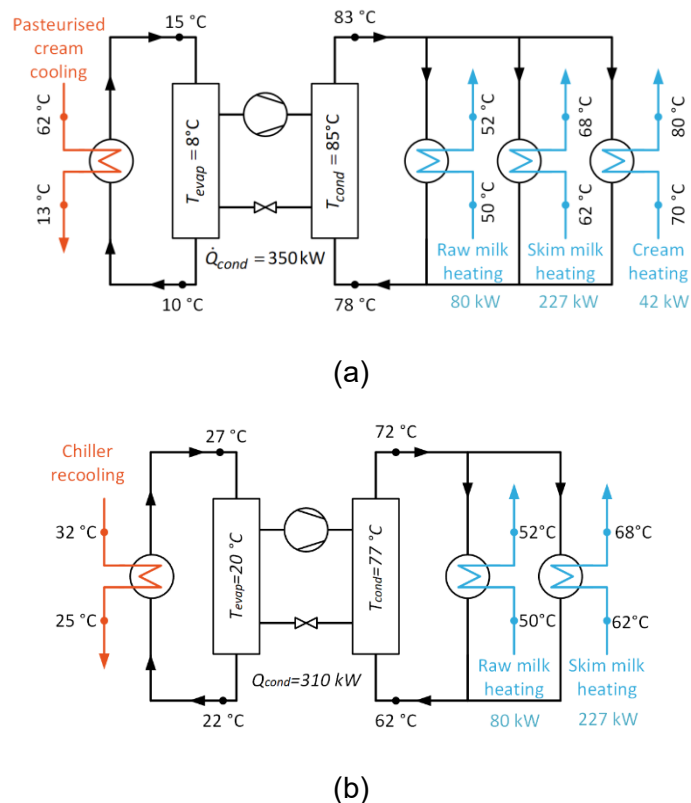


Figure 10: Sinks and sources for (a) Fully Localized heat pump solution (b) Semi-localized heat pump solution.



Variante 2: Heat pump solution for medium-sized cluster of sources and sinks

Similarly, a HP with a thermal capacity of 760 kW can be integrated at 78 °C to fulfill the heating demand of a medium-sized cluster. As shown in Figure 11, this HP configuration covers the heating demand processes such as pasteurizers, CIP, UF, and non-process related requirements, leading to a potential reduction of 6'541 MWh/year in natural gas and 1.5 kt in CO₂ emissions compared to the current utility supply system. Heat sinks and sources identified for the clustered HP integration concept is presented in the following schematic (Figure 11).

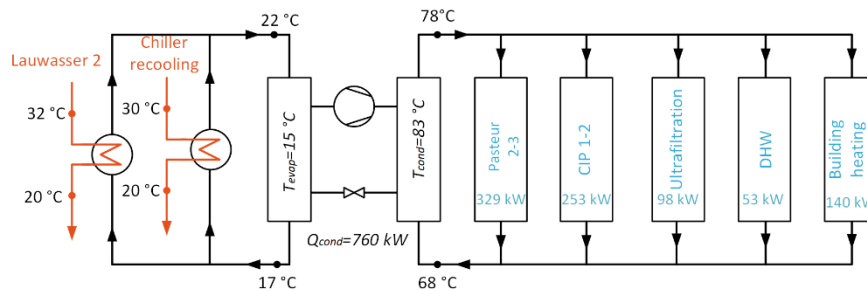


Figure 11: Centralized heat pump integration between pasteurizer and ultrafiltration.

However, in both cases of HP integration, as a result of excess heat availability at a low temperature, COP values are about 2.5 and 2.9, leading to relatively higher electricity demand and lower cost-effectiveness (see Table 3).

Variante 3: Heat pump solution for total site solution

All processes identified in Table 2 along with non-process related heating demands are included for the evaluation of total site options for PUI improvement. However, it should be noted that some processes are eliminated due to the spatial and scheduling constraints (according to criteria presented in step 3). The HP configuration for total site results in 8'550 MWh of annual reduction in natural gas consumption and 2.03 kt-CO₂ emissions reduction.

