Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

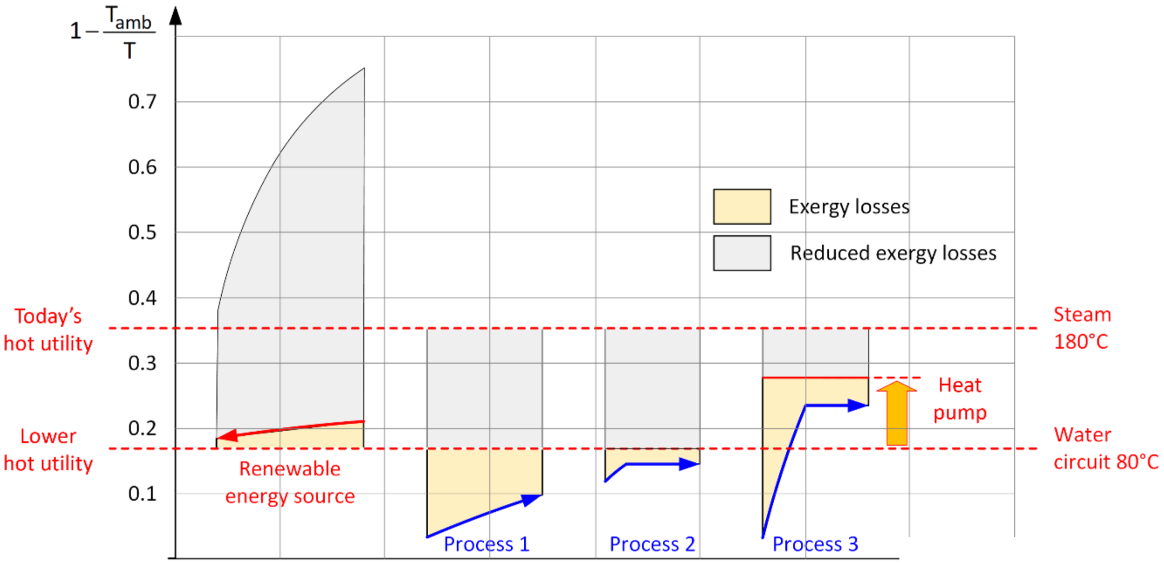
Federal Department of the Environment,
Transport, Energy and Communications DETEC

Swiss Federal Office of Energy
Energy Research and Cleantech

Final report from 31 March 2025

DeCarb-PUI

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



Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Berne
www.energy-research.ch

Subsidy recipients:
HEIG-VD
Institute of Energies (IE)
Thermal Systems Thematic Competence Group
Av. des Sports 20
CH-1401 Yverdon-les-Bains
https://heig-vd.ch/rad/instituts/ie

Lucerne University of Applied Sciences and Arts
Competence Center Thermal Energy Systems and Process Engineering
Technikumstrasse 21
CH-6048 Horw
https://www.hslu.ch/

Authors:
Pierre Krummenacher, HEIG-VD, pierre.krummenacher@heig-vd.ch
Navdeep Bhadbhade, navdeep.bhadbhade@hslu.ch
Donald Olsen, donald.olsen@hslu.ch
Benjamin H.Y. Ong, HSLU, benjamin.ong@hslu.ch

SFOE project coordinators:
Elena-Lavinia Niederhäuser, elena-lavinia.niederhaeuser@bfe.admin.ch
Stephan Renz, info@renzconsulting.ch

SFOE contract number: SI/502298-01

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. Decarbonization of Industrial Processes through Redesign of the Process-Utility Interface, DeCarb-PUI, project addresses these inefficiencies by redesigning process-utility interfaces to achieve greater energy efficiency, reduce exergy losses, and enable deep decarbonization.

DeCarb-PUI emphasizes exergy efficiency—a critical metric in resource-constrained industries—over mere energy savings. Traditional utility systems, such as medium-pressure steam networks, often lead to inefficient resource use due to mismatched energy supply and process requirements. By rethinking utility supply temperatures and integrating advanced technologies like heat pumps, DeCarb-PUI delivers solutions that 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 report provides a practical methodology to guide industrial stakeholders and equipment manufacturers through the decarbonization potential of PUI redesign. It demonstrates how larger heat recovery, enhanced energy efficiency, and increased profitability can be achieved using methodology developed in DeCarb-PUI. The core of DeCarb-PUI lies in its integrated approach, which consists of three key techniques:

- Pinch Analysis: Framework for data extraction to identify heating and cooling requirements across processes to determine optimal heat recovery opportunities,
- Exergy Analysis: Quantification of inefficiencies in energy systems, focusing on losses at various levels such as thermodynamic requirements, technological, and utility supply,
- Techno-economic Analysis: Assess the cost-effectiveness of proposed measures using metrics like the Levelized Cost of CO_2 Abatement to identify impactful and economically viable solutions.

DeCarb-PUI considers these losses holistically, identifying where the largest inefficiencies occur and tailoring solutions to address them. Depending on the facility, solutions can be applied at three integration levels:

- Localized: solutions focused on a single process,
- Cluster: A “cluster” of processes is served by a single intermediate loop,
- Total site: solutions addressing the energy needs of an entire facility.

The added value of exergy analysis lies in its ability to align energy supply with process needs, quantify decarbonization potential, and provide actionable insights for process redesign. The DeCarb-PUI methodology is applied to two case studies: a industrial dairy plant and an animal feed plant. The application to the dairy plant revealed that supplying hot utility between 50–100 °C can reduce exergy losses by up to 46% and CO_2 emissions by up to 66%. A centralized heat pump for a cluster of processes with intermediate loops emerged as the most cost-effective and technically viable solution based on the Levelized Cost of CO_2 Abatement.

DeCarb-PUI provides a robust methodology for moving the industrial sector towards carbon neutrality. By adopting this methodology, industrial stakeholders can balance sustainability goals with practical and financial considerations, setting a benchmark for energy-efficient and low-carbon operations.

Zusammenfassung

Bei den Bestrebungen der Industrie zur Dekarbonisierung spielen Prozessintegration, Energieumwandlung und erneuerbare Technologien eine entscheidende Rolle. Wenn man sich jedoch ausschließlich auf diese Technologien verlässt, kann eine tiefgreifende Dekarbonisierung aufgrund der inhärenten Ineffizienzen herkömmlicher Versorgungssysteme oft nicht erreicht werden. In vielen Industriesektoren sind die Versorgungssysteme so ausgelegt, dass sie den höchsten Temperaturanforderungen gerecht werden, was oft zu erheblichen Exergieverlusten führt. DeCarb-PUI (*Decarbonization of Industrial Processes through Redesign of the Process-Utility Interface*) befasst sich mit diesen Ineffizienzen, indem es die Schnittstellen zwischen Prozessen und Versorgungssystemen neu gestaltet, um eine höhere Energieeffizienz zu erreichen, Exergieverluste zu verringern und eine weitgehende Dekarbonisierung zu ermöglichen.

DeCarb-PUI legt den Schwerpunkt auf die Exergie-Effizienz - eine entscheidende Kennzahl in ressourcenbeschränkten Branchen - und nicht auf reine Energieeinsparungen. Herkömmliche Versorgungssysteme, wie z. B. Mitteldruckdampfnetze, führen häufig zu einer ineffizienten Ressourcennutzung, da Energieversorgung und Prozessanforderungen nicht aufeinander abgestimmt sind. Durch ein Umdenken bei der Wahl/Auslegung der Vorlauftemperaturen und die Integration fortschrittlicher Technologien wie Wärmepumpen bietet DeCarb-PUI Lösungen, die die Wärmeübertragung optimieren, die Energieverschwendung reduzieren und eine nachhaltige Energienutzung fördern. Dieser Ansatz wird durch die Einbeziehung von Partnern aus der Prozessindustrie und von Anlagenherstellern umgesetzt.

Dieser Bericht bietet eine praxis-orientierte Methodik, um industrielle Interessengruppen und Anlagenhersteller durch das Dekarbonisierungspotenzial der PUI-Neugestaltung zu führen. Er zeigt, wie mit der in DeCarb-PUI entwickelten Methodik eine größere Wärmerückgewinnung, eine verbesserte Energieeffizienz und eine höhere Rentabilität erreicht werden können. Der Kern von DeCarb-PUI liegt in seinem integrierten Ansatz, der aus drei Schlüsseltechniken besteht:

- Pinch-Analyse: Rahmen für die Datenextraktion der Heiz- und Kühlbedarf in verschiedenen Prozessen, um optimale Möglichkeiten der Wärmerückgewinnung zu bestimmen,
- Exergie-Analyse: Quantifizierung von Ineffizienzen in Energiesystemen mit Schwerpunkt auf Verlusten auf verschiedenen Ebenen wie thermodynamische Anforderungen, technologische Anforderungen und Energieversorgung,
- Technoökonomische Analyse: Bewertung der Kosteneffizienz der vorgeschlagenen Maßnahmen unter Verwendung von Kennzahlen wie den CO_2-Vermeidungskosten, um wirksame und wirtschaftlich tragfähige Lösungen zu ermitteln.

DeCarb-PUI betrachtet diese Verluste ganzheitlich, ermittelt, wo die größten Ineffizienzen auftreten, und entwickelt maßgeschneiderte Lösungen, um diese zu beheben. Je nach Anlage können die Lösungen auf drei Integrationsebenen angewendet werden:

- Lokal: Lösungen, die sich auf einen einzigen Prozess konzentrieren,
- Cluster: Ein „Cluster“ von Prozessen wird über einen einzigen Zwischenkreislauf versorgt,
- Gesamter Standort: Lösungen, die den Energiebedarf einer gesamten Anlage abdecken.

Der Mehrwert der Exergieanalyse liegt in ihrer Fähigkeit, die Energieversorgung mit dem Prozessbedarf abzustimmen, das Dekarbonisierungspotenzial zu quantifizieren und umsetzbare Erkenntnisse für die Prozessumgestaltung zu liefern. Die DeCarb-PUI-Methode wird auf zwei Fallstudien angewendet: eine industrielle Molkerei und eine Tierfutterfabrik. Die Anwendung auf die Molkerei ergab, dass die Bereitstellung von Heißwasser zwischen 50-100 °C die Exergieverluste um bis zu 46 % und die CO2-Emissionen um bis zu 66 % reduzieren kann. Eine zentralisierte Wärmepumpe für einen Cluster von Prozessen mit Zwischenkreisläufen erwies sich als die kosteneffizienteste und technisch praktikabelste Lösung basierend auf der CO_2-Vermeidungskosten.

DeCarb-PUI bietet eine robuste Methodik für den nachhaltigen industriellen Wandel, die es der Industrie ermöglicht, eine tiefgreifende Dekarbonisierung, verbesserte Energieeffizienz und wirtschaftliche Machbarkeit zu erreichen. Durch die Anwendung dieser Methodik können industrielle Akteure Nachhaltigkeitsziele mit praktischen und finanziellen Erwägungen in Einklang bringen und einen Maßstab für energieeffiziente und kohlenstoffarme Betriebe setzen.

Résumé

Alors que les industries s'efforcent de décarboner leurs activités, l'intégration des procédés, la conversion de l'énergie et les technologies renouvelables jouent un rôle crucial. Toutefois, s'appuyer uniquement sur ces technologies ne permet souvent pas de parvenir à une décarbonation « profonde » en raison des inefficiences inhérentes aux systèmes d'utilités conventionnels. Dans de nombreux secteurs industriels, les systèmes d'utilité sont conçus pour répondre aux demandes de température les plus élevées, ce qui entraîne souvent des pertes d'exergie considérables. Le projet DeCarb-PUI (*Decarbonization of Industrial Processes through Redesign of the Process-Utility Interface*) s'attaque à ces inefficacités en repensant les interfaces entre les procédés et les utilités afin d'améliorer l'efficience énergétique, de réduire les pertes d'exergie et de permettre une décarbonation accrue.

DeCarb-PUI met l'accent sur l'efficience exergétique - une mesure-clé dans les industries aux ressources limitées - plutôt que sur les simples économies d'énergie. Les systèmes d'utilités traditionnels, tels que les réseaux de vapeur à moyenne pression, conduisent souvent à une utilisation inefficiente des ressources due à l'inadéquation entre l'alimentation en énergie et les besoins effectifs des procédés. En repensant les températures d'alimentation et en intégrant des technologies telles que les pompes à chaleur, DeCarb-PUI propose des solutions qui optimisent le transfert de chaleur, réduisent le gaspillage d'énergie et favorisent une utilisation durable de l'énergie. Cette approche est mise en place en impliquant des partenaires issus à la fois des industries des procédés et des fabricants d'équipements.

Ce rapport fournit une méthodologie pratique pour guider les acteurs industriels et les fabricants d'équipements à travers le potentiel de décarbonisation de la reconception/modernisation du PUI. Il démontre comment une plus grande récupération de chaleur, une meilleure efficience énergétique et une rentabilité accrue peuvent être obtenues grâce à la méthodologie développée dans DeCarb-PUI. Le cœur de DeCarb-PUI réside dans son approche intégrée, qui consiste en trois techniques clés

- analyse Pinch : cadre pour l'extraction de données permettant d'identifier les besoins de chauffage et de refroidissement dans les procédés afin de déterminer les possibilités optimales de récupération de la chaleur,
- analyse exergétique : quantification des inefficiences dans les systèmes énergétiques, en se concentrant sur les pertes entre les différents niveaux tels que les exigences thermodynamiques, technologiques et l'approvisionnement en services publics,
- analyse technico-économique : évaluer la rentabilité des mesures proposées à l'aide de métriques telles que le coût de réduction des émissions de CO_2 afin d'identifier des solutions efficaces et économiquement viables

DeCarb-PUI considère ces pertes de manière globale, en identifiant où se situent les plus grandes inefficiences et en adaptant les solutions pour y remédier. En fonction de l'installation, les solutions peuvent être appliquées à trois niveaux d'intégration :

- local : solutions axées sur un seul procédé,
- cluster : un groupe de procédés est desservi par une seule boucle intermédiaire,
- site global : solutions répondant aux besoins énergétiques de l'ensemble d'un site industriel.

La valeur ajoutée de l'analyse exergétique réside dans sa capacité à faire correspondre l'approvisionnement en énergie avec les besoins effectifs des procédés, à quantifier le potentiel de décarbonation et à fournir des connaissances réalisables pour la transformation des procédés. La méthode DeCarb-PUI est appliquée à deux études de cas : une laiterie industrielle et une usine d'aliments pour animaux. L'application à la laiterie a révélé que la fourniture d'eau chaude entre 50 et 100 °C pouvait réduire les pertes d'exergie jusqu'à 46 % et les émissions de CO_2 jusqu'à 66 %. Une pompe à chaleur centralisée alimentant un groupe de procédés par le biais de circuits intermédiaires s'est avérée être la solution la plus rentable et la plus viable sur le plan technique, basée sur coûts d'évitement de CO_2.

DeCarb-PUI fournit une méthodologie robuste pour la mutation du secteur industriel vers la neutralité carbone. En appliquant cette méthodologie, les acteurs industriels peuvent concilier les objectifs de durabilité avec des considérations pratiques et financières et établir une référence, pour leurs opérations, en matière d'efficience énergétique et de réduction des émissions de carbone.

Main findings («Take-Home Messages»)

- Process-Utility Interface, complements Pinch Analysis, identifies solutions that address residual inefficiencies, offering a pathway for deeper decarbonization before transitioning to sustainable fuel switching.
- The DeCarb-PUI methodology provides a flexible and scalable framework, accommodating localized, cluster, and total site solutions, making it adaptable to diverse industrial processes, varying operational constraints, and site-specific needs.
- Integrating exergy analysis into Pinch Analysis helps identify inefficiencies at various levels of utility systems, such as energy conversion and heat transfer, pinpointing processes with excessive exergy destruction to prioritize for further investigation and optimization.

List of figures (optional)

List of tables (optional)

List of abbreviations

CA	CO_2 abatement potential
CAPEX	capital cost
CC	composite curves
CHP	combined heat and power
CIP	cleaning in place
COP	coefficient of performance
CU	cold utility
EEM	energy efficiency measure
EGCC	exergy grand composite curve
EPTA	exergy problem table algorithm
GB	grey box (model)
GCC	grand composite curve
HEN	heat exchanger network
HEX	heat exchanger
HP	heat pump
HR	heat recovery
HTHP	high temperature heat pump
HU	hot utility
ITec	improved technology (model)
IUtil	improved utility (model)
LLCO2	Levelized Cost of CO_2
MILP	mixed integer linear programming
MVR	mechanical vapor recompression
OPEX	operating cost
PA	pinch analysis
PFD	process flow diagram
PTA	problem table algorithm
PUI	process-utility interface
RCC	residual composite curves
TAC	total annual cost
TAM	time average model
Tec	technology (model)
Thm	thermodynamic (model)
TS	total solids
TSHI	total site heat integration
TSC	total site composite curve
TSI	total site integration
TSP	total site profile
TVR	thermal vapor recompression
UF	Ultrafiltration
Uti	utility (model)
WB	white box (model)

Contents

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), see Figure 1.

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 for a large share of the processes. 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 CO_2 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 promotion and financial support of EnergieSchweiz over one decade has allowed to establish Pinch Analysis (PA) as an essential practical method to optimize heat recovery and achieve heat integration of industrial processes. However:

- the savings potential of heat integration using PA remains partially underestimated and hence under-exploited, especially for semi-continuous and batch processes requiring heat storage and heat upgrading using HPs;
- questioning the established utility systems is tricky and perceived as being too big a challenge for both the industry and the engineer in the absence of a method allowing the quantification of the potential benefits and costs. The optimization of the utilities is therefore seldom addressed by the PA performed.

On the academic level, many research projects have addressed the optimal design of the energy conversion and distribution system. Various methodologies combining graphical tools for engineer's insight and mixed integer linear programming (MILP) formulations for optimization have been proposed. However, there is a lack of comprehensive practical methodology derived based on the real-world examples. The DeCarb-PUI project addresses this gap by providing a structured framework to reduce carbon emissions through the redesign and improvement of the Process-Utility Interface, enhancing both energy and exergy efficiency. Rather than stopping at theoretical optimization, the framework identifies high-impact areas for decarbonization within industrial systems. These solution pathways are then verified by the industry partners.

1.2 Purpose of the project

The overall objective of DeCarb-PUI is to optimize the exergy efficiency of the **process-utility interface (PUI)**[1] to unlock site-wide decarbonization potentials of heating and cooling in process industries. The exergy efficiency is not an objective in itself, but essentially a means to make the best use of limited renewable energy resources. Figure 1 sketch the approach; these schematic diagrams represent the hot utility and the net process heating requirements in a Carnot factor versus Heating duty ($\dot{H}$) instead of the usual Temperature versus Heating duty.

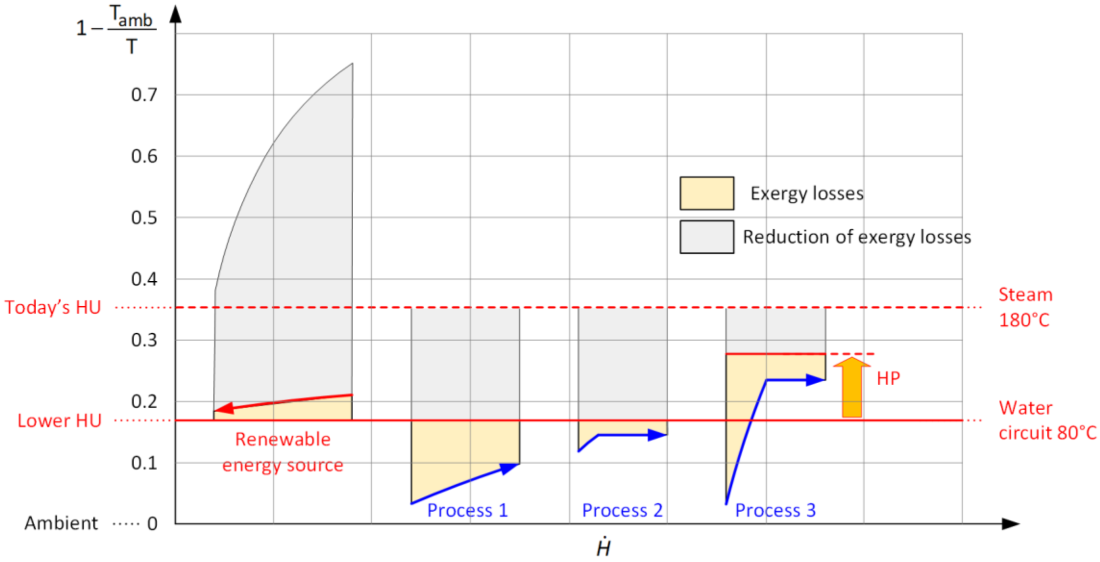


Figure 1: Illustration of heat transfer exergy losses for hot utility production and at the process-utility interface: a significant reduction of exergy losses can be achieved thanks to lower supply temperature (Lower hot utility, HU) and the use of renewable energy technologies, as compared to the current practice (Today's HU).

In this way, the area between the utility supply and the process heating requirements corresponds to the heat transfer exergy losses:

- Due to the utility system being designed to meet the temperature required by the most demanding process, significant heat transfer exergy losses appear for the supply of less demanding processes in “Today's HU”; in other words, more exergy than required to supply the processes.
- The redesign of the HU to operate at a lower temperature (“Lower HU”) decreases the exergy losses significantly and allows to take advantage of increased intra- and inter-process heat integration, as well as increased efficiency and lower capital cost (CAPEX) of renewable energy technologies. The resulting lower operating cost (OPEX) and larger decarbonization potential must be traded-off against larger CAPEX for the new/additional/larger utility supply network, the larger area of the utility-process heat exchangers (HEX) (and/or heat transfer enhancement devices), and possibly “local” high-temperature heat pump (HTHP) to specifically supply the most demanding processes. Depending on the number of processes/fractions of total heat duty actually required at high temperatures, the HU may be kept instead of HTHP (for backup reasons).

---

[1] In the context of DeCarb-PUI, the process-utility interface has a rather broad meaning. The rigorous meaning would be restricted to the heat exchanger transferring heat from the hot utility to process streams and the corresponding exergy losses. In practice however, cases featuring several heat transfer interfaces in cascade (instead of a single one) can often be found. In addition, exergy losses also often take place in the process itself (e.g. heating a process stream by steam injection), also preventing the temperature of the heat supply to be close to the actual process requirement.

Energy and exergy efficiency in industry must be addressed as a whole to achieve optimal trade-off between total costs and efficient use of resources. This means processes, utilities, and energy resources need to be matched together, i.e. designed, and optimized as a whole and not each separately.

Unlike the complex academic approaches striving for optimal solutions, the focus of DeCarb-PUI is rather on simplified, but practice-oriented and applicable, methodologies. DeCarb-PUI considers real case studies from the Food & Beverages sectors that bring together the requirements and needs of manufacturers of industrial thermal equipment and the process industries that use those pieces of equipment.

To allow such a practice-relevant approach to establish itself, DeCarb-PUI must also alleviate or remove several barriers. This will be achieved by:

- Demonstrating and quantifying the improvement potentials (in terms of both energy efficiency and decarbonization) when considering actual process requirements over the existing situation.
- Assessing the overall total costs (CAPEX & OPEX of processes + utilities) when “optimizing” the overall site-wide system (process(es), utility, resources) in a mid-term perspective of complete decarbonization.
- Elaborating practical guidelines and training material for:
  a. Industries: to assess process requirements and to analyze and redesign the utility systems correspondingly.
  b. Manufacturers: to assess the overall improvement potential, identify key changes, and prepare appropriate marketing.

