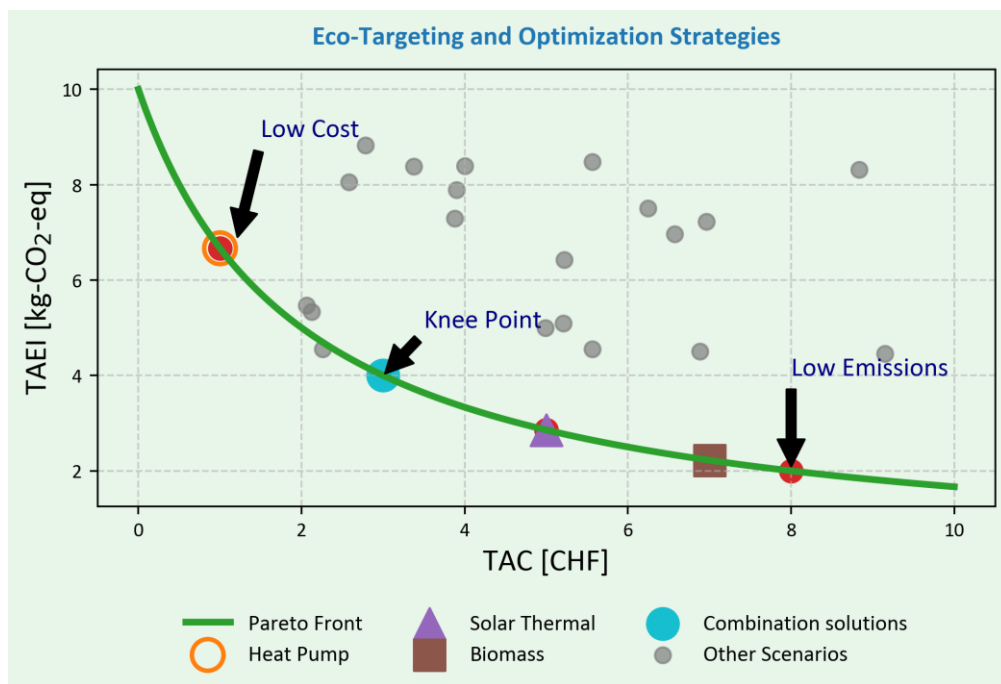




Eco-Targeting

Decarbonization of Swiss Industry through extended Eco-Targeting based on Pinch Analysis method





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Summary

Integration of energy efficiency measures, energy conversion, and renewable technologies is a proven pathway for reducing Scope 1 emissions. However, as integration increases, Scope 2 emissions from operations, Scope 3 emissions along the value chain, and overall costs also rise. Since most industries already report GHG emissions in line with the GHG Protocol (Scopes 1–3), the relative importance of Scope 2 and 3 is increasing. This makes lifecycle-aware integration strategies essential and highlights the need for companies to balance total annual emissions with total annual costs.

Building on HSLU's role as the competence center for Pinch Analysis in Central Switzerland, this project developed a robust and flexible framework that unites Pinch Analysis (PA), Life Cycle Assessment (LCA), and Multi-objective Optimization (MOO) into a single decision-support tool. The framework identifies technically feasible integration options, quantifies environmental impacts, and derives Pareto fronts that reveal trade-offs between emissions and costs under various resource constraints such as solar irradiance, access to clean electricity, biomass availability, etc. These results can be translated into actionable guidance for industry under real-world resource constraints.

The framework was tested in two Swiss dairy case studies (continuous and non-continuous processes). Direct and indirect heat recovery formed the most cost-effective foundation. Heat pumps at low to medium temperatures achieved about 30% Scope 1 emission reduction with a 2.1-year payback. Solar thermal proved highly sensitive to solar irradiance, while biomass offered the deepest cuts, up to 82% reduction in baseline emissions, albeit with higher costs and payback times of up to 21 years. Combining technologies consistently outperformed single-technology solutions in terms of cost-effectiveness. The comparison of direct and indirect emissions across scenarios reveals a threshold integration beyond which the indirect Scope 2–3 emissions became dominant, underscoring the need for lifecycle-aware planning. The threshold was identified at 72% degree of integration for the case study in this work.

Overall, the project emphasizes that decarbonization strategies must be evaluated not only on direct CO₂ reductions but also on upstream and operational impacts. By combining PA, LCA, and MOO into a flexible framework, Eco-Targeting equips industries and policymakers with a structured approach to identify optimal integration strategies. Going forward, the framework can be extended to additional sectors and technologies, offering a robust tool to design cost-effective pathways toward net-zero.

Zusammenfassung

Die Integration von Energieeffizienzmaßnahmen, Energiewandlungs- und erneuerbaren Technologien ist ein bewährter Ansatz zur Reduktion von Scope-1-Emissionen. Mit zunehmender Integration steigen jedoch die Scope-2-Emissionen aus dem Betrieb, die Scope-3-Emissionen entlang der Wertschöpfungskette sowie die Gesamtkosten. Da die meisten Unternehmen ihre Treibhausgasemissionen bereits gemäß dem GHG-Protokoll (Scopes 1–3) erfassen, gewinnen Scope 2 und 3 zunehmend an Bedeutung. Dies macht lebenszyklusbasierte Integrationsstrategien unerlässlich und unterstreicht die Notwendigkeit für Unternehmen, Gesamtemissionen und Gesamtkosten im Jahresvergleich auszubalancieren.

Aufbauend auf der Rolle der HSLU als Kompetenzzentrum für Pinch-Analyse in der Zentralschweiz wurde in diesem Projekt ein robustes und flexibles Rahmenwerk entwickelt, das Pinch-Analyse (PA), Life Cycle Assessment (LCA) und Multi-Objective Optimization (MOO) in einem einzigen Entscheidungsunterstützungswerkzeug vereint. Das Framework identifiziert technisch machbare Integrationsoptionen, quantifiziert Umweltwirkungen und liefert Pareto-Fronten, die Zielkonflikte zwischen Emissionen und Kosten unter verschiedenen Ressourcenrestriktionen (z. B. Sonneneinstrahlung, Zugang zu sauberem Strom, Verfügbarkeit von Biomasse) sichtbar machen. Die Ergebnisse lassen sich in handlungsorientierte Empfehlungen für die Industrie unter realen Rahmenbedingungen übersetzen.



Das Framework wurde in zwei Fallstudien zur Schweizer Milchindustrie (kontinuierlicher und nicht-kontinuierlicher Prozess) getestet. Direkte und indirekte Wärmerückgewinnung bildeten die kostengünstigste Grundlage. Wärmepumpen im niedrigen bis mittleren Temperaturbereich reduzierten die Scope-1-Emissionen um ca. 30 % bei einer Amortisationszeit von 2,1 Jahren. Solarthermie erwies sich als stark von der Sonneneinstrahlung abhängig, während Biomasse die tiefsten Reduktionen ermöglichte – bis zu 82 % weniger Emissionen, jedoch mit höheren Kosten und einer Amortisationszeit von bis zu 21 Jahren. Die Kombination mehrerer Technologien erwies sich durchgängig als kosteneffizienter als Einzellösungen. Über alle Szenarien hinweg zeigte sich, dass ab einem Integrationsgrad von rund 72 % indirekte Scope-2- und Scope-3-Emissionen dominierten, was die Notwendigkeit lebenszyklusbasierter Planung unterstreicht.

Insgesamt zeigt das Projekt, dass Dekarbonisierungsstrategien nicht nur auf direkte CO₂-Reduktionen abzielen dürfen, sondern auch vorgelagerte und betriebliche Auswirkungen berücksichtigen müssen. Durch die Kombination von PA, LCA und MOO stellt Eco-Targeting Industrie und Politik ein strukturiertes Instrumentarium zur Verfügung, um optimale Integrationsstrategien zu identifizieren. Künftig kann die Methode auf weitere Sektoren und Technologien ausgeweitet werden und so robuste, kosteneffiziente Pfade zur Klimaneutralität aufzeigen.

Résumé

L'intégration de mesures d'efficacité énergétique, de technologies de conversion de l'énergie et de solutions renouvelables constitue une voie éprouvée pour réduire les émissions de Scope 1. Toutefois, à mesure que l'intégration s'intensifie, les émissions de Scope 2 liées aux opérations, celles de Scope 3 le long de la chaîne de valeur, ainsi que les coûts globaux augmentent également. Comme la plupart des industries déclarent déjà leurs émissions de GES conformément au GHG Protocol (Scopes 1–3), l'importance relative des Scopes 2 et 3 se renforce. Cela rend indispensables les stratégies d'intégration tenant compte du cycle de vie et souligne la nécessité, pour les entreprises, d'équilibrer les émissions annuelles totales avec les coûts annuels totaux.

En s'appuyant sur le rôle de la HSLU en tant que centre de compétence pour l'Analyse Pinch en Suisse centrale, ce projet a développé un cadre robuste et flexible réunissant l'Analyse Pinch (PA), l'Analyse de Cycle de Vie (ACV) et l'Optimisation Multi-Objectifs (MOO) au sein d'un outil unique d'aide à la décision. Ce cadre identifie les options d'intégration techniquement réalisables, quantifie les impacts environnementaux et établit des fronts de Pareto mettant en évidence les compromis entre émissions et coûts sous différentes contraintes de ressources (par ex. irradiance solaire, accès à l'électricité propre, disponibilité de la biomasse). Ces résultats se traduisent en recommandations concrètes pour l'industrie dans des conditions réelles de ressources limitées.

Cette approche a été testée dans deux études de cas suisses du secteur laitier (processus continu et discontinu). La récupération directe et indirecte de chaleur a constitué la base la plus rentable. Les pompes à chaleur, à basse et moyenne température, ont permis une réduction d'environ 30 % des émissions de Scope 1 avec un amortissement en 2,1 ans. Le solaire thermique s'est révélé très sensible à l'irradiance, tandis que la biomasse a offert les réductions les plus profondes – jusqu'à 82 % des émissions de référence –, mais avec des coûts plus élevés et des temps de retour pouvant atteindre 21 ans. Les combinaisons de technologies ont systématiquement surpassé les solutions monotecnologiques en termes de rentabilité. Dans l'ensemble des scénarios, dès que le degré d'intégration dépassait ~72 %, les émissions indirectes de Scope 2–3 devenaient dominantes, ce qui souligne l'importance d'une planification intégrant l'ensemble du cycle de vie.

Globalement, le projet montre que les stratégies de décarbonation doivent être évaluées non seulement en fonction des réductions directes de CO₂, mais aussi en tenant compte des impacts en amont et en exploitation. En combinant PA, ACV et MOO dans un cadre flexible, Eco-Targeting fournit aux industries et aux décideurs un outil structuré pour identifier les stratégies d'intégration optimales. À l'avenir, ce cadre pourra être étendu à d'autres secteurs et technologies, offrant un outil robuste pour concevoir des trajectoires rentables vers la neutralité carbone.



Main findings («Take-Home Messages»)

- **Framework validity:** The Eco-Targeting framework, which combines Pinch Analysis, LCA, and Multi-objective Optimization, proved robust and flexible in both continuous and non-continuous case studies. Although the numerical results are case-specific, the methodology is transferable to other sectors and geographies.
- **Cost-effective first step:** Direct and indirect heat recovery consistently formed the foundation of optimal solutions, delivering immediate cost savings and modest emission reductions with relatively low investment
- **Role of heat pumps:** Heat pump technology is most effective below 100°C, with diminishing returns beyond the so-called knee point
- **Limits of solar thermal:** Solar thermal systems have long Carbon Payback, limiting immediate emission reduction benefits
- **Role of biomass:** Aggressive decarbonization strategies, like integrating solar thermal (ST) and biomass, reduce emissions significantly but require higher investments and longer payback periods.
- **Holistic decarbonization:** Higher degrees of integration (up to 72%) significantly reduce Scope 1 emissions but shift the emission burden to Scope 2 and Scope 3 due to lifecycle impacts.



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List of abbreviations

BM	Biomass
CAPEX	Capital Expenditure
DHR	Direct heat recovery
EC	Enthalpy coordinate
ECT	Energy conversion technology
EEM	Energy efficiency Measure
EI	Environmental Impact
HEN	Heat Exchanger Network
HEX	Heat Exchanger
HP	Heat pump
HTHP	High Temperature Heat Pump
IHR	Indirect heat recovery
IP	Integration point
ISSP	Indirect Source Sink Profiles
LCA	Life cycle assessment
LCI	Life cycle inventory
MER	Maximum Heat Recovery
NG	Natural gas
PA	Pinch Analysis
Q_{cond}	Condenser heat load
Q_{evap}	Evaporator heat load
Q_{ST}	Solar thermal heat load
RCC	Residual Composite Curves
RT	Renewable technology
SHP	Standard Heat Pump
ST	Solar Thermal
TAC	Total Annual Cost
TAEI	Total Annual Environmental Impact
TAM	Time Averaged Model
TSM	Time Slice Model



1 Introduction

1.1 Context and motivation

Stationary fuel combustion and the electricity used in the Swiss industry are responsible for about 25% of the total annual CO₂ emissions in Switzerland [1]. Thus, the decarbonization of industrial processes plays an important role in achieving the net-zero emissions target for Switzerland set for the year 2050. Key strategies for industrial decarbonization include improving energy efficiency through heat exchanger networks (HENS), process heat electrification via heat pumps (HPs), and the integration of renewable technologies (RTs). While these measures and technologies hold great promise, they also introduce economic and environmental trade-offs. As the degree of integration increases, total annual costs (TAC) rise, and indirect emissions along the supply chain grow, making it critical for industries to identify the optimal balance between economic feasibility and ecological benefits. The current project addresses this need by developing a systematic framework to guide industrial decision-makers in achieving sustainable decarbonization. By providing actionable insights into the trade-offs between TAC and environmental impact, this framework aims to support industries in reducing their carbon footprint while maintaining economic competitiveness, aligning with Switzerland's long-term climate goals.

Pinch Analysis (PA) is an established tool for analyzing the heating and cooling demands of industrial processes [2, 3]. Over the past four decades, PA has been expanded to accommodate dynamic industrial processes such as batch and semi-continuous operations through Time Averaged Models (TAM) and Time Slice Models (TSM). Since 2010, the CC-TEVT at HSLU has served as the Pinch Center (Pinch Stützpunkt) for Central Switzerland, developing additional aspects of PA methodology through several applied research projects.

Within CC-TEVT at HSLU, Olsen et al.[4] demonstrated integration of thermal storage for a non-continuous process based on the concept of indirect source and sink profiles (ISSP). Building on this, Agner et al. [5] developed a graphical method for the combined integration of HPs with thermal energy storage (TES). In the context of the BillySolar research project [6] a concept of residual composite curves (RCC) to estimate the realistic potential for solar thermal (ST) and HP integration following direct heat recovery was introduced. Stampfli et al. [7] further extended PA with a hybrid methodology coupling PA-based insights with genetic algorithms to optimize HP integration in non-continuous processes.

Within the EPFL-led project on integrated industrial heat pump systems, Wallerand et al. [8] developed an HP design tool that provided systematic guidelines for correct HP integration and quantified the large CO₂ reduction potential across Swiss industry. Their analysis highlighted, for example, that in the food and beverage sector, emission reductions of 25–58% could be achieved with typical payback times of 3–6 years.

Building on these complementary national efforts, the DeCarbPUI project extended the scope of PA to the process–utility interface (PUI). By combining PA with exergy analysis and techno-economic evaluation, it introduced a structured methodology for redesigning utility systems, optimizing supply temperatures, and reducing exergy losses. Applications at local, cluster, and total site levels demonstrated pathways to deeper decarbonization beyond conventional heat recovery.

Together, the concepts of ISSPs and RCCs provide the basis for practical sizing of Energy conversion technologies (ECTs) and RTs, while the knowledge transfer from DeCarbPUI and EPFL's HP integration work establishes a solid foundation for multi-technology, multi-level integration. These competencies converge in the present Eco-Targeting project, which combines PA with Life Cycle Assessment and Multi-Objective Optimization to deliver a holistic decision-support framework for industrial decarbonization.

In addition to the developments in the Pinch Methodology and frameworks for the integration of HPs and TES, various mathematical programming and optimization techniques have been developed to find the economically and environmentally optimum solutions [2]. López-Maldonado et al. [9] proposed a model consisting of a multi-objective Mixed-Integer Non-Linear Programming (MINLP) problem that considers the optimal location and use of different types of hot and cold utilities, minimising the cost for the



utilities and capital for the heat exchanger (HEX) units, as well as the environmental impact (EI) for different types of utilities. Vaskan et al. [10] addressed the optimal design of HENs considering economic and environmental concerns, and posed the design task as a multi-objective MINLP problem accounting for the simultaneous minimization of several environmental metrics based on the superstructure introduced by Yee and Grossmann [11]. Ravagnani et al. [12] presented a multi-objective MINLP model to find the optimal HEN considering total cost as well as the EI minimization based on Particle Swarm Optimization and a superstructure that considers the number of stages as an optimization variable. Mano et al. [13] incorporated external costs associated with the EIs caused by energy generation and equipment construction in the synthesis of HENs using the eco-costs methodology, considering the most used fuels in the chemical and petrochemical industries and different boiler technologies. Pavao et al. [14] proposed an approach to yield Pareto fronts providing good intermediate solutions for decision-makers to search for a trade-off HEN configuration that can present low costs and also be environmentally friendly.

