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Base case process development for energy efficiency improvement, application to a Kraft pulping mill. Part II: Benchmarking analysis☆

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ABSTRACT

A new procedure for benchmarking analysis has been developed to evaluate the energy efficiency of a chemical process. Benchmarking is performed to identify process inefficiencies before developing energy enhancement measures. The new procedure combines typical techniques, such as the comparison with current practice, with utilization of new performance indicators based on exergy and energy content and the targeting by Pinch Analysis and Water Pinch. All process sections and the steam and water utility systems are evaluated. The procedure consists of five phases. In the first phase the data required is compiled. The second phase consists of comparing the energy and water efficiency of the base case to the current practice of the industry. In the third phase, the new energy and exergy content indicators are used to analyze the efficiency of utilities systems and to quantify the heat rejected by the process. In the fourth phase the minimum energy and water requirements are determined. The last phase is a synthesis by which the inefficiencies are identified and guidelines established for process improvement. Interactions between the utilities systems and the process are developed. The procedure has been applied to an operating Kraft pulping mill in Eastern Canada.

Keywords: Benchmarking analysis; Energy efficiency; Pinch Analysis; Water Pinch; Exergy analysis; Kraft process

1. Introduction

An approach to the definition and characterization of the base case model of an operating process has been presented in Part I of this paper. It has been applied to an operating Kraft pulping mill. The model was specifically designed to support an in depth energy analysis of the mill, it has been implemented as a steady state simulation on the CADSIM PLUS® software. It is focused on the steam and water systems. Both utilities are traced rigorously from production (for steam) or preliminary treatment (for water), through their distribution, utilization and post-utilization fate: recovery, reutilization, and eventual reject to the environment. The simulation generates mass balances (water, fiber and total dissolved solids) as well as heat balances on all the major unit operation and for the global process and its principal sectors.

Part II of the paper presents a fundamental analysis which must be performed before the development and evaluation of energy enhancing measures is undertaken. This analysis is the process benchmarking. The object of this task is to asses the current energy performance of the process globally and by sector in order to identify areas of inefficiencies and to establish enhancement targets. Benchmarking can also be used to identify where the most likely energy gains can be obtained and to guide engineering efforts.

2. Literature review

The pulp and paper (P&P) industry is among the largest industrial consumers of energy and water. Rising energy costs and more stringent environmental regulations have led the industry to refocus its efforts towards identifying ways to improve

☆ This article has been submitted in two parts. Part I presents the definition and characterization of a base case.

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Nomenclature

η_i	Carnot coefficient
C_{pi}	heat capacity (kJ/kg °C)
DSC	dissolved solids concentration (ppm)
E_{SP}	energy supplied to the process (MW)
EC_E	indicator energy content effluents
EC_{FG}	indicator energy content flue gases
EC_T	indicator for the total energy content of effluents and flue gases
EC_{WTot}	indicator energy required to heat up water
Ex_{Proc}	exergy required by the process (MW)
Ex_{SP}	exergy supplied by fuels for steam production (MW)
Ex_{Water}	total exergy required to heat up water (MW)
$Ex_{dest,\Delta THX}$	exergy destroyed associated by the temperature difference between steam and process heat sink (MW)
$Ex_{dest,PRV's}$	exergy destroyed associated with the adiabatic expansion of HP steam for producing MP and LP (MW)
$Ex_{dest,HPprod}$	exergy destroyed associated with the temperature difference between combustion gases and the HP steam temperature (MW)
$Ex_{lost,eff+FG}$	exergy lost associated with the effluents and flue gases (MW)
ExC_E	indicator exergy content of effluents
ExC_{FG}	indicator exergy content of flue gases
ExC_T	indicator of the total exergy content of effluents and flue gases
ExC_{Cog}	indicator cogeneration potential
ExC_{WTot}	indicator exergy required to heat up water
EX_{RP}	useful exergy supplied to the process
HP	high pressure steam (MW)
LP	low pressure steam (MW)
m	mass flow (kg/s)
MCR	minimum cooling requirement (MW)
MER	minimum energy requirements (MW)
MEP	minimum effluent production (MW)
MP	medium pressure steam (MW)
MHR	minimum heating requirement (MW)
MWC	minimum water consumption (MW)
PP	pinch point (°C)
PRV	pressure release valve
T_{in}	inlet temperature (°C)
T_{target}	target temperature (°C)
T	temperature of heat sources or sinks (°C)
T_{ET}	effluent treatment temperature (°C)
T_{SAC}	condensation temperature of sulfuric acid (°C)
T_o	ambient temperature (°C, K)
T_{lm}	mean logarithmic temperature (°C)

energy and water conservation. In a typical Kraft process, the larger the amount of water consumed and effluent produced, the larger will be the energy required for heating, cooling and pumping. The evaluation of a process before implementing enhancement measures is often based on a comparison of its efficiency to that of other similar processes by the utilization of performance indicators (Francis et al., 2004).

The utilization of performance indicators as a benchmarking tool is common practice to measure the variability and correct the operation of a process (Klatt and Marquardtb, 2009). Francis et al. (2006) proposed indicators that are normalized to the production rate. These indicators include fuel consumption, boilers efficiency and thermal energy consumption of the overall process and of each individual operation. Lang and Gerry (2005) used indicators to monitor control systems by identifying the periods where control loops are out of normal mode or oscillating. Buckbee (2007) defined indicators such as the ratio between the set points and the actual targets achieved. Van Gorp (2005) proposed a methodology where the ratio of the steam consumption of a unit and the final product tonnage were compared to the goals set for the energy reduction projects. A mathematical relation is used to target the potential energy consumption, which is compared to the actual. Retsina (2006) suggested a similar methodology, with the same type of indicators, adding a real-time analysis to identify gaps between target and actual values so as to take measures to maintain the energy efficiency. Sivill et al. (2009) used indicators to link energy efficiency monitoring with business strategy and process integration options. They monitor the changes to the minimum energy requirements as the operation of the process fluctuates. Sivill and Ahtila (2009) relate the production of the paper machine with the energy efficiency and monetary parameters. Retsina (2005) has also developed a software for monitoring the indicators of different processes. However, there are no indicators that reflect the causes of possible inefficiencies such as the equipments maintenance, internal heat recovery or water reutilization.