1.3 Objectives

The DeCarb-PUI project framework aims to unlock deeper decarbonization potential through the improvement of the process-utility interface. The central objective is to rethink the PUI by optimizing the temperature levels at which the hot and cold utilities are supplied to industrial processes. This approach enables industries to transition away from conventional, inefficient heating and cooling systems, reducing their reliance on fossil fuels while maintaining process performance.

The key objectives of DeCarb-PUI are:

- Optimize utility supply temperatures
  - Reduce exergy losses by ensuring that heating and cooling utilities are provided at temperatures closer to actual process requirements.
  - Shift from medium-pressure steam and other high-temperature utilities to lower-temperature alternatives, improving overall efficiency.
- Enhance heat recovery and process integration
  - Maximize direct and indirect heat recovery by identifying opportunities for intra- and inter-process heat exchange.
  - Improve the integration of heat pumps and other energy conversion technologies to upgrade heat efficiently.
- Enable a more effective use of renewable energy
  - Reduce the temperature gaps between renewable heat sources (e.g., solar thermal, geothermal) and process requirements, improving their feasibility.
  - Increase the potential for integrating waste heat recovery, reducing reliance on primary energy sources.
- Techno-economic assessment of decarbonization solutions for various scales
  - Develop solutions for heat integration at three levels: Localized (single process unit), Cluster (multiple related processes), and Total site (facility-wide energy integration).
  - Provide a systematic method to evaluate trade-offs between CAPEX and OPEX for three levels.
  - Provide a clear framework for assessing CO_2 abatement potential, including economic factors such as the Levelized Cost of CO_2 Abatement ($LCCO_2$).

By applying these principles, DeCarb-PUI extends beyond traditional energy efficiency approaches by focusing on exergy efficiency. The method ensures that industrial heating and cooling systems are not only energy-efficient but also thermodynamically optimized, leading to long-term cost savings and sustainability benefits.

This methodology provides a practical roadmap for industries to transition towards low-carbon and energy-efficient operations, ensuring that the process-utility interface is optimized for future energy scenarios while remaining technically and economically viable. The general purpose and the goals presented above are to be split into specific objectives and a corresponding structure of the project (see Figure 2).

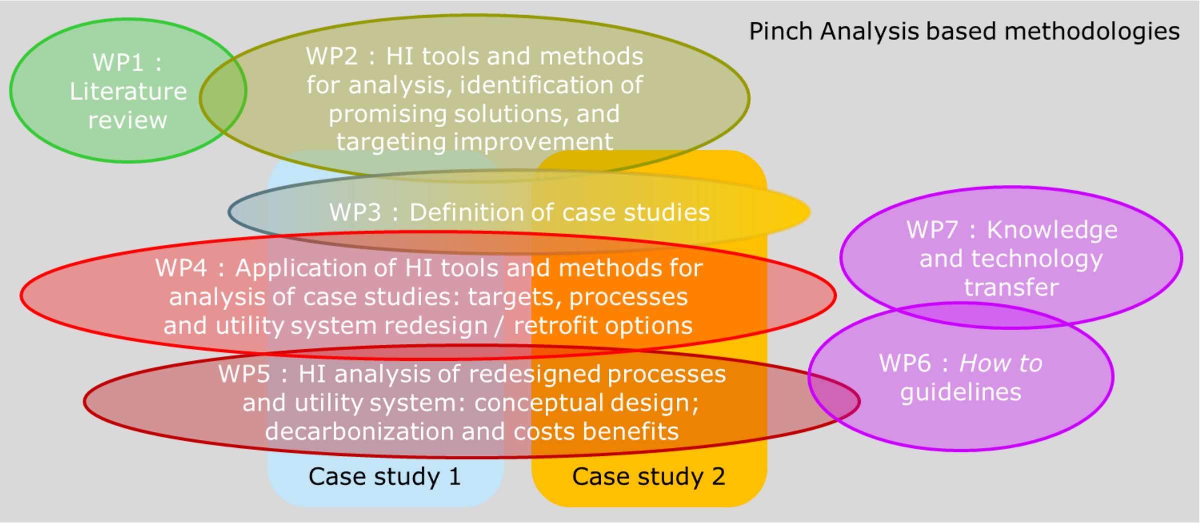


Figure 2: General organization of DeCarb-PUI into work packages.

1.4 State-of-the-art

The DeCarb-PUI project builds upon established principles in energy efficiency and exergy optimization, extending these frameworks to address inefficiencies at the PUI). To inform the development of practical tools and methodologies, this literature review focuses on:

- Exergy and Pinch Analysis,
- Total Site Heat Integration,
- Integration of heat pumps,
- Integration of solar heat.

In addition, as regards the Total Site Heat Integration (TSHI) approach, large scale and complex steam systems involving cogeneration scheme and several pressure levels are disregarded in the literature review. This is because Switzerland has very few large industrial parks, where such systems are technically and economically relevant, most industries being of small to middle size and operating their own energy conversion system.

This chapter aims to summarize the key aspects of methodological novelties identified from the literature survey that are leveraged to construct the methodological framework in this project.

1.4.1. Exergy and Pinch Analysis

Exergy analysis has increasingly been incorporated into pinch analysis to provide a more comprehensive understanding of energy losses within industrial processes. Staine and Favrat (1996) extended traditional PA by introducing the Carnot composite curves (CCs), which graphically represent exergy losses as the area between the hot and cold composite curves. These curves are useful for identifying inefficiencies in heat transfer but remain complex to interpret for economic decision-making.

Feng and Zhu (1997) advanced these ideas by introducing exergy CCs, which combine pinch and exergy analyses into a unified framework. Their method identifies avoidable exergy losses, isolating opportunities for process improvement. This approach is particularly relevant for evaluating process modifications, as it quantifies the thermodynamic inefficiencies resulting from current operations.

Further refinements were made by Brown et al. (2005), who proposed a dual representation of process requirements. Their method distinguishes between the thermodynamic requirements of processes and their current technological implementations. This approach highlights exergy penalties incurred due to technology choices and offers insights into retrofit potential. By comparing thermodynamic and technological composite curves, process engineers can identify operations where adjustments may yield significant energy and cost savings.

Maréchal and Favrat (2006) advanced the integration of energy conversion technologies by combining exergy and PA. They demonstrated how optimizing utility systems, including steam networks and heat pumps, can minimize exergy losses. Their graphical tools, such as Carnot grand composite curves (GCCs), visually capture exergy availability and losses, providing actionable insights into energy conversion optimization.

Marmolejo-Correa (2013) extended exergy analysis to low-temperature processes, introducing new graphical representations such as exergetic composite curves and exergy cascades. These tools simplify the identification of exergy targets, though they are more applicable to sub-ambient systems than standard industrial processes.

1.4.2. Total Site Heat Integration

TSHI methods have evolved to address challenges associated with multi-process facilities. Tarighaleslami et al. (2017) developed the Unified Total Site Targeting Method, which introduces fixed supply and return temperatures for non-isothermal utilities like hot water loops. This approach ensures realistic energy targets, a crucial consideration for low- and intermediate-temperature processes in industries such as food and beverage.

In parallel, researchers have explored optimizing utility levels to minimize total annual costs (TAC). By applying exergy derivatives, utility temperatures can be optimized for both fuel efficiency and operational costs. However, incorporating these optimized temperatures into practical utility exchanger network designs remains a challenge, particularly for retrofit projects.

Chew et al. (2015) extended the application of TSHI to process modifications, linking changes in total site profiles to specific adjustments at the process level. Their methodology uses graphical tools like Total Site Profiles and Utility GCCs to identify strategic opportunities for heat recovery and utility integration.

Additional work by Liew et al. (2014) proposed a retrofit framework for TSHI, emphasizing the need for site-wide optimization before addressing individual processes. This framework aligns well with DeCarb-PUI's objective to systematically redesign utility systems to improve exergy efficiency.

These advancements align with DeCarb-PUI's objectives by addressing site-wide heat integration challenges while considering practical constraints.

1.4.3. Integration of Heat Pumps

The integration of HPs into industrial processes has become a focal point for decarbonization strategies. Shenoy (1995) developed a systematic methodology for optimizing HP placement and design, balancing utility flows and operating conditions to maximize performance.

Berntsson (1990) and Townsend and Linnhoff (1983) laid the groundwork for integrating HPs into continuous processes. Building on this foundation, recent studies have incorporated exergy analysis to evaluate the thermodynamic and economic performance of heat pump systems.

For instance, Wang et al. (2018) introduced a novel criterion, Exergy per TAC, to assess the economic viability of heat pumps. This metric accounts for the quality of heat upgrades, offering a more comprehensive evaluation than traditional coefficient of performance (COP) metrics.

1.4.4. Solar thermal integration

Solar thermal systems can be optimally integrated into industrial processes using the PA. Following the PA principle help facilitate the identification of suitable integration points for solar heat—typically above the process pinch—to ensure minimal interference with internal heat recovery. Extensions of classical PA, such as Residual Composite Curves (RCC) (Rittmann-Frank et al., 2020) and Time-Averaged Models (TAM) (Olsen et al., 2016), have proven especially effective in addressing the complexities of batch and semi-continuous operations.

A SFOE project, BillySolar, presents a methodology to identify modular solar thermal units for industrial processes, demonstrating the potential of combining modular solar units and evacuated tube collectors with optimized storage-to-collector ratios, yielding competitive heat production costs and up to 14% overall energy savings. Application of PA to optimally integrate solar thermal to dairy processes is demonstrated for Spain (Quijera & Labidi, 2013) and Switzerland (Wallerand, 2018). Walmsley et al. (2013) based on a case study from New Zealand highlighted the advantages of series-integration schemes and Heat Recovery Loops for enhancing solar thermal uptake under variable operational conditions. Resources like the IEA SHC Task 49 (Muster et al., 2015) guidelines and the SHIP-Plant info database (IEA, 2023) provides standardized benchmarks and empirical evidence for best practices. Moreover, There is an emerging methodological trend toward coupling PA with exergy analysis, life cycle assessment (LCA), and techno-economic modeling to assess the integration of solar thermal in industrial processes (Jouhara et al., 2018).

1.4.5. Graphical Representations

Graphical tools are essential for illustrating the interactions between energy and exergy in industrial systems. Several representations, including Carnot CCs, temperature-exergy GCCs, and exergy diagrams, have been developed to enhance visualization and decision-making.

Carnot CCs (Staine & Favrat, 1996) depict exergy availability and losses across temperature ranges, enabling the identification of inefficiencies. Similarly, temperature-exergy GCCs map cumulative exergy requirements, highlighting opportunities for optimization.

Marmolejo-Correa (2013) introduced new exergetic diagrams that simplify the identification of exergy targets, while Maréchal and Kalitventzeff (2003) proposed integrated CCs to evaluate utility system designs, including combined heat and power (CHP) setups.

1.4.6. Relevance to DeCarb-PUI

The reviewed methodologies and tools underscore the importance of integrating exergy considerations into process and utility optimization. By leveraging dual representations of energy requirements, DeCarb-PUI can quantify retrofit potential and identify practical pathways for decarbonization. Additionally, advancements in TSHI and HP integration provide scalable solutions for improving energy efficiency at both the process and site levels. Overall, this review highlights the need for systematic workflows that incorporate graphical tools and practical constraints. By adapting and extending these methodologies, DeCarb-PUI aims to deliver actionable strategies for enhancing energy efficiency and reducing exergy losses across diverse industrial sectors.

2 Methodologies

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 Analysis is used to assess the efficiency of the processes, and techno-economic analysis is performed to assess the new designs is carried out in three different system boundaries, (i) localized, (ii) cluster of processes, and (iii) total site.

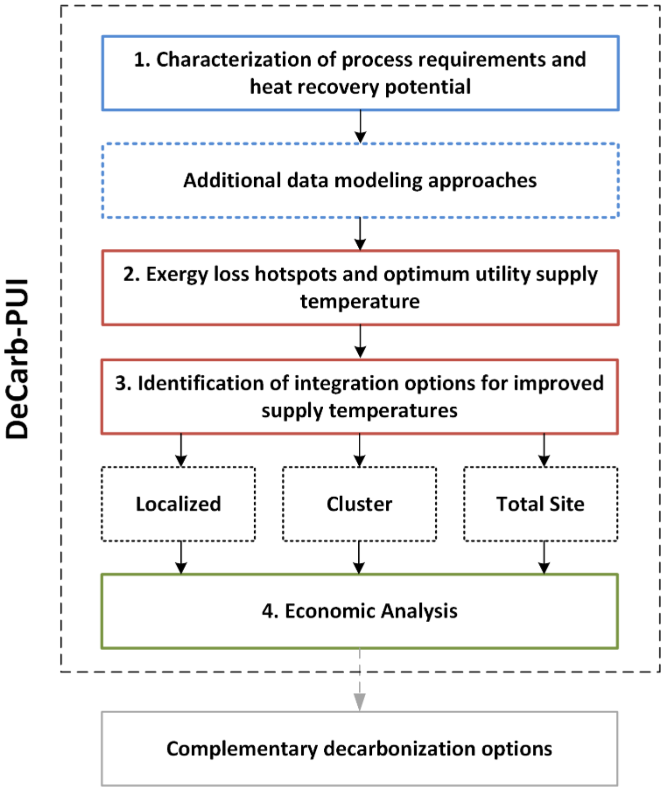


Figure 3: Overall methodology for retrofit of process-utility interface.

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 energy efficiency measures (EEMs) (e.g. HEX), energy conversion technologies (e.g. HP), and/or renewable energy technologies. After following DeCarb-PUI methodology, it can be extended by looking at other decarbonization options (e.g. fuel substitutions).

2.1 Pinch Analysis: Process requirements characterization and heat recovery potential identification

2.1.1. Pinch Analysis fundamentals

PA is a graphical approach and a key methodology in Process Integration. It is a systematic and practical technique for analyzing the heating and cooling demands (process requirements) of an industrial process, grounded in the fundamental laws of thermodynamics. Process requirements are determined by identifying the heating or cooling demands of process streams to achieve the necessary production temperatures (e.g., a process stream must reach a certain temperature for a reaction to occur).

By analyzing these process requirements using PA, it is possible to determine the cost-optimal heat recovery and utility demand by minimizing the TAC, which involves a trade-off between operating and investment costs.

In PA, process streams with heating and cooling demands are combined into two CCs. The "cold CC" represents the heating demand, and the "hot CC" represents the cooling demand (Figure 4, left). The "pinch" is the point of the smallest temperature difference between the hot and cold CCs, characterized by a temperature difference ΔT_{min}. The horizontal overlap between the two CCs shows the maximum theoretical potential for heat recovery (HR). Moving the CCs horizontally changes the ΔT_{min}, the HR potential, and the amount of external heating and cooling required (HU, cold utility, CU).

By minimizing the TAC, the optimal temperature difference $\Delta T_{min,opt}$ (Figure 4, right) can be identified as a tradeoff between investment and operating costs. A larger ΔT_{min} results in smaller overlapping area and, therefore, a reduced potential for HR. However, it also increases the heating and cooling demands, leading to higher energy costs but lower investment costs for the HR system due to the greater temperature differences.

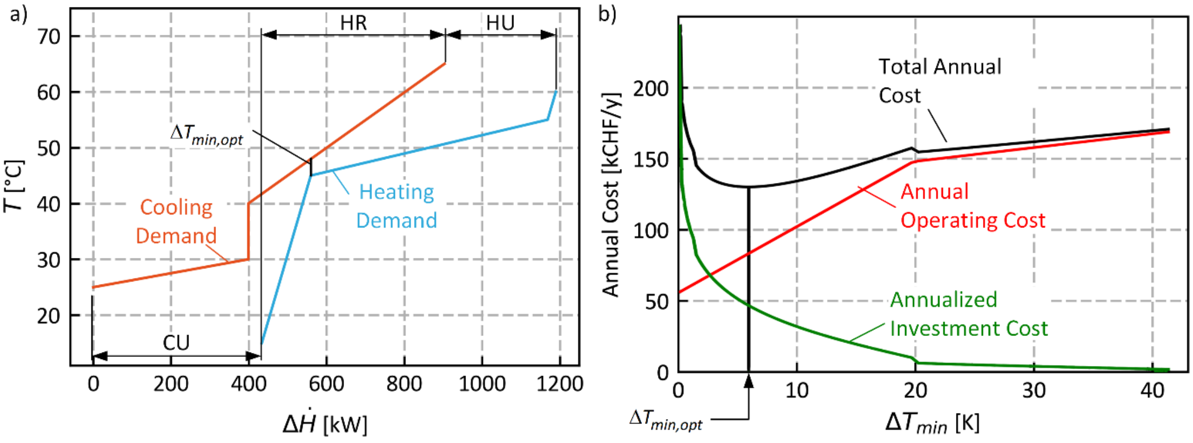


Figure 4: Exemplary CCs and cost curves. Left: CCs of the cooling (red curve) and heating (blue curve) demands showing the potential HR and HU and by the CU for the cost optimal temperature difference $\Delta T_{min,opt}$. Right: cost curves showing total annual cost (black curve), annual operating cost (red curve), and annualized investment cost (green curve). The optimal temperature difference $\Delta T_{min,opt}$ is found at the minimum of the total annual cost curve.

The GCC (Figure 5), derived from the CCs, is a valuable tool for visualizing utility demand across different temperature levels. Above the pinch, the GCC indicates a heat deficit, and a heat surplus below it. At the pinch point, there is neither a deficit nor a surplus. On the GCC, temperatures of net heat deficit are shifted by $+\Delta T_{min}/2$, while that of net heat surplus are shifted by $-\Delta T_{min}/2$. The grey areas are called pockets, which represent temperature ranges requiring neither external heating nor external cooling (i.e. self-balanced regions), net heat surplus being “cascaded” to lower temperatures to supply net heat deficit. From an exergy point of view, the pockets highlight the part of internal heat recovery, which takes place at $\Delta T > \Delta T_{min}$, i.e. involving exergy losses.

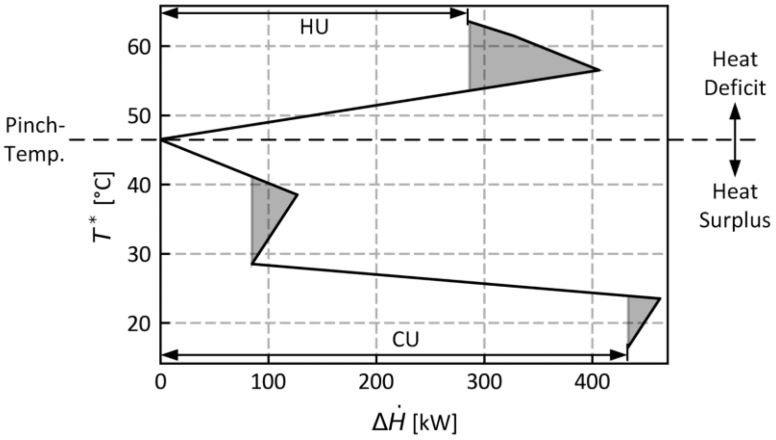


Figure 5: The exemplary GCC shows the heat deficit and surplus depending on the temperature level. Above the pinch there is a heat deficit and below a heat surplus.

Implementation of EEMs, energy conversion technologies (ECTs), and renewable technologies (RTs):

PA tools can be leveraged to identify opportunities for the integration of EEMs, ECTs and RTs. However, while doing some, some of the key principles of PA should be respected:

1. **Keep hot streams hot and cold streams cold**: to maximize the HR 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. **Evaluate features of the existing solution**: 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.).
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 rules decreases the heat recovery potential and entails an increase of OPEX or a reduced heat recovery for a given CAPEX.

EEM: Heat Exchanger Network (HEN)

To implement the HR for the given $\Delta T_{min,opt}$, the HEN for the process needs must be designed. To achieve the targeted HR, the design process must adhere to three main pinch rules: (1) no external cooling above the pinch, (2) no external heating below the pinch, and (3) no heat transfer across the pinch, meaning no heat transfer from a hot stream above the pinch (heat surplus) to a cold stream below the pinch (heat deficit) is allowed.

If there are multiple operating cases, the HEN design must be repeated for each of the operating cases and then combined into one overall design with works for each of the operating cases.

Energy conversion technologies and renewable technologies

HPs utilize heat at a lower temperature level and release it at a higher temperature by increasing the pressure of the working fluid. To integrate a HP correctly, the three main pinch rules must be considered to ensure a reduction of the heat deficit above the pinch and the heat surplus below the pinch. A common mistake in industry is the incorrect integration of HPs. The position of the pinch point and the shape of the GCC are crucial in determining whether it makes sense to integrate a HP or whether an existing HP is correctly integrated into the process.

There are three ways to integrate a HP into a process: (1) below the pinch, (2) above the pinch, and (3) across the pinch. However, only one of these options is energetically beneficial. If a HP is integrated below the pinch (1), where the process has a heating surplus, the additional compressor power required to increase the temperature level will result in an increased need for CU (see Figure 6, left). Integrating a HP above the pinch (2) reduces the HU demand by the amount of compressor power, effectively making the HP act as an electric heater (see Figure 6, middle).

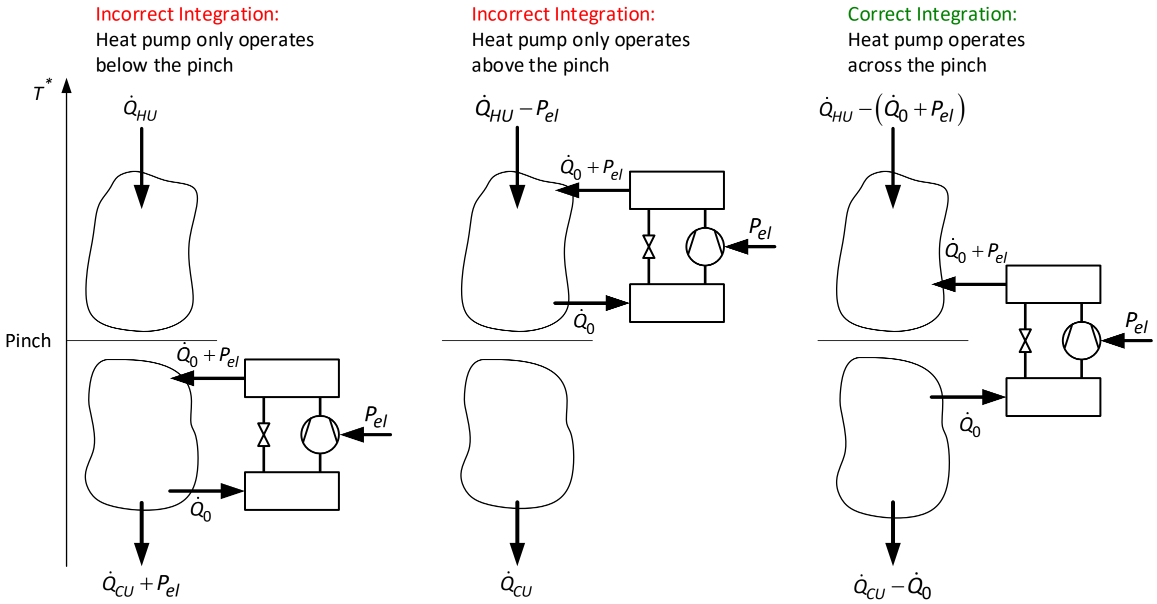


Figure 6: Correct and incorrect HP Integration into a continuous process.

