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Integration of Heat Pumps and Thermal Energy Storages in Non-Continuous Industrial Processes

HPTES

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Zusammenfassung

Mehr als die Hälfte des Endenergieverbrauchs in der Schweizer Industrie entfällt auf Prozesswärme. Dies entspricht etwa 11 % des gesamten Endenergieverbrauchs in der Schweiz. Um das Ziel des Bundes von Netto-Null Treibhausgasemissionen bis zum Jahr 2050 zu erreichen, ist es von entscheidender Bedeutung, die Energieeffizienz in der Industrie zu verbessern und auf erneuerbare Energiequellen umzustellen. Die Industrie ist aufgrund der hohen Komplexität, Heterogenität und Temperaturniveaus der Heiz- und Kühlanforderungen der anspruchsvollste Sektor für die Dekarbonisierung. Die Anforderungen an die Prozesswärme und -kälte sind in der Industrie sehr fallspezifisch. Wärmepumpen (WP) können diese Anforderungen oft erfüllen. Sie stellen eine umweltfreundliche und wirtschaftlich attraktive Alternative zu herkömmlichen Heizsystemen mit fossilen Brennstoffen dar. Die Elektrifizierung der Wärmeversorgung mittels Wärmepumpen ist ein energetisch überzeugendes Konzept zur Dekarbonisierung industrieller Prozesse, da dies die Integration erneuerbarer Energiequellen erleichtert. WP sind also eine der Schlüsseltechnologien für die Elektrifizierung von Industrieprozessen.

Aufgrund des nicht kontinuierlichen Charakters vieler industrieller Prozesse in der Schweiz ist jedoch die Integration von WP zusammen mit thermischen Energiespeichern (TES) erforderlich, um das Potenzial der Wärmerückgewinnung (WRG) auszuschöpfen. Bestehende Methoden der Pinch-Analyse ermöglichen entweder die Integration von WP in kontinuierliche Prozesse oder von TES in nicht-kontinuierliche Prozesse, deren Kombination ist jedoch bisher nicht untersucht worden. In diesem vom Bundesamt für Energie (BFE) mitfinanzierten Forschungsprojekt wird eine neue praktische Methodik für die kostenoptimale Integration von Wärmepumpen und thermischen Energiespeichern in nicht-kontinuierliche Prozesse entwickelt. Das Ziel der Methodik ist, Ingenieurinnen und Ingenieure in der Praxis zu ermöglichen, WPTES-Systeme korrekt in nicht-kontinuierliche Prozesse zu integrieren. Die Methodik wird auf zwei Fallbeispiele aus der Industrie angewendet, um die Plausibilität und Machbarkeit der Methode zu prüfen und die erhaltenen Ergebnisse zu evaluieren. Darüber hinaus wird ein Regelungskonzept erarbeitet, das den Betrieb des resultierenden Systems ermöglicht.

Methodik für die WPTES-Integration

Die Methode zur WPTES-Integration wird in Form eines Arbeitsablaufs dargestellt. Der Arbeitsablauf knüpft am bestehenden Arbeitsablauf der Pinch-Analyse an. Er baut auf Elementen der bereits vorhandenen Pinch-Analyse für die direkte Wärmerückgewinnung, dem Indirect Source Sink Profile (ISSP) für die indirekte Wärmerückgewinnung sowie auf einer Erweiterung des ISSP für die Integration des WPTES-Systems auf. Die Erweiterung besteht aus der Ableitung einer angepassten Grand Composite Curve (GCC) für das ISSP und dem Inverted Residual ISSP, die beide die Platzierung der WP im System unterstützen. Beim Arbeitsablauf handelt es sich um einen variantenbasierten Ansatz. Er überlässt den Ingenieurinnen und Ingenieuren in allen Phasen die Kontrolle über die Entscheidungen, so dass sie die zu evaluierenden Lösungsvarianten auswählen und direkt beeinflussen können. Mit einem Optimierungsprogramm können die minimalen Investitionskosten für eine gegebene Lösungsvariante berechnet werden. Das Optimierungsprogramm besteht aus einer Kombination von Heuristiken und einem nicht-linearen Programm. Es ist nicht auf die WPTES-Integration beschränkt, sondern kann allgemein für die indirekte Wärmerückgewinnung mittels ISSP eingesetzt werden.

Regelungsstrategie

Aus Sicht Regelung bringt die Umsetzung eines WPTES-Systems zusätzliche Herausforderungen mit sich, da neue Abhängigkeiten zwischen den verschiedenen Prozessströmen geschaffen werden. Alle Prozessströme sind potenziell Schwankungen in Bezug auf die Zeitpläne und Eintrittsbedingungen (vor allem Temperatur und Massenstrom) unterworfen. Diese Schwankungen wirken sich auf den Betrieb der WPTES-Anlage aus und damit möglicherweise auch auf die Erwärmung oder Abkühlung anderer Ströme. Steht beispielsweise aus beliebigen Gründen ein geringerer Wärmeüberschuss aus den Wärmequellen zur Verfügung, kann das WPTES-System nicht genügend Wärme an die Wärmesenken liefern. Ungeplante Änderungen im Zeitplan erfordern ebenfalls Eingriffe des Steuerungssystems, um die Prozessanforderungen zu erfüllen. Um solche unerwünschten Einflüsse zu vermeiden, wird die

Regelungsstrategie von WPTES-Systemen untersucht, um einen stabilen Betrieb des integrierten Prozesses zu ermöglichen. Die Arbeit umfasst die Untersuchung des multivariablen Regelungsproblems von Wärmepumpen, die mit Schichtspeichern zur Wärmerückgewinnung in industriellen Prozessen gekoppelt sind. Ein dynamisches Modell des Systems ermöglicht die Bewertung der Regelstrategie. Aus der Analyse des Regelungsproblems wird eine Regelungsstrategie vorgeschlagen, die aus einer zweistufigen Regelungshierarchie besteht. Die beiden Ebenen trennen die übergeordnete Energiemanagementaufgabe (high-level) und die untergeordnete Echtzeitsteuerungsaufgabe (low-level). Die Regelungsstrategie wird anhand eines Testfalls evaluiert, um die Funktionsfähigkeit der Strategie zu demonstrieren. Die Low-Level-Aufgabe kann mit Standardreglern (z.B. PID) bewältigt werden. Für die High-Level-Aufgabe ermöglicht die geeignete Platzierung der Utility-Wärmeübertrager innerhalb des WPTES-Systems eine vereinfachte Regelungsaufgabe, während gleichzeitig ein minimaler Verbrauch an Utilities gewährleistet wird.

Fallstudien

Um die Praxistauglichkeit des Arbeitsablaufs für die WPTES-Integration zu überprüfen, wurde dieser an Fallbeispielen aus der Industrie erprobt. Es wurden zwei Arten von nicht-kontinuierlichen Prozessen ausgewählt, ein Batch-Prozess und ein Prozess mit mehreren Betriebsfällen, beide aus der Lebensmittelindustrie. Die ausgewählten Fallbeispiele repräsentieren damit die Art von nicht-kontinuierlichen Prozessen, wie sie in der Schweizer Industrie häufig anzutreffen sind. Die Evaluation der Fallbeispiele zeigt, dass der WPTES-Arbeitsablauf in Verbindung mit den entwickelten Software-Tools praktikable Integrationsoptionen liefert, die eine fundierte Design-Entscheidung ermöglichen. Es zeigt sich, dass die Betriebsdauer und die Anzahl der Chargen eine wichtige Rolle für die wirtschaftliche Machbarkeit der Lösungen spielen.

Wichtigste Ergebnisse

- Der entwickelte benutzergeführte Arbeitsablauf ermöglicht die Integration der Wärmepumpe und des zugehörigen Wärmeübertrager- und Speichernetzwerks in nicht-kontinuierliche Prozesse über zwei mögliche Pfade. Der Arbeitsablauf beinhaltet eine neuartige, adaptierte Grand Composite Curve, basierend auf dem Indirect Source Sink Profile, für die Integration der WP. Um die Platzierung der WP zu unterstützen, wird eine Enumeration der möglichen Platzierungsoptionen durchgeführt. Das Ergebnis wird in der angepassten Grand Composite Curve dargestellt, um die Auswirkungen der WP-Platzierung auf die Komplexität des resultierenden Systems zu zeigen. Zudem erleichtert ein Optimierungsprogramm für die ISSP die Variantenanalyse.
- Die Auswertung der Fallbeispiele zeigt, dass die WPTES-Integration im Fallbeispiel 1 den Heizbedarf eliminiert und den Kältebedarf um 71-79 % reduziert, während die Treibhausgasemission der Utilities um 84-87 % reduziert werden. Die jährlichen Gesamtkosten werden um 22 % gesenkt. Die resultierende Wirtschaftlichkeit der Varianten ist mit einem statischen Payback von durchschnittlich 5 Jahren ähnlich für geschätzte Investitionskosten von rund 700'000 CHF. Die Auslegung und die Komplexität der WPTES-Systeme sind jedoch unterschiedlich. Die Analyse von Fallbeispiel 2 zeigt hingegen auf, dass die WPTES-Integration in diesem Fall wirtschaftlich nicht sinnvoll ist und ein indirektes WRG-System mit TES (ohne WP) integriert werden sollte. Die in den Arbeitsablauf integrierte Variantenanalyse bietet Ingenieurinnen und Ingenieuren einen systematischen Weg zur Entscheidungsfindung.
- Es wurde eine Regelungsstrategie für das WPTES-System entwickelt und mittels Simulationen getestet. Das System kann mit der vorgeschlagenen Regelungsstrategie zuverlässig betrieben werden, wobei ausschliesslich auf industrieerprobte Standardkomponenten und -regler zurückgegriffen werden kann.

Résumé

Plus de la moitié de l'énergie finale utilisée par l'industrie suisse est consacrée à la chaleur industrielle. Cela représente environ 11 % de la consommation totale d'énergie finale en Suisse. Pour atteindre l'objectif politique suisse de zéro émission nette de gaz à effet de serre d'ici 2050, il est donc crucial d'améliorer l'efficience énergétique et d'accélérer la transition vers des sources d'énergie renouvelables dans l'industrie. En outre, l'industrie est le secteur le plus difficile à décarboniser en raison de la complexité, de l'hétérogénéité et des niveaux de température élevés des besoins de chauffage et de refroidissement. Dans l'industrie, les exigences en matière de chauffage et de refroidissement des procédés sont très spécifiques. Les pompes à chaleur (PAC, HP) peuvent souvent répondre à ces besoins. Elles représentent une alternative écologique et économiquement intéressante aux systèmes de chauffage conventionnels à combustibles fossiles. L'électrification de la fourniture de chaleur est un concept énergétiquement convaincant pour la décarbonisation des processus industriels, car elle facilite l'intégration des sources d'énergie renouvelables. Les pompes à chaleur sont donc l'une des technologies clés pour l'électrification des processus industriels.

Cependant, en raison de la nature discontinue de nombreux procédés industriels en Suisse, l'intégration de PAC avec des systèmes de stockage d'énergie thermique (TES) est nécessaire pour l'exploitation des potentiels de récupération de chaleur. Alors que les méthodologies existantes de l'analyse Pinch permettent soit l'intégration de PAC dans des procédés continus, soit l'intégration de TES dans des procédés discontinus, leur combinaison n'a pas été étudiée à ce jour. Dans ce projet de recherche cofinancé par l'Office fédéral de l'énergie, HPTES, une nouvelle méthodologie pratique pour l'intégration optimale en termes de coûts de pompes à chaleur et de stockage d'énergie thermique dans les procédés discontinus est développée. L'objectif de cette méthodologie est de permettre aux ingénieurs praticiens d'intégrer correctement les systèmes HPTES dans les procédés discontinus. La méthodologie est appliquée à deux études de cas industriels pour étudier la plausibilité et la faisabilité de la méthode et les résultats associés. Un concept de contrôle permettant l'exploitation du système obtenu est également élaboré.

Méthodologie d'intégration HPTES

La méthode d'intégration HPTES est présentée sous forme d'un processus de travail. Elle est intégrée dans le processus de l'analyse Pinch tel qu'il est utilisé en Suisse. Elle se compose de l'analyse Pinch existante pour la récupération de chaleur directe, des profils indirects des sources et des puits (ISSP) pour la récupération de chaleur indirecte, et d'une extension des ISSP pour l'intégration du système HPTES. L'extension consiste en la dérivation d'une courbe grande composite (GCC) adaptée pour les ISSP, et les ISSP résiduels inversés, qui aident tous deux à placer la PAC dans le système. Le processus de travail est une approche de la tâche basée sur des variantes. Le processus proposé est conçu pour que les ingénieurs praticiens gardent le contrôle des décisions à tous les stades, en leur permettant de décider quelles variantes de solution évaluer et de les influencer directement. Un programme d'optimisation pour la détermination du coût d'investissement minimal pour une variante de solution donnée est élaboré. Ce programme d'optimisation combine des règles d'heuristiques et une formulation par programmation mathématique non linéaire, et son usage n'est pas limité à l'intégration HPTES seule mais s'applique à l'intégration de la récupération indirecte de chaleur avec l'ISSP en général.

Stratégie de contrôle

Du point de vue du contrôle, la mise en œuvre d'un système HPTES implique des défis supplémentaires car de nouvelles dépendances entre les différents flux de procédés sont créées. Tous les flux de procédés sont potentiellement soumis à des fluctuations en termes de planning temporel et de conditions d'entrée (principalement la température et le débit massique). Ces fluctuations affectent le fonctionnement du système HPTES et peuvent donc éventuellement affecter le chauffage ou le refroidissement des autres flux. Si, par exemple, pour des raisons quelconques, l'excédent de chaleur des sources de chaleur disponibles est moindre, la PAC ne pourra pas fournir suffisamment de chaleur

aux puits de chaleur. Les changements non planifiés dans le programme nécessitent des actions similaires de la part du système de contrôle afin de répondre aux exigences des procédés. Pour éviter ces influences indésirables, le concept de contrôle des systèmes HPTES est étudié pour permettre un fonctionnement stable du procédé intégré. Le travail comprend l'étude du problème de contrôle multivariable des pompes à chaleur couplées à des stockages d'énergie thermique stratifiés pour la récupération de chaleur dans les procédés industriels. Un modèle dynamique du système permettant l'évaluation de la stratégie de contrôle est décrit. En outre, le problème de contrôle est analysé et une stratégie de contrôle consistant en une hiérarchie de contrôle à deux niveaux est proposée. Les deux niveaux séparent la tâche de haut niveau de gestion de l'énergie et la tâche de bas niveau de contrôle en temps réel. La stratégie de contrôle est ensuite évaluée à travers différentes variations d'un cas test qui démontre la performance de la stratégie. La tâche de bas niveau peut être traitée avec des contrôleurs distribués standard de l'industrie (par exemple, PID). Pour la tâche de haut niveau, le placement approprié des échangeurs de chaleur d'utilité dans le système HPTES permet de réaliser un contrôle simplifié tout en assurant une consommation minimale d'utilité.

Études de cas

Pour vérifier la praticité du processus de travail développé pour le système HPTES dans les procédés industriels, des études de cas industriels ont été évaluées. Les études de cas de la base PinCH et les analyses Pinch soutenues par l'Office fédéral suisse de l'énergie ont été étudiées pour trouver des cas tests appropriés pour ce projet. Deux types de procédés discontinus ont été sélectionnés, un procédé par lot et un procédé avec cas de fonctionnement multiples, tous deux issus de l'industrie alimentaire. Les études de cas sélectionnées veulent ainsi représenter des procédés discontinus typiques fréquemment rencontrés dans l'industrie suisse. Les analyses des études de cas montrent que le processus de travail HPTES, avec les outils logiciels développés, produisent des options d'intégration HPTES pratiques et réalisables, permettant des choix conceptuels éclairés. Cependant, la période de fonctionnement et le nombre de lots jouent un rôle important dans la rentabilité économique des solutions.

Principales conclusions

- Le processus de travail développé, guidé par l'utilisateur, permet l'intégration d'une PAC et du réseau d'échangeurs et de stockage de chaleur (HESN) associé dans les procédés discontinus, et ceci selon deux voies possibles. Le processus comprend une nouvelle courbe grande composite adaptée, basée sur les profils indirects des sources et des puits, pour l'intégration de la PAC. Pour faciliter le placement de la PAC, une énumération des options de placement réalisables est effectuée. L'effet du placement d'une PAC sur le nombre de zones d'assignation (nombre de niveaux de température du TES) est représenté dans cette courbe grande composite adaptée. Le processus de travail met également en œuvre un programme d'optimisation pour faciliter l'analyse des variantes.
- Dans l'application aux études de cas, l'intégration du système HPTES dans l'étude de cas 1 élimine l'utilité chaude et réduit l'utilité froide d'environ 71-79 % ; les émissions de GES de l'utilité sont réduites d'environ 84-87 %. Le coût annuel total est réduit de 22 %. La rentabilité économique résultante des variantes est similaire avec un payback statique d'environ 5 ans pour un investissement estimé à environ 700'000 CHF. Cependant, la conception et la complexité des systèmes HPTES sont différentes. En revanche, l'analyse de l'étude de cas 2 montre que l'intégration HPTES n'est pas économiquement viable dans ce cas et qu'un système de récupération de chaleur indirecte avec TES (sans PAC) devrait être intégré. L'analyse des variantes intégrée au processus de travail fournit aux ingénieurs une démarche systématique pour la prise de décision.

- Une stratégie de contrôle pour le système HPTES a été développée et testée au moyen de la simulation du procédé. Le système peut être contrôlé avec la stratégie de contrôle proposée, en utilisant uniquement des composants et des régulateurs standards éprouvés dans l'industrie.

Summary

More than half of the end energy use in the Swiss industry is dedicated to process heat. This amounts to approximately 11 % of the entire end energy use in Switzerland. To achieve the Swiss policy objective of net zero greenhouse gas emissions by the year 2050, it is therefore crucial to improve the energy efficiency and transition towards renewable energy sources in industry. Furthermore, industry is the most challenging sector to decarbonize due to the high complexity, heterogeneity, and temperature levels of the heating and cooling requirements. In industry, the requirements for process heating and cooling are highly specific. Heat pumps (HPs) can often satisfy these needs. They represent an environmentally friendly and economically attractive alternative to conventional fossil fuel heating systems. Electrification of heat supply is an energetically convincing concept for decarbonization of industrial processes as this facilitates integration of renewable energy sources. HPs are thus one of the key technologies for electrification of industrial processes.

However, due to the non-continuous nature of many industrial processes in Switzerland, integration of HPs together with thermal energy storage (TES) systems is required for the exploitation of heat recovery potentials. While existing pinch analysis methodologies enable either the integration of HP in continuous processes or TES into non-continuous processes, the combination thereof is, however, not investigated to date. In this Swiss Federal Office of Energy co-financed research project, HPTES, a new and practical methodology for the cost-optimal integration of heat pumps and thermal energy storage in non-continuous processes is developed. The aim of the methodology is to enable practicing engineers to correctly integrate HPTES systems in non-continuous processes. The methodology is applied to two industrial case studies to study the plausibility and feasibility of the method and the associated results. In addition, a control concept to enable the operation of the resulting system is established.

Methodology for HPTES integration

The method for HPTES integration is presented as a workflow. It is integrated into the pinch analysis workflow as used in Switzerland. The HPTES workflow consists of existing pinch analysis for direct heat recovery, and the Indirect Source Sink Profile (ISSP) for the indirect heat recovery as well as an extension of the ISSP for the integration of the HPTES system. The extension consists of the derivation of an adapted Grand Composite Curve for the ISSP and the inverted residual ISSP, which both assist the placement of the HP in the system. The workflow is a variant based approach to the task. The developed workflow is intended to keep the practicing engineers at all stages in control of the decisions, allowing them to decide which solution variants to evaluate and influence them directly. An optimization program for the determination of the minimal investment cost for a given solution variant is derived. This optimization program comprises a combination of heuristics and a nonlinear program and is not limited to the HPTES integration alone but applies to the indirect heat recovery integration with the ISSP in general.

Control strategy

From a control perspective, the implementation of a HPTES system implies additional challenges as new dependencies between the different process streams are created. All process streams are potentially subjected to fluctuations in terms of schedules and inlet conditions (mostly temperature and mass flow rates). These fluctuations affect the operation of the HPTES system and thereby may possibly affect the heating or cooling of the other streams. If, for example, there is for arbitrary reasons a smaller heat surplus from the heat sources available, the HP will not be able to provide sufficient heat to the heat sinks. Unplanned changes in the schedule require similarly actions from the control system in order to fulfill the process requirements. To avoid such undesirable influences, the control design of HPTES

systems is investigated to allow a stable operation of the integrated process. The work includes the investigation of the multivariable control problem of heat pumps coupled to stratified thermal energy storages for the heat recovery in industrial processes. A dynamic model of the system allowing for the evaluation of the control strategy is described. Furthermore, the control problem is analyzed and a control strategy consisting of a two-level control hierarchy is proposed. The two levels separate the high-level energy management task and the low-level real-time control task. The control strategy is subsequently evaluated through a test case which demonstrates the performance of the strategy. The low-level task can be handled with distributed industry standard controllers (e.g. PID). For the high-level task, the suitable placement of the utility heat exchangers within the HPTES system allow for a simplified control task while ensuring minimal utility usage.

Case studies

To verify the practicality of the developed workflow for the HPTES system in industrial processes, industrial case studies were evaluated. The case studies of the PinCH base and the pinch analyses supported by the Swiss Federal Office of Energy were studied to find suitable test-cases for this project. Two types of non-continuous processes were selected, a batch process and a process with multiple operating cases, both from the food industry. The selected case studies are intended to represent the type of non-continuous processes that are frequently encountered in Swiss industry. The analyses of the case studies show that the HPTES workflow alongside with the developed software-tools yield practical feasible HPTES integration options allowing for an informed design-decision. However, the operating period and number of batches play important roles in the economic feasibility of the solutions.

Main findings

- The developed user guided workflow allows the integration of HP and the associated heat exchanger and storage network in non-continuous processes through two possible pathways. The workflow includes a novel adapted Grand Composite Curve, based on the indirect source sink profile, for the integration of the HP. To support the placement of the HP, an enumeration of the feasible placement options is performed. The result of this enumeration is presented in the adapted Grand Composite Curve to show the impact of the HP placement on the complexity of the resulting system. The workflow also implements an optimization program to facilitate the variant analysis.
- In the case study application, the integration of HPTES system in case study 1 eliminates the hot utility and reduces the cold utility by approximately 71-79 %; the utility GHG emissions are reduced by approximately 84-87 %. The total annual cost is reduced by 22 %. The resulting economic efficiency of the variants are similar with a static paybacks of averagely 5 years for the estimated investment of about 700’000 CHF. However, the design and the complexity of the HPTES systems are different. The analysis of case study 2, on the other hand, shows that HPTES integration is not economic in this case but that an indirect HR system with TES (without HP) should be integrated. The variant analysis incorporated in the workflow provides a systematic way for the engineers for decision making.
- A control strategy for the HPTES system has been developed and tested by the means of process simulation. The system can be controlled with the proposed control strategy, relying solely on industry-proved standard components and controllers.

Contents

Abbreviations

AZ	Assignment zone
CC	Composite curve
COP	Coefficient of performance
CU	Cold utility
EEM	Energy efficiency measure
GCC	Grand Composite Curve
GHG	Greenhouse Gases
HEN	Heat exchanger network
HEX	Heat exchanger
HESN	Heat exchanger storage network
HP	Heat pump
HR	Heat recovery
HU	Hot utility
HPTES	Heat pump and thermal energy storage
HS	Heat storage
IHR	Indirect heat recovery
IL	Intermediate loop
ISSP	Indirect Source Sink Profile
LMTD	Logarithmic mean temperature difference
LTES	Latent thermal energy storage
MINLP	Mix integer nonlinear problem
MOC	Multiple operating cases
NLP	Nonlinear programming
PA	Pinch analysis
PCM	Phase change material
PCD	Phase change dispersion
PCS	Phase change slurry
SFOE	Swiss Federal Office of Energy
SoA	State-of-the-Art
SROP	Stream-Wise Repeated Operation Period
TAC	Total annual cost
TAM	Time average model
TES	Thermal energy storage
TS	Time slice
TSM	Time slice model
VSU	Volume storage unit
WP	Work packages

1 Introduction

1.1 Background and motivation of the project

The end energy demand of the Swiss industry amounted to approximately 41 TWh in 2019 (pre-COVID-19 Pandemic), of which about 54 % was used as process heat [1]. Process heat therefore equates to approximately 11 % of the entire end energy use in Switzerland. In the study commissioned by the Swiss Federal Office of Energy (SFOE) on the energy perspectives 2050+ for Switzerland, the savings potential for the generation of process heat, up to the year 2050, is estimated at 22 % in the "ZERO Basis" scenario versus the “Weiter wie bisher” scenario [2]. In order to exploit this potential, innovative technologies and Energy Efficiency Measures (EEMs), among other things, must be developed and implemented. The federal government is making great efforts to achieve the goals of the Energy Strategy 2050, e.g. with the "Coordinated Energy Research Switzerland" [3].

Today, industrial companies must meet a wide range of requirements. Industrial processes should not only exhibit maximum economic efficiency, but also should have high energy efficiency and low emission production. In addition, in the medium to long term, rising energy prices and incentive levies will make it essential for energy-intensive companies to increase their energy efficiency to remain competitive. In recent years, industry has made great efforts in the field of energy efficiency, but there is still considerable potential for further increment [4].

Classical approaches for energy optimization usually focus on improving the efficiency of individual pieces of equipment. However, experience shows that the optimal coupling of energy flows in the overall process often yields much greater efficiency gains than the costly efficiency improvement of individual pieces of equipment. Techniques and methods for increasing the Heat Recovery (HR) have been well-developed, under the umbrella of Process Integration. One standout method is Pinch Analysis (PA), which is one of the most important tools of process integration [5]–[7]. It helps to find the optimal plant design under the constraint of minimum costs by optimizing the energy usage and to improve the economic efficiency. From the results of the analysis, measures for HR and improved energy supply can be derived.

One of the key ways to further improve the efficiency of industrial processes is the integration of Heat Pumps (HPs). HPs can upgrade the often-existing low temperature heat surplus to a higher (i.e. useful) temperature level. However, only a correctly integrated HP increases the HR potential and reduces the heating and cooling demands of the process. For industrial processes that are operated continuously, methods for the integration of HPs are well established in industry.

For various reasons (irregular production schedules, high demand for flexibility, product changes, different workloads, interruptions for cleaning, etc.), many industrial processes are, however, non-continuous in nature. In such processes, a HR system with Thermal Energy Storage (TES) is often the only possible optimization strategy. PA can be used to determine whether energy storage is technically and economically feasible, which heat sources and sinks should be considered, and how storage capacities and temperatures should be selected.

Like continuous processes, non-continuous processes do often have a heat surplus at a low temperature level and a heat deficit at a high temperature level, but in the case of non-continuous processes they occur not necessarily at the same point in time. Through the combined integration of a HP and TES, this indirect heat recovery can be exploited to increase the efficiency.

The systematic potential integration of a HP and TES into non-continuous processes is, however, a major challenge in terms of conceptual design, layout and planning as well as for operation. Various approaches from the literature (Section 2) are very complex and require long computation times. They lead to optimal, but mostly not feasible results (e.g. plant design with very many splits). The SFOE project "Integration of heat pumps and thermal energy storage in non-continuous industrial processes - HPTES" addresses this challenge.