The current performance indicators that monitor energy efficiency quantify the energy utilization without focusing on the quality of the energy used and produced by the process. Exergy is not often used in engineering analysis despite its usefulness to assess the efficiency of energy transfer and conversion operations. It combines in a single function the quality (temperature) and quantity (enthalpy) of the heat content of material streams. Therefore, while energy is preserved in transformation processes by virtue of the first law of thermodynamics, exergy can be destroyed by virtue of the second law. As the thermodynamic efficiency of a process operation increases, less exergy is destroyed; however, ultimate efficiency is only achieved at equilibrium, i.e. for infinitely slow processes which are not practical engineering options. Much work has been devoted to the use of exergy in process design (Kotas, 1985; Szargut et al., 1988; Brodyansky et al., 1994; Sorin and Paris, 1997; Sorin et al., 1998). It has been applied in the P&P industry (Wall, 1988; Asselman et al., 1996; Brown et al., 2005; Gong, 2005; Mateos-Espejel et al., 2007). The destruction of exergy is associated with the irreversible transformation that occurs in the process. Exergy is destroyed in the heat exchangers because of the temperature difference between hot and cold streams or by the adiabatic expansion of steam in a valve. The exergy which is no longer useful or available for the process is considered lost; it encompasses the streams vented or sewered, the flue gases or losses to the environment. Reduction of the exergy destroyed and lost can be accomplished by internal heat recovery, effluents reutilization, cogeneration and energy upgrading. Therefore, exergy can also be used as an indicator of process inefficiencies, although it rarely is.

Energy and water efficiencies are typically analyzed individually by the application of Pinch Analysis® and Water Pinch respectively (Noel, 1995; Noel and Boisvert, 1998; Koufos and Retsina, 1999, 2001; Jacob et al., 2002; Wising, 2003; Axelsson

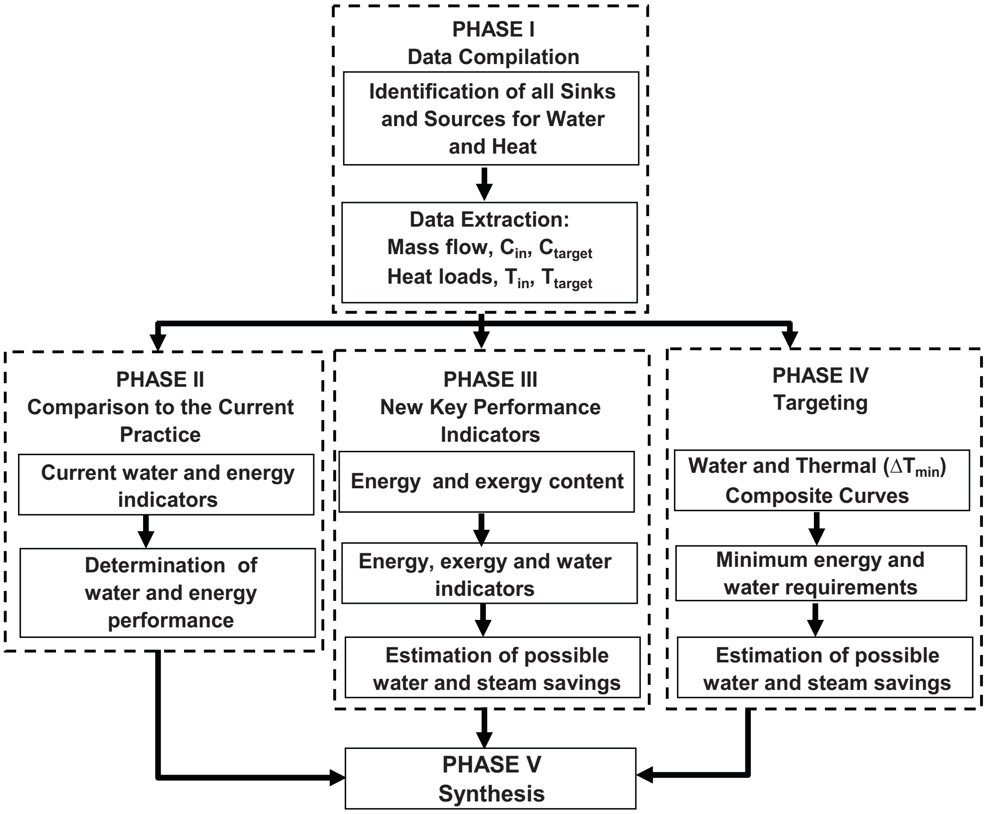

Fig. 1 – Methodology.

Table 1 – New KPI.

Name	Symbol	Equation
Energy indicators		
Energy rejected in effluents	EC_E	$mC_p(T - T_{ET})/E_{SP}$ (1)
Energy rejected in flue gases	EC_{FG}	$mC_p(T - T_{SAC})/E_{SP}$ (2)
Total energy rejected	EC_T	$EC_E + EC_{FG}$ (3)
Energy for heating water	EC_{WTot}	$mC_p(T - T_i)/E_{SP}$ (4)
Exergy indicators		
Energy conversion	ExC_{EC}	$(Ex_{dest,HPprod} + Ex_{dest,PRV's} + Ex_{dest,\Delta THX})/Ex_{SP}$ (5)
Exergy rejected in effluents	ExC_E	$mC_p(T - T_{ET})\eta_E/Ex_{Proc}$ (6)
Exergy rejected in flue gases	ExC_{FG}	$mC_p(T - T_{SAC})\eta_{FG}/Ex_{Proc}$ (7)
Total exergy rejected	ExC_T	$ExC_E + ExC_{FG}$ (8)
Exergy for heating water	ExC_{WTot}	Ex_{Water}/Ex_{Proc} (9)

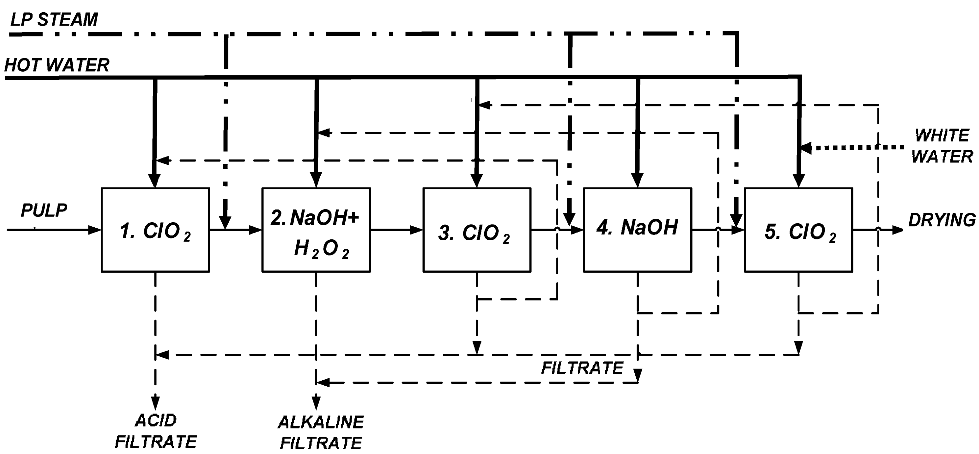

Fig. 2 – Bleaching section.

