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A dual representation for targeting process retrofit, application to a pulp and paper process

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Abstract

A method for the analysis of process energy requirements has been used to identify in an early design stage the potential process retrofit measures in an integrated pulp and paper mill. The minimum energy requirements (MER) of the process were computed by means of a dual representation that segregates the thermodynamic requirement of the process from its technological implementation. Energy and exergy recovery opportunities have been examined to improve the integration of the utility system to the process. An MILP optimisation targeting method has been applied to identify the best energy conversion options and to optimise the production of combined heat and power (CHP). Replacing the steam injections to mixing tanks by heat exchangers would decrease the MER by 10%, and increase the combined production of heat and power by a factor 1.7. Improving the exergy efficiency of the paper drying technology would be more difficult to implement, but the results indicate that this could bring an additional 12% gain of electricity cogenerated with no change to the MER.

Keywords: Utility system; Cogeneration; Process retrofit; Composite curves; Process integration; Pulp and paper; Combined heat and power; CHP; Targeting; Pinch analysis; Exergy analysis

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1. Introduction

The optimal design of a utility system should seek to meet the energy requirements of the process that it serves at a minimal cost. Pinch analysis [1] is a mature technology, which has been applied with success to the design of heat exchange networks (HEN) in a broad variety of industries including the pulp and paper industry [2]. In the targeting step performed before the HEN design, the minimum energy requirement to heat and cool all process streams to their functional specifications is first established. However, the method, as first proposed, is not well suited to tackle certain issues encountered when attempting to increase the energy efficiency of a process beyond the maximum internal heat recovery that can be achieved by implementing an optimised HEN. Furthermore, it only deals with the reduction of the heat requirement rather than reducing the process energy expenses.

Heuristic rules were first proposed by the developers of pinch analysis to provide guidance for the selection and the appropriate integration in a process of energy converting equipment such as turbines and heat pumps [3,4] while the concept of balanced composite curves [5,6] also broadened the scope of conventional pinch analysis to this type of application and the systematic search for solutions was made possible by developments of adapted optimisation algorithms [7]. The introduction of exergy composite curves [8] brought a new perspective to the identification and evaluation of process enhancement opportunities involving energy upgrading and conversion.

Maximising the flowrate of the cheapest utility leads to the creation of utility pinch points [5,6] and underscores the need to analyse simultaneously the utility and the process networks. Graphical techniques become impractical when cycles are concerned. A method based on the use of optimisation techniques [10,12,13] and the corresponding graphical representations [9] has therefore been proposed by Marechal and Kalitventzeff.

The cost of energy is a very significant factor in pulp and paper manufacturing [16] and the industry has invested many efforts to reduce it over the year [17]. System closure, i.e. the internal reuse of excess process water, using simulation and observation [20,21] or optimisation techniques [22], often entails a significant reduction in energy cost [18,19] and should be a preliminary to any energy optimisation project. For energy analysis *per se*, Pinch analysis has now become a routine tool and incursions have been made in extensions of the technique to specific cases such as, temperature mitigation by process streams mixing [23,24] or evaporator trains optimisation [25]. Effect modelling and optimisation concepts have also been applied in design methodologies related to reactive systems [15], or combining energy efficiency and environmental concerns [14,26].

The purpose of this work has been to develop a new method based on pinch analysis techniques and optimisation to identify and evaluate, at a very early stage of the study, the opportunities for reducing energy costs by improving the energy conversion in the process.

2. Illustrative case study

The method is applied to an integrated newsprint mill located in Canada. The nominal production of the mill is 1230 odt/d of paper with a feedstock of 1060 odt/d of thermomechanical pulp (TMP) and 170 odt/d of deinked pulp (DIP) also produced on site. A simplified process flow diagram focusing on steam and fresh water requirements is given in Fig. 1. The reference state of the