Most studies from the currently published literature focus on the EI of HEN. However, due to their longer useful lifetime, the EI of HEN contributes minimally to the overall energy system. Moreover, HEN is not the only EEM solution sought by industry; HPs and renewable technologies have been gaining significant attention. Therefore, there is a growing need to integrate the EI of these technologies into PA. Additionally, despite numerous studies on EEMs and RTs integration using PA and optimization techniques, there is a noticeable lack of clear and practical guidelines for determining the economically and ecologically optimal degree of integration of various configurations of EEMs, ECTs and RTs with sustainable fuels across various industrial processes and locations. While the existing literature on process integration suggests prioritizing EEM integration before the ECT and RT integration, no systematic attempt has been made to test these established heuristics rigorously. Furthermore, the optimization techniques proposed in literature often rely on simultaneous approaches, which are computationally expensive and not user-friendly.

1.2 Project objectives

In view of the challenges highlighted in the previous section, the purpose of this research project is to develop a practical methodology to identify optimal solutions for various degrees of EEMs, ECTs and RTs integration along with conventional utilities. This research project builds on the sequential optimization approach for total annual costs (TAC) and total annual environmental impact (TAEI) considerations introduced by Ong et al. [20]. To simplify the overall workflow and minimize the computational load, multi-objective optimization is incorporated at the utility targeting stage of PA with the RCCs. Application of the methodology to two case studies will test the existing integration heuristics as well as the robustness of the methodology and will help to derive practical guidelines for identifying optimal integration of EEMs, RTs, and conventional utilities, thus bridging the gap between research and implementation.



1.3 Objectives

The main objective of the project is to develop an energy optimization framework to identify optimum degree of integration of EEMs, ECTs, RTs, along with conventional utilities for the given process heating and cooling demands. While the adoption of these measures typically results in the reduction of scope 1 CO₂ emissions (i.e., onsite emissions), it can result in an increase in scope 2 (emissions due to electricity consumption) and scope 3 (upstream emissions caused by production) CO₂ emissions. Thus, other supporting objectives of the project are:

1. Development of costs and environmental impact functions for EEMs, ECTs, and renewable heating and cooling technologies relevant to the Swiss industry.
2. Development of a framework for semi-automated integration of various EEMs, ECTs, and RTs based on PA and systematically testing the existing integration heuristics for continuous and non-continuous processes.
3. Development of a framework for accommodating supply and demand variability of renewable heating and cooling integration in industrial processes.
4. Development of general guidelines/heuristics for optimal degree of integration for EEMs, ECTs and RTs.

2 Data and methodology

The overarching aim of the Eco-Targeting project is to develop a framework to allow decision-makers to identify the tradeoff between the total costs and overall life cycle emissions of the decarbonization options such as EEMs, ECTs, and RTs. The framework relies on the fundamentals of Pinch Analysis along with the compilation of an extensive database of costs, life cycle assessment and the multi-objective optimization algorithm to identify a Pareto front of optimum integration configurations. The following section describes the database, approach and methods employed to design the overall framework for the continuous and non-continuous processes.

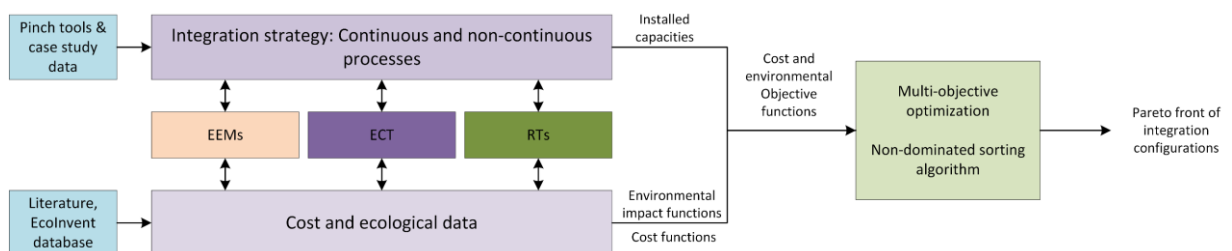


Figure 1. Scope of Eco-Targeting project

2.1 Database of costs and environmental impact

2.1.1. Selection of technologies

A shortlist of renewable sources and technologies relevant to the Swiss industry was prepared based on a literature survey and previously conducted work. The database contains various types of available RTs (e.g., flat plate collectors, parabolic trough collectors, deep geothermal, etc.). Figure 2 presents EEMs and RTs relevant to the Swiss industry and the temperature range over which they can be integrated. These temperature ranges are used for integration heuristics in the framework for EEM and RT integration and are imposed as constraints in the optimization algorithm.

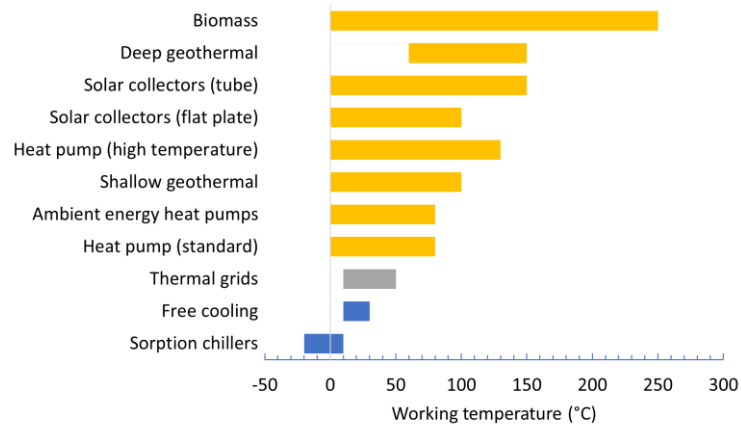


Figure 2: Working temperature ranges of EEMs, ECTs, and RTs used in Eco-Targeting.

2.1.2. Database structure

A database of cost and environmental impact from the implementation and operation of the decarbonization options was compiled to derive the cost and environmental impact functions (power law relations). The industrial process decarbonization options included in the database can be broadly split into two parts, namely, EEMs and technologies. The technologies are further classified as ECTs and RTs. Actions that result in incremental improvement of energy efficiency are categorized as EEMs (HEX, thermal storages). The technologies that valorize energy from lower to higher temperature (e.g., HP) or one form to other are classified as ECTs (CHPs). Technologies implemented to utilize renewable sources are categorized as RTs (solar thermal, geothermal, biomass, etc.). Some technology categories are further classified into specific technology types (e.g., standard heat pumps (SHP), solar collectors, direct geothermal, etc.). The database comprises information on technology identification, economic data, technical data, and ecological data. A simplified structure of the database is presented in Figure 3.

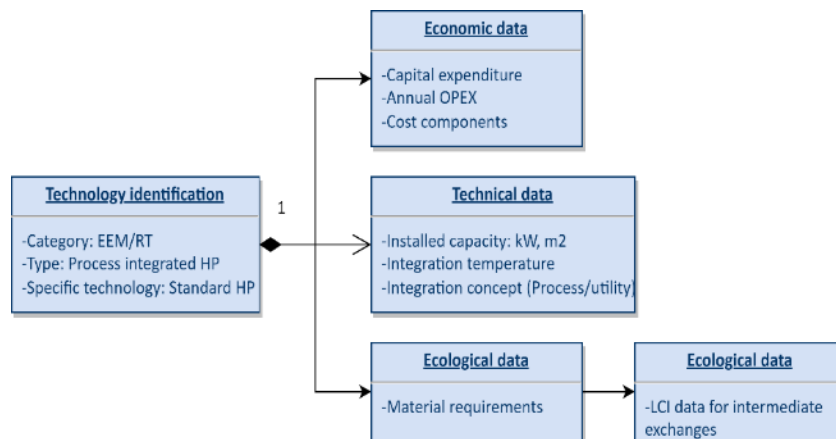




Figure 3. Database structure for cost and environmental impact data



2.1.3. Costs

The total cost of all EEMs, ECTs, and RTs consists of capital expenditure (CAPEX) and operating expenditure (OPEX). The total CAPEX is converted to annualized CAPEX using the annuity factor, which in turn is a function of the discount rate and the lifetime of the technology (equation 1). The cost functions derived in this project 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.

$$CAPEX_{annual,i} = CAPEX_i \times \frac{1-(1+r)^{-L_i}}{r} \quad (1)$$

Where,

L_i = Lifetime of the EEM, ECT, or RT i (see Appendix)

r = Discount rate (chosen to be 10%)

Heat exchanger

Since the case studies included in this report are from the food and beverage industry, it is assumed plate HEXs are implemented for internal heat exchange as well as utilities heat exchange. The investment cost of a HEX having specification L and an average heat transfer area \bar{A}_L (m²) is approximated with a cost law function (Figure 4) depending on the fixed cost C_0 , the base cost C_b , the base area $A_{0,L}$ (m²) and an exponent m_L . The parameters for the heat exchanger cost function are adopted from Ong et al. [15] and presented in the appendix.

$$CAPEX_{HEX} = C_0 + C_b \left(\frac{\bar{A}_L}{A_{0,L}} \right)^{m_L} \quad (2)$$

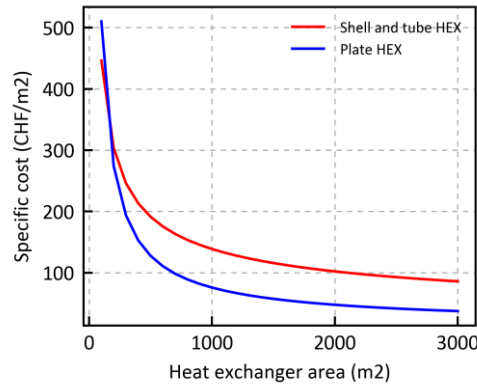


Figure 4. Specific costs for heat exchangers (Rast [16])

Heat pump

Techno-economic data of HPs implemented in the Swiss industry and other European countries obtained from various databases were used to derive the power law relationships for the HP CAPEX. Two power law relationships are derived for SHP and high-temperature heat pumps (HTPH).



$$CAPEX_{HP} = a \times (Q_{cond,HP}/100)^b \quad (3)$$

Where,

$CAPEX_{HP}$ = specific cost (CHF/kW heat)

$Q_{cond,HP}$ = heat pump condenser capacity (kW)

a, b = constant and exponent for each type of power law relationship are found using the regression analysis of the cost data included in the database and presented in the Appendix.

Figure 5 presents the specific cost of HP modules for SHPs and HTHPs. However, the HP integration strategies considered for this project typically include intermediate loops. Thus, the installation costs for HPs are derived using Lang factor 3. The Lang factor accounts for piping, building, installation, site preparation, and engineering costs. The breakdown of these factors is provided in the appendix.

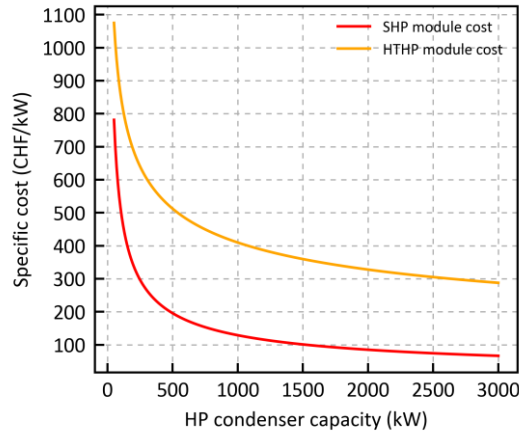


Figure 5. Specific module costs for heat pumps (Rast [16]; Arpagaus [17])

Solar thermal

The cost functions for ST systems are adopted from Billy Solar project [6] and derived based on the data published in the SHIP database [18]. Total CAPEX for ST system includes the cost for solar collectors, the cost of integration (storage tanks, connections, HEX), and personnel costs. Total CAPEX for solar collectors is estimated using equation 4. Due to the intermittent nature of solar energy, ST system is always assumed to be integrated with a storage tank. A ratio of 1:10 is assumed for the volume of the storage tank (m^3) compared to the collector field area (m^2) [6] and capital cost is estimated using equation 5. Annual OPEX for the ST system is assumed to be 1% of the total initial CAPEX. Figure 6 shows the specific cost for solar collectors (CHF/ m^2) as a function of solar collector area.

$$CAPEX_{solar\ collectors} = a \times A^b \quad (4)$$

Where,

A = Solar collector area (m^2)

a, b = constant and exponent for power law relationship fore flat plate collectors and are found using the regression analysis of the cost data included in the database and presented in the Appendix

$$CAPEX_{storage} = a \times V^b \quad (5)$$

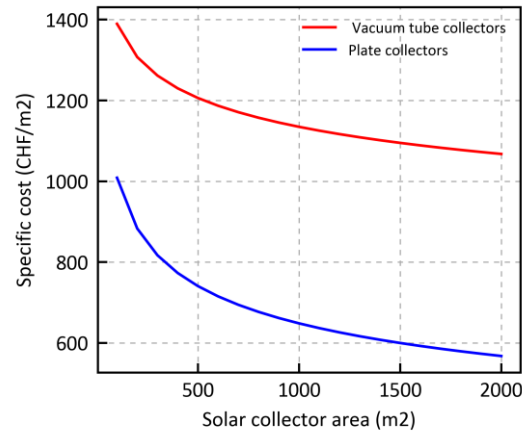


Figure 6. Specific costs for solar thermal system [6].

The constants estimated for all EEMs and technologies considered are presented in the appendix.

2.1.4. Environmental impact – Life Cycle Assessment

The LCA models developed for technologies included in this study apply a cradle-to-gate system boundary, capturing Scope 3 emissions from raw material extraction, component manufacturing, assembly, and transport. The use phase (Scope 2 emissions) is intentionally modeled separately to reflect company- and site-specific electricity supply conditions (e.g., Swiss clean electricity vs. fossil-intensive imports). This modular setup allows a consistent comparison of upfront Scope 3 burdens across technologies, while retaining flexibility to evaluate Scope 2 impacts under different operational scenarios. The end-of-life phase is intentionally excluded, as our decision question focuses on upfront, pre-operation emissions required to unlock downstream Scope 1/2 reductions; under the cut-off model, recycling credits from EOL accrue to subsequent product systems and would not affect the upfront balance. The climate change impact category is selected to align with the study's focus on decarbonization and global warming potential, while simplifying the analysis by excluding other environmental impacts, and LCA scores are presented in kg of CO₂-equivalent units.

The estimation of raw material requirements for each technology component is based on parameterized relationships derived from literature and product catalogs, ensuring scalability (presented in the appendix). Life Cycle Inventory (LCI) data for raw material extraction and component manufacturing is sourced from the Ecoinvent 3.9 database, which provides a robust and consistent foundation for modeling. The Allocation, Cut-off system model is employed in this study due to its widespread acceptance and practicality in life cycle assessment. The LCA models are implemented using the Brightway 2.5 framework, enabling detailed and transparent analysis. Impacts are quantified using the IPCC 2021, Climate Change, GWP100 method, which offers the most up-to-date characterization factors for evaluating global warming potential over a 100-year timeframe. The choice of manufacturing locations in the LCA models followed the availability of regionalized datasets in the Ecoinvent 3.9 database. Priority was given to Switzerland (CH), reflecting the geographic context of the project. Where CH-specific datasets were unavailable, Germany (DE) was selected as a representative alternative. If neither CH nor DE datasets were provided, Rest of Europe (RER) was used as a proxy. This hierarchical approach ensures that the modeling remains consistent with data availability while maximizing regional relevance.

To ensure credibility, the LCA models developed in this work were validated against peer-reviewed literature and relevant case studies. While literature provides valuable reference points for specific technologies and sizes, it generally reports results as single values or case-specific assessments. Such data cannot be directly used to represent the broad range of installed capacities and configurations considered in this project.

Therefore, parametric LCA models were developed in the Brightway framework to generate capacity-dependent power law functions, presented by equation 6. These functions allow consistent scaling of



Scope 3 emissions across different technology sizes. The parameters of the power law relations (coefficients a and b) were derived from regression analysis of LCA results generated over a range of installed capacities for the chosen technologies (for example, HP sizes between 50 kW and 1000kW) and are reported in the appendix. This approach ensures both flexibility in modeling and alignment with literature benchmarks, while providing the functional relationships necessary for multi-scenario optimization.

$$EI_{i,scope3} = a \times Functional\ unit_i^b \quad (6)$$

While the parametric models used in this study offer flexibility, it is important to acknowledge that linear assumptions in material requirements for some components introduce an error. The following section presents the system boundaries, life cycle phases, specific modeling considerations, and the share of LCA impact for prominent Technosphere flows for all the technologies considered in this project.

Heat exchanger

HEX consists of chemically integrated stainless steel and copper. The raw material extraction and manufacturing are modeled for copper and low-alloyed steel for HEX production. The HEX assembly is modeled at the location in Switzerland, and packaging materials after the assembly are modeled separately, along with the land occupation for the assembly site. HEX mass is chosen as a functional unit, which is estimated as a function of HEX area. The system boundary and lifecycle phases considered for HEX are presented in Figure 7.

