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Ref.: D. Brown, F. Maréchal, J. Paris
A dual representation for targeting process retrofit, application to a pulp and paper process
PUR manuscript

Dear Ron,

Please find enclosed a manuscript submitted for approbation as a PUR.

Thank you for your attention.

Jean Paris
Professor of Pulp and Paper Engineering
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F. Maréchal

PJ

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

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PUR ### August 2004

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 optimized 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. This led to the development of the integrated composite curves as an alternate representation which combines both networks while distinguishing utility from process streams [9]. Graphical techniques become impractical when cycles are concerned. A method based on the use of optimisation techniques has therefore been proposed by Marechal and Kalitventzeff [10, 13].

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 combining energy efficiency and environmental concerns [14, 26], as well as reactive systems [15].

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 thermomechanical pulp, TMP, (1060 odt/d) and deinked pulp; DIP, (170 odt/d) also produced on site. A simplified process flow diagram focusing on steam and fresh water requirements is given in Figure 1. The reference state of the 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.

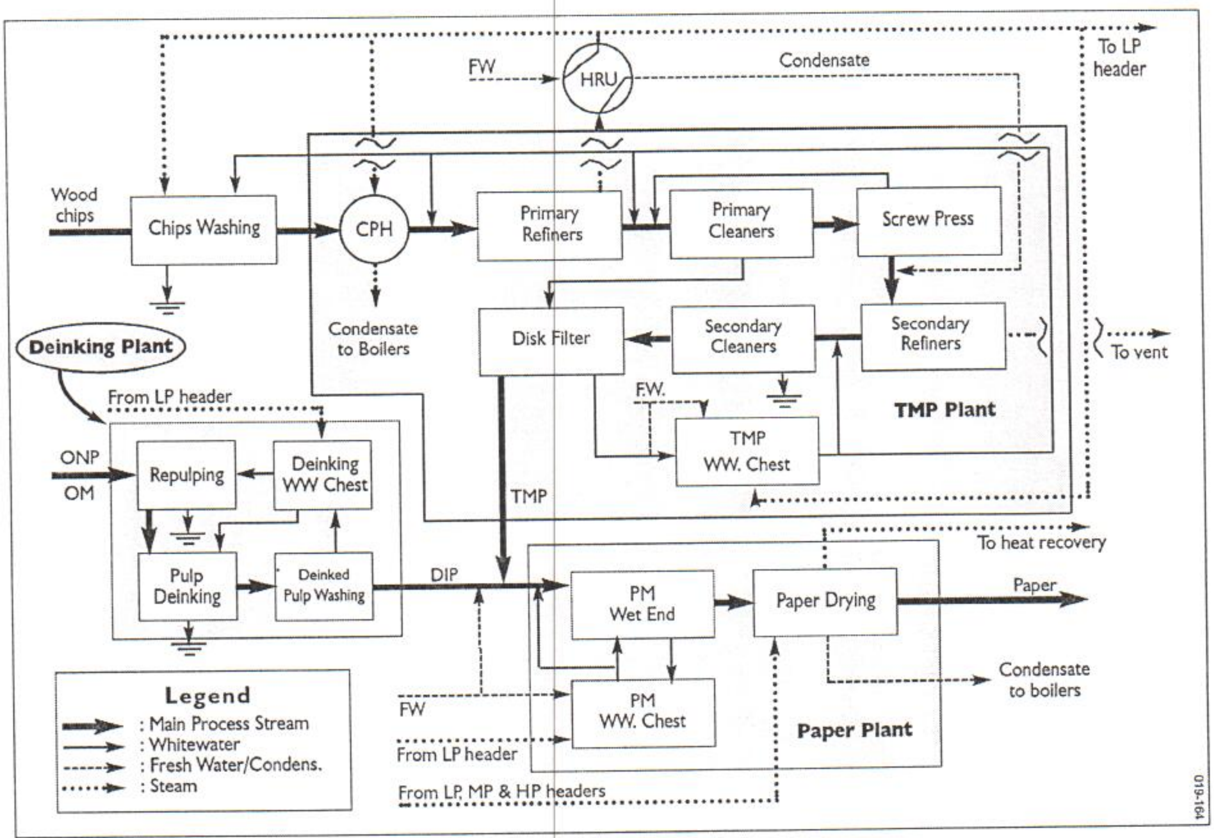

Figure 1. Simplified Reference Process Flow Diagram. Abbreviations: **CPH:** Chips pre-heather, **HRU:** Heat recovery unit, **OM:** Old magazines, **ONP:** Old newsprint, **PM.:** Paper machine.