By integrating a HP across the pinch (3), the heat absorption by the evaporator below the pinch reduces the heat surplus, while the heat released by the condenser above the pinch reduces the heat deficit. Although this contradicts the third main pinch rule, the HP effectively reverses the heat transfer from a lower to a higher temperature level, thereby simultaneously reducing the heat deficit above the pinch and the heat surplus below the pinch.

Similar to heat pumps, for the integration of solar heat, it can thus be read directly from the GCC at which temperature level the solar thermal system must be operated in order to be able to cover the corresponding heat deficit. Furthermore, it follows from the three main rules that the integration of solar heat must always be carried out above the pinch point.

The appropriate definition of process heating and cooling requirements (also called “process data extraction”) is a key step for a successful and meaningful PA. Correctly defining the temperatures and the heat loads of the heating and cooling requirements is crucial in process integration projects (energie360°, 2020). For this reason, the first step is to **define the operations required to transform raw materials into the desired products**. The heating or cooling requirements are inferred from the operating conditions, applying, as much as possible, the basic principle “keep hot stream hot, and keep cold stream cold”.

2.1.2. Process data extraction and modeling approaches

The data extraction may be conducted in three different ways, namely thermodynamic requirement (Thm), technological requirement (Tec), and utility supply (Uti) (Brown et al., 2005), which are explained in Table 1 below. The three main models (Thm, Tec, Uti) are highlighted in bold, while ITec (improved technology) and IUti (improved utility) are added to name intermediate situations (variation of the main models). Although ITec et IUti models would mean changes to the process itself or to its PUI respectively, it is worth reminding that these models still describe process heat transfer requirements and don’t say anything about the solution to supply these requirements (steam at reduced pressure, hot water loop supplied by a heat pump, etc.).

Indeed, the models result in different temperature profiles, leading to different shapes of the composite curves and hence different GCC. In retrofit projects, the engineer has the choice between the three models for each of the processes included in the boundaries of the system being analyzed. Depending on the "region" of the CC impacted by the change in the shape of the temperature profile, the different models can lead to variations in both maximum energy recovery and exergy (in case of pinched regions with tight temperature driving forces) or of exergy only (in case of regions with large vertical temperature differences). "Thm" modeling approach allows the estimation of exergy requirement of the process, whereas "Uti" models provide an indication of exergy delivered to the process. In the context of this project, the comparison of these two models is used to estimate the exergy losses due to heat transfer at the process-utility interface.

Table 1: Definition of various models considered in DeCarb-PUI.

Model name	Definition	Comment
Thermodynamic requirement (Thm)	The process heat transfer requirement is defined as the enthalpy change at the "level" of the material to be processed (i.e. modelling the final "fundamental" heat transfer requirement). Note: defining the "path" (state evolution) of a process heat transfer requirement is particularly difficult when both heat and mass transfer occur, as is the case e.g. in drying processes.	The Thm model describes: • a real situation in case the processed material is being subject to heat transfer without particular limitation; or, • An ideal/abstract concept in case the material or its final form require a particular way of heat transfer to achieve the goal (e.g. spray drying, beans roasting, etc.)
Technology implementation (Tec)	The process heat transfer requirement is defined as the enthalpy change at the "level" of the stream ensuring the heat transfer to the material being processed, using the current technology as implemented (named substitution stream), i.e. considering that this technology cannot/should not be changed without impairing the process "quality" (in the general sense).	The Tec model doesn't exist (or is identical to "Thm" model) whenever the processed material is being subject to heat transfer without particular limitation.
Improved technology implementation (ITec)	An alternative model proposal "approaching" the Tec model, i.e. a possible solution reducing the exergy requirement of the corresponding Tec model.	A model that makes sense when the Thm model is not feasible or would be much too expensive to implement.
Intermediate Utility supply (IUti)	An intermediate model between Uti and Tec, featuring a lower temperature level and hence reduced exergy requirement.	E.g. an intermediate hot water loop between steam and product to be heated (typically for thermal treatment of milk and other food material)
Utility supply (Uti)	The process heat transfer requirement is defined as the enthalpy change at the "level" of the utility supply, considering the process can't be changed in any way.	The utility conditions (steam pressure, or inlet / outlet temperatures in case of sensible heating) should be defined at the level of the utility/process heat exchanger, i.e. after the control valve, not upstream of it.

The terminology of Table 1 (Thm, Tec, Uti) is easier to understand and communicate since it reflects more explicitly the “type” and goal/scope of the model than the usual and somewhat similar categorization into white box/grey box/black box models. As a reminder, the latter are defined as follows:

- 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 EEM solutions are not constrained by pre-existing process features.
- Grey box (GB): it is defined by a restricted list of heating and cooling requirements after excluding the requirements achieved by the existing 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”.
- Black box: the process is considered to be unknown, untouchable, or unchanging economically. The thermal requirements are defined as utility requirements as supplied at the process interface.

The appropriate modelling alternative depends on the location of the boundary between where heat transfer can be modified (and process data are known or can be determined) and 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 the reasonable and easier approach. Except in particularly constrained cases, it is also worth building the CCs and the heat recovery targets with the WB model. In this way, the improvement of the heat recovery 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. Hence it is possible to check the impact of using GB model.

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.

PA typically precedes PUI improvements, 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, and not involving changes to the technology. Once PA is completed, PUI improvements can be targeted using GB modelling, which factors in HEN and focuses on residual heating and cooling requirements.

2.1.3. Workflow for the identification of heat recovery potential

Once the list of heat transfer requirements of the different processes has been set up through data extraction, it is suggested to follow the simplified workflow presented in Figure 7 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.

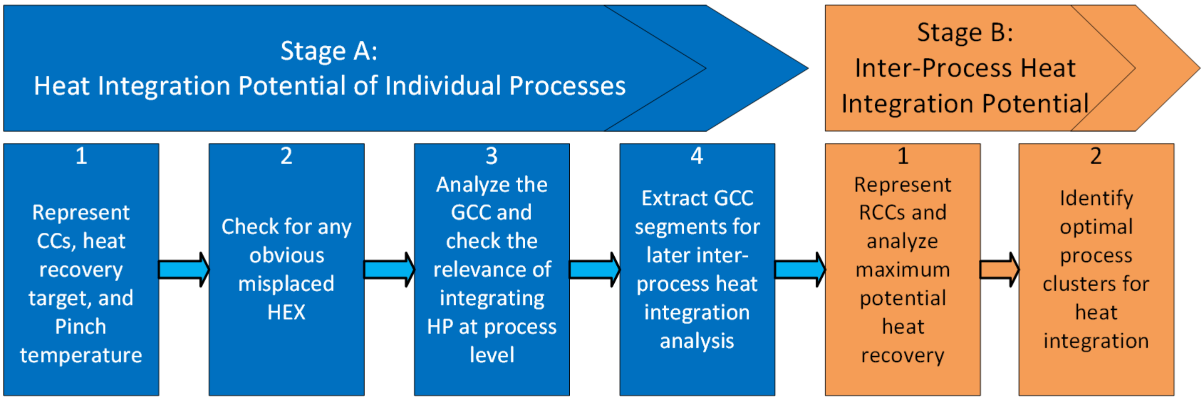


Figure 7: Simplified workflow for targeting and optimizing an industrial site's heat recovery and upgrading via HP(s), including several processes (extract from *HTHP Guidelines* draft document from the SFOE co-funded *HTHP-CH – Integration of High-Temperature Heat Pumps in Swiss Industrial Processes*).

For a clearer understanding, heat recovery and heat upgrading are distinguished in the context of De-Carb-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.

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

- **Simultaneously**: during targeting, the HP is “defined” (i.e. by selecting the appropriate heat duty, the condenser and evaporator temperatures) against the profile of the 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 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 heat recovery 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. To account for seasonal variations and scheduling differences between processes, multiple operating cases may need to be considered.

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 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 HP 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.

2.2 Identification of exergy loss hotspots and improved utility supply temperatures

The following section elaborates the step 2 of the overall workflow of DeCarb-PUI (Figure 3). The Exergy GCC (EGCC) can be constructed using the same procedure as GCC, with the Carnot factor as the ordinate. Conventionally the GCC is obtained by shifting the CCs vertically until they touch at the pinch point and then calculating the horizontal distance of a vertex from the other composite curve. The horizontal distance will be zero at the pinch points. Such a vertical shifting is not desirable when constructing the EGCC because the area enclosed by the EGCC represents the exergy losses. Therefore, this can be simply achieved by using the true temperature scale (column 1,

Table 2) and by maintaining the horizontal distances between the CCs in the GCC as well. Hot and cold stream temperatures are merged and then sorted in ascending order to obtain column 1 in

Table 2. Corresponding hot and cold enthalpies are then identified, and missing values are interpolated to obtain columns 2 and 3 in

Table 2. This generates the balance EGCC.

The Exergy Problem Table Algorithm (EPTA), as outlined in

Table 2 is modified from Hamsani et al. (2018) and it closely resembles the traditional PTA, with one notable variation concerning the input enthalpy cascade, known as H_{input}. The H_{input} is calculated as the difference between Q_h and Q_c at the given temperature. The surplus/deficit values are determined using the H_{input} cascade. The surplus/deficit exergy values (ΔX) as well as the initial and final exergy cascades (X_i and X_f), follow the same procedure as the standard PTA. The initial exergy cascade commences from the first temperature row, with an enthalpy value of 0 MW. In contrast, the final exergy cascade descends from top to bottom, considering the modulus of the negative value observed at the Pinch point, as defined by the enthalpy PTA, in the initial exergy cascade. It's important to note that, unlike energy, exergy doesn't adhere to the principle of conservation, hence the presence of negative exergy values in the final cascade, X_f, is entirely normal.

Using the EPTA and basic rules to construct a GCC, the EGCC can be constructed.

Table 2: Exergy Problem Table Algorithm.

Temperature T (K)	Q_h (kW)	Q_C (kW)	Carnot Factor	H_{input} = Qc-Qh (kW)	Net Surplus/Deficit ΔX (kW)	Cascaded Exergy (kW)	Final Cascaded Exergy (kW)
T_1	0	0	$1-T_o/T_1$	H_1		$X_{1(i)}=0$	$X_{1(f)}= \min\lvert X_i\rvert$
					$(\Delta H\cdot(1-T_o/T))_{1-2}$		
T_2	Q_{h1}	Q_{c1}	$1-T_o/T_2$	H_2		$X_{1(i)}+\Delta X_{1-2}$	$X_{1(f)}+\Delta X_{1-2}$
					$(\Delta H\cdot(1-T_o/T))_{2-3}$		
…							
					$(\Delta H\cdot(1-T_o/T))_{[n-1]-n}$		
T_n	Q_{hn}	Q_{cn}	$1-T_o/T_n$	H_n		$X_{n-1(i)}+\Delta X_{[n-1]-n}$	$X_{n-1(f)}+\Delta X_{[n-1]-n}$

To complement the PA with the estimation of exergy losses, a new representation named EGCC is developed. As mentioned above, it uses the Carnot factor instead of the temperature for the vertical axis. In the Energy Availability Diagram (Figure 8 (a)), the process part of hot and the cold CCs provide a quantified and direct view of exergy requirements, whereas the utility part of the curves provide the measure of exergy supplied. A cumulative net process exergy demand can then be estimated and plotted with the exergy supplied by the utilities (shaded grey Figure 8 (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 PUI, 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 analysis 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.

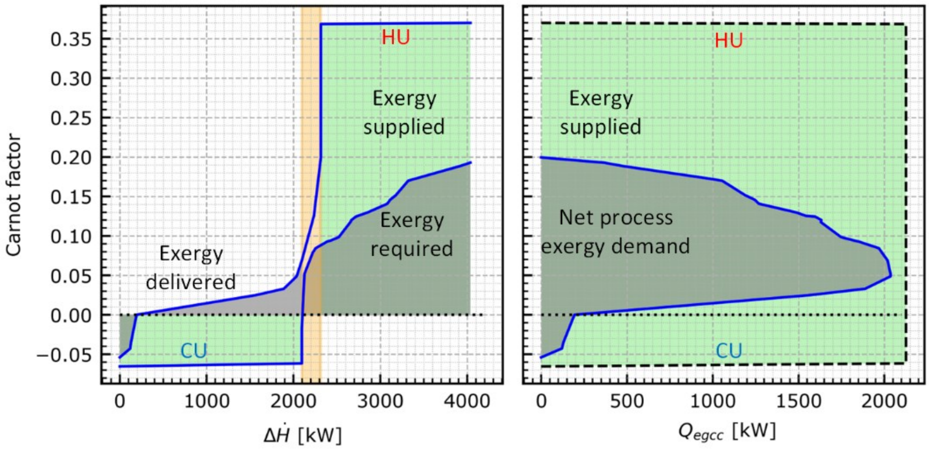


Figure 8. (a) Energy availability diagram (b) Exergy GCC.

2.3 Total Site Integration

Total Site Integration (TSI) represents a strategic extension of PA, wherein multiple processes within an industrial site are evaluated collectively to optimize heat recovery through both direct and indirect integration. Unlike conventional PA applied to individual processes, TSI aggregates the thermal requirements of all processes at a site, thereby enabling waste heat from one unit to serve as a thermal resource for another. This systemic approach aims to maximize overall energy efficiency and reduce reliance on external utilities.

The methodological core of TSI lies in the generation of Total Site Profiles (TSPs), which synthesize the GCCs of individual processes. These curves are constructed using a shifted temperature scale ($\pm\Delta T_{min}$) to incorporate the minimum driving force for heat exchange and reflect actual utility temperatures. Within this framework, the overlapping areas of the site source and sink profiles are identified, and the point of maximum thermal overlap is termed the site pinch. At this site pinch, maximum feasible heat recovery is achieved through coordinated process integration.

Direct heat integration, wherein processes are interconnected without intermediary heat transfer loops, is particularly advantageous due to minimized thermal degradation and infrastructure demands. In practice, all processes are conceptually treated as a single integrated system, allowing maximal inter-process heat exchange and reducing the need for external heating and cooling utilities. The Total Site Composite curves (TSC) generated from the TSPs enable the visualization and quantification of required utilities. The horizontal distance between the hot and cold composite curves represents the net utility demands, providing insights into the potential for utility system optimization.

Implementation of TSI often leads to design modifications in the utility network. Examples include replacing steam with lower-temperature hot water circuits or introducing additional steam pressure levels tailored to the thermal needs of specific processes. Such adjustments enhance flexibility and reduce fuel consumption, as demonstrated by various studies employing TSC analysis for fuel targeting and co-generation potential (Ong, 2019).

2.4 Identification of integration options for improved utility supply temperatures

As depicted in step 3 of the overall workflow (Figure 3), in the DeCarb-PUI framework, the traditional Pinch Analysis is complemented by the estimation of exergy losses, which leads to the identification of improved utility supply temperatures and uncovers opportunities for additional integration options at lower temperatures. The analysis of various additional integration options is typically a combinatorial problem, and multiple solutions can be derived. However, three primary levels of system boundary are considered for the identification of appropriate integration options: (i) localized, (ii) cluster of processes, and (iii) total site. While the localized options include only one process, a cluster of processes includes multiple processes carefully selected based on various criteria. The total site, on the other hand, typically considers all processing units in the industrial plant. *However, it should be noted that some of the selection criteria used for identifying clusters can also be used to eliminate some processes from the total site solution.*

The following criteria are considered to identify the process clusters:

1) Temperature level compatibility:
    - Source Temperature: Temperature of the heat sources (or that or the heat transfer loop collecting the heat sources) to supply the evaporator should be withing the effective operating range of the heat pump.
    - 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.
    - 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.), 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 shutdowns 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.

2.5 Economic Analysis

Once the improved utility temperatures and the measures to achieve those temperatures are identified, the cost-effectiveness of all the options is evaluated in step 4 of the DeCarb-PUI workflow (Figure 3). 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.

The module cost functions for the different technologies are estimated based on historical data (Rast, 2018) or data collected from various literature sources. The generic CAPEX factor breakdowns, presented in Table 3, are adapted from literature which have been widely applied in early-stage cost estimations for industrial projects, including PA. These factors serve as a generalized benchmark during the conceptual phase of a project, where detailed cost data is typically unavailable.

In subsequent project phases—particularly during detailed engineering design—these factors are refined using site-specific information, including insulation type and quantity, pipe routing complexity, or building and structural constraints. Additionally, individual company-specific guidelines (e.g., from Emmi or UFA) regarding depreciation periods or cost structures are used during final evaluations.

Since these refinements are highly dependent on the local project context, they are not included in this generic-level report. However, the case study annex provides more detailed estimations where appropriate, reflecting the real-world conditions and internal specifications of participating industry partners.

Table 3: Capital cost factors adapted from literature

Cost component	**Factors**		
	Smith (2005)	**(Brennan & Golonka, 2002)**	**(Peters et al., 2004)**
Module	1	1	1
Piping	0.7	0.6	0.66
Building	0.3	0.22	0.18
Installation	0.4	0.19	0.47
Site Preparation	0.1	0.04	0.1
Engineering	0.8	0.25	0.74
Total	2.3	1.3	2.15

The factor is adapted to estimate the additional cost needed for the distance and necessary work for the installation of the solutions.

The total CAPEX (CHF) 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 (eq. (1)). The cost functions derived for this work are used for the estimation of the total CAPEX and are presented in the power law relationships between CAPEX and the installed capacity in terms of thermal output, surface area, or volume.

$$CAPEX_{annual} = CAPEX \cdot \left(\frac{1-(1+r)^{-L}}{r}\right) \qquad (1)$$

where,

L = Depreciation period (years)

r = Discount rate (chosen to be 10%)

The economic evaluation of the different heat sources is performed using the criterion of Levelized cost of CO_2 (LCCO2) abatement as presented in eq. (2).

$$LCCO2 = \frac{I \times ANF + O\&M - B}{CA} \tag{2}$$

where,

I = Initial investment cost for HP (CHF)

ANF = Annuity factor for the given discount rate and technology lifetime

O&M = Annual operation and maintenance cost (CHF)

B = Annual benefits, i.e., cost of saved total final energy and of avoided CO_2 tax payments (CHF)

CA= CO_2 abatement potential (t-CO_2 emission reduction/year)

The CO_2 abatement potential (CA) is estimated based on the natural gas saved annually as a result of the HP integration. Only scope 1 (onsite) CO_2 emissions are considered in the present analysis.

However, the set of economic parameters for each industrial process is unique. 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. Breakdown CAPEX by equipment type, piping, instrumentation, and installation costs.
    - OPEX: Include maintenance costs, labor, 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 operational costs. Account for potential energy savings from heat recovery or conversion technologies.
    - Carbon Costs and Savings: Estimate CO_2 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., heat pumps, 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 ROI calculations.
    - Operating Hours: Estimate the number of annual operating hours to ensure accurate calculation of energy savings and equipment utilization.

3 Emmi case study

A Pinch Analysis report for Emmi's Dagmersellen production site October 2022 by HSLU & Flimatec (Wellig et al., 2022) is available. This industrial dairy processes milk, buttermilk or whey concentrate and produces mainly Mozzarella and milk powder. Although the company has already implemented local hot water heat recovery loops, there is still scope for improvement. Further, the processes involved are found throughout the dairy industry, so a large multiplication potential can be ensured.

3.1 Case Study Description

3.1.1. General overview

The Emmi Group is an international player in the milk processing sector, operating 25 production sites in Switzerland, as well as production sites in 14 countries internationally. In Switzerland, the Dagmersellen site is Emmi's largest production site (see Figure 9 and Figure 10).

Figure 9: Top view of the Emmi industrial dairy, Dagmersellen (source: map.search.ch).

Figure 10: View of Emmi Dagmersellen (Wellig et al., 2022).

The site generates about CHF 3.5 billion in annual turnover, processes daily up to 1.2 million litres of milk, and up to 50’000 litres of buttermilk or whey, and produces mainly Mozzarella and various types of milk powder. According to the detailed PA report (Wellig et al., 2022), approximately 68 GWh of fossil fuels are consumed annually for heat production and 19 GWh of electricity is consumed. Figure 11 presents the breakdown of fuel consumption by individual consumers (estimated by bottom-up calculations). Spray drying (involving ambient air heated up to 185 °C) is the largest consumer of process heat followed by drum drying (“Roller”) and evaporation.

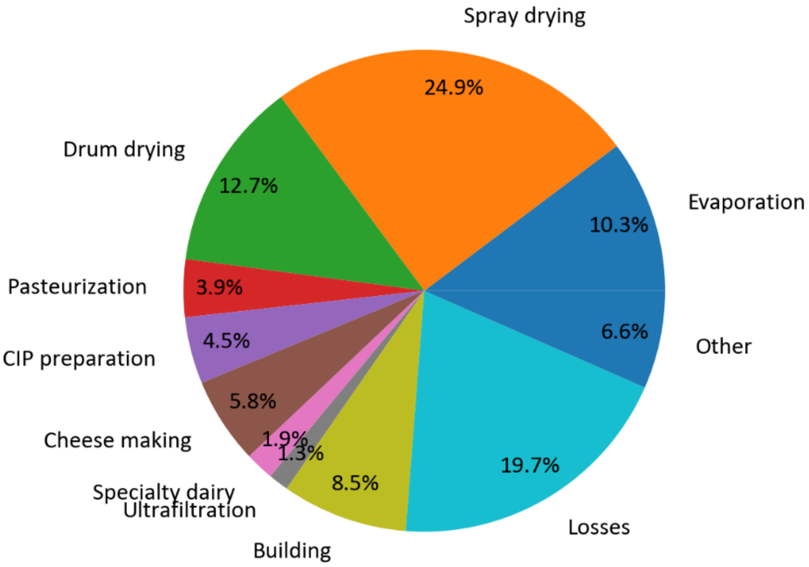


Figure 11: Breakdown of fuel consumption at Emmi Dagmersellen (Wellig et al., 2022).

The quantities of milk to be processed show significant seasonal variations, particularly due to the summering of cattle and to suckler cows. Emmi Dagmersellen site plays a balancing function in the group as it varies its milk powder production to ensure the other processes of the production sites in Switzerland can be run without interruption according to the demand. This strategy influences the set of processes running simultaneously and the utility consumed at Dagmersellen significantly, so that it cannot be assumed that the process CCs are essentially the same over the year. The PA has considered a typical winter workday as a determining base case, time averaged.

3.1.2. Overview of processes and general constraints

Figure 12 sketches the simplified production route. Some of the processes involving significant heating and/or cooling are listed in Table 4.

Table 4: Significant processes operated on Dagmersellen site.

