PinCH Tutorial 4

Welcome! The PinCH team of the Lucerne University of Applied Sciences and Arts offers tutorials for the PinCH software to present to you the possibilities of the software and how to use it. In five tutorials, you will learn the basics of using PinCH for energy and cost optimization in industrial processes:

PinCH Tutorial 0	Quick Overview
PinCH Tutorial 1	Continuous Production Plant
PinCH Tutorial 2	Production Plant with Multiple Operating Cases
PinCH Tutorial 3	Discontinuous Production Plant
PinCH Tutorial 4	**Integration of Thermal Energy Storage**

The tutorials are sequential. If you are using PinCH for the first time, we recommend that you start with Tutorial 0 entitled "Quick Overview".

The tutorials and the associated "finished" PinCH files can be downloaded from the website www.pinch-analyse.ch. The tutorials can be solved with the trial version of PinCH (full version, but limited to eight process streams). To obtain the trial version, please send an E-Mail to pinch@hslu.ch.

The tutorials are available in German, English and French. The labels in process flow charts and the names of processes, streams, etc., as well as software-related terms, are always kept in English. The used currency is Euro.

Energy and cost optimization with PinCH is carried out in 10 Steps. You will find an overview of the 10 Steps and a list of symbols and abbreviations in Tutorial 0.

The tutorials focus on using the PinCH software. It is assumed that you are familiar with the basic principles of the pinch analysis. We recommend the following books as an introduction or for a deeper insight into the pinch method:

- F. Brunner, P. Krummenacher: Einführung in die Prozessintegration mit der Pinch-Methode – Handbuch für die Analyse von kontinuierlichen Prozessen und Batch-Prozessen. Swiss Federal Office of Energy SFOE, 2017 (available from www.pinch-analyse.ch)

- R. Smith: Chemical Process Design and Integration. 2nd Edition, John Wiley & Sons, 2016; Pinch Analysis from Chapter 15 onwards (ISBN 9781119990130)

- I. C. Kemp: Pinch Analysis and Process Integration – A User Guide on Process Integration for the Efficient Use of Energy. 2nd Edition, Elsevier Butterworth-Heinemann, 2007 (ISBN 978-0-7506-8260-2)

You are currently working on PinCH Tutorial 4. It is about integrating thermal energy storage in a nutrient salt production plant. Tutorial 4 is structured as follows:

Contents

I Introduction to Tutorial 4

Learning objective:	To understand how thermal energy storage can be systematically integrated with PinCH.
Duration:	1-2 hours

Tutorial 4 is based on the results of Tutorial 3, i.e. it is assumed that you have worked through Tutorial 3. This tutorial, in turn, guides you through the pinch analysis one step at a time, and you will learn about the possibilities the software offers and how to use it. Follow the steps below to integrate thermal energy storage (Steps 7 and 9 are not required for this case study):

Figure 1: Sequence in PinCH for integrating thermal energy storage

The PinCH team of Lucerne University of Applied Sciences and Arts hopes you find this tutorial instructive and wishes you every success!

II Case Study: Chemical Process

Since this tutorial deals with the process from Tutorial 3, a detailed description of the plant is not provided. In particular, the scheduling and utilities are identical and are no longer listed. In this tutorial, we are integrating thermal energy storage. Reference is made at this point (see references on page 1) for the functioning of the storage (stratified storage and storage with a fixed temperature and variable mass) considered in PinCH.

Process Description

The nutrient salt production plant optimized for direct heat recovery (HR) in Tutorial 3 is dealt with further in this tutorial. Here, we are only considering the non-overlapping operating mode.
The additive in the C100 reactor is added to the B100 stirrer tank once the inorganic salt has dissolved in the water-based solvent. The solution is evaporated in the C100 reactor. The pure substance is extracted using cooling crystallization in the B102 crystallizer. The detailed process steps are described in Tutorial 3. The process optimized for direct HR is illustrated in Figure 2.

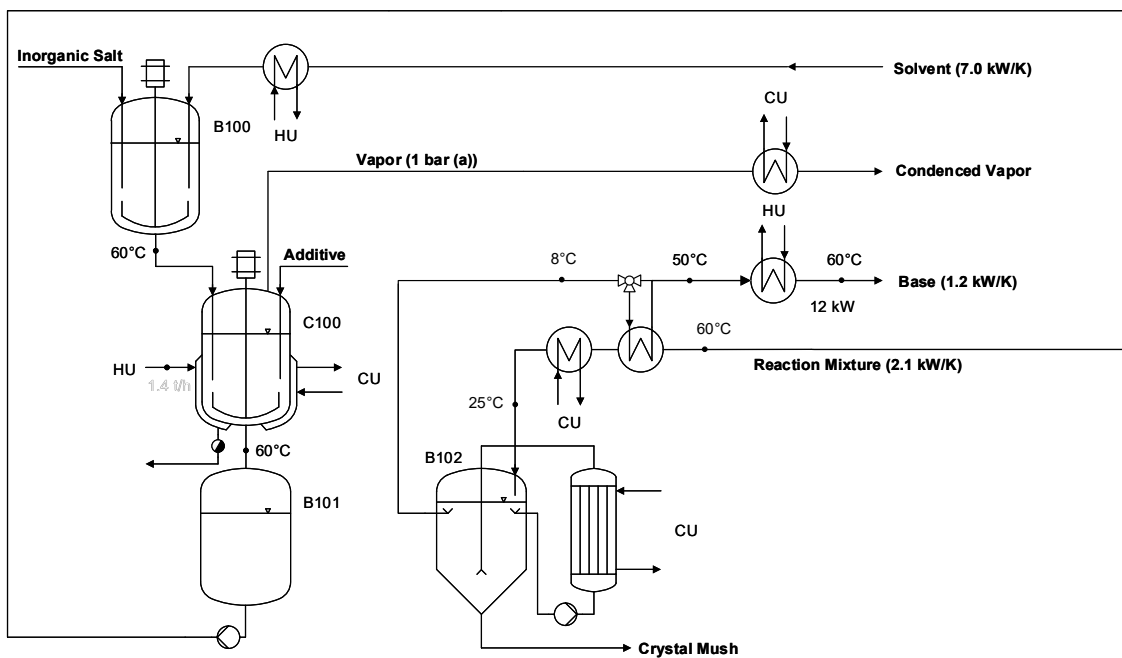Figure 2: Process flow chart of the production plant optimized for direct HR

