Computer aided integration of utility systems

Francois Marechal, Boris Kalitventzeff

WILEY-VCH Verlag Berlin GmbH
July 23, 2004

Contents

0.1 Introduction

The integration of utility system concerns the way distributed energy entering a production plan will be transformed into useful energy for satisfying the needs of a process. In order to identify the best options for the utility systems, one has to consider the production process (CIP : Chemical Industrial Plant) as a system (figure 1) that converts raw materials into valuable products and by-products. The production is realised by a list of interconnected physical unit operations that will together form the chemical process. These transformations are made possible by the use energy and support media, like sovent, water or catalysts. The transformations being not perfect, the process results in the production of waste by the application of the first principle. Waste are emitted under several forms :

- waste heat in the cooling water or the air;
- emissions as combustion or other gases (e.g. humid air, steam vent,...);
- liquid streams as polluted water or solvent;
- solids.

The emissions being regulated or taxed, the waste emissions should reach levels that require waste processing strategies. When performed on site, the waste treatment integration offers opportunities for reducing the treatment cost by material recycling, waste energy recovery or by using process waste heat to improve the treatment efficiency.
In this chapter, the utility system will be considred as being composed of different sub-systems that serve the production processes:

- Energy conversion;
- compressed gases : air, O2, N2, H2,....
- Cleaning in place;
- Air conditioning and space heating;
- Catalysts recovery;
- Solvent recovery;
- Water treatment;
- Effluent treatment;
- ...

We will however focus our presentation on the energy conversion and the water integration. Referring to figure 1, the goal of the engineer is to maximise the efficiency of the horizontal transformations from raw materials to products, by minimising the use of resources in the vertical transformations, leading by balance to the reduction of the emissions.

The process integration techniques based on the pinch analysis (e.g. [1]) have mainly focussed on the definition of the minimum energy requirement (MER), expressed as the minimum (useful) heat requirement, and the definition of the optimal heat exchanger network (HEN) design that will realise the energy recovery between the hot and the cold streams of the production processes at a minimum cost, achieving this way the best trade-off between the heat exchangers investment and the energy savings. In this approach, utilities are not really considered since they appear only as being a way of supplying the minimum energy requirement. Using the analogy between temperature and concentration and between flowrate and heat, the water usage may be tackled using a similar approach (e.g. [2]). We will therefore first present the integration energy conversion units integration methods and consider after water the water usage aspects.
The role of the energy conversion sub-system will be to supply the energy requirement of the process at a minimum cost or with a maximum of efficiency. This means converting the available energy resources into useful energy (energy services) and distribute it to the process operations. From the process synthesis perspective, the problem concerns five aspects :

- the definition of the most appropriate energy resources;
- the selection of the conversion technologies;
- the definition of the most appropriate size of the equipment considered for the system (i.e. the investment);
- the defintion of the most appropriate way of operating the conversion system;
- the definition of the utility-process heat exchanger network (energy distribution and interface between the utility system and the process).

In order to increase the efficiency of the energy conversion system, the rational use of the energy resources will be obtained by the combined production of different services (polygeneration), for example combined heat and power, combined production of hydrogen and steam or refrigeration.
In a process, the utilities are considered as a service that is provided to the process plants. The control and the reliability issues are also part of the problem. For example, steam condensers are placed in such a way that these will control the target temperatures of the process streams. when the investment are made, the optimal management of the utility system will cover the aspects of exploiting market opportunities (e.g. electricity prices,...) and using at best the energy conversion equipment. The scheduling and the optimal management will then be an issue for the process.
The role of the utilities becomes even more important when considering multi-processes plants that will be served by one utility system. In this case, the utility system will transfer heat between processes. Considering the variations of the demand with times, the definition of the optimal system a multi-modal multi-period problems where the best sizes of the equipment will have to be defined considering annualised value on a yearly production basis. In this perspective, another dimension to consider is the influence of the ambient conditions that will influence both the process demands and the conversion process efficiency (e.g. the influence of the ambient temperature on the refrigeration cycle COP).

0.1.1 Defining the process requirements using the utility system

In the ideal situation, the definition of the hot and cold streams of a process is obtain from process simulation tools. The data of the process are however not always available when doing a process integration study. This is particularly the case when the chemical production site utility system is managed by an energy service company that is different from the production companies on the site. Furthermore, if utility systems are easy to instrument, instrumenting processes are not always so easy particularly when dealing with processes in food and agro industry. Taking advantage of the utility system instrumentation, it is possible to deduce the definition of the hot and cold streams of the process from the data collected on the utility system. Data reconciliation tools will be used to combine on-line measurements with other information from the specification sheets of the processes and obtain a coherent picture of the process.

Correctly defining the temperatures and the heat loads of the hot and cold streams is crucial in process integration projects. For this reason, the first step of the analysis 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 2 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.

A systematic analysis [3] should therefore be followed to define most of the process requirements from the knowledge of the process utility interface.

0.2 Methodology for designing integrated utility systems

The process integration techniques aim at identifying the maximum energy recovery that could be obtained by counter-current heat exchange between the hot and the cold streams of the process. This technique, based on the assumption of a minimum temperature difference between the hot and the cold streams ($\Delta Tmin$), allows the calculation of the so-called minimum energy requirement (MER) target for the system. The identification of the pinch point, the point where the hot and cold composite curves of the process are the closest, is further used to design the heat recovery heat exchanger network structure. Using the concept of the hot and cold composite curves, it is possible to compute graphically the MER. Mathematically, the minimum energy requirement is computed by solving the heat cascade model (1). This model is a one degree of freedom linear programming problem that computes the the energy required to balance the energy required by the cold streams with the hot streams for each temperatures of the problem. The Grand composite curve is the plot of this heat requirement as a function of the temperature.

$$\min_{R_r} R_{n_r+1} \tag{1}$$

subject to heat balance of the temperature intervals

$$\sum_{i=1}^{n} Q_{i,r} + R_{r+1} - R_r = 0 \quad \forall r = 1, ..., n_r \tag{2}$$

$$R_r \geq 0 \quad \forall r = 1, ..., n_r + 1 \tag{3}$$

with n the number of specified process streams;
n_r the number of temperature intervals;
R_r the energy cascaded from the temperature interval r to the lower temperature intervals in the time period p;
Q_{ir} the heat load of the reference level of process stream i in the temperature interval r; $Q_{ir} > 0$ for hot streams and ≤ 0 for cold streams;

The heat cascade constraints (2) is the equation system that is solved by the problem table method. An alternative set of equations (4) may be used to compute the heat cascade. This formulation has the advantage of involving only one R_r per equation, each of the equation being related to one temperature in the temperature list. From the analysis of the pinch point location it may be demonstrated that the list of temperatures (and therefore of equations) may be reduced in this case to the list of inlet temperature conditions of all the streams. By saying that, we assume that the fluid phase changing streams are divided into streams segments.

$$\sum_{k=r}^{n_r} (\sum_{i=1}^{n} Q_{i,k}) + R_{n_r+1} - R_r = 0 \quad \forall r = 1, ..., n_r \tag{4}$$

When considering the overall system (including the utility streams), it is necessary to define the complete list of streams to be considered in the system including the hot and cold streams of the utility sub-system, prior any heat exchanger network design. Compared to the conventional pinch analysis where hot and cold streams of the process are considered as constant, the utility system integration has a much larger number of degrees of freedom that will be dealt with modelling and optimisation techniques.