Processes	Description	Comment
Milk treatment		
Raw milk centrifugation, cream and skim milk pasteurization, cooling for temporary storage (3 facilities)	This step includes significant product-product counter-current heat recovery. Complementary heating to pasteurization uses 4.5 bar(a) steam.	See Figure 14 for details. New pasteurization units include raw milk splitting to ensure heat recovery from pasteurized cream as well.
Micro- and/or ultrafiltration (UF), cooling for intermediate storage (2 facilities)	These processes require heating milk up to about 50 °C to 60 °C prior to filtration; heating is achieved by product-product heat recovery (from retentate and permeate), followed by post-heating by a hot water loop supplied by steam. During UF, the recirculated retentate (heated by pressure losses) is kept at about 50°C using ice water.	From a PUI perspective, exergy losses occur with both process heat sinks (steam for heating to 50 °C-60 °C) and heat sources (ice water for cooling to 50°C). Yet limited operation duration and energy consumption
Powder production		
Concentration by evaporation (3 facilities)	Complex system to allow flexible operation (different products & operating conditions). Includes pasteurization of feed with various heat recovery schemes. Falling film evaporator operated under vacuum. Two facilities using multiple effects evaporator technique, one resorting to MVR (for pre-concentration stage) and TVR (for final high concentration).	Requires detailed process knowledge / understanding. Opportunity to compare MVR with TVR from an exergy perspective (in a limited scope)
Spray drying (3 facilities)	“Classical” spray drying system (MSD type) including spray drying tower, vibro-fluidizer, cyclone and bag filter. Fitted with indirect heat recovery (water loop) on exhaust air to preheat main supply air. Heating of air flows with steam and condensate (main drying air up to about 180°C-195°C).	Largest steam consumer. Significant exergy losses in the air heaters.
Drum drying (2 facilities)	An alternative to spray drying, used to produce milk powder for the chocolate industry. Heat to dry the product supplied as steam in hollow cylinders. 9.5 bar(a) steam is necessary to caramelize the product. Hot humid air extracted by the hood above the	Second larger steam consumer, large operation duration. Significant exergy losses, inherent to selected technology and need to caramelize product.

	drums, make-up air heated by 4 bar(a) steam.	See Figure 15.
Mozzarella production		
Cream pasteurization, including homogenization at intermediate temperature (2 facilities)	Pasteur with indirect heat recovery using a HW loop, complementary heating by HW heated with steam	There is potential for improving heat recovery by better integrating the heating and cooling steps of cream and whey.
Whey cooling	Lukewarm fat whey separated from mozzarella is used to preheat cream.	
Auxiliary / support processes		
CIP	Two CIP concepts co-exist: 1) centralized system supplying multiple satellite CIP, each cleaning a single circuit 2) full CIP stations including 4 tanks to clean several circuits (where alkaline, acid, and recycled water are each heated by steam injection, and make-up water is added cold.	All heating requirements are significantly below 100°C, but heat is supplied by steam in any case. See Figure 16.

The Emmi Dagmersellen site, bordered by buildings and the railway line, has existed for several decades and has undergone several stages of growth. This has resulted in very dense production areas, with little or no spare room. Hence:

- utility supply or inter-processes heat integration by means of a hot water loop is, for space reasons, hardly possible in practice (independently of profitability considerations);
- Emmi looks for local heat integration measures, where possible, with priority given to processes with large yearly duration of operation. Although the contribution of spray dryers to total steam consumption is large, the improvement of their heat integration is not the focus.
- in general, there is limited scope for heat integration optimisation within each process, so in most cases, the existing heat recovery HEX shall not be modified, obliging to work with the remaining part of process heating requirements, resp. cooling requirements. The design of process facilities to allow flexible operation with multiple product specifications leads to complex schemes requiring a detailed understanding of the process (which involves the manufacturer) as a preliminary step and making heat integration improvements difficult.

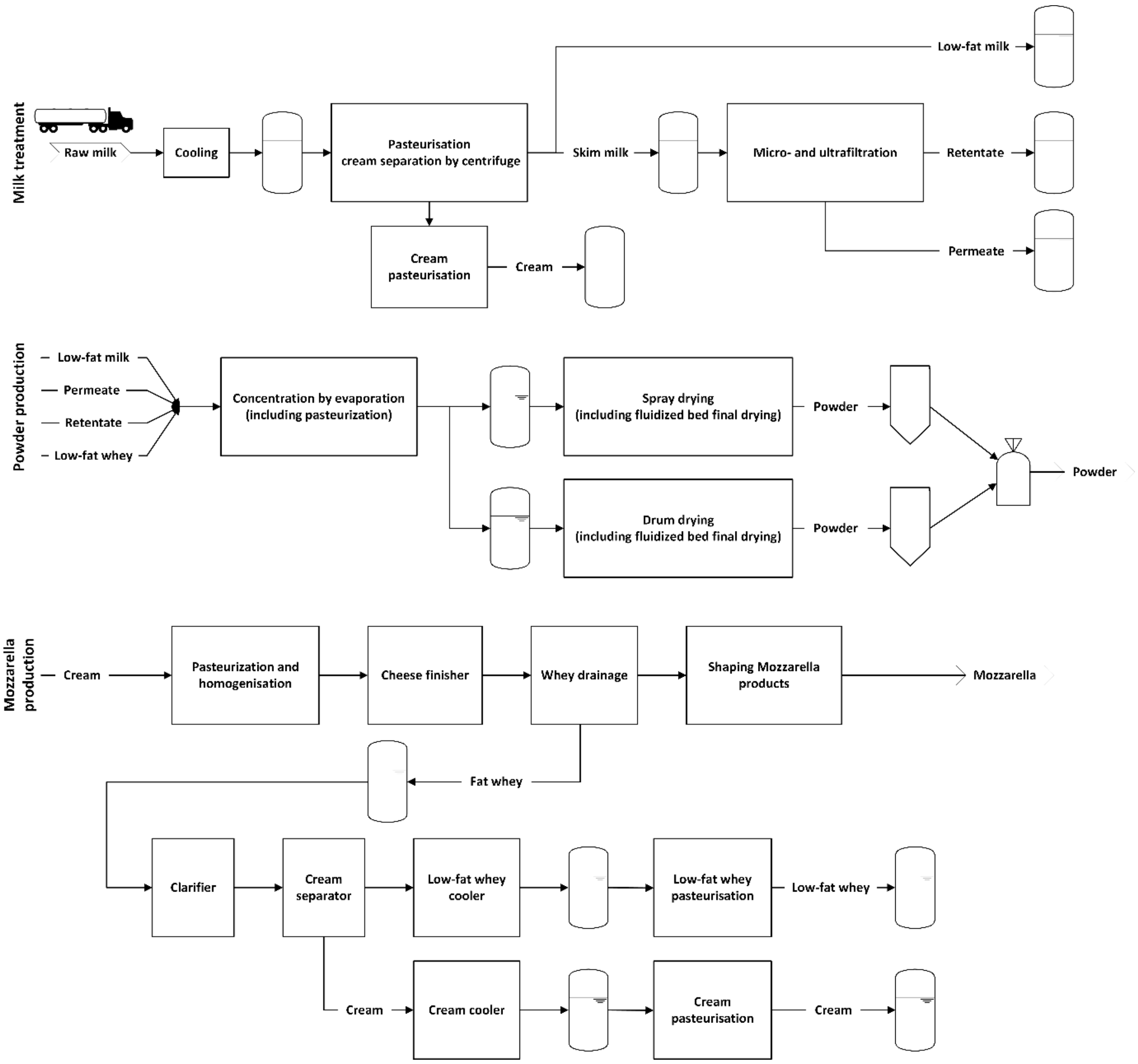


Figure 12: Simplified production route at Emmi Dagmersellen (small volume products such as ricotta, cottage cheese, etc. are not considered).

3.1.3. Hot and cold utilities

Process heating and cooling requirements not covered by internal heat recovery are ensured by the following thermal utilities:

- Hot utilities:
  - Steam (2 steam boilers, producing at 18 bar(g) and 13 bar(g) respectively);
  - Local heat recovery loops.
- Cold utilities:
  - Cooling water (pumped groundwater and re-infiltrated);
  - Ice water (1-2 °C / 5-6 °C, produced by 5 chillers).

3.2 Case Study Results

In DeCarb-PUI, no additional effort on top of the data available collected in the PAs is made for data extraction. The additional process models presented for selected processes are developed based on the already available data. To simplify the example, the following assumptions are made based on the PA reports:

1) A typical winter day is used to represent the heating and cooling demands, as it has the greatest demand for heating given the colder outside temperature.
2) CO_2 contribution of electricity: the electricity is assumed CO_2-free to directly correlate energy savings with CO_2 savings. This assumption simplifies the CO_2 reduction calculation, which could otherwise be impacted by the carbon intensity of electricity.
3) Process Continuity: Assume continuous processes to negate the need for complex scheduling or storage considerations, making it simpler to analyze heat recovery and energy flows.
4) Simplified COP Calculation for HPs: Exclude intermediate loops in the COP calculation for heat pumps, focusing only on direct heat source and sink connections.
5) Market Conditions and Prices: Set assumptions for energy prices, CO_2 pricing, and any relevant subsidies or incentives.
6) Capital Cost: In the cost analysis, different generalized factors are used for piping for localized, clusters, total site variants.

The case studies included in this report demonstrate the application of the methodological framework developed in this project. The results and discussion 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 to the case studies are site-specific, and although they may exhibit trends consistent within the case studies, they cannot be generalized for the Food and Beverage industry.

In addition, the information from the process flow diagrams (PFDs) shown in this report are illustrative only and do not necessarily correspond to actual processing conditions.

3.2.1. Characterization of process requirements and heat recovery potential

The process stream table consists of data for 52 process streams. The production processes and infrastructure systems are considered in PA under various operating cases (seasonal fluctuation, variable utilization of the systems). Representing almost 25% 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. Therefore, PAs were carried out separately to certain processes due to the temporal aspects necessary for conceptual storage integration.

In order to keep the example concise, an abridged version of the process stream table for residual streams is presented in Table 5. However, the results include detailed heating and cooling requirements of the selected 52 process streams. For example, the GCC prepared based on the TAM approach presented in Figure 13(a) includes all process streams. However, in DeCarb-PUI, only selected processes were optimized individually due to convenient localization and synchronization of the heating and cooling demands e.g., the pasteurizers (marked in Table 5).

Table 5: Typical process requirements for Emmi Dagmersellen.

Process	**Hot/cold**	**T$_{in}$ (°C)**	**T$_{out}$ (°C)**	**In the analysis**
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 (DHW)	Cold	50	60	✓
Pasteurization cooling	Hot	62	5	✓
UF cooling	Hot	42	15	
Chiller recooling	Hot	30	20	✓
Wastewater	Hot	27	20	✓

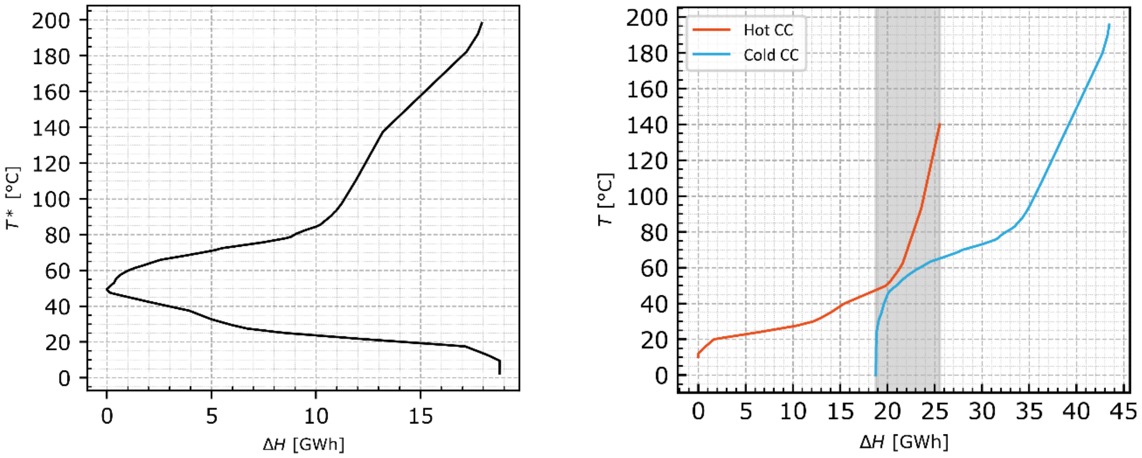


Figure 13: (a) Residual GCC based on TAM and (b) residual CCs for Emmi Dagmersellen with ΔT$_{min}$ of 10 K.

The GCC shows a significant difference between the temperature level of the hot utility and the actual temperature levels of the residual heating and cooling requirements. Over 75% of residual heating requirements are between 50 and 100 °C and could be met by HPs and solar thermal. Figure 13(b) shows the residual CCs after the implementation of several measures. The highlighted grey region shows further potential of HR, but it is not achievable due to constraints within the plant.

Several key measures were identified to improve their overall energy efficiency and reduce emissions, where the summary of the proposed measures can be found in the final report of the detailed PA. In general, the challenges identified for the implementation of these measures are:

(1) limited space for the installation of new equipment,
(2) high upfront investment costs for heat recovery systems, and
(3) existing infrastructure constraints that limit process modifications.

Theoretically, usable waste heat amounting to 38.2 GWh is generated at the Dagmersellen site every year. The waste heat, in this context, is bound in tangible material flows, e.g. wastewater, cooling water or exhaust air flows, which are discharged into the environment.

3.2.2. Additional process data modeling approaches

In practice, the constraints mentioned in Section 3.1.2 make it impossible to envisage one or more hot water networks for the entire site. As a result, in this analysis, we focus on optimizing heat recovery/transfer loops for selected subsets (clusters) of processes. The processes to be considered for PUI improvement are shortlisted based on the criteria explained in section 2.4 (processes are listed in Table 4).

The following section tabulates different modeling approaches considered for the chosen processes. Various modeling approaches allow the estimation of exergy requirements of the process (Thm), exergy delivered to the process as a result of current technology, and the utility system (Tec and Uti) (refer to Table 1 for a detailed description of modeling approaches). The difference between the required exergy identified based on the Thm model and the current exergy supplied based on the Tec and Uti models leads to the identification of exergy loss hotspots and improved utility supply temperatures. Although the various modeling approaches are presented separately for chosen processes, the exergy losses are presented and analyzed in the section 3.2.3.

Milk and cream separation and pasteurization

Pasteurization, processing raw milk into pasteurized skim milk and pasteurized cream, is shown schematically in Figure 14. This PFD corresponds to the original implementation before the raw milk split was proposed and added by the manufacturer to optimally match heating and cooling mass flows. Four different process models are developed for pasteurization[2].

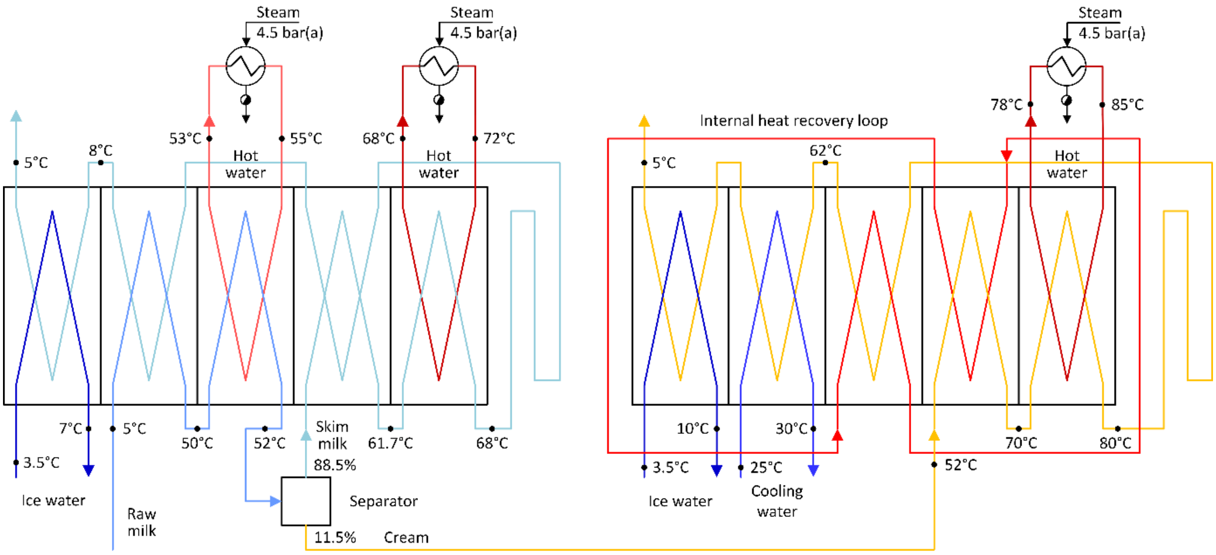


Figure 14: Simplified PFD of Pasteurization process (before implementation of raw milk split).

Table 6: Thermodynamic model data of the heat transfer requirements of the Pasteurizer (ignoring existing internal heat recovery HEXs). See explanations in the text.

Pasteur 3 (milk centrifugation + milk & cream pasteurization) **Thm model**								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
RawMilkHeatingToCentrifuge	Cold	5.0	52.0	10.360	3.890		1500	1894.1
SkimMilkHeatingToPasteurize	Cold	52.0	68.0	9.170	3.932		1500	576.8
CreamHeatingToPasteurize	Cold	52.0	80.0	1.190	3.570		1500	119.0
PastMilkCoolingToStoTank	Hot	68.0	5.0	9.170	3.932		1500	2271.3
PastCreamCoolingToStoTank	Hot	80.0	5.0	1.190	3.570		1500	318.6

---

[2] Here, the technology implementation is identical to the thermodynamic model.

Table 7: Thermodynamic, grey box model data of the heat transfer requirements of Pasteurizer (excluding part of the heat transfer requirements satisfied by existing HEXs).

Pasteur 3 (milk centrifugation + milk & cream pasteurization) **Thm-GB model**

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
Res_RawMilkHeatingToCentrifuge	Cold	50.0	52.0	10.360	3.890		1500	80.6
Res_SkimMilkHeatingToPasteurize	Cold	61.7	68.0	9.170	3.932		1500	227.2
Res_CreamHeatingToPasteurize	Cold	70.0	80.0	1.190	3.570		1500	42.5
Res_PastMilkCoolingToStoTank	Hot	8.0	5.0	9.170	3.932		1500	108.2
Res_PastCreamCoolingToStoTank	Hot	62.0	5.0	1.190	3.570		1500	242.2

Table 8: Utility model data of the heat transfer requirements (i.e. excluding part of the heat transfer requirements satisfied by existing HEXs).

Pasteur 3 (milk centrifugation + milk & cream pasteurization) **Uti model**

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
St4.5b_RawMilkHeatingToCentrifuge	Cold	147.9	147.9	0.038		2120.25	4000	80.6
St4.5b_SkimMilkHeatingToPasteurize	Cold	147.9	147.9	0.107		2120.25	4000	227.2
St4.5b_CreamHeatingToPasteurize	Cold	147.9	147.9	0.020		2120.25	4000	42.5
IW_PastMilkCoolingToStoTank	Hot	7.0	3.5	7.350	4.205		2000	108.2
CW_PastCreamPreCooling	Hot	30.0	25.0	7.114	4.180		2000	148.7
IW_PastCreamPostCoolingToStoTank	Hot	10.0	3.5	3.422	4.201		2000	93.5

Table 9: Intermediate utility model data of the heat transfer requirements (i.e. excluding part of the heat transfer requirements satisfied by existing HEXs).

Pasteur 3 (milk centrifugation + milk & cream pasteurization) **IUti model**

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
HW_RawMilkHeatingToCentrifuge	Cold	53.0	55.0	9.636	4.182		2000	80.6
HW_SkimMilkHeatingToPasteurize	Cold	68.0	72.0	13.557	4.190		2000	227.2
HW_CreamHeatingToPasteurize	Cold	78.0	85.0	1.446	4.198		2000	42.5
IW_PastMilkCoolingToStoTank	Hot	7.0	3.5	7.350	4.205		2000	108.2
CW_PastCreamPreCooling	Hot	30.0	25.0	7.114	4.180		2000	148.7
IW_PastCreamPostCoolingToStoTank	Hot	10.0	3.5	3.422	4.201		2000	93.5

Drum drying

Drum drying technology is a competitor to spray drying for powder production. Its advantage lies in its enhanced ability to dissolve the product, thanks to the empty spaces left by bubbles during the evaporation process. Milk powder produced by drum drying is appreciated by chocolate manufacturers as an economical substitute for cocoa butter, and because of the caramel taste produced by the Maillard reactions that occur when the product is exposed to “high” temperatures (about 150 °C) during drying.

The simplified flowsheet is depicted in Figure 15. The concentrated product (about 45% TS) is deposited in the middle space between two hollow cylinders rotating in opposite directions. The surface of the cylinder is heated by the steam injected inside (at about 9.5 bar(a)) evaporating the water present in the product layer adhering to the surface. The dry product layer is then detached from the surface by scraping knives. A suction hood extracts hot air laden with moisture from the drying process. The extracted air flow must be compensated by an equivalent dry air flow, filtered/treated in accordance with the manufacturing specifications.

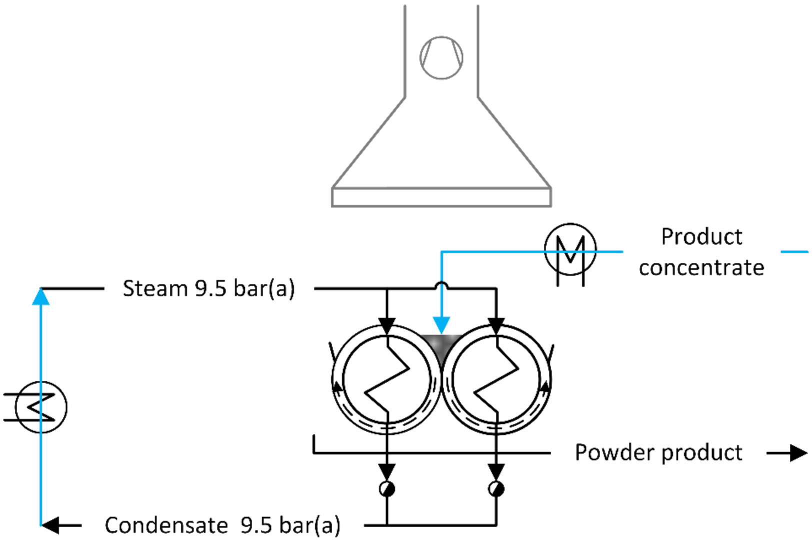


Figure 15: Simplified PFD of the currently implemented drum drying technology (auxiliary air flows are not shown).

In this section, we present three different models for the individual process of drum drying (see Table 1 for definitions). Each model leads to different estimates for exergy losses.[3]

Table 10: Thermodynamic model data of the heat transfer requirements of drum dryer.

Drum Dryer (evaporation to dry and caramelization) **Thm model**								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
FeedHeatingDrying-Seg#1	Cold	50.0	60.0	0.597	3.783		500	22.58
FeedHeatingDrying-Seg#2	Cold	60.0	70.0	0.597	9.803		400	58.52
FeedHeatingDrying-Seg#3	Cold	70.0	80.0	0.597	21.843		300	130.40
FeedHeatingDrying-Seg#4	Cold	80.0	90.0	0.597	39.903		200	238.22
FeedHeatingDrying-Seg#5	Cold	90.0	100.0	0.597	63.983		100	391.98
PowderHeatingToCaramel	Cold	100.0	150.0	0.269	1.600		50	21.52

Table 11: Technology model data of the heat transfer requirements of drum dryer.

Drum Dryer (evaporation to dry and caramelization) **Tec model**								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
St9.5b_FeedHeatingDryingCaramel	Cold	177.7	177.7	0.422		2022.41	4000	853.46

Table 12: Improved technology model data of the heat transfer requirements of drum dryer.

Drum Dryer (evaporation to dry and caramelization) **ITec model**								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
FeedPreHeating	Cold	50.0	80.0	0.597	3.030		500	54.27
St1.5b_PreheatedFeedDrying	Cold	111.4	111.4	0.349		2225.98	4000	776.87
PowderHeatingToCaramel	Cold	100.0	150.0	0.269	1.600		50	21.52

---

[3] Here only the main process heating requirement (in both temperature and heat rate) is considered, not the requirements of the ”side processes” and soft streams (notably hood exhaust humid air).

Cleaning-In-Place (CIP)

Different configurations of CIP facilities can be found centralized (with satellite local units) or decentralized. Heat needed for heating make-up water and temperature holding of acid and alkaline detergents tanks, can be supplied in various ways: heating through an HEX (with steam or hot water), or by steam injected. The latter solution is commonly found in practice.