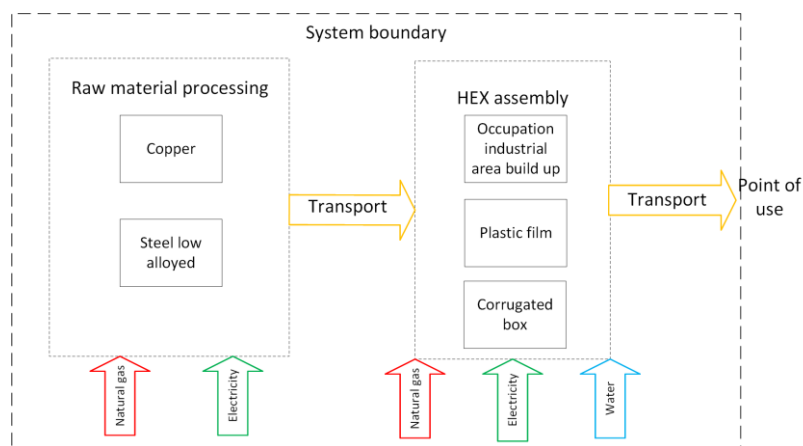


Figure 7. System boundary and life cycle stages for heat exchanger

The quantities of required materials are estimated based on the parametric relations provided by Ong et al.[15]. LCA scores for each Technosphere flow and total LCA score is then estimated for a range of heat exchanger sizes using the Brightway model and LCI data from EcoInvent database (see appendix for detailed parametric model and LCA scores of all prominent Technosphere flows). The largest share of life cycle emissions from HEX manufacturing is contributed by the manufacturing and assembly of heat exchangers, followed by steel production (Figure 8). These emissions are mainly driven by electricity consumption during the manufacturing and assembly process.

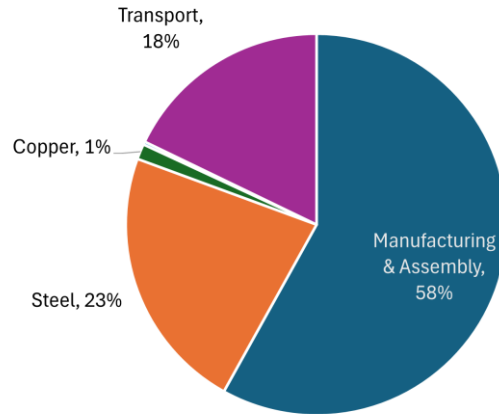


Figure 8. Share of life cycle emissions from various life cycle stages for HEX.

Heat pump

The HP system analyzed in this study consists of key components, including a condenser, evaporator, compressor, piping, and an expansion valve, with a working fluid circulating during operation. The life cycle phases included in the HP model—raw material processing, component manufacturing, assembly, and transport—are depicted in Figure 9. These stages are evaluated within a cradle-to-end-use system boundary to estimate the upfront Scope 3 emissions associated with HP manufacturing.

The material requirements for raw material extraction and component manufacturing are estimated based on the parametric relations proposed by Autelitano et al. [19]. The LCI data for the estimated quantities is then sourced from the Ecoinvent 3.9 database, with scaling factors provided in the Appendix. The HP manufacturing and assembly is modeled at a facility located in Switzerland, and the emissions from electricity consumption during assembly are based on the average Swiss electricity emission factor. Transport emissions include the movement of raw materials to manufacturing sites, and the assembled HP to the point of use.

To harmonize the functional unit across cost and environmental impact functions, the condenser capacity (kW) is used as the reference unit. The total HP mass is estimated using the empirical relationship proposed by Caduff [20] (Equation 7). The resulting environmental impact function based on the modeled LCI data is presented as Equation 6.

$$Mass_{HP} = (HP_{cond} \times 0.3539) - 18.3 \quad (7)$$

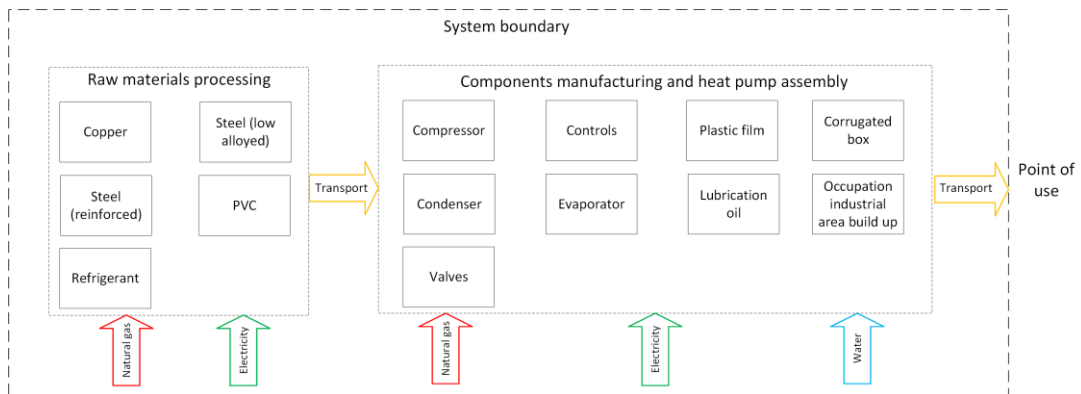


Figure 9. System boundary and life cycle stages for heat pump manufacturing

The LCA results show that HP component manufacturing and assembly accounts for the largest share of life cycle emissions, contributing approximately 87% of the total impacts (Figure 10). This is primarily



driven by natural gas combustion during the manufacturing and assembly phase (for processes such as, brazing, annealing, coating, curing, casting, surface finishing, etc.), highlighting its significant role in HP's manufacturing footprint. The second largest contributor is steel manufacturing, responsible for 8% of emissions, followed by insulation production (4%). The contributions of PVC and transportation are comparatively minor, each representing less than 0.2% of the total emissions (see appendix for detailed parametric model and LCA scores of all prominent Technosphere flows).

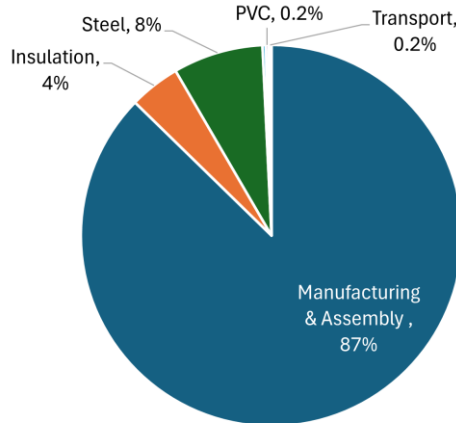


Figure 10. Share of life cycle emissions from various life cycle stages for heat pump

Solar thermal

The ST systems analyzed in this study consist of key components such as solar collectors, storage tanks, and auxiliary components, including piping, insulation, and pumps. The system boundary and life cycle phases considered for the ST systems are depicted in Figure 11. Two ST systems are modeled for different operating temperature ranges:

1. Flat plate collectors (FPC) for lower-temperature applications.
2. Vacuum tube collectors (VTC) for medium and high-temperature applications.

The functional unit for both systems is defined as the area of solar collectors (m^2) to harmonize cost and environmental impact assessments. The material requirements for thermal storage, piping, and other auxiliary components are estimated as a function of the solar collector area using parametric relationships derived from the literature (details provided in the Appendix). The system boundary and life cycle stages for the solar collectors are presented in Figure 11.

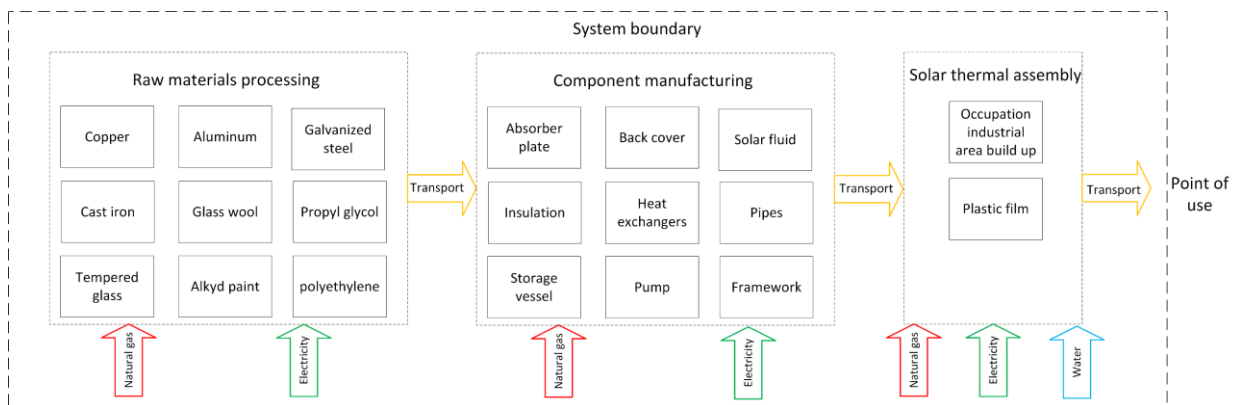


Figure 11. System boundary and life cycle stages for manufacturing of solar thermal unit



For ST systems with flat plate collectors, the manufacturing of the collectors represents the largest share of the life cycle impacts, accounting for 43% of the total emissions (Figure 12 (a)). This is followed by aluminum processing (25%) and assembly (20%). The flat plate collector is modeled with a copper absorber and is assumed to be manufactured in Switzerland. The emissions during the production of flat plate collectors are primarily driven by heat production using hard coal in industrial furnaces for flat glass production, which significantly contributes to the overall impact.

In contrast, for ST systems with vacuum tube collectors, the aluminum processing required for the framework dominates the life cycle emissions, contributing 36% of the total impacts (Figure 12 (b)). The assembly phase accounts for 28%, while glass tube manufacturing contributes 17%. Aluminum processing is modeled in Germany, where emissions are largely attributed to electricity consumption during the production phase.

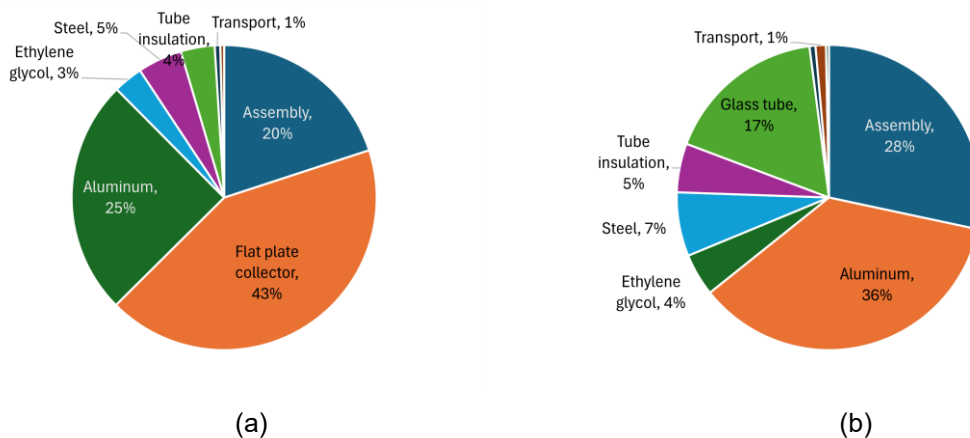


Figure 12. Share of various phases in LCA impact for Solar thermal system with (a) flat plate collector (b) vacuum tube collector.

Biomass boiler

A biomass boiler is modelled as a typical boiler vessel with additional contributions from the transport of required biomass for different sizes of biomass boilers. The system boundary and life cycle stages for biomass boilers are presented in Figure 13. Like other technologies considered for this project, the manufacturing is assumed to be located in Switzerland. Three different sizes of biomass boilers are modeled to estimate the LCA impact.

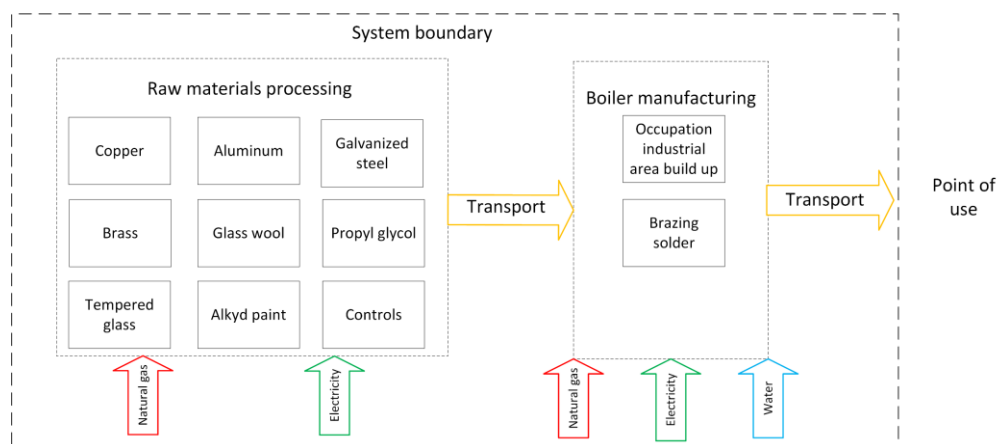


Figure 13. System boundary and life cycle stages for biomass boiler

The largest share of overall life cycle emissions is contributed by steel production (Figure 14), which is modelled at RER (Rest of Europe) location. The assembly represents the second-largest share of



emissions. The emissions related to steel manufacturing are mainly caused by pig iron production and iron sinter production.

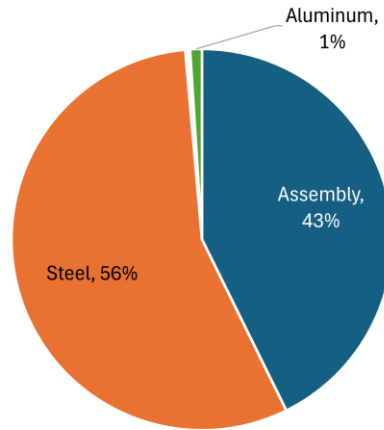


Figure 14. Share of life cycle emissions from various life cycle stages for biomass boiler

2.2 Framework

The overall framework is divided into three distinct phases (see Figure 15). This framework leverages Pinch Analysis as the foundation, followed by LCA and economic assessment of EEMs and technologies, and identification of trade-offs between environmental impact and economics using MOO. The following section elaborates on each phase, describing how the integration strategies are derived, evaluated, and optimized for cost and environmental impact. These three phases are implemented sequentially. The integration framework is designed to identify all technically feasible configurations of HR, ECTs, and RTs. It supports the evaluation of multiple integration sequences, conventional and non-conventional, by combining PA with heuristic and optimization principles.

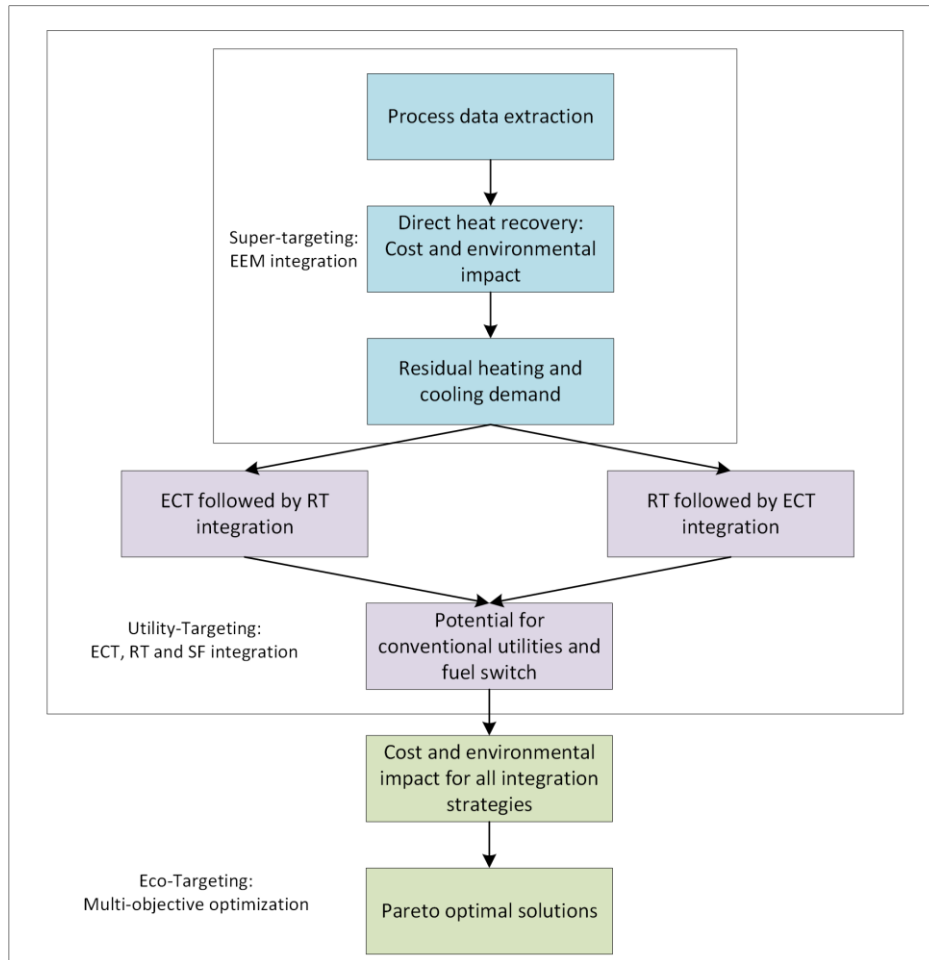


Figure 15. Simplified workflow of the integration framework

2.2.1. Phase 1 Super-Targeting - EEM integration

While the fundamentals of the framework are similar for continuous and non-continuous, the PA tools to identify the potentials heat recovery (direct and indirect) and technology integration differ for two process types.