Investment Costs

In this case study, the investment costs for the combined heat exchanger and storage network (HESN) must be taken into account. Since we are not taking any ECUs into account in this tutorial, the following applies:

$$C_{Inv} = C_{HESN} \qquad (1)$$

The costs for the HESN are made up of the costs for the heat storage (HS) C_{HS}, the storage medium (SM) C_{SM}, the heat exchangers (HEX) C_{HEX} and a fixed amount C_{IL} per intermediate loop (IL), which is independent of the storage capacity. The fixed amount per IL can be selected by the user in Step 8. You will find the process for setting up stratified storage with the terms used in Figure 11 in Step 8 on page 13.

$$C_{HESN} = \sum_{HS} \left(C_{HS} + C_{SM} + C_{IL} \right)_{HS} + \sum_{HEX} C_{HEX} \tag{2}$$

The costs for the heat exchangers are calculated as in Tutorial 1 based on the specific heat transfer area A:

$$\sum_{HEX} C_{HEX} = \sum_{HEX} \left(C_0 + C_b \cdot \left(\frac{A_{HEX}}{A_b} \right)^m \right) \tag{3}$$

whereas $C_0 = 0$, $C_b = 110'000 \text{€}$, $A_b = 100 \text{ m}^2$ and $m = 0.71$ (see Tutorial 1).

The costs for the HS and the SM are calculated as a function of the storage volume V or the mass of the storage medium m_{SM}:

$$C_{HS} = C_0 + C_b \cdot \left(\frac{V}{V_b} \right)^m \quad \text{bzw.} \quad C_{SM} = m_{SM} \cdot c_{SM} \tag{4}$$

In this case study, we are using the following values:

- HS basic costs (regardless of the storage volume): $C_0 = 0 \text{€}$

- Costs for reference HS: ($b = $ base): $C_b = 150'000 \text{€}$

- Volume of reference HS: $V_b = 100 \text{ m}^3$

- Degression exponent: $m = 0.71$

- Specific SM costs (water in this case): $c_{SM} = 0.001 \text{€}/\text{kg}$

The investment costs are the total costs for the installed and commissioned HESN.

Total Costs

During the pay-off period, i.e. once the direct HR measures have been implemented, the annual total costs C_{tot} [€/a] are $50'800 \text{€}/\text{a}$ as shown in Tutorial 3.

Problem

The company would like to examine the production plant optimized for direct HR from Tutorial 3 with regard to the indirect HR potential. It should be checked whether integrating thermal energy storage is reasonable. In this tutorial, we will show you how you can systematically and purposefully complete the analysis and optimization with the PinCH software.

Step 0: Define Process Requirements

The process requirements for indirect HR corresponds to the heating and cooling requirements which cannot be covered by direct HR. The process requirements for indirect HR of nutrient salt production in the non-overlapping operating case are shown in Figure 3 and specified in Table 1. We are now working directly with the heat capacity stream $CP = \dot{m} \cdot c_p$, because we are already familiar with the values from Tutorial 3. The Base process stream is heated from $8\,°C$ to $50\,°C$ using the direct HR from the Reaction Mixture process stream. But because the Base process stream is 30 minutes longer (for emptying the crystallizer) and heating from $8\,°C$ to $60\,°C$ must take place during this time, these two process requirements must be defined as one process stream.
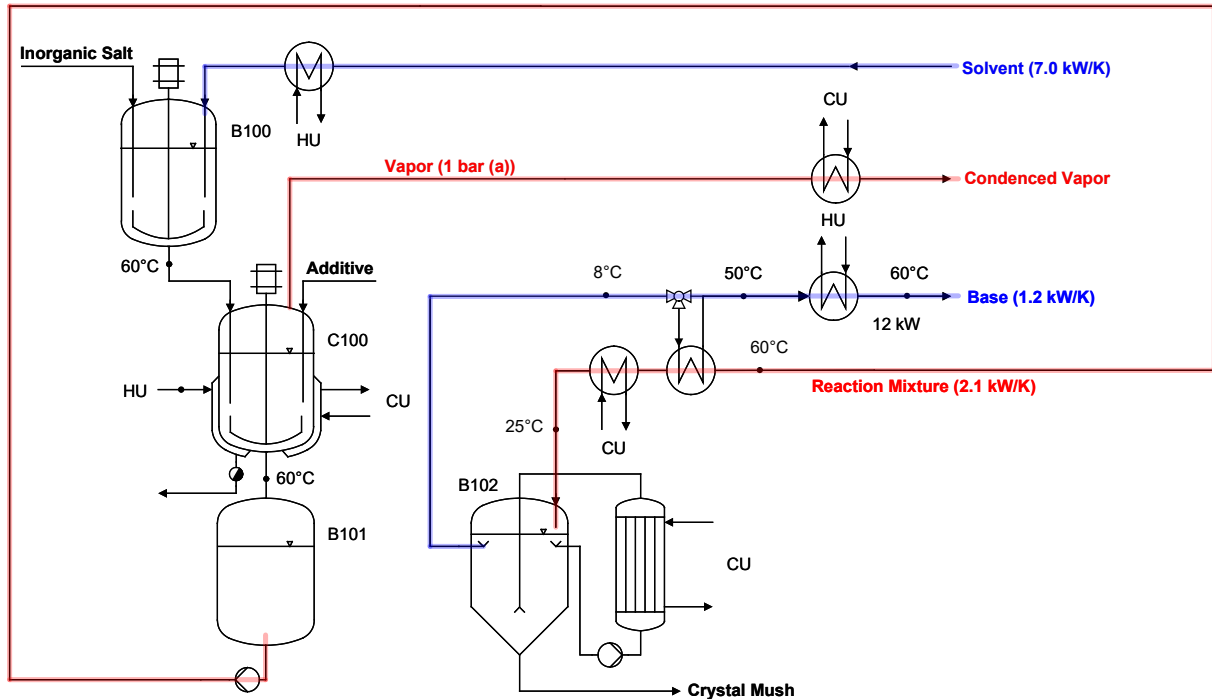