Figure 16 illustrates the simplified schematic of an alkaline tank of a CIP facility (same schematic as for acid and recycled water tanks). As can be seen, cold make-up water is added directly into the alkaline tank, and temperature holding is achieved by steam injection in a recirculating loop “around” the tank.

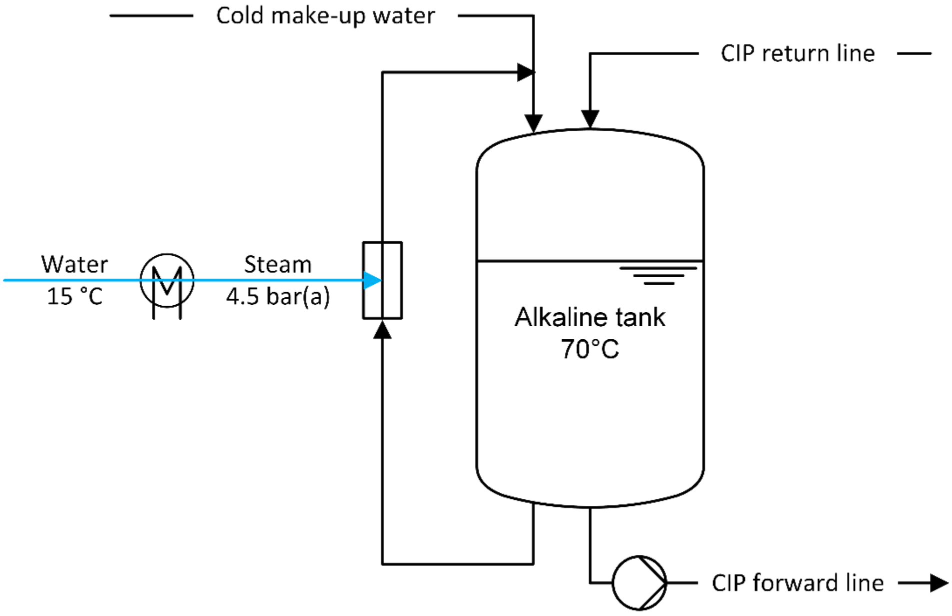


Figure 16: Simplified schematic of alkaline tank of a CIP facility

Process heat transfer requirements can be defined in two ways (or at two levels). The stream data of the two models is summarized in the following tables. Note that the values considered are rough estimates, and that, with the existing technology, injected steam contributes to the total make-up water quantity.

Table 13: Thermodynamic model data of the heat transfer requirements of CIP.

CIP alkaline tank (make-up water heating and temperature holding) **Thm**

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
MakeUpWaterHeating	Cold	15.0	70.0	0.1596	4.200		2000	36.87
AlkaTankTempHolding	Cold	70.0	75.0	4.0033	4.200		2000	84.07

Table 14: Technology model data of the heat transfer requirements of CIP.

CIP alkaline tank (make-up water heating and tank temperature holding) **Tec**

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
InjSt4.5b-MUWHeatingTankHolding-Seg#1	Cold	15.0	147.9	0.0454	4.212		2000	25.41
InjSt4.5b-MUWHeatingTankHolding-Seg#2	Cold	147.9	147.9	0.0454		2120.25	4000	96.26

Concentration by evaporation

Concentration of liquids up to 50-60% TS before drying involves evaporation of water. Energy efficient schemes such as multiple effects and/or mechanical vapor recompression (MVR) are used. The understanding and analysis of the whole concentration facilities (including pasteurization with heat recovery) is beyond the scope of the project. However, due to customer limitations and quality constraints in the DeCarb-PUI perspective, we made the decision to focus on the high concentrator involving thermal vapor recompression (TVR) to highlight the possible benefits of changing to MVR (open cycle heat pump). Although, in principle, the whole system should be considered and not parts of it in isolation, the consideration of the high concentrator in isolation should allow us to derive some interesting conclusions.

Figure 17 illustrates the simplified schematic of the high concentrator, with the existing TVR scheme. Process heat transfer requirements can be defined in several ways depending on the position of the boundary between what can be modified and what must be considered imposed and non-modifiable.

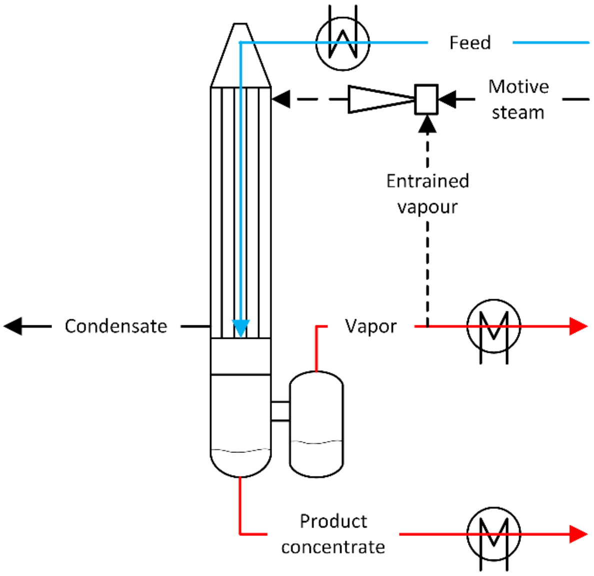


Figure 17: Simplified schematic of high-concentrator using TVR.

The stream data of the three models are summarized in

Table 15, Table 16, and Table 17 respectively.

Table 15: Thermodynamic model data of the heat transfer requirements of high-concentrator.

HighConcentrator (from Evaporator facility Nr2) **Thm model**								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
FeedHeatingToEvaporationTemp	Cold	20.0	62.0	1.325	3.400		1000	189.2
WaterEvaporation	Cold	62.0	62.0	0.261		2364.98	1000	617.5
ConcentrateCooling	Hot	62.0	20.0	1.064	3.100		1000	138.5
VapourDesuperheating	Hot	62.0	57.0	0.261	1.952		1000	2.6
VapourCondensation	Hot	57.0	57.0	0.261		2364.98	1000	617.5
VapourSubcooling	Hot	57.0	20.0	0.261	4.181		1000	40.4

Table 16: Technology model data of the heat transfer requirements of high-concentrator.

HighConcentrator (from Evaporator facility Nr2) **Tec model**								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
SteamCondensateHeating	Cold	80.0	89.7	0.329	4.201		1000	13.4
SteamCondensateEvaporate	Cold	89.7	89.7	0.329		2283.35	1000	752.0
ConcentrateCooling	Hot	62.0	20.0	1.064	3.100		1000	138.5
VapourDesuperheating	Hot	62.0	57.0	0.261	1.952		1000	2.6
VapourCondensation	Hot	57.0	57.0	0.261		2364.98	1000	617.5
VapourSubcooling	Hot	57.0	20.0	0.261	4.181		1000	40.4

Table 17: Utility model data of the heat transfer requirements of high-concentrator.

HighConcentrator (from Evaporator facility Nr2) **Uti model**								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
SteamCondensateHeatingForTVR	Cold	80.0	141.8	0.254	4.233		1000	66.3
SteamCondensateEvaporateForTVR	Cold	141.8	141.8	0.254		2138.97	1000	542.3
RemainingSteamCondensateCooling	Hot	80.0	20.0	0.076	4.184		1000	19.0
ConcentrateCooling	Hot	62.0	20.0	1.064	3.100		1000	138.5
RemainingVapourDesuperheating	Hot	62.0	57.0	0.185	1.952		1000	1.8
RemainingVapourCondensation	Hot	57.0	57.0	0.185		2364.98	1000	438.3
RemainingVapourSubcooling	Hot	57.0	20.0	0.185	4.181		1000	28.7

3.2.3. Exergy loss hotspots and optimum utility supply temperatures

Based on the methodology presented in Section 2.2, heat transfer exergy losses are estimated for all selected processes (Table 4) based on the current utility design. The “Thm” models for all the processes are used to estimate the exergy required for the process, whereas the exergy delivered to the process is estimated based on the “Uti” models. The overall exergy losses due to heat transfer are estimated using the difference in “Thm” and “Uti” models. Figure 18 presents an example of exergy GCC and estimated exergy losses for selected processes from Emmi (see Table 18).

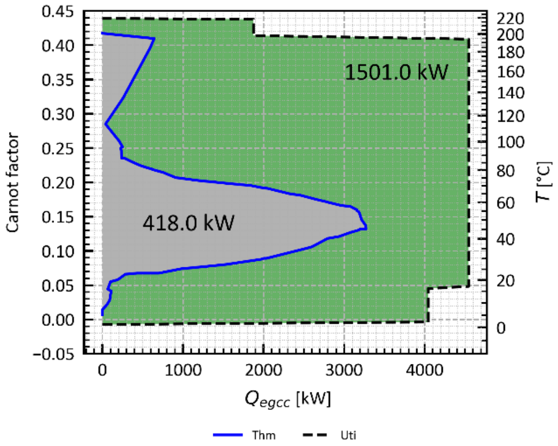
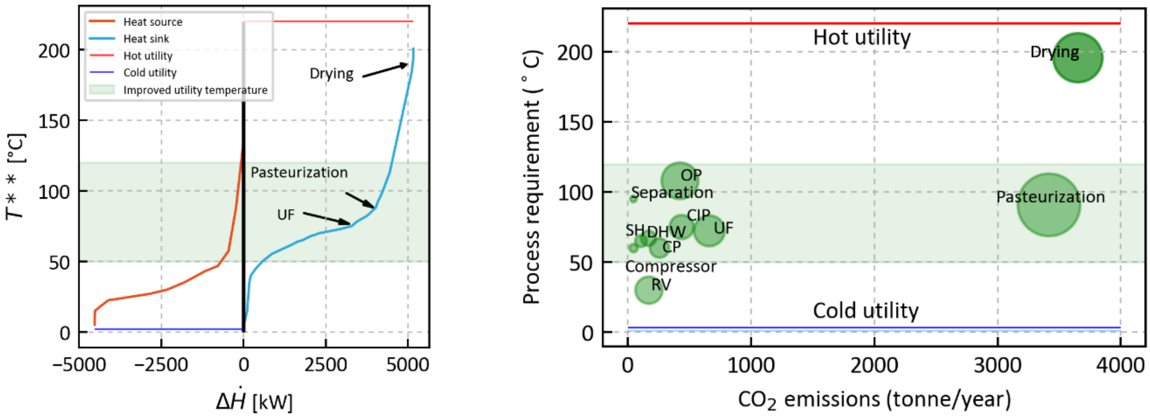


Figure 18: Exergy GCC for dairy processes and utility for a winter day.

This figure represents an EGCC that compares the exergy requirements of the process (blue curve labeled "Thm") and the utility supply (dashed black curve labeled "Uti"). The areas enclosed between these curves and the y-axis provide insight into the exergy flows and losses in the system. With the assumption of a winter day, the ambient temperature of the exergy is assumed to be 3 °C.

The blue curve Thm, (Process Exergy Requirement) represents the exergy required by the process to meet its heating and cooling demands. The area under this curve (421 kW) corresponds to the total exergy demand of the process. The dashed black curve Uti, (Utility Exergy Supply) represents the exergy supplied by the utilities (both hot and cold utilities) to fulfill the process requirements. The exergy for both, hot and cold utilities are estimated with reference to ambient temperature. The area under this curve (1’512 kW) corresponds to the total exergy input from the utilities. The exergy loss, shaded green, represents the exergy losses in the system due to irreversibility in heat transfer between the utilities and the process.

The exergy analysis reveals inefficiencies in the system, with approx. 72% of the utility exergy input being lost due to irreversibility. This exergy loss, totaling 1’091 kW, underscores a mismatch between utility temperature levels and process requirements, as evidenced by the gap between the "Uti" and "Thm" curves. This mismatch causes thermodynamic inefficiencies, particularly during heat exchange, and suggests a need for better heat integration strategies. Reducing the temperature difference between utilities and the process, potentially through the use of intermediate loops (ILs) or advanced heat exchangers, could substantially decrease these losses. Moreover, integrating energy conversion technologies, such as HPs, could better align utility temperatures with process needs, further minimizing exergy destruction. From an energy efficiency perspective, this system meets its energy demands with high improvement potentials in thermodynamic terms, emphasizing the value of exergy-based analysis for pinpointing quality-related inefficiencies. The exergy analysis is then conducted for all the processes (see Figure 19 (b)). The heating requirement for most of the 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 exergy losses across the entire plant has drying, pasteurization, and ultrafiltration contributing the largest share towards overall exergy losses as well as CO_2 emissions.



(a) (b)

Figure 19: (a) Source-sink profile[4] for the dairy process on a typical winter day, with global ΔT_{min} of 10 K (b) Exergy analysis for all processes (size of bubbles represent process-level exergy losses due to supplying heat at current utility temperatures).

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 (**Erreur ! Source du renvoi introuvable.**) shows a significant difference between the temperature of hot utility and real process requirements for many processes. The exergy analysis of all processes reveals that about 75% of heating requirements are between 50 °C and 100 °C. Thus,

---

[4] The y-axis on the source-sink profile is T** which shifts the streams by ΔT_{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.

reducing the current utility supply temperature can potentially result in a reduction of steam demand (if energy conversion technologies are used) and the corresponding CO_2 emissions.

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 19(b)) and CO_2 emissions are selected for further analysis in this work and presented in **Erreur ! Source du renvoi introuvable.**. The exergy losses include the exergy required by the process and exergy losses due to the high temperature supply of hot utility Process optimization and the identification of opportunities for local networks can improve the heat supply to the selected processes.

Table 18: Exergy losses and CO_2 emissions for selected processes.

Process	**Exergy losses (kW)**	**CO_2 emissions (t/a)**	**Operating hours (hr/a)**
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 tons of CO_2 emissions per annum (86% of total annual CO_2 emissions from the plant). The exergy losses can be reduced by supplying heat closer to the process requirements, thus leading to a reduction in CO_2 emissions, if the energy conversion technologies use CO_2-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.

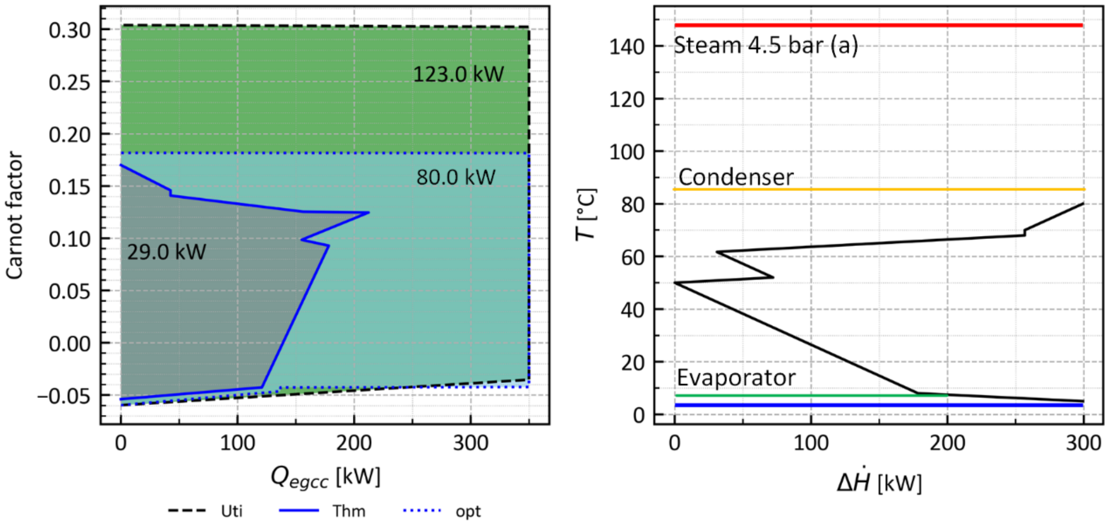
3.2.4. Identification of integration options

Following the identification of exergy loss hotspots and improved utility temperatures, 4 variants of different HP integration concepts for localized, clusters, and total site improvements (heat networks at intermediate temperatures) are evaluated. Since the PUI improvement, in this case, is analyzed after the implementation of PA-related improvements, only the residual heating and cooling requirements are considered for the analysis of PUI improvement.

Each variant represents a different system boundary. The localized HP integration concept 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.

Variant 1: 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 (Figure 20 (b)), potentially resulting in 1’853 MWh/a of natural gas savings and a 440 ton/a reduction in the CO_2 emissions compared to the current utility supply system. Identified heat sinks and sources for the fully localized HP integration concept are presented in Figure 21.



(a) (b)

Figure 20: Variant 1 (a) EGCC with potential exergy reduction and (b) GCC for fully localized HP integration for milk and cream pasteurizer.

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 only focuses on HP integration.

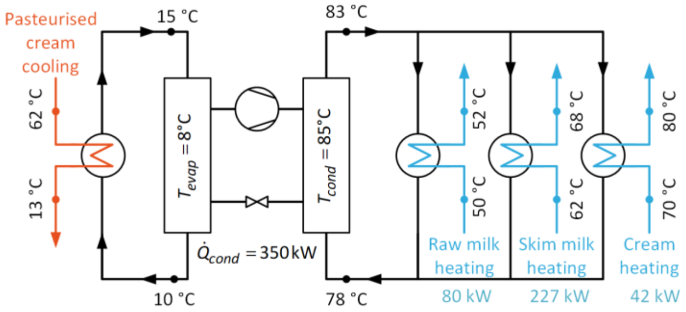
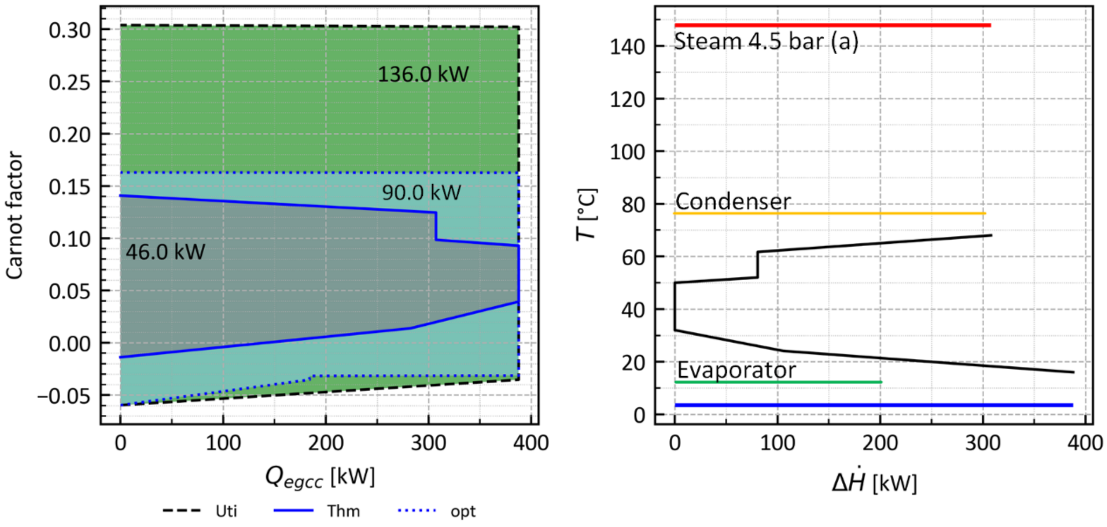


Figure 21: Variant 1 - Sources and sinks for fully localized heat pump configuration.

Variant 2: Heat pump solution for small-sized cluster



(a) (b)

Figure 22 : Variant 2 - (a) EGCC with potential exergy reduction and (b) GCC for heat pump integration in small-sized cluster for milk and cream pasteurizer and warm water.

The second variant for the pasteurizer is evaluated for lower heat sink temperatures and higher source temperatures (Figure 22) that are not local (lukewarm water). This configuration results in a slightly smaller heat pump with lower potentials (390 t-CO_2/year for CO_2 abatement and 1'589 MWh/a of natural gas savings) but better COP (3.4) than a fully localized solution.

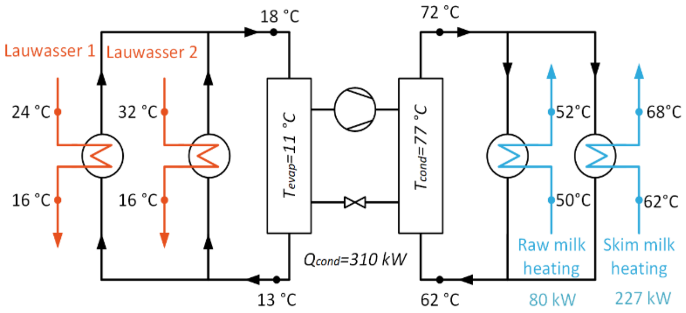


Figure 23: Variant 2 - Sources and sinks for small-sized cluster heat pump configuration.

Variant 3: 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 (Figure 24).

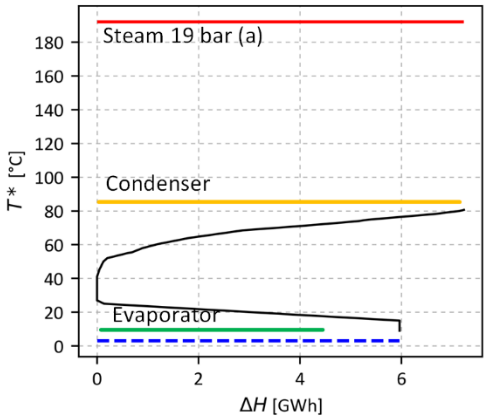


Figure 24: GCC with potential supply temperature reduction.

This HP configuration covers the heating demand processes such as pasteurizers, CIP, ultrafiltration, and non-process related requirements, leading to a potential reduction of 6’541 MWh/year in natural gas and 1.5 kt in CO_2 emissions compared to the current utility supply system. Heat sinks and sources identified for the clustered HP integration concept are presented in the following schematic (Figure 25).

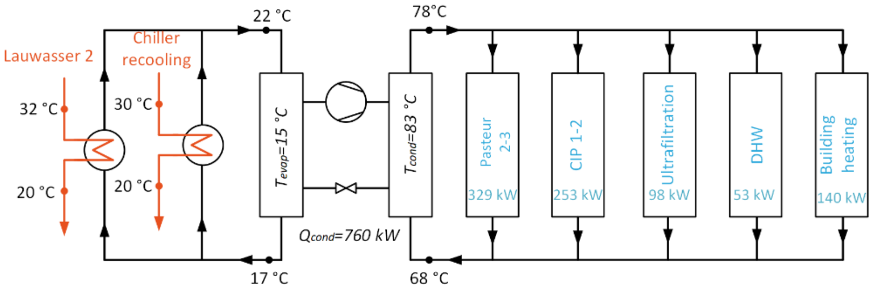


Figure 25: Variant 3 - (a) GCC with potential supply temperature reduction and (b) Sinks and sources for medium-sized cluster heat pump configuration.

However, in both cases of HP integration, as a result of excess heat availability at a low temperature, the integration results in COP values of about 2.5 and 2.9, leading to relatively higher electricity demand and lower cost-effectiveness (see Table 20).

Variant 4: Heat pump solution for total site solution

All processes identified in Table 18 along with non-process related heating demands are included for the evaluation of total site options for PUI improvement. A HP with a capacity of 1’000 kW is identified for this variant Figure 26.