Direct heat recovery for continuous process

For the continuous process, the potential for direct heat recovery (DHR) is estimated using the composite curves (CC) (Figure 16). DHR potential and corresponding HEN area are calculated by assuming maximum theoretical HR and vertical heat transfer (spaghetti design [21]). This assumption simplifies the objective space and reduces the computational burden in the subsequent optimization phase.

The HEN area is estimated for various global minimum approach temperatures (ΔT_{\min}) ranging from 5 °C to 20 °C. This estimation allows the framework to assess the feasibility of different approach temperatures and evaluate how reducing or increasing ΔT_{\min} influences the efficiency of HR. Smaller values of ΔT_{\min} typically lead to more efficient HR but increase the capital cost due to the larger HEN area required.

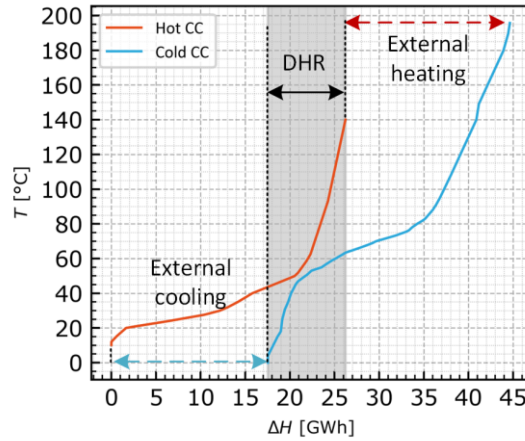


Figure 16. Composite curves for direct heat recovery potential in continuous process

Indirect Heat Recovery for non-continuous system

Contrary to the continuous processes, in non-continuous processes, heat sources and sinks do not occur simultaneously, and the temporal shift between demands occurs and can be high. Therefore, process heat integration can generally be achieved only via indirect heat recovery (IHR) i.e., Thermal Energy Storage (TES). The time averaged model (TAM), developed to handle the non-continuous process is the foundation for identifying IHR potential. In TAM, a representative of one repetitive period of the process is considered at a time. The heat duty of each process stream is averaged over this period, giving the maximum HR potential, neglecting time constraints.

The IHR potential in this project is estimated using ISSPs, which are based on the TAM approach and allow for the integration of TES into non-continuous processes [22, 23]. It represents heat sources and sinks over a batch process; in case of cyclic repetition the periods are called Stream-wise Repeated Operation Period (SROP). The used ISSP methodology ensures technical feasible solution with guaranteed heat balances and as-low-as-possible complexity. An example of the ISSP can be seen in Figure 17, the ISSP resembles CCs, but due to the consideration of a temporal view, the ISSP typically displays the demands in terms of thermal energy [kWh]. The overlap between the hot and cold curve is a measure of the achievable IHR and the black lines within the overlap region represent the transferred heat in the storage system and the Intermediate Loops (ILs) respectively. The method is well established and is used today by engineers for the dimensioning of TES systems using the software PinCH.

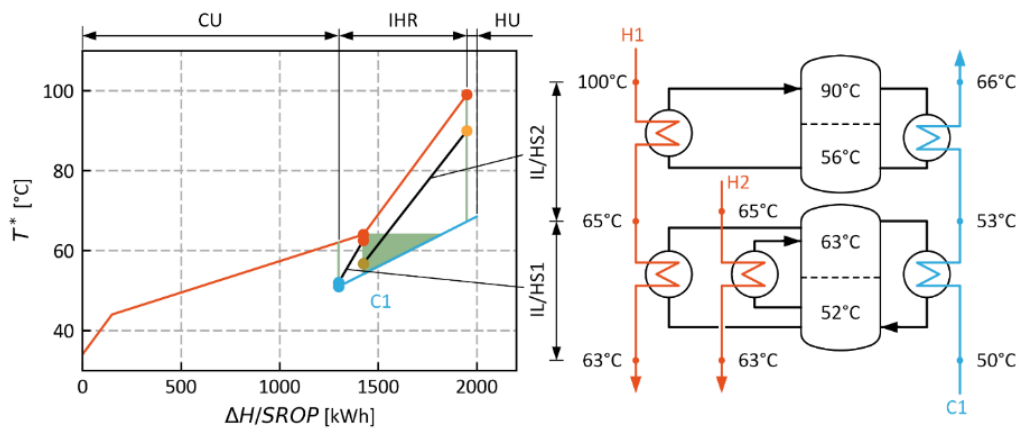


Figure 17: Storage integration for non-continuous processes using ISSP

2.2.2.Phase 2 Utility Targeting: ECT, RT, and Sustainable Fuel integration



Continuous process

In the utility targeting phase, the residual energy demand remaining after DHR is extracted from the hot and cold CCs for each ΔT_{\min} value. In the context of this project, maximum HR is assumed to ensure that the potential for internal energy savings is fully exploited before introducing external technologies. This means that the residual source sink profiles (SSPs) represent only the portion of energy demand that cannot be fulfilled through HR (see Figure 18).

Various integration points (IPs) are identified on the Y axis of SSPs. These IPs are essentially the target temperatures of the process streams that are not included in the DHR. Thus, the IPs represent suitable locations in the process for additional technologies, such as ECTs (e.g., heat pump) or RTs (e.g., solar thermal), can be introduced to meet the remaining heating or cooling demands. The temperature constraints for each technology are carefully set to ensure that integration occurs within the working temperature range of each technology without violating the golden rules of Pinch Analysis (Table 1).

For each IP, the corresponding heating and cooling capacities of ECTs and RTs are estimated using the enthalpy coordinates (ECs) on the x-axis of the SSP. This allows for precisely determining the energy that needs (kWh) to be supplied by each technology to satisfy the residual energy demand. The installed capacities (kW) for ECTs and RTs are then estimated based on the energy contribution for the given technology and annual operating hours. Any remaining heating or cooling demands after integrating these technologies are fulfilled by conventional utilities (e.g., natural gas (NG)) or sustainable fuels (e.g., biomass (BM)).

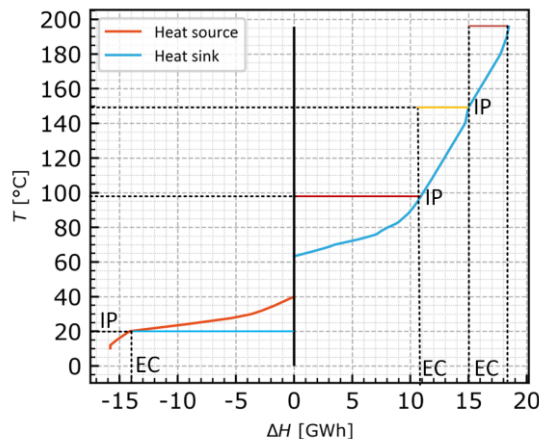


Figure 18. Identification of ECT and RT potentials based on residual source sink profiles

Non-continuous process

Due to the temporal shift as mentioned in the previous subsection, all the ECTs and RTs are also only feasible using a TES and therefore, at least partly IHR is needed for each solution. Thus, IHR replaces HR explained for continuous processes and the potential for ECTs and RTs is estimated using the ISSPs instead of SSPs.

Integration of ST as a heat source is modelled in the same way as any other heat source from which heat can be extracted and stored in the TES (e.g., hot streams). However, due to its nature as a soft stream, it does not have to be cooled. By integrating an additional ST stream, the ISSPs for a given system change, resulting in another possible level of IHR.

The HP integration in this projects follows a similar method as outlined in Agner et al. [24]. i.e., the HP integration potential is estimated based the ISSPs with two different integration approaches:

- Integration of HP into a secondary heat exchanger and storage network (HESN) (additional) to the IHR HESN,



- Integration of HP into the same IHR HESN of the process.

The first option leads to an additional and, thus separate, TES system for the HP, which, in theory, means less complexity and thus easier controllability. The second option allows HP to be closer to the process and therefore a more efficient operation, however, at the cost of an increased complexity of the system.

In both cases, the process with predefined IHR, either with or without ST integration, lies the basis for integration. A complete explanation of the integration process of the HP can be found in Integration of "Heat Pumps and Thermal Energy Storages in Non-Continuous Industrial Processes – HPTES" [24].

2.2.3.Phase 3 Eco-Targeting: Optimization framework

The eco-targeting phase evaluates the economic and environmental impacts of each potential integration configuration and identifies the Pareto optimal combination of technologies. In order to reduce the computational load, the optimization algorithm is divided into two parts. The first part consists of deterministically evaluating the objective functions for a set of identified decision variables (**Erreur ! Source du renvoi introuvable.**), followed by a non-dominated sorting algorithm to find the set of Pareto optimal solutions (referred to as configurations henceforth). The CAPEX and OPEX are estimated based on the installed heating/cooling capacities identified in the previous phase. CAPEX includes the investment required for equipment, such as HPs, ST collectors, and HEXs, along with the other cost components (see Appendix), whereas OPEX includes the annual energy consumption and maintenance costs of the equipment. The CAPEX is converted to an annualized investment cost based on equation 1. CAPEX and OPEX, thus estimated for each technology i , allow the formulation of the cost objective for a configuration including n technologies presented by equation 8.

$$TAC = \sum_{i=1}^n CAPEX_{annual,i} + \sum_{i=1}^n OPEX_i \quad (8)$$

Environmental Impact is assessed based on the direct emissions from fuel combustion (scope 1), indirect emissions from electricity use (scope 2), and lifecycle emissions associated with manufacturing and transporting equipment (scope 3). The direct emissions are estimated based on the type of fuel consumed and the corresponding CO₂ emissions factor. Scope 2 emissions are estimated based on CO₂ emissions factor of the electricity grid, whereas the Scope 3 emissions are estimated based on the LCA analysis of the technology manufacturing (see section 2.1.4). This leads to the formation of the environmental objective function presented by Equation 9.

$$TAEI = \sum_{i=1}^n EI_{scope 1} + \sum_{i=1}^n EI_{scope 2} + \sum_{i=1}^n EI_{scope 3} \quad (9)$$

Each combination of ΔT_{min} and integration point results in one possible configuration for integrating EEMs, ECTs and RTs. These configurations form an objective space in which each point represents a unique combination of energy technologies and their corresponding total annual cost (TAC) and total annual environmental impact (TAEI).

Equality constraints are introduced to ensure the total installed capacity of EEMs, ECTs, RTs, and conventional utilities equal the hot and cold utility requirements identified after MER HEN and are presented by equations 10 and 11.

$$Q_{HP,cond} + Q_{ST} + Q_{HU,res} = Q_{HU,min} \quad (10)$$

$$Q_{HP,evap} + Q_{CU,res} = Q_{CU,min} \quad (11)$$

Where,

$Q_{HP,cond}$ = Heat provided by HP condenser (kWh)

Q_{ST} = Heat provided by solar thermal system (kWh)

$Q_{HU,res}$ = Residual heating demand after EEM and RT integration (kWh)



$Q_{HU,min}$ = Minimum heating demand after the identification of DHR potential (kWh)

$Q_{HP,evap}$ = Heat removed by HP evaporator (kWh)

$Q_{CU,res}$ = Residual cooling demand after EEM and RT integration (kWh)

$Q_{CU,min}$ = Minimum heating demand after the identification of DHR potential (kWh)

Inequality constraints are imposed on each decision variable to make sure the ECTs and RTs are integrated within the working temperature ranges presented in Figure 2 and are presented in **Erreur ! Source du renvoi introuvable.**

Table 1: Decision variables and inequality constraints for optimization.

EEM/ Technology	Decision variable	Continuous process constraints	Non-continuous process constraints
HR	Minimum approach temperature (ΔT_{min})	$5\text{ }^{\circ}\text{C} \leq \Delta T_{min} \leq 20\text{ }^{\circ}\text{C}$	
	Amount of indirect HR (IHR_{set})	-	$0\% \leq IHR_{set} \leq 95\%$
Solar thermal (flat plate)	Integration temperature (T_{solar_fp})	$Pinch \leq T_{solar_fp} \leq 100\text{ }^{\circ}\text{C}$	$Pinch \leq T_{solar_fp} \leq 100\text{ }^{\circ}\text{C}$
Solar thermal (vacuum tube)	Integration temperature (T_{solar_vt})	$100\text{ }^{\circ}\text{C} \leq T_{solar_vt} \leq 150\text{ }^{\circ}\text{C}$	-
SHP condenser	Integration temperature (T_{cond_shp})	$Pinch \leq T_{cond_shp} \leq 100\text{ }^{\circ}\text{C}$	$Pinch \leq T_{cond_shp} \leq 100\text{ }^{\circ}\text{C}$
HHP condenser	Integration temperature (T_{cond_hthp})	$100\text{ }^{\circ}\text{C} \leq T_{cond_hthp} \leq 150\text{ }^{\circ}\text{C}$	-
HP evaporator	Integration temperature (T_{evap})	$T_{h_min}^* \leq T_{evap} \leq Pinch$	$T_{h_min}^* \leq T_{evap} \leq Pinch$

*Minimum target temperature for hot streams

Pareto front and Optimization

During the second part of the optimization algorithm, a non-dominated sorting algorithm is employed to identify the Pareto front of optimum configurations. The Pareto front represents the set of configurations where no single configuration is better in both objectives (i.e., cost and environmental impact) simultaneously. In other words, moving along the Pareto front involves a trade-off—reducing environmental impact will typically increase cost, and vice versa. The Pareto front helps in understanding the trade-offs between cost and environmental impact, providing decision-makers with a clear visualization of the most efficient and sustainable configurations of measures and technologies available for decarbonizing the industrial process. Each configuration from the objective space evaluated during the first part is compared with every other configuration, leading to the identification of a set of Pareto optimal configurations. This is repeated for every approach and scenario described in the section 2.3 and ultimately, an overall Pareto front is identified.

2.3 Integration approach and scenario design

The technologies considered for continuous process in this project can provide heat up to 300 °C and cooling demands down to -20 °C. Potentially, multiple technologies can be employed for heating at low (<100 °C) and medium temperature (100 °C to 150°C) ranges. The impact of different integration sequences for technologies is analyzed using two primary approaches, as shown in Figure 19. Each approach aims to assess the trade-offs between environmental impacts and costs for various combinations of EEMs, ECTs, and RTs:

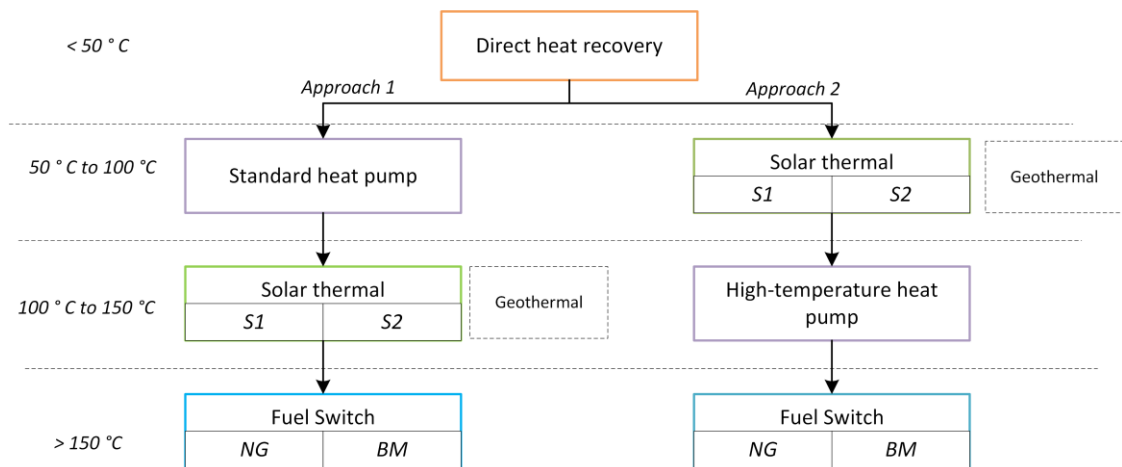


Figure 19. Integration approaches and scenarios.

