Thermal Energy Storage Integration Based on Pinch Analysis – Methodology and Application

Donald Olsen[1], **Peter Liem**[2], **Yasmina Abdelouadoud**[1], **and Beat Wellig**[1,*]

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Supporting Information
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Reducing thermal energy use in industry is an effective way to improve energy efficiency. Process integration methods tackle this challenge, of which pinch analysis is a popular approach for identifying direct heat recovery measures. Many processes are batch processes that can profit from indirect heat recovery using thermal energy storage (TES). This paper presents a systematic conceptual TES integration methodology. In addition, functionality to support this methodology has been implemented in the PinCH software and is presented in a case study.

Keywords: Batch processes, Conceptual design, Heat recovery, Pinch analysis, Thermal energy storage

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1 Introduction

Industry consumes a significant proportion of the total energy consumption in many industrialized countries. For example, industrial energy use is now reported being as high as 70 % in China [1]. Typically for most industrialized countries the percentage of total industrial energy consumption is reported as being around 25 % of which more than half is used for process heat [2]. As a result, reducing thermal energy needs in industry is an effective way to improve energy efficiency and reduce CO_2 emissions.

Different methods are available to help reduce thermal energy use in the industrial sector. These range from an energy audit to a more detailed energy use analysis to ascertain concrete measures for improvement. Certain types of measures can be easily determined based on best practices [3]; however, optimizing heat recovery (HR) based on process integration techniques offer the highest potential for reducing energy demand [4]. Such process integration techniques for improving energy efficiency are challenging and require experience, a strong engineering background, and the right methods to complete successfully. Various process integration methods tackle this challenge, among which pinch analysis [5] has proved to be a commonly used practical approach for identifying heat recovery potential and measures and for optimizing the utility systems. Alongside with the rise in popularity of this approach, the need for inexpensive and effective software [6] and interfaces [7] has also arisen.

Traditionally, the focus in using pinch analysis has been on large continuous processes as they represented significant energy consumers. As a result, the software tools that support this type of analysis have been tailored to continuous processes to optimize them for direct heat recovery (DHR), often neglecting the needs for batch or semicontinuous processes. However, some estimates are as high as 50 % for the share of batch processes of all industrial processes worldwide [8]. Even though such processes exhibit time-dependent behavior that can include inherent variability in the heating and cooling demands, a significant potential for thermal efficiency improvement exists. This conclusion is primarily due to the fact that HR measures for such processes have been often neglected in the past [9]. As a result, research has progressed in the area of batch process heat integration with a focus on optimizing for DHR using heat exchangers as well as for indirect heat recovery (IHR) using thermal energy storage (TES).

This paper presents the latest developments in the PinCH software tool that has been specifically designed to support the application of pinch analysis techniques to continuous, batch, and semicontinuous processes. First the overall methodology for supporting both direct and indirect heat recovery is reviewed. Next, new methods and their functionality to support the integration of thermal energy storages to provide cost-effective and practical conceptual

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[1] Donald Olsen, Yasmina Abdelouadoud, Prof. Dr. Beat Wellig
beat.wellig@hslu.ch
Lucerne University of Applied Sciences and Arts, Technikumstrasse 21, 6048 Horw, Switzerland.
[2] Peter Liem
Flimatec AG, Technikumstrasse 21, 6048 Horw, Switzerland.

TES designs are presented. Finally, a case study from the chemical industry is given to show the results using the described methodology.

2 Batch Process Heat Integration Overview

The heat integration of batch processes is a complex optimization problem given their time-dependent behavior. To reduce the complexity, an initial conceptual design step is needed before detailed design for fast elimination of ineffective designs and focusing on cost-effective options. Pinch analysis has proved to be an effective and practical approach for the support of such a conceptual design approach [5].

Process understanding and in particular the understanding of its energetic behavior is the foundation for a successful pinch analysis. Once these process heating and cooling requirements and their time-dependent behavior have been determined, it is possible to establish the most cost-effective and practical measures for HR. The PinCH software has been developed to support this process through three main types of energy efficiency improvement: (1) DHR, (2) IHR, and (3) utility system optimization. Each of these types and their associated functionality can be used independently of each other. However, the general workflow is to first optimize for DHR opportunities as these types of measures are the most cost-effective and easiest to implement. If there are any remaining heating and cooling needs or if the requirements themselves are too variable to guarantee adequate direct heat transfer, then the IHR type and associated functionality can be used as discussed in Sect. 3. Finally, the utility system can be optimized, typically at the end of the workflow. This approach ensures the engineer is in control of the entire decision-making process and can rapidly develop practical solutions for more efficient and profitable industrial processes. Specific details of the software workflow are given in the Supporting Information.

3 Targeting and Design for Thermal Energy Storage Integration

The ability to determine a conceptual design for IHR using TES has been implemented in the PinCH software. This section describes the methodology and associated functionality.