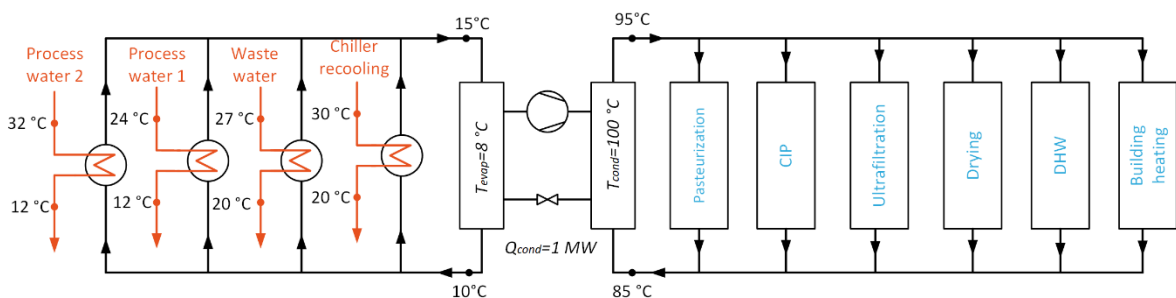


Figure 12. Sinks and sources for total site heat pump configuration.

It should be noted that for a total site HP, supplying heat to multiple processes would inevitably require thermal energy storage.

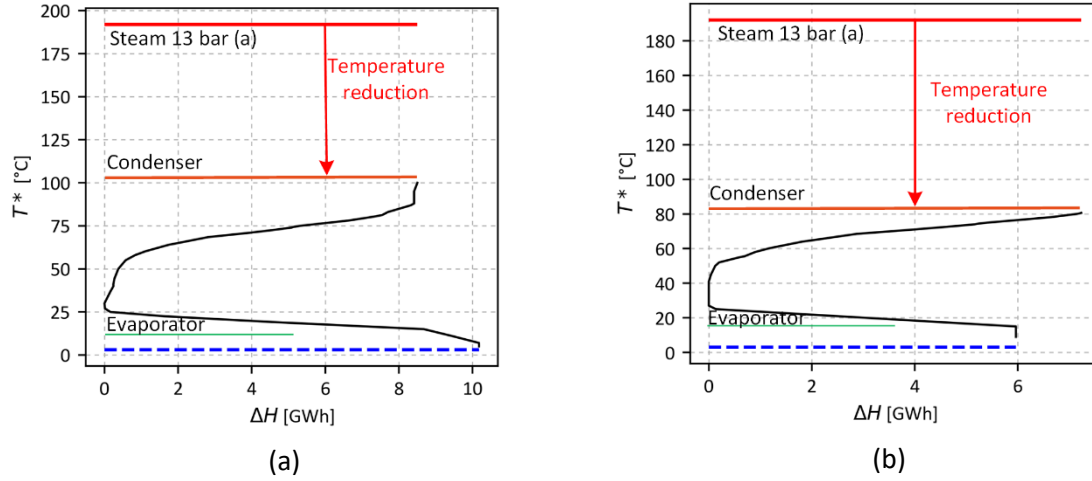


Figure 13: Exergy GCC for PUI improvement for a: Variant 3a (HP integrated at 100 °C) and b: Variant 3b (HP integration at 80 °C) for selected processes.

The results of the economic analysis of all evaluated options are summarized in Table 3. The typical equations used for the estimation are presented in section 5.2.

Table 3: Results of the economic analysis of process-utility interface improvement.

Integration option	Natural gas reduction (MWh)	CO ₂ emissions Reduction (kt-CO ₂)	COP	CAPEX (CHF)	LCCO ₂ (CHF/tco ₂)
Variant 1a	1'835	0.44	2.5	826'000	292
Variant 1b	1'589	0.39	3.4	774'000	266
Variant 2	6'541	1.5	2.9	1'140'000	86
Variant 3	8'550	2.0	2.2	1'200'000	122

According to Table 3, the best option for the case study is Variant 2 due to the high potential for emissions reduction and, in addition, the lowest LCCO₂. The case study demonstrates that the cost-effectiveness of PUI HP solutions depends on (1) choice of sinks and sources (temperature lift), (2) additional costs for heating networks (especially pipework costs), and (3) spark spread (ratio of electricity prices to natural gas prices). Points 1 and 2 were discussed in the earlier sections.

Pipework for retrofitting or expanding heating networks for PUI is significant. These costs can vary substantially depending on the layout and scale of the industrial facility. Piping and installation costs are also impacted by factors like distance between sources and sinks, required insulation to minimize heat losses, and any specific safety or regulatory requirements associated with transporting heat at specific temperatures. For larger systems, optimizing the pipework configuration can lead to savings by reducing both heat losses and material costs. However, the complexity and upfront installation expenses make it essential to consider these infrastructure costs when evaluating the economic feasibility of heat pump integration, as considered in the case study.

