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PROCESS INTEGRATION AND OPPORTUNITY FOR HEAT PUMPS IN INDUSTRIAL PROCESSES

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Abstract *Process integration methods allow one optimizing industrial processes. The main goals are decreasing energy demand and operating costs as well as reduction of pollutants emissions. High fuel costs promote installations of heat pumps. In a heat pump process waste energy is valorized by electrical power to produce higher quality energy. This energy is used to satisfy a part of the process demand so that less fuel is required and* CO_2 *emission will decrease. This paper presents a methodology, based on pinch analysis, which demonstrates the opportunity of integrating heat pumps in industrial processes. The method considers the whole process including utilities and the energy conversion system. A combined analysis which considers thermal and material streams in the process is realized to optimize the heat recovery and the integration of energy conversion units. By analogy all material streams are listed and the potential of water recuperation is obtained. The combination of appropriate refrigeration and heat pump cycles leads to an important energy saving potential. The respective flow rates are defined by optimization. The application case of a dairy is used to calculate the energy and operating cost savings potential.*

Keywords: *energy integration, pinch analysis method, heat pumps, dairy*

Nomenclature

$\dot{E}_{el}$	Electricity demand or excess [MW]
$\dot{E}_{fuel}$	Energy delivered by fuel (natural gas) [MW]
$\dot{E}_{hp}$	Electricity supply to heat pump [MW]
$\dot{M}_{ck}$	Consumed water flow rate in interval k [kg/s]
$\dot{M}_{c}$	Mass flow rate of cold streams [kg/s]
$\dot{M}_{h}$	Mass flow rate of hot streams [kg/s]
$\dot{M}_{pk}$	Produced water flow rate in interval k [kg/s]
$\dot{q}$	Heat load per mass flow [MJ/kg]
$\dot{Q}_{th}$	Heat load substituted by heat pump [MW]
η_{COP}	Heat pump efficiency with theoretical COP [-]
η_{th}	Boiler efficiency [-]
θ	Carnot factor [-]
c_{el}	Electricity price [CHF/MJ]
c_{fuel}	Fuel price [CHF/MJ]
CO_{2-elec}	CO_2 content of electricity [kg/MJ]
CO_{2-LHV}	CO_2 content of fuel [kg/MJ]
COP	Coefficient of performance
d	Operating time [s/year]
I_{annual}	Annualized investment cost [CHF/year]
k_{el}	Electricity to fuel price ratio: $c_{el}/\ c_{fuel}$ [-]
M	Maintenance cost [CHF/year]
R_k	Excess heat; unabsorbed heat by interval k and superior [kW]
RW_k	Excess water; not reusable by interval k and superior [kg/s]
T	Temperature [K]
$T0$	Ambient temperature [K]
T_{sink}	Hot source temperature [K]
T_{source}	Cold source temperature [K]

1 INTRODUCTION

Heat pump technology has a high potential to use energy more rationally in industrial processes, and thus, to reduce CO_2 emissions, especially when hot and cold utilities are used at the same time. In this article electrically driven heat pumps are considered.

The optimal integration and placement of an industrial heat pump may be evaluated by pinch analysis. The goal of pinch analysis and process integration techniques is first to identify, in a system, the heat recovery potential between hot and cold streams (Kemp, 2007). Process integration also concerns the integration of energy conversion technologies to supply the heating and cooling requirements of the process. Among the energy conversion technologies, heat pumps allow one to transfer heat from a heat source to a heat sink, saving therefore both, heating and cooling requirements. An appropriate integration of heat pumps aims at identifying the optimal heat pump type, its operating conditions and the corresponding flow rates. It is also important to consider the interactions between the heat pumping system, the process and other energy conversion technologies.

A typical dairy process is analyzed in this article. A lot of waste heat is produced and a conceivable solution to use this heat is necessary. Currently this heat is lost; projects to sell this heat have been evaluated. A systematical analysis with pinch and exergy techniques, including a combined water-energy approach, will be detailed in this article. The minimum energy requirement is evaluated and the integration of optimal utilities is analyzed. It will be shown that heat pumps have a high potential to valorize waste heat in the process.

2 HEAT PUMP INTEGRATION BASED ON PINCH ANALYSIS WITH EXERGY FACTORS

The optimal integration, and positioning, of an industrial heat pump is evaluated by pinch analysis. This is widely discussed in the literature. Lots of publication cited below about industrial heat pumps were written between 1980 and 1990. Nowadays, heat pumps become interesting again because of higher fuel costs, but saving potential is only fully exploited when the heat pump is correctly integrated in the process. Rules for optimal placement of a heat pump in an industry process have been introduced by Linnhoff and Townsend (1983). The major contribution of the proposed approach is to adopt a system vision, considering heat pump integration with a global perspective, instead of searching for local benefit at the implementation level. Loken (1985) has analyzed the integration of heat pump in a process using a computer program that systematically allows one to change the temperature level of individual streams, involved in the heat pump. The approach takes into account the pinch location. However there is no systematic approach to calculate the optimal operating conditions of the heat pump in the system.

