Energy integration study of a multi-effect evaporator

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Abstract

In the pulp and paper industry, multi-effect evaporators are used to evaporate water from black liquor solutions to allow its recycle as chemicals and fuel for the process. The thermodynamic principle of the multi-effect evaporator consists in a serie of reboilers operating at different pressures; the water evaporated at one stage is condensed and used as the heat source for another stage. Due to its strong integration with the process, it is worth to analyse the integration of the multi-effect evaporator with the rest of the process.

To do so a thermo-economic analysis model of the evaporation system has been developped. The example is based on the evaporation system of a calcium bisulfite pulp manufacturing mill located in Switzerland. This system involves 3 multi-effect evaporators fed at different concentrations of black liquor. A systematic analysis of the system Grand composite curve has been developed to identify pertinent process modifications. From this analysis, several modifications like decreasing the ΔTmin of a stream, increasing or decreasing pressures of evaporation effects have been evaluated. For each of these measures, we have analysed the thermo-economic aspects, adapting the pinch analysis rules to account for the thermo-econmic benefit of integration. By these measures, the minimum energy requirement of the multi-effect evaporation system can be reduced by up to 20%. Resulting from the integration of the utility system, the related utility cost can be diminished of up to 23% from the base case model.

The integration of heat pumping system and the utilities has then been analysed in order to reduce the exergy degradation in the energy conversion system. A thermo-economic analysis including operating and investment cost estimation, evaluation of the Net Present Value and Payback Time of different process configurations corresponding to different energy savings scenarios has been performed. The integration of a heat pump system shows a reduction of the Net Present Value and an acceptable Payback Time compared to the base case model. A sensitivity analysis on electricity and natural gas prices has then been performed in order to better understand the economic condition of the integration.

Keywords: multi-effect evaporators, energy integration, heat pumps, thermoeconomic analysis, pulp and paper, pinch analysis

Nomenclature

Abbreviations

HEX	Heat exchanger	-
IC	Investment cost	k€
$MILP$	Mixed Integer Linear Programming	-
N_{minMER}	Minimum number of HEX units	-
NPV	Net Present Value	k€
OC	Operating cost	k€
PBT	Payback Time	y

Thermoeconomic analysis

$A_{HEX_{n+1}}$	Remaining HEX area	m^2
$C_{HEX_{n+1}}$	Cost of the remaining HEX area	k€
ΔTln_V	Temperature difference	K
$\dot{C}_e$	Electricity cost	k€/MWh
$\dot{C}_f$	Fuel cost	k€/t
$\dot{C}_v$	Steam cost	k€/t
$\dot{E}$	Electricity power	kW
$\dot{m}_f$	Fuel flowrate	t/h
$\dot{m}_v$	Steam flowrate	t/h
$\dot{Q}_i$	Heat load of effect i	kW
$\dot{Q}_t$	Total heat load of all evaporator effects	kW
$\dot{Q}_v$	Heat load of vertical exchange	kW
A_i	HEX area of effect i	m^2
A_{total}	Total HEX area	m^2
$C_{HEX_{total}}$	Cost of total HEX area	k€
C_{inv}	Annualised value of the investment cost	k€
C_i	Cost of HEX area of effect i	k€

C_{op}	Annual operating cost of the process	k€
C_{total}	Annual total cost of the process	k€
i	Annualised interest rate	%
l	Expected lifetime of the equipment	y
n_V	Number of vertical sections in the composite curve	-
$time$	Yearly operating time	h/y
U_V	Heat transfer coefficient	W/m^2K
Model		
ΔT_{BP}	Boiling point rise	°C
$Sicc$	Solid content	% wt
T_{boil}	Boiling temperature of the substance	°C
$T_{BP}(P)$	Boiling temperature of pure water (at the pressure P)	°C

1 Introduction

The reduction of the energy costs is one of the main concerns of the pulp and paper industry. In chemical pulping processes, such as Kraft or sulfite wood pulping, the main energy source comes from the residual liquor charged in lignin and exiting the chips cooking section. Multi-effect evaporators are used to evaporate water from black liquor solutions to allow its recycle as chemicals and fuel for the process. The thermodynamic principle of the multi-effect evaporator consists in a serie of reboilers operating at different pressures; the water evaporated at one stage is condensed and used as the heat source for another stage [9]. The objective of the evaporation process in a pulp mill is to increase the pulp solid content from 10-18% after pulp washing up to 60-70% in order to obtain a liquor with the highest possible solids concentration and minimal corresponding viscosity. The concentrated liquor is then treated to produce lignosulfonate products and/or to recycle the chemicals and produce process heat in the recovery boiler. Large amount of water (between 5 and 7 kg water per kg dry solids [3]) must be evaporated in order to maximize the net calorific value in the boiler. Due to its strong integration with the process, it is worth to analyse the integration of the multi-effect evaporator with the rest of the process.

The recovery boiler typically produces 60 to 80% of the steam demand of the mill [1] in which liquor evaporation accounts for almost 12% [3]. The objective of this study has been to identify the opportunity of reducing the energy consumed in the evaporator section of a sulfite wood pulping mill located in Switzerland. The project includes an energy integration study, a thermo-economic analysis and a sensitivity analysis on uncertain parameters such as electricity and natural gas prices.