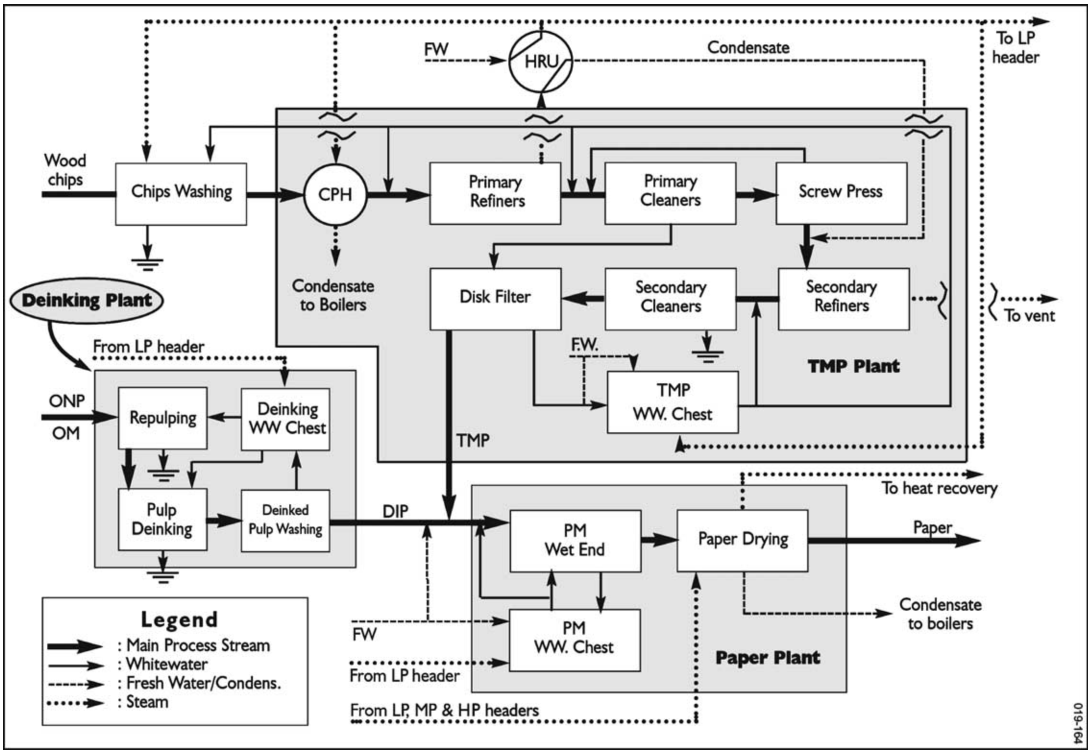


Fig. 1. Simplified reference process flow diagram. *Abbreviations*: CPH: chips pre-heather, HRU: heat recovery unit, OM: old magazines, ONP: old newsprint, PM: paper machine.

mill was based on information from several sources that have been reconciled using the VALI III software [27] to produce a coherent set of heat and mass balances and determine the hot and cold process streams characteristics.

High pressure steam (16.5 bar, 540 K) is produced by boilers burning biomass (wood residues) and natural gas (NG). It is in part directly used to meet some mill needs and in part depressurised through turbines and headers to three lower pressure levels: MP (4.5 bar, 421 K), LP (3.4 bar, 415 K) and VLP (1.7 bar, 408 K). As indicated on Fig. 2, steam is then directed to the TMP, DIP, paper making plants and other miscellaneous operations. Steam is also exported to an adjoining saw mill. The turbines produce 2 MWe of electricity, while the mill purchases 125 MWe.

The two most important operations from the energy standpoint are wood chips refining and paper drying.

Refining consists in disintegrating wood into individual fibres by forcing the chips between two grooved disks rotating at very high speed. It is a very energy intensive operation. In the mill analysed, the refiners consume 83.7 MWe or 6820 kJ/odt, (i.e. 2/3 of the total electrical consumption). The mechanical energy supplied to the refiners is largely dissipated into heat, which evaporates whitewater injected with the chips. In most mills, as in this one, the heat content of this medium steam is recovered through heat exchange with fresh water in the heat recovery unit (Fig. 1) since it contains wood contaminants and cannot be reused directly. In the reference case, the steam

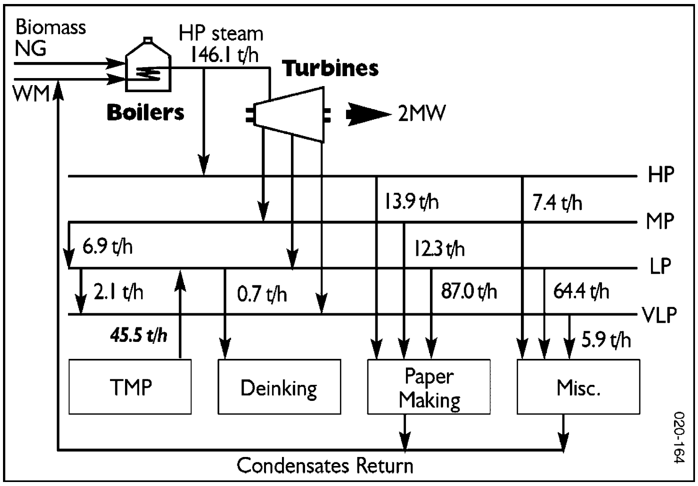


Fig. 2. Reference steam distribution system. *Abbreviations*: NG: natural gas, WM: water make-up.

from the primary refiner is released at medium pressure (MP) but is subsequently depressurised to low pressure (LP). The steam from the secondary refiners (1 bar, 273 K and 1.4 bar, 282 K) is not recovered currently.

Paper is dried in the end section of the paper machine by passing the sheet of paper over a series of steam-heated steel rolls. High-pressure steam is used at the end of the drying section where a high driving force is required, LP steam is used at the beginning and MP in the intermediate zone.

3. Representation of the thermodynamic and technological requirements

Correctly defining the temperatures and the heat loads of the hot and cold streams is crucial in process integration projects [6]. For this reason, the first step [14] is to define the operations required to transform raw materials into the desired products. The heating or cooling requirements are inferred from the operating conditions. In this respect, the MER may be computed in two different ways. The first (thermodynamic requirement) consist in determining the temperature profiles of the process streams that maximize the exergy supplied by the hot streams and minimize the exergy required by the cold streams. The second (technological requirement) is to consider the equipment used to convert utility streams into useful process heat. Those two approaches produce the same overall energy balance but with a different temperature profile. The shape of the composite curve may differ from one representation to the other. An example of this dual representation is shown on Fig. 3 for the case of water preheating by steam injection: the thermodynamic requirement corresponds to water preheating from its initial to its target state, while the technological requirement corresponds to the production of the injected steam. The area between the two exergy composite curves corresponds to the ”thermal” exergy losses due to the technological implementation of the operation.

