Integration of Heat Pumps in Industrial Processes with Pinch Analysis

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Abstract

The industrial sector consumes a considerable amount of energy. In many countries it is 20% or more of the total energy use of which a major proportion is used solely for heating leading to the need to improve thermal energy efficiency. Process integration methods involving thermal systems such as pinch analysis provide ways to reduce energy use and environmental emissions in the process industry. Using pinch analysis it can be systematically shown how the heating and cooling demands of a process should be matched in order to improve heat recovery based on an economic optimum between investment and operating costs. An additional measure to help reduce energy needs is to use a heat pump. However, the integration of heat pumps in industrial processes is a challenge as it is difficult to choose which parts of the process should be connected to the heat pump. Pinch analysis provides a convenient rule to help meet this challenge: A properly integrated heat pump works across the pinch point, *i.e.* a heat pump takes heat from below the pinch point, where there is an excess, converts it to a higher quality and transfers it across the pinch point where there is a heat deficit. The aim of this paper is to present the methodology of how to properly integrate a heat pump using pinch analysis and to apply the methodology to an industrial case study. With the correct integration of the heat pump it is shown how the overall process energy efficiency can be significantly increased though the reduction in the hot and cold utilities resulting in lower energy costs.

Keywords: heat pump integration; industrial processes; pinch analysis; heat recovery; grand composite curve

1. Introduction

Energy use within the industrial sector can constitute a significant portion of a countries total energy requirements. In many cases, the percentage is 20% or more of which more than half is used to meet the need for process heating (*e.g.* US 25% [1]). Industrial companies are continually under pressure to achieve maximum economic benefit from their processing operations, but also need to consume less energy as well as produce fewer emissions. Rising energy prices and carbon/energy taxes invariably lead to higher operating costs and the necessity of increasing energy efficiency to remain competitive [2].

In order to improve energy efficiency in industry, process integration techniques are used for integrated process optimization. Pinch analysis [3] has arisen as an important and popular method of process integration often used in the praxis. It is based on the fact that the thermal energy for heating and cooling of material flows within a process often consumes a substantial share of the total energy demand. Therefore, in-process heat

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recovery becomes central for increasing energy efficiency. This is exactly the focal point of pinch analysis: it helps, under the objective of minimal costs, to determine the optimum set of connected streams used in heat recovery. To do this, pinch analysis is based on the natural cascade of thermal energy from high temperature to low temperature and differentiates, at a pinch point, two thermodynamically independent zones where no heat transfer between should occur. An optimal set of connections between different hot and cold streams can then be determined for the whole system to achieve maximum heat recovery at minimum cost.

Heat pumps (HPs) are increasingly being used in industrial processes to improve overall energy efficiency by the reduction of hot and cold utilities [4-5]. However, experiences from different pinch analyses show that the proper and optimal integration of a heat pump is a challenge [2]. The main question to be answered is which streams to connect to the heat pump. In the praxis examples can be found of heat pumps that were not correctly integrated and were either unable to achieve increased overall process energy efficiency or were not cost effective. The poor selection of streams to connect to the heat pump can, depending on the circumstances, result in an increase in the utilities and operating cost.

This paper presents the methodology to integrate a heat pump based on a case study from the process industries using pinch analysis. The method was first presented by Townsend and Linnhoff [6] and later in practical application such as in [7]. Further work identified the need to address the larger optimization problem to include determination of heat pump type, size and heat source and sink temperatures. As a result, a relatively straightforward optimization methodology based on the composite curves [8] was developed and extended to include the grand composite curve [9]. Latest research has developed methods to optimize simultaneously multiple combinations of heat engines and heat pumps together with the energy conversion and utility system of the process [5] or extending to include the total site in the optimization [10].

Notwithstanding this work done in area of global optimization of industrial heat pump integration, the approach in this study has been to focus on the relatively simpler method of optimizing heat recovery first before integrating the heat pump [6][9]. This approach ensures that the total energy demand is reduced and enables a rapid assessment of the opportunity for using a heat pump. The method is considered in this publication to provide a solution to be near optimum for the retrofit constraints imposed by the given medium sized industrial case study presented. The goal of this paper is to re-enforce the basic principles of integrating a heat pump into an industrial process and demonstrate the analysis using a case study.

2. Fundamentals

The clear advantage of pinch analysis [3] is the systematic approach of how the user is guided through the process optimization: Targets before design – the energy and cost targets are determined before designing the process equipment configuration. This basic idea is prevalent throughout the whole concept of pinch analysis with the starting point of **defining the needed heating and cooling requirements** based on a deep process understanding from an energetic perspective. This is the foundation for the pinch analysis and must be completed by extracting stream data from process flow diagrams and operating documents, process simulation, plant measurement data, etc. It is a crucial task and not to be underestimated in importance and effort [11].