3.1 Overall Methodology

Thermal energy storage integration design is based on the time average model (TAM) [10] where the process heating and cooling needs are distributed over the duration of the batch, i.e., time constraints are ignored. However, in the presented overall methodology, the TAM has been extended to include temperature shifting of the streams and is called the indirect source/sink profile (ISSP). This shifting gives higher priority to streams that have a longer duration or have a large film heat transfer coefficient as shown in Eq. (1) [11].

$$\Delta T_{\mathrm{min,s}} = fp\left(\frac{1}{U_{\mathrm{s}} t_{\mathrm{s}}}\right)^{\mathrm{y}} \tag{1}$$

In this equation, U_{s} is the overall heat transfer coefficient between the TES thermal fluid and the process stream and t_{s} is its duration within the single batch. The variable fp is a proportionality constant that is determined beforehand using a specified minimum overall temperature difference $\Delta T_{\mathrm{min,ov}}$ as shown in Eq. (2).

$$fp = \max\{(U_{\mathrm{s}} t_{\mathrm{s}})^{\mathrm{y}}\}\Delta T_{\mathrm{min,ov}} \tag{2}$$

In addition, the temperature shifting allows placing the required intermediate loop and heat storage (IL/HS) systems between the source and sink profiles in real temperature, as represented by a black line in Fig. 1. In this graphical based model, the IL/HS systems extract heat from the source profile, transfer it to the heat storage, and distribute it to the sink profile at a later time. This model assumes vertical heat transfer ensuring the projection of the black line on the *x*-axis matches the HR during the entire batch duration. Once the IL/HS system has been conceptually placed within the ISSP, the streams can be allocated to the individual IL/HS system as shown in the heat exchanger and storage network (HESN) on the right in Fig. 1. This allocation enables the computation of the required heat exchanger areas for HR.

Storage capacity cannot be directly read from the graph as the distribution of HR on the time scale must be considered. The general constraint that the hot stream must occur before the cold stream [12] does not need to be strictly respected as repeated batch operation is assumed. Therefore, a heat balance at each time slice within the single batch defines the loading and unloading profile of each heat storage from which the required capacity and volume is derived. The model used distributes the heat recovered between streams over the whole batch duration rather than at the time when heating and cooling demands are simultaneous. Therefore, this model does not minimize the required storage volume but provides a conservative design based on the expected variability in the heating and cooling demands. However, knowing the heat exchanger areas and heat storage volumes, a conservative value for the investment costs can be calculated using standard investment cost functions. In addition, the utility savings can be determined based on the achieved HR over the considered period of time, e.g., one year.

The combination of the two models (the vertical model based on the ISSP and the model for storage capacity calculation) is the basis for the overall methodology for the

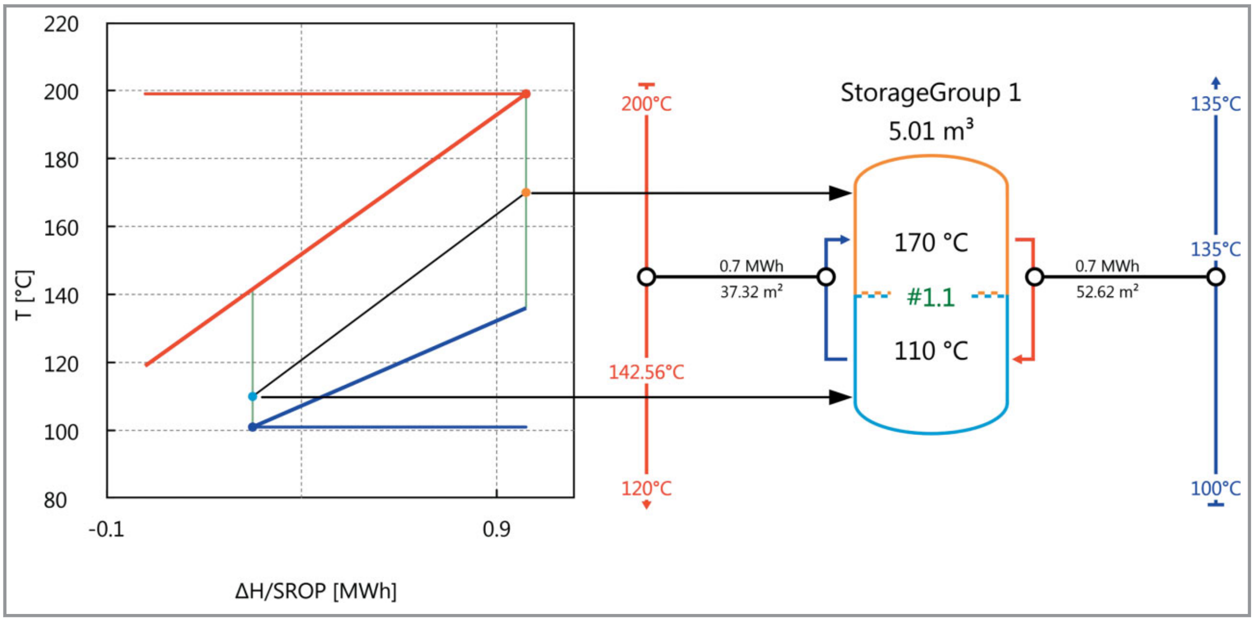


Figure 1. Placement of the IL/HS system within the ISSP and the associated HESN schema for a stratified tank. In case consecutive batches are overlapped in time, the Gantt chart is defined by the stream repeat operation period (SROP) to account for heat transfer between the different batch cycles.

HESN conceptual design. Further, the engineer must consider the following key decision factors: (1) total IHR, (2) minimum number of IL/HS systems, (3) HESN characteristics, and (4) investment costs and utility savings. The next subsection describes specific aspects of the overall methodology available to the user to further improve a TES conceptual design by changing HESN characteristics.

3.2 HESN Characteristics and Design Methodology

The following HESN design characteristics can be adapted by the engineer: (1) the type of heat storage, (2) the storage media cost and physical properties, (3) the type of connection between heat storage, and (4) the temperature enthalpy (TH) placements of the IL/HS system within the ISSP.