Energy conversion units modelling will be used to determine the operating temperatures and compositions allowing the definition of the hot and cold streams of the utility sub-system. The flowrates will be determined by optimisation in order to minimise the cost of the energy delivered. The constraints of the heat cascade will be considered in the problem and the solution will be characterised by a list of pinch points. One of these being the process pinch point, representing the maximum energy recovery between the process streams , the others corresponding to the maximum use of the cheapest utility. If, in the simplest cases, the calculation of the utility streams may be done graphically, it is more convenient to use optimisation techniques to solve the problem, especially when cycles like steam network integration is considered.

There exist several ways of solving the optimal integration of the energy conversion system. All of these strategies will be based on the definition of a utility system superstructure that will include the possible conversion technologies that are envisaged. Although it is possible to set up a generic problem that would state and solve the problem in an automatic manner, it is more convenient to proceed by successive iterations, keeping in mind that learnings from one step will results in new problem definitions and perhaps news ideas for the integration of alternative energy conversion technologies. This is particularly true because the problem definition is usually not known from the beginning and because the utility system integration may influence the process operating conditions.

The philosophy behind the computer aided utility system integration is to have a method that supports engineers creativity, helping him in identifying the most promising options.

Three major aspects have to be considered :

- Technology data bases including thermo-economic models of the different technologies available on the market. These models will be used to constitute the energy conversion system superstructure that will be consistent with the technologies available on the market.

- An optimisation framework for targeting the optimal integration of the utility system prior any heat exchanger network design. The optimal utility system integration is by definition a mixed integer non linear programming problem (MINLP), the integer variables being used to select in the superstructure the equipment to be used in the final configuration while the continuous variables will be the operating conditions and the flowrates in the utility system.

- Graphical representations applying thermodynamic based principles to assess, analyse and understand the solutions obtained by optimisation and to help in the definition of the superstructure. Graphical representations are used to support the engineers when stating the problems and analysing the results.

0.3 The energy conversion technologies data bases

When considering energy conversion technologies, we switch from the energy dimension to the thermo-economic dimension, where cost of energy and the investments are considered simultaneously. It is therefore necessary to represent the market state by introducing market related relationships between cost, sizes and efficiencies. There is therefore a need to develop technology data bases for the different conversion technologies. Today, the web based techniques give access to the needed information [4]. The required data are the following :

- Investment costs refer to the installed cost. It is computed by :

$$CI_e = CP_e + CC_e + CE_e + CG_e + CO_e \tag{5}$$

with	CI_e	the installed cost of the equipment e
	CP_e	the purchased cost of equipment e
	CC_e	the cost of connexions and piping
	CE_e	the cost of engineering for equipment e
	CG_e	the cost of civil engineering for equipment e
	CO_e	the other costs like taxes, land,... e

- Maintenance cost required to operate the technolology on a yearly basis;
- Operating cost that refer to the man power, and the consumables related to the use of the technology;
- The fuel consumption and the type of the fuel concerned. This usually refers to as the thermal efficiency computed by $\eta_{th} = \frac{useful_heat(kJ)}{LHV(kJ)}$. Ideally, efficiency should include partial load information;
- The electricity consumed or produced;
- The hot and cold streams that define the energy service delivery (process/utility heat exchange interface);
- The standard prescriptions for the technology specification;
- Any information concerning the technology implementation;
- Time to market information;
- The list of suppliers.

From data collection using a technology market study, correlation equations are obtained. These give, as a function of the sizing parameters, the required values for the optimal integration models. For the efficiencies correlation, it is important to analyse the degrees of freedom in order to avoid developing correlation that would be inconsistent with the rules of thermodynamics. For this reason it is usually prefered to use simulation models for the technologies in which the model parameters are defined as correlation functions, e.g. isentropic efficiency as a function of the turbine size. Two types of approaches may be used. The first aim at representing the technology market by functions that correlate the model parameters with technology design parameters like temperature, pressure or size. The model has the following generic form :

$$\begin{array}{ll} \text{Heat and mass balances} & B(X,S,P)=0 \\ \text{Efficiency equations} & F(X,S,P)=0 \\ \text{Cost correlations} & CI=CI(X,S,P) \\ \text{Correlations limits} & S_{min} \leq S \leq S_{max} \end{array} \tag{6}$$

with X the list of state variables characterising the streams of the technology
S the set of sizing variables of the technology
P the set of characterising parameters of the technology identified from the market data base correlations

When detail thermo-economic models are available, the efficiency equations will be become more complex. Some examples of such relationships are given by Pelster et al. [5], [6],[7]. With this approach, it is assumed that the technology may be custom made. It applies therefore well for steam turbines, heat pumps or heat exchangers. The second approach considers that the technologies are available on the market with fixed sizes and operating design conditions. This is the case for example for the gas turbines market in which a limited number of models is available. In both situations, the data from data bases are used to calibrate the thermoeconomic models. The thermoeconomic model is first calibrated by computing the model parameters in the standard conditions in which the reference data base have been collected. A parameter identification method is then used to determine the best parameters to compute the state variables of the system. The paramters are then used to compute the system performances in the operating conditions of the plant under study. Consider for example a gas turbine defined in a data base. The efficiencies are given for standard operating conditions defined in ISO standards (e.g. pure methane, 15C, 1atm.). The efficiencies of the compressor and turbines as well as geometrical parameters (e.g. Stodola numbers) are computed. The gas turbine performances with the temperature, pressure and natural gas available on the plant are then computed by fixing the values of the simulation parameters. The model will also give the values of the part load efficiencies.

The cost correlation have to be used with caution considering the conditions, the area, the date and the ranges for which they have been established. Consider for example the results of Pelet [8] shown on figure 5. The different correlation obtained from the literature and other market surveys are compared and show big differences..

The following tables give the values and corelations for the major energy conversion technologies. These data are representative from the European market in 2000. They have been gathered mainly by the partners of the European project EXSYS ([9], [10]). All the data are given with a CEPI index of 382. For other equipments, usefull references like [11] may be used.

When data are available from another sources, e.g. from quotations, the effect of size is represented by the relation (**??**), the exponent being given on table **??** obtained mainly from the following sources [12], [11],[13] and xxxxx.

$$C(y) = C_{ref} * (\frac{S}{S_{ref}})^e * \frac{CEPI(y)}{CEPI(y_{ref})} \quad (7)$$

with	$C(y)$	the installed cost of the equipment at the year y
	S	The size of the equipment
	S_{ref}	the size of the known equipment
	C_{ref}	the cost of the known equipment
	$CEPI(y)$	The chemical engineering plant index for the year y;
	y_{ref}	The year of the reference cost C_{ref}

The total cost of the energy conversion system is given by :

$$\sum_{p=1}^{n_p} d(p)(\sum_{f=1}^{n_{fuels}} (\dot{m}_f(p) * C_f(p)) + Cel(p)\dot{W}el(p) - Cel_s(p)\dot{W}el_s(p)) + \sum_{e=1}^{n_e} Cm_e + \sum_{e=1}^{n_e} CI_e(\frac{i(1+i)^{n_e}}{(1+i)^{n_e}-1}) \quad (8)$$

with	$\dot{m}_f(p)$	the flowrate of fuel f during the period p (kg/s);
	$C_f(p)$	the cost of fuel f during the period p (in ϵ/kg);
	$\dot{W}el(p)$,$\dot{W}el_s(p)$	resp. the electrical power imported (exported) during period p (kW) ;
	$Cel(p), Cel_s(p)$	resp. the cost of electricity for import (export) during the period p (ϵ/kJ);
	$d(p)$	the duration of period p in is $s/year$;
	Cm_e	the maintenance cost of equipment e ($\epsilon/year$);
	n_e	the number of equipments;
	CI_e	Installed cost of equipment e in ϵ;
	i	the interrest rate for annualisation;
	n	the expected life time of the installed equipment e;

0.4 Graphical representations

From the begining, composite curves have been used to explain the integration and identify energy savings opportunities. In most of the representations, the temperature is a topological indicator in the sense that it allows to pinpoint the process operations concerned with the pinch points or the pseudo pinch points.