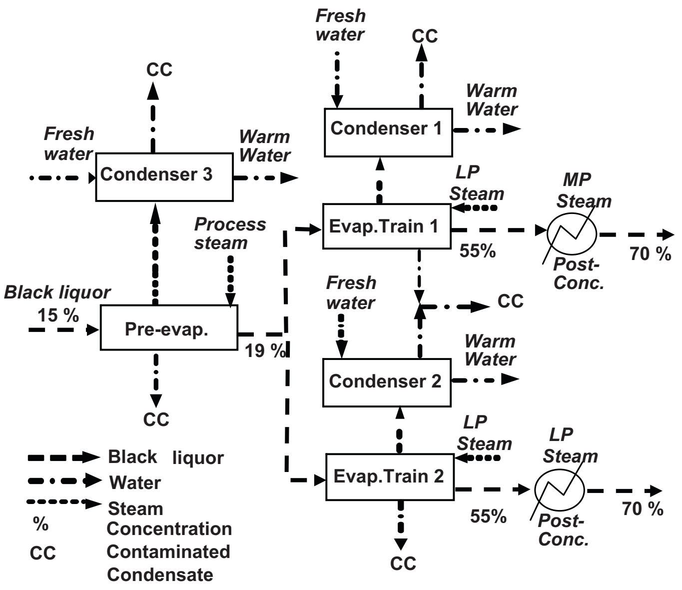

Fig. 3 – Black liquor concentration section.

and Berntsson, 2005; Axelsson et al., 2006; Lutz, 2008). Pinch Analysis is used to determine the minimum heating and cooling requirements to be supplied by utilities (Linnhoff et al., 1994; Smith, 1995). The core of Pinch Analysis is the display in a temperature vs. enthalpy diagram of all possible heat transfers within a process. It consists of the hot and cold composite curves, which respectively represent the heat availability and demand in the process. Water Pinch is used to determine the minimum water requirements and minimum effluent production. El-Halwagi and Manousiouthakis (1989) have first proposed a method which is a direct extension of thermal pinch based on the analogy between heat and mass exchanges. Shafiei et al. (2003) applied the method to different types of water using operations. Wang and Smith (1994) have proposed a method for networks of washing operations of organic process streams immiscible with water. Dhole (1998) proposed another approach for single phase processes (as the Kraft process), generally water based, where the main streams content of the desired product are enriched by reducing the level of contamination through a succession of operations, such as dilution, displacement and thickening. The basis is the representation in the purity vs. mass flow rate diagram of the aggregate of all possible mass transfers between water streams. It consists of two composite curves, one for water sources and the other for water sinks, which respectively represent the effluents produced and the water demand in a process. However, these individual analyses ignore the interactions between the water and steam systems and this may result in counter productive measures and increased energy cost (Mateos-Espejel et al., 2008). The development of improvement scenarios with regards to energy and water issues could lead to more attractive projects, because appropriate water reutilization reduces the surface area needed for increasing internal heat recovery (Savulescu et al., 2005).

A benchmarking procedure has been developed to evaluate a process as a prerequisite step to an energy enhancement retrofit project. The procedure highlights issues that should be considered in the water and energy data extraction stage. The conventional comparison with current practice is performed. The procedure evaluates energy, water and exergy characteristics of the process. New performance indicators of the internal heat recovery have been developed. These indicators quantify the excess utilization of steam that is reflected in the energy rejected by the process in hot effluents and flue gases. The

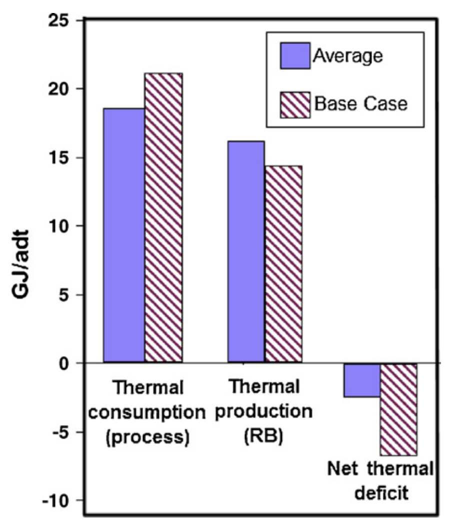

Fig. 4 – Overall thermal consumption and thermal energy production.

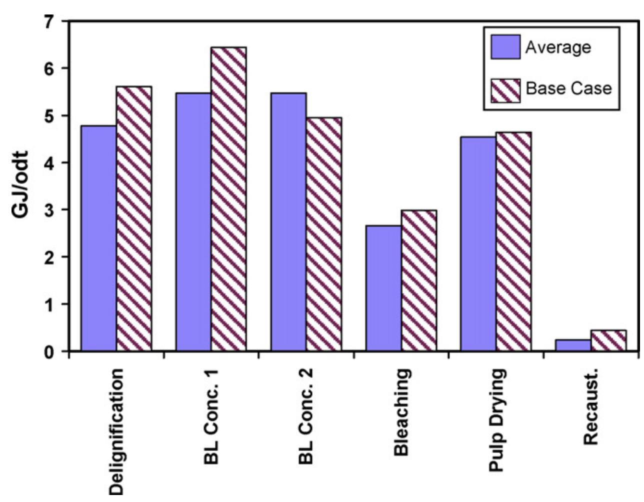

Fig. 5 – Thermal consumption by process section.

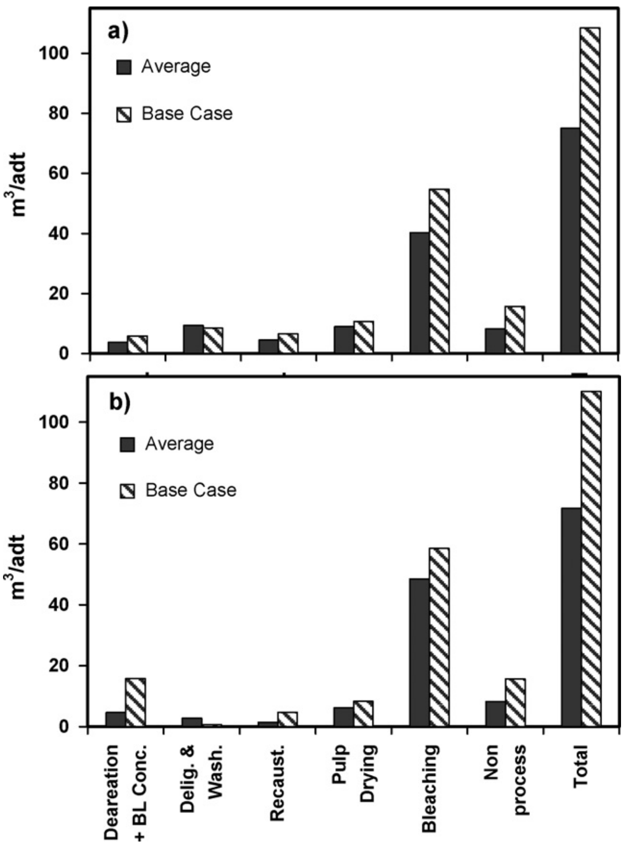

Fig. 6 – (a) Water consumption and (b) effluent production.