The spark-spread between electricity prices and natural gas prices, plays a pivotal role in determining the operating cost-effectiveness of HPs compared to conventional natural gas sources. A favourable spark spread (where electricity prices are lower relative to natural gas) can make HP solutions more economically attractive, as it reduces operational expenses. Conversely, high electricity prices relative to natural gas can reduce the cost competitiveness of heat pumps, especially in regions where electricity from CO₂-free sources is expensive.



In the mid- to long-term, as CO₂-free energy sources become more available, it is expected that electricity prices will stabilize or potentially decrease relative to fossil fuels, improving the economic outlook for HPs. This anticipated shift helps to contextualize the economic viability of HP systems within a future where CO₂-free energy source are prioritized. Figure 14 shows the spark-spread of the different variants.

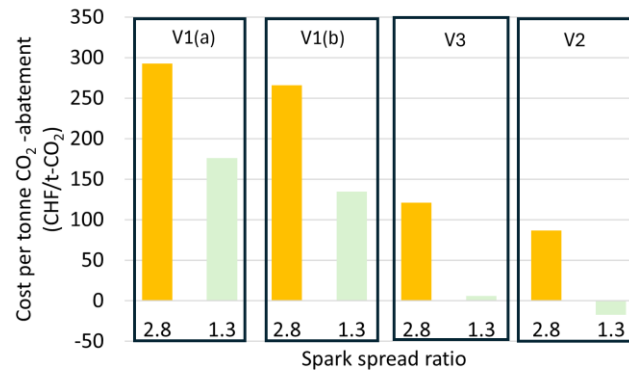


Figure 14: Spark spread ratio of case study.

For instance, targeting electricity and natural gas prices at 0.121 CHF/kWh and 0.044 CHF/kWh, respectively, creates a more favourable economic condition for HP operations. This price structure helps make HPs more viable and cost-effective alternative to conventional heating methods, particularly when CO₂-free electricity sources are available.

In the context of the dairy industry case study, improvements to the PUI enhance and extend the benefits achieved through PA. PA typically identifies heat recovery potentials and optimal utility targets, and PUI improvements add an additional dimension by redesigning utility systems to reduce exergy losses and align heat provision more closely with process requirements.

By integrating PUI improvements alongside fuel-switching measures, a more comprehensive decarbonization pathway emerges. Figure 15 presents how PUI improvements serve as a complementary approach to PA and fuel switching, providing additional decarbonization potential that enhances the overall sustainability of the industrial process.

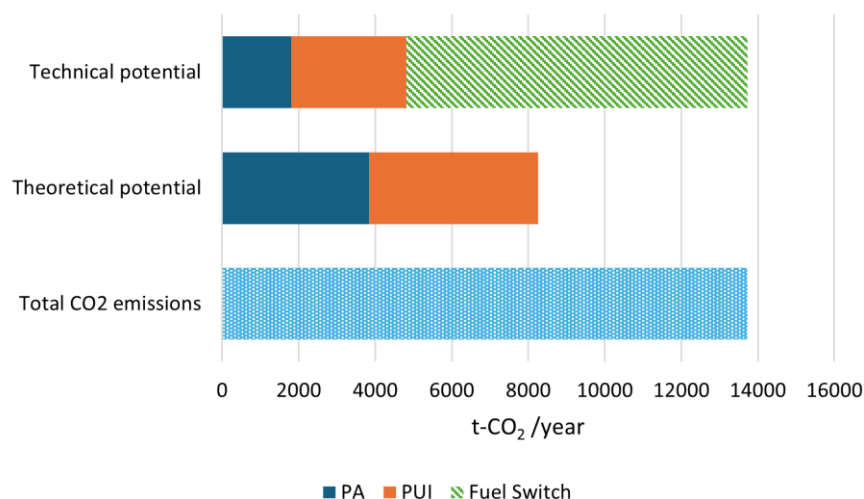


Figure 15: Contribution of PA, DeCarb-PUI and fuel switching.



4 Conclusions

Pinch Analysis helps to identify cost-optimum heat exchanger networks for local heat recovery. However, integrating energy conversion and renewable energy technologies at cluster or total site levels (which requires intermediate loops (ILs) to collect and distribute) becomes a highly combinatorial problem. Therefore, DeCarb-PUI, by using exergy analysis in combination with Pinch Analysis, helps to identify how to better improve the energy efficiency of the processes through redesigning of utility supply temperatures. The identification of optimum utility supply temperatures uncovers the potential for integrating less carbon-intensive heating sources such as heat pumps.