The hot and cold composite curves concern mainly the process streams, they are used to quantify the possible energy recovery by exchanging heat between the hot and cold process streams. Four zones are of importance in the hot and cold composite curves (figure **??**). The hot utility requirement, the heat recovery are and the cold utility requirement. The later being divided between cooling requirements above the ambient temperature and the refrigeration section below the ambient temperature that should be considered as an independent sub system.

0.4.1 Grand composite curve

For analysing the energy conversion system integration, the Grand composite curve (figure 15) will be used. It describes as a function of the temperature, the way energy has to be supplied to or removed from the system. The process Grand composite curve is divided into three zones : above the process pinch point, the system is a heat sink to be supplied by a hot utility. Below the process pinch point and above the ambient temperature, the process is a heat source. The heat has to be evacuated from the process by a cold utility or used in another energy consuming sub-system like another process or a district heating system. Below the ambient temperature, the process requires refrigeration. The feasibility rule of the utility integration is that the Grand composite curve of the utility system should envelop the process Grand composite curve. Resulting from the linear nature of the composite curve calculation, the optimal integration of the utilities will result in the definition of utility pinch points (intersection between the utility composite and the process composite). Each of them will correspond to the optimal use (maximum flowrate) of the cheapest utility stream. Above the pinch point, the Grand composite curve represents as a function of the temperature the heat that has to be supplied to the process by the hot utility. When deleting the pockets in this curve, the process appears as a cold stream to be heated up by the hot utility. Knowing the temperature-enthalpy profile of the utility, it is possible to determine the flowrate of the utility stream by activating the appropriate pinch point as illustrated on figure 3 for one hot utility whose inlet temperature is higher than the maximum temperature of the process streams. In this situation, the flowrate of the utility stream is computed by :

$$f_w = \max_k \frac{R_{n_k+1} - R_k}{cp_w * (Tin_w - max(Tout_w, T_k + \Delta Tmin/2_w)} \tag{9}$$

with	f_w	the flowrate of utility w in kg/s;
	$Tin_w, Tout_w$	respectively the inlet and the outlet temperature of the utility stream w;
	cp_w	the specific heat of the utility w in $kJ/kg/C$

$\Delta Tmin/2_w$	the contribution to the minimum approach temperature if the utility stream w;
R_k	for k=1,$n_k + 1$ the values of the heat cascade, R_{n_k+1} is the MER of the process;

It should be mentioned that in the example, the heat delivered by the hot utility is higher than the MER. The pinch point that is penalising the cost of energy is different from the process pinch point. Additional heat is available from the hot utility and should be valorised. This situation is the typical situation in high temperature processes like reforming processes where the high temperature pinch point is activated by the integration of the combustion flue gases and where the heat excess available in the flue gases at lower temperature is used to produce high pressure steam that will be expanded in a condensing turbine to transform the excess heat into useful mechanical power.

The same principle applies for the cold utility requirement and the refrigeration requirements. This approach can not however be applied when utility streams interact as it is the case when steam is produced in a boiler, then expanded before being condensed in the process. The utility system is made of more than one stream and the flowrate of one (e.g. the steam flowrate) will define the flowrate of the other (e.g. the fuel consumption in the boiler. Furthermore, the heat of the flue gases being available for the process, nothing restrict its usage to a temperature above the steam condensation temperature. As it will be demonstrated later on, the problem has to be solved by optimisation in this case. Nevertheless, the Grand composite curve representation will be a primal importance to define the possible utilities that may be envisaged for the process under study. An other important aspect of the utility system integration is the combined production or consumption of mechanical power. Townsend and Linnhoff [14] have made a complete analysis on the use of the Grand composite curves to analyse the optimal placement of the energy conversion systems and the combined heat and power production. Following the prescribed rules, the engineer is able to define a list of possible energy conversion technologies that may be envisaged for the process under study. The creativity of the trained engineers will unfortunately create a problem at this stage since it will usually be able to identify more than one technology per requirements.

0.4.2 Using exergy analysis

The exergy analysis is a thermodynamic based useful concept that helps understanding and analysing the efficiency of energy conversion systems. Exergy measures the thermodynamic value of energy. It defines the maximum work which could ideally be obtained, from each energy unit being transferred or stored, using reversible cycles with the atmosphere as one of the energy sources either hot or cold. The exergy approach (e.g. Kotas [15]) is used to represent in a coherent way both the quantity and the quality of the different forms of energy considered. The concept of exergy presents the major advantage of efficiency definitions which are compatible with all cases of conversion of energy resources into useful energy services (heat and electricity, heat-cold-electricity, refrigeration, heat pumps, etc.) and for all domains of use of energy. While energy efficiencies are higher than 100 % for heat pumping systems (because ambient energy is not accounted), exergy efficiencies are always lower than

100%. It gives an indication of how well the potential of an energy resource is exploited in different technical concepts in competition.

In the context of process integration analysis, the exergy concept is combined with the pinch analysis for both for reducing the energy requirement of the process ([16], [17] and for optimising the energy conversion system integration and the combined heat and power production. The exergy composite curve concept has been introduced by Dhole [18] for this purpose. The exergy delivered by a stream exchanging heat ($\dot{Q}$) from T_{in} to T_{out} is computed by : $\dot{E} = \dot{Q}(1 - \frac{T_0}{T_{lm}})$ where T_{lm} is the logarithmic mean of temperatures computed by $T_{lm} = \frac{T_{in}-T_{out}}{ln(\frac{T_{in}}{T_{out}})}$ and T_0 is the ambient temperature, all temperatures being expressed in K. When representing the heat exchange in the temperature-enthalpy diagram, the exergy delivered may be computed by exchanging the temperature axis with the Carnot efficiency $(1 - \frac{T_0}{T})$, it corresponds then to the area between the exchange curve and the enthalpy axis (figure 4).