The integration of heat pumps in industry requires the complete understanding of thermodynamics, process economy, and the utility system integration. For example, Ranade (1987) presents a general equation which defines the best economic temperature lift, corresponding to the difference between the two temperature levels, for a heat pump system. As demonstrated by Wallin and Berntsson (1994), characteristics of both, industrial process and heat pumps, must be taken into account. The analysis of the composite curves of the process helps to identify proper heat pump type and temperature levels. The same authors (Wallin and Berntsson, 1990) propose a methodology to optimize heat source and heat sink temperature, heat pumps size and the choice of streams used by the heat pump. In his thesis, Leyland (2002), has developed a multi objective optimization approach to define the optimal placement of temperature levels in a heat cascade. An algorithmic approach has also been developed by Dubuis (2007).

Different optimization strategies can be found in the literature: Colmenares and Seider (1987) present a non linear optimization method to place heat pumps across the pinch point. Swaney (1989) proposes a transportation model to determine the optimal heat load of heat pumps by using fixed temperature levels. Shelton and Grossmann (1986) propose a mixed linear integer programming model to show the economic potential of properly integrated heat recovery networks and refrigeration systems. Maréchal et al. (2002) have developed a tool to optimize the integration of refrigeration systems. This approach optimizes the flow rates in refrigeration systems. As demonstrated in (Maréchal, 1997), the mixed integer linear programming (MILP) formulation of the heat cascade can be used to optimize the flow rates in heat pumping systems. The interest of applying these optimization methods is to consider simultaneously the heat cascade, electricity consumption and production balances. This allows one to evaluate, in the same problem, the combined use of different utilities like cogeneration and heat pumping systems.

More recently, Holiastos and Manousiouthakis present a mathematical formulation for the optimal integration of heat pumps. The formulation evaluates the minimum hot/cold/electric utility cost and introduces a linear dependence on the number of temperature intervals (Holiastos and Manousiouthakis, 2002). Bagajewicz and Barbaro (2003) consider temperature levels as decision variables to avoid discrete temperature levels which need a fine interval partition to find good solutions. This can give non realistic solutions, due to the fact that generally, industrial heat pumps only have one condenser and one evaporator. They also make a difference between assisting heat pumps (situated above or below the pinch) and effective heat pumps (situated across the pinch point). Economically, an assisting heat pump in combination with an effective heat pump can be optimal. Also Holiastos and Manousiouthakis (2002) find an optimal case where the heat pump does not cross the pinch point. Berntsson mentions that heat pumps below or above the pinch can be economically interesting, for example when heat exchange gets expensive due to large distances between streams (Berntsson, 2002). One could argue in this case, that this corresponds to an inappropriate choice of the ΔT_{min} value.

Périn-Levasseur et al. (2008) have analyzed the integration of heat pumps in a multi-effect evaporators system. They propose a three level heat pumping system, in which the optimal flows are evaluated. The system analysis concludes that only a part of the heat load available has to be pumped and that heat pumping will deliver their energy savings only if they are installed simultaneously. However their study is concentrated on a multi-effect evaporator and they do not consider the whole system.

Exergy factors help to identify the optimal integration of utilities. Wall and Gong (1995) consider an exergy concept in addition to pinch technology for optimizing heat pump integration. Staine and Favrat (1996) include exergy factors to process integration. For this they propose a graphical representation method to show the main exergy losses, which is particularly useful when introducing heat pumps or cogeneration units. Maréchal and Favrat (2006) discuss the application of exergy concepts to design the optimal energy conversion systems for given processes.

In this paper we will show that the rule for optimal placement is still valid but has to be adapted, considering the multiple utility pinch points created by optimal integration of heat pumps and the utility system. It is also shown that the optimal combination of appropriate utilities is crucial in process integration.

3 PERFORMANCE INDICATORS TO ESTIMATE THE HEAT PUMPS INTEGRATION

The COP of a heat pump depends mainly of the temperature difference between the heat source and the heat sink. It can be defined as a first approximation by considering an efficiency with respect to the theoretical value. The coefficient of performance (COP) of a heat pump is defined by equation (1) and may be estimated considering the Carnot factor. Typical value for η_{cop} is 55%.

$$COP = \frac{\dot{Q}_{th}}{\dot{E}_{hp}} = \eta_{COP}\frac{T_{sink}}{T_{sink} - T_{source}} \tag{1}$$

The economic assessment of the interest of a heat pump is defined by equation (2).

$$I_{annual} + M + \dot{Q}_{th} \cdot d \cdot \left(\frac{c_{el}}{COP} - \frac{c_{fuel}}{\eta_{th}}\right) \leq 0 \tag{2}$$

$$I_{annual} + M + \frac{\dot{Q}_{th} \cdot d \cdot c_{fuel}}{\eta_{th}}\left(\frac{c_{el}}{c_{fuel}} \cdot \frac{\eta_{th}}{\eta_{COP}} \cdot \frac{T_{sink} - T_{source}}{T_{sink}} - 1\right) \leq 0 \tag{3}$$

In this equation, $\frac{Q \cdot d \cdot c_{fuel}}{\eta_{th}}$ is the present energy bill, corresponding to the operating cost of the boiler in one year.