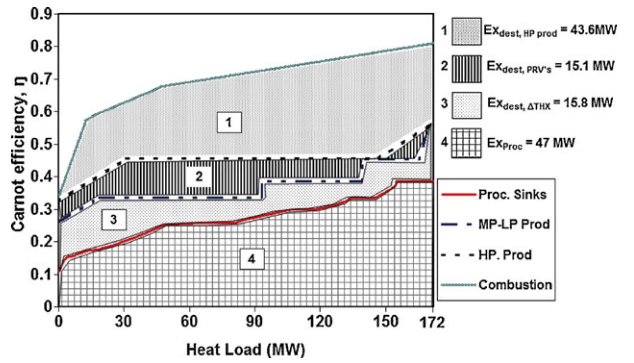

Fig. 7 – Exergy composite curves of the current process.

more energy is rejected in these heat sources the more hot utility will have to be supplied to the process. Furthermore, the excess water utilization is also reflected in the production of effluents. Exergy indicators have been defined to take also into account the quality of the energy produced, supplied to and used by the process and rejected to the environment. A targeting step involves the utilization of the thermal and water composite curves to determine the maximum heat recovery and water reutilization theoretically possible. The final phase of the procedure consists of a synthesis of all results previously obtained. This is a crucial task as the main water and energy efficiency problems of a process are identified and the targets for the posterior development of energy efficiency measures are fixed.

3. Methodology

The benchmarking procedure developed in this work is summarized in Fig. 1. Typically, the evaluation of a process only considers the quantification of energy factors. However, as energy is measured by its final consumption in the process, the energy conversion stages when the energy is degraded are ignored. The results of Pinch Analysis are based on a comparison between the current process energy consumption and the result after internal heat recovery is maximized. The quality of the energy produced is only indirectly evaluated when power production potential is analyzed. Exergy is used in the proposed procedure to quantify the inefficiencies in the production, utilization and distribution of the utilities, and the heat rejected in the current process operation. Therefore, the information obtained from the exergy analysis complements the comparison to the current practice and the targeting by Pinch Analysis and Water Pinch.

The benchmarking procedure combines different methods for evaluating the current water and energy efficiencies. Process inefficiencies are identified and targets are established for developing effective energy improvement measures. The procedure will identify:

- The unit operations with poor energy performance.
- The efficiency with which the thermal energy is produced and used in the process.
- The amount and quality of the wasted energy.
- The maximum water reutilization and energy recovery theoretically possible.

3.1. *Phase I: data compilation*

This phase consists of gathering all the data necessary to perform the benchmarking analysis. This information will be later be used for energy and water analysis and simultaneous optimization. Phase I is done in two steps. First, all sources and sinks for both heat and water are identified. Heat sinks, or cold

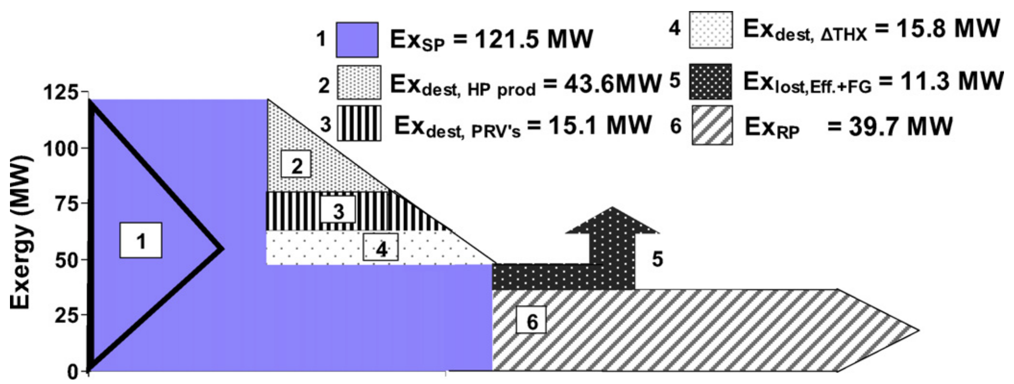

Fig. 8 – Sankey diagram of the exergy heat flows supplied to the process.

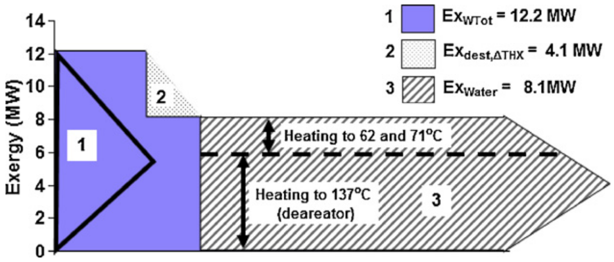

Fig. 9 – Sankey diagram of the exergy supplied for producing hot water.

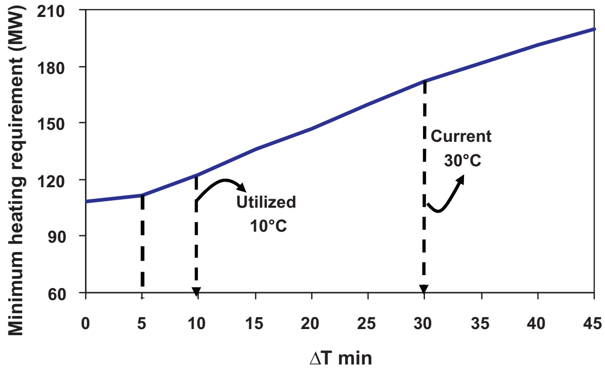

Fig. 10 – ΔT_{min} targeting.

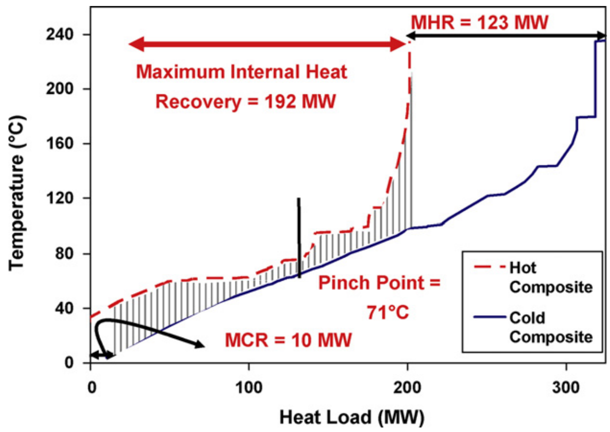

Fig. 11 – Thermal composite curves of the process.

streams, are streams that need to be heated. Heat sources, or hot streams, are streams that can be cooled down and should be, whenever this is possible to put their heat content to good use. Water sources designate the streams that can be re-used or that are process effluents. Water sinks are the operations where water is required.