When applied to the concept of the composite curves, the exergy composite curves (figure 6) represent the exergy losses that will occur in the heat exchange between the hot streams and the cold streams of the system. The exergy delivered by the hot streams (shaded area between the hot composite curve and the X axis) is deduced from the exergy required by the cold streams (shaded area between the cold composite curve and the X axis). As for the hot and cold composite curves, there are four zones to be considered in the representation. The hot utility requirement is defined by an area (below the cold composite curve) that represents the corresponding exergy requirement. The area between the two curves represents the amount of exergy that will be lost in the heat recovery heat exchange network. This exergy loss may be recovered in part by properly integrating combined heat and power devices. Therefore, the area between the curves and above the pinch point should be deduced from the hot utility exergy requirement to define the minimum exergy requirement of the prcoess. After the heat recovery exchange, the remaining heat, to be evacuated from the system, is divided into two parts, above the X axis (ambient temperature) the area between the hot composite curve and the X axis represents the exergy that could be obtained by integrating low temperature heat recovery devices like ORC. Below the X axis, the area represents the exergy required by the refrigeration system. Favrat and Staine [16] have added to this representation, the exergy losses related to the compression work (as a function of the pressure drop) and the gray exergy. The gray exergy is the exergy required to build the heat exchangers that may take some importance when the process and the heat recovery exchangers are operated only part time. When considering the exergy Grand composite curve, the diagram represents the exergy required by the process. In this diagram, it should be noted the special role of the pockets, the area of which represents the possible mechanical power recovery by the combined heat and power (figure 7). From this analysis, it is possible to identify the possible characteristics of the steam cycle as demonstrated by Marechal et al. in [19] . This is done by integrating rectangles in the Grand composite curve. The basis of the rectangle being the vaporisation and the condensation temperatures of the Rankine cycle. The use of the exergy concept allows to quantify the exergy required and therefore allows to set a target for the energy conversion system. Because the grand composite curve is computed in the corrected temperature domain, we consider that there will be an exergy loss that is a priori accepted for limiting the heat exchangers investment and which is related to the definition of the $\Delta Tmin$. The exergy analysis has been extended to account for the chemical reactions or the physical separations of the process operations [**?**]. In this representation, the temperature axes is replaced by $\frac{\Delta H - T_0 \Delta S}{\Delta H}$ that is an extension of the Carnot factor $(1 - \frac{T_0}{T})$.

One heuristic rule resulting from the exergy analysis is to try to reduce to a minimum the area between the hot and cold composite curves of the integrated systems.

0.4.3 Balanced composite curves

The optimisation models as presented hereafter allow to overcome such difficulties by computing the optimal flowrates in the utility system in order to minimise the cost of supplying the energy requirement. The composite curves of the process together with the utility system is known as being the balanced composite curves. An example of such curves is given on figure **??**. This representation is characterised by a number of pinch points, one being the process pinch point, the others corresponding to the maximum use of the cheapest utilities to satisfy the process requirement. These curves are however difficult to analyse and do not really help in improving the system.

0.4.4 Integrated composite curves

The integrated composite curves [20] will help analysing the results of the optimisation or understanding the integration of sub-systems. This representation is based on the decomposition of the system into sub-systems : processes, boiler house, refrigeration cycle, steam network, heat pump, utility system,... even very detailed sub-systems may be considered like the existing heat exchangers.

The Integrated composite curves of a sub-system is obtained by subtracting from the Grand composite curve of the overall system, the Grand composite of the sub-system under study. The next step is to mirror the sub-system curve. The two curves intersect at the pinch points of the balanced composite curves. In order to locate the Y zero axis, it is useful to consider the process pinch point location as a reference. From a mathematical point of view, the integrated composite curves are computed using the following formula.

The set of streams is divided into two sub-sets. The first (set A) defines the sub-system whose integration should be checked, the second (set B) being formed by all the other streams. The set B will be referred to as being the reference set.
The set B will be represented by a curve (RB_k,T_k), where T_k is the kth corrected temperature of the heat cascade and RB_k is computed by :

$$RB_k = R_r + \sum_{r=k}^{n_k} \sum_{s=1}^{N_B} Q_{sr} \qquad \forall k = 1, ..., n_k \tag{10}$$

with N_B the number of streams in sub-system B;
Q_{sr} the heat load of stream s in the temperature interval r
R_r the enthalpy reference that defines the position of the temperature axis (see below).

The opposite curve (RA_k,T_k), corresponding to the sub-set A, is computed to make the balance of the first one. It defines the integration of the streams of set A to the others (reference set B):

$$RA_k = R_r - R_{n_k+1} - \sum_{r=k}^{n_k} \sum_{s=1}^{N_A} Q_{sr} \quad \forall k = 1, ..., n_k \tag{11}$$

with N_A the number of streams in sub-set A;
R_{n_k+1} the additional energy that can not be provided by the proposed utility set.

The R_{n_k+1} has been introduced to obtain a general definition. When the utilities are well integrated $R_{n_k+1} = 0$.
The value Rr, that appears in the definition of the two curves, defines the position of the temperature axis. The value of Rr is computed by considering that the curve of set B (the reference set) will intercept the temperature axis at the process pinch point temperature. The latter being identified by computing the heat cascade where only the process streams are considered. If k_p refers to the process pinch point, R_r is obtained by fixing RB_{k_p} = 0 in equation 10. That gives:

$$R_r = \sum_{r=k_p}^{n_k} \sum_{s=1}^{N_B} Q_{sr} \tag{12}$$

Using this definition, the temperature axis divides the energy range into two parts, the positive values correspond to the MER of the process, while the negative values refer to the energy involved in the integration of set A. The application of the integrated curves representation is described in more details in Marechal and Kalitventzeff [20]. Some applications of the integrated composite curves are given in the example hereafter. Such representation is really useful when analysing the integration of cycles. In this case, the difference between the hot and the cold streams corresponds to the mechanical power that closes the energy balance. The representation will therefore be used to verify the integration of steam networks or refrigeration cycles and confirming the appropriate placement of the cycles in the process integration.

When the sub-system considered is a heat exchanger, the integrated composite curves of the heat exchanger is the graphical representation of the remaining problem analysis. When the two curves are separated by the temperature axis, no heat exchange is needed between the streams of the heat exchanger and the rest of the process, when this is not the case, the size of the heat exchange between the two curves will represent the energy penalty that would be associated to the heat exchanger under study. The graphical representation in this case gives also an indication on the temperature profile of the heat exchange required to reduce the penalty. An example is given on figure 8

0.5 Solving the energy conversion problem using mathematical programming

The analysis of the process requirement using the analysis of the grand composite curve and by applying the rules of optimal placement of Townsend et al. [14] and other rules for the optimal CHP schemes allows to propose a list of energy conversion technologies able to supply the energy requirement of the process with a maximum of efficiency. The mathematical formulation of the targeting problem exploits the concept of Effect Modelling and Optimisation (EMO) developed by the authors [21],[22]. It will be used to select the equipment in the superstructure and determine their optimal operating flowrates in the integrated system. This approach assumes that the temperature and pressure levels are fixed, resulting from the analysis of the Grand composite curve and the application of rules for the appropriate placement of utility streams [14]. The problem is then a Mixed Integer Linear Programming (MILP) formulation where each technology in the utility system is considered with an unknown level of utilisation to be determined in order to satisfy the heat cascade constraints, the mechanical power production balance and additional modeling constraints. Two variables are associated with the utility technology w : the integer variables y_w represents the presence of the technology w in the optimal configuration and f_w its level of utilisation. The objective function is the total cost including the operating costs and the annualised investment cost both expressed in Monetary Units (MU) per year. Other objective function like minimum operating cost or minimum of emissions may also be used. The annualising factor is computed from the annualising rate and the life time of the investment. In the equation system, we complete the model by an additional set a constraints 17 that are written in a generic form.

$$\min_{R_r,y_w,f_w,y_w} (\sum_{w=1}^{n_w} (C2_w f_w) + CelWel - Cel_s Wel_s) * t_p + \sum_{w=1}^{n_w} (C1_w y_w^{max}) + \frac{1}{\tau} \sum_{w=1}^{n_w} (ICF_w y_w^{max} + ICP_w f_w^{max}) \quad (13)$$

subject to

Heat balance of the temperature intervals

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{i=1}^{n} Q_{i,r} + R_{r+1} - R_r = 0 \forall r = 1, ..., n_r \quad (14)$$