1.2 Goals of the project

The overarching goal of the project is to facilitate the integration of HPs in non-continuous industrial processes. This SFOE project, "Integration of heat pumps and thermal energy storage in non-continuous industrial processes - HPTES" addresses exactly this challenge. Specifically, the following three main objectives are defined:

1. Development of practical methods for HPTES integration in non-continuous processes. The focus is on the practical applicability for engineers and planners from engineering firms and industrial companies.
2. Development of control strategies and concepts for the HPTES system to ensure operation under real operating conditions. The control strategies and concepts to be developed include classical as well as modern control methods.
3. Verification of the methods for HPTES integration in non-continuous processes and the associated control strategies by applying them to two case studies.

1.3 Procedure

To achieve the goals of this project, the procedure is divided into the following six work packages (WP):

- WP1 State of the art literature review
- WP2 Case study analysis
- WP3 HPTES method development
- WP4 HPTES control strategy development
- WP5 Method verification through application on case studies
- WP6 Identifying alternative storage technologies

Firstly, a literature and state of the art (SoA) review was conducted. Subsequently, case studies from industry were analyzed for their suitability as case studies in the HPTES project. With this step the typical characteristics of non-continuous processes with HP integration potential could be identified at the beginning of the project.

In the subsequent method development WP, the defined goals are addressed with the development of a structured method. The method development was based on the detailed analysis of literature case studies, self-derived benchmark cases, and on inputs from a group of experts, (pinch, storage, heat pump experts, and others).

The derivation of a suitable control strategy for the HPTES system was targeted with a simulation-based analysis of the behavior of the individual components of the system and the study of existing control strategies. The overall control strategy was then implemented in a dynamic simulation model of the overall system and tested.

Verification of the method and the control strategy with case studies from the food industry was subsequently performed. Alongside with the overview of possible extensions towards other storage technologies than stratified storage systems.

2 State of the Art

The SoA is divided into two sections: Section 2.1 introduces the current PA used in the industry which is the basis of the developed method of this project, and the subsequent sub-sections introduces the history and current state of research in the field of PA and integration of HP and TES.

2.1 Established tools of pinch analysis in industry

PA is used to properly integrate HPs into processes. In general, processes are categorized into continuous and non-continuous processes, where the latter can later be further defined as batch or semi-continuous processes. The types are described as following:

- Continuous processes: raw materials pass through unit operations at a constant flowrate and heat load, and is present at all times.
- Batch processes: raw materials pass through unit operations stepwise, in discrete amount.
- Semi-continuous processes: continuous operation during cycling time intervals periodically (e.g. shut down due to cleaning purposes, daily or weekly operation).

Townsend and Linnhoff [8] and Berntsson [9] have developed methodologies to support the integration of HPs in continuous processes. Olsen et al. [10] later used the methodologies in a case study to show how to apply the methodologies to handle time dependence within a single process. Even though methods for HP integration are well developed, they still face multiple challenges in the industry, which has prevented their widespread adoption [11].

In non-continuous processes, HR is usually limited due to different process schedules of the single plants [12]. Due to the temporal variations in the heating and cooling requirements integration of HPs in non-continuous processes presents particular difficulties when selecting a HP with appropriate operational characteristics such as feasible evaporation and condensation temperature ranges, as well as evaporator and condenser duties for optimal placement across the pinch point [10]. In addition, start-ups and shut down of single plants due to cleaning purposes are a common occurrence. This tends to be one of the challenge of properly integrating HPs. Furthermore, limited expertise and experience represent barriers to entry for the technology and directly affect adoption of the HP technology in industry because of the uncertainty and subsequent financial risks. This is despite such systems being shown to be economically viable, e.g. waste HR from batch reactor systems [13], and a small but growing number of non-continuous process HP integration case studies [14]. Consequently, HP integration has often been relegated to the integration of continuous processes only, restricting the possible contributions of HP technology to the reduction in energy consumption across the industrial sector.

2.1.1 Status of the practical application of pinch analysis: Principle of pinch analysis

"Targets before design" is the basic philosophy of PA: the determination of energy and cost targets is done before the design of the plant [5]–[7]. The process streams to be heated and cooled are combined into two Composite Curves (CCs). The cold CC represents the heat sinks and the hot CC represents the heat sources (Figure 1, left). The overlapping area represents the feasible HR from heat sources to heat sinks. Moving the CCs horizontally changes the minimum temperature difference, ΔT_{min}, between the curves, the HR potential and the required heating and cooling capacity (Hot Utility HU, Cold Utility, CU). With the objective of minimizing the annual total costs, the optimal temperature difference $\Delta T_{min,opt}$ is obtained (Figure 1, right). The larger the ΔT_{min}, the smaller the overlapping area and thus the potential for HR. At the same time, more heating and cooling capacities are required, which leads to higher operating costs. The investment costs for HR is the opposite: they decrease with increasing ΔT_{min}, as smaller Heat Exchangers (HEXs) are required.

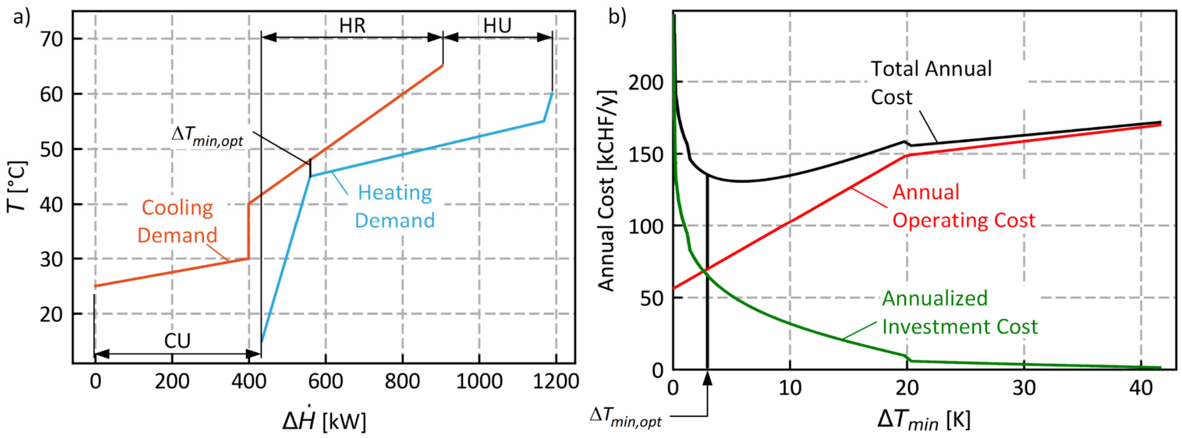

Figure 1: Example of a a) composite curves, and b) cost curve

Subsequently, the design of the Heat Exchanger Network (HEN) is carried out, in which the energy and cost targets from the CCs are turned into concrete designs, in compliance with the $\Delta T_{min,\ opt.}$, can be achieved. The following three main rules ("Golden Rules") must be observed: (1) no cooling above the pinch, (2) no heating below the pinch, and (3) no heat transfer across the pinch. The PA systematically leads to the goal of an energetically and economically optimized plant. For complex plants with a large number of process streams, PA is the only practicable tool for plant design.

2.1.2 Integration of heat pumps in continuous processes

The Grand Composite Curve (GCC) is created by combining the shifted hot and cold CCs [15]. It shows how much net heat deficit (heating demand) and net heat surplus (cooling demand) exists at any temperature level (Figure 2). The heat deficit of the process exists above the pinch, heat surplus exists below the pinch, and neither a deficit nor surplus is present at the pinch point. The GCC is a useful graphical tool to determine the required HU and CU temperatures for a given heat duty and thus allows for an exergetic optimization of the utility system. Likewise, the net heat deficit and surplus shown in the GCC needs to be considered when integrating a HP.

The required utility temperatures read from the GCC do not correspond to the real temperatures: these are higher above the pinch by $\Delta T_{min}/2$ and lower below the pinch by $\Delta T_{min}/2$ than the temperatures in the diagram (see e.g. [5]–[7]).

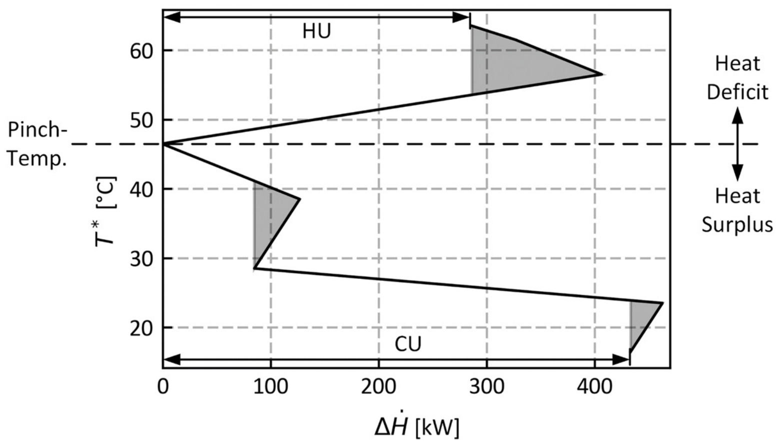

Figure 2: Example of a Grand Composite Curve.

From the "Golden Rules" it can be deduced that a HP should absorb heat below the pinch (where there is a heat surplus) and release heat above the pinch (where there is a heat deficit). It is said that "**the heat pump operates across the pinch**." (Figure 3). If a HP operates only below the pinch, the heat surplus is increased, and additional compressor power must be dissipated through the CU. Integrating a HP only above the pinch results in a reduction of the HU by the compressor power – energetically an electric heater.

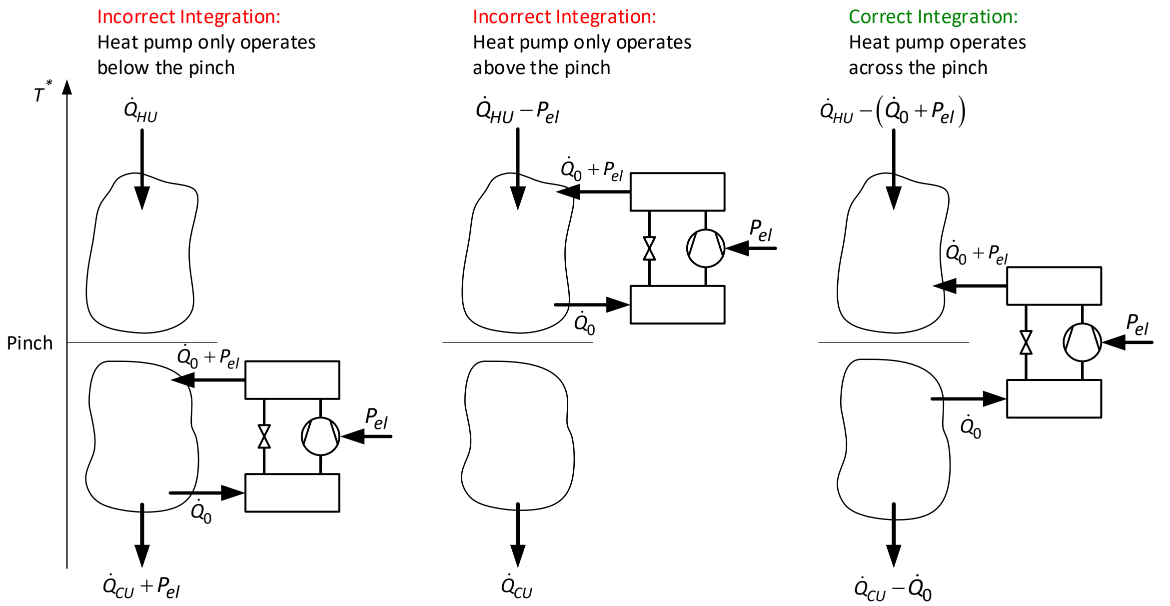

Figure 3: HP Integration into a continuous process (adapted from [10], [16]).

One of the reoccurring mistakes in industry is that HPs are not correctly integrated. The position of the pinch point and the shape of the GCC indicate whether it makes sense to integrate a HP or whether an existing HP is correctly integrated into the process. With a correctly integrated HP, the heating and cooling requirements and the associated energy costs can be reduced simultaneously (Figure 4).

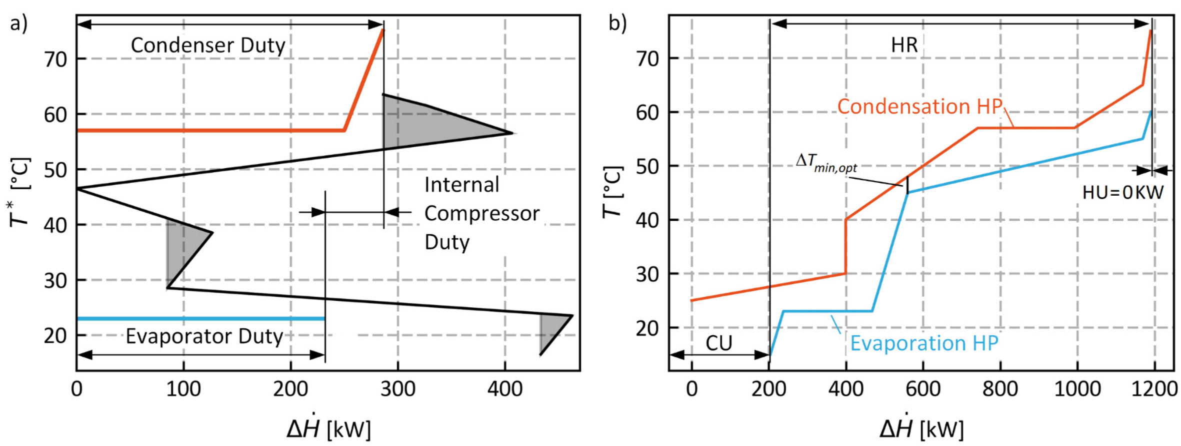

Figure 4: Heat pump integration in metal processing plant. a) GCC with evaporating and condensing temperature of WP. b) CCs with integrated heat pump streams.

2.1.3 Integration of thermal energy storage systems

In non-continuous processes, heat sources and sinks do not occur simultaneously, and the temporal change of the heating and cooling demand is sometimes high. HR can often only be achieved by integrating TES, which is referred as Indirect Heat Recovery (IHR).

Pinch analysis can be used to determine which heat sources and sinks should be considered, how storage capacities and temperatures should be selected, and whether the storage solution is economical. In practice, tools based on time-averaged methods have proven to be effective (Time Average Model, TAM). In the 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 Indirect Source Sink Profile (ISSP) is based on the TAM approach and allows for the integration of TES into non-continuous processes (see, e.g., [17], [18]). It shows the whole heating and cooling demands over the batch process in cycles. When batch processes are delivered in a cyclic manner, (periods in which streams occur in a repeated order), these periods are called Stream-wise Repeated Operation Period (SROP). As a difference to continuous processes the ISSP displays the needs of heat load in kilowatt hours instead of the heat rate in kilowatts. The ISSP method ensures that the resulting storage system is technically feasible, the heat balance is guaranteed, and the complexity is as low as possible. The temperature-enthalpy regions where placement of storage is feasible are termed as Assignment Zones (AZs). Abdelouadoud et al. [18] introduced the AZs graphically on the ISSP to represent the ISSPs constraints and degrees of freedom that apply when designing the HESN that can achieve the target heat recovery, given by ISSP overlap. Figure 5 shows an example of an ISSP and its associated TES system. The ISSP is reminiscent of CCs, but the thermal requirements are shown as heat quantity (in kWh over the period) rather than heat output (in kW). The black line between the red source profile and the blue sink profile shows the transferred heat quantity (IHR) and temperature levels of the storage tank and the Intermediate Loops (ILs), respectively. The method is well established, it is used today by engineers for the dimensioning of TES systems with the software PinCH.

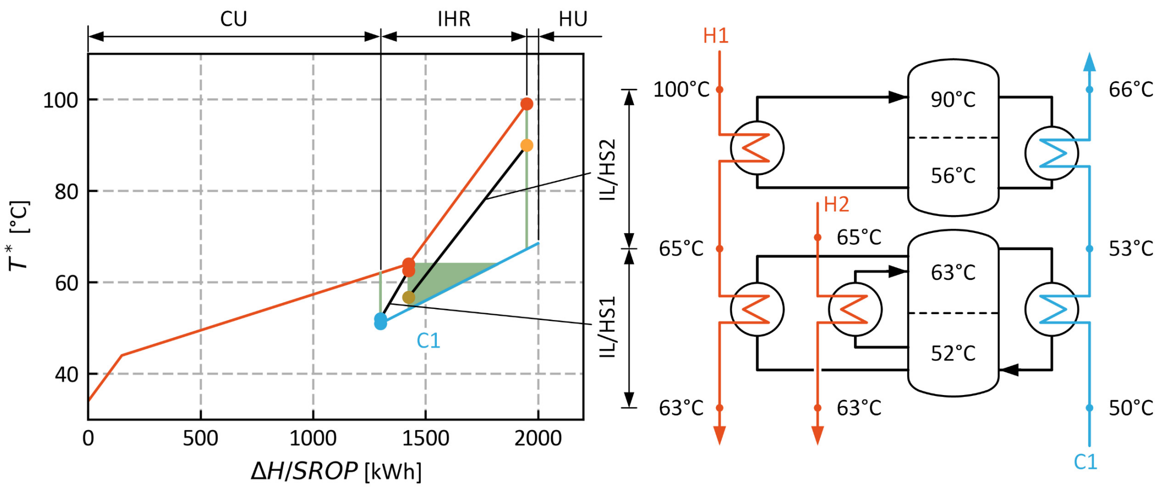

Figure 5: Storage integration in non-continuous processes using ISSP. HS represents Heat Storage.

2.1.4 Combined integration of a heat pump and thermal energy storage

The combination of the HP and the HR system with storage units is the core of the SFOE project HPTES. Until now, no practical method existed for this challenge. In the HPTES project, such a method is developed based on an earlier project on HPTES integration [10].

2.2 Pinch analysis for non-continuous processes

With the TAM, the first heat integration for non-continuous processes was developed by Clayton [19]. This technique treats non-continuous processes as continuous, where it assumes that process streams exist simultaneously. Due to the neglect of a schedule, the resulting energy target is usually not met if only direct HR is considered.

Olsen et al. [20] developed the Indirect Source and Sink Profile, which is an extension of the Site Source Sink Profile introduced by Dhole and Linnhoff [21]. The ISSP is a further development of the TAM. The process streams are weighted by their IHR potential (duration and heat transfer coefficient). This method can be used to reduce costs for HEXs that have low benefits due to short operating durations or inefficient heat transfer (low heat transfer coefficients). Walmsley et al. [22] showed that the TAM also comes close to the optimal results using Nonlinear Programming (NLP), which in turn results in a minimum of HEX area to be expended.

Obeng and Asthon [23] developed a method using the Overall Plant Bottleneck approach to identify the bottlenecks that limit the performance of a plant. In this approach, overall energy targets are established using the TAM. In a further step, the Time Slice Model (TSM) introduced by Kemp and MacDonald [24], [25] defines the energy targets with regard to the schedule. Each batch cycle is divided into Time Slices (TSs), in which the process is considered continuous.

Wang & Smith [26] developed the Time Pinch Analysis which reverses the TSM approach. Instead of transferring heat between temperature intervals in one time interval, heat is transferred to the future time intervals, using storage. Temperature intervals limit the possible IHR. This approach prefers indirect rather than direct HR, which is in general considered to be more expensive. Nevertheless, this approach is an appropriate method for dimensioning utility storages. Stampfli et al. [27] used this method to design the HP from the process in time.

All methods described so far are based on graphical approaches. In contrast to these methods, Majozi [28] developed the State Sequence Network method based on mixed-integer linear programming techniques to integrate batch processes using TES. Further developments have been made to extend the method of multi-product to multi-purpose batch plants [29]. This approach includes optimizing storage capacity and initial storage medium temperature. Krummenacher et al. [30] developed an automated optimization and design method for indirect and mixed direct/indirect HR for batch processes using a genetic algorithm. In this method, the HEX connections, and the temperature levels of the layers in the reservoir are determined for each TES system.

HR in semi-continuous processes was investigated by Atkins et al. [12], among others, to reduce energy consumption at a milk powder plant in New Zealand. This involved integrating TES with intermediate cycles (IC). Atkins et al. [31] further investigated the impact of process flow variability, particularly flow velocity, as temperatures, storage volumes, shift temperatures, and temperature level of the TES are typically controlled.

An iterative procedure for designing an indirect CC which uses variable temperature storage to optimize a batch process was developed by Chen and Ciou [32]. This was an extension of their earlier work in which the limitation of constant temperatures of the storage medium was removed to increase the HR potential [33]. Further research on variable temperature storage systems was conducted [34], which involved fixing the temperature difference between process streams and the heat recovery loops (HRLs). It was pointed out that further research is needed to show the specific behavior between HR and cost. The variable temperature storage approach has been shown to be advantageous for solar heat integration [35].

2.3 Integration of heat pump and TES systems

Townsend and Linnhoff [36] defined the rules for HP integration in continuous processes, using GCC for HP Integration. Based on this approach, Hindmarsh et al. [37] showed the influence of the evaporating temperature of refrigeration systems on their power consumption. Wallin et al. [38], developed a method for determining the optimal temperature level, HP size and type, using CCs. This work was extended by using the GCC [39], and consideration of CO_2 emissions [40]. It is shown that there is a big difference in terms of CO_2 emission reduction between water- and air- based HP. Yang et al. [41] investigated the impact of HP integration on the GCC and pinch temperature. The integration of two HPs is considered (one each for process pinch and utility pinch). This graphical approach using GCC for HP integration has been applied to several case studies, such as a whiskey production process [42], a cheese factory [43], a biomass gasification process [44], and a confectionery production plant [10].

Loken [45] developed a computer program for HP integration, where the condensing and evaporating streams are integrated into the process. However, this approach does not optimize the HP operating conditions. An approach that takes into account the operating condition of the HP is studied by Ranade [46], which determines an economically optimal temperature swing in the WP. Using a mixed-integer linear programming approach, Shelton and Grossmann [47], [48] showed the economic potential of properly integrated HR and cooling system networks. Colmenares and Seider [49] proposed a formulation based on nonlinear programming for HP integration. This allows the HP to absorb heat at different temperature levels. Holiastos and Manousiouthakis [50] introduced an analytical approach to determine the optimal temperature levels of a reversible HP. The work was extended to include a transport problem formulation to determine an optimal heat transfer and WP system [51]. Wilkendorf et al. [52] developed a mathematical model to minimize the annual cost of utility systems. This model was developed for continuous processes but can be extended to non-continuous processes. Zhang et al. [53] developed a mathematical model to minimize the total annual operating cost of a HP by considering the variation of ambient temperature,

Considering the environmental impacts during HP integration, Wall and Gong [54] formulated exergy factors for PA. Staine and Favrat [55] included exergy analysis in the graphical PA methods introduced by Dhole and Linnhoff [56]. This extends the CCs and the GCC: instead of using temperature as the y-axis, the Carnot factor is used. In this work, exergy losses during production, dissipation, and heat transfer are considered. With this extended PA, Marechal and Favrat [57] developed a method for the optimal integration of utility systems. This work was continued, by considering multiple utility pinch temperatures [58]. Multi-objective optimization of operating and capital costs for single-stage, multi-stage, and combinations of multiple HPs is applied. In addition, the model was extended to non-continuous processes using the TSM and TESs [59]. This model was applied to a case study of a cheese factory [58]. Dumbliauskaite et al. [60] used the TAM model in combination with an exergy analysis to optimize utility systems and WP integration.

To smooth fluctuations in power consumption, TES are usually integrated in addition to the HP. Glembin et al. [61] demonstrated a methodology for TES integration in a solar thermal power system including a HP. Energy demand can be reduced by increasing the number of temperature levels at which heat is stored or delivered. Renaldi et al. [62] developed a formulation based on mixed-integer linear programming for TES integration in domestic HP systems. The advantage of such systems is that the peaks of the heat demand can be supplied by electricity surpluses of renewable energy sources, in a time-shifted manner. In addition, the size of the HP can be reduced. Another approach for TES integration in HP systems was developed by Floss and Hofmann [63]. In this work, control strategies for the HPTES system were defined by considering both stratified storage and fully mixed storage.

Methods for HP integration considering non-continuous processes are applied for various case studies, for example, upgrading a shower for residual water Chen et al. [64]. Furthermore, Miah et al. [65] developed a methodology for HP integration in simple and complex factories. This methodology was applied in a large non-continuous confectionery factory with multiple production areas. Additional methodologies for HP integration in a milk powder production facility were developed by Walmsley et al. [66]. Instead of using the environment as a heat sink, the pressure is increased to integrate the waste heat into the process. A non-convex, mixed-integer, NLP approach was applied by Wallerand et al. [67] to optimize HP integration on various case studies from the literature. They decomposed the optimization problem into subproblems and solved each subproblem separately.

Prendl et al. [68] carried out a mathematical optimization to simultaneously integrate HPs and storage into multi-period superstructure formulation. The work is built on the optimization superstructure [69] with a convex linearization of the cost function based on the size and energy consumption of HPs [70], with the continuation to extend the works by introducing additional storage considerations to allow and enhance HR between the operating cases. The study modeled and simulated a real vapor compression HP to obtain a realistic HP characteristic. Also, the solution space for the Coefficient of Performance (COP) has been tightened to improve the accuracy of the approximation and to reduce the computational effort. This work linearized the relationship between COP and the ΔT to identify the HP characteristics rather than just assuming a typical characteristics of a typical HP [70].

2.4 Research gap

The systematic integration of HP and TES into non-continuous processes is a major challenge in terms of conceptual design, layout and planning as well as for operation. In addition to the mentioned literature of HP integration using PA, HP integration in non-continuous processes is usually formulated in mathematical programming as a mixed-integer nonlinear problems (MINLP). Although mathematical programming provides a wide variable solution space and optimal design, they tend to be long in their computation time and restrict the use to specialized engineers. They lead to optimal, but often not practical results.

Therefore, this work aims to develop a methodology that assists the engineers and planners for a correct integration of HPTES into non-continuous processes. The current gap in literature is, that there is no method to evaluate the integration of HPs combined with IHR systems or separate from them. Theoretically, in a combined HP and IHR system, the number of TES can be reduced. However, with a separate HP system, the HP is less interconnected with the processes and may be more robust in the operation. In addition, the HPTES project is inspired by the work carried out by Stampfli et al. [71], where the authors considered HP integration in the utility system. However, Becker et al. [72] has shown that direct heat exchange between the process and the HP yields higher efficiency. Integrating the HP system directly into the process can reduce the temperature lift of the HP (less heat exchanger between the process streams and the HP). This work uses and extends the graphical method, the ISSP method, for the integration of HPs in combination with TES into non-continuous processes, to improve energy efficiency.

3 Description of Methodology

3.1 Overview on the methodology

The core of the research project HPTES is the development of a practical method for the integration of heat pumps combined with thermal energy storages in non-continuous processes, as they are often found in industry. A workflow for integration of HPTES has been developed, which fits into the established Pinch Analysis workflow, as applied in the Swiss industry, as described e.g. in Brunner and Krummenacher [5].

To exploit indirect heat recovery potential, Time Average Model based methods are generally used for analysis. The TAM represents the average heat flow over a repetitive time-period of the process. As it disregards the scheduling of the process, the TAM provides an upper bound for the direct and indirect HR potential of a process. IHR solutions can, however, not directly and solely be derived from the TAM, as the scheduling of the process streams and the used storage design need to be taken into account for targeting and design. With the ISSP, which is based on the TAM, the integration of TES into non-continuous processes can be enabled. The ISSP is hereinafter used as a basis for HPTES integration. The later analyzed different HP integration options are integrated into the ISSP as additional process stream, as it is also done for HP integration in continuous processes.