Approach 1: Energy Conversion Technologies First, Renewables Second

In this approach, ECTs, such as HPs, are integrated first to fulfil the heating demands at lower temperatures (<100 °C). Following this, RTs, such as ST systems, are used to meet the medium temperature demands (100 °C to 150 °C). Finally, for higher temperature requirements (>150 °C), traditional utilities (e.g., NG) or sustainable fuels (e.g., BM) are employed to provide the necessary energy.

This strategy prioritizes using efficient energy conversion technologies for lower temperatures, ensuring maximum effectiveness in cost and environmental impact reduction. The subsequent use of renewables at medium temperatures further reduces dependency on fossil fuels, and sustainable fuels are only considered for the highest temperature needs where other technologies may not be sufficient.

Approach 2: Renewable Technologies First, Energy Conversion Technologies Second

In this approach, the RTs are integrated first to address the lower temperature demands (<100 °C). After meeting the low-temperature needs, HTHP or other ECTs are used for medium temperature demands (100 °C to 150 °C). For high-temperature demands (>150 °C), this approach, like Approach 1, relies on traditional utilities or sustainable fuels.

By prioritizing renewables at lower temperatures, this approach aims to maximize the use of sustainable energy sources early in the process. The remaining demands at medium and high temperatures are then managed using a combination of energy conversion technologies and sustainable fuel options, creating a different balance between cost and environmental impact compared to Approach 1.

In both approaches, the integration begins with the aid of PA tools, ensuring that internal heat integration is maximized before any external technologies are introduced.



Scenario design to account for resource constraints

In addition to the typical working temperature ranges for ECTs and RTs, the feasibility of the integration strategy depends on certain physical resources, such as the availability of clean electricity, solar irradiance, or BM. To analyse the effect of these resource constraints on the integration approaches under different conditions, several scenarios were developed. These scenarios simulate typical resource constraints faced by industries, considering the following key factors:

1. Availability of solar irradiance: Since solar energy availability is geographically dependent, different irradiance levels were considered to estimate the effect of ST integration. The base case assumes the average annual irradiance of the case study location. This simplification allows for a consistent comparison of integration strategies, while recognizing that actual solar performance depends on hourly and seasonal variability, as well as site-specific factors¹.
2. Access to clean electricity: The scenarios account for differences in access to clean electricity, which directly impacts Scope 2 emissions generated by HPs. The base case scenario is the Scope 2 emissions reported for the chosen case study.
3. Biomass availability: The availability of BM as a sustainable fuel also varies, influencing the choice of fuel for higher temperature demands.

By simulating these resource constraints, the scenarios enable a more realistic evaluation of the performance of each integration approach. This ensures that the proposed configurations are not only technically feasible but also environmentally sustainable and cost-effective under typical industrial conditions. Following this approach, overall, ten scenarios are evaluated. Table 2 presents the nomenclature followed to identify the configurations resulting from each scenario.

Table 2. Nomenclature for scenarios

Scenario nomenclature*	Descriptions
A1-S1-NG or A1-S2-NG	Direct heat recovery followed by standard heat pump, solar thermal, natural gas
A2-S1-NG or A2-S2-NG	Direct heat recovery followed by, solar thermal, high-temperature heat pump, natural gas
A1-S1-BM or A1-S2-BM	Direct heat recovery followed by standard heat pump, solar thermal, biomass & natural gas
A2-S1-BM or A2-S2-BM	Direct heat recovery followed by, solar thermal, high-temperature heat pump, biomass & natural gas
*S1 indicates solar thermal integration under low solar irradiance. S2 indicates high solar irradiance	

¹ In practice, solar irradiance should be modelled using temporal profiles (monthly or hourly) to capture realistic variations. As Eco-Targeting is a framework, users can replace the average values with site-specific irradiance data or add scenarios representing different solar conditions to increase the fidelity of results.



3 Results and discussion

The framework developed in this project is applied to two case studies. To ensure the robustness of the framework, continuous and non-continuous processes are selected as case studies. The following section presents the results of implementing the Eco-Targeting framework and related discussion.

3.1 Non-continuous case study

3.1.1. Case study description

To apply the derived methodology for non-continuous processes the following case study has been conducted. The case study is based on a PA of the large Swiss dairy producer with a production capacity of 26 t/y and 150-160 Mio CHF/a turnover. The data used from the case study is extracted from WPTES [24]. The considered process requires a total of 4.5 MWh of cooling and 4.9 MWh of heating which can be broken down to the processes according to Figure 20.

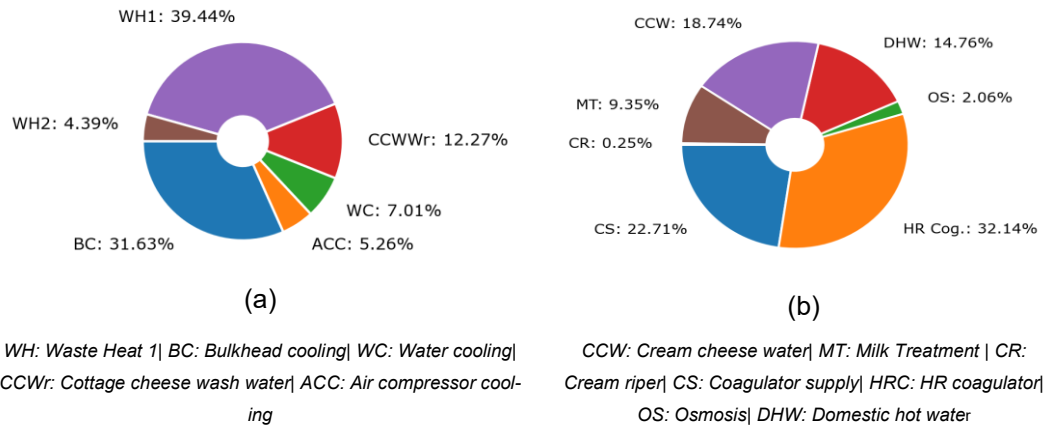


Figure 20: Process-wise energy demand for (a) cooling & (b) heating.

Based on the GCC (Figure 21) and the typical temperature range, the process has a substantial potential for HP and ST integration. The pinch temperature is identified at 30°C.

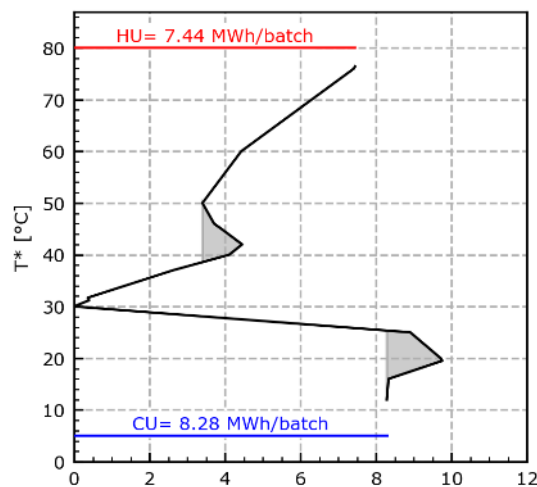




Figure 21: Grand Composite Curve of the non-continuous case study



As it is a batch process, each stream occurs at a certain time period (from t_{start} to t_{end}). The mass flow (\dot{m}) as well as the specific heat capacity of all streams are given. The process requirements can be seen in Table 3. A supplementary graphical representation of the batch process as a Gantt chart is presented in Figure 22.

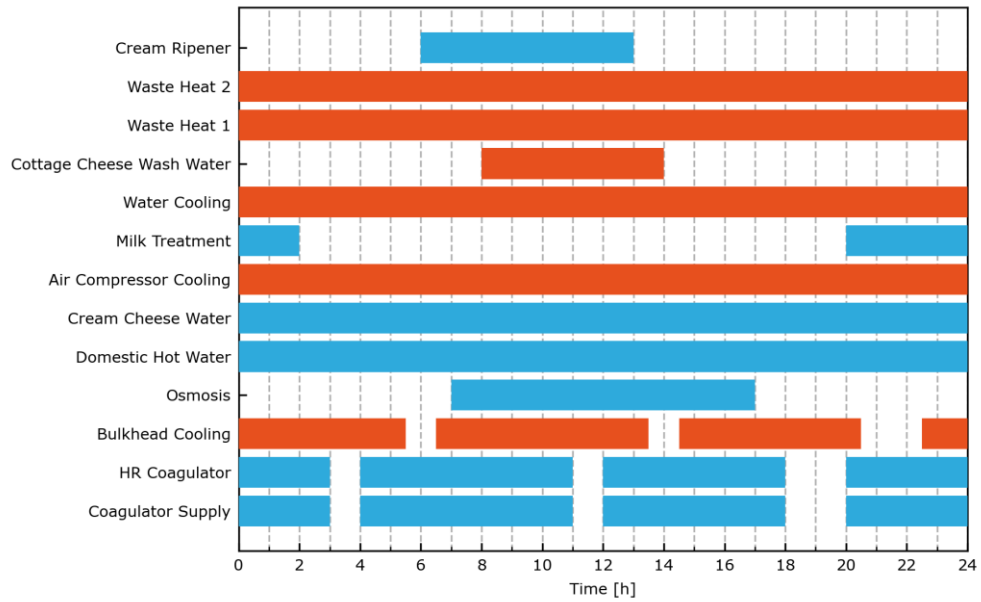


Figure 22: Gantt chart of the non-continuous case study



Table 3. Stream table for the non-continuous case study.

Stream	T_{α} [°C]	T_{ω} [°C]	\dot{m} [kg/s]	c_p [kJ/kg]	t_{start} [h]	t_{stop} [h]
Heating Requirements						
Coagulator Supply 1	30	42	4.2	4.2	0	3
Coagulator Supply 2	30	42	4.2	4.2	4	11
Coagulator Supply 3	30	42	4.2	4.2	12	18
Coagulator Supply 4	30	42	4.2	4.2	20	24
HR Coagulator 1	16	31.2	4.7	4.2	0	3
HR Coagulator 2	16	31.2	4.7	4.2	4	11
HR Coagulator 3	16	31.2	4.7	4.2	12	18
HR Coagulator 4	16	31.2	4.7	4.2	20	24
Osmosis	12	45	0.3	4.2	7	17
Domestic Hot Water	37	76.4	0.7	4.2	0	24
Cream Cheese Water	46	76	1.2	4.2	0	24
Milk Treatment MB1	30	40	6.9	4.2	0	2
Milk Treatment MB1	30	40	6.9	4.2	20	24
Cream Ripener	20	30	0.2	4.2	6	13
Cooling Requirements						
Bulkhead Cooling 1	31.7	19.5	6.3	3.85	0	5.5
Bulkhead Cooling 1	31.7	19.5	6.3	3.85	6.5	13.5
Bulkhead Cooling 1	31.7	19.5	6.3	3.85	14.5	20.5
Bulkhead Cooling 1	31.7	19.5	6.3	3.85	22.5	24
Air Compressor Cooling	60	40	0.5	4.2	0	24
Cottage cheese wash water	50	20	3.3	4.2	8	14
Waste Heat	30	25	16.1	4.2	0	24
Waste Heat	60	30	0.3	4.2	0	24

As the main focus of the project is the comparison of different energy integration variations and their impact on both the economic and ecological viability of the systems, the utility costs and emission factors can be found in Table 4. Non-continuous case study assumptions. Additionally, it is assumed that all implemented HPs operate with a 2nd law efficiency of 55%.

Table 4. Non-continuous case study assumptions

Elements	Prices (CHF/MWh)	Reference	Emissions factors (kg-CO ₂ /kWh)	Reference
HU	35	[24]	202	Pinch Report
CU	12	[24]	0	Pinch Report
Electricity	120	Pinch Report	0	[25]

For economic considerations, the interest rate of 10% is assumed. The lifetimes assumed for each technology are presented in the appendix. It should, however, be noted that these assumptions have been chosen based on various research papers and Pinch reports and do not necessarily reflect practical considerations at the company chosen for the case study. These assumptions provide consistency across technologies for the purpose of developing and demonstrating the framework. In practice, com-



panies apply internal depreciation periods that may differ from the technical lifetimes assumed in this report. Since Eco-Targeting is designed as a decision-support framework, users can adapt depreciation periods, discount rates, and cost functions to reflect their specific accounting practices and investment guidelines.

3.1.2. Results

As outlined in the methodology section, as a first step, IHR is applied individually, leading to a set of configurations with various levels of IHR integrated. To limit the subsequent computational effort, the number of configurations is controlled by setting the number of steps between no IHR and 95% maximal possible IHR² to 10., leading to values between 0 kWh/batch up to 8'620 kWh/batch. The relationship between the IHR and the annual costs and total annual emissions is presented in Figure 23.

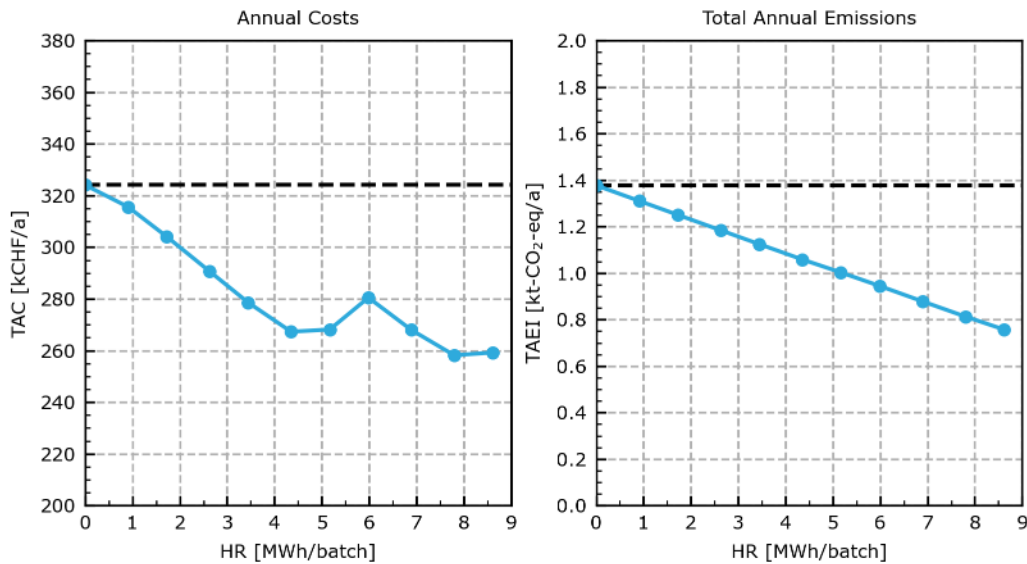


Figure 23: Relation between annual costs, total annual emissions, and IHR

With increasing IHR, both the TAC and TAEI decrease, caused by the reduction in the utility demand. Examining the annual costs reveals a shallower decrease, along with an increase in costs around 4 MWh/batch. This can be accounted for by the increase in required storage systems, whose costs do not scale linearly to the IHR.

By including ST, the objective space evolves with multiple possible configurations. At this stage, several decision variables are involved, as not only the IHR, but also the solar irradiance, the temperature, and the collected solar energy can be varied, leading to a total of 3'714 configurations with ST and IHR.

As described in the section 2.2.2 the ST integration is implemented as an additional constant heat source, which can be stored in the TES. For the example case described, it is assumed that there is constant Irradiance for 8h per day, which represents a mean day in spring or fall.

When plotting the results (Figure 24), only a small share of configurations outperforms the base case without IHR or ST. In Switzerland, where annual solar irradiance is relatively low, ST integration generally increases both costs and environmental impacts due to its comparatively high Scope 3 emissions. If we exclude configurations that perform better solely because of IHR (with little or no ST contribution), the analysis indicates that ST becomes a viable option only at high irradiance levels (>1,000 kWh/m²·a), where it can offer both economic and ecological benefits.

² 95% has been chosen due to the process characteristics, which lead to non-feasible configurations above 95% due to too small ΔT

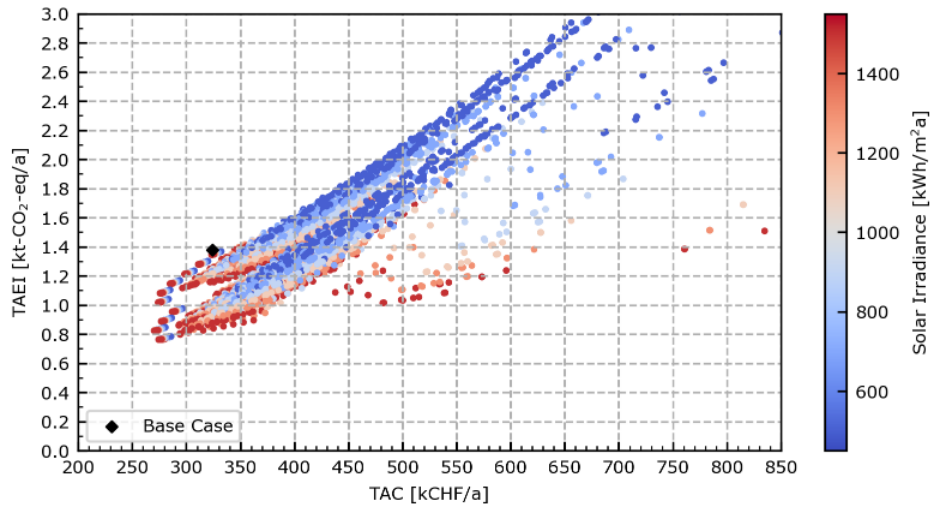


Figure 24: Objective space with all ST configurations for non-continuous process

Feasible HP configurations were generated by varying three parameters: condenser temperature, evaporator temperature, and condenser load. For each condenser temperature, the corresponding heat demand at that level was determined, and only evaporator temperatures with sufficient excess heat were considered. Similarly, configurations were also categorized by evaporator temperature, where the available excess heat defined the evaporator load and the resulting condenser load was calculated. Finally, different condenser loads, expressed as shares of the heating demand, were tested to cover the full range of technically possible configurations. This systematic variation resulted in 864 viable HP configurations.