2 Case study

The method is applied to a bisulfite pulp mill located in Switzerland that produces 127 000 t/y of cellulose as a main product. This cellulose is used for pulp making and as chemical intermediate and plastic moulding. The mill operates also as a biorefinery concept since it produces by-products such as yeast, ethanol and lignin and fuel for the main boiler of the mill. The multi-effect evaporator studied concentrates liquor from 11.8% to 50.1%. The diluted liquor leaving the digester section is collected in a tank (diluted liquor tank) before reaching the evaporator. In the mill, there are three trains of multiple-effect evaporators called *EA1*, *EA2*, and *EA3* (Figure 1). The diluted liquor is sent toward the trains *EA1* and *EA3*. At the exit of these trains the liquor has a solid content respectively equal to 15.2% and 50.7%. The concentrated liquor exiting the EA1 is mixed with part of the liquor diluted and sent in the *EA2* at a solid content of 14.1% to reach, after the evaporators bodies, a solid content of 50%. The concentrated liquor exiting *EA2* is mixed with the output of *EA3* obtaining a concentrated liquor with a solid content of 50.1% that is stored in a tank (concentrated liquor tank). An amount of the evaporated water is present as output from each train. It is collected and sent to the biological treatment plant (cleaning condensate). The total mass flow rate of liquor treated in the evaporators is equal to 9 t/adt of pulp. The mass flow rate of concentrated liquor before combustion in the recovery boiler is equal to 2.2 t/adt of pulp. The balance between these two numbers corresponds to the evaporated water mass flow of 6.8 t/ adt of pulp (76%). The efficiency of the system is calculated considering the flow of steam per unit of evaporated water, it corresponds to 0.33 t of steam/t per ton of water.

The pressure of the liquor in storage tanks is supposed equal to 1 bar. In Table 1, the mass flow and solid content of liquor at the entrance and the exit of evaporator trains are summarized while in Table 2, the steam mass flow injected in each train and the evaporated water exiting each train is shown. Each train is constituted by a multiple-effect evaporator with several stages/effects of evaporation and operated at different pressures as shown in Table 3. In each train, the liquor enters first the evaporator at a lower pressure and, as it is concentrated, it passes through the stages at higher pressure. As the pressure increases, the temperature increases too and the volume of liquor decreases. The evaporator is characterized by a counter-courrent configuration. Trains *EA2* and *EA3* use steam as source of heat for the first stages while *EA1* uses ethanol coming from a distillation column of the process. Ethanol enters stage *ST10EA1* and *ST11EA1* at 107°C and 1.38 bar, steam at 146°C and 2.6 bar enters the *ST1EA3* and steam at 147°C and 2.8 bar enters the *K1EA2* and *K2EA2*.

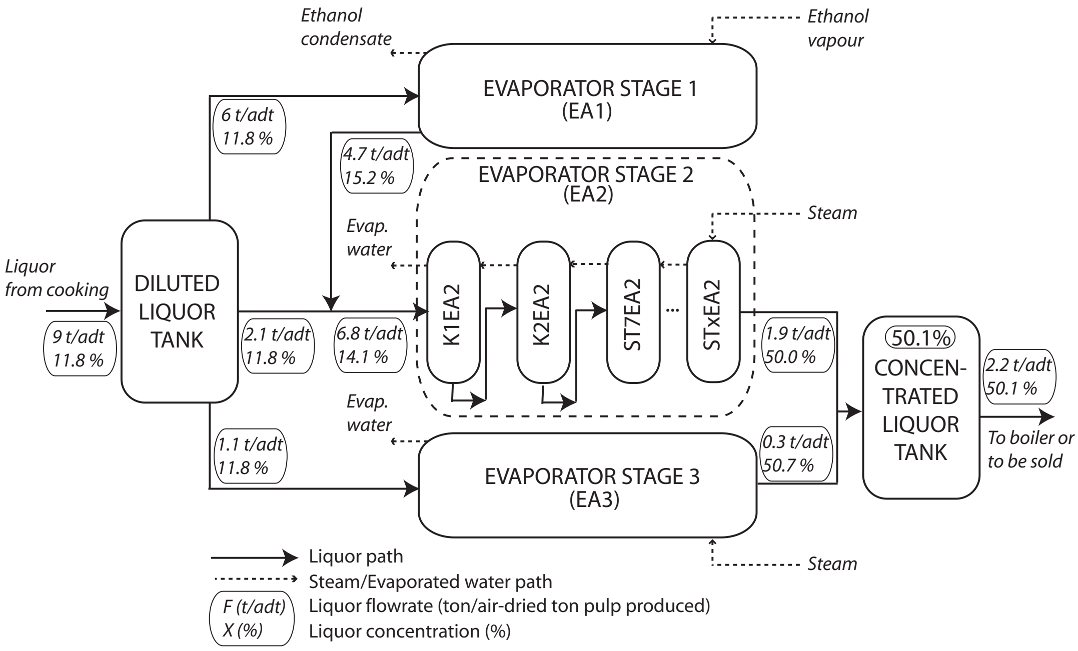

Figure 1: Simplified evaporator diagram

Table 1: Characteristics of liquor

Train	**Input**		**Output**	
	Mass flow (t/h)	Solid content (%)	Mass flow (t/h)	Solid content (%)
EA1	84.0	11.8	5.2	15.2
EA2	94.9	14.1	26.8	50.0
EA3	15.0	11.8	3.49	50.7

Table 2: Characteristics of steam and water evaporated in trains (*equivalent to ethanol vapor used)

Train	**Steam injected** (t/h)	**Water evaporated** (t/h)
EA1	11.3*	18.8
EA2	17.7	67.5
EA3	3.4	11.4
Total	32.4	97.7

3 Model

The model of the evaporator has been built using the equation-solver data-reconciliation software VALI 4.3.0.2 (Belsim s.a, 2005). Liquid and vapor equilibria have been taken into