For the thermal analysis, all steam users and the streams involved in internal heat recovery measures already imple-

Table 2 – Energy and exergy data for the nominal process.

	Energy content (MW)	Exergy content (MW)
Fuels combustion to steam (Ex_{SP})	172	121.5
HP steam production	172	78
Steam utilization	172	62.8
Process consumption (Ex_{Proc})	172	47
Flue gases	11.8	4
Hot effluents	44.9	7.3
Water heating (Ex_{WTot})	37.1	12.2

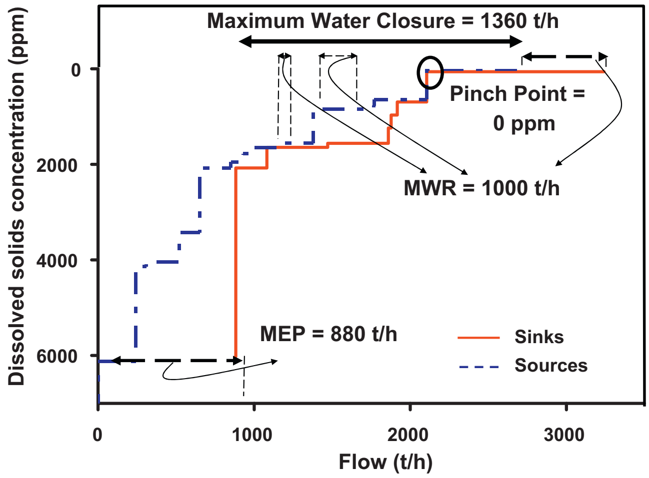

Fig. 12 – Water composite curves of the process.

mented are identified. The streams which are part of non isothermal mixing (NIM) operations, including direct injections of steam, are also taken into account. For the water analysis, all fresh water users and the streams involved in water reutilization measures are identified.

The second step consists of determining the temperature and heat loads for all cold and hot streams. In the case of the cold streams to be heated by steam, the target temperature is the temperature of the condensing steam. For the water streams, it is important to determine the contaminants that affect the operation of the process or the quality of the product. The maximum contaminant concentration allowed by the water sinks is obtained from unit operations specification and constraints (Foo et al., 2006).

This approach to data extraction ensures that of all streams that have an effect on the thermal and water performance of the process are taken into account.

3.2. *Phase II: comparison to the current practice*

The comparison of specific characteristics of a process to the average practices is done to identify inefficient sections. The following key performance indicators (KPI), normalized to the pulp production rate are used for the comparison. They apply to the overall process and to the individual sections:

- Steam consumption.
- Water consumption.
- Effluent production.
- Thermal production of the recovery boilers.

Table 3 – Exergy and energy indicators for the nominal process.

Name	Value (GJ/GJ)
Energy indicators	
EC_E	0.26
EC_{FG}	0.07
EC_T	0.33
EC_{WTot}	0.22
Exergy indicators	
ExC_{EC}	0.61
ExC_E	0.16
ExC_{FG}	0.09
ExC_T	0.25
ExC_{WTot}	0.26

- Net thermal deficit, i.e., the difference between the overall steam consumption and the steam production by the recovery boilers.

3.3. Phase III: new key performance indicators

New indicators have been developed to take into account the energy and exergy content of effluents and flue gases as these variables reflect the excess utilization of steam by the process. The purpose of these indicators is to quantify the energy rejected and its quality. They are used to estimate the savings that can be achieved by recovering this energy. The same indicators will be later used to monitor the improvements achieved by the implementation of energy efficiency measures. Table 1 gives the new energy and exergy indicators.

3.3.1. Energy indicators

Indicators that relate the energy content of effluents and flue gases to the steam produced by the boilers (E_{SP}) have been defined, they are EC_E and EC_{FG}. EC_T represents the total energy rejected. The steam required for water heating is given by EC_{WTot}. The target temperature for the effluents is that of the treatment plant (T_{ET}). For the flue gases the target is the temperature of the sulfuric acid condensation (T_{SAC}), below which the gases must not be cooled to avoid the formation of this corrosive acid from the SO_3 present. This is a typical constraint for the development of heat exchanger networks (Axelsson et al., 2006). However there are cases where the utilization of a scrubber to remove part of the SO_3 increases the energy available at high temperature (Gullichsen and Fogelholm, 1999).

3.3.2. Exergy indicators

Exergy content is used because it involves the quality and quantity of the energy produced, used and wasted. The exergy content is defined as the heat load (Q) multiplied by the Carnot coefficient (η). The ambient temperature to be used corresponds to winter conditions (4 °C). In this work the exergy function has been used in conjunction with the composite curves derived from the Pinch Analysis represented in the Carnot space (Carnot efficiency vs. heat load). In this representation, the exergy destroyed in a heat exchange is graphically displayed as a function of temperature approach (Staine and Favrat, 1996); it can thus be used to determine the efficiency, while maintaining realistic heat exchange conditions. Exergy composite curves of the steam production and utilization and, of the current process requirements are built to quantify the exergy destroyed. Sankey diagrams of the exergy balances are used to identify the exergy lost, and the useful exergy supplied to the process. Estimates of the potential increase of internal heat recovery, of water reutilization and of cogeneration are computed from those KPI.

The exergy destroyed is a measure of the lost potential for energy conversion into power. An indicator to quantify this potential has been defined as ExC_{EC}; it is the ratio between the total exergy destroyed and the exergy supplied to the process (Ex_{SP}). Indicators that relate the exergy content of effluents and flue gases to the exergy required by the process (Ex_{Proc}) have been defined, they are ExC_E and ExC_{FG}. ExC_T represents the total exergy rejected. The exergy required for water heating is given by ExC_{WTot}.

3.4. Phase IV: targeting

The thermal and water composite curves, obtained by thermal and water pinch analyses, are constructed to determine the minimum energy and water requirements as well as the maximum internal heat recovery and water reutilization that can theoretically be accomplished.

3.5. Phase V: synthesis

The main results are analyzed to determine the causes of the inefficiencies and the limits of possible improvements. The energy–water interactions between the utility systems and the process can also be identified. Guidelines for the process improvement of the process are formulated.

4. Case study

The benchmarking procedure has been applied to an operating Kraft mill situated in Eastern Canada. The process and its utility systems have been described in detail in Part I. Additional details pertinent to the case study are given below.