Figure 3: Process flow chart with process requirements

Table 1: Process requirements

Process requirement	T_{in} [°C]	T_{out} [°C]	CP [kW/K]	α [W/(m² K)]	t_{start} [h]	t_{stop} [h]
Solvent	20.0	80.0	7.00	2'000	0.0	1.0
Vapor	x=1	x=0	-*	4'000	2.5	4.5
Reaction Mixture	36.3	25.0	2.11	500	7.5	10.5
Base, TS3	50.0	60.0	1.19	500	7.5	10.5
Base), TS4	8.0	60.0	1.19	500	10.5	11.0

* Condensation at $p = 1$ bar(a)

III   10 Steps in PinCH

Let's get started!

To start, open PinCH. Before we start with the actual project, it is advisable to check and, if necessary, adjust the basic settings in PinCH. Because the costs are specified in euro in our tutorials, you may under certain circumstances have to adjust the currency settings before you start. The units kW and kWh are also used in this tutorial. An explanation of how to proceed is provided in Tutorial 0.

The tutorial follows the 10 PinCH Steps (cf. Tutorial 0). In Steps 1-5, the process-related data is recorded in the Project Explorer. In Steps 6-10, the plant is optimized in the Target Explorer. Create a new project and give it a suitable name.

Step 1: Enter Stream Data

Create a new project and rename it "Fine Chemistry AG". Enter the process requirements in the Process Stream Table. The complete Process Stream Table looks like this:

+/-	Name	Hot/Cold	Tin °C	Tout °C	ṁ kg/s	c_p kJ/(kg K)	Phase Change kJ/kg	α W/(m² K)	Pressure bar(a)	CP kW/K	ΔH kW	Fluid	Humidity Ratio In kg/kg	Soft	tstart h	tstop h
	Solvent		20	80	1.66667	4.2	-	2000	-	7	420	Simple	-	☐	0	1
	Vapor		x1	x0	0.2778	-	2257.08	4000	1	-	627.02	Water	-	☐	2.5	4.5
	Reaction Mixture		39.1	25	0.602	3.5	-	500	-	2.11	29.71	Simple	-	☐	7.5	10.5
	Base, TS3		45	60	0.397	3	-	500	-	1.19	17.87	Simple	-	☐	7.5	10.5
	Base, TS4		8	60	0.397	3	-	500	-	1.19	61.93	Simple	-	☐	10.5	11

Figure 4: Process Stream Table

In a second step, the available utilities (heating and cooling media) must be defined.
Fill out the Utility Stream Table according to the data from Tutorial 3. The finished Utility Stream Table looks like this:

+/-	Name	Hot/Cold	Tin °C	Tout °C	c_p kJ/(kg K)	Phase Change kJ/kg	α W/(m² K)	Pressure bar(a)	Utility Cost EUR/kWh	Fluid	Humidity Ratio In kg/kg
	Heating Steam (HU)		x1	x0	-	2181.27	5000	2.5	0.080	Water	-
	Cooling Water (CU)		8	14	4.1884	-	2000	1	0.030	Water	-

Figure 5: Utility Stream Table

Step 2: Configure Equipment

Consult Tutorial 3 to define the equipment. The now-split Base process stream requires shared equipment (cf. Tutorial 2). The following affiliation results:

- Solvent → B100
- Vapor → C100
- Reaction Mixture → B101
- Base, TS3 & Base, TS4 → B102 (shared)

Step 3: Define Processes

Delete the predefined process, "Process 1", under Base Case and create a batch process. Proceed as follows to do this:

☞ Right-click on "Process 1" in the Project Explorer

☞ Select Remove Process

☞ Right-click on "Processes"

☞ Select Add Batch Process

Now rename the batch process "Nutrient Salt Production" and assign all the defined process requirements to it.

Step 4: Apply Scheduling to Processes

Schedules are required to define the scheduling of the processes defined in Step 3. If there are multiple processes, at least some of which run in parallel, operating cases may occur during which heat transfer is possible between the processes.

Create the Non-Overlapping operating case in the same way as Tutorial 3. Proceed as follows:

☞ Select "Batch Daily" in the Timebase column

☞ Select Mo – Sa as the operating days

☞ Adjust the Daytime Start: 00:00

☞ CW Start: Enter 1

☞ # Weeks: Enter 48

☞ Batch Cycle Duration (BCD): Enter 11 h

☞ # batches: Enter 2

The Equipment-Wise Repeated Operation Period Gantt (EROP Gantt) chart for the process is shown in Figure 6. It is clear that the Vapor and Solvent streams do not take place at the same time. Indirect HR potential *could* exist here. We will examine this more closely in Step 8.
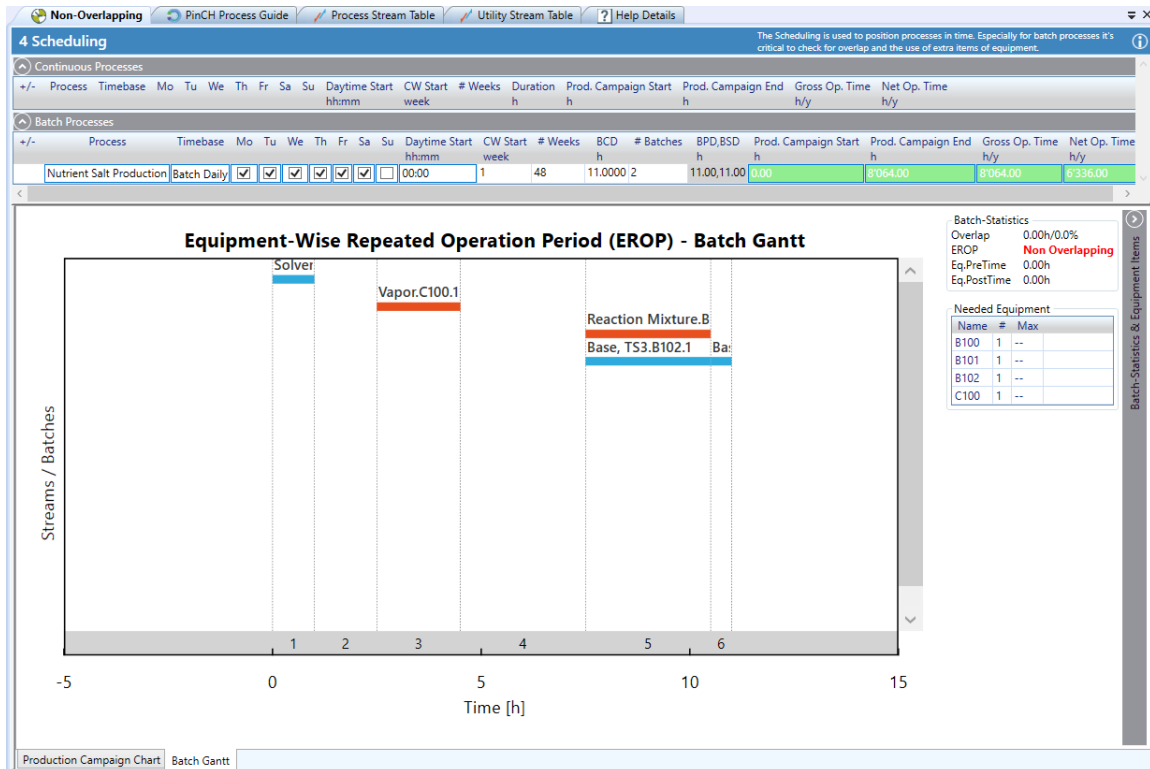
Figure 6: EROP of the non-overlapping batch process

Step 5: Set Economic Data

The economic parameters need to be specified to calculate the investment costs. In PinCH, the investment costs for the heat exchangers and the storage systems are calculated to meet the process requirements. These include heat exchangers between process streams (heat recovery), heat exchangers between one process stream and utilities, and the storage system's heat exchanger.

Under Storage: Media Costs and Media Properties, costs and substance data are defined for the storage media. You can adjust them or define your own storage media. Two storage media, water and heat transfer oil, are predefined in this regard. In our case study, we are considering stratified storage with water as the storage medium and are using the cost parameters defined in the section entitled "Investment Costs" on page 3.

Open the Economic Data tab and adjust the parameters according to the specifications. Because the plant already exists, the investment costs for the utility heat exchangers can be set to zero.

The complete data record includes the following values:

5 Economic Data

The economic Data data is used throughout the software PinCH for calculating the main costs associated with an heat exchanger network

Heat Exchanger Costs ⓘ

$C = C_0 + C_b (A/A_b)^m$

A = Heat Exchanger Area in m²

Type	Fixed Cost C_0 EUR	Base Cost C_b EUR	Base Area A_b m²	Exponent m
Process Heat Exchanger	0	110'000.0	100	0.71
Hot Utility Heat Exchanger	0	0.0	100	0.71
Cold Utility Heat Exchanger	0	0.0	100	0.71
ISSP Heat Exchanger	0	110'000.0	100	0.71

Storage: Tank Costs ⓘ

$C = C_0 + C_b (V/V_b)^m$

V = Tank Volume in m³

Storage	Fixed Cost C_0 EUR	Base Cost C_b EUR	Base Volume V_b m³	Exponent m	Storage Type
FTVM	0	150'000.0	100	0.71	FTVM
Stratified	0	150'000.0	100	0.71	Stratified

Storage: Media Costs and Media Properties

$C = C_b * m_{sm}$

m_{sm} = Mass of Storage Media in kg

Media	Base Cost C_b EUR/kg	Density kg/m³	α W/(m² K)	c_p kJ/(kg K)
Water	0.0010	1000	2000	4.18789
Heat Transfer Oil	5.0000	800	1000	2.00000

Amortisation Parameters ⓘ

Pay Off Period	5	y	Independent	0	EUR
Interest Rate	6	%	Personnel	0	%/y Investment Costs
Annuity	0.237	1/y	Maintenance	0	%/y Investment Costs

Electricity ⓘ

Note: Utility Costs are set on Utility Stream Table   Electricity Cost   0.134   EUR/kWh   Electric Power   0   kW

Figure 7: Economic Data

Your Project Explorer is now structured as follows:

Figure 8: Project Explorer

Step 6: Prepare Targeting Calculations

Once Steps 1-5 have been processed, all of the data required for the pinch analysis is stored in the Project Explorer. You can calculate the energy and cost targets by creating a target group in the Target Explorer. Your Target Explorer should now be structured as follows:
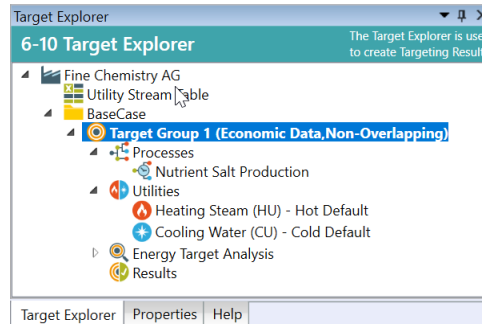

Figure 9: Target Explorer

If you have problems creating the target group, please consult Tutorial 1: In Step 6, the process is described one step at a time.