The main graphic in pinch analysis is the composite curves as shown on the left in Fig. 1. On this graphic both a cooling profile (in red) and a heating profile (in blue) based on the process requirements are drawn together on a temperature versus heat flow diagram. The two profiles can be shifted horizontally relative to each other in heat flow and the amount of overlap gives the heat recovery potential. A pinch occurs where the two curves come closest to each other defining a temperature difference (ΔT_{min}) between the two curves. An economic optimum ΔT_{min} value can be selected based on the tradeoff between investment and operating costs based on the information in the composite curve. The right graph on Fig. 1 shows the resulting total cost curve that can be determined as the ΔT_{min} is changed by shifting the curves from a maximum to a minimum in heat recovery. In addition, the pinch separates the profiles into two independent regions based on temperature above and below this point where there is, respectively, a heat deficit and heat surplus. Three main rules [3] in pinch analysis are identified: i) only hot utility is needed above the pinch, ii) only cold utility is needed below the pinch and iii) no heat transfer from hot streams above the pinch to cold streams below the pinch is allowed.

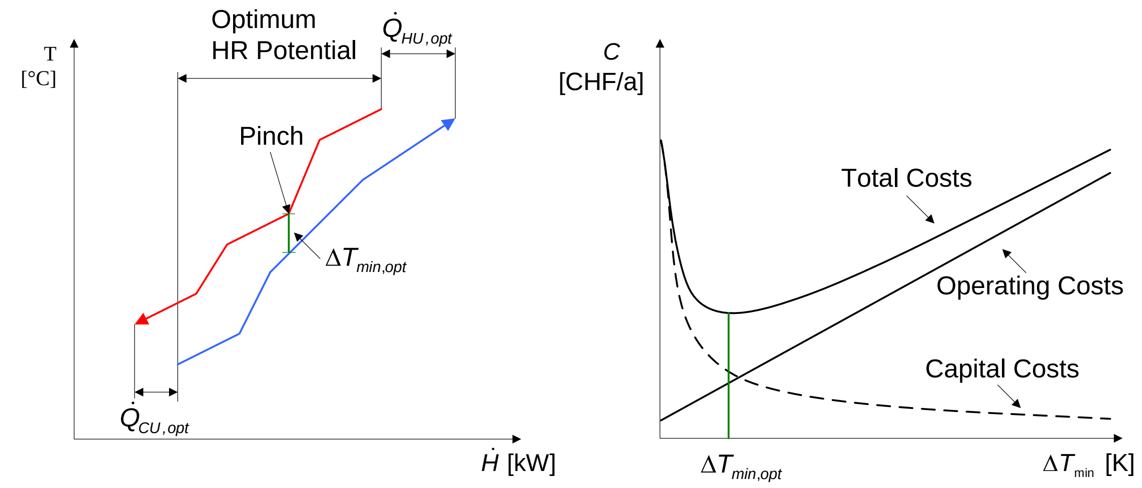

Fig. 1: *Left*: Composite curves showing the pinch point, the related heat recovery as well as cold and hot utility energy targets. *Right*: cost curve showing the trade-off between operating cost and capital cost used in determining an optimum ΔT_{min}.

Using these rules the applicability and benefit of heat pump integration can be evaluated. Townsend and Linnhoff [6] first documented the procedure and distinguished between incorrect and correct placement of heat pumps relative to the pinch point. Fig. 2 illustrates the two options when incorrectly placing a heat pump. The left figure shows the placement below the pinch temperature resulting in an increase in cold utility. Becker [5] called this simply an electrical heater to the environment, clearly the worst case scenario. The figure on the right shows the heat pump acting as an electrical heater to the process [5] that is likely not the most economical approach for reducing the hot utility requirement of the process. Generally, the integration of a heat pump into an industrial process is properly done when it takes waste heat from below the pinch-point (where a heat excess exists), transform it to a higher temperature level and the supplies it back into the process above the pinch-point (where a heat deficit exists) [6]. This approach is still consistent with the third main rule noted above since heat is transferred from below to above the pinch point (not vice versa).