The mill has a five stage bleaching sequence which uses different bleaching agents (ClO_2, H_2O_2, NaOH) at different conditions (Fig. 2). Before stage 1 there is a pre-washer whose effluent is partly reused in the washing section. Part of the effluents of the last three stages is reused; whitewater from the pressing section of the pulp machine is used in the last stage washer. Steam is injected after stages 1, 3 and 4.

The weak black liquor, BL, at 15% dissolved solids concentration, DSC, is concentrated in two steps (Fig. 3); first, it is passed through a set of pre-evaporators driven by recycled steam to reach 19% DSC, and then it is split between two parallel evaporator trains, where it is concentrated to 55% DSC, with post-concentrators where it reaches 70% DSC. Both trains and the post concentrator are driven by live steam. The water evaporated in all equipments is condensed (contaminated condensates) after each train by fresh water which is later reused in the process.

4.1. Phase I: data compilation

The stream tables for the case study are given in annex. A stream ID, attached to each stream, consists of a character segment and a number. The character segment refers to the process section with which the stream is associated. The streams involved in non-isothermal mixing points have been highlighted.

Tables A1 and A2 show the cold and hot streams respectively. The operations where steam cannot be replaced are stripping, soot blowing, recaustifaction, chemical preparation and the steam exported.

Tables A3 and A4 show the water sinks and sources. The concentration of dissolved solids in the water, which includes the organic and inorganic by-products from the chemical delignification of wood, is a constraint to be satisfied by the water sources. The fact that some streams are involved in both energy and water analysis (process effluents and hot water requirements) illustrates the fact that both systems interact.

4.2. Phase II: comparison to current practice

Data from two periods, winter which is the period of maximum utilization of steam and summer which is the period of maximum utilization of water. The steam and water usage is mainly affected by the temperature of the river water intake. That temperature varies from ∼4 °C in winter to ∼20 °C in summer. The pulp production of the mill is essentially constant throughout the year.

4.2.1. Thermal energy consumption

An energy survey conducted at 49 P&P mills (Francis et al., 2006), 47 Canadian mills, 24 of which are Kraft processes and two from the United States has been used as source of data for this task. The results are shown in Figs. 4 and 5. The indicators used to analyze the global efficiency by section are normalized to a unit of production, the oven dried ton (odt) which is the habitual unit in the industry. Other values used are given in terms of air dried ton (adt), i.e. the material dried in the ambiance. The difference in values expressed in both units is generally about 5%. During the summer the steam consumption is reduced by about 10%.

The global consumption and the net thermal deficit are above the average (Fig. 4). The net thermal deficit is a consequence of poor efficiencies of recovery boilers and excess steam required by the process. It is compensated by the substantial steam production by fossil fuel and biomass. In principle, the recovery of the heat content of the concentrated black liquor should cover the process needs for steam (McIlroy and Wilczinsky, 1999). Fig. 5 indicates that the emphasis of the analysis should be put on three sections: delignification, black liquor concentration train 1 and, pulp bleaching, which have consumptions above the Canadian average. These sections are likely to represent, low cost energy saving opportunities.

4.2.2. Water usage

The data used for comparison is the average practice for a Canadian Kraft mill in the 1990s, (Turner, 1994; Gullichsen and Fogelholm, 1999). They encompass total water consumption without regards to pre-usage treatment. The indices for water consumption and effluent produced are both standardized to the pulp production rate in adt. During the summer the overall water consumption increases by 18% because of the need for chilled water to produce the ClO_2 used as the bleaching agent.

Fig. 6 shows that the water consumption is superior to the Canadian average for practically all departments. This reveals a lack of water reutilization within the process principally from the black liquor concentration and bleaching sections. The BL concentration section has high energy consumption and produces about three times the Canadian average amount of sewered effluents. The usage of steam by the bleaching section is also excessive as shown in Fig. 5. Particular attention will be given to water usage for cooling in the ClO_2 making unit, which is included in the bleaching section consumption. The need for cooling water could probably be reduced by increased internal heat recovery.

4.2.3. Remarks

The identification of the inefficient sections of the process is an important first step in the analysis. However, the cause of those inefficiencies cannot be determined at this stage. The quality of the thermal energy as it is produced, used and eventually rejected provides further insights in the matter. This can be done by means of other KPI as discussed in the next section.

4.3. Phase III: new key performance indicators

The exergy composite curves have been constructed (Fig. 7) to show the exergy destroyed in the energy pathway from its production by the combustion of fuels to its utilization by the process equipment. Primary energy, produced by fuels combustion, is used to generate intermediate energy levels in the form of HP, and subsequently MP and LP steam.

- Area 1: exergy destroyed by the HP steam production.
- Area 2: exergy destroyed by the adiabatic expansion and desuperheating of HP steam to produce MP and LP steam.
- Area 3: exergy destroyed by the heat exchange between live steam and the process sinks.
- Area 4: exergy currently required by the process.

The sum of Areas 1 to 4 represents the exergy supplied by the combustion of fuels for steam production in the boilers (Ex_{SP} = 121.5 MW). The exergy currently required by the process Ex_{Proc} (Area 4) is only a small fraction of the supply (39%). The adjustment of the steam pressure levels would reduce the amount of destroyed exergy (Area 3).

Fig. 8 is a Sankey diagram of the exergy flow through the same process pathway.

- Flow 1: exergy supplied by fuels combustion for steam production.
- Flow 2: destroyed exergy in the production of HP steam.
- Flow 3: destroyed exergy by the adiabatic expansion in the PRV's for the production of MP and LP steam.
- Flow 4: destroyed exergy by the heat exchange between live steam and the process heat sinks.
- Flow 5: exergy lost with the hot effluents and flue gases.
- Flow 6: useful exergy supplied to the process.

The exergy currently used by the process is the difference between the exergy used for steam production (flow 1) and the exergy destroyed (Flow 2–4) (Ex_{Proc}). The recovery of the exergy lost by means of internal heat recovery or water reutilization would reduce the need from steam and consequently the requirement of primary energy. The total exergy supplied by fuels combustion includes the exergy used for steam production (flow 1) and the exergy lost with flue gases.

Fig. 9 shows the Sankey diagram of the exergy associated with the production of hot water.

- Flow 1: exergy supplied by steam.
- Flow 2: exergy destroyed by heat exchange between live steam and water.
- Flow 3: exergy required for producing hot water.

About 34% of the exergy supplied for water heating is destroyed. The effect of water reutilization would not only reduce the exergy destroyed but also the steam required in this operation.

Table 2 gives the energy and exergy contents required to compute the new KPIs presented in Table 3.

4.3.1. Indicators analysis

The exergy destroyed in the process accounts for 61% of the total exergy supplied. This value represents the lost potential for energy conversion. The exergy destroyed in heat exchangers cannot be totally eliminated but can be reduced by the adjustment of the steam pressure levels and the improvement of the efficiency of boilers. The implementation of turbines eliminates the exergy destroyed by the PRV's.