The workflow, which is a variant based approach, is shown in Figure 6. The elementary idea is that the engineer or planner (hereinafter referred to as user) is in the center and he/she can always influence the solution variants. A solution variant is composed of a IHR overlap selected by the user in the ISSP, a choice of the HP integration pathway in the workflow and a certain HP-placement. The steps from data extraction up to and including, the analysis of the IHR system (highlighted in dark blue) are based on existing tools, as they are already implemented in the PinCH software. In the following sections the HP integration into the process, and the subsequent required TES system is detailed. In the workflow two general options for HP integration are considered, while each option can be evaluated in different configurations (i.e. variants):

1. Integration of HP into a secondary HESN (additional) to the IHR HESN
2. Integration of HP into the same IHR HESN of the process

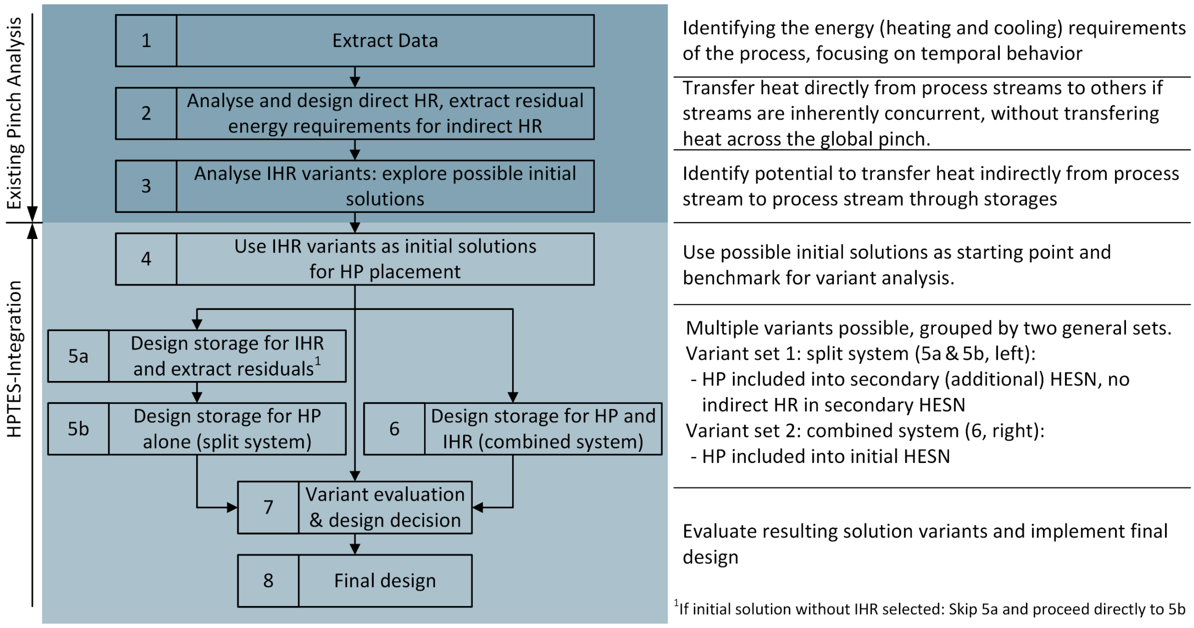

Figure 6: Workflow for the integration of HPTES system into non-continuous processes.

The first option leads to a separate TES system, which hypothetically means less complexity and thus easier controllability. The second option allows the HP to be operated "closer" to the process, which can make its operation more efficient. However, this results in an increase in complexity due to the additional coupling of the storage units. The decision as to which option is more suitable for a specific process must be made by the user. The basis for comparison is always the indirect heat recovery system without HP (feasibility, complexity, economy, etc.).

Both options use an adapted existing method for the placement of the HP. In option 1, to be able to dimension the HP, the residual ISSP is converted to the inverted residual ISSP as shown in Figure 8c. In Figure 8c, the source profile (hot composite curve) is inverted in its enthalpy coordinates. This allows to show the heating and cooling demands similarly as in the GCC, and thus enables users to place the HP, as with a GCC.

For the second option (HP in IHR TES system), not only the heat deficit or surplus evident from the GCC is relevant for the placement of the heat pump. It must also be considered to what extent the TES system is changed by the integration of the HP. With the integration of the HP, two new flows (evaporator and condenser) are introduced into the system. This has the consequence that the degrees of freedom of the resulting TES system are restricted or that its complexity is possibly increased. This does not necessarily have to be a negative aspect, since the increase in complexity may possibly lead to a higher profitability. However, there is the danger that the process control is made more difficult or impossible, whereby the goal of the efficiency increase would be missed. In order to mitigate this problem, the effect of HP placement on the TES system was investigated, using the AZ algorithm. The algorithm is used to determine the minimum number of layers (i.e., temperature levels) required for a given configuration of indirect heat recovery and HP.

The result of these two possible pathway analyses allows to determine a selection of relevant solutions for further elaboration. This selection forms the basis for the variant study and determination of the final HPTES design. An optimization program for the determination of the minimal investment cost for a given solution variant is derived to facilitate the variant analysis.

The subsequent subsections of Section 3 and the optimization (Section 4) for the HPTES integration is further explained in detail. In this workflow, key assumptions are made and as listed below:

1) Continuous operation of HP to minimize capacity at constant operation point

2) Storages to allow continuous operation of HP

3) Stratified storage with two layers with constant temperatures

3.2 Demonstration case

To explain the methodology, a demonstration case is used as the basis of the graphics to illustrate the different steps in the workflow for the design of the HPTES system. The demonstration case contains three streams, as given in Table 1.

Table 1: Process stream table of the demonstration case including the individual shift $\Delta T_{min,s}$ within the ISSP.

Stream name	T_α [°C]	T_ω [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	t_{start} [h]	t_{end} [h]	h [W/(m^2 K)]	$\Delta T_{min,s}$ [K]
H1	35	25	7.2	4.2	0	2	2'000	-1
C1	15	45	1	4.2	2	4	2'000	+1
C2	40	60	2.4	4.2	1	3	2'000	+1

Table 1 contains the individual shifting of the process streams, within the ISSP. The shifting of the process stream within the ISSP is further explain in Section 3.3.

3.3 Data extraction and direct heat recovery (Steps 1 and 2)

For conducting a PA, the heating and cooling demands (also known as process requirements) of the process have to be identified. The process of extracting this data from the real plant is the first step of any PA. Data extraction commences with the development of a clear understanding of the process and assessment of the necessary (measurement) data. Based on this step the heating and cooling requirements are to be defined. The result of the data extraction is a listing of the process requirements (the stream table), including their scheduling.

To achieve this goal, assumptions and simplifications have to be made by the user to compile the vast extent of process information down to a representative set of process requirements. The assumptions made in extracting the process requirements is important to ensure an adequate level of modelling complexity is maintained, yet being certain to not exceed the necessary number of details for an adequate analysis. When analyzing the process, the engineer will typically have to first identify the type of processes present, the range of products (different operating cases) and their different production lines (conditions and schedules). Further information on data extraction is available Klemeš and Varbanov [73] or the Brunner and Krummenacher [5].

After the process stream table is defined, the energy and cost targets for direct HR within the individual operating cases or time slices can be identified using the Composite Curves (as mentioned in Figure 1). The CCs provide a picture of the heat recovery potential and can be used to indicate the theoretical energy and cost targets for the process, with a given specification of a minimum allowed temperature difference, which is an economic parameter for the tradeoff between investment cost and operating cost. This allows quick identification of the scope for energy saving at an early stage. With the energy targets defined, the actual design of the heat exchanger network (HEN) can be carried out for direct HR. Direct HR shall only be realized as a HEN for streams that which schedules are inherently concurrent. The shares of the streams that are heated or cooled with this newly designed direct HR measures are then subtracted from the stream table and only their remainders are used for the further analysis.

3.4 Indirect heat recovery (Steps 3 and 4)

After designing the direct HR, the remaining heating and cooling demands of the process is analyzed for IHR, using the ISSP. The streams in ISSP are rearranged in priority relative to one another using temperature shifting. Streams with “high attractiveness for IHR” are prioritized. Therefore, streams that have a longer duration or have a larger film heat transfer coefficient are prioritized higher in creating the ISSP than those with lower values. The streams are prioritized by shifting the supply and target temperatures based on the calculated stream specific $\Delta T_{min,s}$ contribution shown in Eq. 1.

$$\Delta T_{min,s} = f_p \left(\frac{1}{U_s t_s} \right)^y \qquad \text{with} : f_p = \max \left[(U_s t_s)^y \right] \Delta T_{min,ov} \tag{1}$$

where the U_s is the overall heat transfer coefficient between the IL fluid and the process stream and t_s is the duration of the stream in the TSM. The variable f_p is a proportionality-constant that is determined beforehand based on a user specified minimum overall temperature difference $\Delta T_{min,ov}$. The y exponent influences the magnitude of the temperature shifting. Once the individual stream $\Delta T_{min,s}$ contribution is determined, they are subtracted or added from the stream supply and target temperatures, respectively. The ISSP can then be constructed in a composite manner, using the new shifted stream temperatures. The ISSP displays the potential of possible IHR and shows the amount of residual heating and cooling demands, above and below the pinch respectively, present. This residual heating and cooling demand may be used for HP integration after the degree of IHR is determined. Figure 7 shows the ISSPs for the demonstration case study with three different degrees of overlap a) 0 kWh (i.e. no IHR), with IHR of b) 80 kWh and c) 140 kWh, respectively. The user has to select the degree of overlap as the initial solution for HP integration in Step 4. The user might also apply the well documented rules for individual stream shifting and exclusion if needed as described in [5]. In addition to the ISSP, the sequence of loading and unloading phases is utilized for the computation of the required storage volumes based on the underlying TSM (see Olsen et al. [20]). The cost evaluation to realize the selected ISSP (HESN) is then calculated using the optimization program outlined in Section 4 of the report.

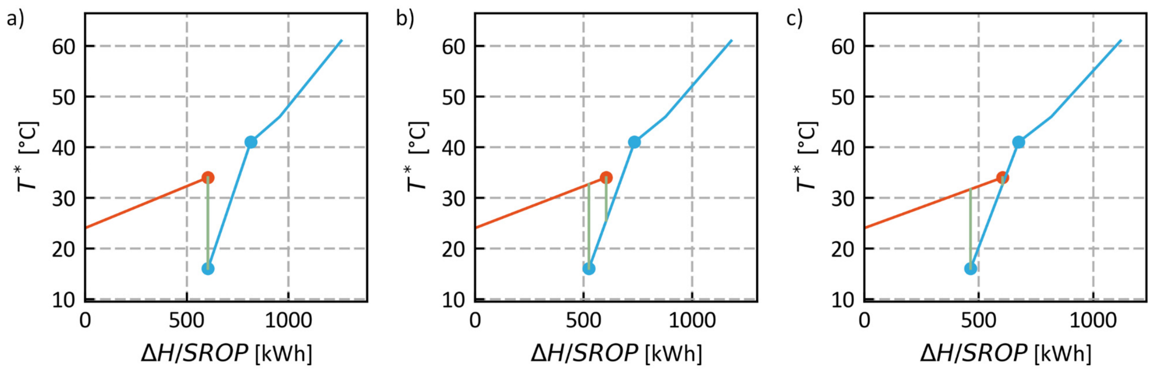

Figure 7: ISSP with different IHR initial solutions for the demonstration case a) no IHR, b) with 80 kWh IHR, and c) with 140 kWh IHR.

After evaluating potential degrees of IHR, one or more possible IHR solutions are to be chosen in Step 4 for further evaluation regarding their HP integration potential. These selected IHR solutions will be used as the benchmark for the final variant evaluation in Step 7. This ensures the comparison of the economic potential of a HP integrated final system against the SoA and IHR alone (i.e. shows whether or not a HP integration is economical after all). After the selection of the initial solution, there are two pathways for the integration of HPs in the workflow: i) integration of the HP into a separate HESN in addition to the IHR HESN and ii) the integration of the HP into the same HESN as used for IHR. The first pathway leads to the execution of Steps 5a and 5b while the latter leads to the execution of Step 6. Solution variants for the HP integration shall be selected such that the initial IHR solution allows for a low complexity, i.e.

low number of to be installed equipment, but also not so easily quantifiable aspects such as the controllability etc.

3.5 IHR solution with separate HP system (Step 5)

Using the selected initial solution, the IHR solution with a separate HPTES system is designed Step 5. Figure 8a shows the placed storage for the selected degree of IHR for the demonstration case. The residual heating and cooling demands (share of streams not included in the IHR) are then extracted to construct a new ISSP (Figure 8b). The residual heating and cooling demands are to be covered by the HP or utility. To be able to dimension the HP, the residual ISSP is converted to the inverted residual ISSP as shown in Figure 8c.

In Figure 8c, the source profile (hot CC) is inverted in its enthalpy coordinates. This shows the heating and cooling demands similarly as in the GCC, and thus enables users to place the HP at the right temperatures and duty. The inverted residual ISSP is, however, to be distinguished from the GCC, since the GCC shows the **net** heat deficit and surplus after HR but the inverted residual ISSP shows the **gross** heat deficit or surplus, i.e. with no further HR implementation.

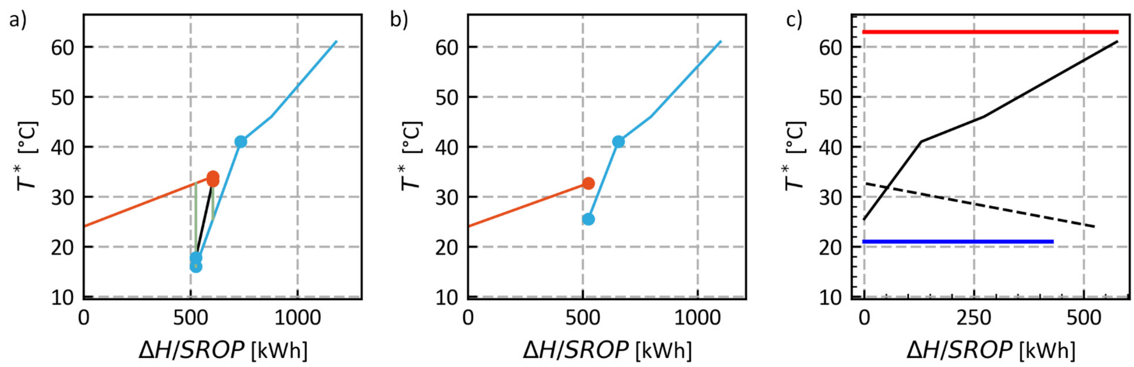

Figure 8: Design stages of split IHR and HPTES system: a) design of HESN for IHR solution, b) residuals of ISSP after design of IHR solution, c) Inverted residual ISSP for HP placement with the residual heating demand (solid black line), residual cooling demand (dashed black line) and HP evaporator and condenser as solid blue and red line respectively.

The HP is placed in Step 5b. The HP characteristics are modelled as a Carnot cycle with a constant second law efficiency according to Eq. 2. ζ_c is the second law efficiency of the Carnot cycle, T_{cond} and T_{evap} are the real condensation and evaporation temperatures, respectively, T^*_{cond} and T^*_{evap} are the ISSP-shifted condensation and evaporation temperatures, and finally ΔT_{cond} and ΔT_{evap} are the condensation and evaporation temperature shifts for the ISSP. The temperature shifts are to be set to typical values of the difference between medium outlet and condensation and evaporation temperatures, respectively. The shifting of the HP streams is therefore not calculated with Eq. 1 as it is for the process streams.

$$\mathrm{COP} = \zeta_c \frac{T_{cond}}{T_{cond} - T_{evap}} = \zeta_c \frac{T^*_{cond} + \Delta T_{cond}}{(T^*_{cond} + \Delta T_{cond}) - (T^*_{evap} + \Delta T_{evap})} = \frac{\dot{Q}_{cond}}{P_{el}} \qquad (2)$$

Once the HP is placed (temperatures and duty determined) using the inverted residual ISSP, the sizing of the HESN can be done with the ISSP and the underlying TSM as it is already established. The optimization program introduced in Section 4 is used to determine the cost-optimal storage temperatures.

3.6 Combined IHR and HP system (Step 6)

Contrary to the pathway through Step 5, it is possible to find solutions where the HP and IHR can be combined within the same HESN (Step 6). In the previous Step 5b the HP placement is supported with the inverted residual ISSP. This was proposed since there is no IHR in the HP-HESN. However, in the combined system, IHR is desired and the **net** heat deficit or surplus after IHR needs to be known for HP placement. For continuous processes the GCC (introduced by Townsend and Linnhoff [36]) shows this net heat deficit and surplus of a process. To date, there is, however, no GCC suitable for the HP integration with the ISSP.

The ISSP poses additional challenges for the derivation of a suitable GCC. First, the streams within the ISSP are already shifted to ensure the practicality and reduced complexity of the IHR solution. Secondly, it is often not desirable to achieve the maximum IHR overlap for an IHR solution as this requires a large number of AZs in the ISSP. Furthermore, when there is a small overlap in the ISSP, the temperature difference at the pinch is large and the temperature shifting of the source and sink profiles would be consequently large. This would in the very end lead to an artificially increased temperature lift of the HP which results in poor HP efficiency.

In contrast to the calculation of the GCC for continuous processes, it is, because of the challenges, proposed to calculate an adapted GCC of the ISSP without temperature shifting of the source and sink profiles. Figure 9 shows the difference in the design temperatures of the HP between the GCC (red lines) and the adapted GCC (black lines). The condensation temperature T_{cond} can be decreased, and the evaporation temperature T_{evap} can be increased, the HP efficiency is thus increased.

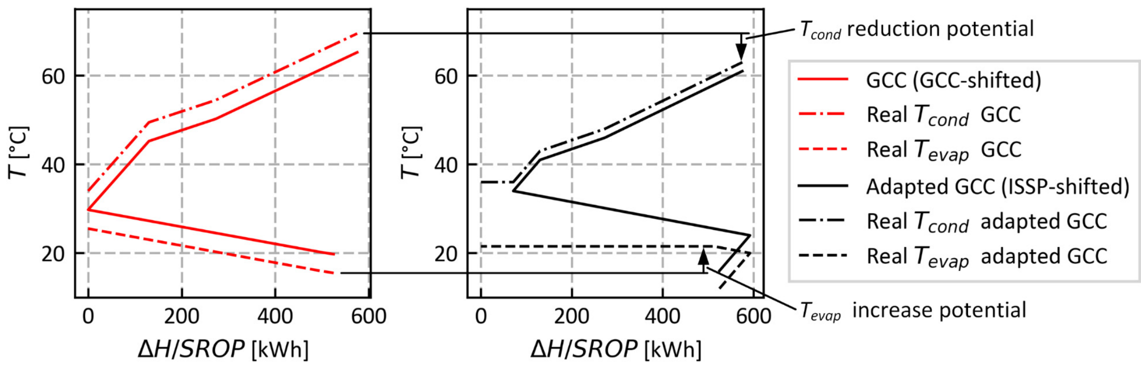

Figure 9: Resulting T_{cond} and T_{evap} if a) HP is integrated with GCC as calculated for continuous process and b) HP is integrated with adapted GCC. Data taken from case study, IHR = 80 kWh.

The adapted GCC shows the desired net heat surplus and deficit of the process. This ensures that the HP is not operated at unnecessary high temperature lifts while the thermodynamical feasibility of the resulting system is ensured due to the individual shifting of the streams in the ISSP.

Without the temperature shifting of the source and sink profile for the adapted GCC it is, however, necessary to impose limits such that the HP can operate across the pinch. The evaporator must extract heat of the subsystem below the pinch and the condenser must add heat to the subsystem above the pinch (see Section 2.1). To achieve this, temperature limits on the shifted evaporation and condensation temperatures are required, as illustrated in Figure 10a. These limits are the temperatures of the source and the sink profile at the pinch. The temperature limits are shown as the shaded and hatched area between the minimum condensation and maximum evaporation temperature (Figure 10b). The evaporator has to be placed below this area, and the condenser above. When following these rules on HP placement, the HESN can be designed such that the HP works strictly across the pinch. To ensure this, the right selection of the enthalpy coordinates in the ISSP when designing the HESN must be followed, such that there is no transfer of heat through the IL from the condenser to the evaporator across the pinch. This is included in the heuristics introduced in the optimization program of Section 4.

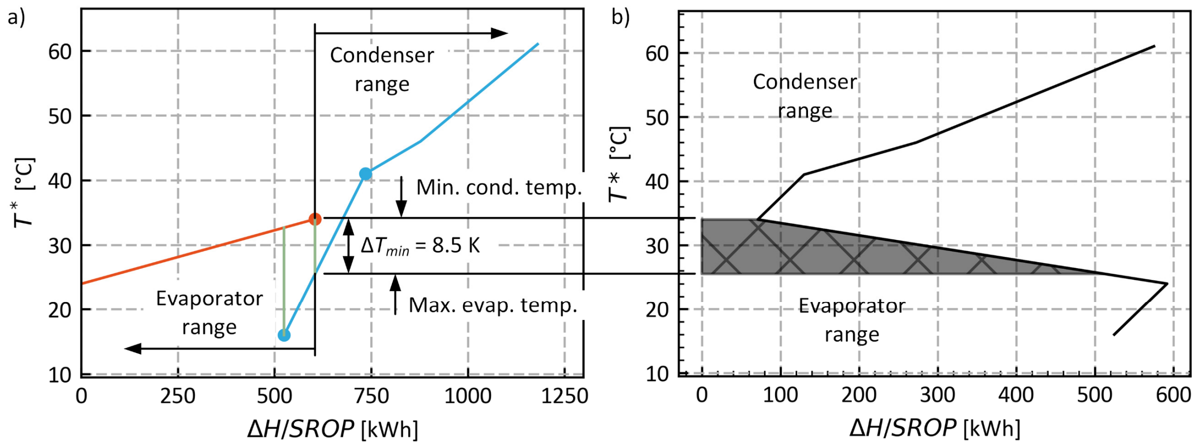

Figure 10: a): ISSP of the demonstration case with IHR=80 kWh. Enthalpy range of the evaporator and condenser are marked with the corresponding maximum evaporation and minimum condensation temperature. b): resulting adapted GCC including restricted temperature range.

As aforementioned, the integration of the HP often leads to the requirement of additional AZs. Every additional AZ is to be understood as an increase in complexity of the system as additional Volume Storage Units (VSUs, [20]) are required. A VSU represents typically a temperature layer in a stratified storage. Since the integration of a HP changes the topology of the system, different placements of the HP can lead to different numbers of AZ. To support the placement of the HP, an enumeration of the feasible HP placement options is performed. This enumeration evaluates the resulting number of AZs if a HP is placed in the feasible regions in the adapted GCC (Figure 5b). The AZ algorithm [18] is applied in a brute force approach. This brute force enumeration evaluates all relevant HP placement options starting from the HP-capacity limiting region (either condenser or evaporator, often it is the condenser region). The corresponding feasible other temperatures (evaporator or condenser, respectively) are evaluated for each placement. The HP characteristics are calculated according to Eq. 2. The enumeration for cases where the condenser range is HP-capacity limiting (as the demonstration case and many other cases, including the two cases studies in this project) is structured as follows:

1) Identify minimum and maximum temperatures from adapted GCC. Some temperature increase above the GCC can be specified. Some limitation of HP-temperatures may be applied.
2) Span grid over the limiting region in temperature and enthalpy, do not exploit pockets.
3) For each grid point, identify feasible evaporator temperature bounds and perform a specified number of enumerations for the given condenser grid point, within the evaporator temperature bounds.
4) Show minimum number of AZ in this enumeration set at the given condenser grid point and show resulting number of AZ and evaporator grid point.

For cases where the evaporator range HP-capacity is the limiting factor, the procedure is the same but mirrored: the grid (2.) is spanned over the evaporator range and the feasible condenser temperatures. Figure 11 illustrates the resulting output of this enumeration for one condenser temperature. It can be seen how the condenser duty affects the number of total AZs needed for the system.

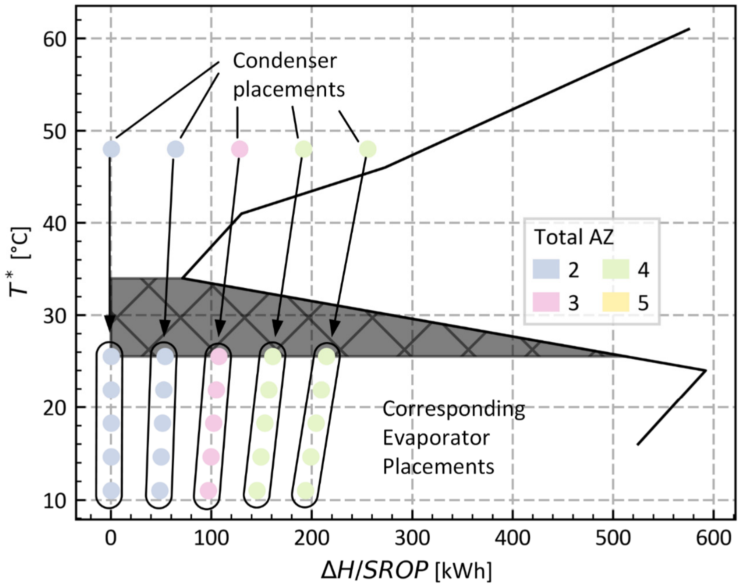

Figure 11: Adapted GCC with AZ information for 80 kWh initial solution for one possible condensation temperature (T^{*}_{cond} = 48°C) and illustrated dependency of evaporator and condenser placement.

The result of this procedure is shown in Figure 12a) and b) for the 80 kWh IHR overlap and 140 kWh IHR overlap variants, respectively.

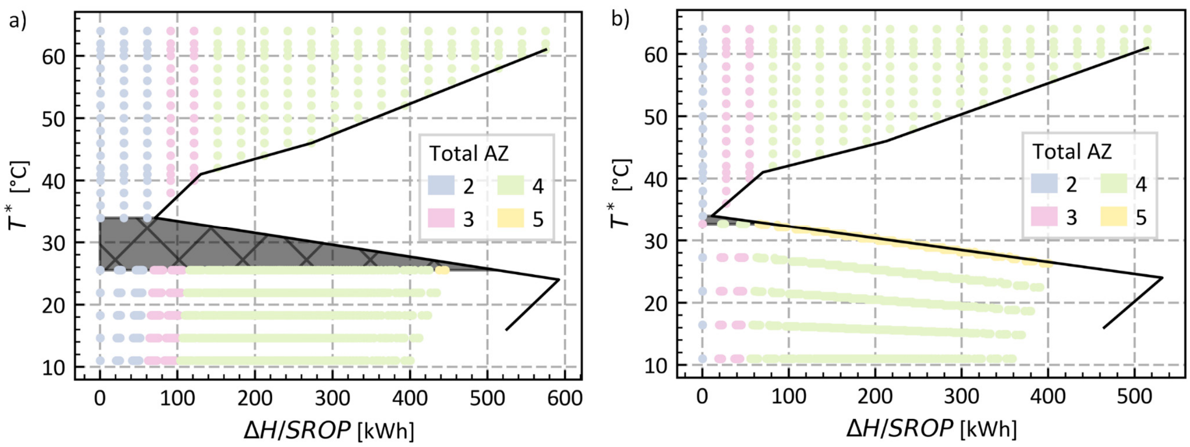

Figure 12: Adapted GCC with AZ information. a) for 80 kWh initial solution, b) for 140 kWh initial solution.