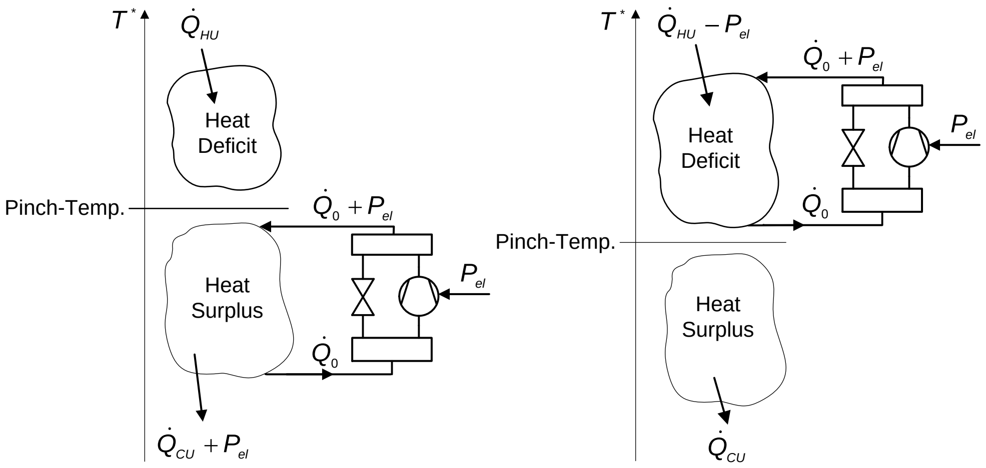

Fig. 2: Inappropriate placement of a heat pump relative to the pinch temperature. *Left*: heat pump is below the pinch point resulting in only an increase in cold utility; *Right*: heat pump is above the pinch point resulting in the direct use of electrical energy to reduce the hot utility.

Fig. 3 graphically illustrates the proper placement of a heat pump. The left diagram illustrates how a heat pump works relative to the grouping of process streams above and below the optimum pinch temperature. It is placed across the pinch temperature taking energy from the region where there is an excess of heat to a region where there is a deficit.

A convenient way to assess the applicability of a heat pump as well as to dimension its size is to use the grand composite curve (GCC) as shown in Fig. 3 on the right. In terms of heat recovery, the GCC graphically represents the feasible cascade of net heat flow needed at specific temperature intervals shifted for a given ΔT_{min} in order to ensure a necessary temperature driving force in the heat transfer process [9]. The process/utility interface is highlighted and helps the designer select between different utility sources and sinks. Conveniently, the curve also shows the applicability of integrating a heat pump which must be of the form to ensure the temperature lift of the heat pump is not excessive for the given reduction in both hot and cold utility. The temperature of the evaporator and condenser as well as the heat flow transferred in each can be directly read from the graphic with the condenser heat flow consisting of the upgraded thermal energy plus the electrical energy needed $(\dot{Q}_o + P_{el})$.

It is critical to note that the GCC is based on the understanding that the necessary heat recovery measures are implemented in order to meet the energy targets defined by the optimum ΔT_{min}. Wallin *et al.* [9] noted that these two common energy efficiency measures (heat recovery heat exchangers or a heat pump) should be seen as a better solution when combined as opposed to the two acting alone. If the heat pump is integrated alone without considering the heat recovery measures then the given design is not at the optimum given by the pinch analysis leading also to the poor selection of the stream connection points.

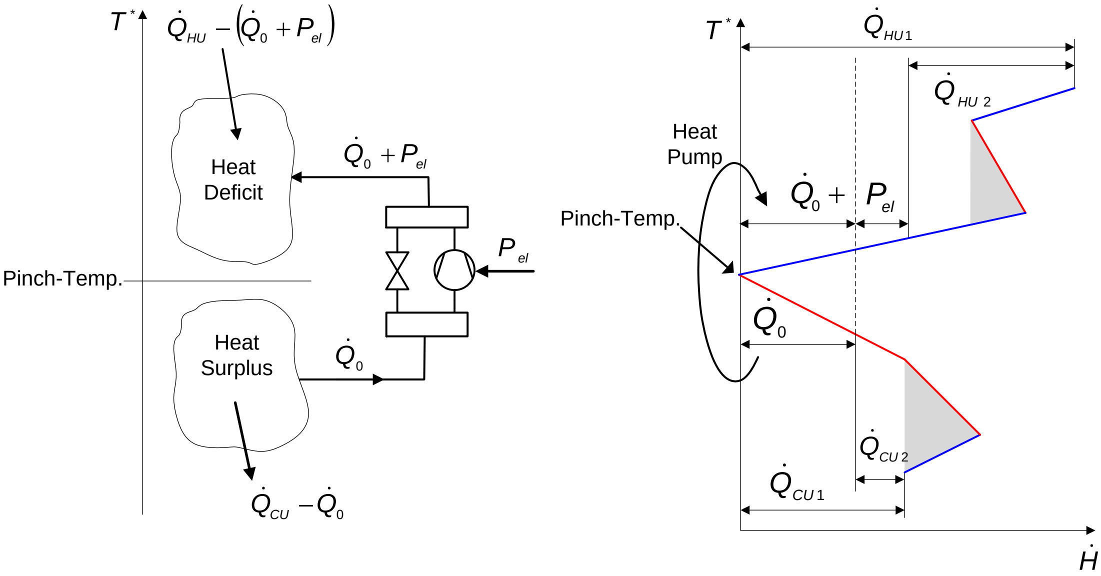

Fig. 3: *Left*: Appropriate placement of a heat pump relative to the pinch temperature. *Right*: Corresponding GCC visualization for the integration of a heat pump showing the associated heat flows and electrical energy.