Step 7: Analyze Energy Targets

In Tutorial 3, a detailed analysis of the energy targets for direct and indirect HR was performed. The identified indirect HR potential can now be analyzed more closely in Step 8.

Step 8: Calculate Energy & Cost Targets

One key aspect of the pinch analysis is the calculation of energy and cost targets before the (otherwise often subjectively influenced) examination of individual HR measures. Since the direct HR potential was identified and developed in Tutorial 3, we will deal with the indirect HR in Step 8 of this tutorial. The targeting for indirect HR serves the purpose of systematically integrating thermal energy storage. First of all, we will use the Indirect Source and Sink Profile (ISSP) to select the streams to be considered and identify the HR potential. We will then specify the storage more precisely and consider its cost-effectiveness.

Start targeting for "Target Group 1":

☞ Right-click on Results

☞ Calculate Target Result with... ☞ Select Indirect Heat Recovery

In the new window, shown in Figure 10, the ISSP, which indicates the indirect HR potential of nutrient salt production, can be found on the left-hand side

Additional information: Targeting for indirect HR is carried out based on the ISSP. The ISSP is based on the Time Average Model (TAM), but assesses the stream's relevance for indirect HR. The duration and heat transfer coefficient α of each stream are incorporated into this weighting. The longer a stream exists and the higher its α value, the higher its relevance for indirect HR. For more specific background information about the ISSP see references on page 1.

The red and blue curves describe the heating and cooling requirements. They are shifted in terms of temperatures according to the relevance for indirect HR (see references on page 1). The black curve in between describes stratified storage, whereby the blue dot represents the cold layer and the red dot represents the warm layer. In the tables below, you will find the sources and sinks which can be indirectly coupled using the storage. They can be selected and deselected by checking and unchecking the box in front of the respective streams.
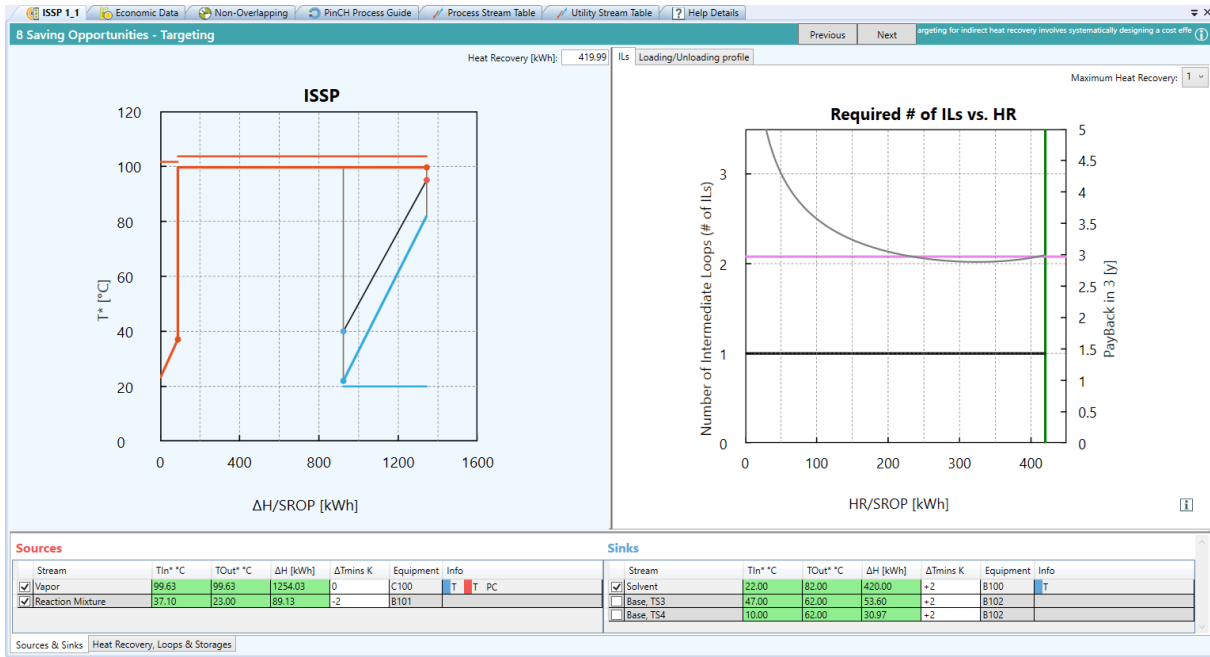

Figure 10: ISSP

> **Note:** Under "View sources and sinks" in the Properties tab (in the Target Explorer), you can show and hide inactive streams, and also visualize the individual streams in the ISSP with "Show streams in chart". Selecting this option causes horizontal lines, which illustrate the enthalpy range of the respective stream, to appear in the ISSP. Clicking on one of these lines also shows its temperature range.
>
> Under Storage, you can specify the storage. Stratified storage with water as the storage medium is defined as the default. The storage media defined in Economic Data can be selected here. You can also define a safety coefficient for the storage volume.

Additional information:

Before we start selecting the streams for indirect HR, we would like to discuss the relevant properties of stratified storage (SS). In Figure 11, general SS with three layers is shown. Hot streams are used for loading, and cold streams for unloading. The storage medium is pumped from one layer to another via an IL and, during this process, heated or cooled in the HEX intermediate loop. The temperatures of the layers should be selected so that the process streams are brought to the desired outlet temperatures and the layer temperatures are complied with. The inlet temperature of the cold streams is limited to the bottom layer temperature, while that of the hot streams is limited to the top layer temperature.