The profitability of the heat pump is therefore defined by equation (4). It depends on the investment cost and the way it is annualized (depending on expected life time and interest rate), the maintenance cost, the fuel to electricity price ratio, the COP of the system and the efficiency (η_{th}) of the present heating system (boiler).

$$\frac{I_{annual} + M}{\left(1 - k_{el} \cdot \frac{\eta_{th}}{\eta_{COP}} \cdot \frac{T_{sink} - T_{source}}{T_{sink}}\right)} \leq Energy - bill \tag{4}$$

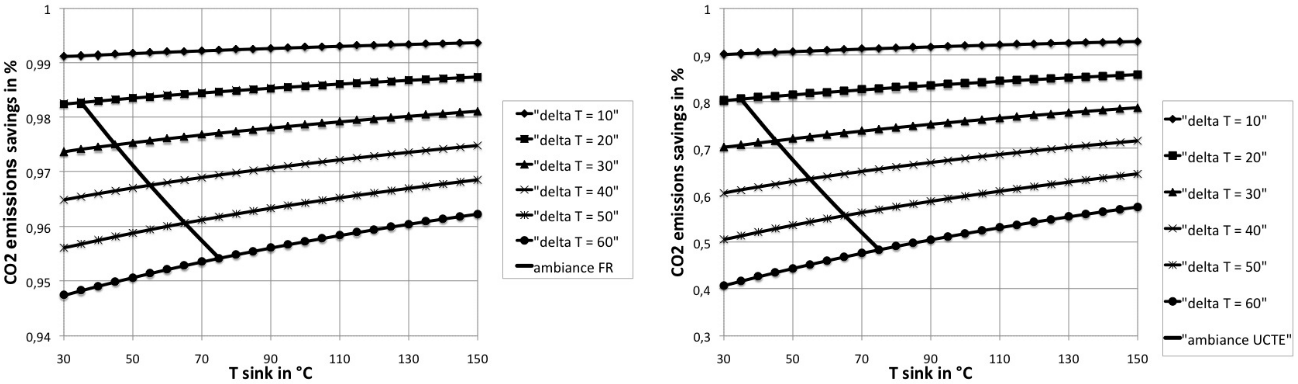
Compared to a boiler, the heat supplied by the heat pump will reduce, by the corresponding amount, the heat supplied by the present system. In consequence, the heat supplied by a boiler is substituted by heat, valorized through electricity, so that less fuel is consumed. Considering the specific CO_2 emission of both, electricity and fuel, the heat pump integration may result in considerable primary energy and CO_2 emissions savings. According to the IEA (International Energy Agency) Heat Pump Center, heat pumps could save up to 5% of the total CO_2 emissions in the industry.
In addition to the profitability factors, CO_2 savings also depend on:

- CO_2 content of the fuel used (CO_{2-LHV} in kg_{CO2}/MJ_{LHV}); CO_2 content of fuel (natural gas): 0.0561 kg/MJ
- CO_2 content of the driving energy, in this article electricity is considered as energy driver; the CO_2 content depends on the electricity mix: CO_2 content of Electricity (France) 0.0111 kg/MJ; CO_2 content of Electricity (UCTE - Europe) 0.125 kg/MJ

$$\Delta CO_2 = \left(\frac{CO_{2-LHV}}{\eta_{th}} - \frac{CO_{2-elec}}{COP}\right)\dot{Q}_{th} \cdot d \tag{5}$$

$$\Delta CO_{2relative} = \left(1 - \frac{CO_{2-elec}}{CO_{2-LHV}} \cdot \frac{\eta_{th}}{COP}\right) \tag{6}$$

By using heat supplied from a heat pump instead of heat supplied from a boiler, the CO_2 saving is expressed by equation (5) and the relative CO_2 emission reduction is given by equation (6). The interest of heat pumps will therefore increase if the CO_2 content of the electricity is small, the CO_2 content of the substituted fuel is high, the COP of the heat pump is high and the efficiency of the boiler is low. With equation (1) equation (6) becomes equation (7).



(a) France-EDF mix

(b) UCTE mix

Figure 1: Relative CO_2 emission savings

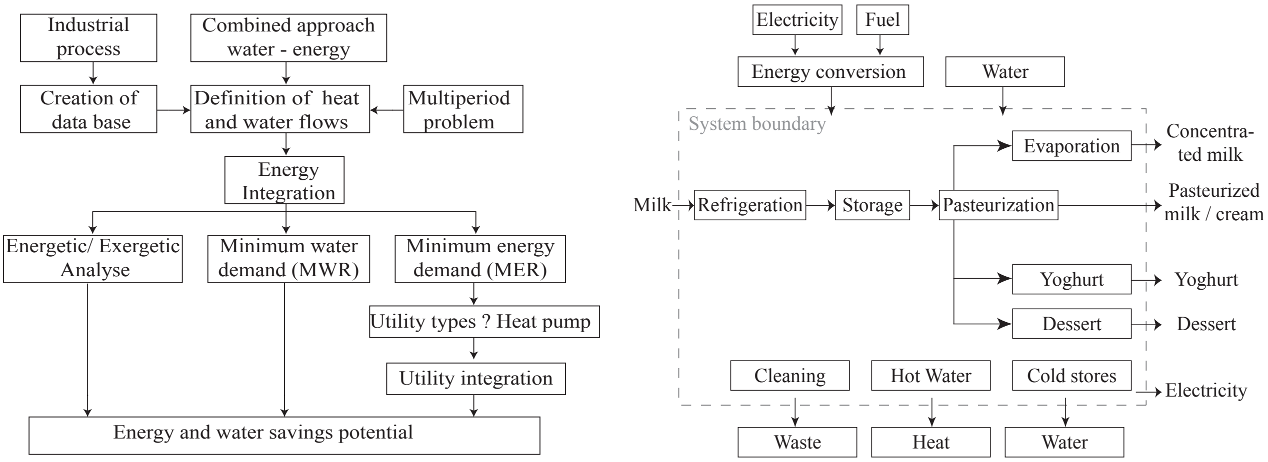
$$\Delta CO_{2relative} = \left(1 - \frac{CO_{2-elec}}{CO_{2-LHV}} \cdot \frac{\eta_{th}}{\eta_{COP}} \cdot \frac{T_{sink} - T_{source}}{T_{sink}}\right) \tag{7}$$