The graph shows in the condenser range the minimally required number of AZs for the respective condenser placement. In the evaporator range (below the pinch), it shows the resulting number of AZs for the corresponding condenser and evaporator placements. Since the evaporator placement is always corresponding to a certain condenser placement, this graph should be presented dynamically to the user, to facilitate reading. Above the pinch one can thus see how many AZs are at least required if the HP is placed with a given condenser duty and temperature, and below the pinch the corresponding evaporator temperatures show their influence on the number of AZs **depending** on the condenser placement.

For the decision of the HP-placement, the proposed adapted GCC with AZ information shows whether the HP temperatures or duties have an impact on the needed number of AZs and thus the complexity of the system. The number of AZs shown in the adapted GCC with AZ information has to be compared to the required number of AZs of the IHR initial solution. HP integrated systems should always have more than two AZs otherwise the HP would be operating with the condenser and evaporator in the same storage IL.

3.7 Variant evaluation (Step 7)

The HPTES workflow is built upon the evaluation of different solution variants. Therefore, it must be possible to compare these variants objectively and efficiently. To enable the objective comparison of different solution variants in terms of cost during the execution of the workflow, an optimization program for the ISSP is developed in this project. The optimization program is detailed in the Section 4. Beside the costs, several other aspects of a resulting solution variant must be considered in the variant evaluation. While some relevant aspects to be considered are listed below, engineering judgment is crucial in this step of the workflow.

1) Energy and greenhouse gas savings (changed demand for electricity, hot and cold utility)
2) costs (Total Annual Cost (TAC), investment cost, energy cost)
3) system complexity of the resulting HESN
4) other constraints such as company structure, space restrictions, etc.
5) controllability
6) practical storage aspects:
    - Discharging speed (depending on temperature [74])
    - Temperature differences between layers

A review of several implemented (large-scale) storage systems in Switzerland can be found in the BigStrat Report [75] and may be used as point of reference for the storage design.

4 Cost Optimization of the ISSP

Contrary to the energy targeting in PA for continuous processes, where the total HEX area can be estimated (See [76]), the ISSP does not yet allow the direct estimation of the cost depending on a given overlap due to the complex trade-off between HEXs area, storage capacity, and schedule. Therefore, the automatic evaluation of the cost of a given solution variant is not possible. The degree of overlap is not the only decision variable to be set by the user but the individual VSU temperatures and their enthalpy coordinates within the ISSP have to be determined as well. While the overlap of the ISSP is decided in Step 3 of the workflow, by the user, the latter two variables need to be determined at the end of the workflow after the HP is placed within the system and shall be addressed in this section.

To date, the determination of the VSU temperature and enthalpy coordinate were left to the user to be resolved in a manual approach. This was sufficient if the user only had to evaluate a limited number of ISSP options (often only one or two). However, for the objective and efficient evaluation of multiple ISSP combinations, an automated calculation of the investment cost is desirable. The existing tools for cost evaluation are hereinafter lined out and the development of the optimization program for the ISSP is presented.

In the description of the optimization program the following sets are to be defined:

$$i \in I = \{1,\ldots,N_{HS}\} \qquad l \in L = \{1,\ldots,N_{IL}\}$$
$$j \in J = \{1,\ldots,N_{CS}\} \qquad n \in N = \{1,\ldots,N_{Eq,HS}\}$$
$$o \in O = \{1,\ldots,N_{Eq,CS}\}$$

where *i* is the index for the hot stream, *j* for the cold stream, *l* for the VSU, *n* for the hot stream equipment and *o* is the index for the cold stream equipment. The index of each IL is the same as for the VSU but there is one less IL than VSU. The notation is chosen such that the for all operator ($\forall$) is always correct.

4.1 Demonstration case 2 for optimization

A second demonstration case is introduced to better explain the optimization algorithm. This case study is the basis of the graphics in Section 4 of the report. The demonstration case 2 contains five streams, as given in Table 2. It is of particular interest because there is one stream (C2) starting within the middle of the AZ.

Table 2: Process stream table of the demonstration case 2.

Stream name	T_α [°C]	T_ω [°C]	c_p [kJ/K]	t_{start} [min]	t_{end} [min]	h [W/(m^2 K)]	$\Delta T_{min,s}$ [K]
H1	120	40	6	70	210	2'000	-1
H2	105	75	16	0	70	2'000	-2
C1	50	85	15	0	70	2'000	+2
C2	68	80	60	70	130	2'000	+2
C3	70	85	12	130	210	2'000	+2

4.2 Existing cost evaluation tools

The ISSP ensures a closed energy balance over time and provides a thermodynamically feasible HESN design to the user, based on which the key equipment size can be calculated. The key equipment for IHR with the ISSP are the TES and the HEX. Accordingly, the cost of the HESN is determined based on the TES volume and HEX area as shown in Eq. 3. Where C_i is the resulting cost of the equipment, $C_{i,0}$ a size independent base cost, $C_{i,b}$ a size dependent base cost, Q_b the base size of the equipment corresponding to $C_{i,b}$ and m the degression exponent. Q is the actual size of the equipment to be priced. For the HEX Q is to be replaced with the HEX area A, and for the storage tank Q is to be replaced with the storage Volume V.

$$C_i = C_{i,0} + C_{i,b} \left(\frac{Q}{Q_b} \right)^m \quad (3)$$

The actual values for the cost functions are generally identified from cost databases. Rast [77] compiled such data for the Swiss market. The cost functions based on this data are subsequently used in this work and simplified, where applicable.

4.3 Characterization of the needed development and the properties of the system under investigation

The goal of the optimization program is the determination of the minimal investment cost of a given ISSP configuration. In the context of the HPTES project an ISSP configuration is specified through the stream data, the individual stream shifting, the overlap of the IHR initial solution and finally, the HP placement according to the chosen pathway through the workflow. The remaining degrees of freedom in the ISSP are:

1) the storage type (stratified or fixed temperature variable mass),
2) the configuration of the storage type (connected or disconnected ILs,),
3) the enthalpy coordinates of every VSU and
4) the temperatures of every VSU.

Regarding the first two degrees of freedom, the problem is simplified to handle only one specific storage type and configuration, namely single-IL stratified storage tanks (disconnected ILs in the ISSP). This results in practical feasible solutions of two-layer storage tanks, which are well implemented in the industry. The disconnection leads to the fact that for every AZ, in general, two VSUs are needed. More advanced, multi-layer storage setups are not regarded in the optimization program, although an extension for these setups, in principle, is possible. This would require further analysis on the simplifications applied.

The latter two degrees of freedom are handled by the optimization program. The decision made by the optimization program are illustrated in Figure 13, with the labeling of the enthalpy coordinates and the temperatures of the VSU:

1) The position of a VSU on the enthalpy axis (H_l) determines which process streams and ILs are connected and the degree of IHR occurring through these ILs shall. The corresponding needed storage capacity is determined based on of the underlying TSM [20]. The first and the last AZs do not have a degree of freedom in enthalpy, because they are needed at the prescribed enthalpy coordinates to ensure the extent of the desired IHR. Therefore, only VSUs between the first and the last enthalpy coordinates have a degree of freedom in enthalpy.
2) The temperature of a VSU (T_l) determines the HEX areas through the determination of the temperature approaches between the ILs and the process streams. Furthermore, the VSU temperature determines the volume of each storage tank.

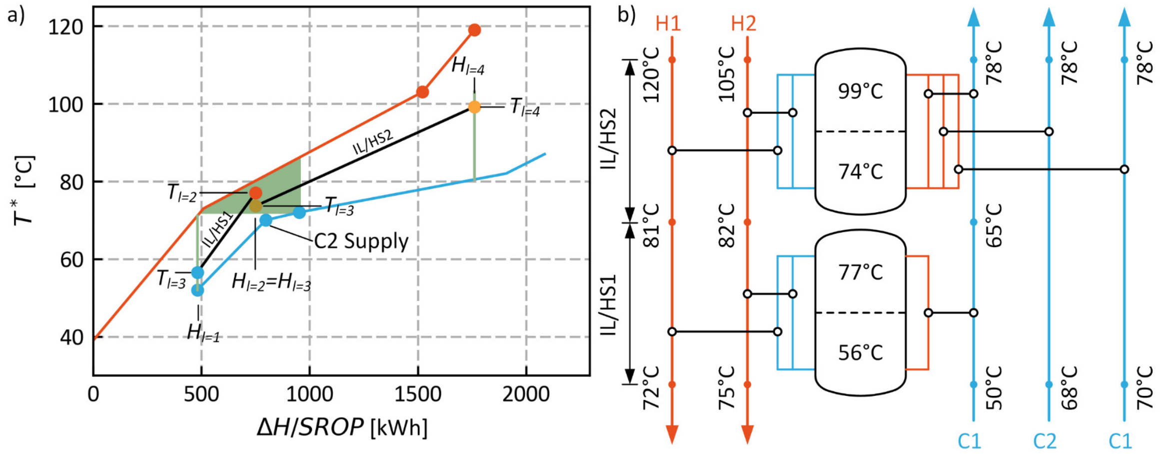

Figure 13: Gantt diagram, ISSP and HESN of a demonstration case with marked enthalpy coordinate and temperature of the second VSU.

The change in enthalpy coordinate of a VSU H_l within the ISSP can lead to changes in the topology of the system. Mainly these are changes in the HEX matches between the ILs and the process streams, which is illustrated in Figure 14. With the choice of $H_{l=2}$ and $H_{l=3}$ below the supply of stream C2 in Figure 14a the resulting HESN in Figure 14b has a total of eight HEXs. With the increase of $H_{l=2}$ and $H_{l=3}$ above the supply of the stream C2, the resulting HESN requires one more HEX. Additionally, the lower bound $T_{l=1}$ is being raised as it can be seen in the HESN in Figure 14d, leading to a significantly larger storage volume.

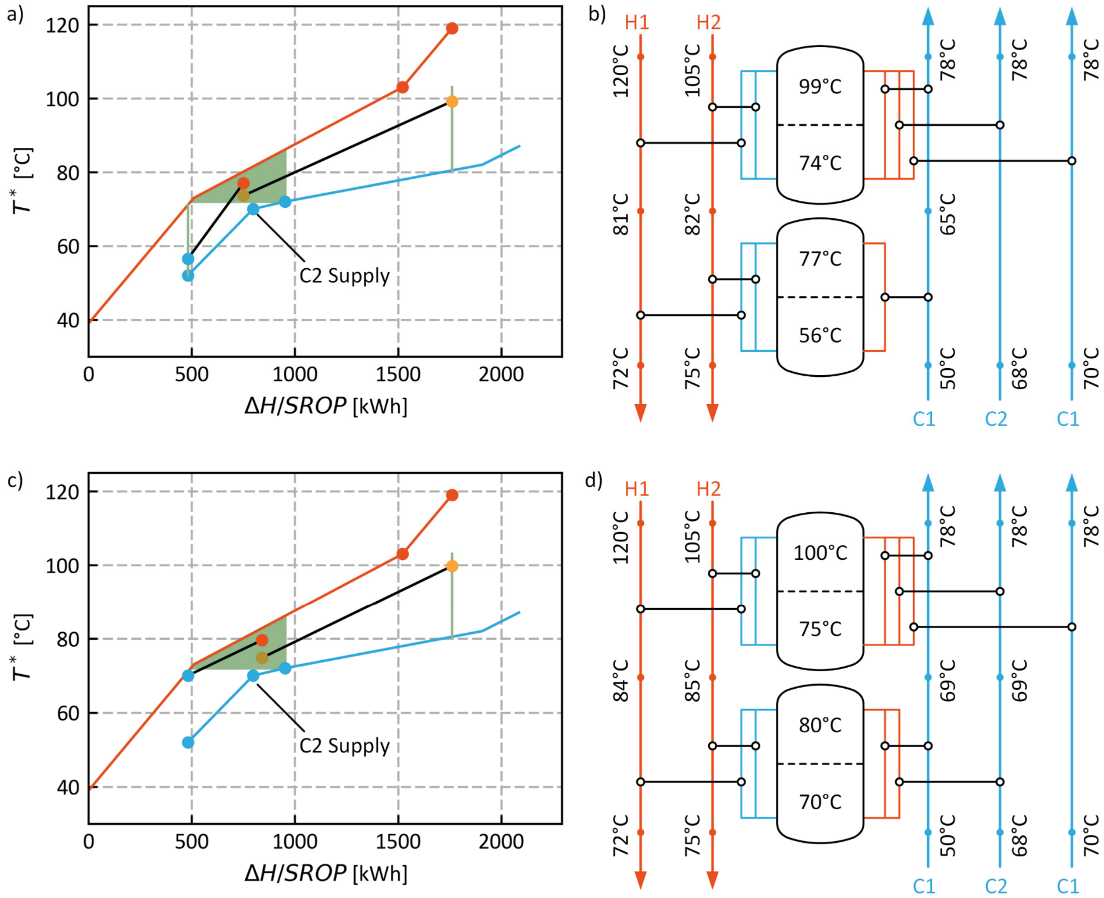

Figure 14: ISSP with two different enthalpy coordinate choices for AZ2 leading to different HEX matches as shown in corresponding HESN. a) ISSP with $H_{l=2} = H_{l=3}$ = 750 kWh, b) HESN corresponding to a), c) ISSP with $H_{l=2} = H_{l=3}$ = 840 kWh, d) HESN of c)

The problem is integer by its nature because the change of the enthalpy coordinate of the VSUs can lead to topology changes within the HESN. Furthermore, there are several nonlinear components within the problem, mainly for the:

1) HEX area calculation
2) storage volume calculation

The complete problem would therefore be a Mixed Integer Nonlinear Problem (MINLP). For MINLP, it is generally challenging to find good modelling-approaches and suitable optimization solvers, even with cost intensive commercial solvers. Due to this, the optimization problem is split into two separate problems, but they are interconnected. The determination of the VSU enthalpy coordinates is addressed with the heuristics that incorporate the process knowledge to simplify the problem and the determination of the VSU temperatures are solved with a Nonlinear Program (NLP). This separation allows for an efficient and controlled solution of the overall problem. In the following section the overall program structure and the two parts are described in more detail.

4.4 Overall program structure

Splitting of the problem leads to the computation schematic as shown in Figure 15. The enthalpy coordinates within each AZ are evaluated only at specific points of interest (see Section 4.5), leading to a set of enthalpy coordinate-combinations (based on all AZs). The NLP for the temperatures is executed for all enthalpy coordinate combinations.

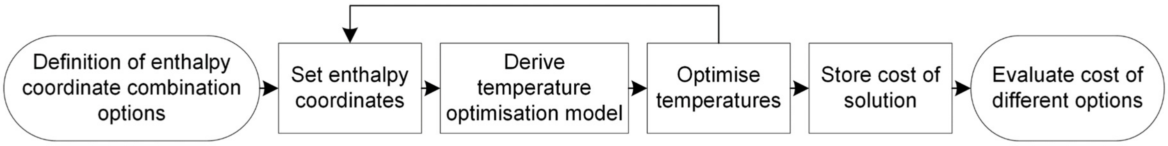

Figure 15: Flow diagram of the optimization program

4.5 Determination of enthalpy coordinate combinations

The heuristics for the determination of the enthalpy coordinates-combinations for the optimization program are based on the aforementioned (Figure 14) knowledge on the points where topology changes are occurring. This is of interest because the necessity of new HEX(s) leads to additional investment cost and can change the constraints on the temperatures of the VSUs, affecting their volume. The experience-based assumption is, that the lowest investment cost occurs when the enthalpy coordinates of the individual VSU are set at the start and end of streams within the ISSP.

Figure 16 illustrates, in detail, the change in the number of HEX when crossing the C2 supply in the AZ2. It is clearly stated that there is no guarantee for finding the global optimum of the entire mixed integer nonlinear problem. The goal is to provide feasible and practically applicable solutions.

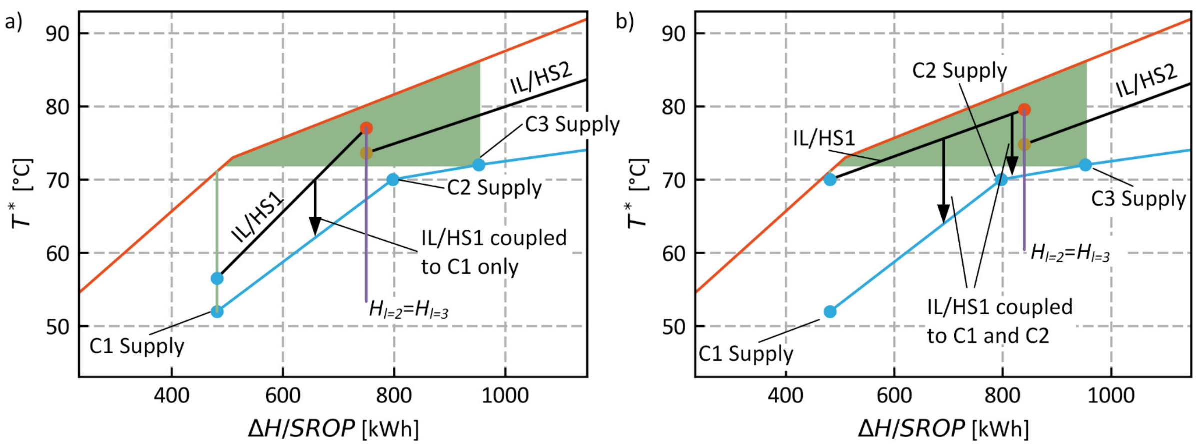

Figure 16: Illustration of influence of start and end of streams on the HESN. a) zoomed in view on IL/HS1 of Figure 14a, b) zoomed in view on IL/HS1 of Figure 14c.

In Figure 16a, the enthalpy coordinate $H_{l=2}$ and $H_{l=3}$ of VSU2 and VSU3 are chosen such that IL/HS1 is only coupled to stream C1, the crossing of C2 with the enthalpy coordinates $H_{l=2}$ and $H_{l=3}$ leads to an additional HEX. When the enthalpy coordinate is chosen at the supply of C2, the HEX is not needed. The situation is the same when dealing with the end of streams.

Additional rules are imposed on the choice of enthalpy coordinates for storages that include HP streams: HP streams may not be split to contribute to several ILs (since the HPs are directly included in the ILs) as the split would require to be in the refrigerant cycle or with an additional IL, which may only be considered for advanced applications. The implemented programs would, in principle, allow for a design change if needed.

4.6 Nonlinear program for VSU temperatures

With the enthalpy coordinates of the VSUs determined by the heuristics, the NLP for the temperature optimization can be derived. The overall optimization problem to be solved is

$$J^*(T_l) = \min(C_{inv,tot}(T_l)) \quad \forall l \tag{4}$$

The goal is thus to find the minimal investment cost J^* by obtaining the optimal VSU temperatures T_l. The following section shows the formulation of the optimization program.

The objective of the optimization is the minimization of the total investment cost $C_{Inv,tot}$ of a given ISSP configuration with pre-set enthalpy coordinates (based on the heuristics). $C_{Inv,tot}$ is the sum of the cost of all hot and cold stream HEX connecting the streams to the storages ($C_{n,l}$ and $C_{o,l}$ respectively) and all TES (C_l) in the system:

$$C_{inv,tot} = \sum_{N,L} C_{n,l} + \sum_{O,L} C_{o,l} + \sum_{L} C_l \tag{5}$$

The derivation of C_l is explained from Eq. 14 onwards. The cost of the individual HEX $C_{n,l}$ and $C_{o,l}$ are determined with the cost function according to Eq. 3, where the relevant size of the HEX is the heat transfer area A:

$$C_{n,l} = C_{n,0} + C_{n,b}\left(\frac{A_{n,l}}{A_{n,b}}\right)^{m_n} \quad \forall n, \forall l; \quad C_{o,l} = C_{o,0} + C_{o,b}\left(\frac{A_{o,l}}{A_{o,b}}\right)^{m_o} \quad \forall o, \forall l \tag{6}$$

A_n and A_o are the required HEX areas for a given equipment. These are determined as the maximum of the required HEX area of the individual stream associated with the respective equipment. For the optimization program A_n and A_o are formulated as so-called slack variables, allowing for the substitution of the necessary maximum formulation without integer variables. This formulation reads as follows: A_n is bound to be larger or equal than all A_i where the set I is filtered to the streams i that are associated with the equipment n. For A_o, the same applies for o and j respectively.

$$A_{n,l} \geq A_{i,l} \quad \forall n, \forall i \in I(n), \forall l; \quad A_{o,l} \geq A_{j,l} \quad \forall o, \forall j \in J(o), \forall l \tag{7}$$

A_i and A_j are calculated based on the respective heat flow rate $\dot{Q}_i$ *and* $\dot{Q}_j$ (Eq. 10), the respective overall heat transfer coefficient U_i and U_j and the approximated logarithmic mean temperature difference (LMTD) $\Delta T_{m,i}$ and $\Delta T_{m,j}$ (Eq. 12 and 13).

$$A_i = \frac{\dot{Q}_i}{U_i \Delta T_{m,i}} \quad \forall i; \quad A_j = \frac{\dot{Q}_j}{U_j \Delta T_{m,j}} \quad \forall j \tag{8}$$

U_i and U_j are thereby as often seen in PA solely calculated with the two film heat transfer coefficients of the process stream i or j respectively and the corresponding IL l. The conductive resistance in the walls of the HEX is neglected:

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{1}{h_l} \quad \forall i, \forall l; \quad \frac{1}{U_j} = \frac{1}{h_j} + \frac{1}{h_l} \quad \forall j, \forall l \tag{9}$$

For the determination of $\dot{Q}_{i,l}$ and $\dot{Q}_{j,l}$, the hot and cold cutoff temperatures of the hot and cold streams $T_{co,i,l}$ and $T_{co,i,l+1}$ and $T_{co,j,l+1}$ and $T_{co,j,l}$ respectively are used.

$$\dot{Q}_{i,l} = CP_i\,(T_{co,i,l+1} - T_{co,i,l}) \quad \forall i, \forall l; \quad \dot{Q}_{j,l} = CP_j\,(T_{co,j,l+1} - T_{co,j,l}) \quad \forall j, \forall l \tag{10}$$

These cutoff temperatures are the stream temperatures at the beginning and end of each IL in the ISSP. They are calculated with the stream specific $\Delta T_{min,s}$ and with the (shifted) cutoff temperatures of the source profile ($T^*_{source,l}$) and the sink profile ($T^*_{sink,l}$) at the start and end of each IL i.e. at each VSU.

$$
\begin{aligned}
T_{co,i,l+1} &= T^{*}_{source,l+1} + \Delta T_{min,s,i} \quad \forall i, \forall l \\
T_{co,i,l} &= T^{*}_{source,l} + \Delta T_{min,s,i} \quad \forall i, \forall l \\
T_{co,j,l+1} &= T^{*}_{sink,l+1} - \Delta T_{min,s,j} \quad \forall j, \forall l \\
T_{co,j,l} &= T^{*}_{sink,l} - \Delta T_{min,s,j} \quad \forall j, \forall l
\end{aligned}
\tag{11}
$$

In case the cutoff temperatures are outside of the real temperature range of the streams, the formulation is limited with an appropriate min-max formulation. Figure 17 shows the cutoff temperatures of the source and sink profiles in the ISSP and the ones of the streams in the HESN. Here the stream supply and target temperatures are already considered.

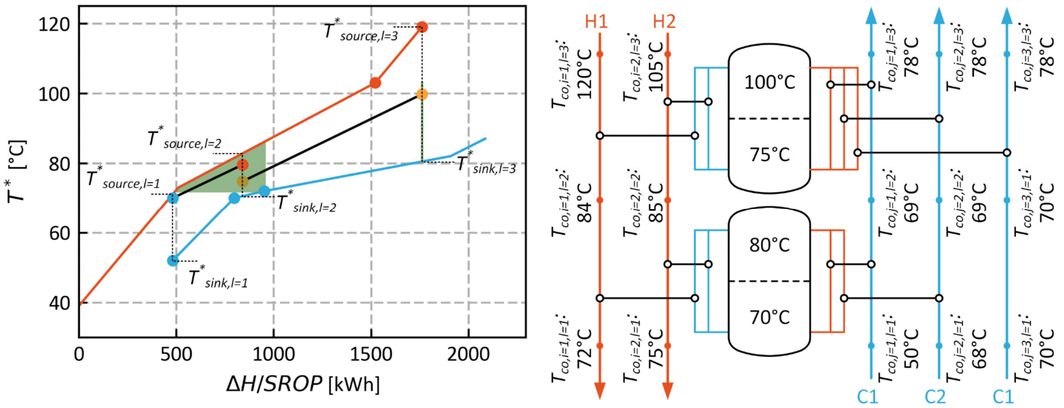

Figure 17: Illustration of cutoff temperatures of individual streams

The approximated LMTD of the hot stream HEXs $\Delta T_{m,i,}$ is calculated according to the simplification of Chen [78]. This simplification is an underestimation of the exact solution and is therefore conservative in the investment cost.

$$
\Delta T_{m,i,k} \approx \left(\Delta T_1 \Delta T_2 \left(\frac{\Delta T_1 + \Delta T_2}{2} \right) \right)^{1/3} \; ; \text{ with: } \begin{aligned} \Delta T_1 &= T_{co,i,l+1} - T_{l+1} \\ \Delta T_2 &= T_{co,i,l} - T_l \end{aligned} \quad \forall i, \forall l \tag{12}
$$

With T_l and T_{l+1} being the VSU temperatures at the hot and cold end of the IL, respectively (**i.e., the decision variables of the problem**). $\Delta T_{m,j}$ is defined as:

$$
\Delta T_{m,j,k} \approx \left(\Delta T_1 \Delta T_2 \left(\frac{\Delta T_1 + \Delta T_2}{2} \right) \right)^{1/3} \; ; \text{ with: } \begin{aligned} \Delta T_1 &= T_{l+1} - T_{co,j,l+1} \\ \Delta T_2 &= T_l - T_{co,j,l} \end{aligned} \quad \forall j, \forall l \tag{13}
$$

The cost of the individual storage tanks C_l is calculated according to the ISSP configuration and the TSM. The ISSP configuration yields the heat duty of each stream to each IL (Eq. 10), the TSM enables the energy balance calculation over time. Where the energy balance of each IL in each TS is defined as the sum of all hot and cold streams heat duty multiplied by the duration Δt_{TS} of a given TS:

$$
\Delta E_{l,TS} = \sum_{I} \dot{Q}_{i,l} \Delta t_{TS} - \sum_{J} \dot{Q}_{j,l} \Delta t_{TS} \quad \forall TS, \forall l \tag{14}
$$

Since the storage design is simplified to yield only two-layer stratified storage systems the cumulative sum over the TS yields for each IL the loading and unloading profile of the TES [79]. The difference between the maximum and minimum of the loading unloading profile is then required storage capacity ΔE_l that is needed in the resulting storage system. The calculation of ΔE_l (Eq. 14) is not part of the optimization program but can be calculated beforehand once the enthalpy coordinate combination is defined. The storage volume is then calculated in the optimization program as:

$$V_l = \frac{\Delta H_l}{T_{l+1} - T_l} \quad \forall l \tag{15}$$

Leading to the storage cost calculation as follows:

$$C_l = C_{l,b} V_l \tag{16}$$

Compared to the general equipment cost equation (Eq. 3), Eq. 16 is a simplification that is based on the investigations on stratified storage tanks with glass wool insulation in Rast [77], where it was shown, that the cost of such systems is proportionally to the storage volume.

The VSU temperatures T_l are subjected to constraints which are all based on the AZ algorithm. It must be ensured, that the ILs can be heated and cooled to their design temperatures. Like the AZ algorithm, the determination of the constraints of T_l is based on the supply temperatures of the streams contributing to a given IL. The supply temperature is decisive, as the hottest cold supply of the streams connected to of an IL provides the lower boundary for the cold VSU of this IL, while the coldest hot supply of the streams connected to an IL provides the upper boundary for the hot VSU of this IL.