Electricity consumption:

$$\sum_{w=1}^{n_w} f_w w_w + Wel - Wc \geq \quad (15)$$

Electricity exportation

$$\sum_{w=1}^{n_w} f_w w_w + Wel - Wel_s - Wc = 0 \quad (16)$$

Other additional constraints

$$\sum_{w=1}^{n_w} a_x^i f_w + c_w^i y_w + \sum_{k=1}^{n_x} d_k^i x_k \overset{=}{\geq} b_i \forall i = 1, ..., n_e \tag{17}$$

$$xmin_k \leq x_k \leq xmax_k \qquad \forall k = 1, ..., n_x \tag{18}$$

Existence of operation w during the time period p:

$$fmin_w y_w \leq f_w \leq fmax_w y_w \qquad {}_{y_w \in 0,1}^{\forall w=1,...,n_w} \tag{19}$$

Thermodynamic feasibility of the heat recovery and utility systems

$$Wel \geq 0, Wel_s \geq 0 \tag{20}$$

$$R_1 = 0, R_{n_{r+1}} = 0, R_r \geq 0 \qquad \forall r = 1, ..., n_{r+1} \tag{21}$$

Maximum size of operation w

$$f_w^{max} - f_w \geq 0 \qquad \forall w = 1, ..., n_w \tag{22}$$

$$x_k^{max} - x_k \geq 0 \qquad \forall k = 1, ..., n_x \tag{23}$$

Use or not of operation w

$$y_w^{max} - y_w \geq 0 \qquad \forall w = 1, ..., n_w \tag{24}$$

with
- y_w the integer variable associated with the use of the technology w;
- $C1_w$ the fixed cost of using the technology w, this value is expressed in monetary units (MU) per year;
- $C2_w$ the proportional cost of using the technology w. This value is defined in MU/unit of the operating period;
- ICF_w the fixed cost related to the investment of using operation w; ICF_w is expressed in Monetary Units (MU) and refers to the investment cost of the combustion and cogeneration equipments as defined above as well as to the other equipments considered in the utility system (turbines, heat pumps, refrigeration systems,...).
- ICP_w the proportional cost related to the investment of using the operation w, ICP_w is expressed in MU/(unit of w).
- τ is the annualising factor of the investment. This value is used to express the investment of the IEST's in MU/year. $\tau = \frac{(1+i)^{n_{years}}-1}{i(1+i)^{n_{years}}}$ is the annualisation factor of the investment ($years^{-1}$) for a annualisation interest i and an expected equipment life n_{years}.
- y_w^{max} the maximum value of the integer variable associated with the use of the operation w over the overall time period. If the operation w is used at least once during the overall time period the value of y_w^{max} is equal to 1 and the related investment will be considered as well as the related fixed operating cost.

f_w^{max}	the maximum value of the multiplication factor of operation w over the overall the time period. This value represents the (maximum) size of the technology to be installed and is therefore related to the investment for the corresponding technology.
n_w	the number of technologies proposed in the super configuration of the utility system;
q_{wr}	the heat load of the technology w in the temperature interval r for a given reference flowrate, $q_w r > 0$ for a hot stream;
f_w	the multiplication factor of the reference flowrate of the technology w in the optimal situation;
w_w	the mechanical power produced by the reference flowrate of technology w; $w_{w,t} < 0$ for a mechanical power consumer and > 0 for a producer;
Cel_s	the selling price of electricity;
Wel_s	the net production of electricity;
Cel	the electricity cost;
Wel^t	the net import of electricity;
Wc	the overall mechanical power needs of the process; $Wc < 0$ if the overall balance corresponds to a mechanical power production
x_k	the (n_x) additional variables used in the additional equations of the technology models
a_w^i c_w^i	respectively $\begin{matrix}\text{the coefficients of the multiplication factor}\\ \text{the integer variables}\end{matrix}$ of technology w in the constraint i in the effect models.
d_k^i b_i	respectively the $\begin{matrix}\text{coefficients of the additional variables}\\ \text{the independent term}\end{matrix}$ in the constraint i in the effect models;
$xmin_r$ $xmax_r$	respectively the $\begin{matrix}minimum\\ maximum\end{matrix}$ bounds of x_r.
$fmin_w$ $fmax_w$	the $\begin{matrix}minimum\\ maximum\end{matrix}$ values accepted for f_w

The method presented may be applied to any kid of energy conversion technologies. It is based on the assumption that the operating conditions have been defined for each of the equipment concerned and that only the flowrates are unknown. This is a limiting assumption but it allows to solve most of the problems of energy conversion integration mainly because non linearities may usually be solved by discretising the search space. The method has been further adapted to compute the optimal integration of steam networks [23], to incorporate restricted matches constraints [24], to integrate refrigeration cycles [25][26] and Organic Rankine Cycles[27] as well as heat pumps [28]. It has been applied to integrate new technologies likes the partial oxidation gas turbine [29], or to design new type of power plants by introducing the concept of isothermal gas turbines [30].

0.5.1 Gas turbine and combustion system

In order to demonstrate the ability of the formulation to tackle complex problems, the model for computing the integration of gas turbines and combustion will be given in more detail . The purpose is to explain how to formulate the problem as a linear problem even if the models appears to be non linear. The model represents the integration of the gas turbine including its partial load operation, the possible post-combustion of the gas turbine flue gas, the use of different fuels in the gas turbine and in the post combustion, and of course the integration of conventional combustion in a radiative furnace with possible air enrichment or air preheating. The post combustion and the partial load models are required because there is no possibility of identifying a gas turbine model whose heat load will perfectly match the heat requirement of the process. The principle of the integration are illustrated on figure 19. The following integration constraints are added to the aforementioned problem. Hot stream corresponding to the flue gas of a gas turbine g :

$$Q_g^{gt} = f_g * \dot{m}_g * cpf_g * (TOT_g - Tstack_g) \qquad \forall g = 1, n_g \quad (25)$$

where	$\dot{m}_g$	is the flue gas flowrate at the outlet of the gas turbine g in nominal conditions. These values result from the simulation of the gas turbine g
	Q_g^{gt}	is the total heat load of the fumes from the gas turbine g
	cpf_g	is the mean cp of the flue gas at the outlet of the gas turbine g
	TOT_g	is the temperature of the flue gas of the gas turbine g
	$Tstack_g$	is the stack target temperature accepted for the outlet of the gas turbine g after heat recovery
	f_g	is level of utilisation of gas turbine g, $f_g^{min} * y_g \leq f_g \leq y_g * f_g^{max}$
	y_g	is the integer variable representing the use or not (1,0) of the gas turbine g
	$f_g^{min(max)}$	is the minimum (maximum) level of utilisation of the gas turbine g
	n_g	is the number of gas turbines proposed in the utility system super configuration

Hot stream corresponding to the post combustion (heat available for convective heat exchange)

$$Q_g^{pc} = f_g^{pc} * \dot{m}_g * cpf_g * (Trad - TOT_g) \qquad \forall g = 1, n_g \quad (26)$$

where	$Trad$	is an arbitrary temperature used in the combustion model and representing the limit of the radiative exchange
	f_g^{pc}	is the fraction of the nominal gas turbine flue gas flowrate used for post combustion
	Q_g^{pc}	is the heat load supplied by the flowrate fraction of the flue gas flowrate of gas turbine g used in the post combustion device