Table 3: Stages and operation parameters of the evaporator system

Train	**Stage**	**Pressure** (bar)	**Concentration** (%)	**Temperature** (°C)	**Evap. water** (t/h)
EA1	*ST10EA1*	0.62	16.2	88.2	3.6
	ST11EA1	0.62	15.5	88.1	2.5
	ST12EA1	0.43	13.9	78.9	4.9
	ST13EA1	0.31	13.1	71.1	3.7
	ST14EA1	0.21	12.4	62.3	4.1
EA2	*K1EA2*	1.78	48.1	124.2	8.3
	K2EA2	1.78	37.5	121.4	8.1
	ST6EA2	0.98	30.7	102.6	14.7
	ST7EA2	0.53	22.9	85.2	14.3
	ST8EA2	0.29	18.4	70.1	10.9
	ST9EA2	0.14	16.1	54.1	11.1
EA3	*ST1EA3*	1.02	49.8	108.1	3.1
	ST3EA3	0.49	26.4	83.7	2.8
	ST4EA3	0.27	18.7	68.6	2.9
	ST5EA3	0.14	14.3	53.9	2.6

account and the boiling rise point of the liquor (ΔT_{BP}) has been calculated taking into account the siccity percentage of the liquor ($Sicc$) at the exit of each stage of evaporation as shown in the equations 1 and 2 below [11]. Heat losses and pressure drops in piping and equipment have been assumed to be negligible. Pump efficiencies have been assumed at 80%.

$$\Delta T_{BP} = \frac{8 * Sicc}{100 - Sicc} \tag{1}$$

$$T_{boil} = T_{BP}(P) + \Delta T_{BP}(Sicc) \tag{2}$$

Starting with the present configuration, the heat transfert requirement model that defines the hot and cold streams to be considered in the pinch analysis, is defined by assembling generic evaporation effect as depicted on Figure 2. The liquor is pumped at the pressure P and enters the actual effect through stream ($LIQ\ IN_N$). Liquor is evaporated using a thermal stream (Q_N) supplied by steam or by evaporated water from the effect (N). The evaporated water ($EVAP\ WATER_N$) exits the effect at a fixed pressure and passes through an heat exchanger (HEX) to extract the heat (Q_{N+1}) used for the evaporation of the liquor of effect ($N + 1$). The concentrated liquor ($LIQ\ OUT_N$) goes to the next effect. The operating condition and the corresponding heat load are obtained when the pressure of the effect is fixed. The initial value of the pressures are the one observed in the actual train.

The objective of an energy integration study is to define the process requirements and identify the energy recovery potentials [5] [6] [8]. In order to identify the heat recovery potentials, the evaporators model has been adapted using a generic evaporation stage heat integration

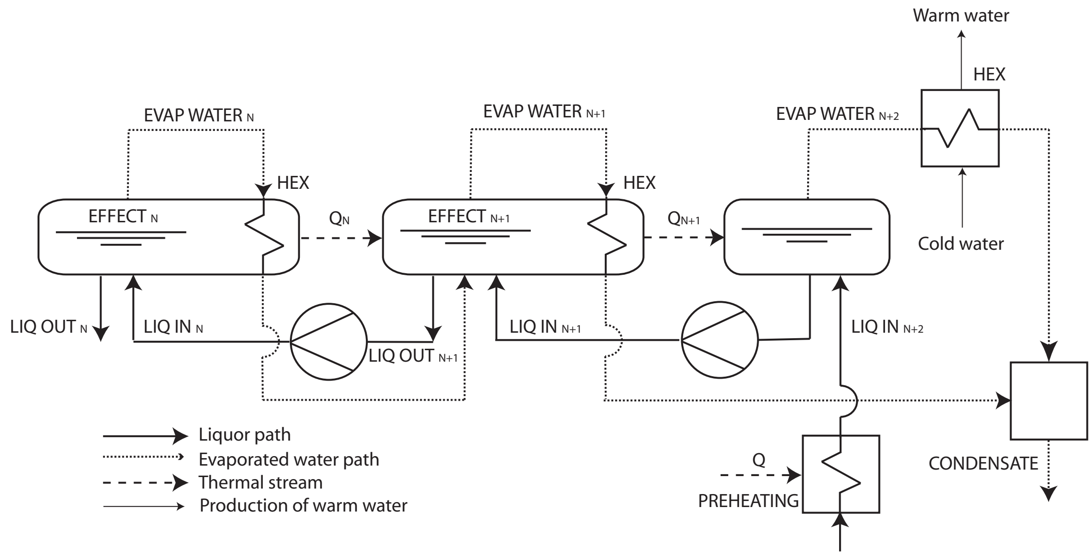

Figure 2: Illustration of the actual model of evaporators

model (Figure 3): the evaporated water leaving each effect is cooled down until ambient temperature (T ambient) and the related heat amount that can be recovered from this stream is obtained. The heat necessary for the liquor evaporation is supplied by thermal streams (Q) at constant temperature. This modelling strategy is creating more streams than really observed since some of them will indeed be mixed before heat exchange. The mixing problem will be solved during the heat exchanger network design phase when the heat recovery target is defined and the operating conditions are fixed. The major advantage of this representation is to decouple the heat exchangers between the evaporation train and therefore take advantage of the heat recovery potentials even between stages.