In this guideline, the exergy analysis of the dairy process presented shows overall exergy losses during heat transfer from the current utility to the process can potentially be reduced by up to 46% by rethinking and lowering the temperature at which the utilities are provided. Improving the utility supply temperatures represents the decarbonization potential of up to 66%. The cost-effectiveness of the local heat pump integration option (process level integration) depends on the temperature at which the excess heat is available. The lower temperature of excess heat results in lower values of COP, leading to higher annual electricity demand and consequently, lower cost-effectiveness. The total site heat pump integration option is more capital-intensive due to the larger heat pump capacity and the requirement for a bigger piping network. However, as a result of the higher potential for CO₂ abatement, for this particular site, this option appears more cost-effective based on the levelized cost of CO₂ abatement. According to Pinch Analysis principles, the direct heat recovery potential should be exploited first. However, practical constraints, such as additional costs caused by complexity, often impede the implementation of these measures. As demonstrated in the present case study, the exergy analysis can further aid in identifying alternative technically feasible solutions for process-utility interface improvement.

While this guideline shows the example of the dairy case study, another example (animal feed) can be found in the final report. The learnings from the analysis of two case studies and from the feedback of industrial partners are as follows:

- **Liquid streams versus solid/bulk materials streams:** whereas facilities processing liquids (e.g. Dairy case study) are more prone to improvements of the PUI, those processing bulk/solid materials (e.g. Animal feed case study) are rather difficult to retrofit;
- **Extension of the PUI scope of analysis:** the initial focus of DeCarb-PUI was strictly on the process-utility heat transfer interface. The Animal feed case study has shown that heat transfer “inside the process” (due to the technology used) has to be considered as well, since it may have a major effect of the minimum temperature required for the utility. Direct steam injection is a commonly used technology, and depending on the purpose, may not be easy to avoid it. Refer to **Erreur ! Source du renvoi introuvable.** below for relevant modelling of heat transfer requirements and opportunities to retrofit the process technology.
- **Identify opportunities to lower the temperature of process streams:** in liquid processing, the process streams are more often at the temperatures actually required. It isn't rare however that they are not, due the process resorting to non-isothermal mixing, or lack of preheating, etc. In these processes, direct steam injection is also found (e.g. in CIP facilities for make-up water heating and temperature holding of soda and acid tanks, in the washing tunnels of industrial laundries, etc.). Another general opportunity to lower the required temperature is preheating of the material before entering a reactor, a furnace, etc.
- **Local versus total site level integration:** as regards energy integration concepts, equipment manufacturers (who e.g. supplies one among several facilities) prefer local integration concepts, within their scope of supply, on which they have an influence (integrators could be more inclined to a broader scope of integration)



- **Operational constraints:** cluster (or total site) integration is likely to bring CAPEX savings and lower CO₂ abatement costs. However, unlike steam production based on external fuel source, heat pumps using process heat sources create links between processes and potentially operational constraints, which is undesirable. In general, due to independent operation management of processes, backup utilities are needed to cope with periods of non- simultaneity (beyond the capacity of the heat storages used).
- **Flexible operation of processes:** the added value of many Swiss industries lies in their ability to provide products that meet the individual specifications of their customers (unlike larger plants of foreign competitors, which deliver standardized products at lower prices). This requires flexible operation of process units, e.g. operation of the same unit at different temperatures, or bypass of a processing stage. This requirement makes the design and operation of the heat integration system (heat pump, heat transfer loop operating temperatures, etc.) more complex or a backup utility is needed (with the disadvantage of increased heat loss, maintenance costs of two systems). Often, a backup utility (existing utility) is needed anyhow, to prevent detrimental impacts on production in case of failure or during maintenance of the heat pump, or to prevent any slowdown in speed when starting of the process (due to limited capacity of the heat pump).
- **Space constraints in retrofit situation:** the spatial layout of processes and space constraints have a key influence on the potential practical solutions. Existing production premises are often very packed with facilities, making the installation of additional piping more costly, if not impossible. It is therefore essential to take due consideration of these constraints when developing and costing the integration solutions. A “rough” spatial model of the premises must be included in a tool for pre-screening / setting up potential integration solutions and for calculating their performances. Such a tool is beyond the scope of DeCarb-PUI and should be developed in a follow-up project.
- **Appropriate placement of heat pumps across the “overall Pinch”:** the above practical constraints of distance and available space modify the definition of the Pinch to be taken into account for the appropriate placement of a heat pump: it is no longer the overall Pinch of the site (including all processes), but at a given point on the site, it is determined by the residual composite curves (from residual heat transfer requirements “after” process internal heat recovery) of the zone around this point including the processes that can reasonably, technically and economically, be integrated together (heat transfer with more distant processes being *de facto* not possible).
- **Tool for screening for DeCarb-PUI solution:** the search space for “intermediate integration solutions” is highly combinatorial; many factors come into play, among which the spatial layout of processes and space constraints, which lead to complex trade-off effects for both energy and economics. A tool for pre-screening / setting up solutions using appropriate criteria, and for calculating the performances of solutions is definitely needed. Such a tool is beyond the scope of DeCarb-PUI and should be developed in a follow-up project.