Fuel consumption in the gas turbine g

$$\sum_{c=1}^{n_{cgt}} f_c^g * LHV_c - (y_g * FCI_g + f_g * FCP_g) = 0 \qquad \forall g = 1, n_g \quad (27)$$

where	n_{cgt}	is the number fuels available for combustion in the gas turbines
	LHV_c	the lower heating value of the fuel c
	f_c^g	the flowrate of the fuel c in the gas turbine g
	$y_g * FCI_g + f_g * FCP_g$	is the linearised fuel consumption of gas turbine g as a function of its level of utilitisation

Electricity production with the gas turbines W_{gt}

$$W_{gt} - \sum_{g=1}^{n_g} (y_g * WI_g + f_g * WP_g) = 0 \tag{28}$$

where $y_g * WI_g + f_g * WP_g$ is the linearised mechanical power production of the gas turbine g as a function of its level of utilisation

The parameters for the linearisation are computed by simulation considering the partial load operation of the gas turbine. For each gas turbine g, the unknowns are f_g, y_g, f_g^{pc} while the other parameters are obtained from the thermo-economic models. The quality of the linearisation will mainly depend on the range in which the partial load operation is expected to happen in the optimal situation.

The operating costs OC_{gt} and the investment costs IC_{gt} of the selected gas turbines are computed by :

$$\sum_{g=1}^{n_g} (y_g * OCI_g + f_g * OCP_g) - OC_{gt} = 0 \tag{29}$$

$$\sum_{g=1}^{n_g} y_g * ICI_g - IC_{gt} = 0 \tag{30}$$

where $y_g * OCI_g + f_g * OCP_g$ is the linearised maintenance cost of gas turbine g as a function of its level of utilisation ;

$y_g * ICI_g$ is the investment cost of gas turbine g from the data base catalog;

The fraction of the flue gas of the gas turbine used in the post combustion is limited to the level of utilisation of the gas turbine g.

$$f_g^{pc} \leq f_g \qquad \forall g = 1, n_g \tag{31}$$

The combustion model is made of different equations: (32) includes different terms representing the oxygen balance required by the combustion of the fuels and the oxygen supplied by air and post combustion flue gas.

$$\sum_{g=1}^{n_g} f_g^{pc} * \dot{m}_g * x_g^{O_2} + f_{air} * x_{air}^{O_2} + \sum_{a=1}^{n_a} f_a * \dot{m}_a * x_a^{O_2} - \sum_{c=1}^{n_c} f_c^c * \kappa_c^{O_2} \geq 0 \tag{32}$$

where $x_g^{O_2}$ is the oxygen content of the flue gas at the outlet of the gas turbine g
$x_{air}^{O_2}$ is the oxygen content of the ambient air
f_{air} is the amount of air used by the combustion in the system
f_c^c is the flowrate of fuel c used in combustion, ($f_c \leq f_c^{max}$), its specific cost is C_c
$\dot{m}_c^f$ is the fumes floware resulting from the combustion of fuel c

cp_c^f	is the mean specific heat of the fumes resulting from combustion. This cp is considered between $Trad$ and $Tstack$
n_c	is the number of fuels that can be used in the system including those for firing the gas turbine (n_{cgt})
$\kappa_c^{O_2}$	is the oxygen requirement per unit of fuel c. For practical reasons, the oxygen requirement includes the minimum oxygen excess for this fuel
$x_a^{O_2}$	is the oxygen content of the enriched air stream leaving the air separation unit a
$\dot{m}_a$	is the flowrate of enriched air leaving the air separation unit a in nominal conditions
f_a	is the level of utilisation of air separation unit a, $f_a^{min} * y_a \leq f_a \leq f_a^{max} * y_a$
y_a	is the integer variable representing the use or not (1,0) of the air separation unit a
$f_a^{min(max)}$	is the minimum (maximum) level of utilisation of the air separation unit a
n_a	is the number of air separation units considered in the system

Fuel consumption balance of any fuel c that might be used either in gas turbine either in standard combustion.

$$f_c^c + \sum_{g=1}^{n_g} f_c^g - f_c = 0 \tag{33}$$

where f_c is the overall consumption of fuel c

High temperature balance : radiative exchange model above $Trad$

$$\sum_{c=1}^{n_c} (f_c * (LHV_c + (cp_{air} * \frac{\kappa_c^{O_2}}{x_{air}^{O_2}} * (Trad - T_0)))) - f_{air} * cp_{air} * (Trad - T_0) \\ - \sum_{a=1}^{n_a} f_a * \dot{m}_a * cp_a * (Trad - TO_a) + Q_{prh} - Q_{rad} = 0 \tag{34}$$

Low temperature balance : convective exchange below $Trad$

$$f_{air} * cp_{air} * (Trad - Tstack) + \sum_{c=1}^{n_c} (f_c * (\dot{m}_c^f * cpf_c - cp_{air} * \frac{\kappa_c^{O_2}}{x_{air}^{O_2}}) * (Trad - Tstack)) \\ + \sum_{a=1}^{n_a} f_a * \dot{m}_a * cp_a * (Trad - Tstack) - Q_{cnv} = 0 \tag{35}$$

where Q_{rad} is the total amount of heat available above $Trad$
Q_{cnv} is the total amount of heat available from $Trad$ to $Tstack$

LHV_c is the lower heating value of the fuel c. This value is the value computed by simulation of the combustion using the minimum accepted value of the oxygen content in the fumes

T_0 is the reference temperature used for computing the LHV

T_{air}^{in} is the inlet temperature of air

Q_{prh} is the heat load of air preheating, the existence of the air preheating equipment is defined by an integer variable y_{prh} and the following equation : $y_{prh}Q_{prh}^{min} \leq Q_{prh} \leq y_{prh}Q_{prh}^{max}$. The investment cost of the air preheating device is computed by linearising the air preheater cost by $IC_{prh} = ICF_{prh}y_{prh} + ICP_{prh}Q_{prh}$

cp_a is the mean specific heat of the enriched air leaving unit a at a temperature of TO_a.

Table 10 gives the values needed to compute the integration of some typical fuels used in the industry including some renewable fuels (wood and biogas).

Air preheating : outlet temperature calculation

When combustion is considered, the air preheating plays the role of a chemical heat pump, it is used to pump waste heat available below the pinch point and make it available above the pinch point (by an increase of the adiabatic temperature of combustion). The effect of air preheating is however limited to the preheating of the stoechiometric air flow. When the flowrate is higher, the adiabatic temperature of combustion decreases and the benefit of air preheating is lost. When combined heat and power is considered using steam network, the process pinch point does not anymore define the maximum preheating temperature. In this case, the combustion air may be preheated up to the highest condensation pressure of steam because this steam will produce mechanical power before being used as a preheating stream. The preheating heat load will become available at a higher temperature to produce an additional amount of steam at the highest pressure or to increase the superheating temperature. The air preheating temperature is therefore unknown and its optimal value has to be computed. Whenheat cascade is considered, computing the optimal preheating temperature is a non trivial task, mainly because the temperature is used to generate the list of the heat cascade constraints. This makes the problem non linear and discontinuous (i.e. according to the temperature the stream will appear or not in a given heat cascade constraint). Some techniques have been proposed to solve this problem as a non linear programming (in our case mixed integer) problem using smooth approximation techniques (e.g. [31]), this approach is explained in more details in another chapter. An other approach consist in keeping the linear programming formulation by discretizing the temperature range in which the air preheating will take place in n_i intervals of ΔT. The air preheating stream is therefore defined by a list of cold streams from T_i^{air} to $T_{i+1}^{air} = T_i^{air} + \Delta T$ and by adding the following constraints :

$$f_{air} \geq fa_i \qquad \forall i = 1, ..., n_i \tag{36a}$$

$$Q_{prh} = \sum_{i=1}^{n_i} fa_i cp_{air,i}(T_{i+1} - T_i) \tag{36b}$$

with fa_i the flowrate of air preheated from T_i to T_{i+1}.
$cp_{air,i}$ the specific heat capacity of the air flowrate between T_i to T_{i+1}.