Figure 1 shows the considerable CO_2 savings that could be achieved as a function of the heat sink temperature for different temperature lifts and for two electricity mix with different CO_2 contents. The boiler uses natural gas ($\eta_{th} = 0.9$) and the graphs are represented for the electricity mix in France and the electricity mix in Europe (UCTE). η_{COP} is considered to be 0.67 (calculated value). The ambient temperature is supposed to be 15°C. The "ambiance UCTE" and "ambiance FR" curves separate the case where the heat source is below the ambient temperature (on the left) from the case where it is above ambient temperature (on the right); (deltaT = T_{sink} - T_{source}). One should note that due to the low CO_2 content of the French electricity mix, the interest of heat pumps is not at the same scale as the one with the UCTE mix.

4 A METHODOLOGY TO ESTIMATE HEAT PUMP INTEGRATION

The used process analysis methodology has been described by Muller et al. (2007). It includes the systematic process unit operation analysis in order to define the hot and cold streams of the process and applies the methodology proposed by Maréchal and Kalitventzeff (1998) for energy integration in industrial sites. They use a MILP formulation to define the optimal flow rates for appropriate utilities.

These tools have been used to study heat pump integration opportunities. Figure 2a summarizes the applied methodology. Because heat pumps are often applied in processes, using water, like food or pulp and paper industry, a combined water and energy analysis should be applied. The first step consists in defining the heat transfer requirements and the water usage in the process operation units. Considering the system boundaries, a lot of renewable heat is found in the effluent streams which are systematically cooled down to the ambient temperature. This corresponds to possible new heat exchangers. The two main advantages of this approach are:



(a) Methodology (b) Process description

Figure 2: Process analysis

- No heat is lost in the effluents, since all effluents leave the process at ambient temperature.
- Water saving potential is evaluated, by performing a water producer-consumer cascade analysis at ambient temperature. The analogy between thermal energy and water is shown in table 1.

Table 1: Analogy energy - water

Thermal Energy	Water
Temperature = energy quality	Index = water quality
Heat load	Water mass flow

In order to determine the flow rates for the utility streams, the heat balance is performed in each temperature interval (from higher temperature interval T_{k+1} to lower temperature interval T_k) by equation (9). The algorithm minimizes the operating cost of fuel and electricity (import or export) in equation (8). The complete formulation is presented by Maréchal and Kalitventzeff (2003).

$$F_{obj} = min(c_{fuel}\dot{E}_{fuel} + c_{el}^{+}\dot{E}_{el}^{+} - c_{el}^{-}\dot{E}_{el}^{-}) \tag{8}$$

$$\sum_{h=1}^{n_{hot}} \dot{M}_h q_{h,k} - \sum_{c=1}^{n_{cold}} \dot{M}_c q_{c,k} + R_{k+1} - R_k = 0 \tag{9}$$

Hot and cold streams can be process streams or utility streams. The difference is that the mass flow rate is fixed for process streams, and variable for utility streams in order to optimize the appropriate flow rates.
By analogy the mass-balance for water consumption can be computed. In this case the interval corresponds to the water quality index. The algorithm minimizes the excess water flow rates after each index interval (10).

$$F_{obj} = min(RW_{k+1}) \tag{10}$$

$$\sum_i \dot{M}_{pk-i} - \sum_i \dot{M}_{ck-i} + RW_{k+1} - RW_k = 0 \tag{11}$$

With these equations the minimum energy and water requirements can be evaluated. To satisfy the process energy demand, appropriate utilities are chosen and corresponding optimal mass-flow rates are computed.
To simplify, only one period will be detailed in this article. However, in order to estimate the investment costs and payback rate, it is important to consider a multi-period strategy as described in (Maréchal and Kalitventzeff, 2003).