The possibility of improvement by internal heat recovery or energy upgrading accounts for 25% (ExC_T) of the exergy required by the process (Ex_{Proc}). The exergy indicator of the flue gases (ExC_{FG}) has a greater value than the corresponding energy indicator (EC_{FG}), because the high temperature of the flue gases increases the quality of their energy content. In contrast, the exergy indicator of the effluents (ExC_E) is lower than the corresponding energy indicator (EC_E) because the effluents have near ambient temperature. The energy used for water heating accounts for 22% (EC_{WTot}) of the total energy required by the process. The exergy required for water heating, 34% of which is currently destroyed (Fig. 9), can be supplied by other heat sources at lower temperature than steam.

4.3.2. Remarks

The new KPIs complement the comparison of the process to the current practice, because they quantify several aspects of the energy efficiency of the process:

- Exergy wasted (lost or destroyed).
- Production and utilization of steam.
- Potential for cogeneration.
- Energy–water issues (exergy and energy required to heat up water).

Nevertheless, the analysis of all sinks and sources for water and heat is needed to establish the limits to increasing internal heat recovery and water reutilization.

4.4. Phase IV: targeting

4.4.1. Pinch Analysis

A ΔT_{min} of 10 °C has been used in previous P&P studies (Savulescu and Alva-Argaez, 2008) as recommended by Linnhoff-March (1998). The variation of the heating requirement with respect to the ΔT_{min} was analyzed to verify that this value is adequate for the present study. The current consumption of heat by the process, 172 MW, corresponds to a pinch diagram based on a ΔT_{min} of 30 °C (Fig. 10). The variation of the MHR is most sensitive between 5 °C and 40 °C and much less below 5 °C, however the capital costs increase rapidly at lower ΔT_{min} (Kemp, 2007). Therefore, the ΔT_{min} of 10 °C was used to construct the composite curves (Fig. 11). The minimum heating requirement (MHR) is 123 MW, the minimum cooling requirement (MCR) is 10 MW and the pinch point (PP) is at 71 °C. The maximum internal heat recovery that the process can achieve is 192 MW.

The difference between current steam consumption (172 MW) and MHR (123 MW) is the maximum amount of steam that could theoretically be saved (49 MW or 29% of current) by maximizing internal heat recovery. Additional savings could be obtained by upgrading the energy of the rejected heat, once internal heat recovery has been maximized. Heat recovery measures have already been implemented by the mill and are shown in Part I. An analysis of pinch rules violations should be performed to asses the practical efficiency of these measures.

The water temperature rise during summer reduces the steam consumption by about 10%. As the requirement for water heating is also decreased, part of the heat load for steam condensation in the black liquor concentration section (BLC10, BLC13, BLC14 in Table A2) becomes an additional cooling need (22 MW) in summer. This will be taken into account when internal heat recovery enhancing measures are formulated.

4.4.2. Water reutilization

The water composite curves are shown in Fig. 12. The pinch point is located at DSC = 0 ppm, i.e., for fresh water. The minimum water consumption (MWC) is 1000 m^3/h and the minimum effluent production (MEP) is 880 m^3/h. The maximum water reutilization that can be achieved is 1360 m^3/h. Thus, overall water consumption of the process could theoretically be reduced by 31%. The implementation of water decontamination devices to further reduce the DSC of water sources would be needed to further increase water savings by reutilization.

4.4.3. Remarks

The water and thermal composite curves include common streams such as the fresh water intake and the amount of effluents rejected. The modification of any of these common streams to improve the process affects the results of both analysis. Therefore, the development of water reutilization and internal heat recovery measures must consider energy and water issues simultaneously.

4.5. Phase V: synthesis

The steam and water consumptions are above the Canadian average practice. The black liquor concentration and pulp bleaching sections are the most inefficient process sections. The amount of exergy lost with effluents and flue gases (25% of the exergy supplied) is caused by the low level of internal heat recovery and water reutilization. The effects of these inefficiencies are observed in the total amount of destroyed exergy (61% of the exergy supplied) and the above average net thermal deficit (8.1 GJ/adt). Targeting establishes the maximum savings of steam (29%) and water (31%) that can be achieved by internal heat recovery and water reutilization. However, as some streams are part of both water and energy systems, the interactions between the two approaches should be identified before formulating energy saving measures. Water reutilization projects will reduce the steam utilization since water heating represents 22% of the total consumption. All these issues are interrelated and cannot be tackled individually. Interactions analysis which considers all the inefficiencies encountered during the base case definition will be performed.

The results obtained by the benchmarking procedure highlight some aspects that should be considered in the development of energy enhancing measures for the case study:

- The analysis of the interactions between the process systems should be conducted prior to developing improvement measures. The effects of water reutilization measures on the MER and pinch point should be determined. The new KPIs can be used to asses the effects of water reutilization and internal heat recovery in the overall energy efficiency.
- The analysis of the operating conditions of black liquor concentration, and pulp bleaching sections is required before applying internal heat recovery measures.

- The evaluation of the efficiency of non isothermal mixing points in the process can be done by analyzing the associated exergy destroyed.
- Energy upgrading, and condensate recovery must be evaluated to obtain further steam reductions.
- The implementation of cogeneration to produce power will reduce the exergy destroyed in the PRV's.

5. Conclusions

The three methods used to evaluate the energy and water performance, complement each other to obtain a detailed perspective of the process inefficiencies. The interactions between the utilities systems and process units have been identified as well as the possible limits of internal heat recovery and water reutilization have been identified.

The comparison to the current practice identifies the sections with low performance and gives an overall perspective of the energy and water consumption of the process. However, the next two stages of the benchmarking procedure are required to establish the sources of inefficiencies and the limits of the improvement that can be achieved.

The utilization of the exergy analysis strengthens the grasp of existing energy inefficiencies of the process. The quantification of the exergy destroyed in the production and distribution of the utilities is a straightforward method to monitor the energy degradation in the process. Additionally, the exergy lost with the rejected heat is an indicator of the inefficiencies and of the possible savings that can be achieved by internal heat recovery and water reutilization.

The targeting sets the limits of the potential energy efficiency enhancements. As thermal and water composite curves include common streams to both systems, the interactions between the water and steam systems should be identified and studied.

The benchmarking analysis establishes the efficiency of the base-case process, and that is the basis for the interactions analysis.

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Annex. Energy and water streams

Tables A1–A4

Table A1 – Cold streams.