Figure 18 illustrates this dependency. The supply temperature of H2 ($T_{H2,\alpha}$) is the coldest hot supply in IL/HS2 leading to the limitation of the upper layer temperature of HS2 ($T_{l=4}$). From a thermodynamic perspective this constraint simply imposes the fact the the upper layer of the storage cannot be heated above the inlet temperature of 105°C of $T_{H2,\alpha}$. All other VSUs are limited in their maximum temperature by the ISSP itself. For the lower bounds, the same applies to the lowest storage layer ($T_{l=1}$). Since C2 is contributing to IL/HS1, the C2 supply temperature $T_{C2,\alpha}$ prescribes the lower bound for $T_{l=1}$. $T_{l=1}$ must be large than the 68°C of of $T_{C2,\alpha}$.

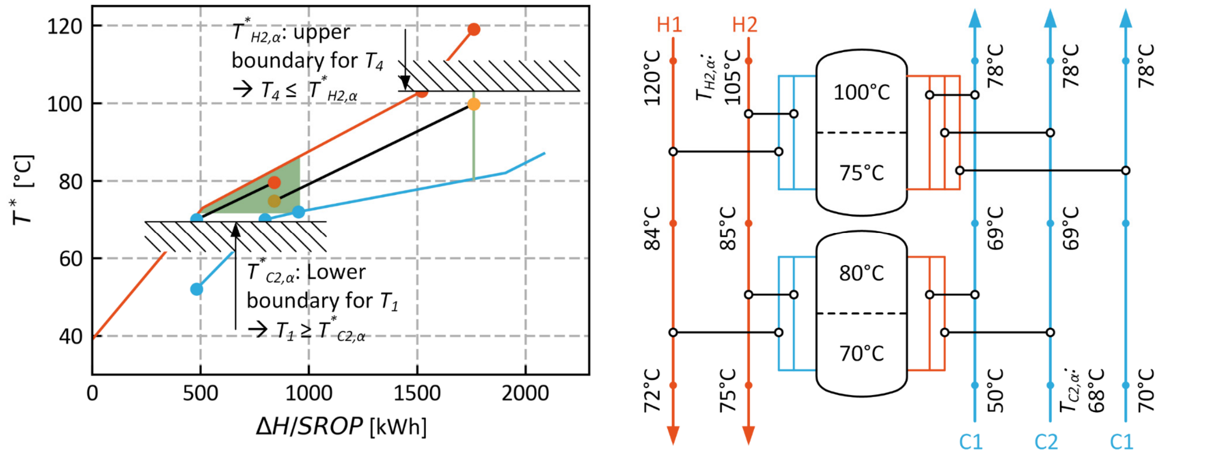

Figure 18: Example of temperature boundaries imposed by supply temperature of streams. $T_{C2,\alpha}$ is providing the lower bound for T_1, $T_{H2,\alpha}$ is providing the upper bound for T_4,

Formalizing this requirement for the optimization problem, each storage layer temperature T_l must be greater or equal than the shifted supply of the cold streams contributing to the corresponding IL above. Additionally, each T_l must be smaller or equal than the shifted supply temperatures of the hot streams contributing to the IL below. In Eq. 17, this constraint is given. The functions *J(l)* and *I(l)* are returning the indexes *i* and *j* of the corresponding streams whose supply are in the respective IL below or above the VSU. In the program they are implemented algorithmically since it can be done before the formulation of the optimization program once the enthalpy coordinates are specified.

$$T_l \geq T^*_{j,\alpha} \quad \forall l, \forall j \in J(l); \qquad T_l \leq T^*_{i,\alpha} \quad \forall l, \forall i \in I(l) \tag{17}$$

Furthermore, it is mandatory that the temperature within each of the storages is increasing from the lower to the upper layer to enable stratification. However, to be able to program all the decision variables as one array of decision variables, one may introduce slack variable $\Delta T_{slack,l}$ in this constraint to simplify the implementation. This tolerance ensures that the VSUs in the same AZ, which are at the same enthalpy coordinate, are not dependent on each other through this constraint. Allowing for the reduction of the resulting storage volume with increase in the IL temperature difference up until its maximum, if the maximum was the cost optimal.

$$T_{l+1} > T_l - \Delta T_{slack,l} \quad \forall l \tag{18}$$

After derivation of the optimization program, the NLP was implemented in Python using the open-source module Pyomo [80] as a high level modelling language and solved using the open-source solver IPOPT [81]. The heuristics are implemented in Python as well.

5 Control Strategy for the HPTES System

The method for HPTES integration leads through the execution of the workflow to a practical feasible conceptual design of the resulting system. In the conceptual design phase, the ideal operation of each individual component and the non-fluctuating existence of the process streams (except modeled in the process stream table) are assumed. The implemented real components are, however, not exactly represented by the models for the conceptual design and fluctuation of process streams is the norm and not the exception. To be able to operate the system under the influence of these disturbances it has therefore to be controlled accordingly. In the following sections, the control concept for the HPTES system is described.

5.1 Characterization of the control problem

The overall goal of the control strategy for the HPTES system is to enable its steady operation while maintaining utility use at a minimal. To be able to operate the system continuously, the system has to be equipped with utility within the HPTES system as process requirements are in general hard requirements (except when they are soft streams). The control strategy for the HPTES system should be able to achieve the design-cutoff temperatures of the streams under typical fluctuations. The general structure of the system under investigation is shown in Figure 19. The inlet conditions ($T_{h,\alpha}$, $T_{c,\alpha}$, $\dot{m}_h$, $\dot{m}_c$) of the process streams are the disturbances acting on the system and the outlet conditions ($T_{h,\omega}$, $T_{c,\omega}$) are the controlled variables.

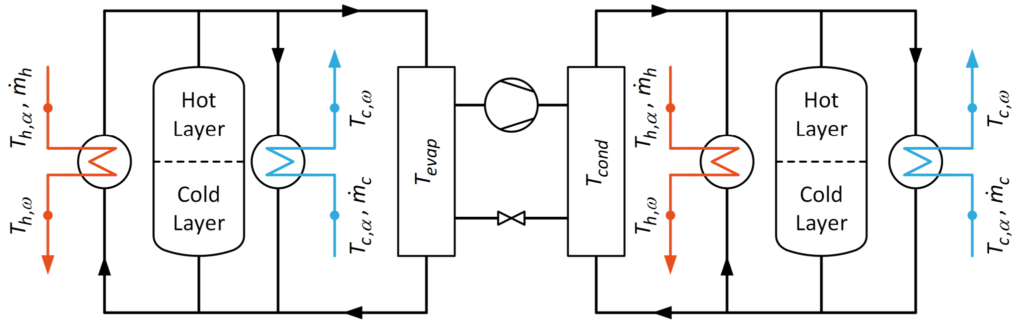

Figure 19: General structure of the controlled system. Each storage can have hot and cold streams connected to it, the HP operates between two storages.

It is noteworthy, that the ability of the HPTES system to handle overload situations is, as with any system, only possible when the components (primarily the HEX) are dimensioned accordingly. When this is fulfilled, the control concept can handle such situations as well.

The technical challenge for the control of the HPTES system lies on the large number of interacting components that must be controlled and in the expected fluctuations of the process flows, which require a balancing of the system by means of utilities. The individual components must be controlled that they function optimally for themselves, but do not negatively influence the other components (both in the static and in the dynamic perspective). Consequently, the selected control strategy must enable the static operating points of the individual HEX and the HP to be reached so that the process requirements are met. At the same time, it must avoid the occurrence of instabilities of the overall system due to the dynamic coupling of the individual components. In addition, energy management is required to maintain the energy balance despite the expected fluctuations of the individual process streams.

Based on this characterization of the control task, the control system is divided into two levels, a "high-level problem" and a "low-level problem". The high-level problem involves the control of the overall system with the goal of maintaining the operability of the system, while minimizing utility usage. The low-level problem involves real-time control of the individual components.

5.2 Low-level control problem

The low-level problem involves real-time control of the individual components and can be solved with standard decentralized controllers (e.g. PID), since the coupling of the individual components has been found to be low with the appropriate hydraulic interconnection. The control of the HP and the HEX is described in detail in the following.

5.2.1 HP control

The HP should be equipped with a recycle circuit at the condenser and at the evaporator. This ensures, that the flow rates through the HP remains approximately constant (valve changes lead to small flow changes) and the admixing of the fluid enables the desired control of the HP outlet temperatures.

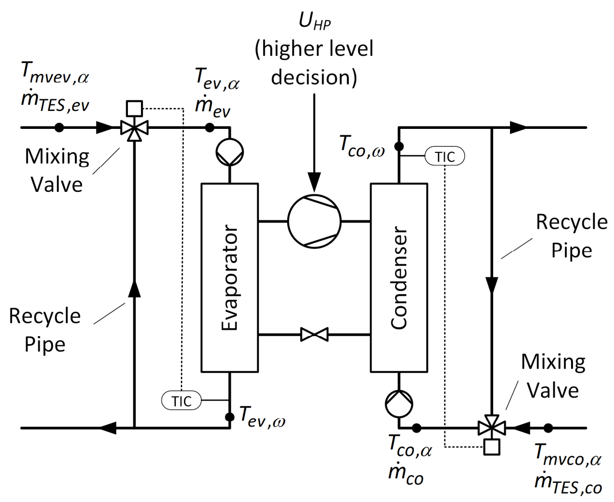

Figure 20: Detailed schematic of the HP System with the controls.

The recycle setup is also beneficial for the HP-internal control as no extreme temperature differences in the evaporator and condenser are occurring.

5.2.2 Heat exchanger control

The control of the HEX is suggested to be resolved with a throttle valve for each HEX and a differential-pressure-controlled pump for all HEX combined. This allows the control of the HEX to the setpoint of the process stream outlet temperature ($T_{PS,\omega}$) while minimizing the IL outlet temperature. This enhances the storage capacity of the stratified storages as the temperature difference of the IL is increased.

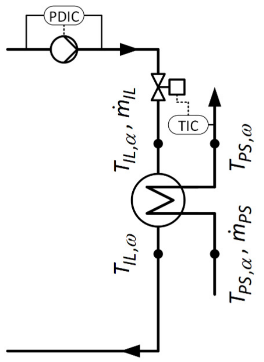

Figure 21: Schematic of the Controlled HEX

5.3 High-level control problem

The high-level control task of the HPTES system is tackled with the right placement of the utility HEX in the system and an on-off control of the HP. As large heat demands can occur, planned or unplanned, the HPTES system should be charged whenever possible. The HP should be controlled based on a temperature sensor in the hot and one in the cold storage tank. In the hot storage tank, this sensor is placed at the lower end of the tank and in the sensor is place at the upper end of the cold storage tank. Equipped with a two-point controller, the HP is turned on when both tanks are not fully charged, and turned off when one of them is. Figure 22 summarizes the high- and the low-level control strategy. The utility is placed such that they are only turned on if the HP is unable to maintain the design temperatures of the respective IL. The presented control strategy should be seen as a blueprint for the general case. It is not always necessary to have, for example, CU in the system if the hot streams are soft-streams.

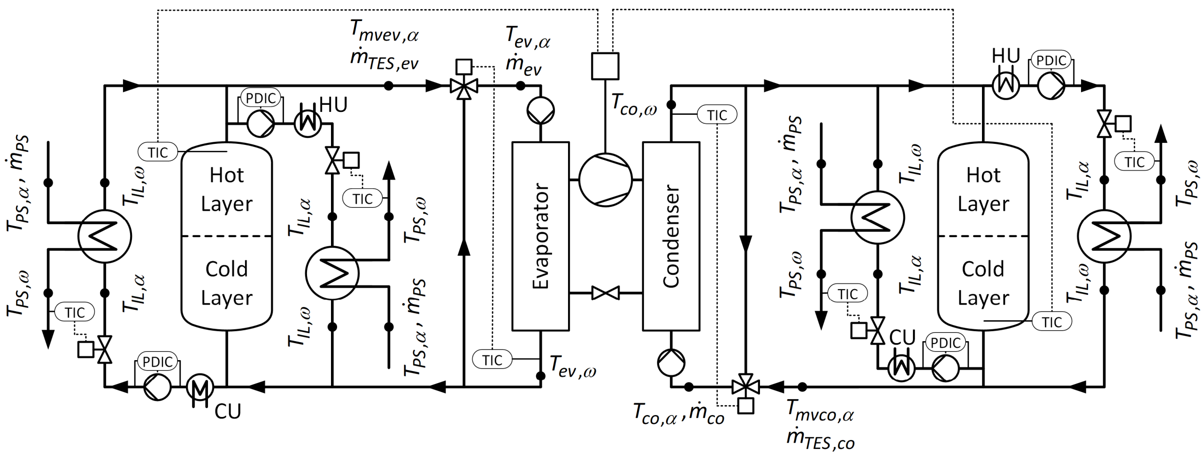

Figure 22: Schematic of the WPTES system with all Control options integrated.

The suggested control strategy provides the conceptual basis for the implementation of HPTES systems. As it relies entirely on industry standard components such as PID controllers with throttle valves, it can be seamlessly integrated into a larger conventional process control system.

However, it is recommendable to conduct further case-specific analyses by means of simulation tools to inform the detailed control design and the tuning of the individual controllers, as it is shown in the later section 7.1.7.

6 Description of Case Studies

There is a high potential for HP integration in companies from the paper, chemical, pharmaceutical and food industries. As shown in Arpagaus [82], food production with processes such as pasteurization, sterilization, drying and evaporation has a particularly high potential. In addition, pinch analyses performed in Swiss industry show considerable potential in other sectors as well (e.g., cooling water circuits in the metal processing industry, in painting and coating plants, or in the textile industry).

Various processes from industry were analyzed for their suitability for use as case studies to verify the method developed in this project. For this purpose, the case studies of the PI/PinCH base and the pinch analyses supported by the SFOE were used [83]. The selected case studies are intended to represent the two main types of non-continuous processes frequently encountered in Swiss industry. These can be divided into two types: and (1) batch process and (2) Multiple Operating Case (MOC) processes.

1. Batch Process: Process in which various unit operations are executed sequentially. This step-by-step execution (a batch) is performed repeatedly. This typically occurs in a time frame of hours or days.
2. Multiple Operating Case process: The plant is operated in different operating cases, e.g. product changes, or cleaning cycles. This often occurs within a day, but may extend beyond that time frame.

Two industry case studies were selected for testing the practicality of the HPTES methodology. One batch and one MOC case study were selected. These two case studies form the basis for the review of the HPTES method.

6.1 Case 1 Batch Process

The case study comes from the PA of a large Swiss cheese factory. Each stream occurs only during a certain time period from t_{start} to t_{end}. The specific heat capacity (c_p) is given according to the streams, and heat transfer coefficient (α) are assumed to be constant. The process requirements are summarized in Table 3 and the Gantt diagram is shown in Figure 23. This represents a representative day of production.

Table 3: Process stream table of the batch process

Streams	T_α [°C]	T_ω [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	α [W/(m^2 K)]	t_{start} [h]	t_{end} [h]
Coagulator Supply_P1	30	42	4.2	4.2	2'000	0	3
Coagulator Supply_P2	30	42	4.2	4.2	2'000	4	11
Coagulator Supply_P3	30	42	4.2	4.2	2'000	12	18
Coagulator Supply_P4	30	42	4.2	4.2	2'000	20	24
Coagulator HR_P1	16	31.2	4.7	4.2	2'000	5.5	6.5
Coagulator HR_P2	16	31.2	4.7	4.2	2'000	13.5	14.5
Coagulator HR_P3	16	31.2	4.7	4.2	2'000	20.5	22.5
Bulkhead Cooling_P1	19.4	10	6.3	3.85	2'000	0	3
Bulkhead Cooling _P2	31.7	10	6.3	3.85	2'000	3	4
Bulkhead Cooling _P3	19.4	10	6.3	3.85	2'000	4	5.5
Bulkhead Cooling _P4	19.4	10	6.3	3.85	2'000	6.5	11
Bulkhead Cooling _P5	31.7	10	6.3	3.85	2'000	11	12
Bulkhead Cooling _P6	19.4	10	6.3	3.85	2'000	12	13.5
Bulkhead Cooling _P7	19.4	10	6.3	3.85	2'000	14.5	18
Bulkhead Cooling _P8	31.7	10	6.3	3.85	2'000	18	20
Bulkhead Cooling _P9	19.4	10	6.3	3.85	2'000	20	20.5
Bulkhead Cooling _P10	19.4	10	6.3	3.85	2'000	22.5	24
Domestic Hot Water	37	76.4	0.3	4.2	2'000	1	23
Air Compressor Cooling	60	40	0.5	4.2	2'000	0	24
Milk Treatment MB1	30	40	6.9	4.2	2'000	0	2
Milk Treatment MB1	30	40	6.9	4.2	2'000	22	24
Cream Ripener Batch 1	19.8	22	8.5	4.2	2'000	16	20
Cream Ripener Batch 2	19.8	22	8.5	4.2	2'000	21	24
Cream Ripener Batch 1-1	19.8	22	8.5	4.2	2'000	0	1
Cottage cheese wash water	50	20	5.0	4.2	2'000	8	9
Cottage cheese wash water	50	20	5.0	4.2	2'000	10	11

The duration of the batch cycle is 24 hours. According to the production schedule, the process is in operation for 339 days/year.

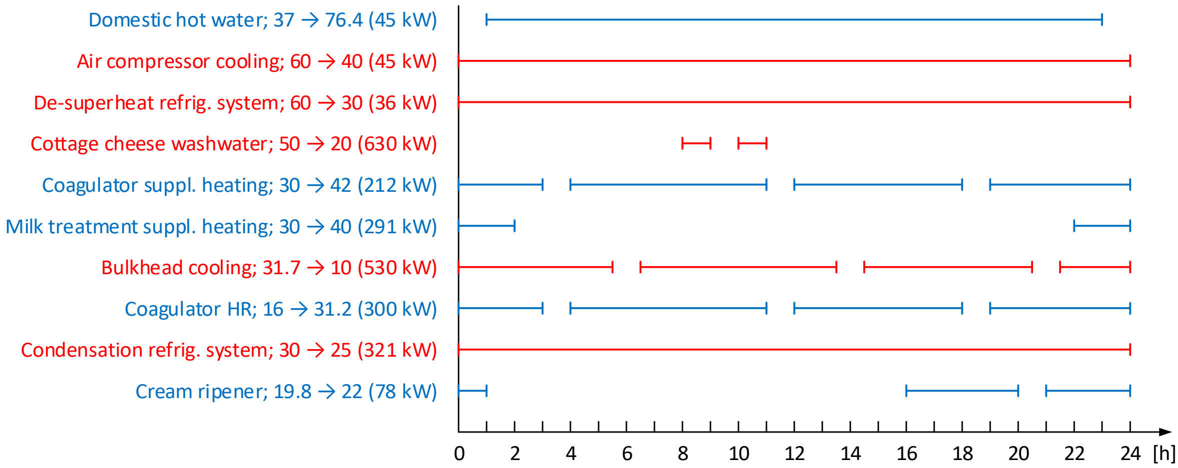

Figure 23: Gantt chart of the representative production day of the batch process of a large Swiss cheese factory selected as a case study.

The utility costs for this case this are listed in Table 4. Furthermore, to estimate the GHG emissions of the energy supply, emission factors are defined. All HU is assumed to be covered by natural gas with a boiler efficiency of $\eta_{boiler} = 0.9$, all CU is assumed to be covered by a chiller with an average performance factor of $EER_{Chiller} = 4$ including recooling. The underlying emission factors are EF_{NG} = 202 kg_{CO2eq}/MWh for natural gas [84] and EF_{el} = 128 $kg_{CO2eq.}$/MWh for electricity [85]. Both values are representative for the year 2018 in Switzerland (latest available values for electricity).

Table 4: Utility costs and emission factors for Case 1

Utility	Cost [CHF/MWh]	*EF* [t_{CO2eq}/MWh]
Hot	64	0.225
Cold	30	0.032
Electricity	111	0.128

6.2 Case 2 MOC Process

A major milk processor in Switzerland. The site focuses on the production of fresh cheese, processed cheese, and fondue. For a period during the winter months, due to increased demand, fondue production occurs in two shifts 03:30 to 21:00 on weekdays (Mon-Fri). A single shift occurs on Sat (03:30-12:00). In January, fondue is produced in one shift during weekdays (07:00-15:00). This period of increased production is referred to as “maximal production”. From February on, fondue production is reduced to between two and four production days per week. This period of operation is termed “reduced production” and occurs throughout the rest of winter and the summer months. Fresh/Processed cheese is produced during a single shift on weekdays throughout the year. A Gantt chart (Figure 24) indicates the representative scheduling of production at the site and the operating cases.

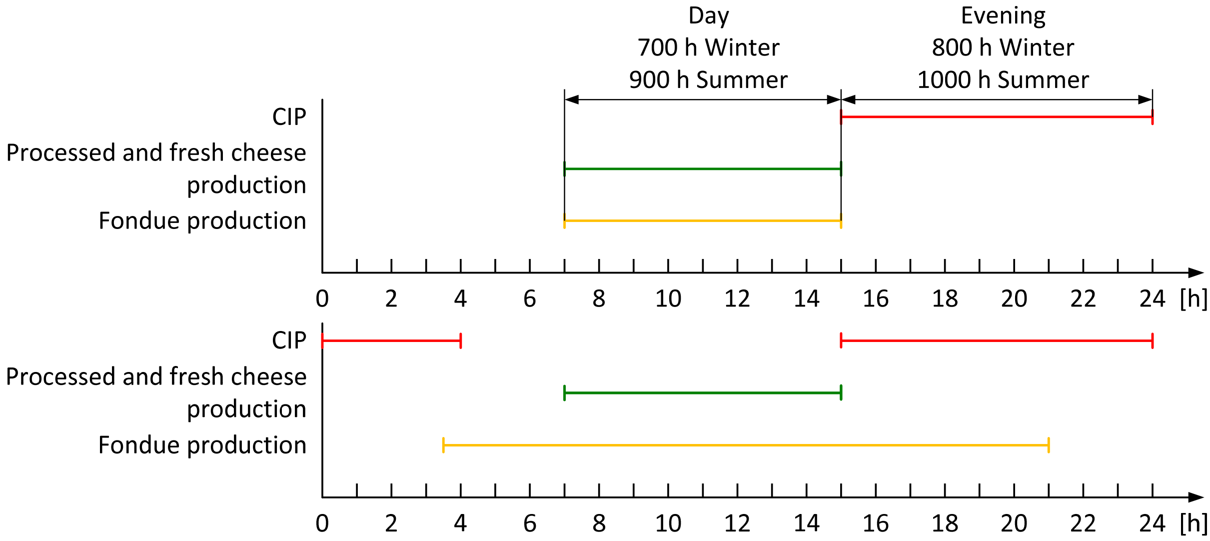

Figure 24: Process Gantt chart: MOC process; reduced production case (above), maximal production case (below)

The differences between reduced and maximum production as well as summer and winter are seasonal variations as shown before. For the HPTES project, the process is reduced to those parts that exist throughout the year, i.e. during reduced and maximum production.

In this MOC process, the variation of production capacity and processes changes throughout the day (for maximum capacity), and season. To design a HP with a variation of heat loads may cause an increase in costs. Therefore, for practical reasons, the process data extracted represent partial process data of each operating case (Table 5). The streams extracted are a subset of the process data in every operating case. They represent the share of the heating and cooling requirements that persist throughout the year, such that the resulting system can be operated all year, round – a key aspect on the economic performance of any HR system. The process is operated for 275 days/year.

Table 5: Simplified process stream table of the MOC process.

Streams	T_α [°C]	T_ω [°C]	$\dot{m}$ [kg/s]	c_p [kJ/(kg K)]	Δh_v [kJ/kg]	α [W/(m^2 K)]	t_{start} [h]	t_{end} [h]
Combustion Air	25	100	0.217	1.01	-	100	7	15
Condensate	80	104	0.005	4.19	-	2’000	7	15
Flue gas (soft stream)	182	25	0.214	2.03	-	2’000	7	15
Heating Water	10	70	0.139	4.21	-	2’000	7	15
Osmosis Water	48	104	0.146	4.20	-	2’000	7	15
De-superheater	68	38.9	0.620	6.59	-	1’000	7	15
Condenser	38.9	38.8	0.62	1919		5’000	7	15
Glycol Loop	-1	-4	10.480	3.63	-	2’000	7	15
Production Steam	104	184	0.194	29.27	-	2’000	7	15
Air Compressor	52	35	0.880	4.22	-	2’000	7	15
Wet Vacuum	62	41	0.025	190.69	-	100	7	15
Base	80	80	0.214	-	330	2’000	15	21
Acid	60	60	0.192	-	330	2’000	15	21
Rinsing Water	10	40	0.062	1.01	-	2’000	15	21

The utility costs for this case are listed in Table 6. The emission factors used are listed in Table 6 as well. While the EF for the boiler is identical to Case 1, the emission factors for the cold utility are derived as follows: The utility “Cold 1” is estimated with a performance factor of 10 since it is ground water and only the pumps of the well must be accounted for. The utility “Cold 2” is estimated with an average performance factor of 2.5 as it is a low-temperature cold utility.

Table 6: Utility costs and emission factors for Case 2

Utility	Cost [CHF/MWh]	*EF* [t_{CO2eq}/MWh]
Hot	106	0.225
Cold 1 (10°C)	1.5	0.013
Cold 2 (-28°C)	27.50	0.051
Electricity	70	0.128

6.3 Equipment cost

The equipment cost used for case studies (Table 7) is based on the module cost estimation functions reported in Rast [77], where the data are compiled from the Swiss market.

Table 7: Cost function for the equipment costs.

Equipment	Cost function
HEX	$8\,\mathrm{kCHF} + 17.5\,\mathrm{kCHF} \cdot \left(\frac{A}{40\mathrm{m}^2}\right)^{0.67}$
TES	$1.5\,\frac{\mathrm{kCHF}}{\mathrm{m}^3} \cdot V_{TES}$
HP	$148\,\mathrm{kCHF} \cdot \left(\frac{\dot{Q}_{HP,cond}}{100\,\mathrm{kW}}\right)^{0.42}$

For the integration of the HP ΔT_{cond} = 2 K and ΔT_{evap} = 4 K, are used for Eq. 1, with a second law efficiency of ζc = 0.55.

7 Results and Discussion

7.1 Case 1 Batch Process

7.1.1 Data extraction and heat recovery (Step 1 and 2)

The process requirements are extracted according to the data extraction rules as listed in the SFOE handbook [5]. In accordance with the plant personnel, only limited subsystems are considered as these systems were possible to be modified for better energy efficiency (Step 1). For this case, Figure 25 shows the reduced process Gantt chart for Case 1. The bandwidth exponent *y* of the ISSP shifting equation (Eq. 1) is for this case set to *y* = 0.2, as there are some streams with short duration (mainly Cottage cheese washwater) which would otherwise limit storage temperatures drastically.