3. Food Industry Case Study - Candy Production

The investigated production site used for this case study manufactures sweet candy for the European market food and beverage industry. For the present paper, the case study has been slightly simplified to focus on the main areas that use thermal energy in order to reduce complexity. The main areas of the site are as follows:

- Fruit Candy Production
- Hard Candy Production
- Utility Systems

Both the fruit and hard candy processes are similar requiring the use of common mixing, boiling, casting, drying and final product treatment steps. The utility systems at the site consists of steam, hot water and warm water circuits prepared using steam purchased from a local waste treatment burner facility. The utilities are used to provide energy to the fruit candy and hard candy production processes as well as to the building air handling and the domestic hot water systems.

3.1. Process Requirements

As noted in the section 2, a key step in a pinch analysis is data extraction. In this case study a mass, component and energy balance was completed using data gathered from process diagrams, the process monitoring system and a measurement program held directly on site. Based on the determined balances, the following heating and cooling process requirements were extracted as shown in table 1. As often the case for food and drink processes, the heating and cooling requirements are dominated by air and water/steam streams.

Table 1: Process Stream Table summarizing all process requirements (S Summer, TP Transition Period, W Winter).

Process Stream	Process period	Inlet T. [°C]	Outlet T. [°C]	$\alpha\left[\frac{W}{m^2K}\right]$	$\dot{Q}\,[kW]$
Vapor 0.5 bar	All year	x1	x0	5000	90
Exhaust Air	All year	55	25	50; 100	73
Vapor 1 bar	All year	x1	x0	5000	90
CIP Water	All year	15	65	1000	125
Waste Water	All year	40	20	1000	50
Drying Air	S	20	64	50	100
	TP	12	41	50	56
	W	5	64	50	100
Warm Water	S	55	70	1000	340
	TP	55	70	1000	154
	W	55	70	1000	200
Hot Water 3 bar	All year	90	105	1000	90
Recooling Water	S	40	32	1000	700
	TP	40	32	1000	200
	W	40	32	1000	120

In the fruit candy production a vapor stream is produced during cooking of the gelatin mass. A humid air stream is also produced as it leaves the dryer preparing the casting forms (it is assumed that the heat transfer coefficient α increases from 50 to 100 W/m^{2}K when cooling the exhaust air down to its dew point). For drying the candies themselves, circulating room air must be dehumidified in an adsorption process that uses for regeneration hot drying air that is prepared by heating outside air. During hard candy production vapor is also produced during the cooking process and hot water must be prepared for heating purposes. For both processes CIP water is needed and after final use it is collected in the company's waste water system. In the summer period (S) there is a high warm water demand since cold fresh air, previously cooled down for dehumidification, must be heated to room temperature. The warm water demand is lower during spring and autumn (transition period, TP) and increases again during the winter period (W) since it also includes the domestic hot water heating demand. Recooling Water from an ammonia based chiller, presently cooled in contact with ambient air, is also included as a potential heat source.

3.2. Schedule and Operating Cases

The schedule and the operating cases for the investigated case study are shown Fig. 4. The pinch analysis is based on the assumption of continuous production of fruit candy over 6000 h per year. Any non-process operational time that occurs on weekends was eliminated to make the management of the operating cases (OCs) more straightforward for energy targeting [11]. Variations in process stream parameters caused by seasonal changes in the heating and cooling requirements are considered by defining a summer, transition and winter period. For example, the energy need for preparing the warm water varies as it represents not only process heat requirements but also energy needs for building air handling and domestic hot water heating. The seasonal variability of the streams is indicated by the color transitions from dark to light grey. Temporal overlapping of the processes fruit candy and hard candy production were investigated as it can affect the overall heat recovery potential. In each seasonal period two operating cases have to be considered. In this case study, there are three personnel work shifts for fruit candy production and one work shift for the production of hard candy that results in an overlapping of these processes on a daily basis. The overlapping and non-overlapping times have been summarized over a seasonal period for simplification. In total six operating cases are identified and used in the pinch analysis energy and cost targeting.