Erreur ! Source du renvoi introuvable. summarizes process technology improvement opportunities for some typical cases. As regards the retrofit of the actual PUI, the following statements apply in general:

- the case of heating liquid products is quite simple, in that the process-utility interface is improved by increasing the UA [kW/K] factor of the heat transfer ⁴;
- on the other hand, the case of combined heat and mass transfer (typically the drying of a solid product) is more complicated: the increase of the UA [kW/K] brings only one part of the improvement potential, the other part of the whole potential requiring a redesign of the process, or even a change in the process technology.

Table 4: Main opportunities of process technology improvements (non-exhaustive list of cases).

Type of transfer	Examples	Models	PUI improvements	Comments
Heat transfer only				
• water & water based liquids by direct steam injection	CIP tanks, laundry washing tunnel baths, feedwater heating, ...	Thm	Replace steam injector by HEX sized for low ΔT	Non-isothermal mixing! Compensate the steam condensate in water balance !
• milk by direct steam injection	uperisation process (UP) (sterilisation)	Tec	Decrease direct steam pressure (T) to allow MVR (?), or optimise use of flash vapour condensation at 80°C	Steam injection imposed by UP technology ! Thm possible only if replacing UP by UHT is acceptable (longer holding time).
• other liquid (indirect)	superheated water or steam HEX	Thm (GB-Thm)	Resize HEX for low ΔT	
• gas (cooling by direct contact)	cleaning of gases (scrubber, ...)	?		
• non isothermal mixing of liquids or gases	numerous processes	Thm	Isothermal mixing	Check the possibility to use multi-streams HEX designs to mitigate effects on HEX costs
• solid (indirect)		Tec (GB-Tec)	Increase heat transfer coefficient (fluidized bed, ...) and/or area	Tec at the level of heat transfer media (gas or liquid)
Heat & mass transfer				
• drying	spray drying, convective drying, roasting, ...	Tec (GB-Tec)	Pre-heating of feed, stage-wise heating of supply hot air	Thm: ideal case but not realistic
• drying	drum drying	Tec (GB-Tec)	Preheating of feed, process change	Thm: ideal case but not realistic
• drying	paddle drying, ...	Tec (GB-Tec)	Preheating of feed	Thm: ideal case but not realistic
• thermal treatment by steam injection	thermal treatment of animal feed (meal or pellets)	Tec ITec	ITec: if preheating of solid feed is acceptable	Thm: ideal case but not realistic
• drying and cooling	cooling of bulk feed product	Tec (GB-Tec)		Evaporative cooling needed for quick cooling

⁴ The increase in the UA factor required to be "economically optimal" is case-specific. On the one hand, it depends on the type of heat exchanger and the possibility of modifying it (e.g. by adding heat transfer area, modifying its hydraulic configuration, adding inserts to increase turbulence and/or heat transfer area). On the other hand, the degree of improvement of UA actually useful depends on the supply temperature of the process heat transfer requirement in question among the other process heat requirements supplied by the heat transfer loop envisaged: if the considered PUI is the one (or among the ones) which is critical (i.e. constraining the temperature of the loop), there is scope for UA improvement with energy efficiency and economic benefits. These considerations presuppose, as a preliminary step, an analysis of the assignment of process heat requirements to one or more loops on the basis of their actually required temperature, and the related choice of temperatures for these loops.





5 Technical supplements

5.1. Reminder: Pinch Analysis in a nutshell

PA is a powerful and proven methodology for analyzing and optimizing the energy integration of any size and complexity of thermal processes.

Its holistic consideration and systematic analysis approach of heating and cooling requirements (so-called cold streams, respectively hot streams) allows the targeting and design of economically close-to-optimum heat recovery systems. At the same time, PA provides for identifying technology shifting opportunities and pre-designing promising energy conversion technologies, among which HPs, to minimize the energy demands, CO₂ emissions, costs, or a combination thereof.