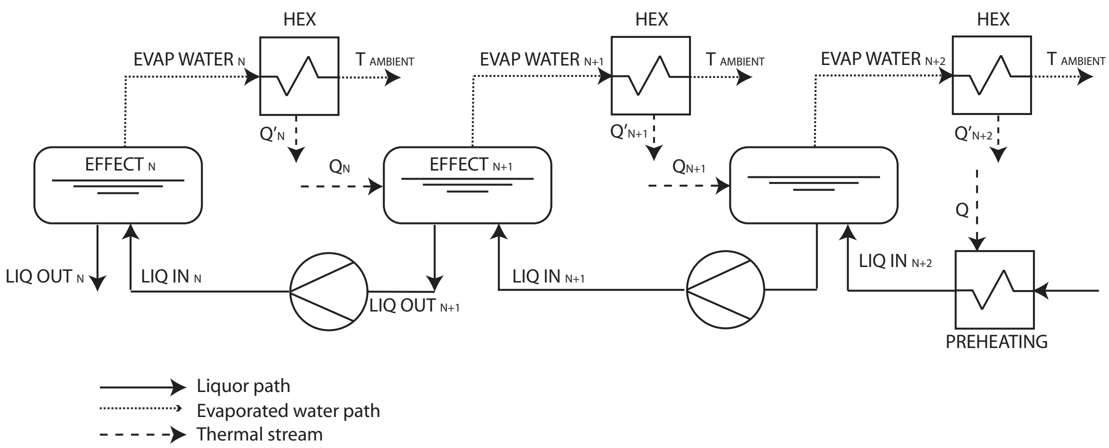

Figure 3: Illustration of the simplified model of evaporators

4 Energy integration

4.1 Defining actual process requirement

Pinch Analysis aims at identifying the heat recovery between hot and cold streams in a system [4]. It is based on the assumption of a minimum approach temperature difference in counter-current heat exchanger. The pinch analysis starts with an inventory of the hot and cold streams of the process. The streams are then integrated to build hot and cold composite curves. Realising counter-current heat exchanger allows one to compute the maximum possible heat recovery between hot and cold streams in the process and by energy balance obtain the minimum energy requirement. The Grand composite curve represents the overall balance and shows in a temperature-enthalpy diagram, the temperature level on which the energy has to be supplied (cold stream) or removed from the process (hot stream). By defining the hot and cold streams, the composite curves can be drawn and are illustrated in Figure 4.

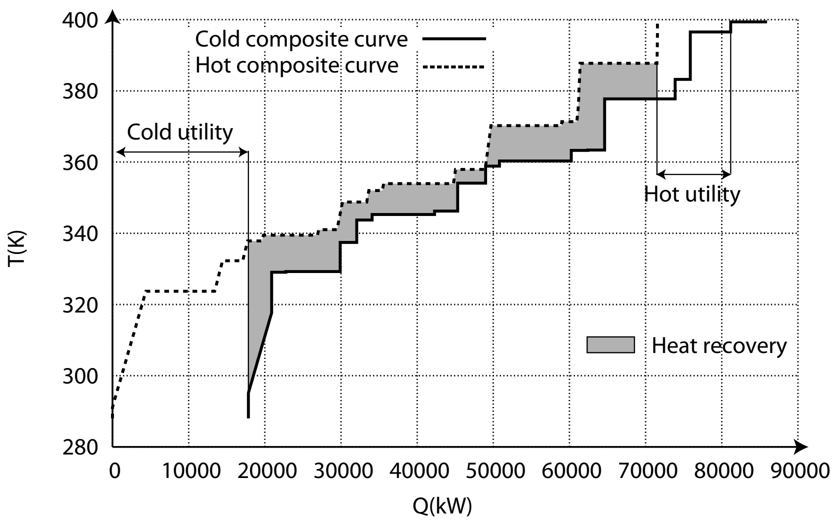

Figure 4: Hot and cold composite curves of the evaporator section

On Figure 4, three important zones can be distinguished: the hot utility requirement (14 405 kW), the heat recovery zone representing the possible heat recovery by exchanging between hot and cold streams of the process and the cold utility requirement (17 843 kW) corresponding to the remaining heat of the hot streams that has to be evacuated by a cold utility.

The Grand composite curve (Figure 5) allows one to analyse the heat-temperature profile of the heat requirement. This curve will also be used to identify the possible changes in the operating pressure that will lead to higher heat recovery opportunities transfering cold streams from above to below the pinch or hot streams from below to above process pinch point. When such condition cannot be reached by process operating conditions changes, the analysis will show the optimal placement of mechanical vapor recompression or thermal recompression.