5 EXAMPLE OF APPLICATION

5.1 Process Description

In this dairy process, milk is transformed to produce concentrated milk, pasteurized milk and cream, yoghurts and desserts. This is mainly achieved by heat exchanges and evaporation. Operating temperatures and conditions are fixed by the process recipes. The process is described in figure 2b. The received milk in the dairy is first cooled down and stored. In the process the milk is treated by pasteurizing. The milk is first preheated and the cream is separated by centrifugation. Both milk and skimmed milk are pasteurized and then cool down to the storage temperature conditions. The pasteurized milk is distributed between concentrated milk, yoghurt and dessert lines.
One of the main energy consumer is the milk evaporation process. The milk is heated up and then sent to a three effect evaporator. Steam is used in the first effect to evaporate a part of the milk. The evaporated steam is then used for heating up the inlet milk stream and to evaporate the milk in the second effect. The same principle is used in the third effect. The evaporation temperature depends on the solid content of milk. To ensure the heat recovery, the pressure in the following effect decreases. The evaporation temperatures and pressures for each effect are given in table 2. A part of the evaporated milk in the third effect is also used to preheat milk feed and the rest is cooled down with cold water. The energy requirements for the yoghurt and dessert lines is heating up the milk, and after homogenization, cooling down the product to the storage temperature.

Table 2: Operating conditions of multi-effect evaporator

Effect	1	2	3
T_{eva} [°C]	70.32	66.42	60.82
P [bar]	0.31	0.26	0.20

In process integration, it is also important to consider the auxiliary processes outside the direct process lines, like the cleaning in place system, the hot water production and the cold stores. Table 3 presents the hot and cold streams of the dairy under study.

5.2 Energy integration

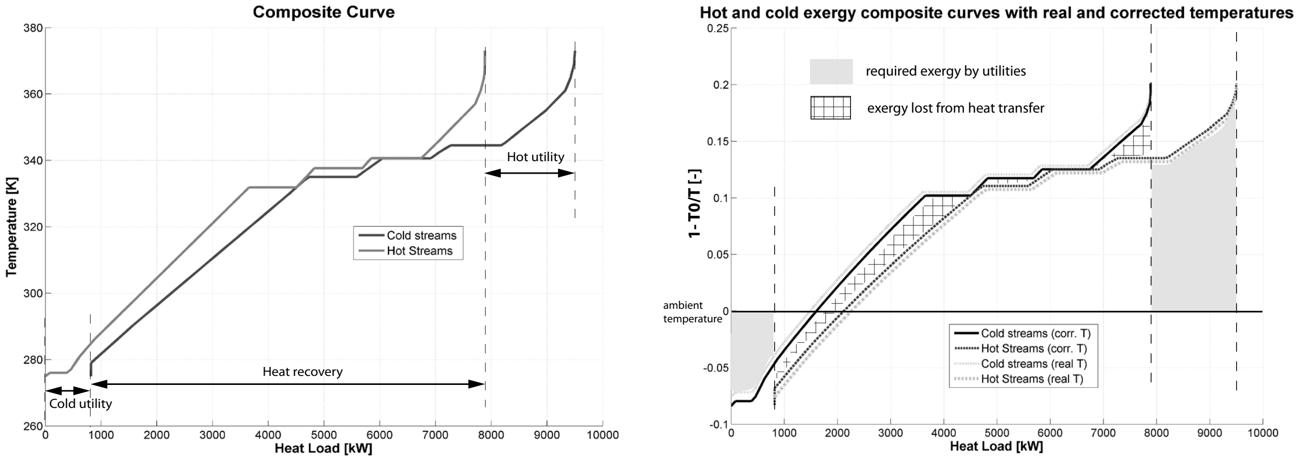
First the heat recovery potential between hot and cold streams is identified. For this, hot and cold streams of the process have to be defined. Based on the definition of a minimum temperature difference (ΔTmin), the minimum energy requirement (MER) is computed and the maximum energy recovery between process streams is calculated. The composite curve of figure 3a shows three zones: the hot and cold utility requirements and the heat recovery. Figure 3b presents a Carnot composite curve. Instead of representing temperatures on y-axis, Carnot factor is used ($\theta = 1 - \frac{T0}{T}$). Areas in this graph represent the required exergy to be supplied or removed, by hot and cold utilities, and the exergy losses in the heat recovery system that could be eventually valorized in the energy conversion system.

By analogy the water pinch analysis is performed. The water production and consumption units are defined in table 4. Figure 4b shows the minimum water requirement and its corresponding required water quality. In the present situation the water consumption is 4.025kg/s. The calculation of the water consumption corresponds therefore to a process water saving of 25 %.

In a second step the utility system has to be first analyzed and then optimized. The grand composite curve 4a separates the process in two parts, above and below the pinch point. It shows the required temperatures levels for the hot and cold utilities and it identifies the optimal placement of refrigeration cycles and heat pumps.