In the combustion model, the optimal temperature calculation model is also used to compute the outlet temperature of the air and enriched air preheating, fuel preheating as well as to compute the outlet temperature at the stack. This calculation is made in two steps :

1. solve the model and compute the optimal flowrates in each interval (fa_i);
2. compute the resulting temperature To_{n_i} by solving from i =1 to n_i ,:
   $To_i = \frac{(fa_{i-1}-fa_i)To_{i-1}+fa_i*T_{i+1}}{fa_{i-1}}$
   with To_0 = Ta_{in} the inlet temperature of the stream a.

The precision of the model is related to the size of the discretizing temperature intervals. A compromise between the precision required for the equipment sizing and the number of variables is therefore required. A similar formulation is also used to compute the optimal temperature of the gas turbine flue gas after heat recovery.

This systematic choice has been made to keep the robustness advantage of the MILP formulation.

0.5.2 Steam network

The steam networks play a very important role in most of the industrial process plants. They are the major interface between the utilities and the process streams while allowing the combined production of heat and power. Furthermore, by transferring heat from one process stream to another, the steam network will be used to reduce the energy penalty resulting from restricted matches. The importance of steam network reveals also for site scale process integration since the steam network will be the only way to transfer heat from one process to another.

Targeting of the integration of the steam network is an important part of the energy conversion technologies integration. In the first attempt to study the integration of energy conversion technologies, the idea has been to consider steam as being a constant temperature stream that supplies or extracts heat from the process. This gave an easy way of understanding the multiple utilities integration from the Grand composite curve analysis. When designing the site scale steam networks, Dhole and Linnhoff [18] introduced the total site integration concept. They defined the total site composite curves to represent the integration of chemical plants that are composed of several processes and that may be integrated. The purpose of these curves is to identify the way energy has to be transferred from one plant section to an other using the steam network. This method assumes that heat recovery inside the process has already been performed before allowing for exchanges between processes. The construction of the total site composite curve is explained on top of figure 11 for the integration of two processes whose Grand composite curves are given on the left. After eliminating the pockets (self sufficient zones), the hot utility and cold utility profiles are composed to build the hot and cold site profiles. The exchange between the processes is then realised using the steam network as heat transfer media. If this approach is convenient from the graphical point of view, it can not be applied when considering the integration of steam networks in practice. Two major defaults should be removed. First, the pockets can not be ignored because these may hide heat exchange potentials. This is demonstrated in the centre of the figure where the integrated composite curves of process 1 versus process 2 shows the energy saving that could be obtained when exchanging heat between the two processes. In this example, the energy saving mainly results from the integration inside the pockets. In reality, the hot and cold composite curves of the whole system should be considered. The second drawback of the total site approach is that it ignores the combined production of mechanical power in the steam network. This is shown in the bottom of the figure where steam is produced at high pressure in process 2 to be used at high pressure in process 1 and low pressure in process 2 together with the low pressure steam produced in process 1. In between, the steam is expanded in a bkac pressure turbine to produce mechanical power. From the exergy analysis, the potential for combined production of mechanical power is proportional to the size of the pockets in the exergy Grand composite curve. These can not therefore be ignored from the heat and from the CHP perspective. Furthermore, in real steam networks, the steam production and condensation can not be considered at a constant temperature. One should consider the preheating and the superheating for the steam production and the desuperheating, condensation, liquid under cooling for the steam condensation. Furthermore, the maximisation of the mechanical power production will be obtained by optimising the heat exchanges within the steam network, e.g. by condensing low pressure steam to preheat high pressure water of the steam network.

The MILP formulation presented here above may be extended to define a more precise model of the stream network. The formulation has been given in [23]. It is based on the definition of a steam network superstructure (figure 9). This superstructure has been first proposed by Papoulias and Grossmann [32]. It has been adapted to account for the temperature-enthalpy profiles of the steam production (i.e. preheating, vaporisation and superheating) and consumption (desuperheating, condensation and undercooling). One of the difficulty of this formulation has been to guarantee a coherency between the heat and the mass balances while using linear equations. This has been obtained by a special formulation of the mass balances of the steam network headers. Hot and cold streams of the steam network are considered in the heat cascade model and the contributions of the steam expansion in turbines are added in the mechanical power balances. It should be mentioned that using this model, the optimal flowrate in the steam network will be determined considering also the possibility of exchanging heat between the streams of the steam network. This leads to an optimised steam network configuration where steam draw offs are used to preheat the high pressure water. The model may therefore be used as a tool for a rapid prototyping of complex steam cycles in conventional power plants [30].

The integrated composite curves of the steam network (e.g. on figure **??**) is used to represent the results of its integration. On the figure, the overall mechanical power production corresponds to the balance between the hot and the cold streams of the system. It is made of the contribution of the expansions between the different pressure levels in the superstructure. A post processing analysis will be required in order to decide the best configuration of the steam turbine(s) : single turbine with multiple draw off or multiple back-pressure turbines. The use of the process pinch point as a reference to locate the zero heat (temperature axis) is used to verify the appropriate placement of the steam headers and the combined production of mechanical power. Combined heat and power is well located when it takes heat above the pinch point and send it above or when it takes heat below and send it to the cold utility [14]. For a well integrated production above the pinch point, the mechanical production should be the only part the steam network integrated composite curve that is on the left of the temperature axis. If not , the rules for appropriate placement are not satisfied and it is recommended to understand the reason for this penalty.

0.5.3 Refrigeration cycles

The refrigeration cycles are used as a cold utility below the ambient temperature. The major principle of the refrigeration cycle is to use the compression power to change the temperature level of the streams. A simple refrigeration cycle is presented on figure 10, it is composed of one compressor, one evaporator (at low temperature), one condenser (at higher temperature) and a valve. From the process integration point of view, the refrigeration cycle is defined by one hot and one cold streams and by the corresponding mechanical power consumption. The optimal flowrate will be determined by the MILP formulation presented above. The temperature levels obtained from the Grand composite curve analysis will usually define the type of fluids to be used but other consideration will have to be taken into account like the environmental aspects (CFC refrigerants) or safety considerations (flammability). The use of fluids already in use in the process plant is also an important criteria. The efficiency of the integration of one refrigeration cycle depends on its compression ratio and on the flowrate. It will depend also on the structure of the cycle and on the possibility of combining cycles with different refrigerants or with different pressure levels. The problem is therefore highly combinatorial since refrigerants, structures, pressure levels and flowrates have to be optimized. A graphical approach based on the exergy analysis has been proposed by [33]. This approach illustrates the methodology of the integration of complex refrigeration systems. A non linear programming model has been proposed by [34]. The method presented by Marechal and Kalitventzeff [25] shows the extension of the MILP formulation to tackle this complex problem. The method first identifies the most important temperature levels in the Grand composite curve using a MILP formulation. The systematic integration of the cycles with the possible refrigerants is made applying heuristic rules. From this first selection, the remaining cycles for which the refrigerants, the configuration, the temperature levels and the mechanical power are known are added in the energy conversion system superstructure and the best configurations are sorted out by solving the MILP problem. When several cycles competes, integer cuts constraints are added to the problem to systematically generate ordered set of solutions. The integer cut constraint is used to avoid the generation of an already known solution when solving the MILP problem. The restriction of the kth solution is obtained by adding the following constraint