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 Figure 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 fibers 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 (Figure 1) since it contains wood contaminants and cannot be reused directly. In the reference case, the steam 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.

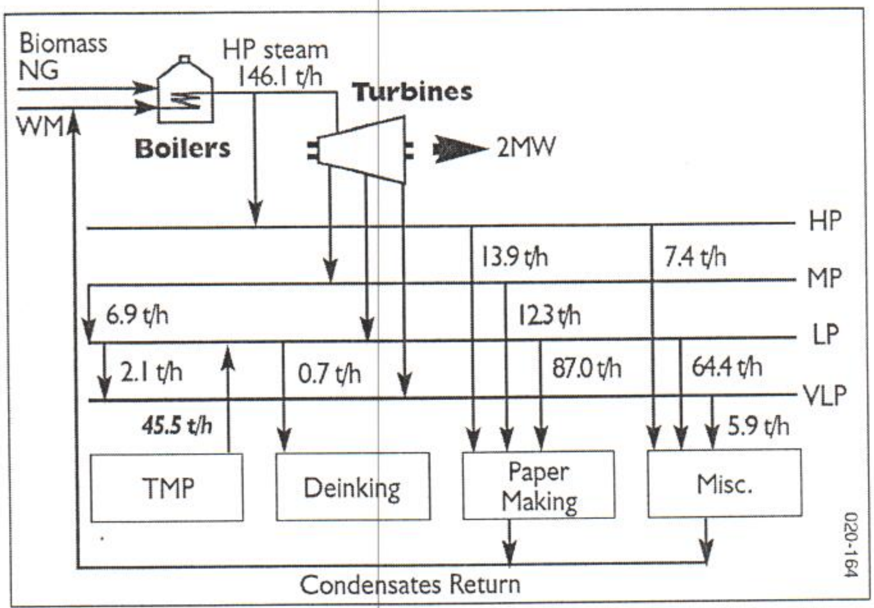

Figure 2. Reference Steam Distribution System.
Abbreviations: **NG:** Natural gaz, **WM:** Water make-up.

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 Figure 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.

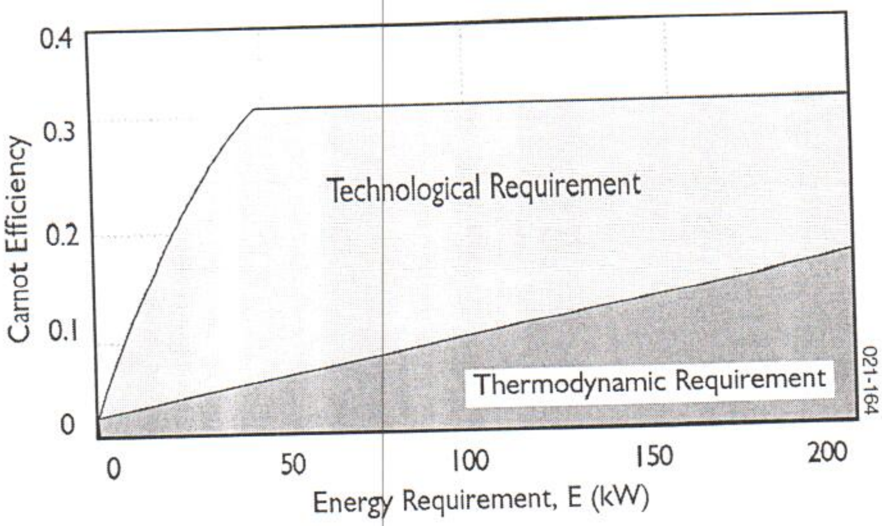

Figure 3. Exergy Composite Curves for Heating by Steam Injection.