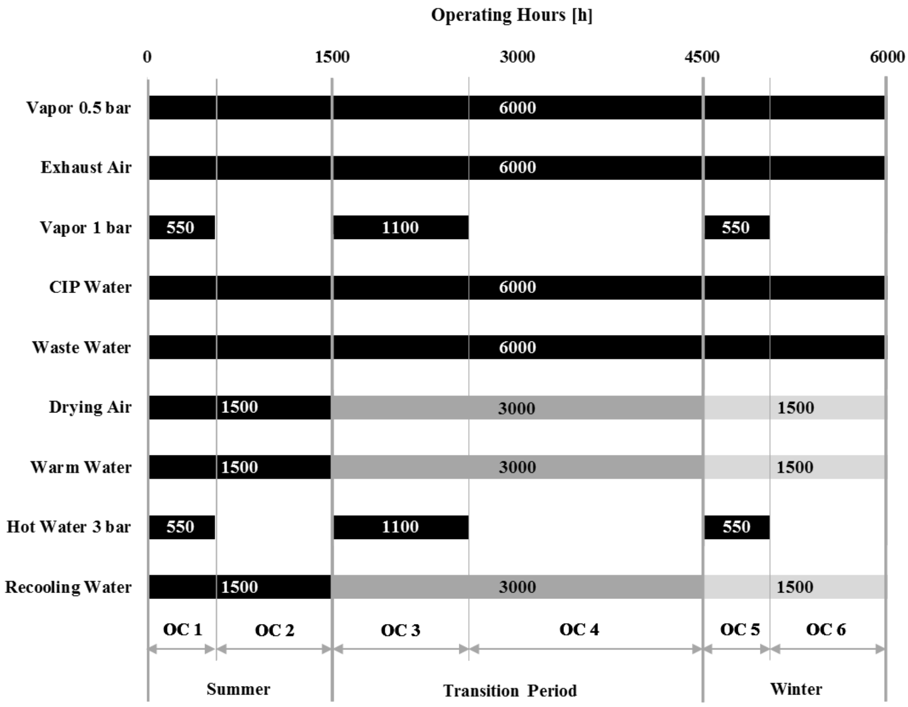

Fig. 4: Gantt-Diagram of the relevant streams for the pinch-analysis with the six different operating cases.

3.3. Pinch Analysis

In Fig. 5 are shown the composite curves and grand composite curve resulting from the pinch analysis for operating case 4 (OC 4), which is most critical to investigate as it has the longest operating time. Based on a global supertargeting calculation across all six operating cases a ΔT_{min} of 5 K is applied. The composite curves in the left diagram show that the heating and cooling requirements can only be partly covered by heat recovery (HR, 196 kW) and the rest must be covered by hot utility (HU, 140 kW) and cold utility (CU, 217 kW), respectively. The pinch point is at a temperature of 37.5°C.

The middle diagram shows the integration of the heat pump (refrigerant R134a) based on the associated grand composite curve. For the operation of the heat pump appropriate conditions are chosen. The refrigerant evaporates at a temperature of 27°C and after compression condenses at 73°C. In this case a condensation duty of 130 kW can be produced based on an evaporation duty of 100 kW – waste heat below the pinch is transferred above the pinch where there is a deficit of heat.

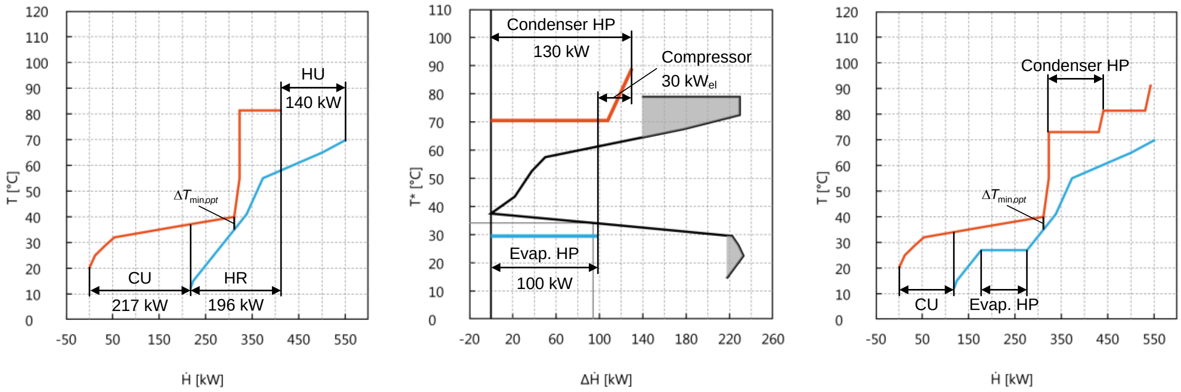

Fig. 5: Composite curves and grand composite curve for OC 4 at a $\Delta T_{min,opt}$ of 5 K. Left diagram shows the composite curves before adding the heat pump. The middle and right diagrams show the grand composite curve and balanced composite curves after integrating a heat pump with 130 kW condenser duty (Graphics from PinCH 3.0 [12]).