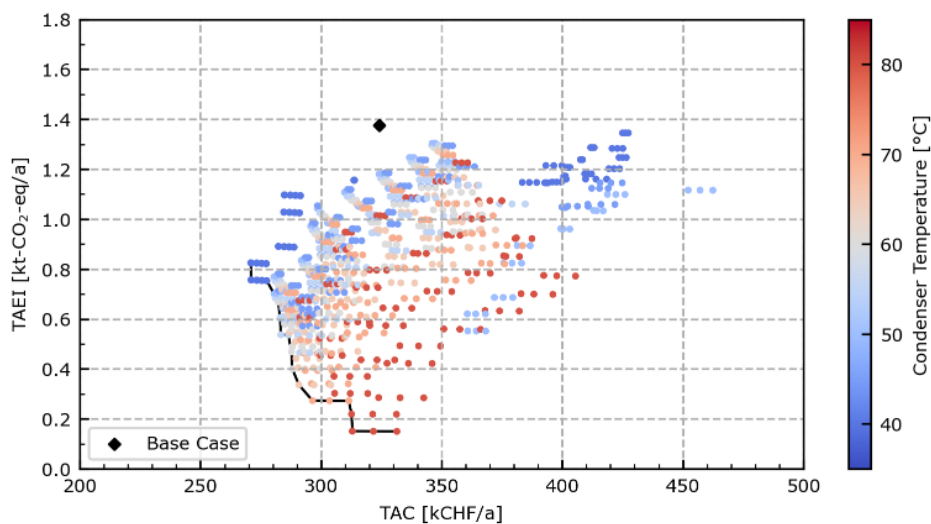


Figure 25: Objective space with all HP configurations for non-continuous process.

Compared to ST configurations, HPs lead to lower TAC as well as lower overall emissions. All configurations, including HP, are better in environmental impact than the base case (Figure 24) due to the replacement of the HU with the HP. This also leads to the result that higher condensation temperatures lead to lower TAEI, as more heat can be provided by the HP. On the other hand, the variation of the evaporating temperature has not impact on the emissions, as currently CU is already provided without any emissions.



The evaporation temperature affects the system's costs, as a decrease in evaporation temperature results in increased lift and, consequently, decreased HP efficiency, which in turn leads to higher operational costs. A higher integration at a certain temperature level, i.e., more heat is provided by the HP, leads to higher TAC, as the HP must be larger.

Combining all the configurations leads to a total of 18'723, which range from TAC between CHF 258'000 and 1'142'000 CHF. Figure 26 shows that the distribution between the different integration approaches.

Due to the high costs and EI, configurations with ST are low in number, compared to the vast number of configurations with HP at the Pareto front. The combined configurations (HP, ST and IHR) lay somewhere in between the HP and IHR. The integration of a HP can counteract the increased costs of ST but cannot outperform it. The most economical configurations are systems with only IHR, mainly because of the low investment costs. The limited integration of alternative HU and CU supply beyond a certain point lead to a minimal decrease in environmental impact (region of diminishing returns).

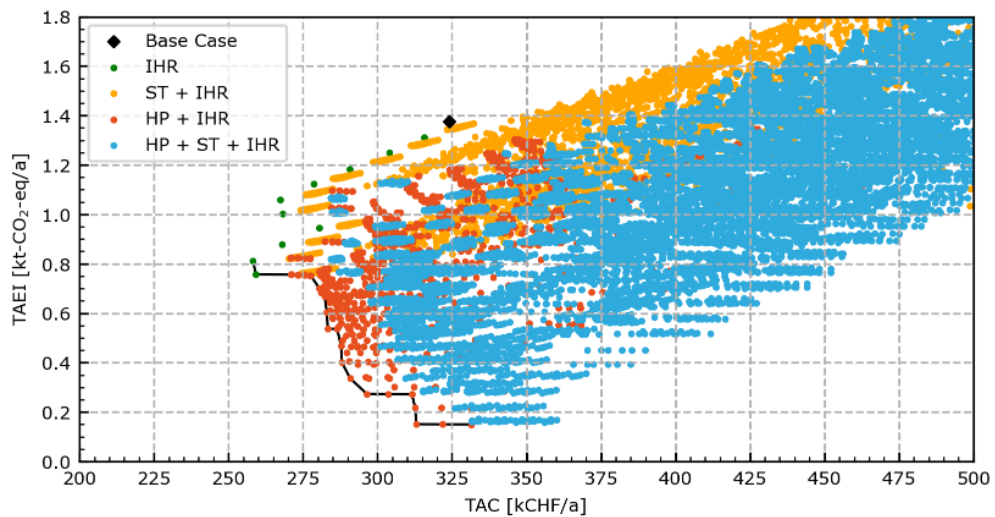


Figure 26: Objective space with all configurations and overall Pareto front for non-continuous process

To further investigate the Pareto front, three specific configurations that represent the minimum cost, the minimal emissions and the knee-point are chosen and marked on the Pareto front in Figure 27. Detailed techno-economic data and estimations related to these configurations are presented in Table 5.

All configurations that appear on the Pareto front lead to lower TAC compared to the current situation (base case). The minimum cost configuration optimizes the IHR to the maximum possible capacity. However, with a relatively small reduction in the hot and cold utility demand. This results in a small investment cost but also a small decrease in the TAEI. In conjunction with all the other configurations on the Pareto front, it can be observed that IHR always results in the most economical reduction of Scope 1 emissions and is therefore a main component in all ideal configurations.

In all three chosen configurations for further investigation, IHR is maximized, aligning with the trend that IHR is the most economical way to reduce the environmental impact. Nevertheless, to further reduce the TAEI (i.e., deeper decarbonization), the HU supply must be substituted, as it is the main source of emissions. In the minimum emissions case, the integration of a HP leads to the highest amount of emissions reduction. The decrease in TAEI stagnates after the knee point, and the costs for any additional reduction in emissions increase disproportionately. Due to this stagnating reduction in environmental impact, the minimum emissions case has only minimal decreases in emissions compared to the configurations that came before it.

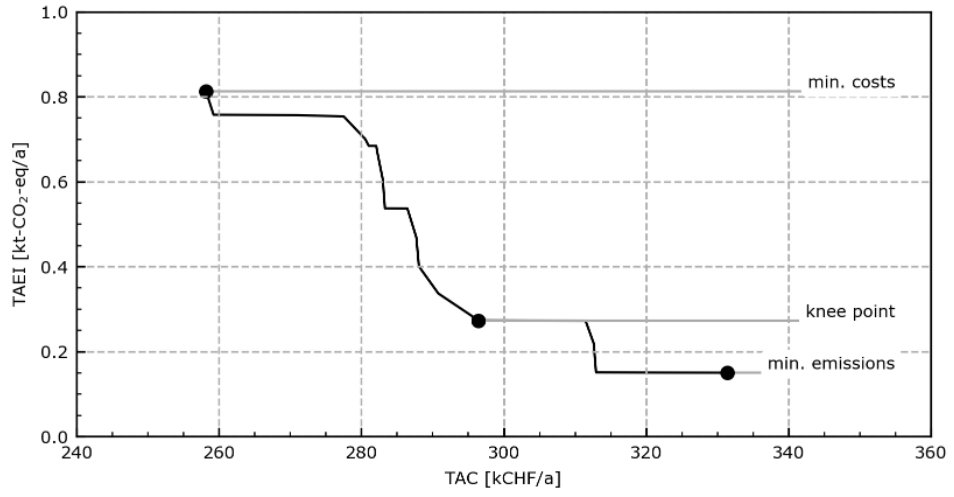
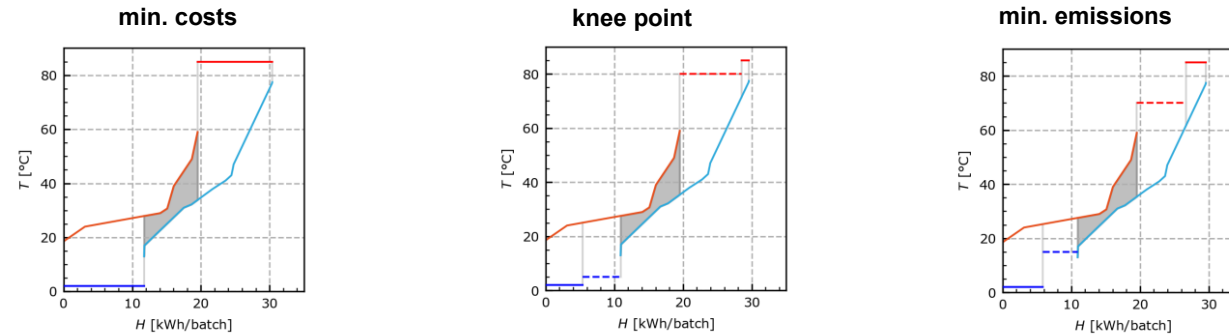


Figure 27: Overall Pareto front for non-continuous process.



Table 5. Selected configurations for non-continuous process from Pareto front: (a) Minimum cost (b) Knee point (c) Minimum environmental impact.



measures	IHR	IHR + HP	IHR +HP
TAC [CHF/a]	258'200	296'500	331'500
TAEI [t-CO ₂ /a]	812	273	150
CAPEX [CHF]	578'000	1'210'000	1'214'000
Annual cost savings [CHF/a]	133'000	170'000	134'000
Annual CO ₂ -savings [t-CO ₂]	560	1'100	1'225
Cost of CO ₂ abatement [CHF/t-CO ₂ -eq]	1'025	1'100	985
Payback [a]	4.3	7.1	8.9



3.2 Continuous case study

3.2.1. Case study description

The company chosen for the case study of the continuous process is one of the largest milk processors in central Switzerland. The company generates about CHF 3.5 million in annual turnover, processes 1.2 million liters of milk, and produces 50,000 liters of buttermilk and whey daily. According to the PA report prepared in 2021, approximately 68 GWh of fossil fuels are consumed annually for heat production and 19 GWh of electricity is consumed. Figure 28 presents the breakdown of fuel consumption by individual consumers. Spray drying (185 °C) is the largest consumer of process heat, followed by drum drying and evaporation [26].

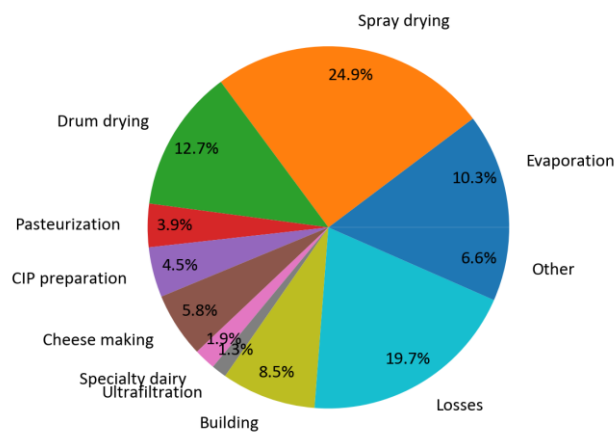


Figure 28. Breakdown of fuel consumption in the continuous case study [26].

The process stream table for the continuous case study consists of data for 52 process streams. To keep the report concise, only the process requirements of major energy consumers are presented in Table 6. However, GCC prepared based on the TAM approach presented in Figure 29 includes all process streams.

Table 6. Summarized process stream table for continuous case study.

Process	T _{in} [°C]	T _{out} [°C]
Evaporation	46	185
Spray drying	46	195
Roller (ventilation)	4	18
Pasteurization	53	82
Specialty production	70	95
Cheese production	15	81
CIP	15	75
Ultrafiltration (UF1 & UF2)	36	72.3
Roller (exhaust air)	27.5	20
Boiler flue gas	140	40
Concentrate cooling	59.4	15
Warm water	32	12
Spray dryer (exhaust air)	51.8	40

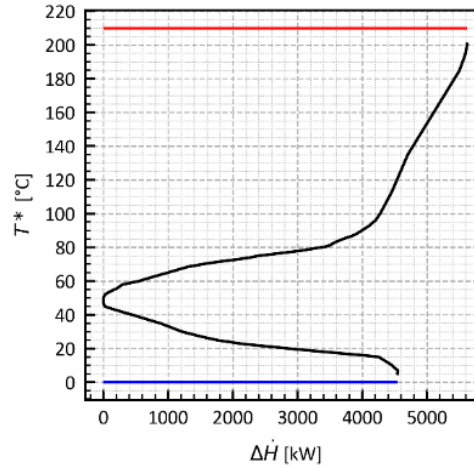


Figure 29. Grand composite curve for continuous process based on time-averaged model

Based on the GCC and typical working temperature ranges for ECTs and RTs, there is a substantial potential for standard HP and ST integration. The pinch temperature is identified at 45 °C and overall excess heat availability below the pinch is estimated at approximately 27 GWh, whereas HP and ST integration can potentially cover up to 30 GWh of annual heat demand.

Table 7. Parameter for the continuous case study.

	Base case	Scenario	Reference
Energy prices (CHF/MWh)			
Hot utility	55	55	Pinch report [27]
Cold utility	12	12	Pinch report [27]
Electricity	120	210	Pinch report [27]/El-com[28]
Wood	30 (BM)	30	PICC [29]
Emission factors (kg-CO₂/kWh)			
Hot utility	202	202	Pinch report [27]
Electricity	0	98	Pinch report [27]/Romano et al.(2024) [25]
Other parameters			
Solar irradiance (kWh/m ₂)	830	1'200	Sonnendach[30]

3.2.2. Results

Based on the methodology outlined in Section 2, each unique combination of decision variables generates a potential configuration within the objective space. For more details on each scenario nomenclature, please refer to Table 2. Each subplot in Figure 30 represents a specific scenario, illustrating the range of possible configurations, from limited integration to comprehensive combinations involving multiple technologies. Examples include scenarios with HP only, HP followed by ST, and ST followed by HP and BM, among others. Altogether, these scenarios yield approximately 58'000 individual configurations. A subset of these configurations was identified based on environmental and economic criteria to narrow down the most feasible configurations. Specifically, only those configurations achieving a lower environmental impact compared to the base case were included in the subsequent optimization phase. This filtering process reduced the total number of potential configurations to 12,000, allowing for a more focused optimization. This subset of feasible configurations demonstrates integration levels ranging from 25% to 82%, with TAC ranging between 1 million CHF and 2.3 million CHF.