The storage media model only sensible heat transfer using heat transfer media such as water or thermal oil. The price and physical properties of the selected media directly affect the cost as well as the HESN design, i.e., when different media is required in two separate storages. The heat storage model consists of two volume storage units (VSUs) at different and most significantly fixed-temperature levels. Two types are considered when designing the VSUs:

- The two VSUs are merged into a single piece of equipment and form a stratified tank. This solution offers the advantage of smaller tank size since it is equal to the required storage media volume (Fig. 1).
- The two VSUs are separated into two tanks and form a fixed-temperature variable-mass (FTVM) system (Fig. 2). This solution offers the advantage of maintaining better temperature and flowrate control. However, the media and tank volumes are larger as each tank has to handle the peak in required storage volume.

The type of connection is also an important HESN characteristic to improve the design when more than two IL/HS systems are required. The connection type between two successive IL/HS systems can be either of the following:

- Hydraulically connected: An intermediate VSU is common to two adjoining IL/HS systems. In this case, the ISSP shows the black lines as connected and continuously increasing (Fig. 3a).
- Hydraulically disconnected: Each IL/HS system has its own set of VSUs allowing the temperature of the VSU to be chosen independent of the other system. This effect is shown in the ISSP with the black line as discontinuous (Fig. 3b).

Both options have advantages with the first offering the possibility for a smaller total volume. The second option allows for more flexibility in allowing different media to be used as well as different temperature levels in the IL/HS systems as they are no longer hydraulically connected. The resulting decoupling can in some cases reduce the investment cost for the same amount of HR.

A final HESN design characteristic is the placement of the IL/HS system within TH assignment zones. This characteristic is physically defined by the temperature of the VSU and the amount of heat transferred in each IL/HS system. It is represented in Fig. 3a by the orange dot which can be placed anywhere within the green area by changing the temperature or enthalpy. The green area represents the valid assignment zone created by the constraint of a hot and/or cold stream supply temperature [11]. Fig. 3a shows, e.g., that the temperature of the middle VSU is limited to a maxi-

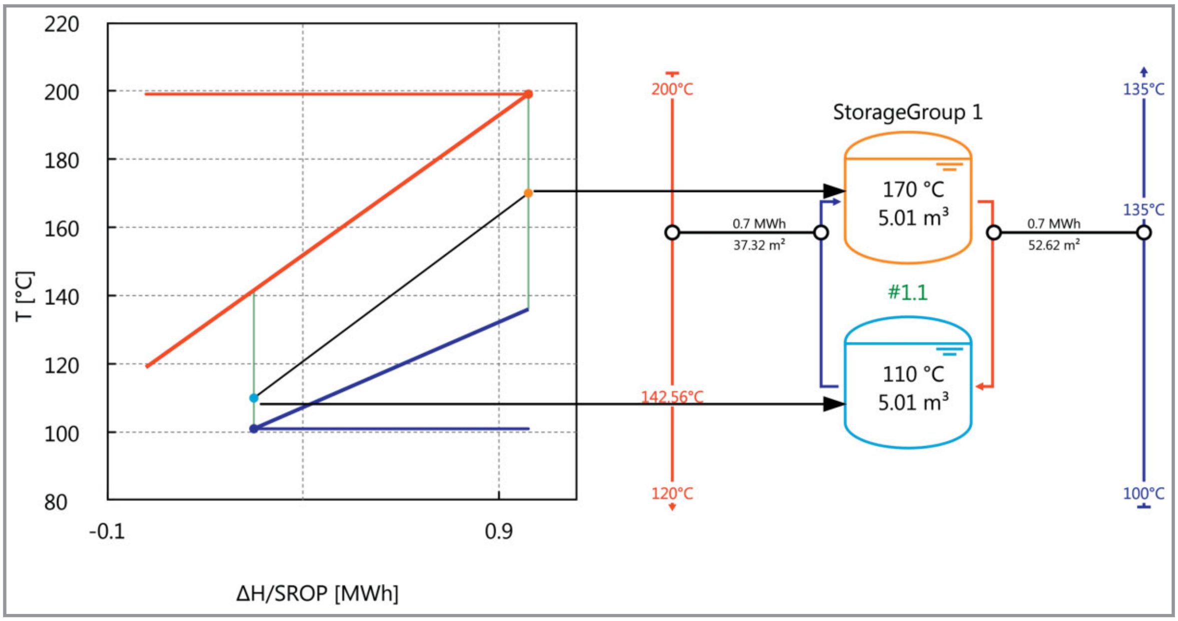


Figure 2. Placement of the IL/HS system within the ISSP and representation of the HESN with FTVM tanks.

mum given by the hot stream supply temperature of 145 °C. Changing this characteristic offers the opportunity to reduce investment cost and in special cases the number of IL/HS systems where assignment zones overlap.

In conclusion, the HESN design methodology is based on the ISSP and the model of vertical heat transfer to ultimately support the design decision making process. Starting from an initial placement of the IL/HS system within the ISSP and default characteristics, it is possible to reduce complexity and decrease the overall cost by systemically setting the HR level and the HESN characteristics based on engineering judgement. The result is a cost-effective and practical TES design. The next subsection focuses on the implemented functionality for application of this decision support-based methodology.