The diagram on the right of Fig. 5 shows the resulting composite curves after the evaporation and condenser energy streams have been included in the cooling and heating profiles. There is (nearly) no more hot utility demand while the need of cold utility is reduced significantly. Heat recovery is still included in the composite curves requiring that such measures are also implemented together with the heat pump integration. The integration of these measures is illustrated in the next section related to heat exchanger network design.

3.4. Heat exchanger network design

After the energy and cost targets have been determined, the new design for the connections between the various process streams as well as the heat pump evaporator and condenser streams must be made. The goal is to ensure the targets as calculated by the composite curves are met and the three main pinch analysis rules are respected. The result is a maximum energy recovery heat exchanger network (MER HEN). Fig. 6 shows the MER HEN for operating case 4. In this figure is shown the optimum set of connections for heat recovery and for the integration of the heat pump. Of particular note are the connections of the heat pump evaporator and condenser streams to the process streams. Below the pinch temperature the refrigerant is evaporated by using waste heat from the recooling water. Above the pinch temperature (and after the compression of the refrigerant in the heat pump) the heat of condensation is used to prepare the warm water. It is to be noted that a portion of the dry air heating demand was modelled using the warm water as a replacement stream since it was determined in discussion with the customer that the entire condenser heat flow can be transferred first to the warm water after which it is then used for preheating the drying air. The total energy balance and the amount of heat recovery is not affected. It should also be noted that no connection between the exhaust air as well as the remaining recooling water cooling demand with the ambient air (Cold Utility) is drawn as they are, in practice, sent to the environment.

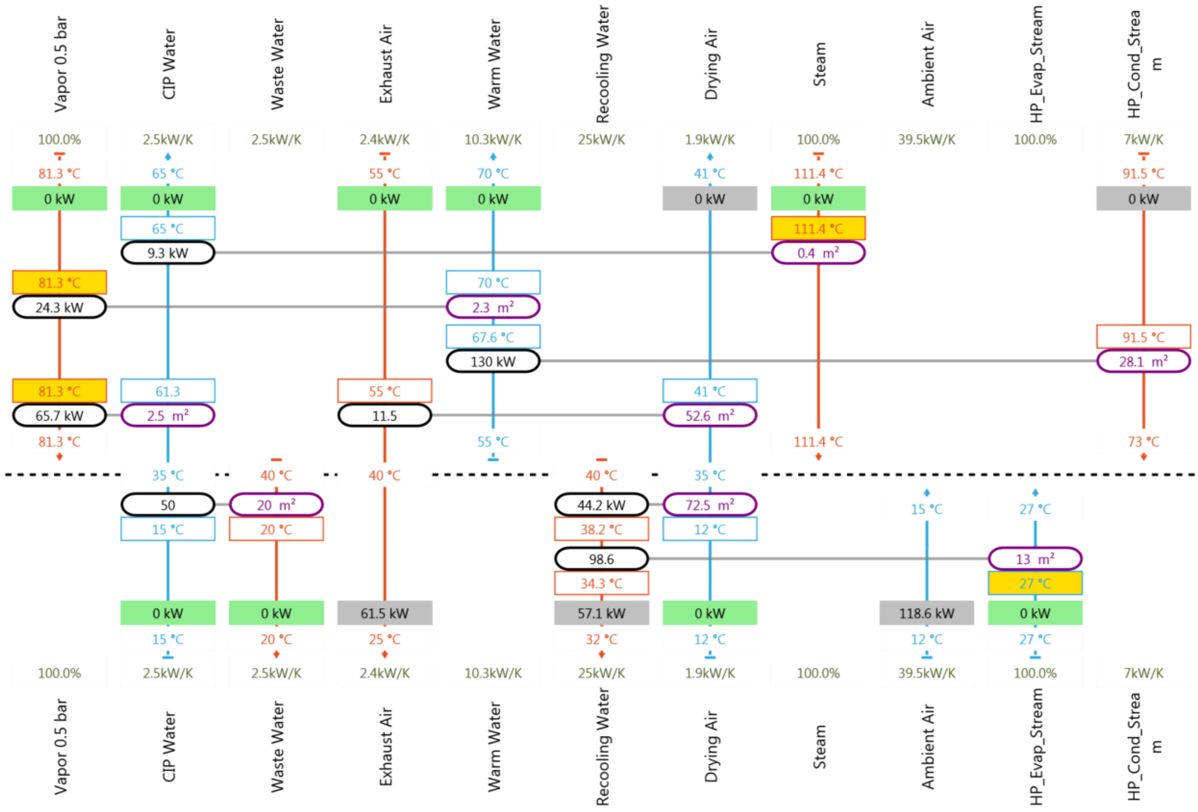

Fig. 6: Heat exchanger network for operating case 4 during the transition period showing heat recovery measures and heat pump integration (note: HP_Evap_Stream and HP_Cond_Stream are for the heat pump refrigerant; graphic from PinCH 3.0 software [12]).