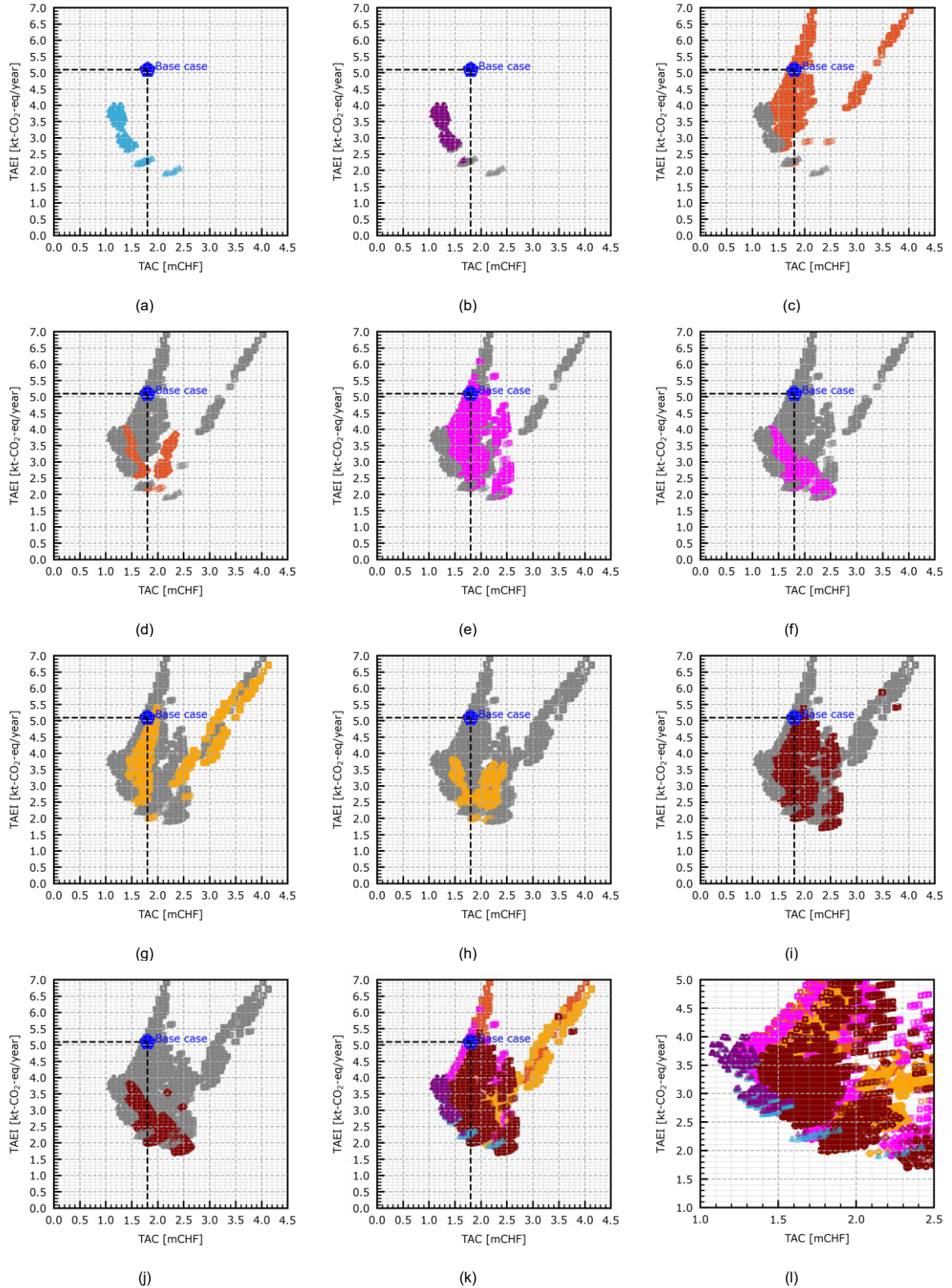


Figure 30. Evolution of objective space generated for all scenarios of continuous process

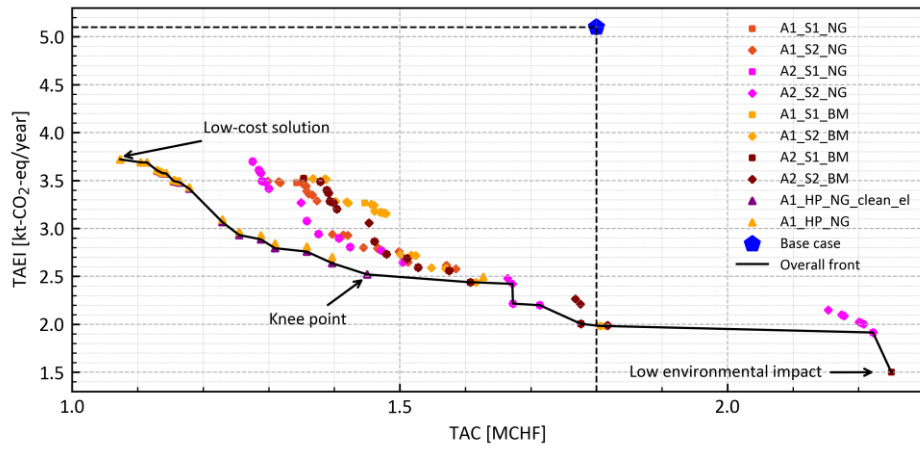
Configurations involving only HP integration generally result in lower TAC, as shown in Figure 30 (a) and (b). However, these configurations achieve smaller reductions in Scope 1 CO₂ emissions, leading



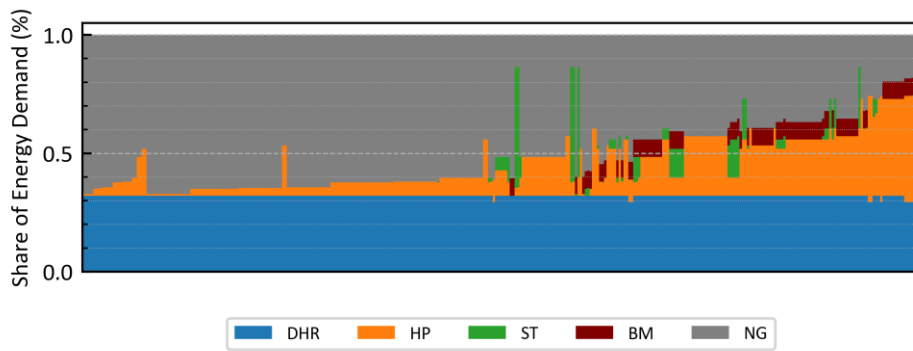
to a relatively higher overall EI when compared to more integrated scenarios. In contrast, configurations involving ST integration tend to have higher TAC values. This is primarily due to the limited solar irradiance available and the relatively higher Scope 3 emissions associated with the materials and installation of ST systems. As a result, integrating ST alone is generally less economically attractive, as depicted in Figure 30 (c). The integration of multiple technologies, such as HP, ST, and BM, can significantly reduce the overall environmental impact, although this comes at a higher cost. These scenarios are illustrated in Figure 30(d) to Figure 30(i), where combinations of technologies yield more substantial reductions in Scope 1 emissions but also require increased capital investment, which raises the TAC. In scenarios where BM is used to meet residual heating demands at higher temperatures, there is a significant reduction in Scope 1 CO₂ emissions, as BM combustion is assumed to be carbon neutral. However, the TAEI reduces only marginally compared to the configurations with natural gas (NG), since the remaining emissions are increasingly dominated by Scope 2 and 3 contributions. In other words, while BM-based configurations offer additional decarbonization benefits, they operate in the zone of diminishing returns and incur higher capital costs due to infrastructure requirements and fuel logistics.

A non-dominated sorting algorithm was used to identify the Pareto optimal set from the restricted objective space. The Pareto front, depicted in Figure 31(a), represents the best trade-offs between EI and economic cost for each integration strategy considered. This allows decision-makers to select configurations that offer the most effective balance between TAC and TAEI. The knee point on the Pareto front, marked in Figure 31 (a), represents the configuration with the optimum trade-off between cost and emissions reduction. This point is considered significant because it is the area where incremental improvements in environmental impact require progressively higher costs, beyond which further investment yields diminishing returns. Configurations before the knee point on the Pareto front are characterized by relatively lower costs for reducing CO₂ emissions. Specifically, these configurations require an additional TAC of CHF 90 per ton of CO₂ reduced, which indicates a favorable cost-efficiency. In contrast, configurations after the knee point require an increased TAC of CHF 120 per ton of CO₂ reduced, indicating less favourable economic performance due to diminishing returns on environmental benefits for every unit of additional cost.

Figure 31 (b) provides further insight into the technologies contributing to each point on the Pareto front. It shows the energy supply composition for each configuration, highlighting the technologies that play a role in optimizing cost and environmental performance. Most of the configurations on the Pareto front include DHR and HP integration as core components. For configurations before the knee point, HP integration dominates, reflecting its cost-effectiveness and significant potential for reducing Scope 1 emissions. This aligns with the trend of using HP configurations to achieve lower TAC while also reducing environmental impacts. On the other hand, for configurations after the knee point, ST and BM begin to appear more frequently on the Pareto front. While these technologies offer additional benefits in terms of renewable energy and emission reductions, they come with higher costs and are most often used in combination with HPs and DHR. The higher capital and operating costs associated with ST and BM lead to their presence primarily in scenarios emphasizing greater emissions reductions, albeit at the cost of increased TAC.



(a)



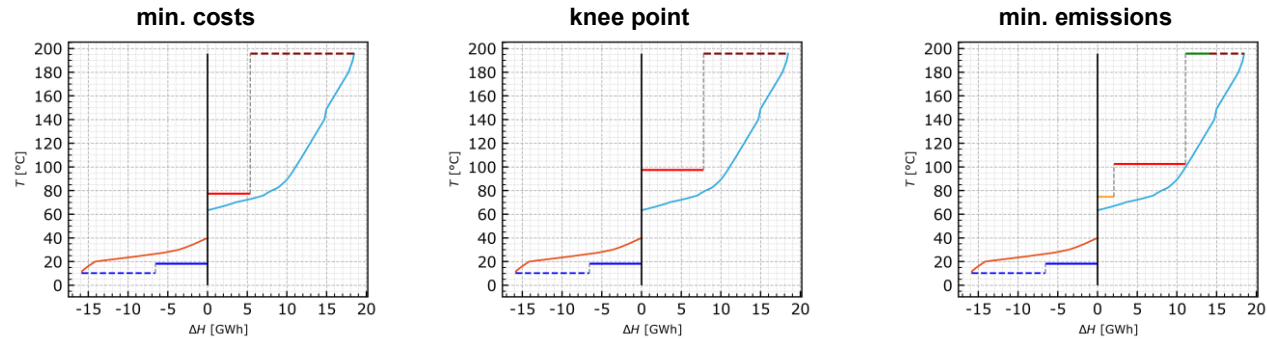
(b)

Figure 31. (a) Overall Pareto front for continuous process (b) Degree of integration for Pareto front configurations.

When analyzing the trade-offs represented by the Pareto front, three key configurations warrant particular attention: those corresponding to the minimum TAC, the knee point, and the minimum TAEI. These configurations are summarized in Table 8.



Table 8. Selected configurations for continuous process from Pareto front: (a) Minimum cost (b) Knee point (c) Minimum environmental impact.



measures	DHR+SHP	DHR+SHP	DHR+ST+HTHP+BM
TAC [MCHF/a]	1.13	1.41	2.2
TAEI [kt-CO ₂ /a]	3.5	2.5	1.5
CAPEX [MCHF]	1.04	5.8	9.2
yearly cost savings [MCHF/a]	0.53	0.9	1.2
yearly CO ₂ -savings [kt-CO ₂]	1.9	3.3	4.6
Cost of CO ₂ abatement [CHF/t-CO ₂ -eq]	314	149	112
Payback [a]	2.1	10.5	21



The minimum TAC configuration is achieved through a combination of DHR and a SHP with a capacity of 580 kW operating at an intermediate temperature of 78 °C. This setup covers approximately 35% of the total process heating requirements. The relatively low investment cost for this configuration results in a payback time of 2.1 years, making it the most economically attractive option on the Pareto front.

The knee point on the Pareto front represents the optimal trade-off between cost and environmental impact. The configuration at the knee point also integrates DHR and a larger SHP with a capacity of 1 MW. Unlike the minimum TAC configuration, this HP serves a larger cluster of processes, covering about 52% of total heating demand and offering a greater potential for Scope 1 emissions reduction. However, the larger HP capacity and associated intermediate loop size result in higher investment costs and a longer payback time. The knee point is significant as it marks the onset of diminishing returns, where further reductions in environmental impact require increasingly higher costs.

The minimum TAEI configuration lies beyond the knee point on the Pareto front and represents the most aggressive decarbonization strategy. This configuration integrates DHR, ST at lower temperatures, and a HTHP at medium temperatures, and BM is used to meet the residual heating demand. Despite achieving the lowest environmental impact, this configuration incurs significantly higher costs, leading to a payback time of 21 years. This configuration also achieves the highest degree of integration.

3.2.3. Use of Pareto front for decision making

One of the key objectives of the framework developed in this project is to guide industrial decision-makers in identifying the optimal trade-off for the defined objectives. The Pareto front generated in this work serves as a valuable tool for balancing the TAC and the TAEI under varying resource constraints. Its application is demonstrated in this section using a continuous case study, which considers constraints related to solar irradiance availability and BM resources. Table 9 presents an example of how the Pareto front can be interpreted for various constraints for demonstrated using two hypothetical scenarios. It also highlights the recommended integration configurations that can be derived from the Pareto front under the given conditions.

Table 9. Decision-making using the Pareto front example

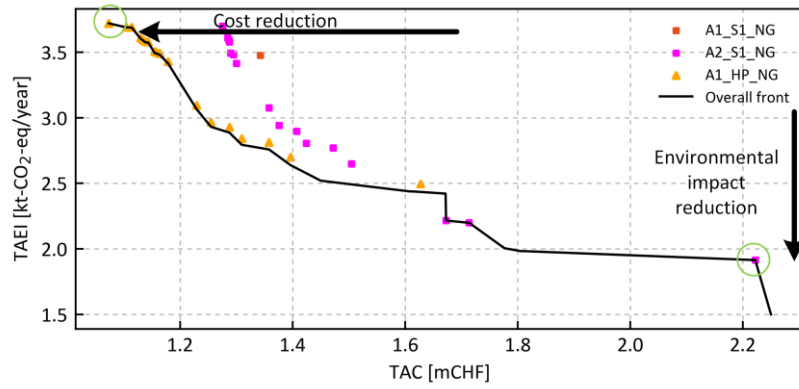
Resource Constraints	Main Objective	Recommended Integration Configuration	Simple Payback (years)
Low irradiance Biomass unavailable No access to clean electricity	Reduce cost	DHR + SHP + NG	2.1
	Reduce EI	DHR+HTHP+NG	18
Low irradiance Biomass available No access to clean electricity	Reduce cost	DHR + SHP + NG	2.1
	Reduce EI	DHR + ST + HTHP +BM	21

The first scenario assumes a company located in a region with low solar irradiance, no BM availability, and no access to clean electricity³. Under these constraints, the Pareto front provides optimal configurations for either objective by identifying suitable configurations specific to this scenario, i.e., configurations denoted by the suitable scenarios, such as A1_S1_NG, A2_S1_NG, and A1_HP_NG.

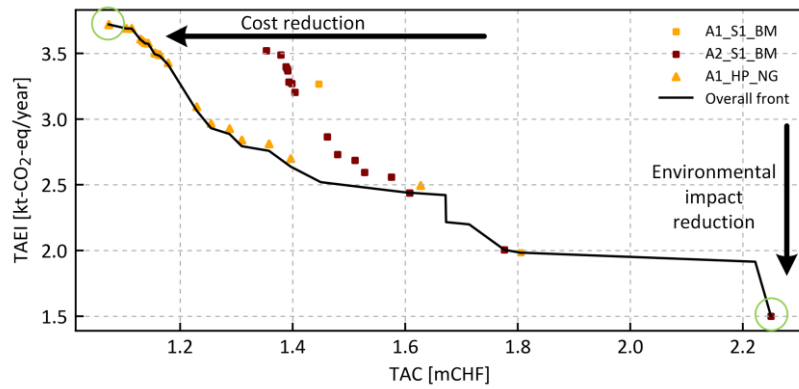
Figure 32 (a) illustrates the configurations for a location with low solar irradiance (denoted by S1 in the scenario label), where NG is used to meet residual heating demand. In the second scenario, the BM constraint is removed while all other constraints remain unchanged.

Figure 32 (b) presents the configurations applicable to scenarios where BM is available. In both scenarios, the minimum-cost configuration remains consistent. However, BM availability enables a greater potential for reducing TAEI, though this comes at an additional cost.

³ This scenario was designed solely for demonstration purposes. In practice, Swiss industry always has access to clean electricity, given free market access and the dominance of low-carbon sources such as hydropower and nuclear energy.



(a)



(b)

Figure 32. Example of pareto front selection for decision making: (a) scenarios without biomass and low solar irradiance (b) scenarios with biomass available and low solar irradiance

By systematically evaluating the configurations that end up on the Pareto front under various constraints, a comprehensive decision-making matrix can be developed. This matrix provides a structured, first theoretical basis for selecting optimal integration configurations depending on the specific resource constraints and objectives of the decision-maker. Table 10 summarizes the recommended configurations for all scenarios and constraints considered in this study, offering simplified guidance that can support future detailed site-specific analyses.



Table 10. Decision-making matrix.

Primary Objective	Resource Constraints			Recommended Integration Configuration	Simple Payback (a)
	Solar irradiance	Biomass availability	Electricity emissions		
Reduce Cost	Low	Low	High	DHR + SHP + NG	2.1
	High	High	Low	DHR + SHP + NG	2.1
Reduce Emissions	Low	Low	Low	DHR + HTHP +NG	11
	High	Low	Low	DHR + HTHP +NG	11
	Low	High	High	DHR+SHP+BM	16.7
	High	High	Low	DHR+ ST (plate collector) +HTHP+BM + NG	21

3.2.4. Techno-economic analysis of integration configurations

To quantify economic viability from the Scope 1 perspective, the cost of CO₂ abatement is used as a criterion to evaluate the cost-effectiveness of configurations resulting from different integration approaches and scenarios. The CO₂ abatement cost for a technology or a combination of technologies is estimated as the ratio of the annual cost of implementation (annualized CAPEX, annual OPEX, and annual benefits) to the annual reduction in Scope 1 CO₂ emissions. Figure 33 illustrates the range of abatement costs for configurations identified on the Pareto fronts for individual integration approach and scenario combinations. Each box plot represents a specific integration approach, with scenarios differentiated by color. The abatement costs are estimated in such a way that negative costs imply the profitability of the implementation.

Overall, the Pareto-optimal configurations span a wide range of CO₂ abatement costs, from 10 to 600 CHF per ton of CO₂ reduced. Among the various configurations, ST integration as a standalone measure is identified as the least cost-effective method for reducing Scope 1 emissions. However, when ST is combined with other technologies, such as HPs and BM, the resulting configurations demonstrate significantly improved cost-effectiveness.