The following sections discuss the dual representations of specific types of operations in the paper mill.

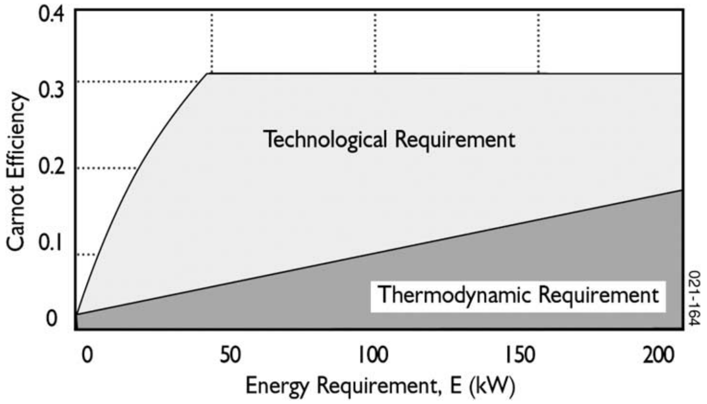
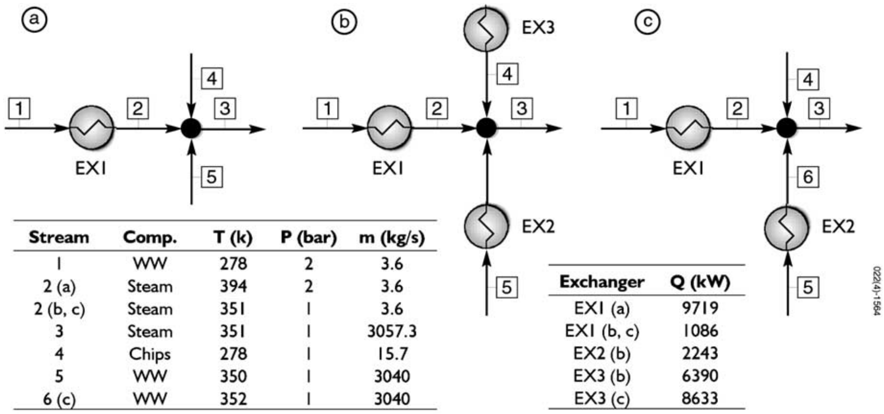


Fig. 3. Exergy composite curves for heating by steam injection.

3.1. Preheating by steam injection

The chip washing operation and the three main whitewater chests are heated by direct contact with steam (Fig. 1). This steam must be treated as loss by the utility network since it is not returned to the boilers as condensate. The thermodynamic requirement is defined by two cold streams in order to separate mass exchange from heat exchange. The first represents the heat required to raise the temperature of the process stream to tank mixing conditions. The second cold stream represents the heat required to raise the liquid water makeup that completes the mass balance from ambient (i.e. the water inlet temperature) to the reservoir mixing conditions. The technological requirement is a cold stream corresponding to the steam production from the water make-up temperature including its vaporisation at a constant temperature. Data are given on Fig. 4 for the wood chip washing operation. In the thermodynamic representation isothermal



Stream	Comp.	T (k)	P (bar)	m (kg/s)
1	WW	278	2	3.6
2 (a)	Steam	394	2	3.6
2 (b, c)	Steam	351	1	3.6
3	Steam	351	1	3057.3
4	Chips	278	1	15.7
5	WW	350	1	3040
6 (c)	WW	352	1	3040

Exchanger	Q (kW)
EX1 (a)	9719
EX1 (b, c)	1086
EX2 (b)	2243
EX3 (b)	6390
EX3 (c)	8633

Fig. 4. Thermodynamic and technological requirements for chips washing; (a) technological (reference case); (b) thermodynamic (reference case); (c) technological (proposed).

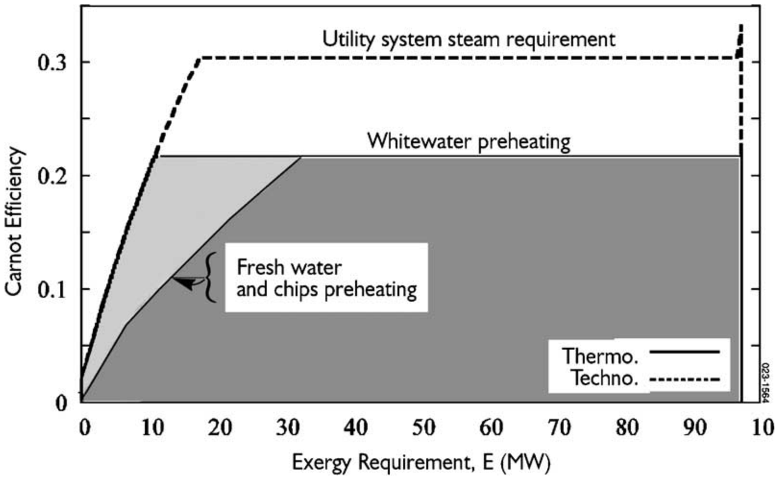


Fig. 5. Grand composite curves (GCC) for thermodynamic and technological exergy requirements for chips washing.