Stream ID	Description	T start (°C)	T target (°C)	Heatload (MW)
BLC1	Water – Cond. 3	4.0	61.7	32.7
BLC2	Water – Cond. 1	4.0	44.2	13.6
BLC3	Water – Cond. 2	4.0	44.2	12.5
WP1	Make up water–warm water tank (NIM)	4.0	44.2	7.5
WP2	Water – 58 °C	4.0	58.0	7.6
WP3	Water – 58 °C	44.2	58.0	2.9
WP4	Water heating	44.2	53.3	8.7
WP5	Water – 62 °C (NIM)	53.3	62.0	8.3
WP6	Water – 71 °C	62.0	71.0	5.6
DEL 1	Delignification	63.2	170.0	32.4
DEL 2	Contaminated water (NIM)	60.2	93.4	22.4
DEL 3	Wood chips to delignification (NIM)	4.0	63.2	4.1
BLEA 1	Stage 1 – steam mixer (NIM)	49.5	56.0	2.0
BLEA 2	Stage 3 – steam mixer (NIM)	68.6	75.0	2.9
BLEA 3	Stage 4 – steam mixer (NIM)	71.9	85.0	2.6
DRY 1	White water direct heating (NIM)	62.1	63.1	2.8
DRY 2	Dryer – hot air	78.0	160.0	21.8
DRY 3	Dryer – indirect heating	100.0	101.0	7.7
DRY 4	Whitewater – reheating	38.0	60.0	4.0
BLC4	BL – train pre-evap	63.4	78.0	4.3
BLC5	BL – PC train 1	101.4	127.8	7.4
BLC6	BL – train 1	121.8	122.8	9.6
BLC7	BL – PC train 2	104.9	132.2	8.9
BLC8	BL – train 2	98.2	99.2	11.9
BLC9	Water heating pre-evap	80.3	96.0	10.2
DEA 1	Cold water to deareator (NIM)	4.0	57.1	7.1
DEA 2	Deareator (NIM)	57.1	137.7	23.2
LP 1	REC, Chem. prep, aux. equip.	143.4	143.5	12.5
MP 1	REC, Stripper, sawmill	179.4	179.5	13.1
HP1	Soot blowing, aux, equip.	235.0	235.1	5.9

WP, water preparation; DEL, delignification; BLEA, bleaching; DRY, drying; BLC, black liquor concentration; DEA, dearator; BOIL, boilers; Cond., condenser; PC, post concentrator; REC, recaustification; CC, contaminated condensate; Chem. Prep., Chemical preparation.

Table A2 – Hot streams.

Stream ID	Description	T start (°C)	T target (°C)	Heatload (MW)
WP 6	Warm water from Cond. 3 (NIM)	61.7	44.2	10.3
WP 7	Contaminated water to heat water	72.9	60.0	8.7
WP 8	Flashed steam – delignification (NIM)	138.3	137.3	1.0
WP 9	Warm water tank overflow	58.0	33.0	0.9
DEL 4	White liquor to delignification (NIM)	85.0	63.2	2.2
DEL 5	Pulp recycled to delignification (NIM)	81.0	63.2	1.6
DEL 6	Flash steam-blow down tank (NIM)	96.0	93.4	22.4
DEL 7	CC	96.1	33.0	1.4
BLEA 4	Stage 1 effluent	58.1	33.0	6.1
BLEA 5	Stage 2 effluent	68.6	33.0	9.9
BLEA 6	Stage 3 effluent	68.2	33.0	2.8
BLEA 7	Stage 4 effluent	66.8	33.0	1.3
BLEA 8	Stage 5 effluent	73.1	33.0	6.0
BLEA 9	Prewasher – effluent	49.4	33.0	1.5
DRY 5	Drying – effluents	62.1	33.0	4.5
BLC 10	Steam condensation Cond. 3	62.2	61.2	32.7
BLC 11	Flash steam to train pre-evap	80.3	79.2	2.6
BLC 12	Flash steam to train pre-evap	72.9	69.3	1.6
BLC 13	Steam condensation Cond. 2	60.1	59.5	11.0
BLC 14	Steam condensation Cond. 1	75.9	74.9	12.3
BLC 15	CC – effluent	71.9	33.0	9.1
BLC 16	CC – effluent	79.2	33.0	9.6
BLC 17	Flash steam evaporators	113.1	113.0	8.2
BLC 18	Flash steam from stripper	110.0	89.0	10.2
DEA 3	Condensate mixed with water (NIM)	115.5	57.1	7.5
DEA 4	Flash steam to deareation (NIM)	143.3	137.7	1.7
BOIL 1	Flue gas from RB 1	164.0	105.8	4.3
BOIL 2	Flue gas from RB 2	199.0	117.6	4.6
BOIL 3	Flue gas from BB	182.0	126.5	2.9
BOIL 4	Boilers-blow down	235	33.0	2.1

Table A3 – Water sinks.

Stream ID	Description	Flow (t/h)	Max. DSC allowed (ppm)
DRY 6	Drying – whitewater tank (62 °C)	6	6043
BLEA 15	Stage 1 requirement (71 °C)	200	2072
BLEA 17	Stage 3 requirement (71 °C)	191	1643
BLEA 18	Stage 2 requirement (71 °C)	199	1557
WASH 1	Washing (71 °C and 58 °C)	406	1240
DRY 7	Drying – separator (62 °C)	39	965
BLEA 19	Stage 5 requirement (71 °C)	189	693
BLEA 20	Pre-washer requirement (58 °C)	228	0
BLEA 21	Gas washer	1	0
BLEA 22	ClO_2 preparation	129	0
BLEA 23	$NaClO_3$ preparation	10	0
DEA 5	Deareator	139	0
REC 1	Reacaustification (44 °C)	59	0
DRY 8	Drying requirement (62 °C)	216	0
BLEA 24	NaOH preparation	16	0
WP12	Vacuum pumps	69	0
BLEA 25	Stage 4 requirement (71 °C)	190	0
BLEA 26	Static mixers	19	0
WP 13	Water by passed (clarification)	134	0

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Table A4 – Water sources.

Stream ID	Description	Flow (t/h)	DSC (ppm)
BLEA 5	Stage 2 effluent	241	6125
BLEA 6	Stage 3 effluent	68	4137
BLEA 4	Stage 1 effluent	212	4036
BLEA 7	Stage 5 effluent	130	3428
BLEA 10	Water (71 °C) + Stage 3 filtrate	200	2072
BLEA 9	Pre-washer – effluent	78	1952
BLEA 8	Stage 4 effluent	34	1775
BLEA 11	Water (71 °C) + Stage 4 filtrate	191	1643
BLEA 12	Effluent separator	26	1618
BLEA 13	Water (71 °C) + Stage 5 filtrate	199	1558
WASH 2	Water (71 °C) + filtrate pre-wash	388	842
DRY 5	Drying – effluents	337	641
DEL 7	CC – effluent	19	0
BLC 19	CC – effluent	171	0
BLC 20	CC – effluent	190	0
BOIL 4	Boilers – blow down	12	0
WP 10	Water by-pass (clarification)	134	0
WP 11	Vacuum pump sealings – effluent	69	0

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