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

a) Preheating by steam injection

The chip washing operation and the three main whitewater chests are heated by direct contact with steam (Figure 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 Figure 4 for the wood chip washing operation. In the thermodynamic representation isothermal 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 (Figure 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 Figure 5.

b) 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 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:

$$\eta_{CHP} = \frac{W_{CHP}}{Q_F - Q_F^0} \qquad (2)$$

With:

Q_F^0 : the fuel consumption without CHP production (kW_{LHV})

Q_F : the fuel consumption with CHP production (kW_{LHV})

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

Table 3. Fuels and electricity costs

Resource	LHV (kJ/kg)	Availability (t/h)	Cost [30] ($Can/GJ)
Natural gas	44945	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

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.

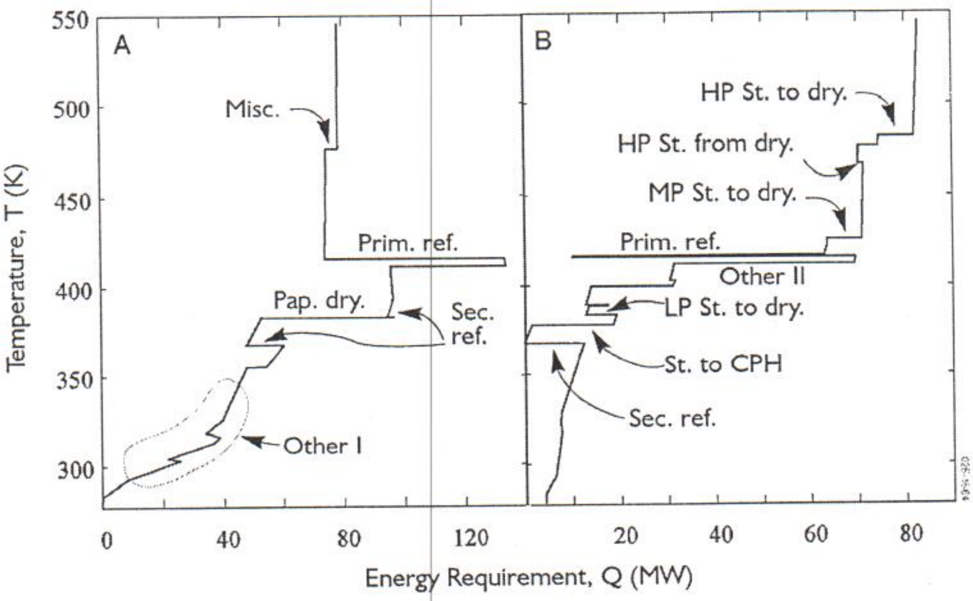

Figure 7. GCC of Thermodynamic (a) and Technological Requirements (b) of the Paper Making Plant. **Other I:** Chips Washing, CPH, WW Chests; **Other II:** WW chests, Effluent Treatment, Saw Mill, General Heating.