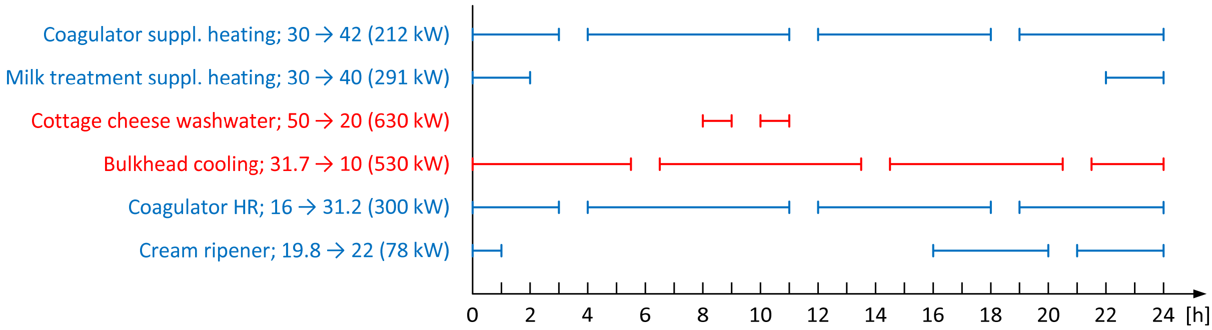

Figure 25: Reduced process Gantt Chart for Case 1.

There is already existing HR implemented for these subsystems. The residual energy demands are used for this analysis. In the HR for these subsystems, the utility cost is 216 kCHF/y.

7.1.2 Indirect heat recovery possibilities (Step 3)

Figure 26 shows examples of possible IHR for Case 1, the IHR potential is up to 2’400 kWh/day. The ISSP shows the range of heat sink and source of the case is 45°C and 10°C, respectively. The heating and cooling required before IHR are 7’231 and 7’050 kWh/day, respectively.

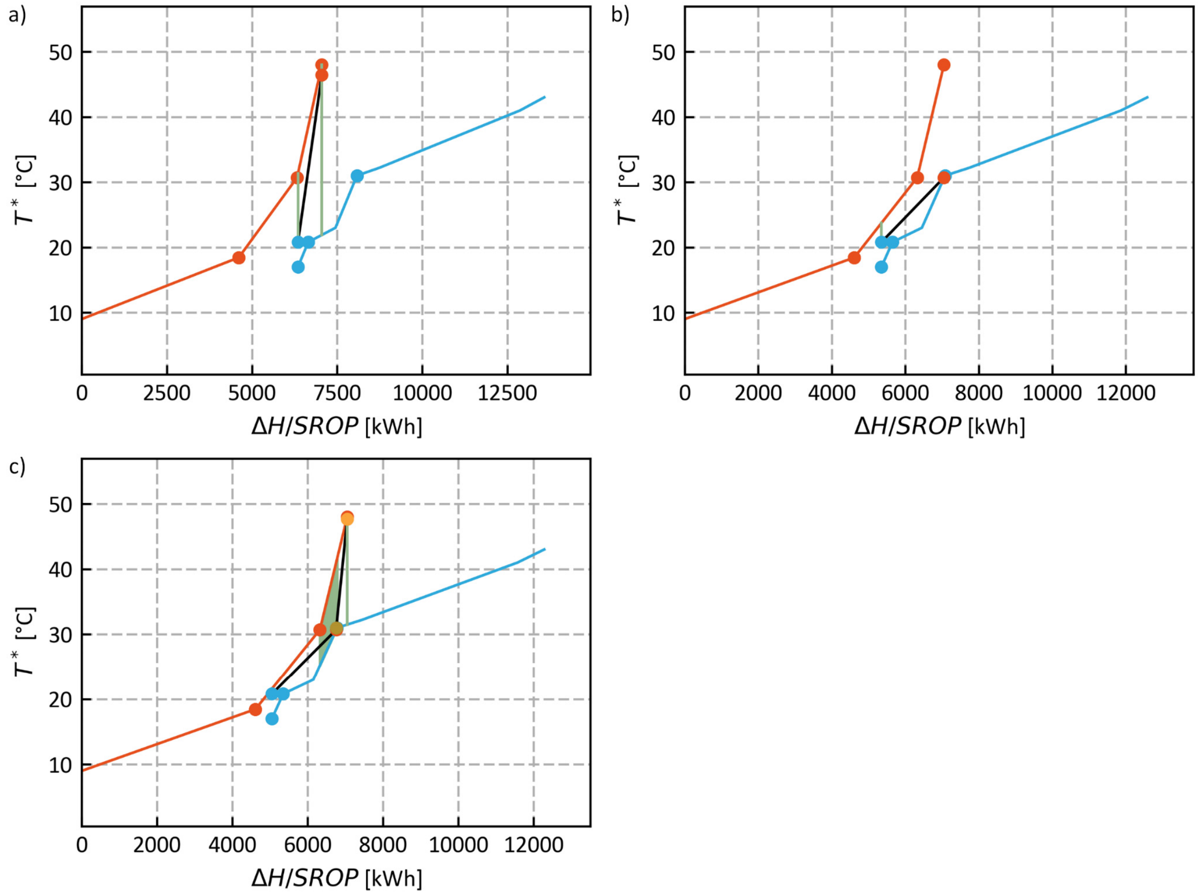

Figure 26: ISSP for Case 1 with IHR of a) 700 kWh, b) 1'700 kWh, and c) 2'000 kWh.

The IHR can be identified with the PinCH software. However, an additional step of a parameter sweep through all the IHR overlap is carried out with the optimization program in Section 4. Figure 27 shows the optimized cost to realize the different overlaps of IHR.

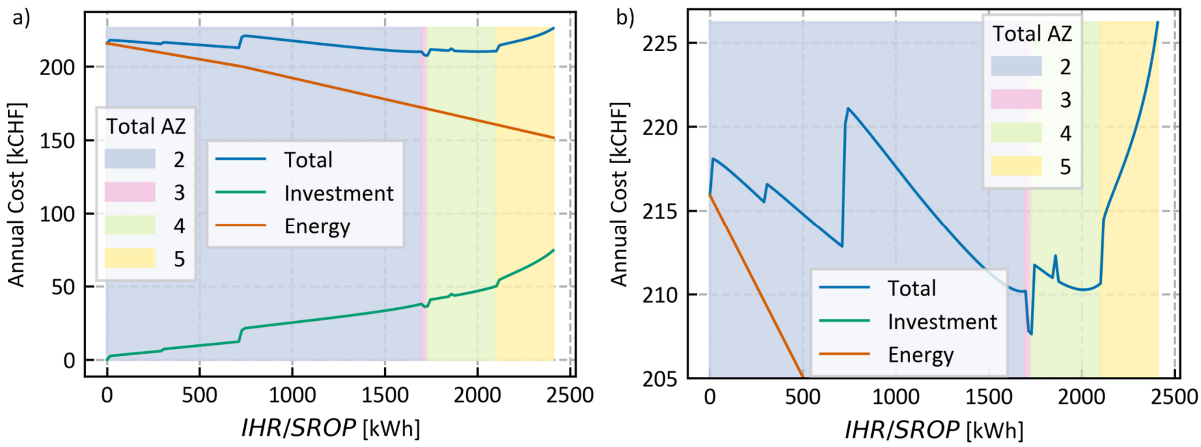

Figure 27: a) The annual cost of the different overlap of the IHR, b) a zoomed in version on the total cost.

From Figure 27, the integer nature of this problem can be observed. The higher HR may cause a dramatic increase of cost because creation of the new AZ or HEX storage matches. For example, at 700 kWh, there is a drastic increase in TAC with increasing IHR, which is not economic. According to Figure 27b, there are three interesting (local minimum) points 700, 1’700, and 2’000 kWh. Although 1’700 kWh is right below the second local minimum, it is selected instead of taking the sharp minimum at rightly 1’750 kWh into account, as it adds an additional TES without major increase in HR (increase of complexity).

7.1.3 Initial IHR solution (Step 4)

Based on the consideration of cost and number of AZ of the mentioned IHR overlaps, 1’700 kWh is taken as the initial solution. Figure 28 shows the schematics of the HPTES system for IHR of 1’700 kWh.

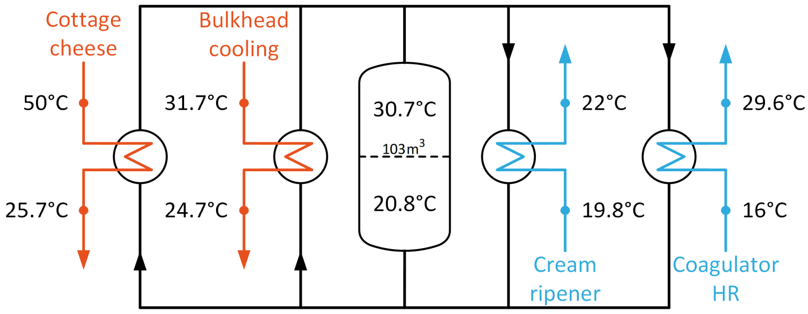

Figure 28: Schematics for IHR of 1'700 kWh (Variant 1).

The economic performance and energy demand is presented in Section 7.1.6 in Table 8.

7.1.4 IHR solution with separate HPTES system (Step 5)

After selecting and designing the IHR system for the 1’700 kWh, the remaining energy demand are extracted from the steam table. Figure 29a shows the inverted residual ISSP for Case 1 with 1’700 kWh IHR extracted. From Figure 29a, it shows that there is approximately 5’800 kWh of heat sink remaining. Figure 29b shows that the heatsinks can be potentially covered with 5’800 kWh of condenser duty, with a maximum shifted temperature of about 40°C.

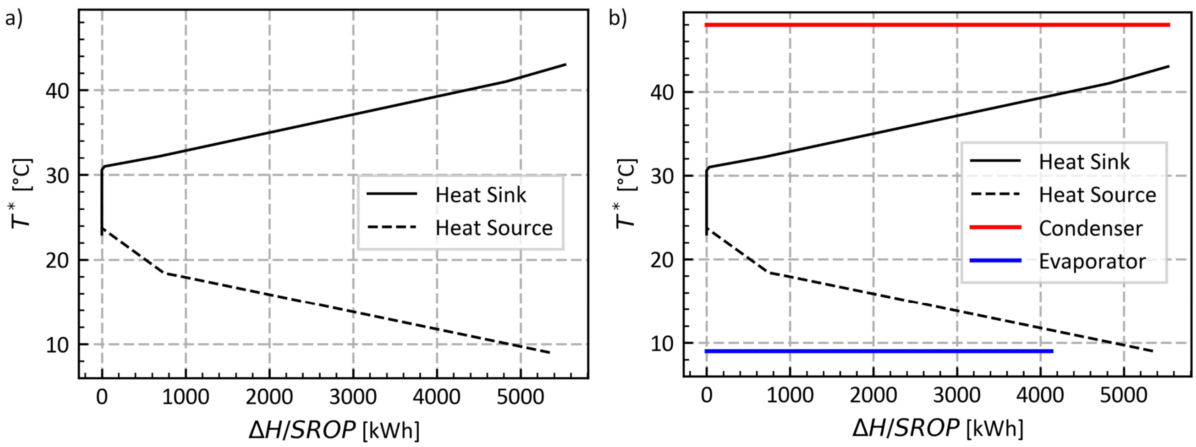

Figure 29: Inverted Residual ISSP for Case 1.

Based on the inverted residual ISSP, the shifted condenser temperature is selected at approximately 48°C and the shifted evaporator temperature at 9°C. Based on this, the HPTES design for this HP-placement is shown in Figure 30.

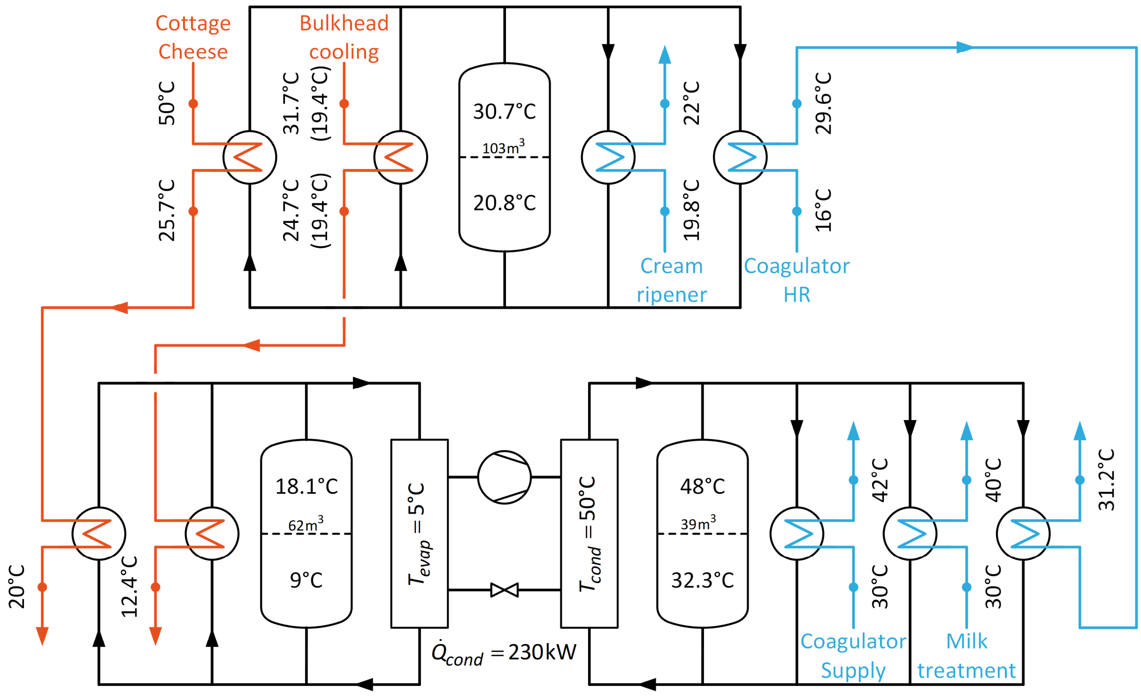

Figure 30: IHR solution with Split HPTES System (Variant 2).

The top half of the schematics in Figure 30 is the IHR solution from Figure 28, and the bottom half of the schematics shows the integration of the HP and its corresponding storage system. Looking at the red lines, the hot streams are discharging to the evaporator side of the HP. The temperatures are then lifted with a 230 kW HP to provide the heating required for the cold streams on the right. However, the splitting of the system leads to 3 TES, where they are interlinked through the streams. The interlinked TES system can pose challenges when it comes to energy management and controllability of the system. The other alternative to Step 5 is to consider the split system without IHR and the combined system. Figure 31 show the Inverted residual ISSP for Case 1 without any HR.

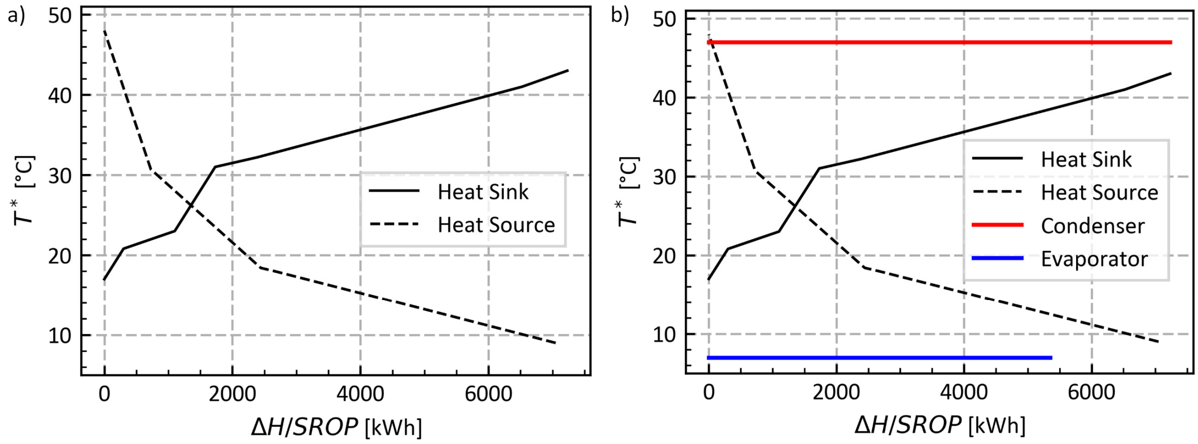

Figure 31: Inverted Residual ISSP for Case 1 without any IHR.

The overlap of the heat sink and heat source in the inverted residual ISSP shows, that there is unexploited IHR potential. Figure 31 shows that the HP potential is approximately at 7'200 kWh/day at the condenser. Figure 32 shows the schematics for the HPTES system without any IHR.

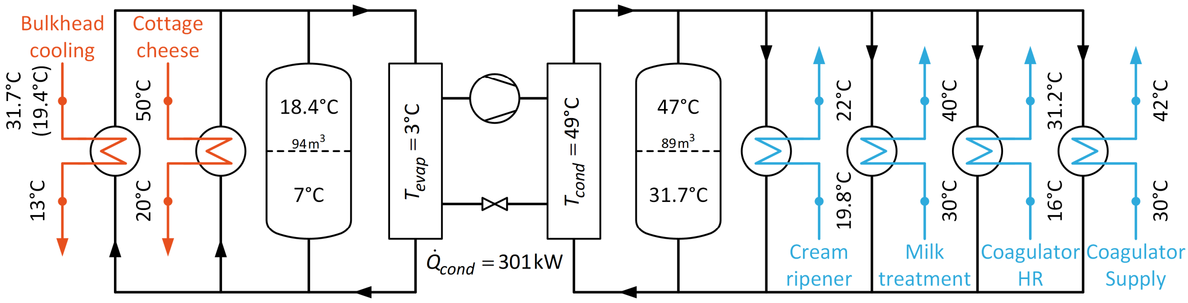

Figure 32: No IHR solution with Split HPTES System (Variant 3).

Comparing Figure 32 with Figure 30, a simpler system is obtained with 2 storages, which are bigger, but there is no interlinking of the storages through the process streams. The two same hot streams are discharging to the evaporator side of the HP, and the HP lift the temperature level to provide all the heating. The drawback to this is the larger HP with 300 kW condenser duty which operates 24 hours a day. Based on the number of TES and the absence of interlinking storages, the user may prefer this implementation due to the complexity. One interesting point is the temperature level of the cottage cheese washing water existing at 50°C. The high temperature has the potential to be exploited.

7.1.5 Combined IHR and HPTES system

The aim of the combined system is to search for a simpler system with minimal number of storages. The user at this stage has to look at not only the degree of overlaps (Figure 26), but also the schematics and the cost associate with the final design. Figure 27 showed the cost curve of the IHR, with the three points of interest mentioned. In the points of interest, there are 2 with only one IL and the other point with a more complicated system of 4 AZ (where 2 TES are needed). Based on these three points of interest, the adapted GCC is constructed and show in Figure 33.

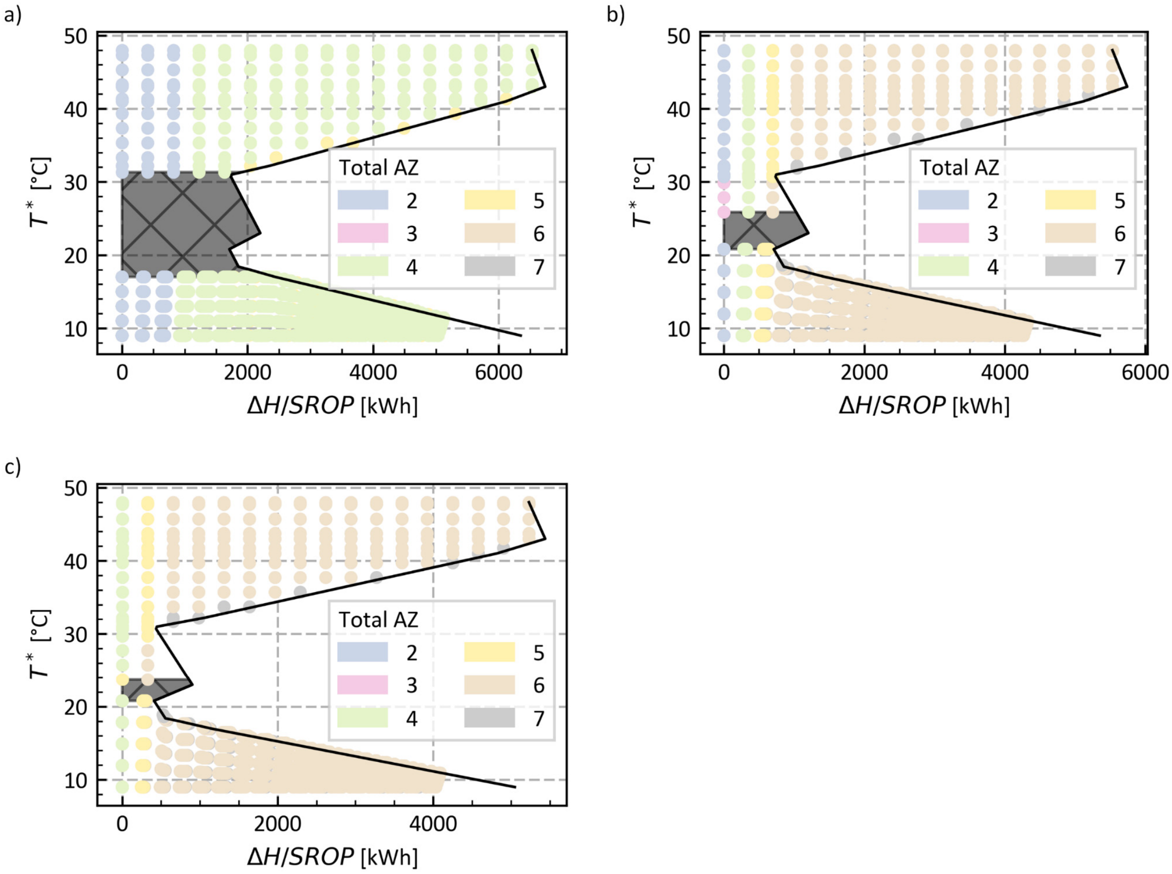

Figure 33: Adapted GCC for Case 1 with IHR of (a) 700 kWh, (b) 1'700 kWh, and (c) with 2'000 kWh.

Based on the adapted GCC, the 700 kWh overlap shows to be the simpler system with 4 AZs, even if the HP is placed with the maximum condenser duty. In the case for 1'700 and 2'000 kWh, with the maximum duty, the system ends up in 6 AZs. However, if the condenser is placed at an unfavorable temperature region, the number of AZ increases to 7 AZs. Based on Figure 33, investigation of the 700 kWh is conducted due to the lower number of AZs. Figure 34 shows the ISSP with the HP placement, with maximum condenser duty.

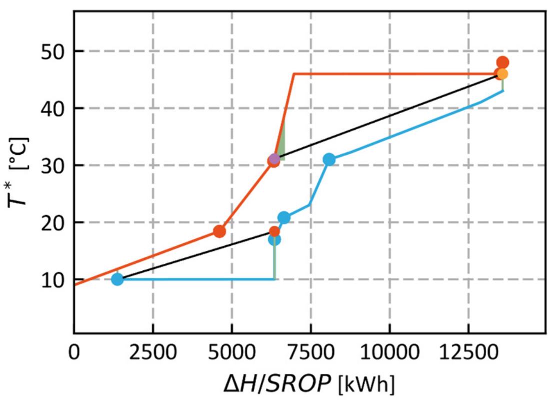

Figure 34: ISSP of the combined case (Variant 4), with the inclusion of the evaporator and condenser of the HP.

The HP potential of the given solution is approximately 6'500 kWh/day, condenser duty. The resulting ISSP with the HPTES solution is optimized with 2 ILs. Figure 35 shows the schematics of the combined IHR and HPTES system.

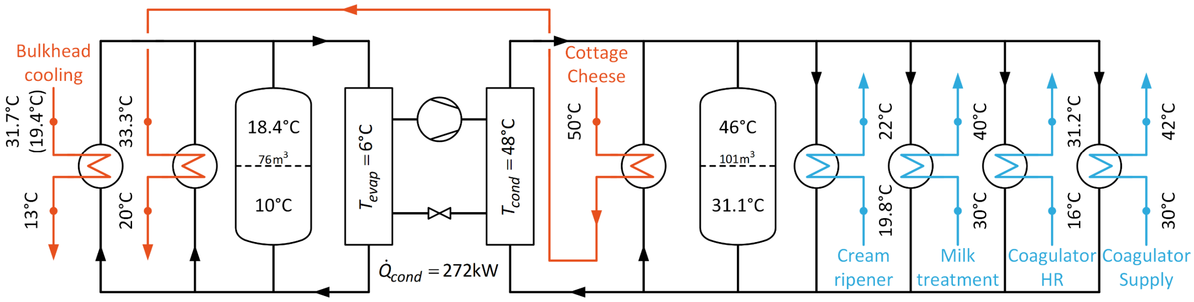

Figure 35: Combined IHR and HPTES System with 700 kWh IHR (Variant 4).

The system results in Figure 35 is relatively similar as the split system with no IHR (Figure 32). The difference between the two systems is the better exploitation of the cottage cheese wash water. The cottage cheese wash water first discharges into the hot storage, to a temperature of 33.3°C. and the discharging to the evaporator side of the storage system to 20°C. The HP duty is also reduced from 300 kW to 270 kW.

7.1.6 Variant evaluation (Step 7)

Table 8 shows the comparison of the different variants in terms of energy demands, cost, and economic performances. The number of TES and HEX is used to measure the complexity of the systems.

Table 8: Comparison of energy demand, utility GHG emissions, cost, and economic performance of the variants for Case 1.

Elements	SoA	Variant 1 IHR only	Variant 2 IHR + Split	Variant 3 HP only	Variant 4 Combined
HP Electricity Demand [MWh/y]	-	-	475	636	526
HU Demand [MWh/y]	2451	1875	0	0	0
CU Demand [MHW/y]	1963	1732	414	575	465
GHG Emissions [t_{CO2eq}/y]	614	477	74	100	82
Investment cost [kCHF]	-	280	767	659	703
Energy cost savings [kCHF/y]	-	44	150	131	143
Total Annual Cost [kCHF/y]	216	210	169	174	168
Static Payback [y]	-	6.4	5.1	5.0	4.9
15 y IRR [%]	-	13.2	18.0	18.3	18.9
No. of TES	-	1	3	2	2
No. of HEX	-	4	9	6	7

SoA represents the current situation of the Case 1, with direct HR already implemented. Variant 1 is used as the reference for comparison. In the SoA, the TAC is at 216 kCHF/y. With the integration of HP, the HU can be eliminated, and the CU can be reduced by 71-79 %; GHG emissions can be reduced by 85-88 %. The TAC is reduced to 168 kCHF/y which is a reduction of 22 %. The investment costs of the variants have an average of 700 kCHF, for HP, TES, and HEX networks. However, the energy savings is significant, of about 2/3 of the current energy costs. The IRR for variants 2, 3, and 4 are also interesting at a minimum of 18 % if the operation of 15 years is possible. Solely based on the economics, Variants 2, 3, and 4 are comparable. However, the design and complexity of the systems are different. Users have to decide whether to implement the system with lowest TAC, or same TAC with more complexity. Based on the results in Table 8, Variants 3 and 4 are favorable for implementation.

7.1.7 Control system simulation Case 1

To evaluate the control strategy in higher detail, the operability of the system in Variant 3 of Case 1 is evaluated with a simulation study. The simulation model is implemented in Modelica using the open source library Buildings Library [86]. The following describe the key properties of the model:

- The HEX models are NTU-based and are parametrized according to the specification of the conceptual design.
- The storage tanks are discretized with a finite volume approach and dimensioned with a 15 % extra capacity for stratification inefficiencies.
- Heat losses of piping and storages are not considered.