mixing is assumed, all the process streams entering the mixer having first been heated to the mixing temperature. In this case, the question of the feasibility of separately preheating wood chips in a heat exchanger may be raised. A compromise between the technological and the thermodynamic representation consists in increasing the temperature of the whitewater by heat exchange before mixing it with the chips (Fig. 4). In this alternative representation, the exergy loss is lower and does not imply any change in the mixing control strategy, since steam injection may be kept to control the temperature. The exergy composite curves of those three representations are given on Fig. 5.

3.2. Paper machine drying

There are two thermodynamic requirements for the drying section of the paper machine: preheating the humid sheet, and evaporating its water content which is reduced from 58% at the inlet of the drying section to 8% in the exiting paper. The technological requirements are defined by the steam production (cold streams) from water deaerator conditions to the steam temperature and pressure levels in the drying rolls. Since the steam is not fully condensed in the rolls, hot streams are added to represent the possibility of condensing and cooling down the remaining steam (about 15% of the steam delivered to the rolls) back to the deaerator conditions. The comparison of the two representations, based on the exergy composite curves is given on Fig. 6.

3.3. Primary and secondary refiners

Since the steam produced by evaporation of the white water in the refiners is not returned in the steam network, the thermodynamic and technological requirements are identically defined as a hot stream to be condensed and cooled to the ambient temperature.

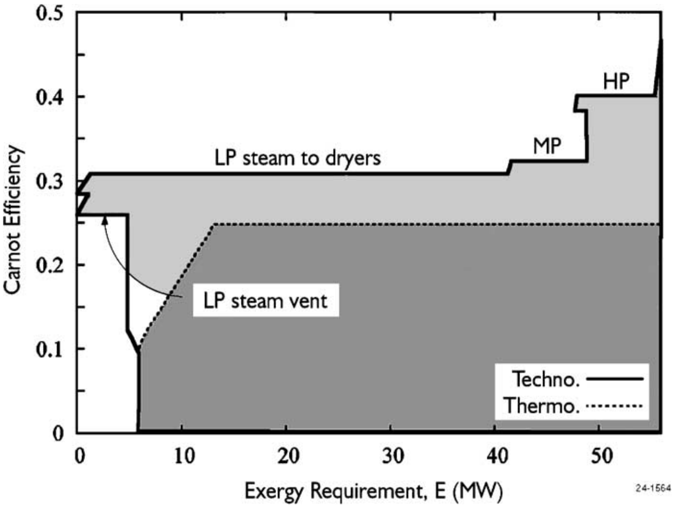


Fig. 6. Dual representation of the exergy GCC for the paper drying section.

4. Integration of the energy conversion system

The dual representation of energy requirements can be used in a retrofitting project to identify the operations that should be modified in order to reduce the energy costs. Two levels of energy savings are considered: the reduction of the MER and the maximisation of the combined heat and power (CHP) production (reduction of the exergy losses). The identification of the most profitable option cannot practically be done by graphical techniques due to the combinatorial nature of the problem. Using the optimisation algorithm given in [13,28], it is possible to determine the optimal integration of the energy conversion system, by minimizing the fuel and electricity consumption while maximizing the CHP production. The optimal flowrates to be considered in the energy conversion system can thus be computed. The dual representation is integrated in this approach; it is assumed that the process is defined by a set of operations, and that each operation may be represented by different sets of hot and cold streams (options). An integer variable y_{oi} represents the selection (or not) of the option *i*. The problem formulation is given in Appendix A. For each of the options, an implementation cost C_{oi} has to be introduced. The value of C_{oi} is zero when an option of the reference case is maintained or the annualised capital cost of a new retrofitted configuration. Using integer cut constraint [14], sets of options are systematically generated and compared on the cost of energy basis.

5. Pulp and paper process illustration

Table 1 gives the characteristics of the hot and cold streams for thermodynamic and technological requirements of each of the major energy consuming operations in the process shown on Fig. 1. Steam consumption for soot blowing and general heating has been assimilated to process requirements and the consumption for deaeration is treated as part of the steam network model. The secondary refiner steam will be recovered.