Because SS is sensitive heat storage, the difference between the layer temperatures is crucially significant for the storage capacity. If the difference between the layer temperatures can be increased by selecting

the "right" sources and sinks, this enables storage of the same amount of energy in a smaller storage unit.
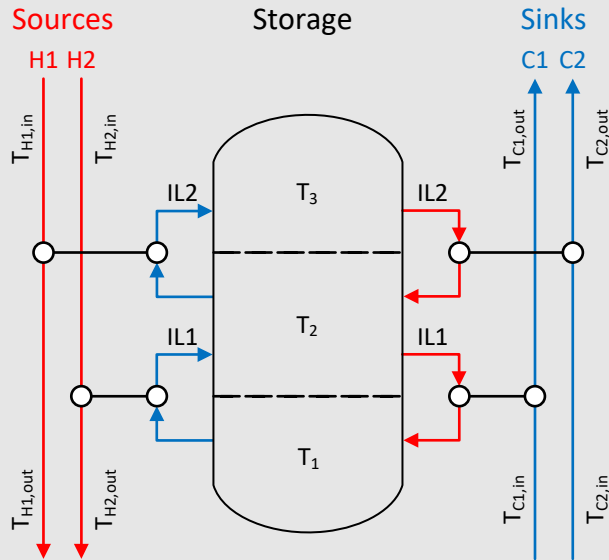

Figure 11: General stratified storage with three layers, two ILs with two sources (hot streams, H1 and H2) and sinks (cold streams, C1 and C2) each

Since the "Base, TS3" stream (cold stream) can only be cooled to $47\,°\text{C}$ at most with the shifted inlet temperature $T_{in}^* = 47\,°\text{C}$ compared to the other two streams of the storage IL, it would significantly limit the lower temperature in the case of stratified storage with two layers. This would lead to a far bigger storage unit having to be installed for the same storage capacity. This is why we are deselecting the "Base, TS3" stream, in consideration of the small amount of heat (approx. $54\,\text{kWh}$). Without this stream, the bottom layer can now be theoretically reduced to $22\,°\text{C}$. To reduce another IL, in consideration of the small amount of heat (approx. $31\,\text{kWh}$) we are also deselecting the "Base, TS4" stream. Above the ISSP, you can specify how much HR the storage should cover under Heat Recovery. In our case, we are choosing $420\,\text{kWh}$, which corresponds to the total heat requirement of the "Solvent" stream.

☞ Click in the checkbox in front of the "Base, TS3" stream.

☞ Click in the checkbox in front of the "Base, TS4" stream.

To integrate the storage, click on Next above the "Required # of ILs vs. HR" graphs.
Two new graphs and new tables now appear (Figure 12). The loading / unloading profile now shows the volume of the layers over time. You can now set the temperatures of the two layers in the "Specification" table.

☞ Select the following: for $T_{low} = 40\,°\text{C}$ and for $T_{high} = 95\,°\text{C}$.

The required storage volume, the associated mass, the number of heat exchangers required and the total heat exchanger area required are specified on the right-hand side of the table.
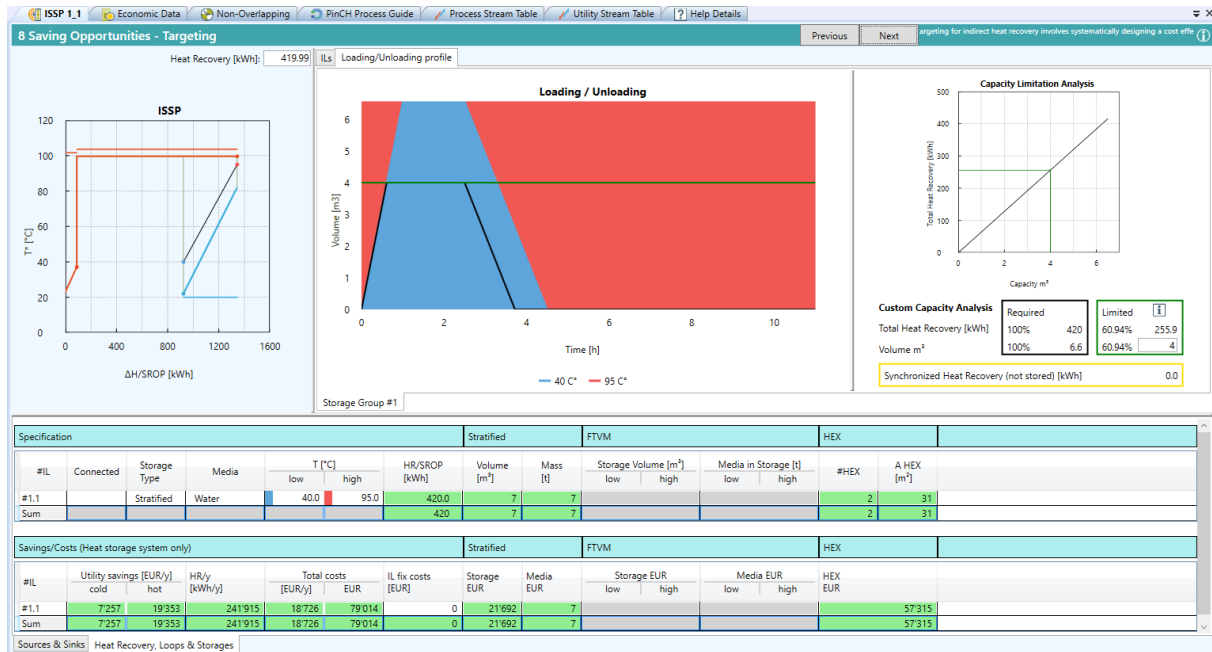
Figure 12: ISSP, loading / unloading profile and capacity limitation graph