Table 3: Hot and cold streams of the process

Unit	T$_{in}$ [°C]	T$_{out}$ [°C]	Heat Load [kW]	Remark
Refrigeration	6	4	76.00	Refrigeration inlet milk
Pasteurization	4	66	2356.00	Preheating
	66	86	676.40	Pasteurization milk
	86	4	2773.24	Refrigeration milk
	66	98	119.68	Pasteurization cream
	98	4	351.56	Refrigeration cream
Evaporation	4	70.32	504.03	Preheating
	70.32	70.32	904.17	Evaporation 1.effect
	66.42	66.42	864.11	Evaporation 2.effect
	60.82	60.82	849.80	Evaporation 3.effect
	60.82	4	151.48	Refrigeration concentrated milk
	68.87	68.87	904.17	Condensation 1.effect
	65.86	65.86	864.11	Condensation 2.effect
	60.08	60.08	849.80	Condensation 3.effect
	68.87	15	87.82	Refrigeration condensates 1.effect
	65.86	15	80.79	Refrigeration condensates 2.effect
	60.08	15	69.72	Refrigeration condensates 3.effect
Yoghourt	4	95	1026.00	Heating
	95	10	957.60	Cooling
Dessert	4	90	817.00	Heating
	90	70	190.00	Cooling
Cold stores	5		300	maintain the store at a temperature of 5 °C
Hot water	15	55	167.2	Production of hot water
CIP	58.72	70	188.60	Maintain temperature CIP 1
	65	15	104.5	Recuperation waste heat CIP 1
	67.47	85	285.13	Maintain temperature CIP 2
	75	15	125.4	Recuperation waste heat CIP 2



(a) Composite curves

(b) Carnot composite curves

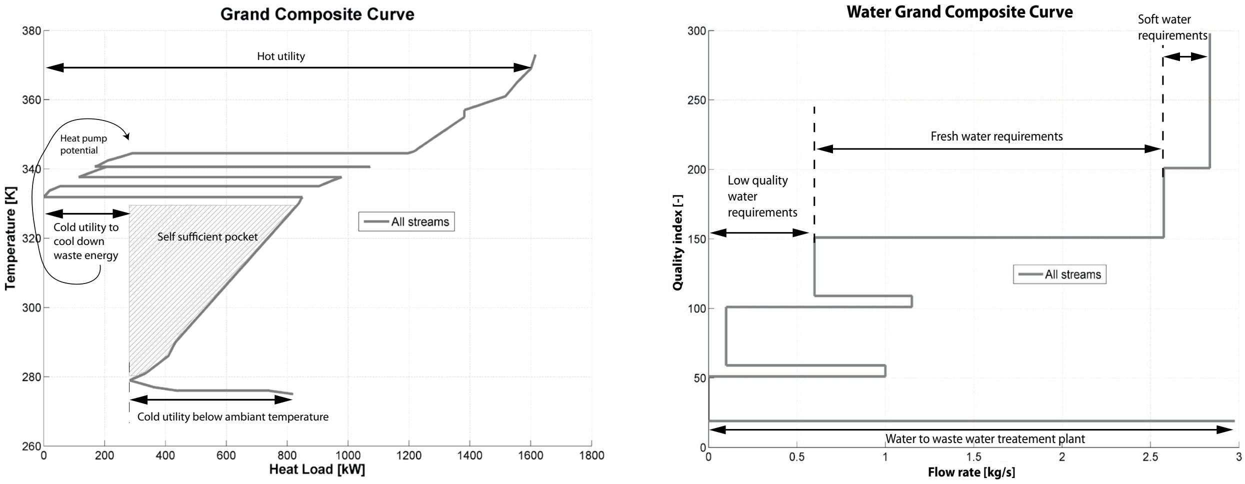
Figure 3: Composite curves

5.3 Heat pump and utility integration

Currently a refrigeration cycle and a conventional boiler are implemented to satisfy the energy needs for the process. The grand composite curve of figure 4a shows that a refrigeration cycle is necessary for satisfying the cold utility below the ambient temperature. The waste heat from the multi-effect evaporator can be used to heat up cold process streams, but a part of the excess energy cannot not be used directly in the process and therefore has to be cooled down by a supplementary cold utility. A heat pump (HP) offers the possibility to valorize this available heat, and to satisfy a part of the hot utility. In addition, the temperature levels are in an acceptable range for considering the integration of cogeneration engines (COG). A cogeneration engine is fed by fuel (natural gas) and produce electricity and heat (two

Table 4: Water consumption & production

	Water consumptions [kg/s]				Water productions [kg/s]		
	Used water level 2	Used water level 1	Fresh water	Soft water	Dirty	Used water level 2	Used water level 1
Index	50	100	150	200	10	60	110
CIP solution			-0.475		0.475		
CIP hot water		-0.5				0.5	
CIP cold water		-0.55					0.55
Boiler						0.4	
Milk evaporation				-0.26			
Hot water			-1.5		1.5		
Other	-1				1		