Table 1
Thermodynamic and technological requirements

Dual representation	Stream type	T_{in} (K)	T_{out} (K)	$\dot{m}\,Cp$ (kW/K)	Q (MW)	P (bar)
Wood chip washing						
Thermo. (chips)	Cold	278	351	31	2.2	–
Thermo. (WW)	Cold	350	351	13,595	6.4	–
Thermo. (makeup)	Cold	278	351	15	1.1	–
Techno.	Cold	278	394	Water	9.7	2.05
Preheat before primary refiners						
Thermo.		351	388	251	9.4	–
Techno.		394	408	Water	9.4	2.05
Preheat before secondary refiners						
Thermo. (makeup)	Cold	278	362	116	9.8	–
Thermo. (pulp)	Cold	324	362	60	2.3	–
Techno.	Cold	278	382	Water	12.1	1.40
TMP whitewater tank						
Thermo. (FW)	Cold	278	321	591	25.7	–
Thermo. (makeup)	Cold	278	321	32	1.4	–
Thermo. (WW)	Hot	324	321	2576	6.5	–
Techno.	Cold	278	373	Water	20.6	1
Deinking whitewater tank						
Thermo. (FW)	Cold	308	313	70	0.3	–
Thermo. (WW)	Cold	313	313	950	0.2	–
Thermo. (makeup)	Cold	278	313	1	0.03	–
Techno.	Cold	278	417	Water	0.5	3.43
Paper machine whitewater tank						
Thermo. (FW)	Cold	288	308	1004	20.2	–
Thermo. (makeup)	Cold	278	308	23	0.7	–
Thermo. (WW)	Hot	309	308	4768	5.8	–
Techno.	Cold	278	417	Water	15.1	3.43
Drying section						
Thermo. (heating)	Cold	309	363	42	2.2	–
Thermo. (drying)	Cold	309	373	Water	48.8	1.01
Techno.						
LP level	Cold	323	417	Water	47.6	3.43
MP level	Cold	323	421	Water	8.7	4.46
HP level	Cold	323	540	Water	10.7	16.52
LP level	Hot	394	323	Water	10.2	2.03
MP level	Hot	407	323	Water	2.3	3.06
HP level	Hot	472	323	Water	3.5	15.12
Conventional representation						
Primary refiners	Hot	421	298	Water	73.7	4.46
Secondary refiners	Hot	373	298	Water	14.3	1.00
Secondary refiners	Hot	388	298	Water	7.5	1.70
Heating	Cold	323	417	Water	30.1	3.43
Soot blowing	Cold	278	540	Water	6.0	16.52

Table 1 (*continued*)

Dual representation	Stream type	T_{in} (K)	T_{out} (K)	$\dot{m}$ Cp (kW/K)	Q (MW)	P (bar)
Effluent treatment	Cold	278	417	Water	1.5	3.43
Saw mill	Cold	278	417	Water	5.1	3.43
Boilers	Cold	323	417	Water	8.3	3.43
Deaerator	Cold	323	408	Water	3.8	1.70

Notes: FW: fresh water; makeup: water make up at the boilers; WW: whitewater.

5.1. Minimum energy requirement target

Fig. 7 compares the grand composite curves (GCC) of the thermodynamic and the technological requirements. The thermodynamic requirements constitute the optimal exergy efficiency solution for heat transfers. It implies that the processing equipments can be modified in such a way that the minimum temperature profile (as shown in Table 1) will be attained for all operations with dual representations. The GCC of Fig. 7A shows that it corresponds to a threshold problem where the process only requires heat. The heating MER is 78.9 MW (Table 2). Conversely, the technological requirements would necessitate little or no modifications of the process equipment. Fig. 7B reveals that a pinch point exists at 370 K (cooling requirement of the secondary refiner steam). It corresponds to an energy penalty of 4.2 MW because the technological implementation produces a transfer of energy through the pinch point. To avoid the penalty, the process equipments should be modified. Fig. 9 compares the hot and cold exergy composite curves of the thermodynamic and the technological requirements. The area between the cold (hot) composite curve and the horizontal axis represents the exergy required (delivered) by the process streams. The exergy composite curves are presented in the corrected temperature domain, implying that the

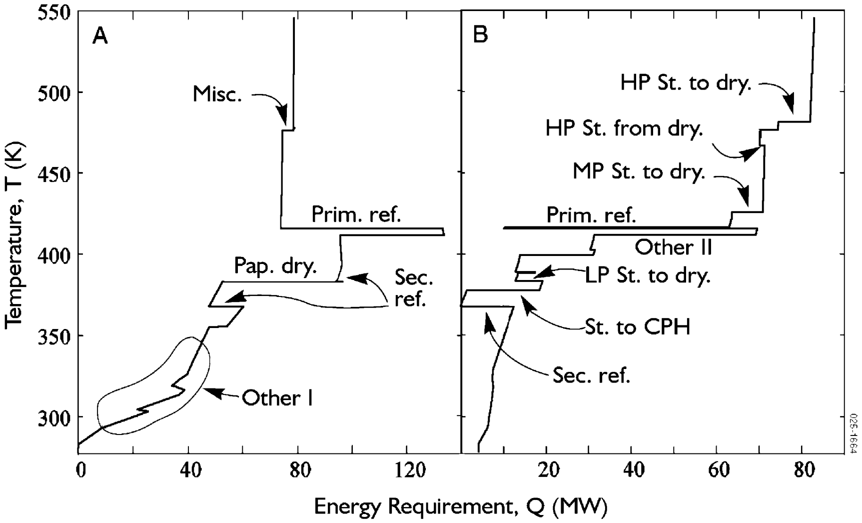


Fig. 7. GCC of thermodynamic (A) and technological requirements (B) of the paper making plant. *Other I*: chips washing, CPH, WW chests; *Other II*: WW chests, effluent treatment, saw mill, general heating.