> **Note:** The capacity limitation analysis can be used to calculate how much HR is possible with storage with a limited volume. Below the graph, you can define the storage volume and obtain the possible HR as a percentage value and in absolute terms in kilowatt hours. In the loading / unloading profile, the limited storage is now illustrated with the green line and the black curve. These curves can be shown and hidden in Properties, using the "Draw capacity limitation" item under Storage. As illustrated in Figure 12, in our case 61% of the HR potential can be used with a $4\,\mathrm{m}^3$ storage unit. Because, in our case study, the storage is only loaded and unloaded once, the capacity limitation analysis graph only represents one straight line. If the storage were to load or unload multiple times per SROP, more cost-effective storage could be found using the capacity limitation analysis.

The utility savings and the investment costs are specified in the "Savings / Costs" table. $241'900\,\mathrm{kWh/a}$ can therefore be saved with the integrated stratified storage. This causes the annual operating costs to drop by $26'600\,\text{€}/\mathrm{a}$, whereby the investments for the storage incl. heat exchangers amount to $79'000\,\text{€}$.

Step 9: Integrate Energy Conversion Units (ECUs)

In many industrial processes, the heating and cooling requirements are large despite HR. In these cases, it is worthwhile reviewing the integration of an ECU. On the one hand, an ECU can be a heat engine whose waste heat is used in the process and therefore replaces HU. In most cases, the heat engine's mechanical energy is converted to electrical energy in a generator (e.g. combined heat and power plant, CHPP or Organic Rankine Cycle, ORC). On the other hand, an ECU can also be a heat pump which raises heat to a higher temperature level using electrical energy. The higher-value heat is, in turn, used to replace HU.

The pinch analysis is an excellent tool for analyzing the integration of an ECU. To optimize (and therefore reduce the costs of) the utilities, the correct integration of a heat pump, a mechanical or thermal base compressor, an ORC plant and a CHPP can be carried out in PinCH.

Step 10: Design Heat Exchanger Network (HEN)

Congratulations! You have successfully completed targeting as the basis of energy and cost optimization of the process. Now another important question needs to be answered: *How should the energy and cost targets be implemented in practice?* You can create a HESN using PinCH. The HESN is less complex than a typical process flow chart, but it shows which process streams should be connected to heat exchangers with the storage and in what order. A plant design can be developed based on this principle. Because the streams to be taken into account and the storage temperatures are selected in Targeting, a HESN does not have to be set up like a conventional HEN. The information in Targeting defines all the couplings and the HESN can therefore only be displayed.

To create a HESN, enter the Target Explorer, right-click "ISSP 1_1" and select Show HESN Schema. By selecting "Show streams outside heat recovery" in the HESN properties, you can also show streams which are not coupled to the storage (Reaction Mixture and Base). You can also show the mass flows of intermediate loops with "Show mass flow on intermediate loop branch". The HESN is illustrated for storage integration in Figure 13.
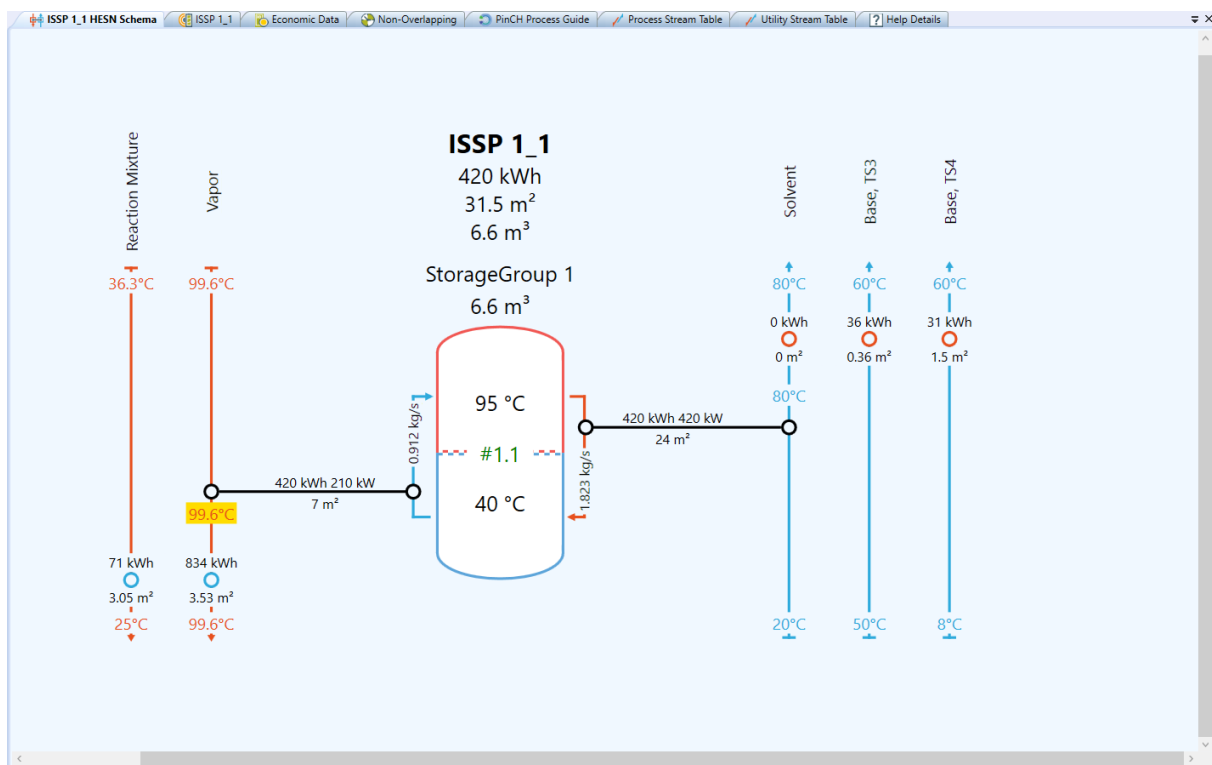