3.3 Decision Support Functionality

In order to guide an engineer through the methodology, various functionalities for decision support have been implemented in the software PinCH. The main function is the dynamic interaction with the ISSP during the targeting and design procedure. As explained in the previous subsection, the TH assignment zones are automatically calculated and displayed on the ISSP. Three types of zones are plotted to clarify the HESN design methodology [11]:

- Restricted zones are based on the intersection of possible assignment zones (always feasible). They provide a quick overview on the number of IL/HS systems required to achieve the desired HR level and identify the constraining supply temperatures.
- Extended zones are based on the union of all possible assignment zones (conditionally feasible) to highlight the possible solution space irrespective of the other assigned zones. Placing an IL/HS system at temperature or enthalpy boundaries, the restricted zones result in certain streams being removed from one IL/HS system and placed entirely within an adjoining IL/HS system.
- Dynamic zones are based on the recalculation of the next feasible assignment zone based on TH placement in the left-to-right direction in enthalpy. As the position changes, certain streams are included or excluded from adjacent IL/HS systems redefining which supply temperatures constrain a particular assignment zone.

A second function is the display of the enthalpy position of the streams on the ISSP with sources shown as horizontal red lines and sinks as blue (Fig. 4a). The stream supply temperature on the ISSP is represented by a full dot providing an indication of which streams constrain the TH assignment zones. Streams that have a low contribution to HR or constrain an assignment zone can be excluded to provide more flexibility in designing the HESN. For instance, H3 is a temperature constraint for the right most restricted zone (orange and black line) in Fig. 4a. As shown in Fig. 4b, the stream has a low heat content (0.03 MWh) and will not contribute significantly to the overall heat recovery. The stream can be excluded using the checkbox shown in Fig. 4b in order to remove the temperature constraint. The automatically calculated default temperature shifting may be manually set allowing the rearrangement of streams according to their design objectives. In both cases, the ISSP and the TH assignment zones are automatically recalculated which ensure quick assessment of the consequence of the modifications on the target.

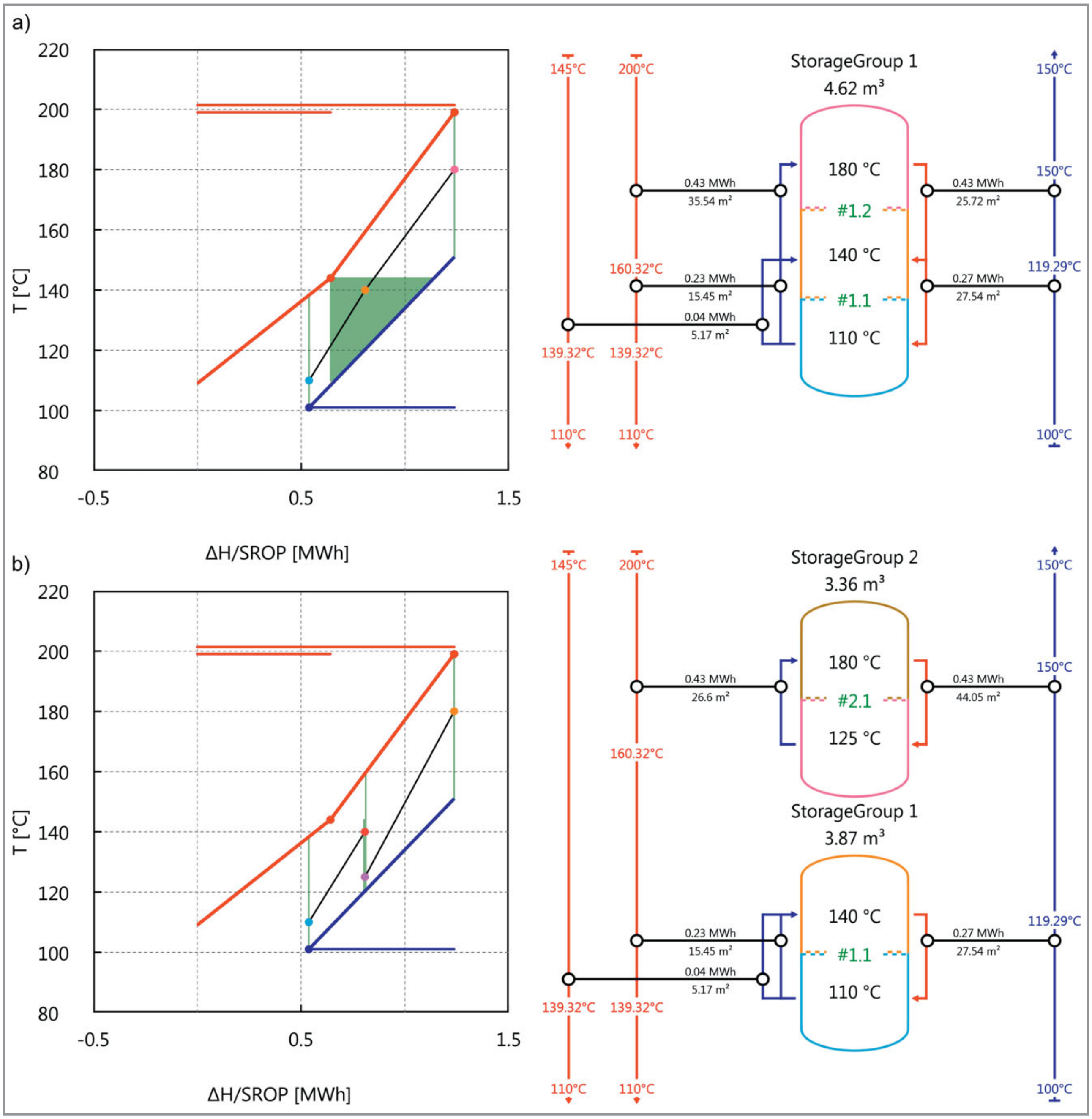
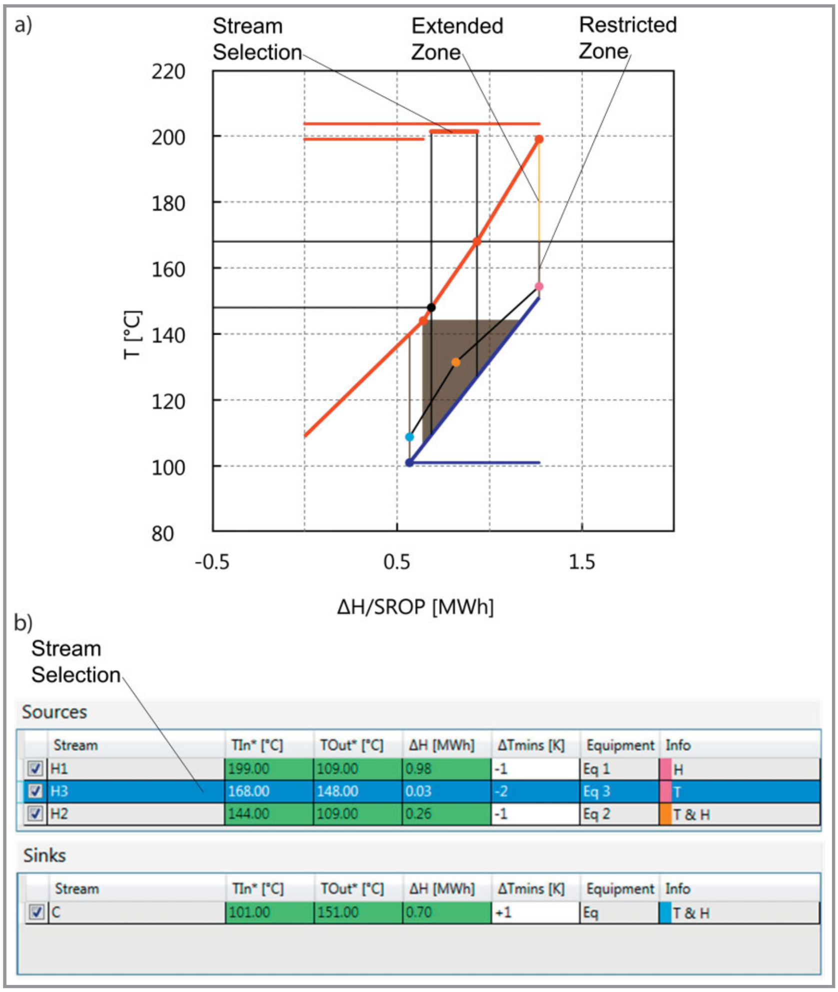