Table 2
MER, fuel consumption and marginal efficiency of electricity production

	Units	Current	Techno.	Thermo.	Mixed
Heating MER	MW	–	83.0	78.9	78.9
Cooling MER	MW	–	4.2	0	0
Energy consumption without CHP					
Biomass	kg/s	–	10.65	10.11	10.11
Natural gas	kg/s	–	0	0	0
Energy consumption with CHP					
Biomass	kg/s	12.216	12.216	12.216	12.216
Natural gas	kg/s	0.7870	0.0182	0.2256	0.1432
Biomass	MW	95.3	95.3	95.3	95.3
Natural gas	MW	35.4	0.8	10.1	6.4
Total	MW	130.7	96.1	105.4	101.7
Generated power	MW	2.4	12.7	24.8	21.9
Marginal efficiency	%	–	96.9	93.4	95.9

exergy losses caused by the definition of the $\Delta T_{\min}/2$ (the energy-capital trade-off) are acceptable. When the hot and cold composite curves are overlapping, the area between them represents the potential for the integrated production of heat and power. From this analysis, a target solution for retrofitting the process, that we name the mixed configuration, is proposed. It consists in replacing steam injections by heat exchangers, without modifying the paper drying section. Compared to the thermodynamic requirements, the GCC of the mixed solution (Fig. 8) shows that this

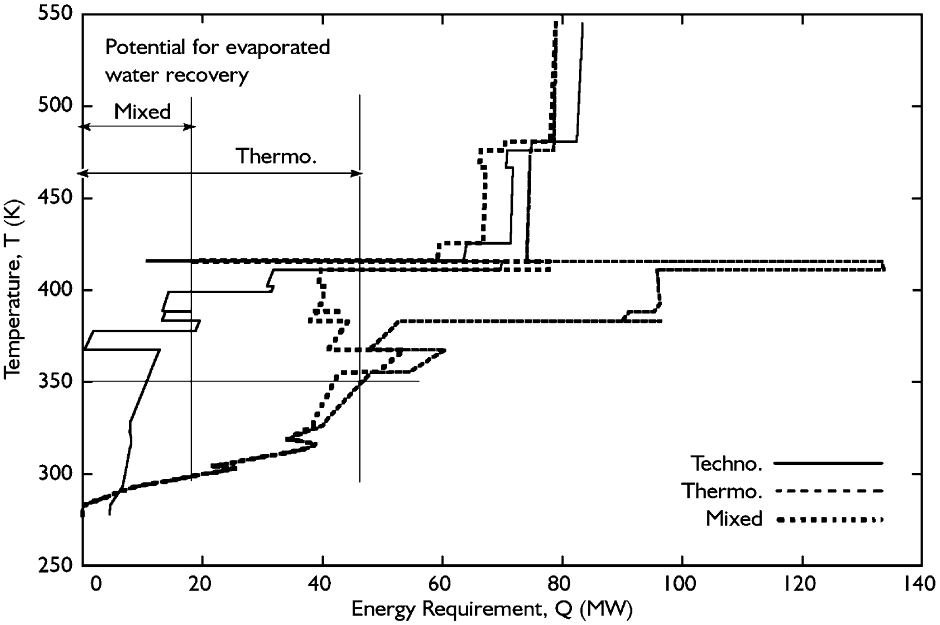


Fig. 8. GCC for the three representations of the process energy requirements.

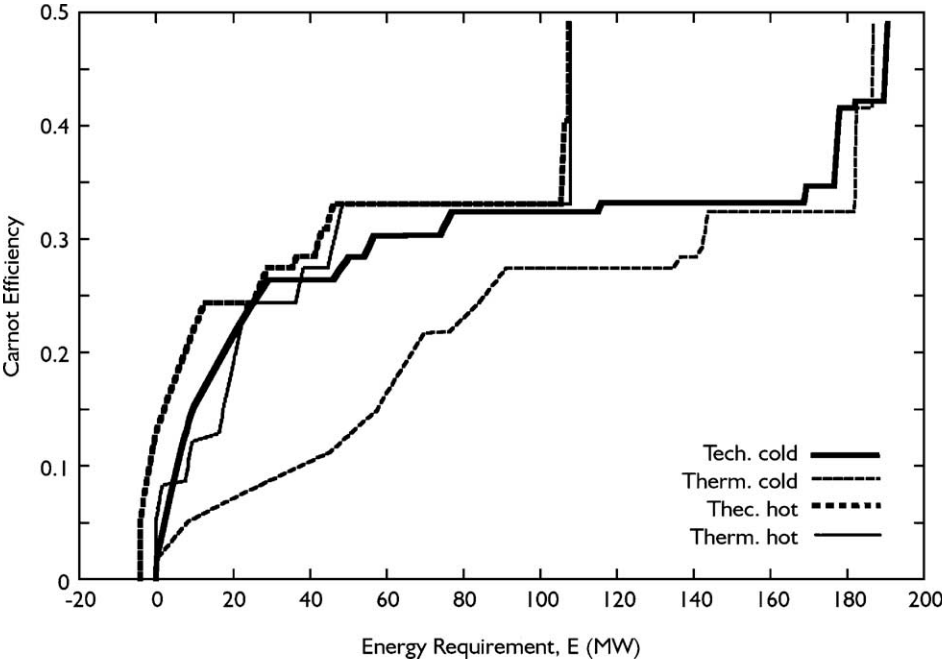


Fig. 9. Hot and cold exergy composite curves for the dual representation of process requirements.

option does not entail any energy penalty. The major difference between the two configurations is the exergy available for the CHP production.