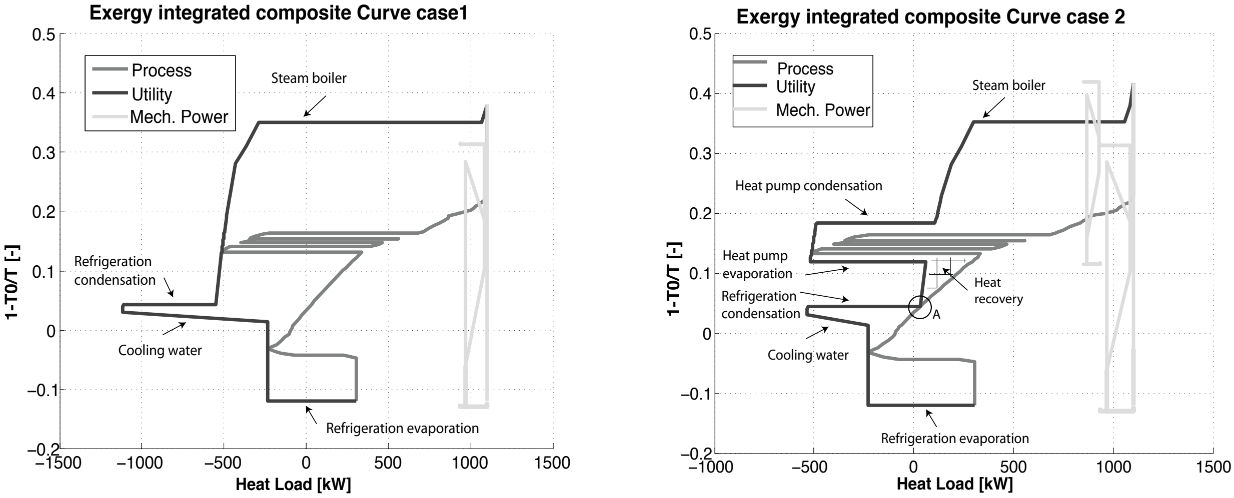
(a) Grand composite curve

(b) Water grand composite curve

Figure 4: Energy and water composite curves

hot streams: the flue gases and the engine cooling) that can be used to satisfy process demand.

It is important to remark that the combination of integrated utilities depends on each other. Figure 5a shows the



(a) Integrated composite curves refrigeration and boiler

(b) Integrated composite curves refrigeration, boiler and heat pump

Figure 5: Composite curves: Integration of heat pump

integration of the boiler and the refrigeration. It is shown that the condensation level of the refrigeration cannot be used as a hot utility in the process due to the self sufficient pocket. The heat from the condensation is considered as excess heat and has therefore be cooled down by cooling water. Figure 5b shows the integration of both, heat pump and refrigeration cycle, the rest of the hot utility is satisfied by a steam boiler. One can see the synergy that exists between the heat pump and the refrigeration cycle: The use of the condensation heat of the refrigeration cycle to preheat process streams allows to increase the amount of heat that could be valorized by the heat pump and therefore reduce the heat supplied by the boiler and the cold utility supplied by cooling water. In this case, the COP of the heat pump is 7.9. Less excess heat is available and the project to sell excess heat has to be re-evaluated.

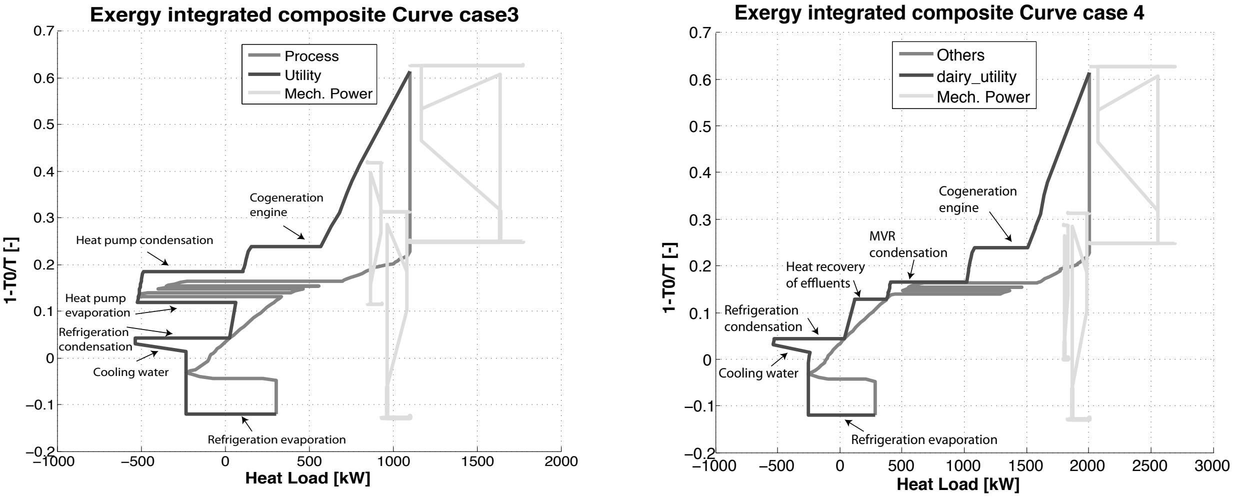
Figures 5 and 6 show exergy integrated composite curves of the utility system, the surface between the process and the utility curve presents the exergy losses. Integrated mechanical devices (compressor for heat pump and refrigeration or cogeneration engine) are represented by the "Mech. Power" line. One can see that the use of a heat pump reduces the exergy losses of the system. Instead of using heat of the self-sufficient pocket to heat the cold streams, at rather low temperature, corresponding to certain exergy losses, a part of this heat is valorized by the heat pump to satisfy a part of the hot utility requirement. The cold streams are preheated with the condensation heat of the refrigeration. The temperature differences between hot and cold streams become smaller and thus exergy losses are reduced.