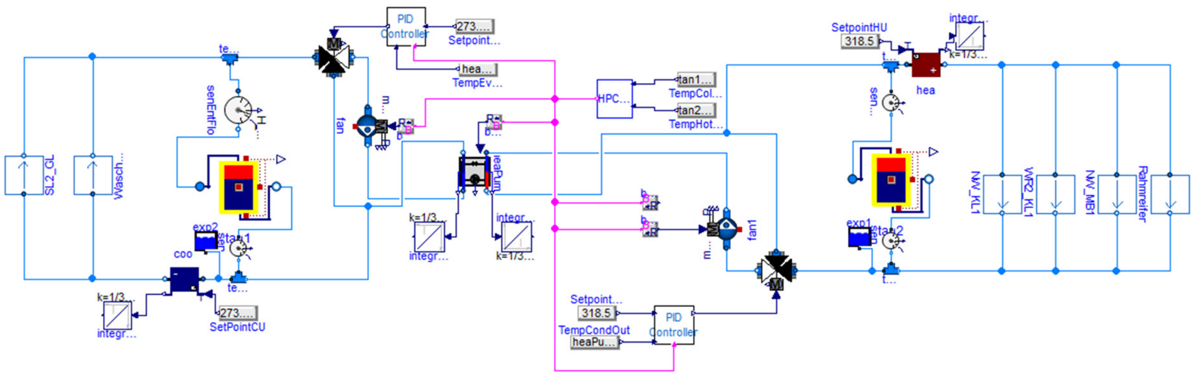

Figure 36: Graphical representation of the simulation model used for control system evaluation

The conducted simulation is a cold-start of the system: both storages are initialized at ambient temperature of 20°C. The system is simulated for 10 days of repeated operation. The resulting storage temperatures at the bottom and top of the hot and cold storage are shown in Figure 37. It can be observed, that after the initialization phase of approximately 1 day, the HP maintains the temperatures of the top layer of the hot storage and the bottom layer of the cold storage at theie design temperatures. From observation it is shown that the bottom layer of the hot storage are being controlled to their setpoint values, with the exception of some peaks where the cold storage is being discharged almost entirely. The utilities are used to compensate this. The top layer of the cold storage is fluctuating due to the fluctuating nature of the hot stream Bulkhead Cooling, which enters the HPTES system at different inlet temperatures, depending on the time as previously listed in the stream table in Table 3.

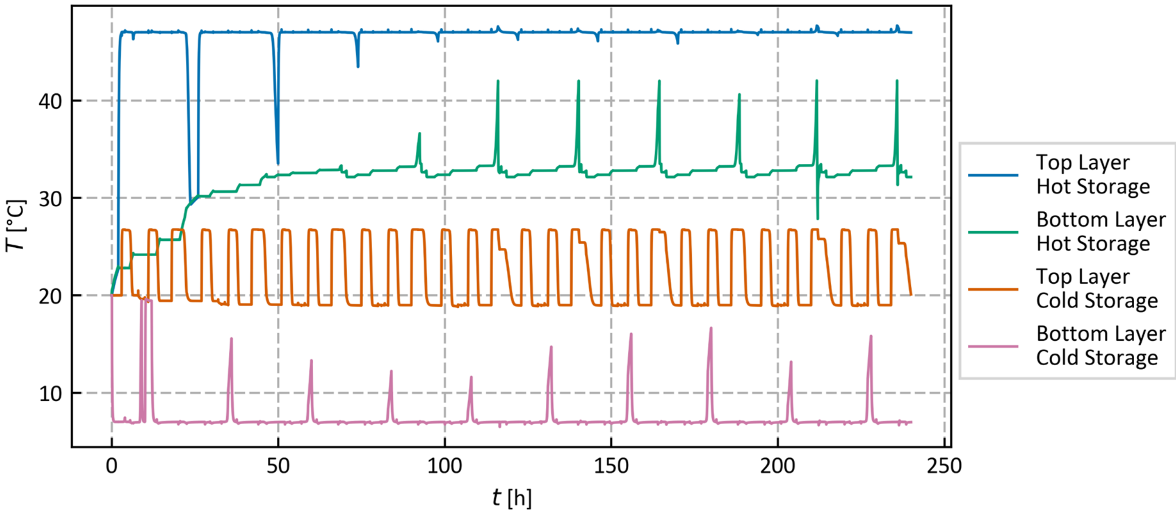

Figure 37: Storage layer temperatures of the hot and cold storage in the simulation of Variant 3 of Case1.

Figure 38 shows the needed hot and CU together with the corresponding HP condenser and evaporator duty, that are heating or cooling the corresponding storage tank. It is observed that the utilities are mainly used at the beginning where the storage is still empty because of the cold start simulation. Thereafter utility usage is moderate

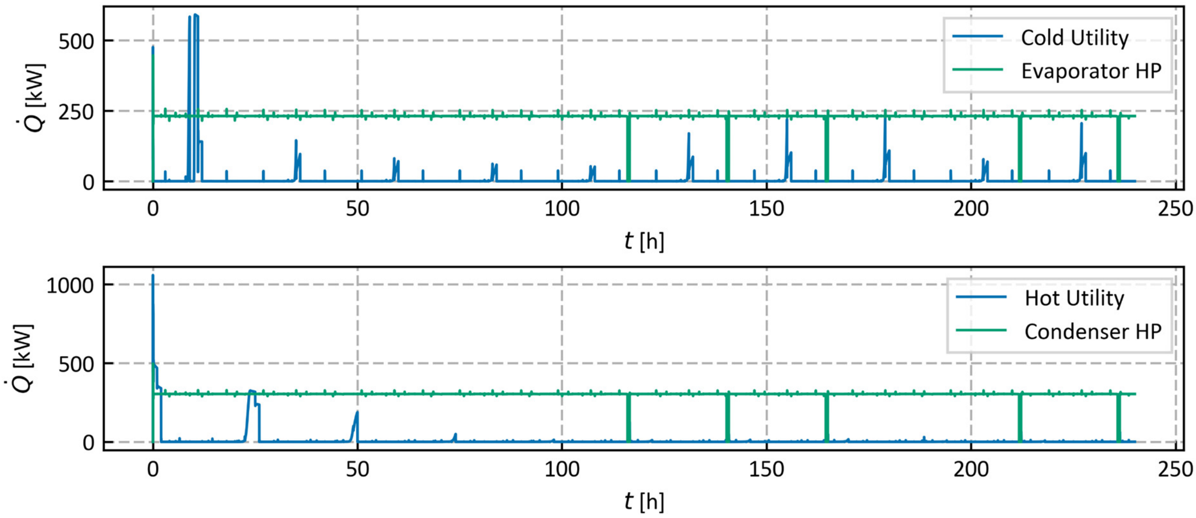

Figure 38: Utility and HP heat duties of the hot and cold storage of Variant 3 of Case 1

As listed in Table 9, the simulation shows a fulfillment of the design target heating and cooling supply of approximately 97 %.

Table 9: Resulting heating and cooling coverage of the controlled system including the cold start utility demands

Element	Heating Demand	Cooling Demand
Covered by Utility	1.9 MWh	1.6 MWh
Covered by HP	72.2 MWh	55.0 MWh
Share covered by HP	97.3 %	97.2 %

Note: As in any heat recovery measure in this design, the utilities are still required for startup and shutdown phases. Therefore, there is no mentionable impact on the sizing of the utilities.

7.2 Case 2 MOC Process

7.2.1 Data extraction and heat recovery (Step 1 and 2)

The data extraction for MOC is different from a typical batch process due to the variation in process streams and heat flows between the different operating cases. In this work, the process streams that occur in every single operating case are extracted as the stream data for evaluation. Figure 39 shows the Gantt diagram of the extracted streams used for the MOC case study.

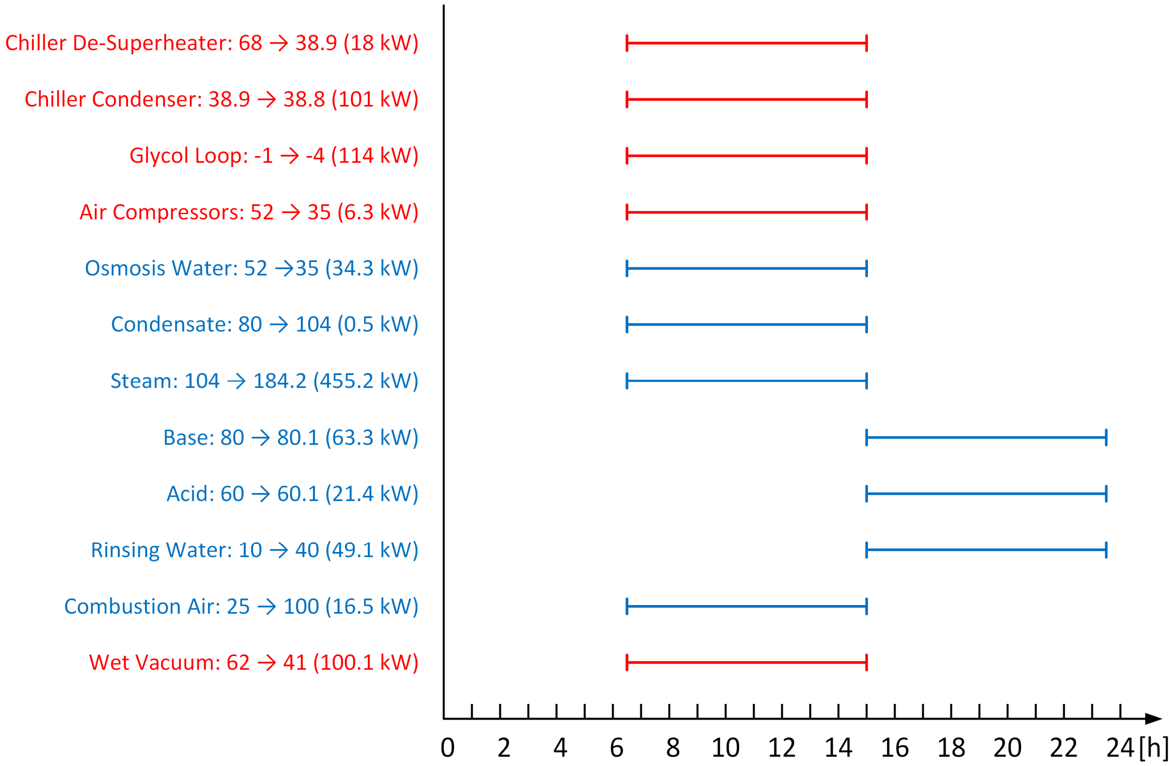

Figure 39: Gantt Diagram of Case 2, where the times are the effective hour of the day

Based on Figure 39, the process is divided into two TSs. One is where the cheeses are produced (OC1, 0700 – 1500 h), and the second TS is the CIP (OC2, 1500 – 2400 h). While in the first times hot and cold streams are present, in the second TS only cold streams are present. By analyzing the two operating cases, it can be seen that there is some extent of direct HR potential present during the day operation, OC1. The PinCH software is used to analyze the possible potential of direct HR of OC1. Figure 40 shows the CCs of OC1 and the associated relaxed HEN of the direct HR. The flue gas stream can be used to directly preheat the osmosis water and the domestic hot water. The design covers the entire heating demand of the domestic hot water stream and pre-heats the osmosis water to 48°C. For this the flue gas stream has to be split in the HEN design-tools. However, the split of the flue gas stream may be realized with an appropriate HEX design (e.g. two HEX in flue gas pipe instead of splitting of the pipe).

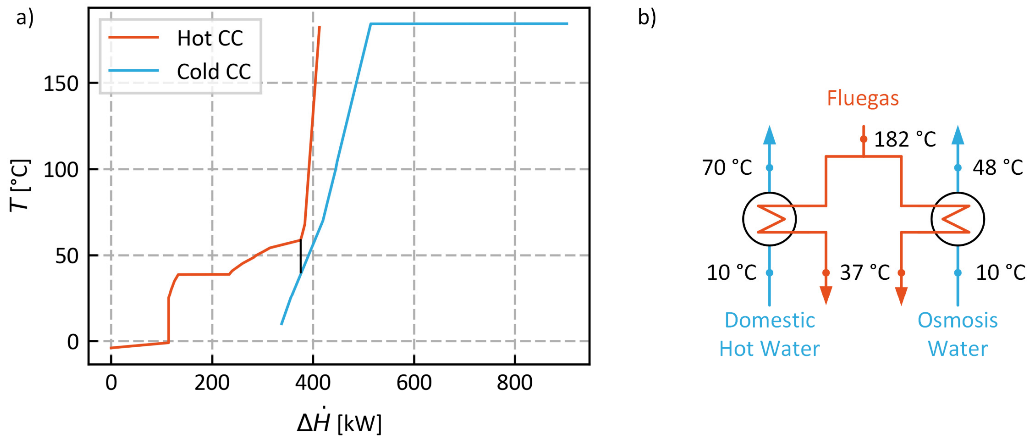

Figure 40: a) CCs of OC1 of Case 2 at ΔT_{min} = 20 K, b) HEN of feasible direct HR measures.

The two HEX are estimated to cost 29’000 CHF including installation and enable direct HR of 58.5 kW during OC1 operation which sums up to 129 MWh/y. With the annual energy cost savings of 13’600 CHF/y a static payback of 2.1 y results. The residual energy demands are then used for the IHR.

7.2.2 Indirect heat recovery possibilities (Step 3)

Figure 41 shows the ISSP with all remaining streams of the MOC case. The ISSP shows that some of the streams are limiting the IHR design while they only provide limited energy content to the IHR system.

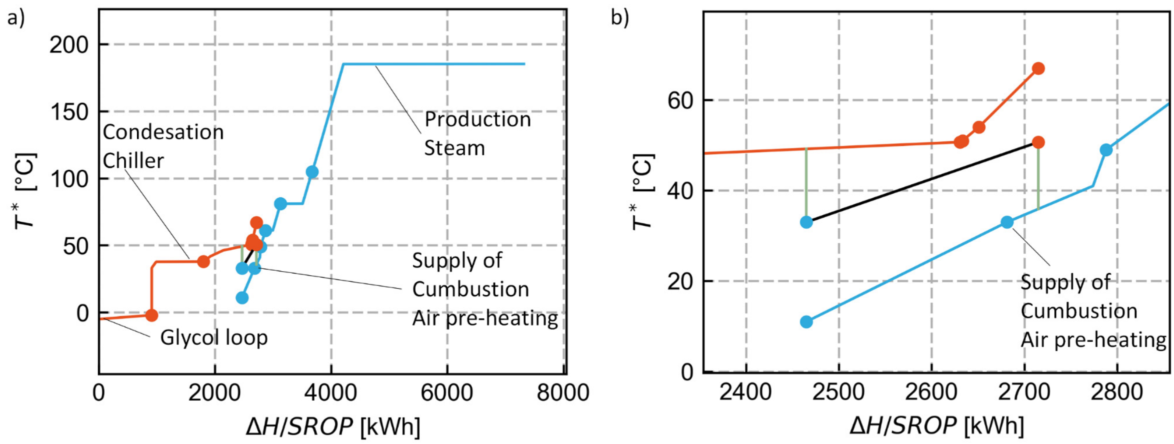

Figure 41: ISSP of Case 2 with all streams after direct HR, a) overview, b) zoomed in view on possible pinch point.

According to the established rule for IHR analysis [5], the irrelevant process streams are therefore excluded to achieve lower complexity solutions. The following process streams are excluded from the further analysis in this case study:

1) Air compressor is a hot stream with very low energy content and rather low supply temperature.
2) Combustion air preheating is a cold stream with high supply temperature and rather low energy content.
3) Chiller condensation and de-superheating are hot streams. The De-superheater has rather low energy content and condensation at rather low temperature levels, additionally, the number of needed equipment can be reduced without reducing possible HP capacity. Furthermore, Chiller retrofitting would be necessary to be able to exploit these potentials.

4) Glycol loop is a cold stream with very low temperature level compared to the sinks at 50-100°C.

5) Steam production is a cold stream with very high (180°C) temperatures and is thus unsuitable for HP application as in HPTES (See Arpagaus [82] for possible high temperature HP applications).

The remaining hot stream "Wet Vacuum" provides sufficient heat surplus to integrate a HP of any possible size and the required number of HEX is due to this excluded process streams reduced. With the reduced set of streams IHR of approximately 295 kWh is possible. Figure 42 shows that the stream can be used to preheat the rinsing water through a storage, but the higher temperature streams may not be supplied with IHR alone.

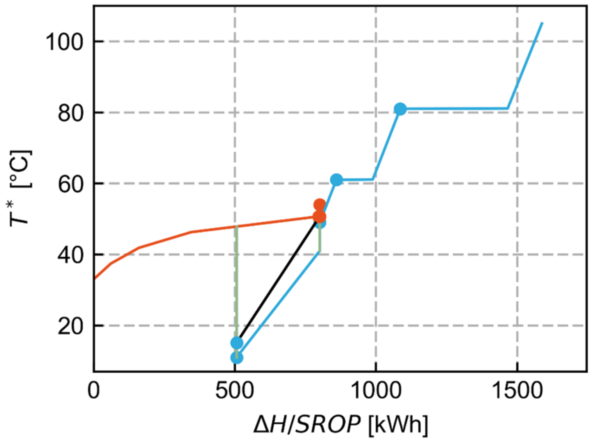

Figure 42: ISSP for Case 2 with 295 kWh IHR overlap

The optimization program is then used to understand the optimized cost of each degree of overlaps of the IHR for the MOC process, as shown in Figure 43.

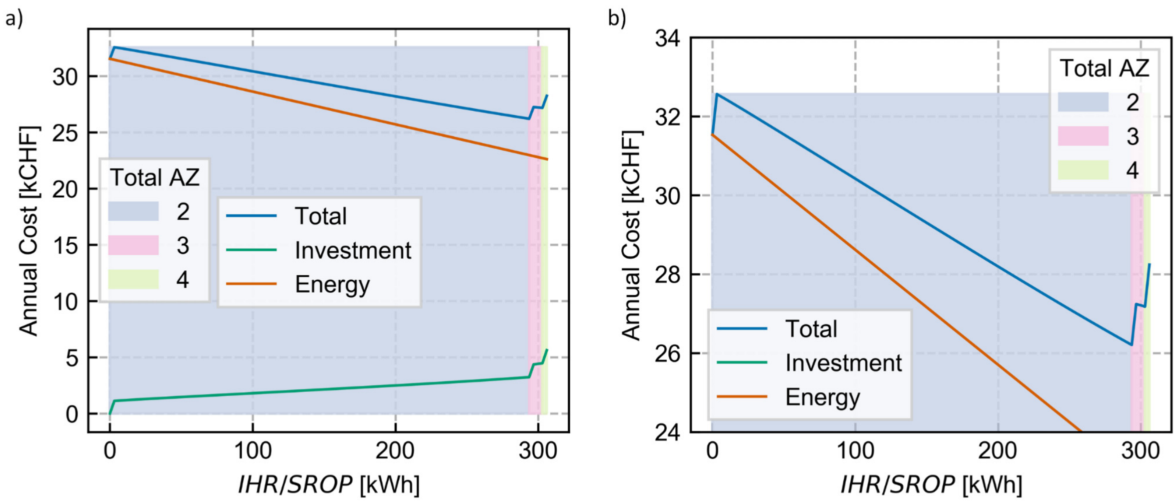

Figure 43 a) The annual cost of the different overlap of the IHR of Case 2, b) a zoomed in version on the total cost.

The point of interest in Figure 43 is 295 kWh of IHR. After that point, the total cost of the system increases with the increase in the IHR due to the increase in the number of total AZs.

7.2.3 Initial IHR solution (Step 4)

Based on the consideration of cost and number of AZ as mentioned before, 295 kWh is taken as the initial solution. Figure 44 shows the schematics of the TES system for the IHR of 295 kWh.

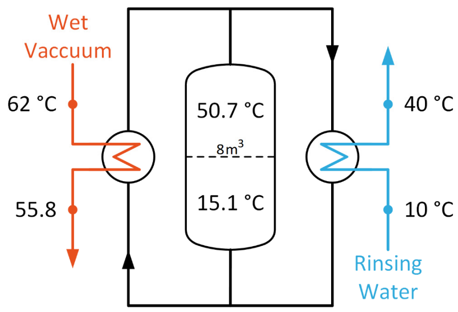

Figure 44: Schematics for IHR of 295 kWh for Case 2 (Variant 1).

The economic performance and energy demand of the IHR is presented in Table 10.

7.2.4 IHR solution with separate HPTES system (Step 5)

After designing the IHR system for the IHR of 295 kWh, the remaining energy demand are extracted from the stream table. Figure 45 shows the inverted residual ISSP for Case 2, with two possible placements of the HP.

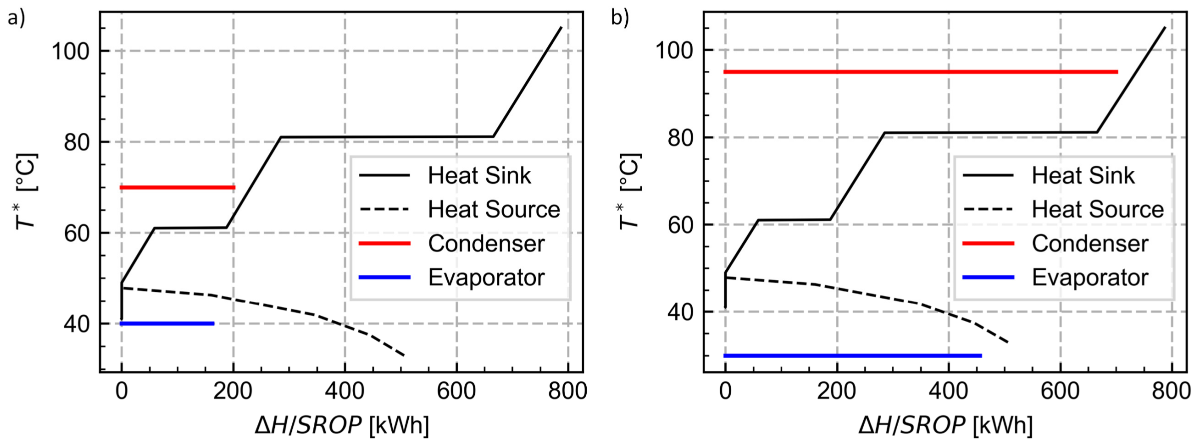

Figure 45: Inverted Residual ISSP for Case 2 with two HP placements possibilities: a) Condenser duty of 200 kWh (Variant 2) and b) with condenser duty of 700 kWh (Variant 3)

Figure 45 shows the possible two condenser placement options. While there is an application with a small duty and thus also smaller lift (Figure 45a), there is also an option with increased temperature lift of the HP (Figure 45b). Both options are evaluated. Figure 46 and Figure 47 shows the schematic design for the condenser duty of 200 kWh and 700 kWh, respectively.

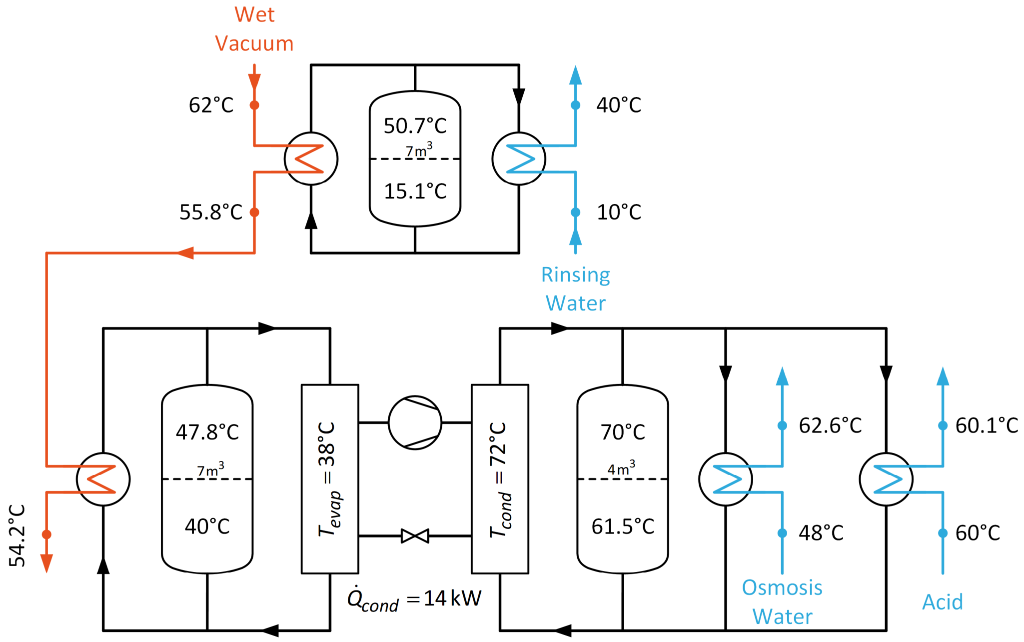

Figure 46: IHR solution with split HPTES System (Variant 2), with condenser duty of 200 kWh.

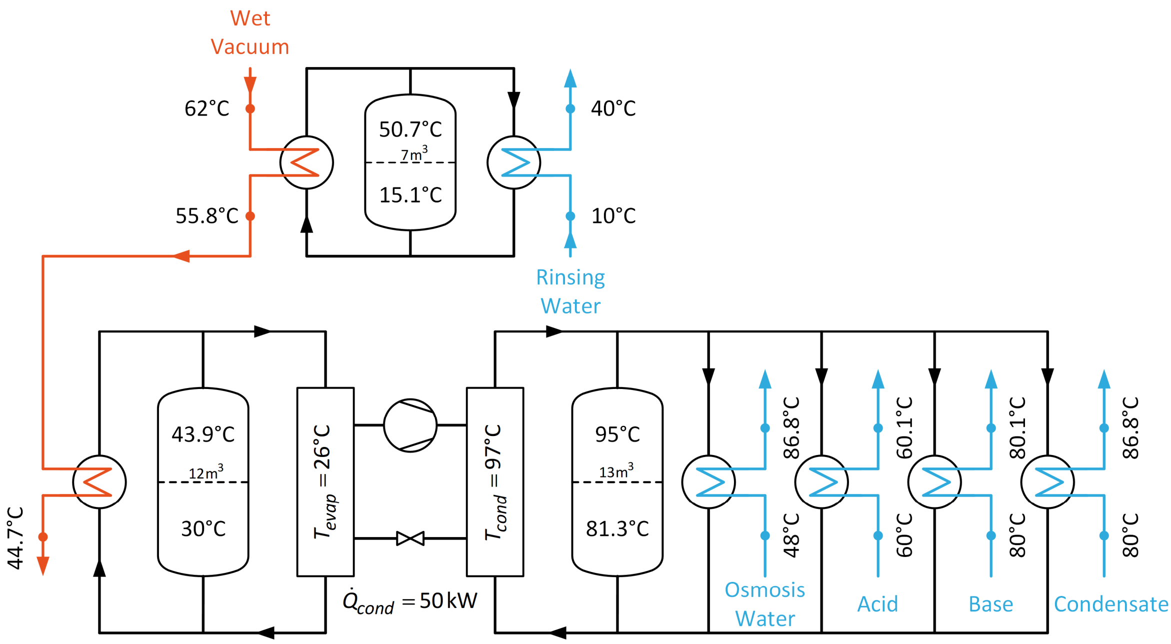

Figure 47: IHR solution with split HPTES System (Variant 3), with condenser duty of 700 kWh.

The top half of both schematics in Figure 46 and Figure 47 are the IHR solution from Figure 44 and the bottom halves of the two schematics show the integration of the HP and its associated storage system. Both variants use the wet vacuum, discharging to the evaporator side of the HP. In the system of Figure 46, a smaller HP of 14 kW is used to provide the heating required for the osmosis water and acid for the CIP. With the larger temperature lift with a HP of 50 kW in Variant 3, it can provide the extra heating for the base used CIP and condensate. The other alternative to Step 5 is to consider the split system without IHR and the combined system and Figure 48 shows the inverted residual ISSP for Case 2 without any HR.