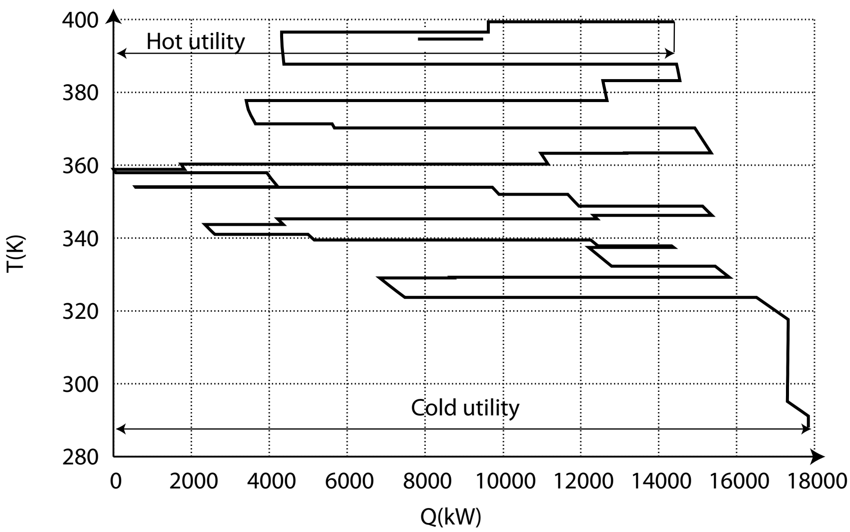

Figure 5: Grand composite curve of the evaporator section

4.2 Scenarios to reduce the utility requirement

The location of the pinch point is the key value for suggesting pertinent modifications of the process [6]. Such modifications can be suggested by analysing the composite curves. Three major modifications have been identified (Table 4) and shown in Figure 6. We first modify the operating pressure. In order to avoid modifying the pressure, another option is to modify the $\Delta Tmin$ assumption of a specific stream. Changing the value of a single $\Delta Tmin$ correspond to decide the investment of a well identified heat exchanger. Therefore the investment-energy trade-off will be analysed for this specific heat exchanger and the feasibility of the $\Delta Tmin$ assumption will be validated by an economical evaluation.

Table 4: Scenarios (modifications) to reduce utility requirement

Scenario	Envisaged modification	Value
0	Reference case	-
1	Increase pressure of effects ST10EA1 and ST11EA1	0.62 to 0.75 bar
2	Decrease $\Delta Tmin/2$ of evaporating stream of ST7EA2	2 to 1 K
3	Increase pressure of effect ST13EA1	0.31 to 0.38 bar
	Decrease pressure of effect ST4EA3	0.27 to 0.20 bar

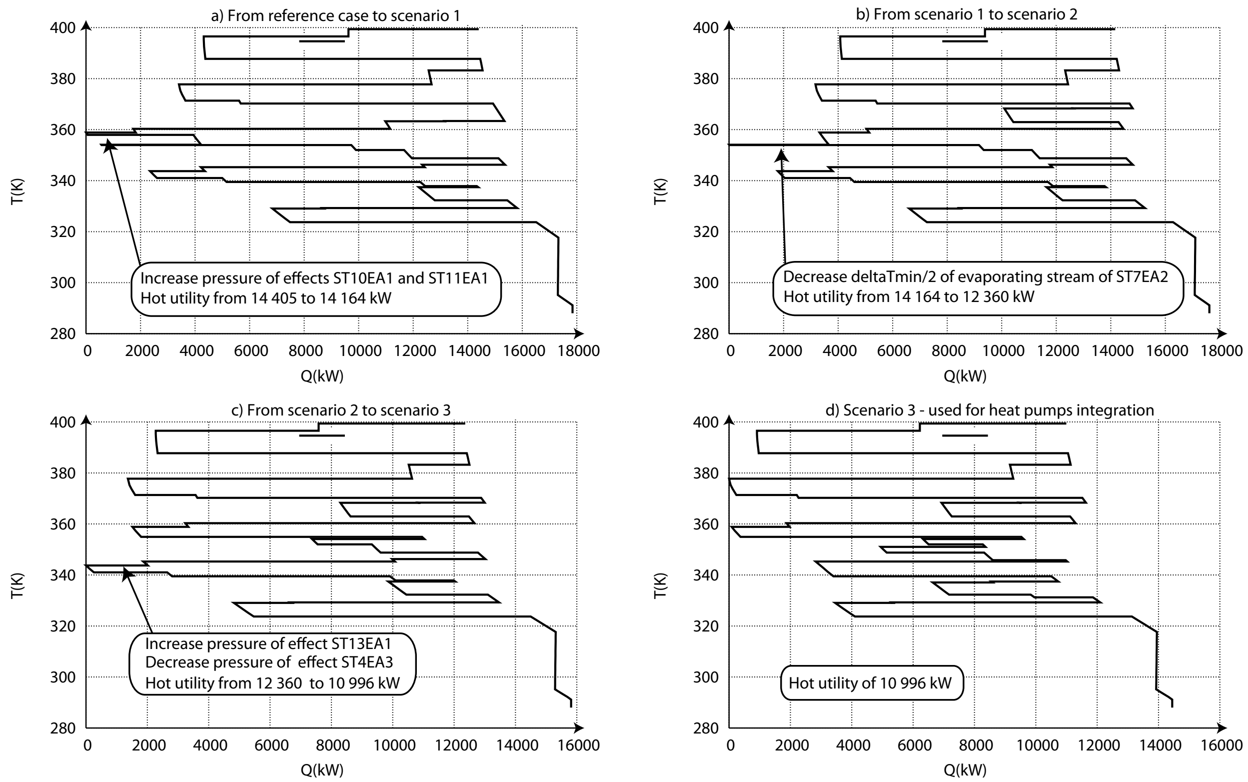

Figure 6: Scenarios to reduce the energy requirement

For each scenario, the utility requirements and the heat exchanger area are calculated and the corresponding costs are estimated in Table 5. The energy integration study has been done with *EASY* and *OSMOSE* (LENI, 2008). *EASY* stands for Energy Analysis and SYnthesis, it has been developed to solve process integration problems for problems where flowrate of streams have to be optimised. It is therefore mainly developed for optimising the integration of the utilities and the combined heat and power production. *OSMOSE* is a Matlab platform designed for the study of energy conversion systems. The platform allows to link several tools, like flowsheeting, process integration optimisation and thermo-economic evaluation softwares. Among other features, *OSMOSE* offers a complete suite of computation and results analysis tools (optimization, sensitivity analysis, pareto curve analysis, etc.).