The configurations that utilize BM to meet residual heating demands at high temperatures appear relatively more cost-effective compared to configurations that use NG based on the reduction of scope 1 emissions. These configurations achieve lower abatement costs while maintaining substantial reductions in Scope 1 emissions.

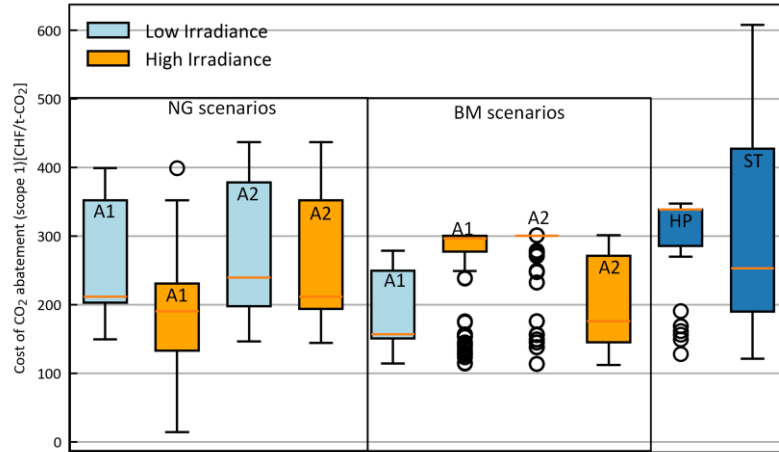


Figure 33. Range of CO₂ abatement costs for integration configurations.

Carbon payback time is defined as the ratio of the Scope 3 emissions accrued upfront during the production and installation of a given technology or configuration to the Scope 1 emissions reduced by that technology. This metric provides a valuable indication of how long it takes for a technology or configuration to achieve carbon neutrality from an emissions reduction perspective. As shown in Figure 34, ST exhibits the longest carbon payback time among the technologies analyzed. This is primarily due to the lower solar irradiance in the region studied, which necessitates a larger collector area and results in high Scope 3 emissions associated with its production and installation.

In contrast, HP demonstrates the shortest carbon payback time in this study. This is attributed to the low Scope 2 emissions resulting from Switzerland's relatively clean electricity grid, which significantly lowers the overall environmental burden of HP operation.

It is important to note that the results presented in Figure 34 are specific to the regional conditions of the case study. Variations in solar irradiance, electricity grid emissions, and technology-specific supply chains can significantly influence the carbon payback time for different regions or scenarios. Therefore, the findings should be contextualized within the geographical and infrastructural constraints of the studied location.

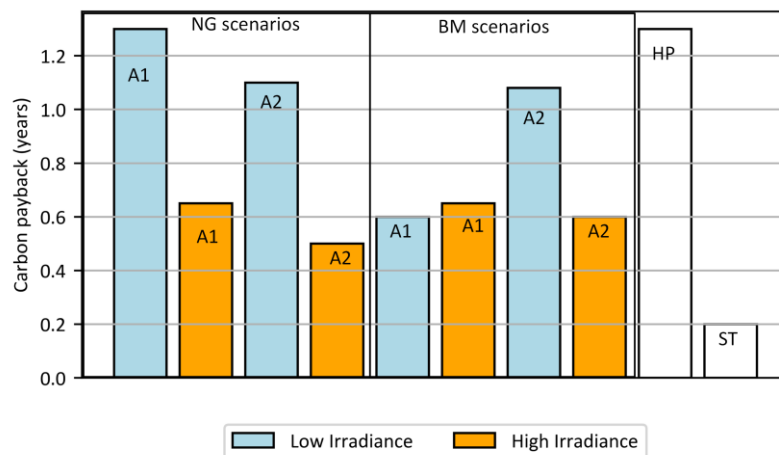


Figure 34. Carbon payback for various configurations and scenarios.

Figure 35 provides a comprehensive overview of the total CO₂ emissions for the continuous case study as a function of the degree of integration. The degree of integration represents the proportion of the total process heating demand met through integrated technologies, such as HPs and ST.



As the degree of integration increases, Scope 1 emissions (direct emissions; green line in Figure 35) are significantly reduced due to the replacement of conventional fossil fuel-based heating systems with energy-efficient and renewable technologies. However, this comes at the expense of an increase in Scope 2 and Scope 3 emissions. The rise in Scope 2 emissions is attributed to the electricity required for operating technologies such as HPs, while the increase in Scope 3 emissions stems from the life cycle impacts of manufacturing and installing these technologies.

The total emissions, combining Scope 1, 2, and 3 emissions, show a net decrease with higher integration levels. This indicates that, despite the additional life cycle impacts, the adoption of energy conversion and renewable technologies results in a net environmental benefit. However, beyond a threshold of 72% degree of integration, a shift in the emissions burden becomes evident. At this point, the majority of the company's emissions are no longer direct Scope 1 emissions but instead arise from the supply chain (Scope 2 and Scope 3 emissions).

This trade-off highlights the critical balance between reducing on-site emissions and mitigating the indirect environmental impacts of the technologies employed. Decision-makers must carefully evaluate whether further integration aligns with their sustainability goals, as the environmental benefits of higher integration levels may diminish due to the growing indirect emissions burden.

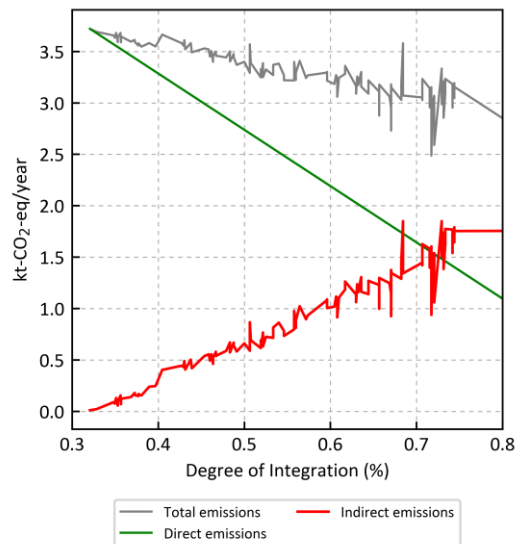




Figure 35. Direct and indirect emissions for various degrees of integration of EEMs, ECTs and RTs.



4 Conclusions and outlook

4.1 Conclusions

This project set out to develop and demonstrate a systematic Eco-Targeting framework that brings together Pinch Analysis (PA), Life Cycle Assessment (LCA), and Multi-objective Optimization (MOO) into a single decision-support tool for industrial decarbonization. The framework was tested on two Swiss dairy processes, one continuous and one non-continuous, chosen to represent typical industrial heating and cooling systems. While the numerical results obtained are specific to these cases and the assumptions made, the exercise confirmed the robustness and flexibility of the methodology, which can be applied to a wide variety of industrial contexts worldwide.

Several hypotheses and boundary conditions underpinned this work. The LCA models were defined with a cradle-to-gate boundary with use phase modelled separately, and the end-of-life phase excluded. Electricity was modelled using Swiss grid factors, with scenarios assuming both average and zero-emission electricity. The integration approach was designed as a stepwise procedure, although with varying sequences of integration. Each case study was limited to a single industrial site, which somewhat constrains the generalizability of the numerical outcomes.

Despite these limitations, the case studies clearly illustrate how the framework enables a structured exploration of the trade-offs between costs and emissions. In the non-continuous dairy process, indirect heat recovery emerged as the most economical option, reducing annual costs by around CHF 130,000 and avoiding roughly 560 tonnes of CO₂ emissions per year. When a heat pump (HP) was added, the annual emission savings doubled to over 1,100 tonnes, albeit with a longer payback of around seven years. Solar thermal (ST) integration alone rarely proved viable under Swiss irradiance conditions. In the continuous process, direct heat recovery combined with a standard HP reduced emissions by close to 30% reduction in Scope 1 emissions with a payback of just over two years. Larger HPs achieved deeper reductions but required greater investment, while the most ambitious configurations that combined ST and biomass reached up to 82% reduction in total annual environmental impact compared to the base case, though at much higher costs and payback times exceeding twenty years.

Across both processes, a consistent pattern emerged: heat recovery forms the cost-effective foundation of any decarbonization strategy, HPs are highly effective in reducing Scope 1 emissions with favourable economics, and renewables such as ST or biomass can play an important role where conditions allow, but generally at higher cost or with resource constraints. Perhaps most importantly, the analyses reveal a threshold effect: beyond about 72% integration, indirect emissions from technology manufacturing (Scope 3) and electricity use (Scope 2) begin to dominate, underscoring the need for lifecycle-aware decision-making. Indicators such as carbon payback and abatement cost proved useful for interpreting these trade-offs, with HPs showing the shortest payback and ST the longest.

The true contribution of this project lies less in the absolute numbers obtained and more in the methodology itself. By uniting PA, LCA, and MOO in a transparent and modular framework, Eco-Targeting provides a tool that can identify the first theoretical basis for selecting optimal integration configurations that industries can use to identify technically feasible and environmentally beneficial integration strategies under their own local constraints. Although demonstrated here only for two Swiss dairies, the framework is sufficiently general and adaptable to be applied to a wide variety of industrial sectors and geographic locations. With appropriate local data on energy prices, emission factors, and resource availability, the methodology can guide companies worldwide in designing cost-effective pathways to deep decarbonization.

4.2 Outlook

Framework Expansion:

The results of this project demonstrate that decarbonization strategies cannot be evaluated solely on the basis of direct (Scope 1) emission reductions. Since many companies already report their green-



house gas inventories according to the GHG Protocol, the relative importance of indirect emissions (Scopes 2 and 3) is increasing. This shift means that lifecycle-aware planning is not only scientifically sound but also directly aligned with current industrial reporting practice. The Eco-Targeting framework developed here provides a structured means of addressing this challenge by balancing Scope 1 savings against the additional Scope 2 and 3 burdens of new technologies.

From a research perspective, the framework can be expanded beyond climate change to include other environmental categories such as water use, land use, and resource depletion, thus offering a more comprehensive sustainability assessment. Likewise, the database of technologies can be broadened to include additional renewable and low-carbon options, such as photovoltaics, combined heat and power, or advanced storage solutions. On the computational side, emerging methods such as machine learning could accelerate the identification of Pareto-optimal solutions, enabling faster and more user-friendly exploration of complex objective spaces.

Regional Adaptations:

While this project has focused on Swiss dairies, the methodology is designed to be transferable across sectors and geographies. By adopting parameters such as emission factors, energy prices, solar irradiance, or biomass availability, the same framework could guide decision-making in regions with very different resource endowments and industrial structures.

Hourly Solar thermal data:

At present, the framework represents ST energy availability using a constant irradiance over predefined hours within the selected timeframe (e.g., a single day). While this approach enables short computation times, it neglects irradiance variability across longer periods, such as seasonal or monthly shifts. A future extension of the framework could therefore incorporate monthly or even daily sunshine duration profiles to provide a more accurate representation of site-specific conditions.

Further validation:

To maximize its impact, the tool will be validated against additional industrial case studies, working closely with researchers from other geographic regions.

Digital Integration and Open Access:

Incorporating the framework into user-friendly software tools would make it accessible for industrial practitioners and researchers. Open access to the database and algorithms used in this project can foster wider adoption and iterative improvement.

The Eco-Targeting framework currently offers a first simplified, structured, and flexible approach to tackling the complex trade-offs between cost, emissions, and resource constraints. With further expansions and validations, the tool can evolve from a research prototype into a practical decision-support tool, helping industries worldwide to navigate the complex trade-offs between emissions, costs, and resource constraints, and to design robust pathways toward net-zero.

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6 Appendix

6.1 Cost estimation

Table A1: Parameters for cost function

EEM/Technology	Constant (a)	Exponent (b)
Plate HEX	17'500, $C_0 = 14'000$	0.61
Shell and tube HEX	45'000, $C_0 = 45'000$	0.71
Standard heat pump	148'000	0.42
High-temperature heat pump	10'757	-0.322
Solar thermal (flat plate)	2'442	-0.19
Solar thermal (vacuum tube)	2'084	-0.088

Table A2: Parameters for Lang factor [31]

Cost component	Factor
Module	1
Piping	0.7
Building	0.3
Installation	0.4
Site preparation	0.8
Engineering	0.8
Total	3.0

Table A3: Technical lifetime of the technologies considered [5]

EEM/Technology	Lifetime (years)
Heat exchanger	20
Heat pump	20
Thermal energy storage	20
Solar thermal	25

6.2 Life cycle assessment

Table A4: Parameters for LCA functions

EEM/Technology	Functional unit	Constant (a)	Exponent (b)
Heat exchanger	Area (m ²)	2.6	
Heat pump	Condenser duty (kW)	126	0.7
Solar thermal (flat plate)	Collector area (m ²)	215	0.85



Solar thermal (vacuum tube)	Collector area (m ²)	350	0.9
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Table A5: Example of material requirements for 100 m² Heat Exchanger ([15])

Activity	Location	LCA Score (kg CO ₂ -eq)	Tag
Electricity	CH	1002	Manufacturing process
Natural gas	CH	549	Manufacturing process
Low alloyed steel	RER	601	Components
Copper (electrowinning process)	GLO	34	Components
Corrugated board box	RER	4.2	Packaging
Plastic film	RER	1.9	Packaging
Transport (freight, light commercial vehicle)	CH	476	Transport

Table A6: Example of material requirements and LCA scores for 200 kW Heat pump ([20] [19] [32])

Activity	Location	LCA Score (kg-CO ₂ -eq)	Tag
Natural gas	Glo	17,533	Manufacturing process
Electricity	CH	113	Manufacturing process
Lubricating oil	RER	81	Manufacturing process
Tap water	CH	0.3	Manufacturing process
Elastomere (Tube insulation)	DE	874	Components
Low alloyed steel	RER	864	Components
Reinforced steel	AT	685	Components
Copper production (electrowinning process)	GLO	56	Components
Polyvinylchloride (emulsion polymerisation)	RER	48	Components
Ammonia production (partial oxidation)	ROW	0.0	Components
Control units	RER	32	Components



Corrugated board box production	RER	5	Packaging
Plastic film	RER	2	Packaging
Transport (freight, lorry)	RER	43	Transport

Table A7: Material requirements for flat plate solar collector [33]

Activity	Geography	Unit	Flat plate collector production
Market for Aluminum, Wrought alloy	GLO	kg	3.9 A _{collector}
Market, anti-reflex-coating, etching, solar glass	GLO	m ²	A _{collector}
Market, brazing solder, cadmium free	GLO	kg	3.6 A _{collector}
Market, copper cathode	GLO	kg	2.8 A _{collector}
Sheet rolling, copper	GLO	kg	2.8 A _{collector}
Market, silicone Product	RoW	kg	0.0058 A _{collector}
Electricity	EU	kWh	0.14 A _{collector}
Market, propylene glycol	RoW	kg	1.01 A _{collector}
Market, selective coat, copper sheet	GLO	m ²	A _{collector}
Market, Solar glass, low iron	GLO	kg	9.12 A _{collector}
Market, stone wool, packed	GLO	kg	2.45 A _{collector}
Market, hot rolled chromium steel	GLO	kg	4.14 A _{collector}
Market, Corrugated board box	RoW	kg	2.54 A _{collector}

Table A8: Example of material requirements and LCA scores for solar thermal system (10kW) [33]

Activity	Location	LCA Score (kg-CO ₂ eq)	Tag
Aluminum sheet rolling	RER	338	raw materials
Steel production	RER	2,533	raw materials
Elastomere (Tube insulation)	DE	1,936	raw materials
Ethylene glycol	RER	1,683	raw materials
Aluminium ingot (primary)	GLO	13,450	raw materials
Water (softened)	RER	1	raw materials
Heat storage production	CH	9,822	components manufacturing
Flat plate solar collector production (Cu absorber)	CH	229,321	components manufacturing



Expansion vessel	CH	480	components manufacturing
Pump production	CH	236	components manufacturing
Steel pipes (drawing)	RER	204	components manufacturing
Powder coating (aluminum sheet)	RER	100	components manufacturing
Packaging film (LDPE)	RER	118	Packaging
Transport (freight, light commercial vehicle)	CH	318	transport

Table A9: Example of material requirements and LCA scores for boiler [32]

Activity	Location	LCA Score (kg-CO₂eq)	Tag
Steel (unalloyed)	RER	4,277	raw materials
Steel (low alloyed)	RER	233	raw materials
Aluminium sheet rolling	RER	81	raw materials
Copper (electrowinning process)	GLO	8	raw materials
Brass	CH	7	raw materials
Building construction, hall	CH	2,066	manufacturing
Brazing solder production (cadmium free)	RER	941	manufacturing
Natural gas	CH	287	manufacturing
Water	CH	0	manufacturing
Alkyd paint (white, solvent-based)	RER	36	manufacturing
Electricity	CH	36	manufacturing
Glass wool mat	CH	18	Components
Control units	RER	306	Components
Transport (freight, light commercial vehicle)	CH	795	transport