Figure 3. Placement of two IL/HS systems within the ISSP and the equivalent representation of the HESN schema for a) a stratified tank with connected IL/HS systems and b) disconnected IL/HS systems.

One of the main assessment criteria is the economic performance of the design. This is directly linked to the amount of HR of the storage system and is indicated through the static payback. For each possible heat recovery level, the payback time of the default HESN is plotted in grey in Fig. 5. Additionally, the number of IL/HS systems versus HR defined per batch is plotted as a step function and can be used by the user to find the maximum HR that can be achieved for a given number of IL/HS systems.

Another key decision support function is the storage loading and unloading profile (Fig. 6). This profile is affected by the allocation of streams to the IL/HS system and by the occurrence in time of those streams. Changing the schedule of those streams affects the Gantt diagram and hence the loading/unloading profile. This profile is therefore valuable information for the designer as it allows quick assessment of which process requirement has the most dominate contribution to the volume. In addition, the effect of rescheduling a stream can be assessed.



Sources

☐	Stream	TIn* [°C]	TOut* [°C]	ΔH [MWh]	ΔTmins [K]	Equipment	Info
☑	H1	199.00	109.00	0.98	-1	Eq 1	H
☑	H3	168.00	148.00	0.03	-2	Eq 3	T
☑	H2	144.00	109.00	0.26	-1	Eq 2	T & H

Sinks

☐	Stream	TIn* [°C]	TOut* [°C]	ΔH [MWh]	ΔTmins [K]	Equipment	Info
☑	C	101.00	151.00	0.70	+1	Eq	T & H

Figure 4. Software implementation of the ISSP with the extended and restricted zones (a) and the stream sources and sinks table used to analyze the contribution of each stream and its selection or deselection (b).

4 Application Example

In this example, a chemical batch process as given in [13] has been chosen to show the overall workflow. The process is shown in Fig. 7a and has two main parts: a front-end separation system and a back-end reactor system. At the front end, a chemical feedstock is fed into a batch distillation column to produce a bottom product and an intermediate overhead stream that is transferred to the reactor part. The overhead intermediate product is cooled and stored. During the short storage period, the intermediate product is mixed with additives and catalytic substances before entering the batch reactor. Since the reaction is exothermic, cooling of the reactor is required during operation. The reactor product is directly discharged after which the next batch can begin assuming that there is no overlapping between consecutive batches.