Figure 13: HESN of the optimized process

IV Optimized Process

In Tutorial 3, the nutrient salt production process flow chart is illustrated for each individual TS. We are now transferring the HESN to the process flow chart. The process streams which are covered by indirect HR are colored. The hot stream (Vapor) does not occur at the same time as the cold stream (Solvent). The process flow chart with the integrated storage is illustrated in Figure 14.
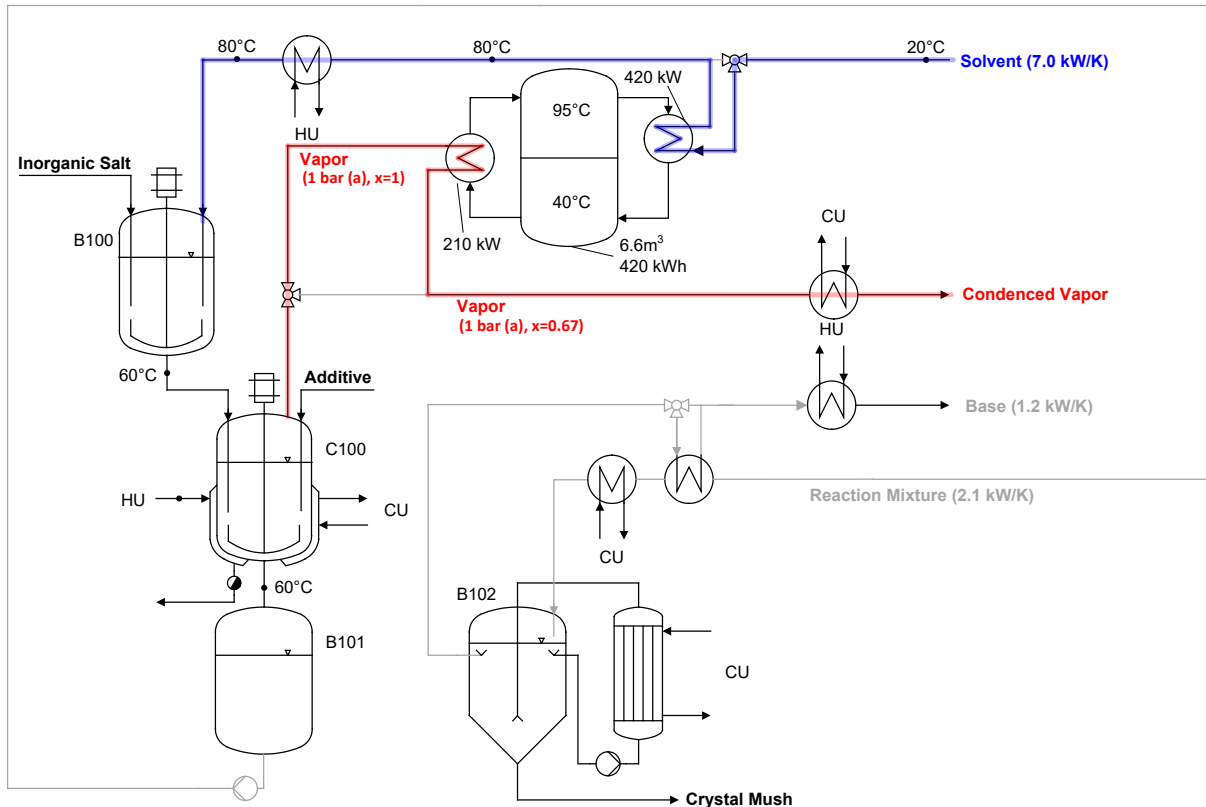

Figure 14: Nutrient salt production process flow chart with integrated thermal energy storage

The necessary utilities can be reduced by integrating the storage. The installed storage system incurs investment costs of 79'000 €. These are depreciated over five years and therefore annual investment costs of 18'700 € are incurred. The costs and the energy requirement for the process are listed in Table 2. It is clear that the operating costs can be reduced by 64 % by means of direct and indirect HR. The annual total costs therefore drop by 22 % during the first five years. After the five years, the investment is depreciated and the total costs then correspond to the operating costs. 235'000 € can be saved over a period of ten years with this measure.

Table 2: Comparison of the existing and optimized plant with and without indirect HR

	HU	CU	Operating costs	Annual inv. costs	Annual total costs
	[MWh/a]	[MWh/a]	[€/a]	[€/a]	[€/a]
Starting situation	367	850	54'858	0	54'858
Direct HR	291	774	46'459	4'333	50'792
Direct and indirect HR	50	532	19'849	23'059	42'908
Saving	318	318	35'009	-23'059	11'950

Thank you for your time!

You are now familiar with the most elementary steps of using PinCH to perform a pinch analysis for a batch process with integrated thermal energy storage. Please don't hesitate to contact us if you have any questions. The PinCH team of the Lucerne University of Applied Sciences and Arts and the Centre de Compétence PinCH Francophone of the School of Management and Engineering Vaud are available at your convenience. Please also note the option of coaching to assist with and ensure the quality of your pitch analyses. Learning by doing in this way has already proved to be an excellent experience on multiple occasions. In any case, we hope you have lots of fun and wish you every success with PinCH. Thank you so much for taking the time to join us! For more information, please visit our website, www.pinch-analyse.ch. You will find our contact details below.

Kind regards,
the PinCH team of Lucerne University of Applied Sciences and Arts

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