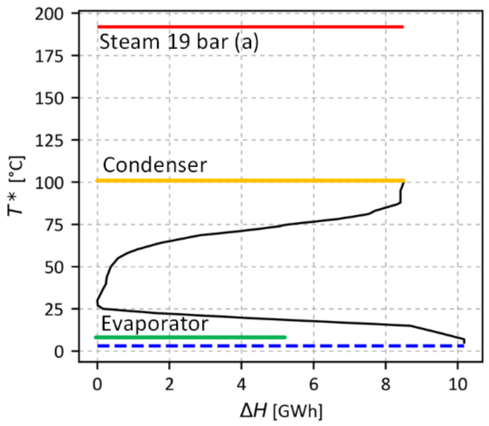


Figure 26: Variant 4 - GCC with potential temperature reduction.

However, it should be noted that some processes are eliminated due to spatial and scheduling constraints (according to criteria presented in step 3). The HP configuration (Figure 27) for the total site results in 8’550 MWh of annual reduction in natural gas consumption and 2.03 kt-CO_2 emissions reduction.

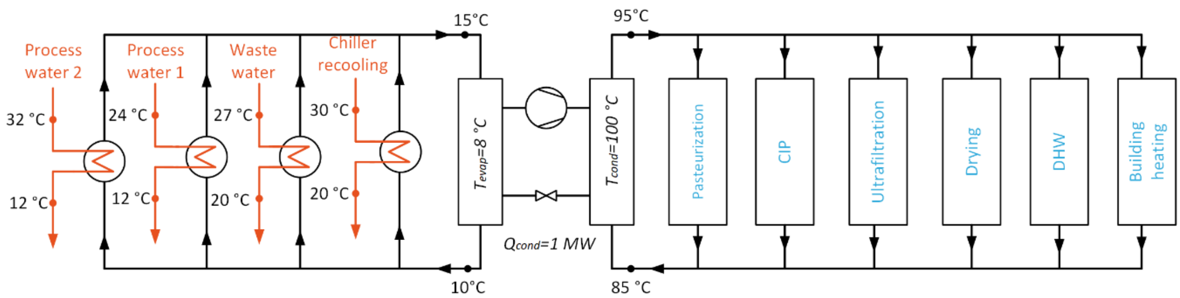


Figure 27: Variant 4 - Sinks and sources for total site heat pump configuration.

It should be noted that for a total site HP, supplying heat to multiple processes would inevitably require thermal energy storage. However, due to the lack of detailed scheduling information, the storage integration is not included in the scope of the current report.

3.2.5. Economic analysis

The results of the economic analysis of all evaluated options are summarized in

Table 20, based on the economic parameter shown in Table 19. All the identified variants are evaluated economically based on the economic criteria explained in section 2.5.

Table 19: Parameter of the techno-economic analysis, extracted from the PA conducted.

Parameter	**Value**	**Unit**
Hot utility price, steam (two boilers: 18 bar(g) and 13 bar(g)), local heat recovery loops	c	CHF/MWh
Cold utility price (cooling water)	c	CHF/MWh
Electricity prices	c	CHF/MWh
Natural gas emission factor	0.202	kg CO_2/kWh$_{HU}$

Table 20: Results of the economic analysis of process-utility interface improvement.

Integration option	Natural gas reduction (MWh/a)	CO_2 emissions reduction (t-CO_2/a)	COP	CAPEX (CHF)	Annual savings (CHF/year)	LCCO2 (CHF/t_{CO2})
Variant 1	1’835	440	2.5	826’000	4’970	292
Variant 2	1’589	390	3.4	774’000	13’976	266
Variant 3	6’541	1’500	2.9	1’140’000	52’179	86
Variant 4	8’550	2’000	2.2	1’200’000	12’899	122

According to

Table 20, the best option for the case study is Variant 3 due to the high potential for emissions reduction and, in addition, the lowest $LCCO_2$. 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 is a useful initial metric for screening in determining the operating cost-effectiveness of HPs compared to conventional natural gas sources. A favorable 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 CO_2-free sources is expensive.

In the mid-to-long-term, as CO_2-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 heat pumps. This anticipated shift helps to contextualize the economic viability of HP systems within a future where CO_2-free fuels and electricity are prioritized. Figure 28 shows the spark-spread of the different variants of the case study.

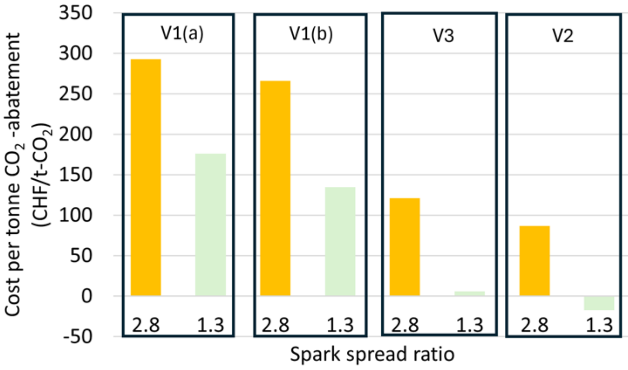


Figure 28: Spark spread ratio of case study.

For instance, targeting electricity and natural gas prices at 0.121 CHF/kWh and 0.044 CHF/kWh, respectively, creates a more favorable economic condition for HP operations. This price structure helps make HPs a more viable and cost-effective alternative to conventional heating methods, particularly when CO_2-free electricity sources are available. However, it should be noted that the Spark spread ratio as a standalone criterion does not provide a comprehensive economic analysis for decision-makers. It should rather be used to complement other criteria, such as electricity price to evaluate the OPEX of HP integration solution. For example, HP integration can be considered cost-effective if the electricity price is lower than the product of effective COP and fuel price (i.e., $P_{electricity} < (COP_{eff} \times P_{useful\ heat})$). Here, COP_{eff} accounts for both the heat pump's COP and additional electrical consumption for auxiliary systems such as pumps for heat transfer and distribution. Furthermore, potential savings in electricity usage through reduced demand for cold utilities (e.g., chillers and cooling towers) should be considered. The comparison must also reflect the current overall heat conversion efficiency of conventional systems, including boiler efficiency and heat distribution losses, to provide a holistic evaluation of cost competitiveness. While the spark spread provides a quick snapshot of the relativity, it does not incorporate the broader system-specific considerations essential for assessing HP performance and economics.

In the context of the Emmi, improvements to the PUI enhance and extend the benefits achieved through PA. PA typically identifies HR potentials and optimal temperatures for utility supplies, and PUI improvements add an additional dimension by redesigning utility systems to reduce exergy losses and align heat provision more closely with process requirements. As shown in Figure 29, the measures (M) resulting from the PA (extracted from the final report of the PA) are typically more cost-effective but have a limited impact on overall CO_2 abatement. The solutions resulting from PUI analysis, on the other hand, have a higher cost of CO_2 abatement but also have a higher decarbonization potential. However, larger clusters have relatively lower costs of CO_2 abatement than localized or small cluster HP configurations.

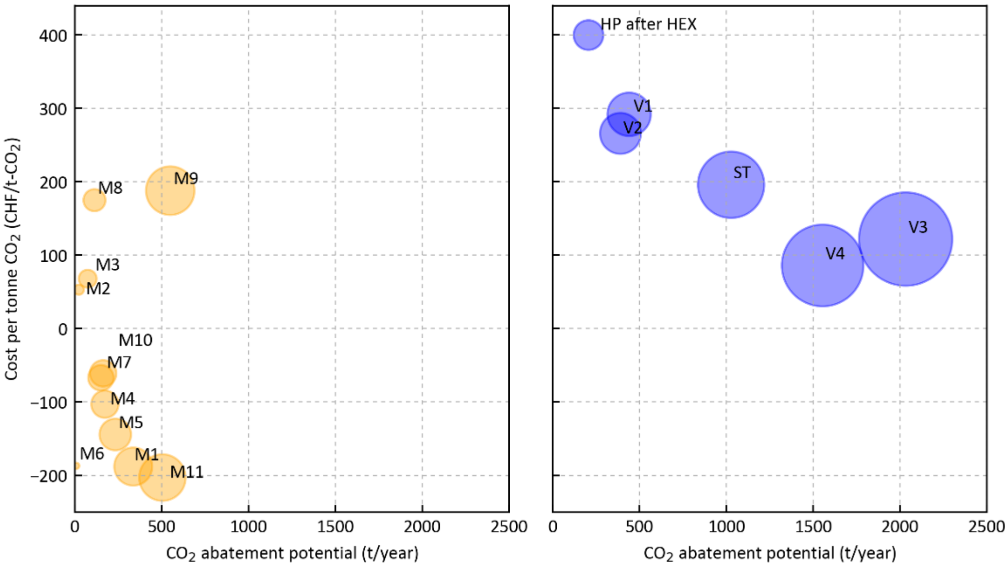


Figure 29. Economic analysis of Pinch analysis and PUI solutions, the size of the bubble reflects the natural gas reduction potential. The data is based on Table 19. M: Measure; V: Variant; ST: Solar Thermal[5].

By integrating PUI improvements alongside fuel-switching measures, a more comprehensive decarbonization pathway emerges. Figure 30 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.

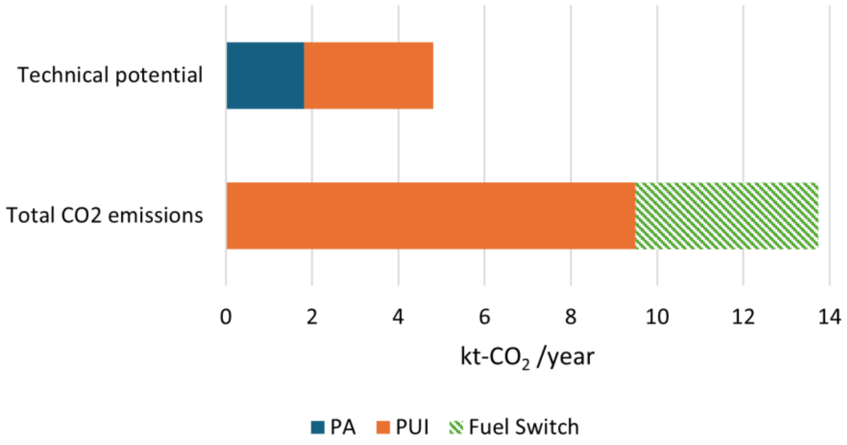


Figure 30: Contribution of PA and DeCarb-PUI to decarbonization.

The processes considered in DeCarb-PUI cover approximately 70% of the total final energy requirement of the process. In DeCarb-PUI, together with the PA, the PA and PUI cover 19% and 31%, respectively. Instead of replacing all the heat requirements by the process through fuel switching, the capacity of the fuel switching is now reduced by approximately 50%.

3.2.6. Conclusions and outlook

This project outlined a high number of solutions to improve the energy efficiency and sustainability of Emmi Dagmersellen. Based on the exergy analysis, it shows that the highest potential for reduction in

---

[5] Although Solar thermal integration is included in Figure 29, this solution was not analysed in detail based on the suggestion from the industrial partner.

exergy losses is in pasteurization, CIP, and ultrafiltration processes. Waste heat recovery and utility redesigns, such as intermediate loops, were shown to align energy supply more closely with process needs, minimizing exergy losses. Economic feasibility is highly sensitive to the "spark spread" (electricity-to-gas price ratio). With current costs of CHF 200/MWh for electricity and CHF 60–80/MWh for gas, achieving cost-effective operation is challenging without price adjustments. The facility's 24/7 production schedule imposes constraints on heat pump implementation, as downtime for integration could disrupt operations. Maximizing availability is critical for ensuring product consistency and quality.

Emmi is evaluating long-term decisions, such as a potential 20-year contract with the planned energy ecosystem project based on wood biomass. This implementation would significantly impact the energy supply cost, making steam 40–50% more expensive but more sustainable. However, clear economic and technical analyses are necessary to support these decisions. Although upfront investment costs are less of a concern, operational costs are critical. Projects with realistic CO_2 abatement costs under CHF 200 per ton of CO_2 per year can be of interest to Emmi.

Therefore, Emmi Dagmersellen requires the development of more accurate cost estimates and technical evaluations for proposed HP clustered concepts that are presented in DeCarb-PUI to support their decision-making for 2025 implementation. This will enable Emmi to make informed decisions about system upgrades and energy partnerships. The work includes development of comprehensive and site-wide concept for HP integration using ILs, which includes assessing technical and economic feasibility, particularly regarding installation, piping, and natural refrigerant options. At the time of this report, concept(s) are being developed based on practical considerations communicated by the cooperation partner plus an update of the process requirements information including any process design changes for 2024. This request from the cooperation partner is based on the review of the research work results shown above in the Techno-economic Analysis in order to extend the results to an up-to-date and practical implementation (re. plausible heating and cooling requirements, schedule, and costs) of IL cluster(s) using a HP. The statement “sustainability has a cost” has been made, yet the goal is to try and answer by how much? This part of the work will not be reported in this final report but will be submitted as an Annex when the work is completed.

4 UFA Biowerk Herzogenbuchsee Case Study

A preliminary Pinch Analysis has been completed for UFA Biowerk Hofmatt at Herzogenbuchsee site in May 2023 (Krummenacher et al., 2023). This facility produces animal feed in meal (flour), pellets and flakes. The production processes involving thermal energy include mainly thermal treatment (by injection of low-pressure steam), pelletizing and pellets cooling. Other less specific side processes include temperature holding of tanks, air heating to preheat the facilities before start-up and to dry them after production. Although less common than dairy processes and more difficult because of the feed material to be processed in bulk form, the involved processes may feature scope for process modification to decrease the required exergy and improve the decarbonization. Such facilities (engineered and manufactured by Bühler) are found in Switzerland and worldwide.

4.1 Case Study Description

4.1.1. General overview

UFA, a Fenaco Group company, produces animal feed at seven production sites throughout Switzerland. The Herzogenbuchsee site includes two plants (see Figure 31): the Biblis plant (Bibliswerk) for conventional feed and the Hofmatt plant (Biowerk) for organic feed. Both plants include similar processes and hence feature similar heat integration issues. However, UFA would like to first focus on the Biowerk as a pilot to become familiar with the methodology and test the proposed solutions before extending the approach to other plants. Animal feed is produced in three forms: meal, pellets, and flakes.

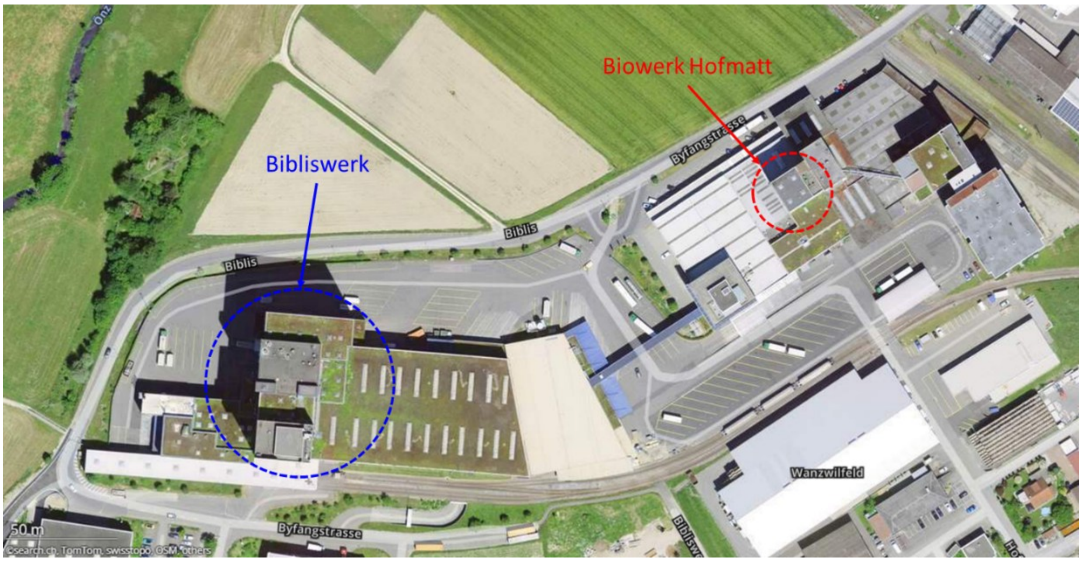


Figure 31: Overhead view of the UFA production site in Herzogenbuchsee (source: map.search.ch).

Planned for the near future is an oil pressing plant that will be built on the other side of the Byfangstrasse (engineered by Bühler AG as well). In addition, a grain collection center including three grain dryers is also in planning stage. The heat transfer requirements of these two plants must also be considered in the heat integration opportunities of the UFA Biowerk. Figure 32 represents the foreseen plant layout.

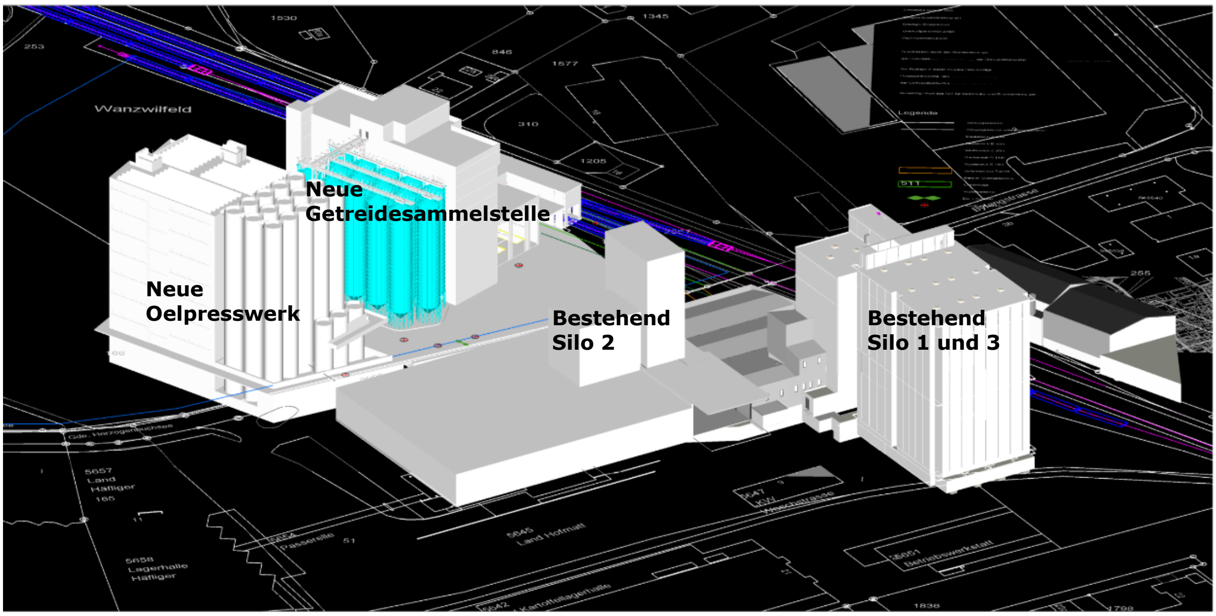


Figure 32: Foreseen plant layout with the new oil pressing plant (Oelpresswerk) and the new grain collection center (Getreidesammelstelle) next to the exiting Biowerk plant.

The existing Biowerk production plant is energy intensive, requiring either steam or hot water for providing the required external heating as well as for achieving the necessary hygiene and quality of the product. As shown in Figure 33 a major portion of the heat (71.9%) is steam injected into the product for thermal conditioning and the process heat is from the hot water network.

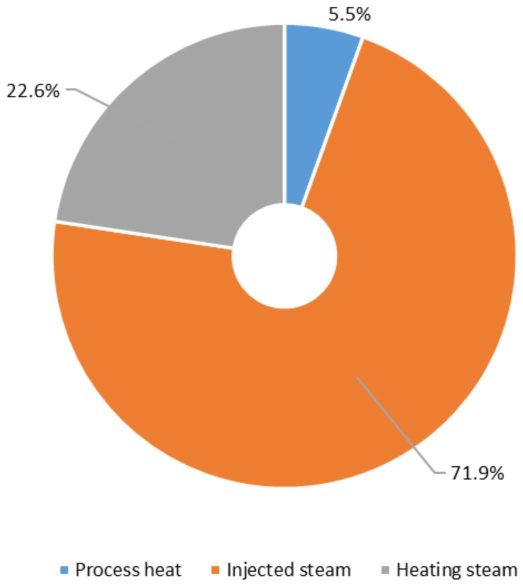


Figure 33: Heat balance of the Biowerk Hofmatt production plant using steam or hot water.

4.1.2. Overview of processes and constraints

The Biowerk plant includes four production lines (L1 to L4), each consisting of the following steps: 1) feed materials feeding/dosing; 2) mixing and thermal conditioning by steam injection (mixer and “residence” delay); 3) pelletizing; 4) drying/cooling; 5) packaging. These steps are described below (with particular focus on those involving heat transfer). The corresponding facilities have been manufactured by Bühler AG, who is actively seeking new solutions to increase the energy efficiency and decarbonize the thermal conditioning step by means of a HTHP.

4.1.3. Hot and Cold Utilities

Process heating and cooling requirements not covered by internal heat recovery are ensured by the following thermal utilities:

- Hot utilities:
  - Steam (9 bar(g)) (produced at the Biblis plant)
  - Hot Water (60/40 °C) (produced at the Biblis plant, partially recovering heat from air compressors)
- Cold utilities:
  - Ambient air
  - Cooling tower water (32/27 °C) (New oil pressing plant)

4.2 Case Study Results

The results of this case study are also obtained based on the same assumptions enlisted in the section 3.2.

4.2.1. Characterization of process requirements and heat recovery potential

The UFA Biowerk Hofmatt in Herzogenbuchsee serves as a pivotal site for grain and oilseed processing, housing a compound feed production facility. By 2025, UFA AG aims to expand the site to include a modern grain collection point and an oil press facility. A PGA was conducted at the site to optimize heat integration, reduce exergy losses, and identify cost-effective energy solutions to support these expansions. The primary objectives included assessing the current energy use, identifying efficiency improvement potentials, and proposing actionable strategies for decarbonization.

UFA operates multiple production lines supported by a steam system. Direct steam (i.e. injected steam) is used in production lines 1 to 4 and the flaking line. Indirect steam supplies hot air fans for heating/drying the productions lines, air heaters (bagging facility, flaking facility, ...), whereas a hot water loop supplies temperature holding molasses, soybean oil, and sunflower oil tanks, as well as building’s HVAC systems. The facility consumed approximately 2’851 tons of steam in 2021, with 77% used for direct steam. Electricity and hot water networks further supplement energy needs. Line 4, the most modern and energy-intensive production line, accounted for over half the total production and was selected as the focus of the analysis.

The PGA provided insights into the HR potential and inefficiencies in the current system. There is a limited waste HR options in Line 4 due to the technical limit of the process (Figure 34). The bulk material mixture (flour) could possibly be pre-heated by means of heat recovery (e.g., from the exhaust air) up to 30 to 40 °C. Any higher than that range causes extra difficulty for further processing. Therefore, steam is often supplied at higher pressures than required by processes, leading to exergy losses. In addition to that, the hot exhaust air from coolers/dryers remains underutilized and the absence of HR mechanisms in auxiliary systems (e.g., hot air fans) exacerbates energy wastage. Although the PGA provided several measures, the analysis identified several technical and operational barriers:

- steam injected in the conditioner must be slightly superheated;
- the power consumption of the pellet press is very sensitive to the humidity of the feed mixture (resulting into a trade-off between thermal and electricity consumption);
- the cooler uses the evaporative cooling effect to speed up / enhance cooling, which requires a certain level of humidity to be effective;
- production lines operate in batches of typically 2 hours, separated by product changeover periods of approx. 15 minutes, therefore heat storage would be required to prevent too many start/stop cycles in case of an HP integration;
- Significant capital expenditure required for the HTHP and infrastructure upgrades, with limited space for HR and intermediate loops.