The time dependences of the heating and cooling requirements are defined by the associated Gantt chart as shown at the bottom of Fig. 7a. This Gantt chart assumes no overlapping of consecutive batches and is used in this application example. However, it must be noted that the original publication [13] used a combinatorial optimization method to determine the DHR potential between batches that overlap during the production cycle. A fixed repetition cycle was used and the total amount of internal heat recovery was found to be 1965 kWh.

As noted above, in this analysis, only the single batch with no overlap is considered. The schedule is cyclic and relatively fixed with minimal variability providing the opportunity for direct HR measures to be determined as a first step in the overall approach. A pinch analysis within three of the seven time slices (Fig. 7a) was done. Three direct heat exchangers at the front end and one at the back end were determined to be economically viable providing in total 1375 kWh per batch of HR.

The second step in the overall approach was to assess the opportunity for IHR. The remaining residual heating and cooling demands have to be extracted after accounting for the DHR measures in each time slice. The adapted process requirements are shown in Tab. 1 with the four highest

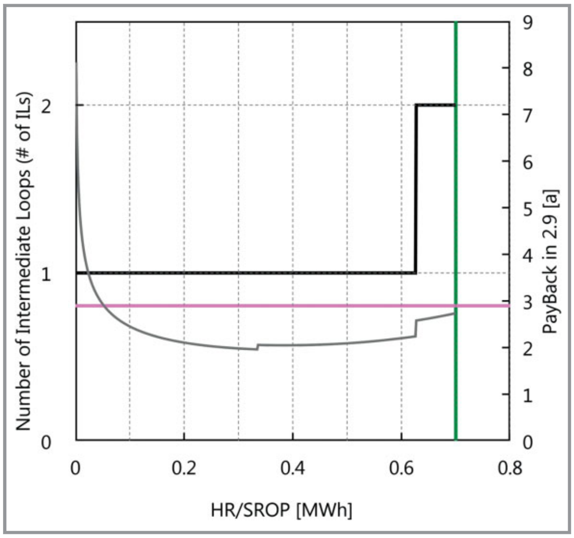


Figure 5. Number of IL/HS systems versus HR (left axis) and static payback versus HR (right axis) graph.

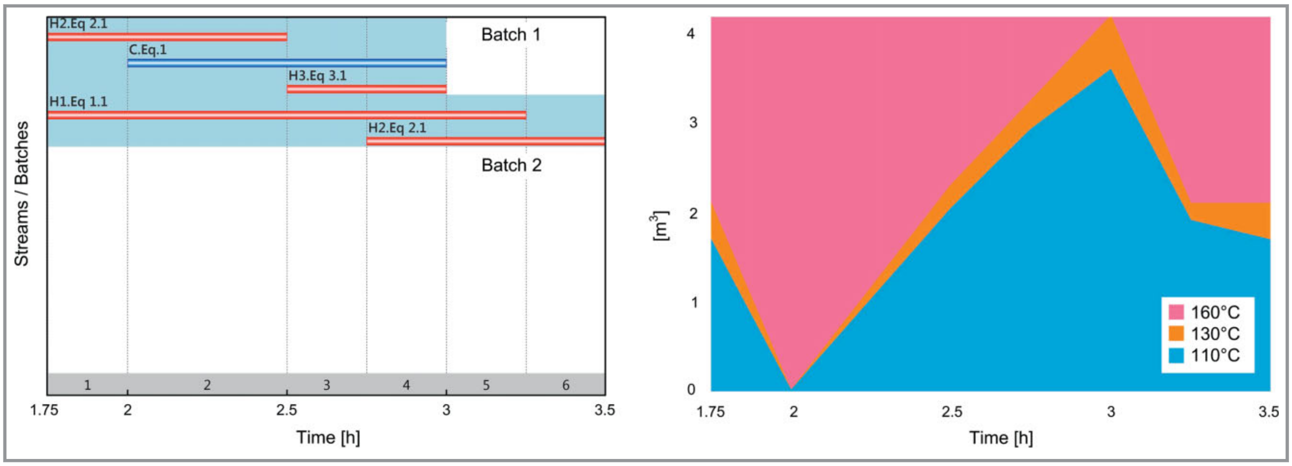


Figure 6. Gantt diagram for a batch process heating and cooling requirements and the corresponding thermal energy storage stratified tank loading and unloading profile.

priority streams in italics to be included in the ISSP shown in Fig. 7b.

The analysis was done using the methodology to derive a HESN at a conceptual design level. Based on the ISSP (Fig. 7b) and engineering judgement, one IL/HS system was selected with a maximum heat recovery of 1 MWh per batch. A stratified tank type was selected with an upper temperature of 120 °C and a lower temperature of 80 °C resulting in a volume of 21 m^3. The lower temperature was found to be pinched by the hot curve and the supply temperature of stream C1 feed at 79 °C. It is not possible to select a higher temperature as this would cause a temperature cross with the streams of the hot curve making it impossible to supply heat at such a high temperature. In an analogous manner, a storage temperature below 79 °C would result in a cross making it impossible for the storage to achieve the lower temperature when stream C1 feed is used to unload the storage. The selected values for this