When compared to the reference case, these changes allow one to reduce the heat requirement from 1.5%, 12.6% and 21.1% respectively; while the heat exchanger area increases by 4.7%, 36.4% and 59.4% respectively. The utility costs are consequently lower from a scenario to another while the investment cost for heat exchanger increases. The greatest change is observed between scenario 1 and 2. Passing from scenario 0 (reference case) to scenario 1 implies a small decrease in utilities cost. The utilities cost decreases significantly when passing from scenario 1 to 2 while the cost of the heat exchanger area increases also a lot. Finally passing from scenario 2 to 3 implies a large diminution of utilities cost but a smaller augmentation of the heat exchanger area cost. All results are resumed in Table 6.

Table 5: Scenarios for reducing the energy requirement for the multi-effect evaporation trains

	Scenario 0	**Scenario 1**	**Scenario 2**	**Scenario 3**
Pinch point (corr.temp) (K)	359	354	344	378
Hot utility requirement (kW)	14 405	14 164	12 360	10 996
Cold utility requirement (kW)	17 843	17 616	15 813	14 447
Hot utility cost (k€/y)	1245	1224	1068	950
Cold utility cost (k€/y)	154	152	137	125
Cost total utilities (k€/y)	1399	1376	1205	1075
Total HEX area (m^2)	3875	4058	5286	6176
NminMER	16	16	16	16
HEX area (m^2)	242	254	330	386
Cost total HEX area (k€)	603	633	749	763
Cost total HEX area/y (k€/y)	70.43	73.95	87.55	88.99

Table 6: Comparison of energy saving scenarios for the multi-effects evaporation train

	Scenario 0	**Scenario 1**	**Scenario 2**	**Scenario 3**
Comparison with the reference case				
Utility demand (%)	-	-1.5	-12.6	-21.1
Cost total utilities (%)	-	-1.6	-13.9	-23.2
Total HEX area (%)	-	+4.7	+36.4	+59.4
Cost total HEX area year (%)	-	+5.0	+24.3	+26.4
Comparison between each scenario				
Utility demand (%)	-	-1.5	-11.3	-9.7
Cost total utilities (%)	-	-1.6	-12.5	-10.8
Total HEX area (%)	-	+4.7	+30.3	+16.8
Cost total HEX area year (%)	-	+5.0	+18.4	+1.6

In Table 6, the heat exchanger investment is estimated applying on adapted formulation of the targeting method [2]. It is based on the assumption of the vertical heat exchanges in the composite curves (Figure 4). The calculation of the minimum number of units (NminMER) accounts for the possible mixing of condensate before heat exchange. Simple calculations have been done to obtain the total heat exchanger area and consequently its cost. The method is resumed in equations 3, 4 and 5. The cost of the remaining heat exchanger used to preheat the liquor is obtained with equation 6

$$A_i = \frac{A_{total}}{\dot{Q}_t} \cdot \dot{Q}_i \tag{3}$$

$$A_{total} = \sum_{k=1}^{n_V} \frac{\dot{Q}_V}{U_V \cdot \Delta Tln_V} \quad (4)$$

$$C_{HEX_{total}} = \sum_{i=1}^{15} C_i = \sum_{i=1}^{15} C(A_i) \quad (5)$$

$$C_{HEX_{n+1}} = C(\frac{\dot{Q}_t - \sum_{i=1}^{15} \dot{Q}_i}{\dot{Q}_t} \cdot A_{HEX_{n+1}}) \quad (6)$$

5 Energy saving options

The analysis of the grand composite curve of the evaporation system obtained after process improvements allows one to identify the characteristics of the energy conversion systems as well as the possibility of integrating heat pumps and cogeneration devices as shown in Figure 7. A heat pump accepts heat at a lower temperature and, by using mechanical power, makes it available for heat exchange at a higher temperature. By balance, the heat available is the sum of the input heat and the mechanical power. Heat pumps provide a way of using waste heat for useful process heating. In the present case, the optimal system consists in the integration of three heat pumps around hot concentrated liquor streams and their corresponding evaporated water streams in train *EA2*, effects *K1EA2-K2EA2*, *ST6EA2* and *ST7EA2*.

In Figure 7, the heat pumps are represented by hot and cold streams. This allows one to visualize the heat pumping effect considering the heat pump as a closed-loop system. On the figure, one could observe that the flow in the heat pumps is optimized to activate the utility pinch points. One can also see the indirect cascading effect between the heat pumps, a lower pressure heat pump requiring at the end a higher pressure heat pump to reveal its effect. The flow is computed by applying the MILP formulation of the heat cascade [7]. In reality the heat pumping effect will be reduced using mechanical vapor recompression. The flows of the recompressed streams will be computed in the closed-loop system.

5.1 Thermoeconomic analysis

The final objective of an energy integration study is the evaluation of the thermoeconomic performance of the best energy savings scenarios. The profitability of the energy integration project (through modifications of the process) and the corresponding energy saving project is assessed by studying the trade-off between the investment and the obtained saving/benefit for a given lifetime of the installation [10].