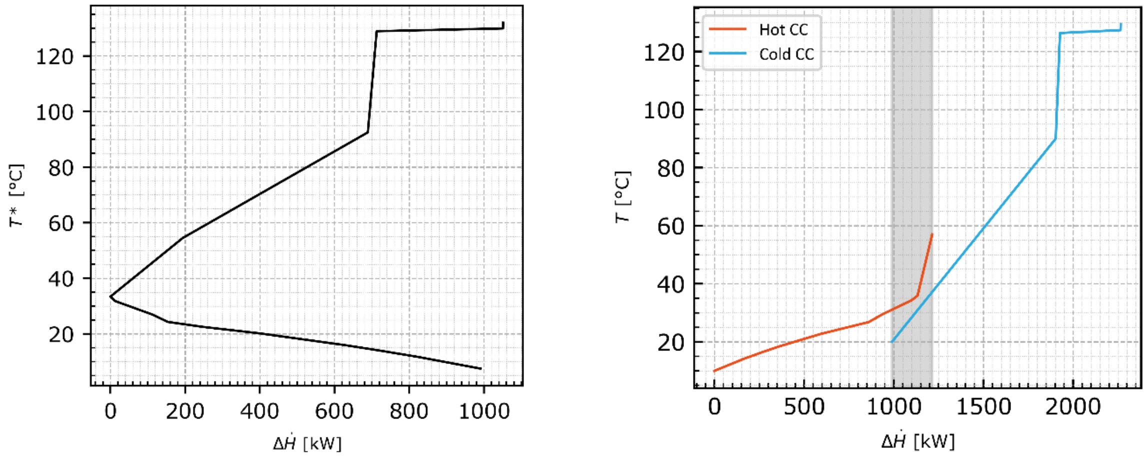


Figure 34: (a) GCC and (b) CCs for line 4 and grain dryers at UFA.

4.2.2. Additional process data modeling approaches

In the PGA, only the production Line 4 and the new three dryers of future grain collection and oil pressing plants were considered. Since the current studies are based on the data collected during the PGA, the same processes are considered in this study. The following section tabulates the additional process models considered for the chosen processes. The "Thm" model helps to identify the exergy requirements for the process, whereas the "Tec" and "Uti" models help estimate the exergy supplied by the current system. The difference between the two models provides an estimate for exergy losses caused by the heat transfer at the Process-utility interface.

Biowerk Meal (Flour) and Pellets Production Plant

Figure 35 shows the simplified process schema of Line 4 for the most common product (meal for pigs). The key process requirement and the most significant heating demand in the entire plant is the steam directly injected into the product mixing equipment. This steam is important not only to provide heat to the feed material but also to sanitize the resulting product to ensure proper hygiene standards and other product quality requirements are achieved. According to test work done internally, the steam is preferred to be at 1.2 – 1.8 bar(g) with several degrees of superheating to ensure the best quality. Fresh ambient air is used to cool product before being packaged or placed in silos.

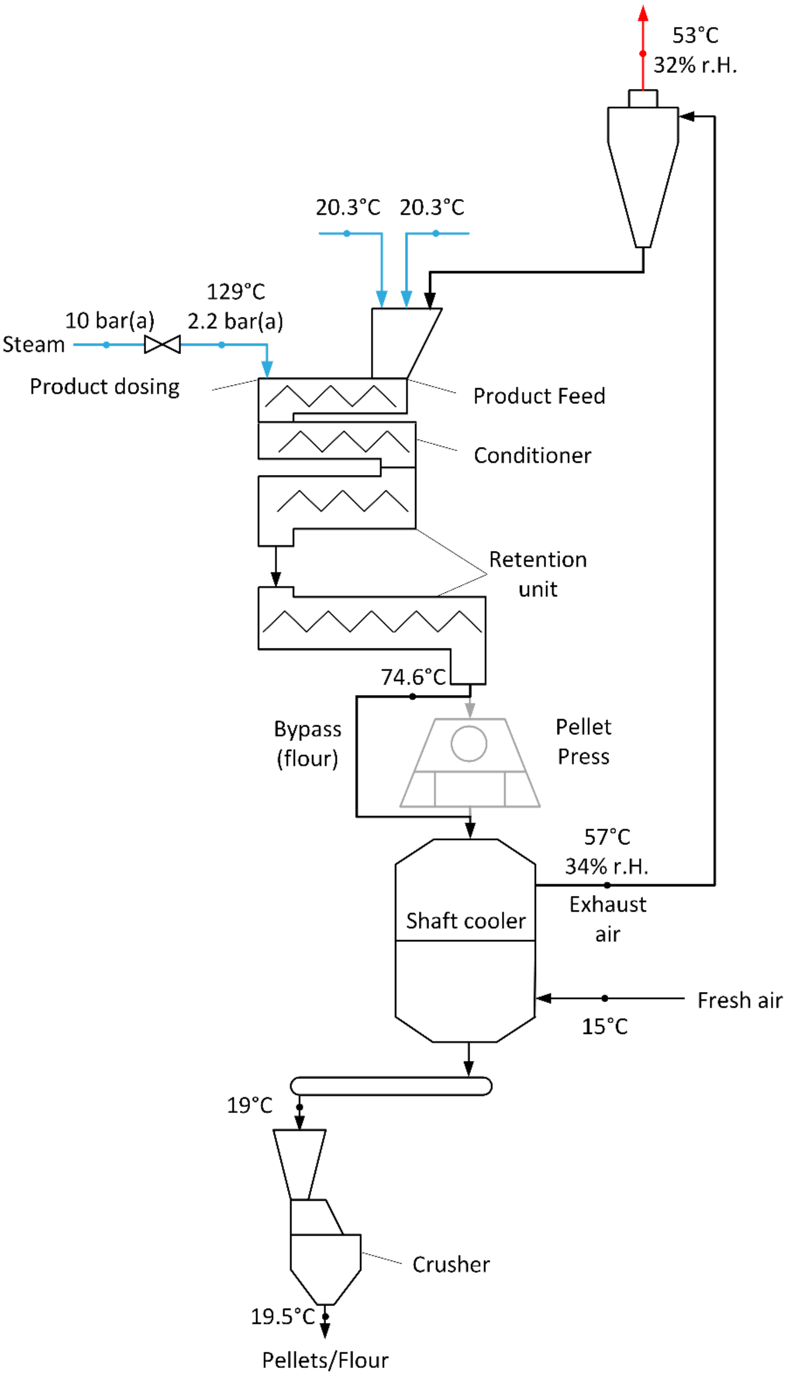


Figure 35: Biowerk plant production line 4 schema for meal or pellets.

Based on the simplified flowsheet showing the heating and cooling demands for the existing line 4 production process, the process requirements have been extracted using different models as shown in Table 21,

Table 22 and

Table 23. It is assumed that the heating and cooling demands for line 1, 2, and 3 are similar as they differ in configuration only in lacking the additional residence delay equipment ("Verweiler") that is in Line 4.

Table 21: Present technology model of the data for the heat transfer requirements in Biowerk Line 4 [6].

Biowerk Plant Line 4 Tec model

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
InjSt2.5b_RawMatHeatingHumidifying-Seg#1	Cold	20.0	127.4	0.155	4.20	-	2000	69.9
InjSt2.5b_RawMatHeatingHumidifying-Seg#2	Cold	127.4	127.4	0.155	-	2181	4000	338.1
InjSt2.5b_RawMatHeatingHumidifying-Seg#3	Cold	127.4	129.4	0.155	2.214	-	100	0.7
CA_ProductCoolingDrying-Seg#1	Hot	57.0	35.9	3.588	1.077	-	50	81.5
CA_ProductCoolingDrying-Seg#2	Hot	35.9	29.4	3.588	5.820	-	100	135.3
CA_ProductCoolingDrying-Seg#3	Hot	29.4	23.0	3.588	4.378	-	100	101.8
CA_ProductCoolingDrying-Seg#4	Hot	23.0	16.5	3.588	3.348	-	100	77.7
CA_ProductCoolingDrying-Seg#5	Hot	16.5	10.0	3.588	2.612	-	100	60.7

Table 22: Improved technology model of the data for the heat transfer requirements in Biowerk Line 4.

Biowerk Plant Line 4 ITec model

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
HydratedRawMatPreHeating	Cold	20.3	40.0	2.724	2.755	-	100	147.8
InjSt2.5b_RawMatPostHeatingHumidif-Seg#1	Cold	20.0	127.4	0.098	4.200	-	2000	44.4
InjSt2.5b_RawMatPostHeatingHumidif-Seg#2	Cold	127.4	127.4	0.098	-	2181	4000	214.8
InjSt2.5b_RawMatPostHeatingHumidif-Seg#3	Cold	127.4	129.4	0.098	2.214	-	100	0.4
CA_ProductCoolingDrying-Seg#1	Hot	57.0	35.9	3.588	1.077	-	50	81.5
CA_ProductCoolingDrying-Seg#2	Hot	35.9	29.4	3.588	5.820	-	100	135.3
CA_ProductCoolingDrying-Seg#3	Hot	29.4	23.0	3.588	4.378	-	100	101.8
CA_ProductCoolingDrying-Seg#4	Hot	23.0	16.5	3.588	3.348	-	100	77.7
CA_ProductCoolingDrying-Seg#5	Hot	16.5	10.0	3.588	2.612	-	100	60.7

Table 23: Thermodynamic, white box model data of the heat transfer requirements in Biowerk Line 4 [7].

Biowerk Plant Line 4 Thm

Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
HydratedRawMaterialHeating	Cold	20.3	74.6	2.724	2.755	-	100	407.5
CA_ProductCoolingDrying-Seg#1	Hot	57.0	35.9	3.588	1.077	-	50	81.5
CA_ProductCoolingDrying-Seg#2	Hot	35.9	29.4	3.588	5.820	-	100	135.3
CA_ProductCoolingDrying-Seg#3	Hot	29.4	23.0	3.588	4.378	-	100	101.8
CA_ProductCoolingDrying-Seg#4	Hot	23.0	16.5	3.588	3.348	-	100	77.7
CA_ProductCoolingDrying-Seg#5	Hot	16.5	10.0	3.588	2.612	-	100	60.7

---

[6] The mass flowrates on Figure 35 REF _Ref184626472 \h Figure 35: Biowerk plant production line 4 schema for meal or pellets.correspond to the actual values in operation. A typical daily operation includes 12 h operation and about 4x 15 min inter-batches idling periods. Therefore, a time average model of the process requirements has been considered when setting up REF _Ref150464568 \h Table 21
Table 22
Table 23, where the mass flowrates are 12/13 of the actual flowrates shown on Figure 35

[7] In this case, the process requirements for cooling and drying the product are still defined at the level of cooling air (as in the Tec and ITec models) and not actually at the level of the product itself. Defining the thermodynamic requirements where heat and mass transfer take place is still subject to discussion (an ITec model by enhanced heat transfer with meal) could hardly be proposed, as evaporative cooling must also be guaranteed. As regards the raw material heating, it is assumed that cold water is mixed before the so hydrated raw materials are heated.

Grain Drying Plant (New)

The new grain drying plant is to have three separate air dryers, two of which will be for grains targeting to produce conventional grains and the third for grains targeted for bio products production. The basic design and the key operation parameters for conventional production are shown in Figure 36, which is optimized by the manufacturer. Given the special and therefore closed design of the dryer, only two technical process requirements have been modelled. The dried wheat product has not been considered a process requirement as it is a solid.

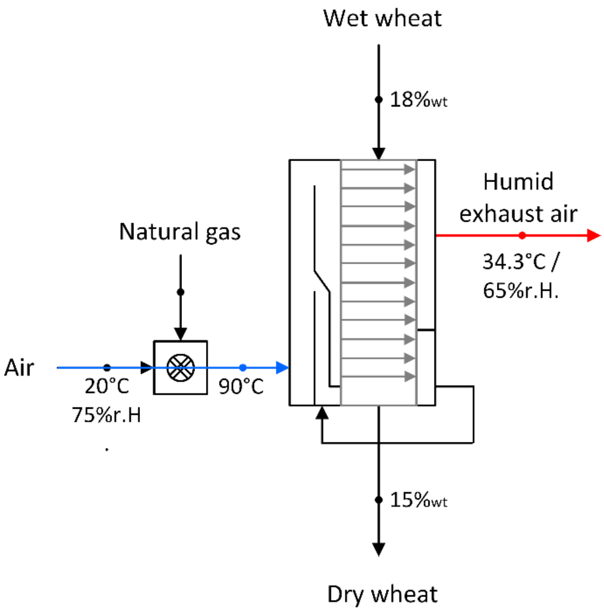


Figure 36: New grain dryer schema showing available technical heating and cooling process requirements.

Based on the simplified flowsheet showing the heating and cooling demands for the designed dryer, the process requirements have been extracted using the technology model as shown in Table 24.

Table 24: Planned technology model of the data for the heat transfer requirements in the new grain drying plant for wheat.

Grain Drying Plant Tec model								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
DryingAirHeatingWheat	Cold	20.0	90.0	12.145	1.02	-	100	871.2
ExhaustAirCoolingWheat-Seg#1	Hot	34.3	26.8	12.145	1.046	-	50	95.2
ExhaustAirCoolingWheat-Seg#2	Hot	26.8	22.6	12.145	4.102	-	100	209.2
ExhaustAirCoolingWheat-Seg#3	Hot	22.6	18.4	12.145	3.449	-	100	175.9
ExhaustAirCoolingWheat-Seg#4	Hot	18.4	14.2	12.145	2.924	-	100	149.5
ExhaustAirCoolingWheat-Seg#5	Hot	14.2	10.0	12.145	2.502	-	100	127.6

Given the proprietary and closed nature of the highly efficient new grain dryer as shown, no thermodynamic model is available for the heating and cooling demand. Nevertheless, the remaining heating and cooling demands will be combined with energy conversion units to illustrate the optimization of process-utility interface.

Oil Pressing Plant (New)

Given the early stage of plant design during the preliminary PA, several oil pressing plant designs were being evaluated for conventional food oil production and bio-production of food oil. Figure 37 shows the expected chosen design for the conventional oil production as it requires higher heating and subsequent cooling demands and had the highest production rate. The most significant heating demands are the conditioning toaster equipment. Losses from the presses are expected to be significant and supported by experience from other operation plants by the manufacturer. The model accounts for the losses; however, the customer was informed of the possibility to insulate the presses to reduce losses and hence the heating demand in the conditioner toaster equipment.

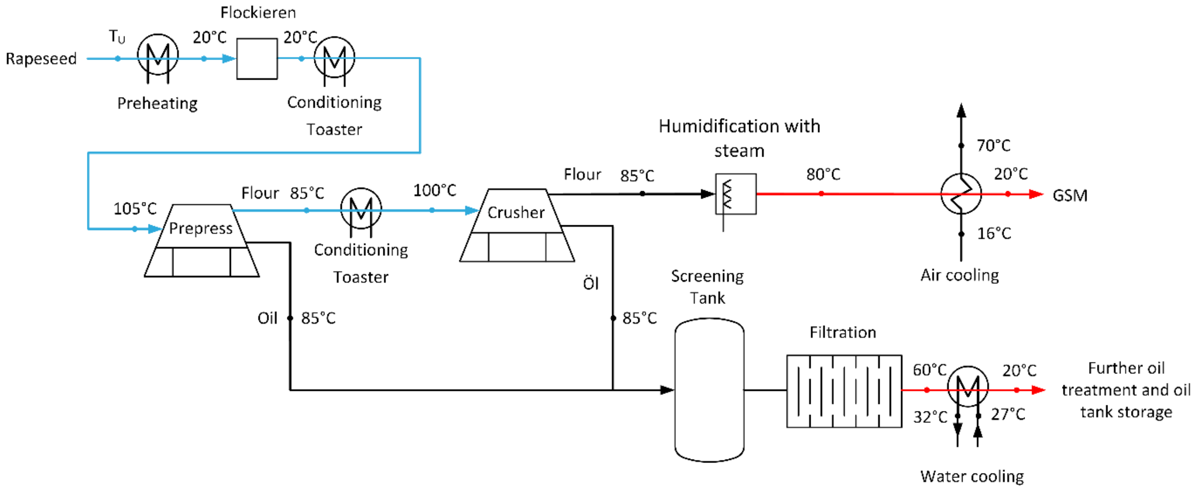


Figure 37: New oil pressing plant scheme showing the technical heating and cooling process requirements.

Based on the simplified flowsheet showing the heating and cooling demands for the designed oil pressing plant, the process requirements have been extracted using different models as shown in Table 25 and Table 26.

Table 25: Planned technology model of the data for the heat transfer requirements in Oil pressing plant.

Oil Pressing Plant Tec model								
Streams	Type	T in [°C]	T out [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Phase change [kJ/kg]	α [W/(m^{2}K)]	$\Delta\dot{H}$ [kW]
RawMaterialPreheating_Raps	Cold	10.0	20.0	3.403	1.576	-	150	53.6
Conditioning/Toaster1Heating_Raps	Cold	20.0	105.0	3.403	1.576	-	150	455.7
Conditioning/Toaster2Heating_Raps	Cold	85.0	100.0	2.526	1.576	-	150	59.7
CA_Meal(Flour)CoolingDrying-Seg#1	Hot	70.1	31.4	4.460	1.060	-	50	183.0
CA_Meal(Flour)CoolingDrying-Seg#2	Hot	31.4	27.5	4.460	5.029	-	100	86.1
CA_Meal(Flour)CoolingDrying-Seg#3	Hot	27.5	23.7	4.460	4.259	-	100	73.1
CA_Meal(Flour)CoolingDrying-Seg#4	Hot	23.7	19.8	4.460	3.628	-	100	62.1
CA_Meal(Flour)CoolingDrying-Seg#5	Hot	19.8	16.0	4.460	3.111	-	100	53.3
CW_RapsOilCooling	Hot	32.0	27.0	5.346	4.180	-	2000	111.7

Table 26: Thermodynamic model data of the heat transfer requirements in Oil pressing plant.

Oil Pressing Plant Thm model								
		T in	T out	$\dot{m}$	c_p	Phase change	α	$\Delta\dot{H}$
Streams	Type	[°C]	[°C]	[kg/s]	[kJ/(kg K)]	[kJ/kg]	[W/(m^{2}K)]	[kW]
RawMaterialPreheating_Raps	Cold	10.0	20.0	3.403	1.576	-	150	53.6
Conditioning/Toaster1Heating_Raps	Cold	20.0	105.0	3.403	1.576	-	150	455.7
Conditioning/Toaster2Heating_Raps	Cold	85.0	100.0	2.526	1.576	-	150	59.7
Meal(Flour)CoolingDrying	Hot	80.0	20.0	2.580	1.576	-	150	243.9
RapsOilCooling	Hot	60.0	20.0	0.997	2.800	-	800	111.7

4.2.3. Exergy loss analysis and optimum utility supply temperatures

Figure 38 shows the EGCC for Line 4 and the grain dryer. The difference between exergy requirements estimated based on the “Thm” models (blue line in Figure 38) and exergy supplied based on the “Uti” models (black line in Figure 38) is categorized as heat transfer-related exergy losses at the PUI. The exergy losses due to the technological requirement are high due to the hygienic requirements for the food Figure 39 (a). The heat supply by steam leads to high energetic losses due to heat transfer with a large temperature drop.

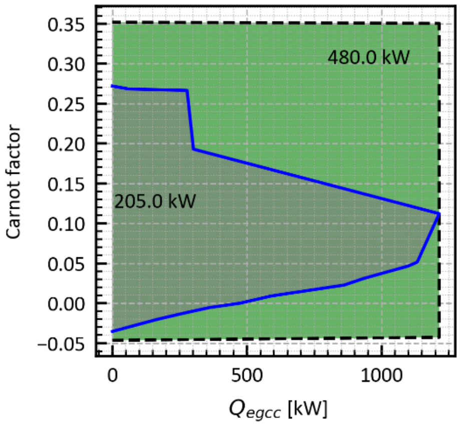


Figure 38: Exergy GCC for Line 4 and grain dryer for the current utility system on a typical winter day.

4.2.4. Identification of integration options

Variant 1: Localized solution: Line 4

UFA plans to integrate a steam-generating heat pump to supply the heat required by the process. The HP is estimated to have a condensing duty of 410 kW with evaporator and condenser temperatures of 25 °C and 135 °C, respectively. However, UFA has confirmed that it is technically feasible to preheat the flour mixture up to a maximum of 40 °C. Therefore, the solution in Figure 40 represents the preheating of the flour through heat recovery from exhaust air. The Figure 39 (b) shows the exergy requirement of the technology selected for the grain dryer. Based on the current plan, the hot air required by the dryer is through the direct firing of natural gas. As this is a new plant, and highly optimized by the manufacturer, the direct HR potential is low.

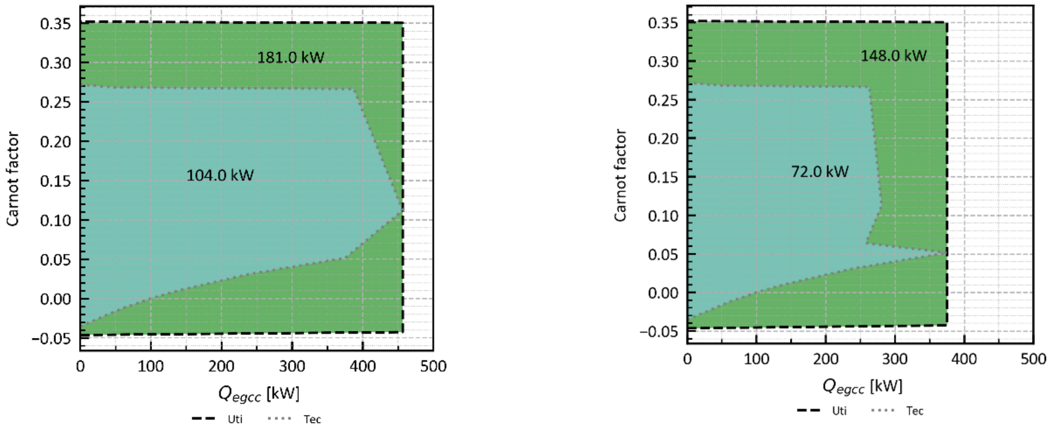


Figure 39: EGCC for (a) current technology and utility supply for line 4 (b) after implementation of heat recovery measure.

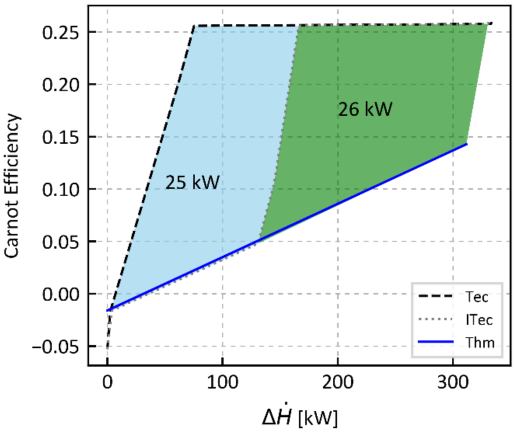


Figure 40: Changes in exergy loss for current technology and improved technology in relation to thermodynamic model.

The preheating heat recovery system also offers energy savings and economic benefits. The solution reduces the exergy losses due to reduced use of steam, and there is a good synchronization of heat source and heat sink. This solution reduces the size of the condenser of the steam-generating HP, which is needed to be approximately between 250 to 320 kW with the same temperatures and the same COP of 2.0.