5.2. Targeting the energy conversion technologies integration

The utility system comprises natural gas and biomass burning boilers and a series of turbines for the production of steam at different pressure levels and the combined production of mechanical power. The costs, the lower heating values (LHV) and the availability of fuels (biomass, natural gas), and also the electricity buying and selling prices, are given in Table 3. To enhance the CHP production, two new pressure levels are proposed: a 0.15 bar low-pressure header, and a 62 bar superheated high-pressure level header. With this scheme (Table 4), the production of mechanical power can be maximised, while saturated steam can be used to meet low temperature heating requirements.

Table 3
Fuels and electricity costs

Resource	LHV(kJ/kg)	Availability (t/h)	Cost [30] ($Can/GJ)
Natural gas	44,945	No limit	4.32
Biomass	7801	43.9	–
Elec. buying price	–	No limit	15
Elec. selling price	–	No limit	11.4

Note: LHV: lower heating value.

Table 4
Steam network definition

Level (K)	*P* (bar)	*T* (K)	VFrac.	Status
VHP	62.05	761	1	New
HP	16.53	540	1	Existing
MP	4.46	421	1	Existing
LP	3.43	418	1	Existing
VLP	1.7	408	1	Existing
Extrac.	0.15	323	0.9	New
Condens.	0.05	306	0	New

Note: VFrac.: vapour fraction.

Table 2 compares the current situation of the mill with the MER calculated for all three representations. In each case, the available biomass is entirely utilized, and the natural gas is only used as a complement. The results of the energy conversion system integration are also indicated, i.e. the fuel consumption required to satisfy the MER and the CHP production with an integrated steam network. The corresponding marginal efficiency (η_{CHP}) of the CHP production is defined as the ratio of the net mechanical power output (W_{CHP}) to the additional energy (LHV) that it requires:

$$\eta_{\mathrm{CHP}} = \frac{W_{\mathrm{CHP}}}{Q_{\mathrm{F}} - Q_{\mathrm{F}}^{0}} \tag{2}$$

with Q_{F}^{0}: the fuel consumption without CHP production ($\mathrm{kW_{LHV}}$); Q_{F}: the fuel consumption with CHP production ($\mathrm{kW_{LHV}}$).

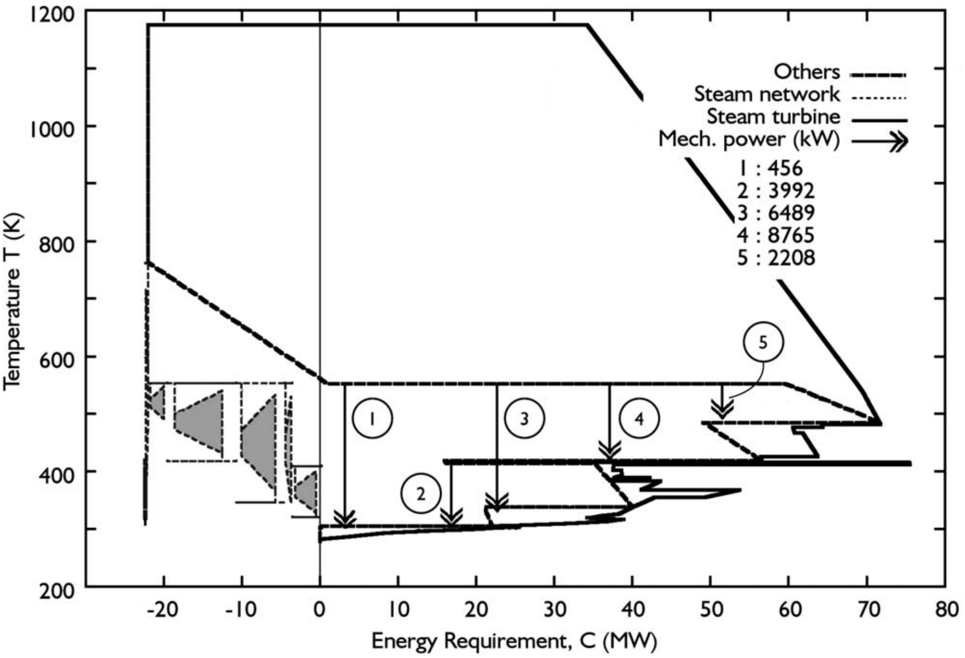


Fig. 10. Integrated composite curve of hybrid representation of process and utility targets.