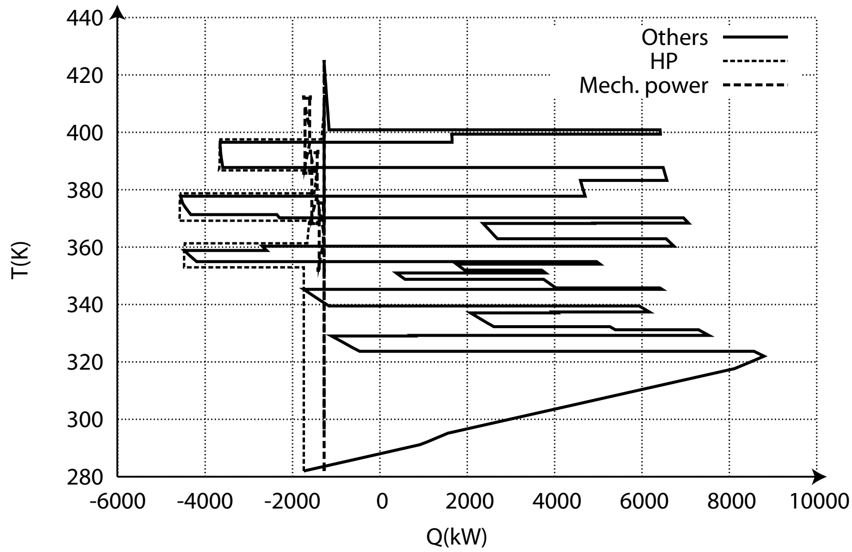

Figure 7: Possibilities of heat pump integration on the Grand composite curve of the evaporation system

In order to compare and evaluate the relevance of the proposed solutions and to study the sensitivity of key parameters, the total cost comprising the investment and the operating costs is calculated with the equations 7, 8, 9.

$$C_{total} = C_{inv} + C_{op} \tag{7}$$

$$C_{inv} = IC\frac{i\,(1+i)^l}{(1+i)^l - 1} = IC\frac{i}{1-(1+i)^{-l}} \tag{8}$$

$$C_{op} = (\dot{m}_v C_v + \dot{m}_f C_f + \dot{E}C_e/1000) * time \tag{9}$$

For this study, the lifetime of the equipment is supposed equal to 15 years and the operating time is 8000 h/y. Saving percentage is evaluated compared to the reference case. The Net Present Value and the Payback Time have been considered as decision parameters for the identification of valuable scenarios.

Table 7 list for each scenario of Table 5 the operating (OC), investment (IC) and total (TC) costs and saving obtained for each scenario compared to the original one. The operating cost reduction (ΔOC) and the investment cost reduction (ΔIC), respectively the difference of operating cost and investment cost between each scenario and the reference case, are computed as well as the difference of the annualized investment cost ($\Delta IC/y$)

Table 7: Operating, investment and total cost and savings for the proposed scenarios

	Steam (kg/s)	**OC** (k€/y)	ΔOC (k€/y)	**IC** (k€)	ΔIC (k€)	$\Delta IC/y$ (k€/y)	**TC** (k€/y)	**Savings** (k€/y)	**(%)**
Scenario 0	6.497	2807	0	4427	0	0	2807	0	0
Scenario 1	6.390	2761	-46	4530	103	112	2773	34	1.2
Scenario 2	5.575	2408	-398	4896	469	55	2463	344	12.2
Scenario 3	4.960	2143	-664	5019	592	69	2212	595	21.2

Table 8 shows Payback Time ($\Delta OC/\Delta IC$) of the options. The Net Present Value corresponds to the excess or shortfall of cash flows, in present value terms, once financing charges are met.

Table 8: Net Present Value and Pay Back Time for scenario

	NPV (k€/y)	**PBT** (year)
Scenario 1	272	3
Scenario 2	2724	2
Scenario 3	4717	1

The heat pump integration is analysed for scenario 3. The operating cost is evaluated in function of the electricity and natural gas costs. The investment cost comprise the purchase of compressors and heat exchanger for each heat pump.

In Table 9, the operating (OC), investment (IC) and total (TC) costs and saving obtained of scenario 3 and scenario 3 with integrated heat pumps compared to the original one are shown.

Table 9: Operating, investment and total cost and savings for the proposed scenarios

	OC (k€/y)	ΔOC (k€/y)	**IC** (k€)	ΔIC (k€)	$\Delta IC/y$ (k€/y)	**TC** (k€/y)	**Savings** (k€/y)	**(%)**
Scenario 0	2807	0	4452	0	0	2807	0	0
Scenario 3	2143	-664	5019	592	69	2212	595	12.2
Scenario 3 + HP	1647	-1160	7007	2555	376	2023	784	27.2

At the chosen natural gas and electricity prices (0.280€/kg and 0.043€/kWh), the scenario 3 with integrated heat pumps is advantageous and shows a Payback Time of 4 years.

5.2 Sensitivity analysis

Since the natural gas and electricity price could vary on the market, as well at the interest rate, a sensitivity analysis has been done on these parameters.

The relative price of fuel and electricity is quite important. A combined analysis of the electricity price and the natural gas price can be useful to evaluate the profitability of the heat pump integration in the process. The break-even value of the electricity price that make the heat pump profitable is given on Figure 8 for a natural gas price varying from 0.013 to 0.021€/kWh.