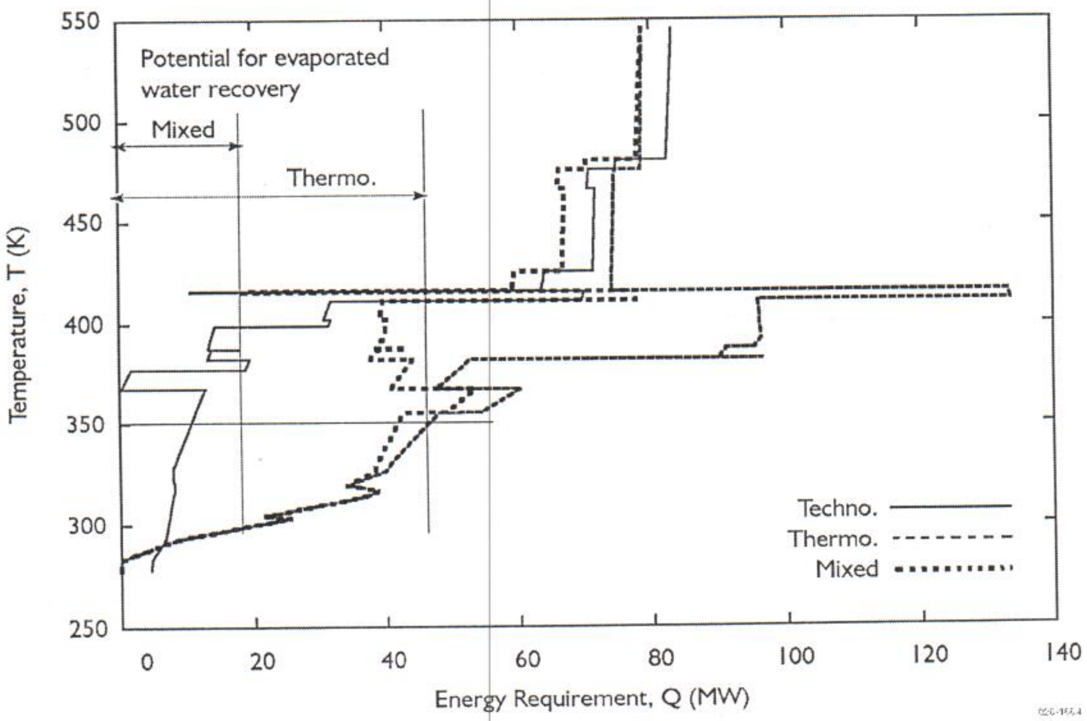

Figure 8. GCC for the three Representations of the Process Energy Requirements.

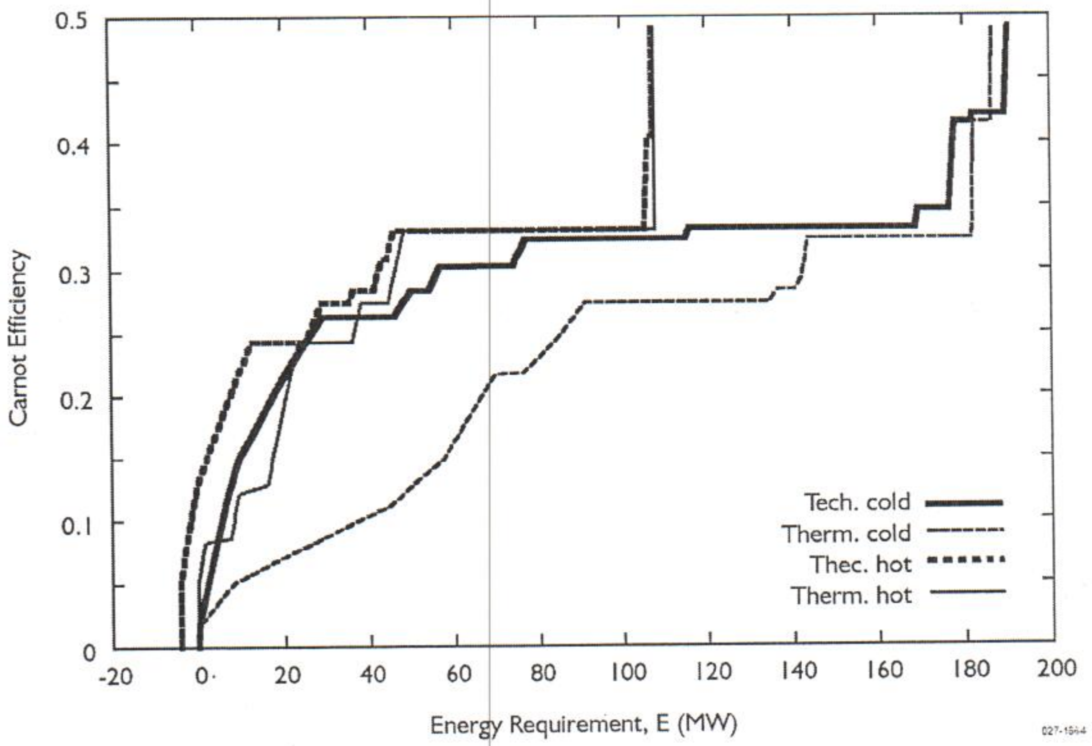

Figure 9. Hot and Cold Exergy Composite Curves for the Dual Representation of Process Requirements.

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

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 are given on Figure 10.