Because the thermodynamic representation offers the best opportunity for exergy recovery, it also enables the highest combined production of electricity, twice the production of the technological representation. Considering the costs of electricity and of natural gas, the difference of 12.1 MWe corresponds to a saving of 44.1 MW_{LHV} (55% of the MER), while the energy required from the additional amount of fuel consumed is only 9.3 MW_{LHV}. Of the three options, the thermodynamic representation also has the highest marginal efficiency. The mixed representation indicates, however, that there is less incentive in changing the paper drying conditions. Therefore, as it has a low economic incentive, this option should be considered as an ultimate target for process retrofit and design of the HEN. It would also carry serious technological challenges. However, the technological requirement of the drying section suggests that a more detailed analysis of the steam pressure levels used in the drying section is warranted to maximise the CHP production. Replacing heating by direct contact with steam with a heat exchanger network appears to be more realistic and would be sufficient to eliminate the energy penalty. However, the feasibility of this option remains to be assessed in terms of economical trade-off and heat exchanger network design. The resulting integrated composite curves of the steam network as defined in [9] are given on Fig. 10.

6. Conclusion

The dual representation of thermodynamic and technological energy requirements has proved to be a valuable tool for the early stages of process energy analysis. By use of an optimisation procedure, energy saving opportunities can be quantified in terms of fuel and electricity costs and with regard to the CHP production. It should be used as a preliminary step in a retrofitting procedure to help identify and assess options prior to further analysis. Pinch analysis, exergy analysis and optimisation techniques have been combined to define energy targets at the system level expressed in terms of the energy costs rather than energy requirements. The illustration of the method by the analysis of a pulp and paper mill has been instrumented in identifying and gaining insight on process retrofitting options for reducing the energy penalty and maximising the energy conversion efficiency. In both representations, the possibility of recovering secondary refiner steam has been considered. An energy saving of 29.7 MW (22%) with an increase of 19.7 MWe in the CHP production has been targeted. In comparison with the technological requirements, replacing the steam injections to whitewater reservoir by heat exchangers would reduce the MER by 4.2 MW and increase the CHP production from 12.7 MWe to 21.9 MWe while incurring an increase of only 5.6 MW_{LHV} in the natural gas consumption. Minimising the exergy losses related to the current paper drying conditions appears to be less attractive since it would only increase the CHP production by 2.9 MWe (12%) with no significant reduction of the fuel consumption. This stresses the importance of separately analysing the energy requirements of the drying section in order to justify the different pressure levels at which steam is supplied.

Acknowledgments

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Paper Industry at École Polytechnique and the Laboratory for Industrial Energy Systems (EPFL) is also gratefully acknowledged.

Appendix A. Formulation of the optimisation problem

The mixed integer linear programming formulation for targeting the minimum of cost of energy requirement target with multiple representations of the process operations is:

$$\mathrm{Min}_{R_k,y_w,f_w}\sum_{w=1}^{n_w}(y_wC_{1w}+f_wC_{2w})+\sum_{o=1}^{n_o}\sum_{i=1}^{n_{oi}}y_{oi}C_{oi}+EL_iC_{\mathrm{eli}}-EL_oC_{\mathrm{elo}} \tag{1}$$

Subject to: Heat balance of the temperature interval k:

$$\sum_{w=1}^{n_w}f_wq_{wk}+\sum_{o=1}^{n_o}\sum_{i=1}^{n_{oi}}y_{oi}Q_{oik}+R_{k+1}-R_k=0\quad\forall k=1,\ldots,n_k \tag{1.1}$$

$$\sum_{i=1}^{n_{oi}}y_{oi}=1\quad\forall o=1,\ldots,n_o \tag{1.2}$$

Electricity production:

$$\sum_{w=1}^{n_w}f_ww_w+\eta_iEL_i-\frac{EL_o}{\eta_o}=0 \tag{1.3}$$

Electricity consumption:

$$\sum_{w=1}^{n_w}f_ww_w+\eta_iEL_i\geqslant 0 \tag{1.4}$$

With

$$R_k\geqslant 0\quad\forall k=1,\ldots,n_k+1 \tag{1.5}$$

$$R_1=0 \tag{1.6}$$

$$R_{n_k+1}=0 \tag{1.7}$$

$$f\min_w y_w\leqslant f_w\leqslant f\max_w y_w\quad\forall w=1,\ldots,n_w \tag{1.8}$$

$$y_w,y_{oi}\in\{0,1\}$$

With

η_I	Efficiency of the conversion of electricity into mechanical power
η_0	Efficiency of the conversion of mechanical power into electricity
C_{1w}	fixed cost of the energy conversion w
C_{2w}	proportional cost of the energy conversion w
C_{oi}	cost of implementing the option i of operation o

EL_i	electricity imported to the system
EL_o	electricity exported from the system
C_{eli}	cost of imported electricity
C_{elo}	cost of imported electricity
f_w	multiplication factor of the reference flowrate of the utility w in the optimal situation
$fmin_w$	minimum value of the multiplication factor f_w of utility w
$fmax_w$	maximum value of the multiplication factor f_w of utility w
n_o	number of operations representing the requirements of the process
n_k	number of temperature intervals
n_w	number of utility streams
n_w	number of options used in the dual representation of operation o
Q_{oik}	cumulated heat load of the process streams of the representation o of the option i in the temperature interval k, $Q_{oik} > 0$ for cumulated heat supply
y_{oi}	integer variable associated to the representation i of the operation o
yr_r	integer variable associated to the use of the cycle r
y_w	integer variable associated to the use of the utility stream w

The constraint equation (1.2) ensures that, for each operation, only one of the representations will be finally selected.

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