In figure 6 a cogeneration engine is integrated and replace the boiler. The electricity produced can be used to drive the heat pump, the refrigeration cycle and process units or can be sold.

The stream concerned for the heat pump integration corresponds to the condensation of the last evaporation effect. This heat is used in part in the heat pump and the rest is directly recovered to preheat process streams. The optimal flow rate in the heat pumping system is obtained by optimization and activates a system utility pinch point (point A on figure 5b). There are two ways of implementing heat pumps, either a closed cycle, shown in figure 6a, or a mechanical vapor recompression, presented in figure 6b. The heat pump valorizes a part (around 70%) of the vapor flow leaving the last effect of the evaporator. The rest of the waste heat is recovered by direct heat exchange. The advantage of the MVR (mechanical vapor compression) is the elimination of one heat exchanger (evaporator) which reduces both, investment cost and temperature lift on the heat pumping system.

Detailed results on operating costs, fuel, electricity and cooling water consumption, and CO_2 emissions are presented in tables 5 and 6.

The COP is defined by equation 1. In this application the COP = 7,9 for the heat pump cycle. The integration of utilities changes the shape of the composite curve, thus the optimal integration of heat pumps and other utilities can only be done simultaneously. In this application the pinch point is located around 330 K. Considering the pinch analysis rule, a heat pump can be integrated to bring heat from 325 K to 355 K. The profitability of a heat pump is analyzed by comparing the "heat recovery" case (reference case) with the "HP" case. The heat load replaced by the heat pump is 664 kW for an operating time of 2650 h/year. Equation (4) gives the relation. Resolving this equation, the rentability indicator is evaluated. It shows the acceptable cost per year (annualized investment cost and maintenance cost) (12). The annualized investment cost depends on the interest and determines the payback time.



(a) Integrated composite curves heat pump

(b) Integrated composite curves mvr

Figure 6: Comparison of integrated composite curves for heat pump and mechanical vapour compression

$$I_{annual} + M \leq 0.178 MCHF/year \tag{12}$$

The reduction of CO_2 emission can be calculated by equation (5). Instead of using heat supplied by a boiler, a heat pump can satisfy a part of the hot utility. In our case (electricity mix in France) this leads to a CO_2 emission reduction

Table 5: Results

	Unit	Heat recovery	HP	HP&COG	MVR&COG
Operating costs	[MCHF/year]	0.6778	0.4865	0.4190	0.4073
Saving potential	[%]	0	-28	-38	-40
Fuel consumption	[kg/s]	0.038	0.019	0.038	0.039
Saving potential	[%]	0	-50	0	+3
Electricity	[kW]	316.77	403.07	-265.37	-331.81
Saving potential	[%]	0	27	-184	-205
CO_2 emissions (EDF mix)	[tons]	979	515	946	971
Saving potential	[%]	0	-47	-5	-1
CO_2 emissions (UCTE mix)	[tons]	1324	951	946	971
Saving potential	[%]	0	-28	-29	-27
Cooling water consumption	[kg/s]	42.11	14.39	14.39	14.39
Saving potential	[%]	0	-66	-66	-66

Table 6: Detailed results

		Heat recovery	HP	HP&COG	MVR&COG
Process & other	Electricity [kW]	150	150	150	150
Refrigeration	Electricity [kW]	166.59	166.49	166.59	166.59
Heat pump	Electricity [kW]	-	83.54	83.54	35.11
Cogeneration	Electricity [kW]	-	-	-673.26	-690.96
Cogeneration	Fuel [kg/s]	-	-	0.038	0.039
Boiler	Fuel [kg/s]	0.038	0.019	-	-

of 386 tons of CO_2 /year. This corresponds to the CO_2 saving, achieved by replacing the boiler by a heat pump to satisfy a part of the hot utility. The global CO_2 savings are shown in table 5. It is important to remark that the CO_2 emission savings strongly depend on the way of electricity production.

6 Conclusion

A method for calculating the optimal integration of heat pumps has been presented. The method is part of a methodology for analyzing the energy efficiency of industrial processes and is demonstrated on an application in the food industry. Heat and water are the major utilities and production supports in the food industry, and therefore the method also integrates an analysis of the water management in the plant. Considering that both the temperature of water and its purity have a value, a combined heat and water approach is proposed. The proposed method is based on the application of process integration techniques that considers not only the heat recovery between process streams but also the integration of the energy conversion system. This is realized by applying a linear programming model that allows one calculating the optimal flows in the integrated utility system. The major advantage of the proposed approach is that it allows to consider the energy conversion system as a whole. The application of such methods shows that the model is able to represent interactions between utility streams. In the calculated solution, the heat pump not only valorizes excess heat from the process but also indirectly valorizes the heat excess of the refrigeration cycle. It is also shown that the integration of a cogeneration unit will profit from the integration of the heat pump. While providing the mechanical power to the heat pump, the cogeneration unit will supply heat to the process, that is not supplied by the heat pump. As for the primary energy savings, this value strongly depends on the electricity production mix. Applying the "more in-more out" principle, this leads also to a reduction of cooling water used in the plant. Although investment cost have not been included in the optimization, the thermodynamic analysis also defines an indicator of profitability of the heat pump by defining the break even cost of the energy conversion system investment.

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