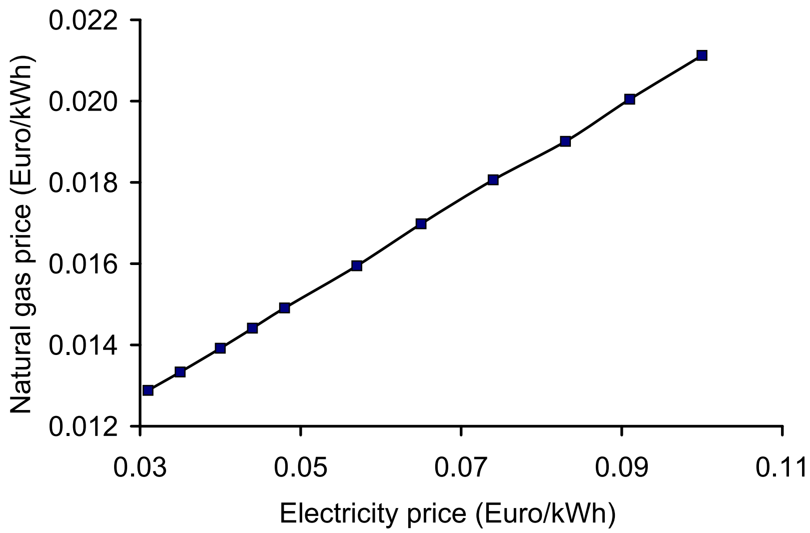

Figure 8: Gas and electricity costs ratio for well integrated heat pumps

The interest rate together with the lifetime and the operating time has also an important impact on the profitability. The original analysis was done with an interest rate equal to 8%. The interest rate has been calculated for each proposed scenario to obtain a net present value equal to zero. Results are shown in Table 10. It corresponds to the interest rate that a bank should proposed to be competitive with the investment.

Table 10: Interest rate, NPV=0

	i (%)
Scenario 1	44.1
Scenario 2	83.6
Scenario 3	110.3

For the scenario 3 with well integrated heat pumps, the minimum interest rate that competes with the investment has been evaluated for a range of electricity prices and is shown in Figure 9.

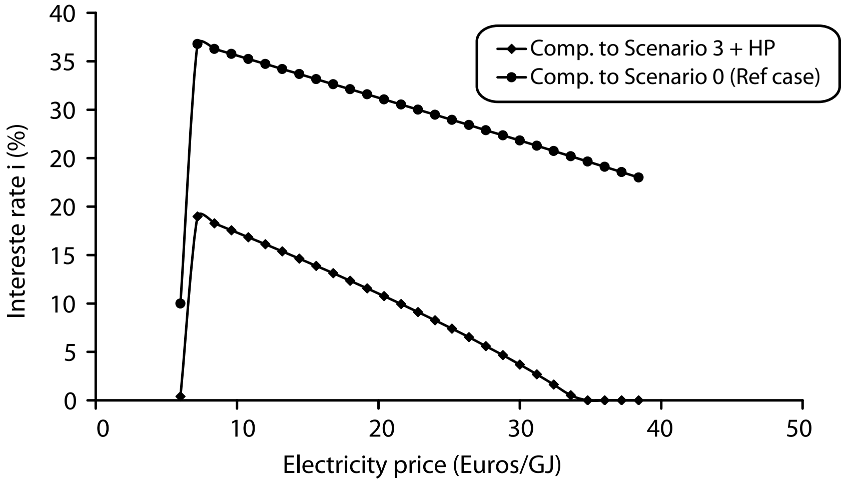

Figure 9: Gas and electricity costs ratio for well integrated heat pumps

6 Conclusion

Liquor evaporation is an important energy consumer in a pulp and paper mill. The study focuses on the identification of actions to reduce the energy cost related to the evaporator section of a sulfite wood pulping mill located in Switzerland. The potential energy recovery by heat exchange has been evaluated using process integration techniques. The energy saving measures concern the modification of the operation conditions of the decrease of the ΔTmin assumption and increasing or decreasing pressures of evaporation effects allowed one to reduce by 20% the minimum energy requirement of the evaporation system with an associated utility cost reduction of 23%. Heat pumps integration has been also included in the study and shows its asset by a cost reduction of 27% comparing with the reference case and a payback time of 4 years. Due to the variability of natural gas and electricity prices on the market, a sensitivity analysis has been done and a corrolation between natural gas and electricity prices for a valid domain of heat pump integration has been elaborated.

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References

[1] NLK Consultants Agra Simons. Energy cost reduction in the pulp and paper industry. *Pulp and Paper Research Institute of Canada*, pages 91–94, 1999.

[2] S. Ahmad, J. Linnhoff, and R. Smith. Cost optimum heat exchanger networks, 2 targets and design for detailed capital cost models. *Computers and Chemical Engineering*, 14(7):751–767, 1990.

[3] J. Jacob. Report for AICHE - Pulp and Paper Industry - Energy Bandwith Study. *Institute of Paper Science and Technology*, pages 59–66, 2006.

[4] Ian.C. Kemp. *Pinch analysis and process integration: a user guide on process integration for the efficient use of energy.* Second Edition, Elsevier, Butterworth-Heinemann, UK, 2007.

[5] F. Marechal and B. Kalitventzeff. Targeting the minimum cost of energy requirements: A new graphical technique for evaluating the integration of utility systems. *Computers and Chemical Engineering*, 20(SUPPL.1), 1996.

[6] F. Marechal and B. Kalitventzeff. Energy integration of industrial sites: Tools, methodology and application. *Applied Thermal Engineering*, 18(11):921–933, 1998.

[7] F. Marechal and B. Kalitventzeff. Targeting the integration of multi-period utility systems for site scale process integration. *Applied Thermal Engineering*, 23(14):1763–1784, 2003.

[8] F. Marechal and B. Kalitventzeff. *Computer aided process and product engineering CAPE, chapter on utilities integration (energy, water).* Wiley - VCH, 2006.

[9] G.A. Smook. *Handbook for pulp and paper technologists.* Tappi Press, Second Edition, 1992.

[10] R. Turton, R.C. Bailie, W.B. Whiting, and J.A. Shaeiwitz. *Analysis, Synthesis, and Design of Chemical Processes.* Prentice Hall, New-York, 2002.

[11] F. Verstraeten. Rapport d'activité d'avril à septembre 1993 au Laboratoire d'Analyse et de Synthèse des Systèmes Chimiques de l'Université de Liège. Technical report, 1993.