Variant 2: Localized solution: grain dryer

In addition to the low HR potential, there is a strong temperature glide which requires combination of heating system for energy recovery solution. For example, a combination of solar thermal energy, heat pump, and/or either a transcritical HP or a HP operating according to the Joule cycle with a high COP. The solution concept of this work consist of a combined heat and power, together with a heat pump. Figure 41 shows the suggested solution for the grain dryer.

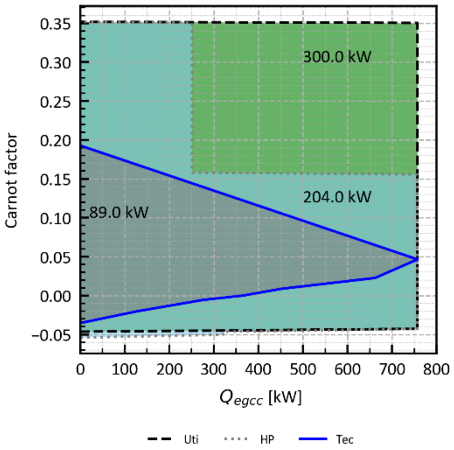


Figure 41: EGCC of Variant 2 with HP.

The solution concept is to heat the dryer supply air in stages. The solution consists of a combined heat and power, with approximately 180 kW elect. (35%) and 320 kW therm., together with a heat pump with a size of approximately 500 kW therm. at 75 °C and evaporation temperature at 8 °C. This gives the heat pump a COP of 2.8 (compressor: 180 kW electricity generated from the CHP). The heat source used is the humid exhaust air from the dryer.

4.2.5. Economic analysis

Table 27 shows the parameters used to calculate the economics of the two variants, and economic indicators are presented in Table 28.

Table 27: Parameters for techno-economic analysis.

Parameter	Value	Unit
Natural gas	60	CHF/MWh
Steam (derivation from natural gas)	78*	CHF/MWh
Electricity prices	200	CHF/MWh
Natural gas emission factor	0.202	kg CO_2/kWh$_{HU}$
**Steam cost is estimated based on following considerations and assumptions: Approximately 20% of losses occur in steam generation and distribution. Approximately 3% of the heat is required for feed water vessel heating.*		

Table 28: Results of the economic analysis of process-utility interface improvement.

Integration option	CO_2 reduction (t-CO_2/a)	COP	Savings (CHF/a)
Variant 1	50	-	19’000
Variant 2*	185	2.8	60’000
**The cost is per dryer*			

4.2.6. Conclusions and outlook

For Line 4, an option discussed with industrial and manufacturing partners was to replace the direct steam heating with a steam generating heat pump, using the hot water loop from the nearby UFA AG Biblis Plant as the heat source. In general, the exergy losses that occur due to the new technology will not change, as the HP will be supplying utility at the same temperature. However, for this solution concept, several vapor recompressors are required in addition to the HP in order to create the necessary vapor conditions for product dosing (approx. one vapor recompressor (MVR blower) per 15 K temperature rise). In addition to that, the hot water loop return temperature is not strictly controlled and is allowed to vary throughout the year. One other possible solution is to do a feasibility study for an alternative sanitization technology, e.g., with water dispersion or microwave. This would lower the temperature level of the utility, and the source could be replaced with a heat pump.

For the grain dryer on the other hand, the lower operation duration is not affecting the CAPEX, but the amortization duration. Due to the lower COP of the current concept in Variant 2, an additional feasibility study has to be conducted to improve the COP, e.g. CO_2 transcritical HP, due to the temperature glide.

One total site concept that was developed during the DeCarb-PUI is to establish a centralized heat recovery by using heat exchangers or intermediate loops to capture energy at various temperatures. The concept is shown in Figure 42. The system also includes a thermal distribution system for the entire site. The solution is to collect waste heat from various processes into a centralized heat recovery network, establish a moderate-temperature heat network (e.g., 40–105°C) to supply processes requiring moderate heating, and integrate a NH_3 heat pump and MVR for high-temperature demands. This maximizes the waste heat usage across multiple processes.

However, only the concept is developed as the grain dryer and the oil pressing plants are based on theoretical data. The total site concept requires significant upfront costs for the heat pump systems (steam generating and transcritical), thermal storage, and piping infrastructure. In addition to that, managing a centralized heat network across multiple processes with varying demands can be operationally challenging.

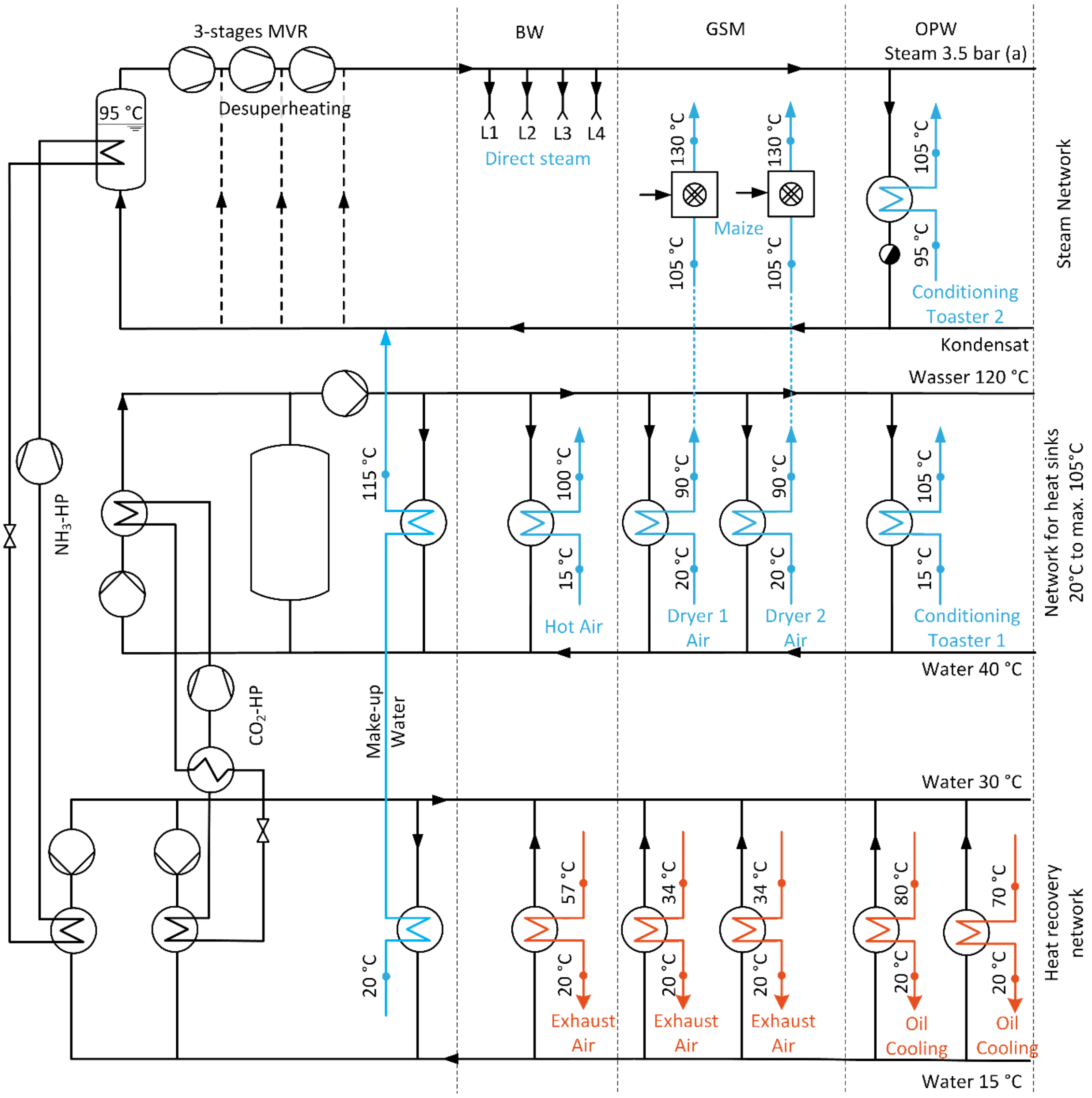


Figure 42: Total site concept for UFA.

5 Learnings, Conclusions and Outlook

5.1 Learnings and Discussion

The learnings from the analysis of two case studies and from the feedback of industrial partners are:

- **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) must 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

- Table 29 below for relevant modelling of heat transfer requirements and opportunities to retrofit the process technology.
- **Limitation of exergy grand composite curve**: The EGCC is a graphical representation used in thermodynamic analysis, plotting the Carnot factor (1 - T_0/T) on the y-axis against the heat flow on the x-axis. The area enclosed between the y-axis and the curve represents the overall exergy requirement of the process, capturing both the heating and cooling demands. However, the inclusion of soft streams can lead to implicit assumptions about heat exchange between streams. In particular, soft streams that are being cooled may be assumed to transfer heat to cold streams requiring heating. This assumption can lead to an overestimation of the exergy requirement because the EGCC does not explicitly account for the practical limitations or physical constraints of the heat exchanger network. While the EGCC is a valuable tool for visualizing and estimating process exergy requirements, careful treatment of soft streams is crucial to avoid overestimations. Incorporating explicit modeling and iterative refinement ensures a more accurate and realistic representation of the process's exergy demands, improving the reliability of the analysis.
- **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 (supply 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 CO_2 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 is the ability to provide products meeting clients specific product specifications (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 RCCs (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 performance of solutions is definitely needed. Such a tool is beyond the scope of DeCarb-PUI and should be developed in a follow-up project.

- Table 29 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.
    - 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 29: 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 ∆T	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 vapor 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 ∆T	
- 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

5.2 Conclusions

Pinch Analysis serves as the foundation of the DeCarb-PUI methodology, providing a structured framework for identifying cost-optimal heat exchanger networks and maximizing local heat recovery. By setting utility system retrofit targets and establishing new utility levels, it enhances energy efficiency across industrial processes. However, applying Pinch Analysis at the total site level introduces complexity, particularly when intermediate loops are required to collect and distribute energy. This often necessitates additional approaches to optimize the system further.

DeCarb-PUI builds on Pinch Analysis by enabling the redesign of utility supply temperatures, which opens pathways to integrate lower utility levels and less carbon-intensive heating sources, such as heat pumps. The methodology’s strength lies in its ability to provide practical, scalable solutions across three integration levels—localized, cluster, and total site. While total site solutions may face spatial or scheduling constraints, the flexible framework developed in this project allows adaptation to specific industrial contexts.

Exergy Analysis, when combined with Pinch Analysis, enhances the identification of inefficiencies within utility systems by focusing on data classification into thermodynamic requirements, technological constraints, and utility supply limitations. This approach pinpoints areas of high inefficiency, such as energy conversion, utility distribution, or heat transfer stages, and provides actionable insights for targeted interventions. For instance, exergy grand composite curves in the case studies revealed processes with significant exergy destruction, guiding the evaluation of different heat pump integration strategies.

According to Pinch Analysis principles, direct heat recovery opportunities should be exploited first. However, practical challenges, such as the complexity of implementation (e.g., sanitary, safety considerations) or additional costs, may limit these measures. In such cases, the PUI framework offers alternative solutions, enabling trade-offs between local and non-localized (clustered) configurations. Expanding the system boundary allows the evaluation of combinatorial solutions for heat pump sources and sinks. While clustered solutions incur higher capital costs due to additional piping and larger heat pump sizes, they typically achieve greater CO_2 abatement, improving cost-effectiveness when measured by the Levelized Cost of CO_2 Abatement.

Finally, exergy supports the "cooler hot utilities and hotter cold utilities" strategy, minimizing temperature gaps between processes and utilities to reduce both energy and exergy losses. Exergy-based assessments also help determine whether technologies like heat pumps, thermal loops, or renewable integration deliver maximum value. By providing a framework for utility system design, exergy ensures resilience to future challenges, such as fluctuating energy prices or stricter carbon regulations.

5.3 Outlook

In the duration of DeCarb-PUI, the methodology was developed and applied to two case studies. However, the learnings and outcomes should be incorporated in a tool. This tool should aim at modelling the main characteristics and calculating the technical performances and costs of a combination of utility systems for an industrial site, including both existing utilities (steam system) as well as new alternative utility systems/retrofit options. The architecture of the tool is as sketched in Figure 43. It could be either a spreadsheet-based tool or a web-based tool, depending on how to best interface with Pinch Analysis tools. The concept for this tool also emerged from a dairy industry case study as part of another R&D project focused on the integration of heat pumps.

Site specific information and process specific data, as well as constraints, are considered for the calculation of relevant indicators. These indicators are part of the heuristic approach proposed to solve the problem: they aim at orientating the user for selecting several promising configurations of alternative utilities/retrofit options, to be compared to the existing situation. Calculating the KPI (CAPEX and OPEX, CO_2 abatement costs, etc.) of both the existing solution (reference case) and the competing alternatives accurately enough (e.g. to within +/- 2 to 5%) to allow well-founded decision-making is a challenge, as numerous parameters and constraints, often difficult to quantify, come into play.

The schedule of individual processes should typically be modelled with a 10 to 15 minutes resolution, and the tool should aggregate the schedule of processes to build hourly TAM source and sink profiles. On this basis, the operation of each alternative of utility system can be simulated over the year. Or at least over a representative period. This approach assumes that only short-term heat storage (typically one hour up to maximum of several hours) would be technically possible (due to limited free space) and economical.

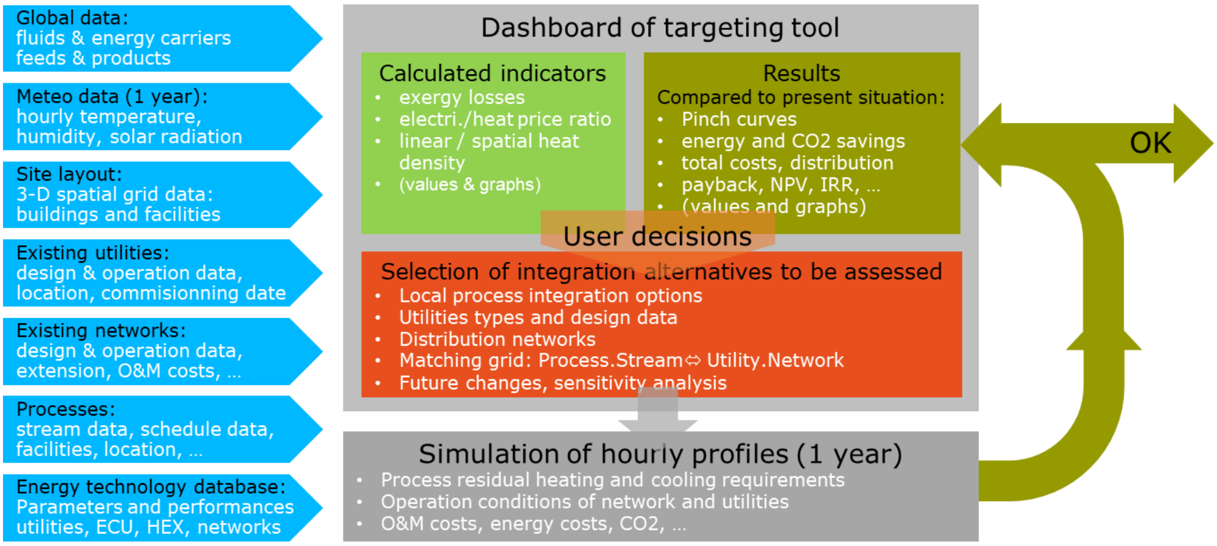


Figure 43: Envisioned tool.

The following **energy conversion and heat distribution technologies** relevant for the Swiss industry should be supported by the tool:

- Hot gas burner
- Steam boiler (without cogeneration)
- Superheated water boiler
- Hot water boiler
- Electrical heater / boiler
- Heat pump (both ≤ 100°C and > 100°C)
- Internal combustion engine CHP
- MVR and TVR
- Heat storage
- Global and local heat distribution network / heat recovery loop

To sum up, the tool should perform all calculations and provide results in a suitable form to help user focusing and making high level decisions.

6 National and international cooperation

This project is a collaboration between HEIG-VD and Hochschule Luzern. The industrial partners in this project are Emmi Schweiz AG Dagmersellen and UFA AG with Bühler AG as manufacturing partner.

7 Publications and other communications

On request of BFE/Renz Consulting, the project has been presented and published in their conference proceedings at the:

1) 28. Tagung des BFE-Forschungsprogramms Wärmepumpen und Kältetechnik, BFH Burgdorf on 22. June 2022.
2) 30. Tagung des BFE-Forschungsprogramms Wärmepumpen und Kältetechnik, Eventfabrik Bern on 26. June 2024.

In addition, the project has also been introduced in the Networking Conference in the Status Update of Work Package 4 in 2022 and 2023, and poster presentation in 2024.

The course materials for Energy Optimization with Pinch Analysis (EOPA, continued education course), Swiss Process and Chemical Engineers (SGVC), and in bachelor/master Pinch Analysis Modules are adapted to introduce the concept of DeCarb-PUI.

8 References

Berntsson, E. W. P.-Á. F. T. (1990). Heat Pumps in Industrial Processes – an Optimization Methodology. *Heat Recovery Syst CHP*.

Brennan, D. J., & Golonka, K. A. (2002). New Factors for Capital Cost Estimation in Evolving Process Designs. *Chemical Engineering Research and Design*, *80*(6), 579-586. https://doi.org/10.1205/026387602760312773

Brown, D., Maréchal, F., & Paris, J. (2005). A dual representation for targeting process retrofit, application to a pulp and paper process. *Applied Thermal Engineering*, *25*, 1067-1082. https://doi.org/10.1016/J.APPLTHERMALENG.2004.07.024

Chew, K. H., Klemeš, J. J., Wan Alwi, S. R., & Manan, Z. A. (2015). Process modifications to maximise energy savings in total site heat integration. *Applied Thermal Engineering*, *78*, 731-739. https://doi.org/10.1016/J.APPLTHERMALENG.2014.04.044

energie360°. (2020). Preislisten Erdgas-Biogas 2013-2020. *21*, 1-9.

Feng, X., & Zhu, X. X. (1997). Combining pinch and exergy analysis for process modifications. *Applied Thermal Engineering*, *17*, 249-261. https://doi.org/10.1016/S1359-4311(96)00035-X

Hamsani, M. N., Walmsley, T. G., Liew, P. Y., & Wan Alwi, S. R. (2018). Combined Pinch and exergy numerical analysis for low temperature heat exchanger network. *Energy*, *153*, 100-112. https://doi.org/10.1016/J.ENERGY.2018.04.023

IEA. (2023). *Solar Heat for Industrial Processe Plant Database (SHIP)* (www.ship-plants.info

Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., & Tassou, S. A. (2018). Waste heat recovery technologies and applications. *Thermal Science and Engineering Progress*, *6*, 268-289. https://doi.org/https://doi.org/10.1016/j.tsep.2018.04.017

Krummenacher, P., Olsen, D., Fesefeldt, M., Ong, B., & Wellig, B. (2023). *Pinch-Grobanalyse UFA, Biowerk Hofmatt in Herzogenbuchsee - Abschlussbericht*.

Liew, P. Y., Lim, J. S., Wan Alwi, S. R., Abdul Manan, Z., Varbanov, P. S., & Klemeš, J. J. (2014). A retrofit framework for Total Site heat recovery systems. *Applied Energy*, *135*, 778-790. https://doi.org/10.1016/J.APENERGY.2014.03.090

Marechal, F., & Favrat, D. (2006). Combined exergy and pinch analysis for the optimal integration of energy conversion technologies. *Proceedings of ECOS*, *18*, 177-184.

Marechal, F., & Kalitventzeff, B. (2003). Targeting the integration of multi-period utility systems for site scale process integration. *Applied Thermal Engineering*, *23*, 1763-1784. https://doi.org/10.1016/S1359-4311(03)00142-X

Marmolejo-Correa, D. (2013). *Analysis and Design of Low Temperature Processes with Focus on LNG : Developing new Thermodynamics based Tools and introducing Exergy in Design Methodologies* [PhD, Norwegian University of Science and Technology, Trondheim Norway].

Muster, B., Hassine, I. B., Helmke, A., Heß, S., Krummenacher, P., Schmitt, B., & Schnitzer, H. (2015). *IEA SHC Task 49, SolarPaces Annex IV; Solar Process Heat for Production and Advanced Applications: Integration Guideline, Deliverable B 2* (Solar Heating & Cooling Programme SHC, Issue. https://task49.iea-shc.org/Data/Sites/1/publications/150218_IEA Task 49_D_B2_Integration_Guideline-final1.pdf.

Olsen, D., Abdelouadoud, Y., Wellig, B., & Krummenacher, P. (2016). Systematic thermal energy storage integration in industry using pinch analysis. *The 29th International Conference on Efficientcy, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 1-14.

Ong, B. H. Y. (2019). *A Kraft Mill-Integrated Biorefinery Design for New Zealand* The University of Waikato].

Peters, M. S., Timmerhaus, K. D., & West, R. E. (2004). *Plant design and economics for chemical engineers* (5. Edition ed.). McGraw-Hill.

Quijera, J. A., & Labidi, J. (2013). Pinch and exergy based thermosolar integration in a dairy process. *Applied Thermal Engineering*, *50*, 464-474. https://doi.org/10.1016/j.applthermaleng.2012.06.044

Rittmann-Frank, M. H., Theiler, D., Ruesch, F., Bamberger, E., Wellig, B., Stirnimann, P., & Olsen, D. (2020). *Konzernrelevante Verringerung von CO2- Emissionen durch die Integration von skalierbaren und kostengünstigen Solarwärme Einheiten (BillySolar)*.

Shenoy, U. (1995). Heat Exchanger Network Synthesis - Process Optimization by Energy and Resource Analysis. In. Gulf Publishing Company.

Staine, F., & Favrat, D. (1996). Energy integration of industrial processes based on the pinch analysis method extended to include exergy factors. *Applied Thermal Engineering*, *16*, 497-507. https://doi.org/10.1016/1359-4311(95)00036-4

Tarighaleslami, A. H., Walmsley, T. G., Atkins, M. J., Walmsley, M. R. W., Liew, P. Y., & Neale, J. R. (2017). A Unified Total Site Heat Integration targeting method for isothermal and non-isothermal utilities. *Energy*. https://doi.org/10.1016/j.energy.2016.12.071

Townsend, D. W., & Linnhoff, B. (1983). Heat and power networks in process design. Part I: Criteria for placement of heat engines and heat pumps in process networks. *AIChE Journal*, *29(5)*, 742-748.

Wallerand, A. S. (2018). *Integration of solar energy with industrial processes* [PhD, Swiss Federal Institute of Technology Lausanne, Switzerland]. https://infoscience.epfl.ch/record/256107?ln=en

Walmsley, M. R. W., Walmsley, T. G., Atkins, M. J., & Neale, J. R. (2013). Integration of Solar Heating into Heat Recovery Loops using Constant and Variable Temperature Storage. *Chemical Engineering Transactions*. www.aidic.it/cet

Wang, M., Deng, C., Wang, Y., Feng, X., & Lan, X. (2018). Process Integration and Selection of Heat Pumps in Industrial Processes. *Chemical Engineering Transactions*, *70*, 1105-1110.

Wellig, B., Stirnimann, P., Liem, P., & Flück, S. (2022). *Schlussbericht Pinch-Analyse Emmi Schweiz AG Dagmersellen*.

9 Appendix

Reminder: Pinch Analysis in a nutshell

Pinch Analysis (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, CO_2 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 **Composite Curves (CCs)** and the **Grand Composite Curve (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 **Grand Composite Curve (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 how to apply PA 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.