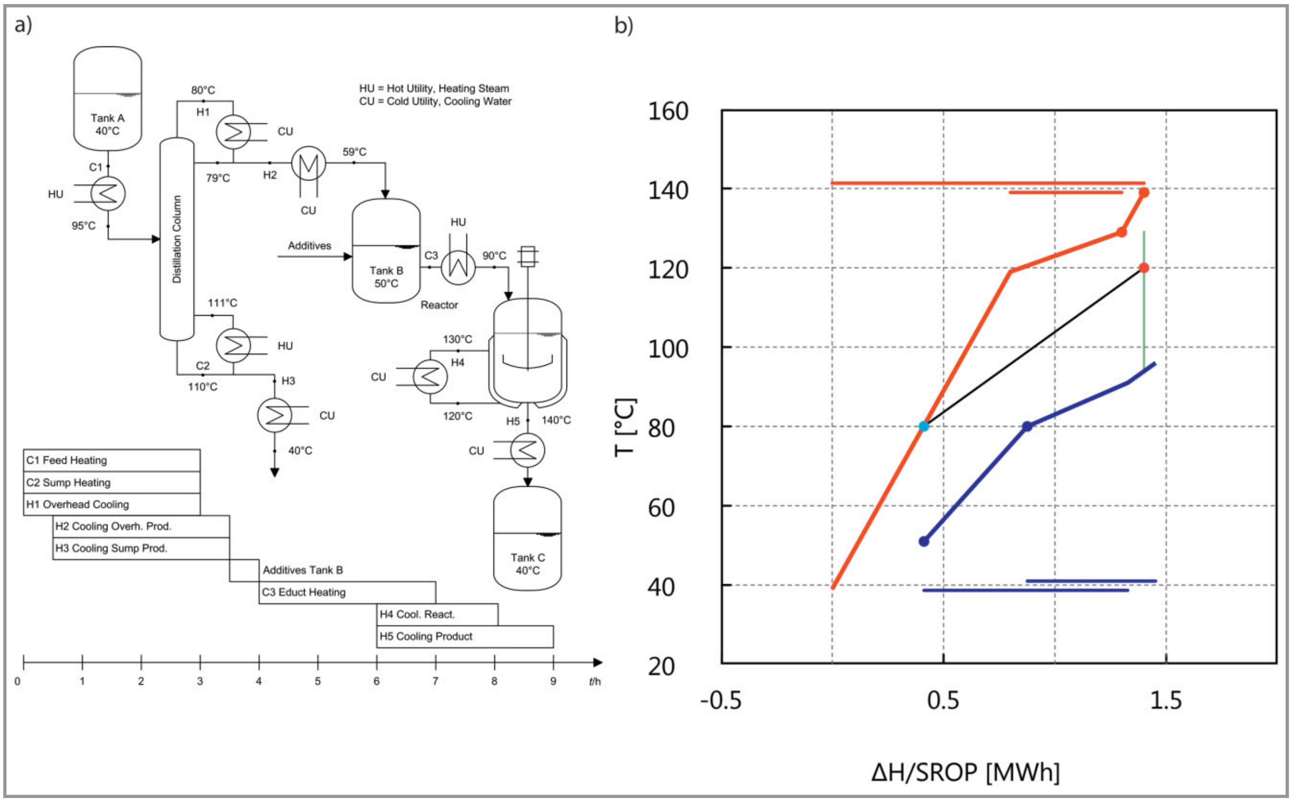


Figure 7. Process schema (a) of batch distillation chemical process [13] and associated ISSP (b) based on highest priority streams (Tab. 1). HU: hot utility, heating steam; CU: cold utility, cooling water.

Table 1. Remaining process requirements after extracting DHR requirements in each time slice.

Name	T_{in} [°C]	T_{out} [°C]	$\Delta\dot{H}$ [kW]	t_{start} [h]	t_{stop} [h]
C1 feed 70-95	*79*	*95*	*250*	*0*	*0.5*
C1 feed 40-54	40	54	140	0	0.5
C1 feed 79-95	79	95	160	0.5	3
C2 sump 110-111	110	111	160	0	3
H2 overhead product 79-59	79	59	140	3	3.5
H3 sump product 80-40	80	40	120	0.5	3
H3 sump product 110-40	110	40	210	3	3.5
C3 educt 50-90	*50*	*90*	*320*	*4*	*6*
H4 reactor 130-120	*130*	*120*	*200*	*6*	*8*
H5 product 140-40	*140*	*40*	*500*	*7*	*9*
H5 product 76-40	76	40	180	6	7

example are shown in the associated process schema in Fig. 8. In addition, the DHR measures are shown in dashed lines and the IHR TES system is shown in bold lines. In total, 2375 MWh per batch of HR are possible based on this conceptual design. The additional savings due to HR using the storage are approximately 35 000 € a^{-1} assuming 70 €MWh^{-1} for hot utility and 500 batches per year and an investment of 215 000 €.