3.5. Energy savings of the heat pump integration

Fig. 7 shows a schema for the integration of a heat pump into the recooling water and warm water circuits. This integration point is found in the MER HEN design as discussed in the previous section. In addition, the industry partner requested to use these existing circuits that created a retrofitting constraint on the proposed solution. Whereas different heat recovery measures have been determined for different operating cases, the heat pump can use this integration point in all operating case - the recooling water circuit as the evaporator heat source and the warm water circuit as the condenser heat sink.

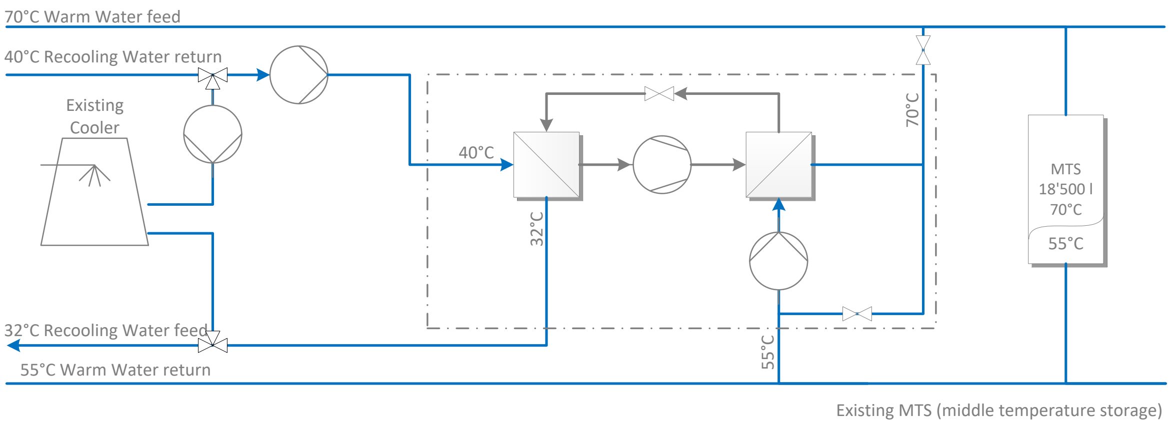

Fig. 7: Schema of the integration of a heat pump into the Recooling Water and Warm Water circuits.

Due to the seasonal dependency of the waste heat available from the recooling water as well as the varying warm water demand, a heat pump will work at different loads. The analysis of maximum heat pump loads via the grand composite curve (as was shown in the middle diagram of Fig. 5) was done for each operating case. The loads as well as the resulting electric power and hot utility savings are shown in Table 2.

Table 2: Heat pump loads and energy savings in an ideal case and for a proposed 155 kW heat pump.

Operating case	**Maximum heat pump loads**			**Proposed 155 kW heat pump**		
	Maximum heat pump condenser load [kW]	**Electric input [kW]**	**Hot Utility savings [MWh/a]**	**Maximum heat pump condenser load [kW]**	**Electric input [kW]**	**Hot Utility savings [MWh/a]**
OC 1	310	70	170.50	155	35	85.25
OC 2	375	85	356.25	155	35	147.25
OC 3	70	15	77.00	70	15	77.00
OC 4	130	30	247.00	130	30	247.00
OC 5	155	35	85.25	155	35	85.25
OC 6	155	35	147.25	155	35	147.25
Sum			**1’083.25**			**789.00**

Taking into consideration that the working load of the heat pump is limited by either the heat available from the recooling water or the warm water needs, a heat pump with a maximum condenser load of 155 kW is proposed. As can be seen in Table 2, the proposed heat pump operates at full load in most operating cases. In OC 3 and OC 4 the condenser load is limited to 70 kW and 130 kW, respectively. Fortunately, on/off operation of the heat pump is still possible given the existing middle temperature storage on the warm water circuit. In addition, the available heat from the recooling water is not limiting and constantly exceeds the need for the operation even at full load.

Maximizing the energy savings by integration of a more powerful heat pump may still be possible and will be assessed in future work. For example, if the maximum heat pump condenser load is 300 kW, more heat could be transferred into the warm water circuit in OC 1 and OC 2. However, this should result in a need for an on/off operation of the heat pump in the other four operating cases. Thus, a storage tank in the recooling water circuit and a larger storage tank in the warm water circuit must be installed to allow buffering the recooling water and warm water to enable more constant operation of the heat pump. However, the new tradeoff between the greater amount of heat recovery and the necessary higher investment cost must be assessed.