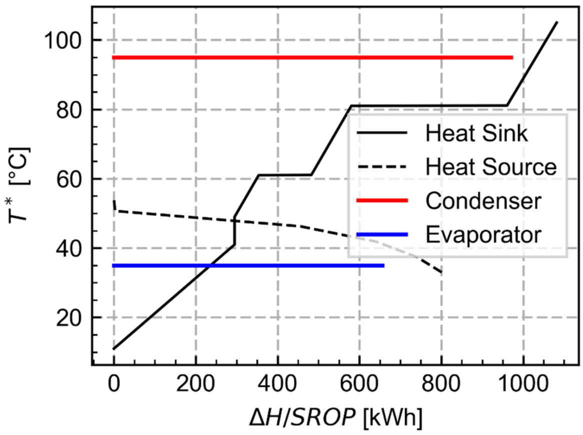

Figure 48: Inverted Residual ISSP for Case 2 without any IHR, with possible HP placements (Variant 4).

In Figure 48, there is a large overlap between the heat sinks and sources. Instead of using the designing a IHR solution, the heat is solely valorized using a HP. Figure 49 shows the schematics of the HPTES system without any IHR.

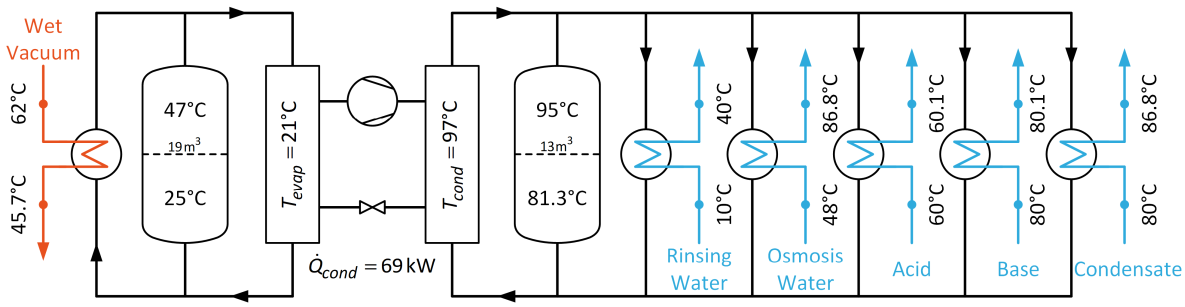

Figure 49: Schematic of the split system without IHR (Variant 4)

Comparing the schematics with IHR (Variant 3), the number of HEXs and storage are both reduced by one. Due to the lack of IHR, this heat also has to be transferred through the HP, increasing the required HP heating capacity to 69 kW for the same remaining HU requirement. Based on the number of HEX and storages, this schematic may be preferred due to the lower complexity.

7.2.5 Combined IHR and HPTES system

In search for a simpler system, Figure 50 shows the adapted GCC with AZ information of Case 2. The number of resulting AZ at larger duties depends on the evaporator temperature, where the number varies between 4 and 5. The two HP placement as mentioned in the split system are possible based on the adapted GCC.

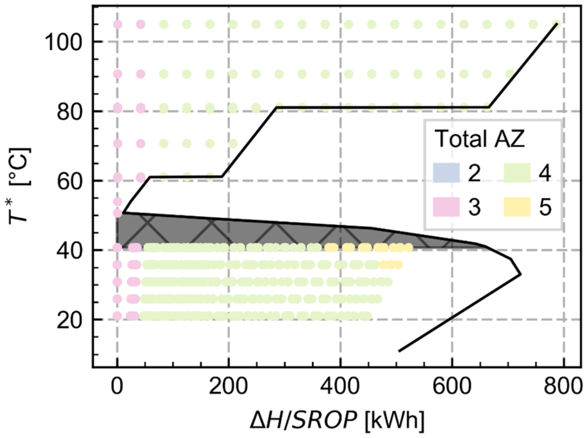

Figure 50: Adapted GCC with AZ information for Case 2 with 295 kWh of IHR.

When integrating the HP with a combined system, the ISSPs in Figure 51 show that there are separated storage systems possible.

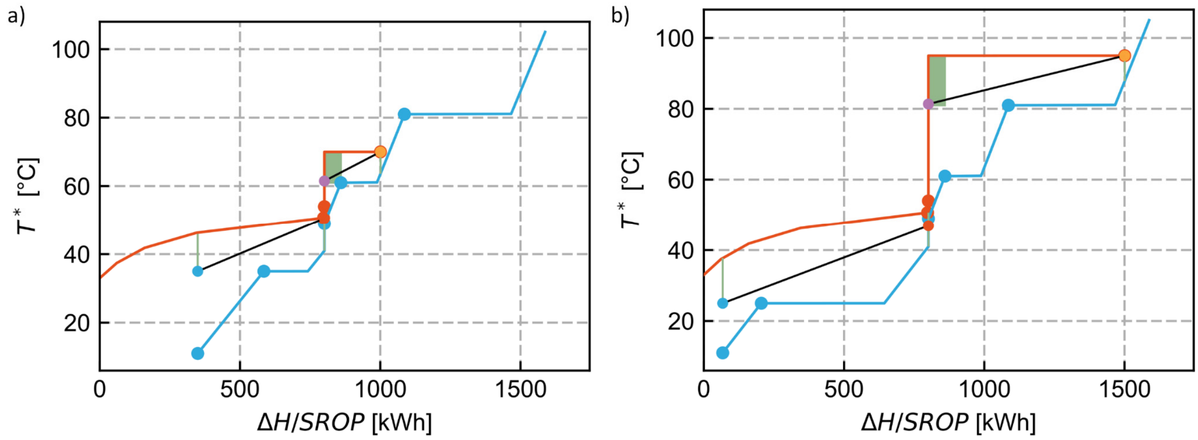

Figure 51: ISSP of combined system with 295 kWh IHR. a) for 200 kWh condenser duty (Variant 5), b) for 700 kWh (Variant 6).

The HP potentials of both are 200 and 700 kWh, condenser duty. The resulting ISSP with the HPTES solution is optimized and shown in Figure 52 and Figure 53.

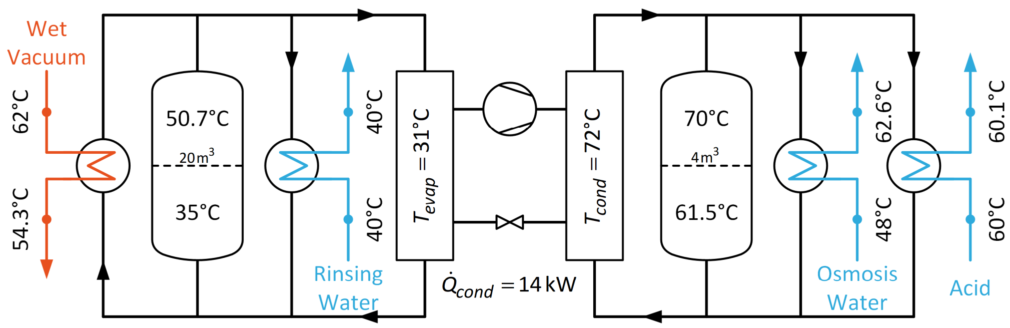

Figure 52: Combined IHR and HPTES System with 200 kWh, condenser duty (Variant 5).

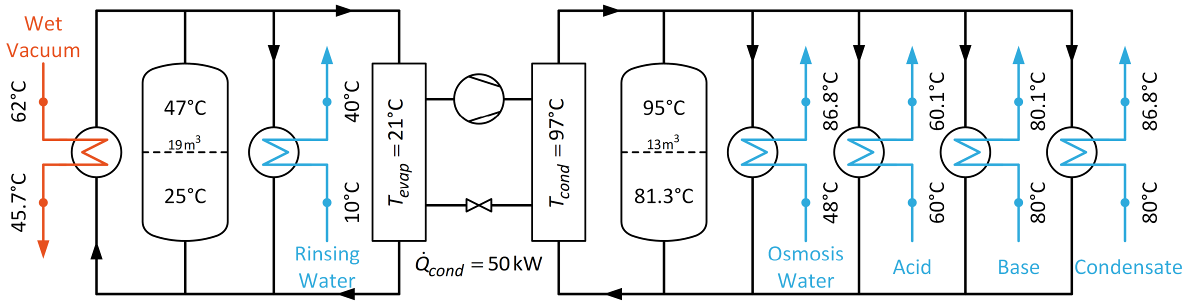

Figure 53: Combined IHR and HPTES System with 700 kWh, condenser duty (Variant 6).

In Figure 53, the number of HEX, storages and HP capacity are similar to Variant 4 (Figure 49). However, the rinsing water is heated with the storage from the evaporator side of the HP. The HP remains the same due to the lack of IHR in the Variant.

7.2.6 Variant evaluation (Step 7)

Table 10 shows the comparison of the different variants for IHR in terms of energy demands, cost, and economic performances. The number of TES and HEX is used to measure the complexity of the systems. The number of HEX in this overview does not include the HEXs for direct HR.

Table 10: Comparison of energy demand, utility GHG emissions, cost, and economic performance of the IHR variants for Case 2.

Elements	SoA	Variant 1 IHR only	Variant 2 IHR + Split 200 kWh	Variant 3 IHR+ Split 700 kWh	Variant 4 Split with no IHR	Variant 5 Combined 200 kWh	Variant 6 Combined 700 kWh
HP Electricity Demand [MWh/y]	-	-	10	67	86	12	72
HU Demand [MWh/y]	297	216	161	24	31	161	24
CU Demand [MHW/y]	220	139	95	14	40	96	19
GHG Emissions [t_{CO2eq}/y]	70	50	39	14	18	39	15
Investment	-	24	140	236	269	154	239
Energy cost savings [kCHF/y]	-	9	16	27	25	15	27
Total Annual Cost [kCHF/y]	35	26	38	39	46	40	40
Static Payback [y]	-	2.4	9	8.6	10.8	10.0	8.9
15 y IRR [%]	-	40.9	7.2	7.9	4.5	5.6	7.4
No. of TES	-	1	3	3	2	2	2
No. of HEX	-	2	5	7	6	4	6

The SoA in Case 2 represents the designed solution for direct HR (Figure 40). Variant 1 is used as the reference for comparison. In the SoA, the TAC is at 35 kCHF/y. With the integration of a HP, HU and CU can be reduced by approximately 46-95 %, depending on the variant; utility GHG emissions can be reduced by approximately 44-80 %. However, the TAC increases up to 46 kCHF/y. Due to low operating hours of Case 2, the high investment cost outweighs the annual energy cost savings. Hence the integration of the HPTES system is not attractive. Solely based on the feasible economics, Variant 1 together with the direct HR solution are favorable for implementation, reducing CU, HU and utility GHG emissions by 27 %, 37 % and 28%, respectively. The variant with no IHR option performs worst at 10.8y payback. This is because approximately 1/3 of the heat supplied with the HP could have been recovered through IHR solutions.

7.3 Alternative storage technologies

The workflow considers sensible thermal storages, which is the common type in industry. In the MOC case (Case 2), the HPTES system is only moderately economic, and would likely not be implemented. One of the cost drivers in Case 2 are the storages with their large volume for the relatively small capacity in terms of energy. This is due to the small temperature differences in the storages, caused by the isothermal heat sinks (acid and base). One of the possible future works of this project is to consider other type of TES system. TES systems are divided into three types, sensible TES, Latent TES (LTES), and thermo-chemical TES. LTES with Phase Change Material (PCM) can have a significant role in saving and efficient use of energy and increasing the efficiency of energy systems [87]. LTES has higher investment costs but have potential of exhibiting higher energy densities and reduces.

7.3.1 Latent thermal energy storage: Phase change material

TES through PCM can store and release large amounts of energy. The system depends on the shift in phase of the material for holding and releasing the energy. In LTES, the phase change of a material is used to absorb, store, and release thermal energy. In most cases the phase change from solid/liquid is considered. The PCM should additionally be readily available in large quantities at low cost. In practice, those criteria are not fully met by most PCMs. However, recent progress in the design and characterization of novel materials for energy storage, including nanomaterials, has opened new possibilities for enhanced performance with extended lifetimes. Due to the fact, that in LTES energy is stored using the enthalpy of fusion, there is a just a small temperature difference caused by superheating and supercooling of the PCM. Therefore, LTES are best used with process streams that either condense or vaporize. For the same HR with a sensible TES, a high temperature difference between the VSUs is needed. If the source and sink profiles have flat slopes, this would cause a loss in possible HR (source and sink profiles has to be shifted away from each other to have an IL with large temperature difference).

7.3.2 Types of latent thermal energy storage technology

For the integration of LTES in batch processes there is an essential difference for PCM which has to be distinct. There are pumpable PCMs as Phase Change Dispersion (PCDs) and Phase Change Slurry (PCSs) which can transfer heat directly with the process streams. PCD is a heterogeneous medium, which contains a liquid continuous phase and the PCM in the disperse phase. If the PCM is in solid state, the dispersion is in a suspension (solid dispersion phase in liquid continuous phase). If the PCM is in liquid state, the dispersions are an emulsion (liquid dispersion phase in liquid continuous phase). The advantage of PCDs as storage medium is, that the medium is in both states (liquid and solid PCM) liquid and can be pumped through a HEX. On the other hand for PCS, the PCM have a solid and a liquid phase at the same time. There are PCSs, which has in the liquid phase an additional transfer medium, for example water, to decrease the viscosity.

Conventional PCMs, which cannot be pumped, have the need for a transfer fluid which transfers the heat from or to the process streams and then from or to the PCM. Another possibility is PCM containers, such as spheres which are filled with PCM. These containers are placed in the storage tank. To store or release heat, the transfer fluid flows around the spheres and through the HEX. For both non-pumpable PCMs, an additional HEX is needed which causes a higher temperature difference between the process streams and the PCM. Figure 54 a and b, shows the difference between a pumpable PCM and a non-pumpable PCM.

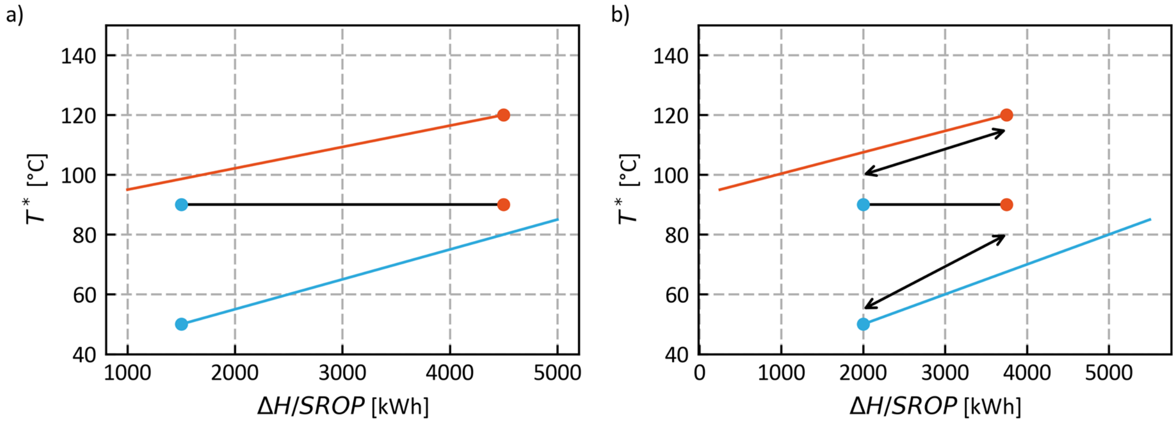

Figure 54: Example ISSP with hot and cold process stream for transferring heat via LTES using a) pumpable PCM, and b) using a non-pumpable PCM and a heat transfer fluid (black arrow).

Due to the fact, that PCMs have in general low heat transfer coefficients, the temperature difference between transfer fluid and PCM is higher. To cover all temperature differences, the process streams have to be pushed away from each other Figure 54. This reduces the amount of indirect HR. For the thermo-economic capacity management, this differentiation has to be covered.

7.3.3 Integration of latent thermal energy storage

Figure 55 shows a superstructure model for LTES, where TES with non-pumpable and pumpable PCM are illustrated. For sensible storage, there are always two VSUs connected to an IL. In contrast to this, the latent model has just one tank at one temperature per IL and due to this, all tanks are hydraulically separated from each other.

As mentioned earlier, pumpable PCMs (PCDs and PCSs) can be pumped through HEX, where the IL is at the phase change temperature. For the non-pumpable PCM storages, an additional transfer fluid is needed as an IL for heat transfer between the process streams and the PCM. The transfer fluid is heated or cooled by the process streams from the supply temperature to target temperature. There are two possibilities to exchange heat between the heat transfer fluid and the PCM. The common solution is to use a HEX. However, area of the HEX tends to be high due to the small heat transfer coefficient of the PCM. The other possibility is PCM containers. These containers do not cover the total tank volume. According to Hales and Ferguson [88], the densest lattice packing for three dimensions is the fac-centered cubic lattice, where the maximal possible volume of the containers is equal to approximately 74 % of the total volume. For non-pumpable PCM storages the limiting factor for the heat transfer in or out of the PCM (HEX or container wall) is the heat conduction in the PCM.

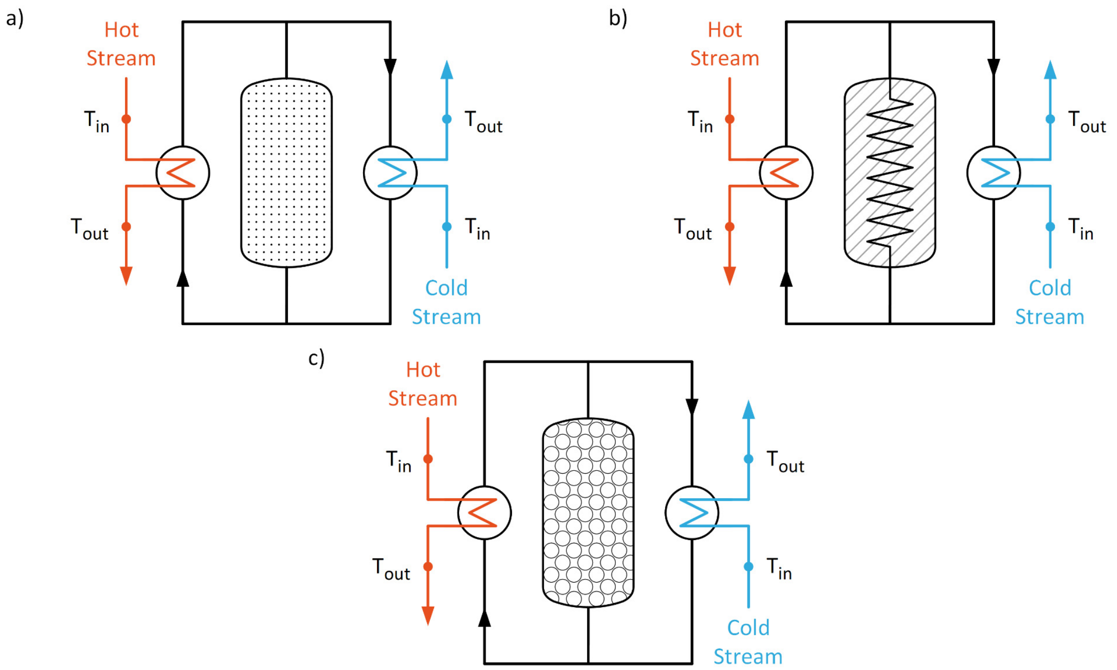

Figure 55: Overview of LTES technology, a) represents a LTES with pumpable PCM (PCD or PCS, b) and c) represent LTESs with non-pumpable PCMs (PCM capsules and HEX, respectively).

The application of the type of LTES technology is dependent on the process. Only options for the possible future work are presented because during the applications and investigations, the low thermal conductivity of the PCM is the most significant drawback of LTES is becoming more and more obvious, which drastically reduces the thermal energy charging and discharging rates. In recent years, research on PCMs and the performance enhancement techniques have been carried out in order to improve the thermal performance of LTES system, which has been reviewed by Tao and He [89]. Although literature on the research works on the performance enhancement of LTES system have been performed and many valuable results have been obtained, there are still many works need to be performed. On top of that, the selection of the PCMs depends strongly on the operation conditions of the respective application. A systematic method is also needed to optimize the selection and design of the LTES.

8 Conclusions

Heat pump integration faces multiple challenges in the industry, which has prevented widespread adoption of the technology. There are limited expertise and experience to properly integrate a HP in processes and these usually are, besides the economic efficiency, the main barriers to implement the technology. The non-continuous nature of many industrial processes also poses additional challenges due to different process schedules of the single plants or change in process requirements. These reasons frequently contribute to the challenge of properly integrating HPs. Due to the temporal variations in the heating and cooling requirements integration of HPs in non-continuous processes present difficulties when selecting a heat pump with appropriate operational characteristics for optimal placement across the pinch point. The developed workflow provides a guideline where engineers and planners from engineering firms and industrial companies can follow to integrate HPs and TES systems into non-continuous processes in a systematic and cost-optimal way.

The workflow includes two novel graphical derivations based on the ISSP, and implements an optimization program to facilitate variant analysis. The engineers are kept at all stages involved in the decision making, allowing them to decide which solution variants to evaluate and influence them. The workflow allows the selection of two pathways for the integration of HP: (i) a separate HPTES system to the IHR-HESN, and (ii) a combined HPTES integration into IHR-HESN. For the separate system, an inverted residual ISSP is derived, where the source profile (hot composite curve) is inverted in its enthalpy coordinates. The inverted residual ISSP shows the gross heat deficit or surplus, and enables users to place a heat pump at the right temperature levels and duties. In the latter system, a novel adapted GCC, based on the ISSP, with information regarding the impact on the system complexity depending on HP placement is developed. The adapted GCC shows the resulting number of AZs for the corresponding condenser and evaporator placement.

Following the developed workflow, shown in Figure 6, the user is guided on how to apply pre-existing and newly-derived graphical tools to evaluate different solution variants. An engineer thus does not require detailed training in the derivation or programming of such tools, and can instead focus on how to best apply them.

To proof the feasibility and the practicality of the result, the methodology is applied to two case studies, which represent the typical operation of the Swiss industrial processes in the food industry. Case Study 1 is a batch process and Case Study 2 is a MOC process. By integrating HPTES into the system of Case Study 1, the HU is eliminated, and the CU demand reduced by 71-79 %. The resulting economic performance of the variants with HPTES systems are similar, with a reduction of the annual energy cost at approximately 22 % and static paybacks of averagely 5 y; the utility GHG emissions are reduced by approximately 85%. However, the design complexity of the combined system is lower than the split system, due to the lower number of storage and HEXs needed, and the interconnected streams to the different storages. The variant analysis carried out facilitates the engineers in their decision making. However, in Case Study 2, due to the smaller number of batch cycles and the short operation period over the year, HP integration has a lower reduction in cost and a static payback between 8.6 to 10.8 y. The HPTES workflow guides the engineer in this case to the informed decision of analyzing only the identified direct HR measure and the indirect HR measure with a single stratified storage tank.

For the control of the system, a two-level control hierarchy is proposed and evaluated. It is concluded from the simulations that the proposed control strategy and especially the separation of control system into two different levels can successfully control the system undergoing disturbances. The lower-level control strategy performed with the test case according to the specifications. It is advantageous to incorporate the throttle valve control with the HEXs as it is shown in the case studies, since the temperature difference in the TESs and thereby the storage capacity can be increased, resulting in a larger safety margin for unexpected disturbances. Furthermore, the proposed arrangement with a differential pressure-controlled pump and the throttle valve allows for a scalable solution with only one central pumping station.

9 Outlook and Next Steps

The key next step to be taken after this project is to bring the developed method for HPTES integration into industrial application, where the focus should lie on the dissemination of the proposed workflow. In addition, the developed optimization program for the ISSP can be disseminated separately. Process integration software such as the PinCH-Software provide the basis and user-community to promote the application of the developed workflow. The developed tools used in the HPTES workflow including the adapted GCC for the ISSP, the inverted residual ISSP and the optimization program for the ISSP are available as software prototypes whose implementation in a wider distributable software such as the PinCH-Software could be planned directly. The dissemination into the field is suggested to be addressed after this implementation phase. For the realization of full-scale applications, accompanying pilot and demonstration projects with the SFOE may be considered to enable appropriate monitoring and impact assessment of the implemented solutions. Furthermore, this could allow for a detailed study and optimization of operational aspects such as the controls and resilience of the energy supply system with HPTES.

As the HPTES system with its implied constraints on the heat pump operating temperatures has shown to be resulting almost at utility temperatures, the combination of HPTES and utility system could be interesting and economical. Further research could therefore be, to investigate the extension of the HPTES system to replace the utilities entirely e.g. by the addition of additional (ambient) heat sources or sinks. However, the operational safety of this possible further research is of concern. This can also include alternative storage technologies as described in Section 7.3. As in the HPTES system, this approach could allow the reduction of the required installed utility system capacity. This extension would be a good contribution to the ongoing project of “Decabonization of Industrial Processes through Redesign of the Process Utility Interface (DeCarb-PUI)”, where the aim of the project to improve the exergy efficiency of the process utility interface for the heating and cooling of industrial processes.

During the execution of this project, it was observed, that the AZ algorithm with its inherent minimization of the number of AZ for every given ISSP overlap can lead to highly constrained designs. The modification of the AZ algorithm in combination with the optimization program developed in this project could lead to better solutions while maintaining the practicality for the executing engineer. Further research could also be devoted towards life cycle assessment of HR and IHR measures.

10 National and International Cooperation

Within the scope of WP3, the expertise of the pinch expert Dr. Pierre Krummenacher was integrated into the project. The project team would like to express its gratitude for the in-depth discussions on the matter. WPTES fits well in the SWEET project DeCarbCH, where the project aims to decarbonize the heating and cooling in Switzerland. WPTES exploits the internal energy efficiency of processes, which will allow the integration of renewables for heating and cooling. WPTES can be the basis for further research and development activities in DeCarbCH. This also leads to the contribution of IEA Task 15 “Industrial Excess Heat Recovery”, where the HPs upgrade excess heat for internal use before other measures for waste heat utilization.

11 Publications

Throughout this project five publications have been published, of which four are in peer reviewed journals or conference proceedings. Accordingly, the work has been presented at the 13th International Heat Pump Conference of the IEA (Jeju, KR, held online) and the Conference PRES’21 in Brno, CZ. A Further publications regarding the developed optimization program are planned.

R. Agner, B. H. Y. Ong, J. A. Stampfli, P. Krummenacher, and B. Wellig, “A Graphical Method for Combined Heat Pump and Indirect Heat Recovery Integration,” *Energies*, vol. 15, no. 8, 2022.

R. Agner, B. H. Y. Ong, J. A. Stampfli, P. Krummenacher, and B. Wellig, “Practical Integration of Heat Pumps with Thermal Energy Storage in Non-Continuous Processes,” in Proceedings of the 24th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, Brno, Czech Republic, November 2021.

B. Wellig, R. Agner, B. H. Y. Ong, J. A. Stampfli, D. Olsen, and P. Krummenacher, “Integration von Wärmepumpen und Speichern zur Effizienzsteigerung nicht-kontinuierlicher Prozesse,” in 27th Conference of the SFOE Research Program “Heat Pumps and Refrigeration”, Burgdorf, Switzerland, June 2021 (in German).

E. J. Lucas, J. A. Stampfli, L. P. Rast, R. Agner, and B. Wellig, “Heat pump and thermal energy storage integration in non-continuous processes-an application to the food industry,” in 13th IEA Heat Pump Conference, Jeju, Korea, May 2020.

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