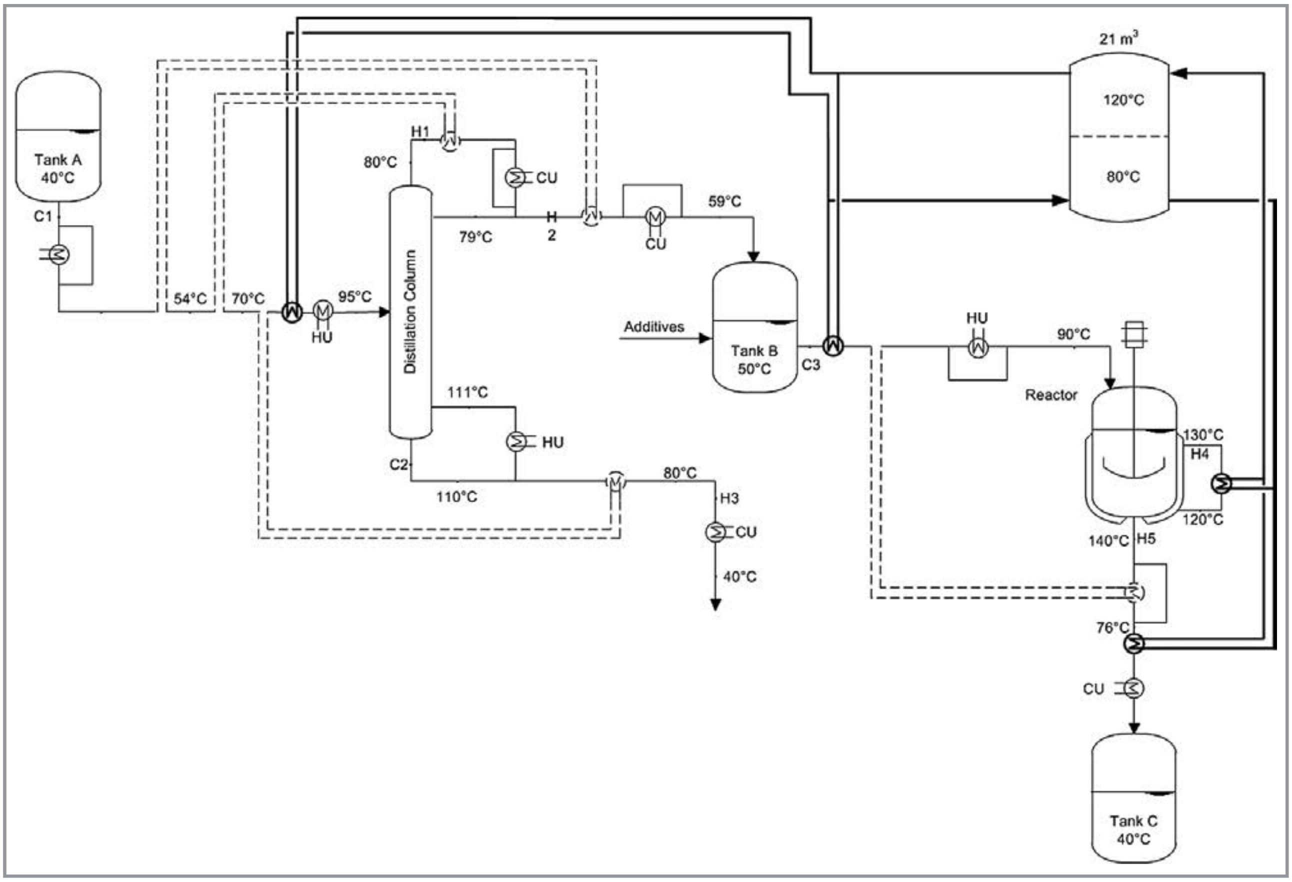


Figure 8. HESN schema for a stratified tank design with 1 MWh HR per SROP and the associated storage integration alongside the new DHR measures. The dashed lines show DHR measures and the bold lines show the IHR using a TES system.

5 Limitations

The most general limitation of the software comes from the chosen approach to problem solving: priority has been set to provide schedule-robust and practical design rather than cost-optimized design. To overcome this weakness, features have been implemented in order to support the user in the targeting and design procedure and to quickly assess the trade-offs between heat recovery and HESN complexity and costs. However, a general guidance and ways to track improvements is missing so far. The overall approach relies on the assessment of DHR opportunities by the user before applying the 100 % indirect HR assessment. Further supportive assessment tools could help the user to globally identify the potential for cascading in time and in temperature before proceeding to integration. Nevertheless, the methodology and methods are relatively easy to understand and ready to be used in practice.

The aim of the target and design procedure is to obtain a rough but strategic concept for direct and indirect recovery and therefore does not tackle challenges related to later stages of engineering. For instance, the storage is considered ideal and thermal losses, loss of stratification as well as inlet and outlet heat power limitations are not considered. Finally, the current methodology and implementation does not allow designing latent heat storages. Indeed, this would require further investigations, in particular considering power rate limitations which are typical for such systems.

6 Conclusions

Energy efficiency improvements in batch processes are a complex challenge given their time dependent behavior and need for TES. This paper presents a methodology based on pinch analysis principles to support the engineer in developing a cost-effective and practical TES design. The methods are primarily graphical and heuristic based which provides the benefit that they are easy to understand and ready to be used in practice. The engineer has a sound understanding of the reasons for the conceptual design and makes the decisions throughout the methodology. Validation of the methodology is presently ongoing through the application in real studies. It is planned to use the experience gained in these studies to provide the basis for improvement of the methodology and its application in the software PinCH. Finally, the methodology is not considered optimal given the very large number of parameters available. However, the designs are considered cost-effective, easy to understand, and practical. Future work would involve combining the methods with mathematical optimization techniques to help finding the true optimum.

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Abbreviations

DHR	direct heat recovery
FTVM	fixed-temperature variable-mass
HESN	heat exchanger and storage network
HR	heat recovery
IHR	indirect heat recovery
IL/HS	intermediate loop and heat storage
ISSP	indirect source/sink profile
SROP	stream repeat operation period
TAM	time average model
TES	thermal energy storage
TH	temperature enthalpy
VSU	volume storage unit

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