3.6. Cost analysis

A total cost analysis has been completed together with the pinch analysis based on data from the industry partner and engineering experience. The industry partner noted the following economic values to be used in the analysis: equipment payback time of maximum 5 years, life time for annuity calculation: 15 years, interest rate: 3%, electricity costs of CHF 100/MWh, hot and cold utility costs of CHF 70/MWh resp. CHF 25/MWh. The estimation of the total investment costs for the heat recovery measures (without the heat pump) is CHF 377’000 plus CHF 160’000 for the proposed heat pump with a maximum condenser load of 155 kW. Both of these costs include equipment, engineering, piping, electrical, instrumentation and installation costs.

The calculation of the yearly cost savings for the heat recovery measures is carried out by simply multiplying the hot utility savings and the hot utility costs. In cases when there was also a reduction in the cold utility demand, the corresponding cost savings have been taken into account as well. For the heat pump the cost savings have been calculated as follows: the delivered heat capacity replaces the hot utility costs, therefore this capacity needs to be multiplied with the hot utility costs, and from the result, the electrical power times the electricity cost as well as the maintenance cost for the heat pump (assumed to be 5% of the heat pump investment cost per year) have to be subtracted giving a yearly cost saving for each operating case.

The heat recovery measures together with the heat pump integration result in a payback time of 3.7 years. Table 3 sums up all relevant data from the pinch-analysis as well as the above mentioned figures and provides context in terms of a return on investment calculation.

Table 3: Payback and return on investment calculation of the heat recovery measures and heat pump integration.

	Scenario 1
Heat recovery measures	CHF 377'000
Heat pump	+ CHF 160'000
Total investment	**CHF 537'000**
Life time	15 years
Interest rate	3%
Annuity	**CHF 45'000**
Total savings of heat recovery measures	CHF/y 114'000
Total savings of heat pump	+ CHF/y 29'500
Total savings	**CHF/y 143'500**
Payback	3.7 years
Net income	CHF/y 98'500
Return on investment	18 %

4. Conclusion

The methodology for integrating a heat pump correctly into an industrial case study has been presented. Pinch analysis is used to ensure the heat pump together with heat recovery are optimized together to ensure the correct streams are used in connecting the heat pump to the process. A concept for integrating the heat pump into the existing candy production process case study was presented as well as a cost analysis was carried out. As future work it is recommended to assess the applicability of integrating a larger heat pump and the necessary additional equipment needed to maintain operation in all operating cases and compare the economic assessment with the 155 kW heat pump proposed in the case study of this paper.

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References

[1] Lovins A.B., Reinventing fire, Chelsea Green Publishing Company, USA, 2011.
[2] Chua K.J., Chou S.K., Yang W.M., Advances in heat pump systems: A Review, Applied Energy, 87, pp. 3611-3625, 2010.
[3] Linnhoff B., Pinch Analysis - A State-Of-The-Art Overview, Trans IChemE, vol. 71, Part A, p. 504, 1993.
[4] Berntsson T., Heat Sources - technology, economy and environment, International Journal of Refrigeration, 25, pp. 428-438, 2002.
[5] Becker H. C., Methodology and Thermo-Economic Optimization for Integration of Industrial Heat Pumps, PhD Thesis, Thèse No. 5341, École Polytechnique Fédérale de Lausanne, 2012.
[6] Townsend D.W., Linnhoff B., Heat and Power Networks in Process Design - Part 1: Criteria for Placement of Heat Engines and Heat Pumps in Process Networks, AIChE Journal, Vol. 29, No. 5, 1983.
[7] Benstead R.; Sharman F.W., Heat Pumps and Pinch Technology, Heat Recover. Syst & CHP,Vol. 10,

No. 4, pp. 387–38, 1990.
[8] Wallin E., Franck P. Á., Berntsson T., Heat Pumps in Industrial Processes – an Optimization Methodology, Heat Recover. Syst & CHP, Vol. 10, No. 4, pp. 437-446, 1990.
[9] Wallin E., Berntsson T., Integration of Heat Pumps in Industrial Processes, Heat Recovery Systems & CHP, Vol. 14, No. 3, pp. 287-296, 1994.
[10] Oluleye G., Jobson M., Smith R., Process integration of waste heat upgrading technologies, Process Safety and Environmental Protection, 103, pp. 315-333, 2016.
[11] F. Brunner, P. Krummenacher, Einführung in die Prozessintegration mit der Pinch-Methode – Handbuch für die Analyse von kontinuierlichen Prozessen und Batch-Prozessen, Bundesamt für Energie, CH, 2015.
[12] Olsen D., Abdelouadoud Y., Wellig B., Krummenacher P., Systematic thermal energy storage integration in industry using pinch analysis, 29th Int. Conf. on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), Slovenia, June 2016.