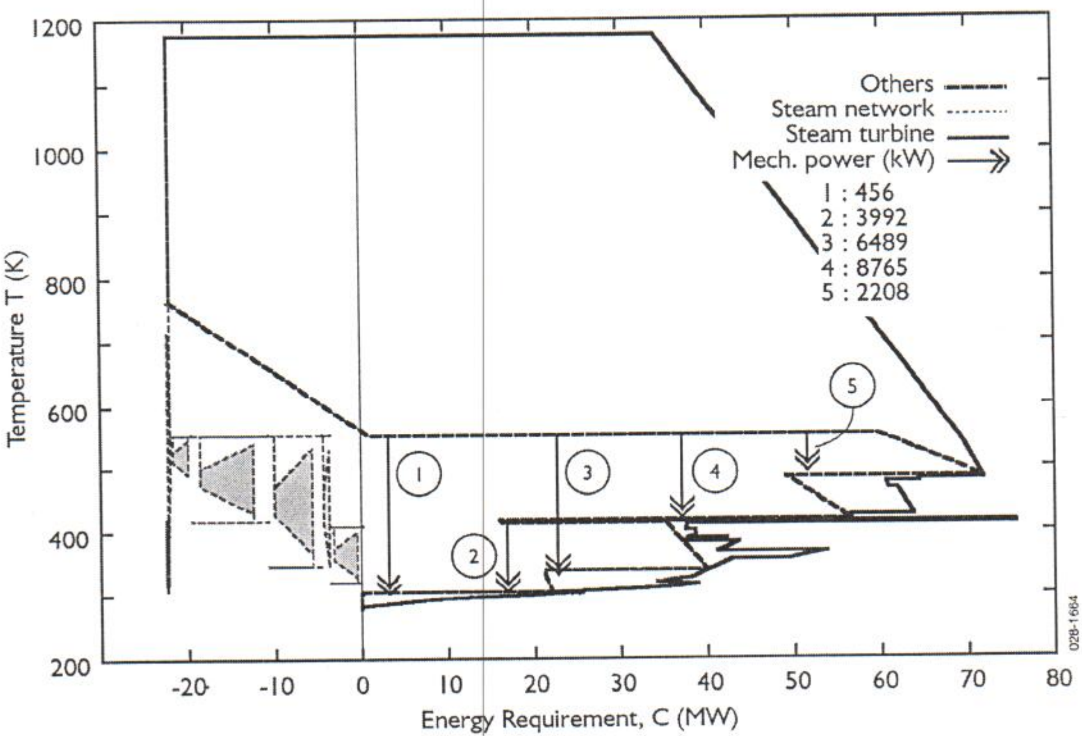

Figure 10. Integrated Composite Curve of Hybrid Representation of Process and Utility Targets.

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.

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Appendix 1: 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:

$$\underset{R_k, y_w, f_w}{Min} \sum_{w=1}^{n_w} (y_w C_{1w} + f_w C_{2w}) + \sum_{o=1}^{n_o} \sum_{i=1}^{n_{oi}} y_{oi} C_{oi} + EL_i C_{eli} - EL_o C_{elo} \qquad (1)$$

Subject to:
Heat balance of the temperature interval k:

$$\sum_{w=1}^{n_w} f_w q_{wk} + \sum_{o=1}^{n_o} \sum_{i=1}^{n_{oi}} y_{oi} Q_{oik} + R_{k+1} - R_k = 0 \qquad \forall k = 1,\ldots,n_k \qquad (1.1)$$

$$\sum_{i=1}^{n_{oi}} y_{oi} = 1 \qquad \forall o = 1,\ldots,n_o \qquad (1.2)$$

Electricity production:

$$\sum_{w=1}^{n_w} f_w w_w + \eta_i EL_i - \frac{EL_o}{\eta_o} = 0 \qquad (1.3)$$

Electricity consumption:

$$\sum_{w=1}^{n_w} f_w w_w + \eta_i EL_i \geq 0 \qquad (1.4)$$

With:

$$R_k \geq 0 \qquad \forall k = 1,..,n_k + 1 \qquad (1.5)$$

$$R_1 = 0 \qquad (1.6)$$

$$R_{n_k+1} = 0 \qquad (1.7)$$

$$f\min_w y_w \leq f_w \leq f\max_w y_w \qquad \forall w = 1,..,n_w \qquad (1.8)$$

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

With:

η_I:	Efficiency of the conversion of electricity into mechanical power.
η_o □	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.