By considering temperature levels and energy flows, PA provides a thorough understanding of the energetics of the operated processes. Based on the 2nd principle of thermodynamics, which assigns different values to different heat flows, PA transcends the energy balance represented by a Sankey diagram, thus highlighting the reasons (i.e., processes, operating conditions, etc.) that limit the heat recovery and helping to devise innovative solutions to overcome these limitations.

The fundamental tools and methods of PA are first set up for a single continuous process, implicitly assuming that its streams are all located “close enough” to each other so that direct heat transfer using heat exchangers between hot and cold stream pairs is physically possible, yet subject to temperature feasibility. For single continuous processes, PA has developed and extensively uses two fundamental graphical representations: the CCs and the GCC.

The Composite Curves (hot CC and cold CC) sum up the heating and cooling requirements of the process as a function of temperature. Hence, they provide a global view of heat availability (heat sources) and heat consumers (heat sinks), allowing for the determination of target values for heat recovery, heat transfer area, number of HEX units, and, as a result, an economically close-to-optimum minimum temperature approach (heat recovery pinch).

The GCC represents the net heat cascaded at a certain temperature level, calculated as the balance of heat supplied by the heat sources minus heat consumed by the heat sinks. The GCC is derived from the CCs, and is used to optimize utility integration (e.g., changing the pressure/temperature levels of processes or steam headers or resorting to more efficient energy conversion systems, such as heat pumps). After the promising utility system alternatives have been conceptually designed leveraging the GCC profile, their corresponding streams are added to the list of process streams, and the CCs are plotted again, now named Balanced CC (BCC). HENs can then be optimized for both heat recovery and utility supply.

CCs and GCC, and their interpretation, can be found in a document prepared in the frame of a separate project (Guidelines for the implementation of HTHPs in industrial processes, 2024). The same document also provides practical information on how to apply PA, in particular for data extraction.

For further reading, refer to e.g. Bodo Linnhoff's PA overview (Introduction to Pinch Technology-Linnhoff-March.doc), which provides a condensed presentation of PA tools and methods. The handbooks of Brunner and Krummenacher (in German: Einführung in die Prozessintegration mit der Pinch-Methode; in French: Manuel_Pinch_OFEN_2017.pdf) provide a detailed and pedagogical presentation of the tools and methods used in PA.



5.2. Economic analysis formulae

The natural gas reduction achieved for each technology solution is estimated from the heating demand of the processes (i) considered. A boiler efficiency of 90% and 10% losses in the steam supply network are assumed.

$$F_{NG} = \sum_{i=0}^n E_i / \eta_{boiler} \quad (A1)$$

CO₂ emission estimations

$$CA = F_{NG} \times \text{Emission factor}_{NG} \quad (A2)$$

Levelized cost of CO₂ abatement

$$C_{CO2,lv} = \frac{ANF \times NPV}{CA} \quad (A3)$$

$C_{CO2,lv}$ = Levelized costs of saved energy for technology integration (CHF/kWh)

ANF = Annuity factor calculated by equation (A4)

NPV = Net present value of the technology integration calculated by equation (A5) (CHF)

ES = Final energy saving achieved by technology integration (MWh)

$$ANF = \frac{(1+r)^L \times r}{(1+r)^L - 1} \quad (A4)$$

$$NPV = \sum_{t=tr}^L CF_{tr} \times (1+r)^{-tr+t} \quad (A5)$$

Where,

CF_{tr} = Annual cash flow for year t calculated by equation (A6) (CHF)

r = Real discount rate (%)

L = Technological lifetime of HP (in years)

tr = running year (e.g., 2020)

t = year of implementation



$$CF_{tr} = CAPEX + OPEX - B \quad (A6)$$

Where,

CAPEX = Initial investment for technology integration (module cost + integration cost)

OPEX = Annual operation and maintenance cost of integrated technology

B = Annual net benefits generated by implementing technology integration calculated by equation (A7)

$$B = (F_{NG} \times P_f) - (ELS \times P_e) + (CA \times P_{CO_2}) \quad (A7)$$

Where,

ELS = Electricity consumed by technology integration (e.g., estimated using COP_{real} in case of HP)

F_{NG} = Saving achieved for fuel by technology integration

P_f = Price of fuel (Since thermal demand is dominated by natural gas, fuel saved is assumed to be natural gas for all establishments)

P_e = Price of electricity

P_{CO_2} = CO₂ levy

CA = CO₂ abatement potential of technology integration calculated by equation A2



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