$$\sum_{w=1}^{n_w} (2 * y_w^k - 1) * y_w \leq (\sum_{w=1}^{n_w} y_w^k) - 1 \qquad \forall k = 1, ..., n_{sol} \tag{37}$$

with y_w^k the value of y_w in the solution k
n_{sol} the number of solutions

The use of the integer cut constraint is an important tool when solving utility system integration. The systematic generation of multiple solutions allows the comparison of the proposed utility system configurations using different criteria (not accounted in the definition of objective function) and to perform a sensitivity analysis to uncertain problem parameters like the cost of energy or the investment.

0.5.4 Heat pumps

When appropriately placed heat pumping systems should drive heat from below to above the pinch point. Several types of heat pumping systems may be considered (mechanical vapour recompression, mechanical driven heat pumps or absorption heat pumps). Table **??** give some useful thermoeconomical values for the evaluation of the industrial heat pumping systems. The optimal integration is determined by first identifying the streams or the temperature levels for which heat pumping is envisaged. The simulation of the heat pump system using process modelling tools defines the hot and cold streams characteristics that are added to the system integration model and the optimal flowrate for each of the levels will be computed by solving the MILP problem. When mechanical vapour recompression(MVR) is used, a hot stream at lower temperature (mvr_{low}) is replaced by another hot stream (mvr_{high}) with a higher temperature and a mechanical power consumption W_{mvr}. From the Grand composite curve analysis, it may happen that only part of the stream will be recompressed. This situation will be represented by associating a multiplication factor to the two streams (resp. $fmvr_{low}$ and $fmvr_{high}$) and by adding the following constraints (38).

$$fmvr_{high} + fmvr_{low} = or \leq 1 \tag{38}$$

The equality represents the situation presented on figure 13 where the stream is partly recompressed, the remaining part being cooled down at lower temperature. It should be noted that the heat load of the high temperature stream is higher than the one of the colder one because it includes the the mechanical power of compression. The target temperature of the high temperature stream is identical to the one of the of colder stream. the adiabatic valve being considered after liquid sub-cooling. The useful heat of the recompressed stream is therefore lower than the total heat load since part of the heat remains available below the pinch point temperature. When the recompressed stream may be vented (e.g. in the case of evaporation stream), the constraints becomes an inequality. In this case, there are in fact three options : 1) venting the stream and the heat lost to the atmosphere, 2) condensing the stream and use it because the heat is needed below the pinch point, and 3) recompress it and use the recompressed stream as a hot utility. The optimal flowrate in each of the options will be obtained from the optimisation and will take into account the constraints of the heat cascade. As for the refrigeration cycles, multiple options corresponding to different technologies with different levels of pressure and temperature may be considered and will be handled by the optimisation. The results of the heat pump integration corresponds to the activation of multiple pinch points. The integrated composite curve of the heat pumping system (figure 21) is a useful tool to verify the appropriate integration of the system.

0.5.5 Handling non linear cost functions

In the problem formulation, linear cost are needed. When the whole range of sizes is covered by the model, a piece-wise linearisation technique may be used to represent non linear cost function. The generic investment cost function $C(S) = C_{ref} * (\frac{S}{S_{ref}})^b$ will be approximated by a set of segments (figure 12) defined by the following set of constraints (39) in the linear optimisation problem.

$$
\begin{aligned}
&C = \sum_{i=1}^{n_{segments}} \{(C(S_{i-1}^{max}) - \frac{C(S_{i-1}^{max}) - C(S_i^{max})}{S_{i-1}^{max} - S_i^{max}} * S_{i-1}^{max}) * y_i + \frac{C(S_{i-1}^{max}) - C(S_i^{max})}{S_{i-1}^{max} - S_i^{max}} * Sp_i\} \\
&S = \sum_{i=1}^{n_{segments}} Sp_i \\
&y_i * S_{i-1}^{max} \leq Sp_i \leq y_i * S_i^{max} \qquad \forall i = 1, ..., n_{segments} \\
&y_i \in \{0, 1\}
\end{aligned}
\tag{39}
$$

with $C(S)$ the installed cost of the equipment of size S
S_i^{max} The maximum size in segment i
Sp_i the size of the equipment in segment i
y_i the integer variable used to select the segment i

0.5.6 Using the exergy losses as an objective function

Due to the linear nature of the problem, the use of the energy cost as an objective function may reveals some difficulties [28]. When the cost of fuel and electricity is such that the electrical efficiency of a cogeneration unit is attractive without the use of heat, the linear programming procedure leads to a situation where the cogeneration unit is used at its maximum. In this case, there is an economical interest of running the cogeneration unit for producing electricity even without using the heat. The situation is less critical when the investment cost is considered or when the cost of the different forms of energy are coherent with respect to the electrical efficiency. When the target is the system efficiency, alternative formulations of the objective functions have to be considered. The minimisation of the exergy losses (40) is an attractive way of formulating the problem.

$$
\underset{R_k, y_w, f_w}{Min} \sum_{w=1}^{n_w} (f_w * (\Delta Ex_w + \sum_{k=1}^{n_k} \Delta ex_{wk})) + EL_i - EL_o \tag{40}
$$

where ΔEx_w is the exergy consumed to produce the hot and cold streams and the electricity of equipment w.
Δex_{wk} is the exergy supplied by the conversion unit w in the temperature interval k,

$$
\Delta ex_{wk} = \sum_{s=1}^{ns_w} q_{sk} * (1 - \frac{T_0 * ln(\frac{T_{k+1} + \Delta T_{min}/2_s}{T_k + \Delta T_{min}/2_s}}{T_{k+1} - T_k}) \tag{41}
$$

$\Delta T_{min}/2_s$	is the contribution to the ΔT_{min} of the stream s, $\Delta T_{min}/2_s \geq 0$ for the hot streams.
q_{sk}	the heat load of the stream s in the temperature interval k computed for the nominal conditions of the related equipment.
ns_w	the number of streams of conversion unit w

0.5.7 Handling restricted matches

The use of mixed integer linear programming in process integration has been first proposed to solve the problem of the heat exchanger network design [35]. The design problem is presented as a transportation problem by Cerda et al. [36] or as a transhipment problem [37] with a significant reduction of the number of variables. Such methods can easily be extended to account for restricted matches by adding constraints to the MILP formulation. The draw back of such approaches is that they are designed either to find a feasible heat load distribution that satisfies the MER target. In this case, the restricted matches are an advantage because they reduce the search space of the possible connexions. When there is no feasible solutions, these methods give the energy penalty of the restricted matches. Unfortunately, none of these methods are searching ways of reducing the penalty. The integration of energy conversion technologies allows to go a step further in the analysis because the utility can be used as an intermediate heat transfer fluid to reduce the restricted matches penalty. Steam or hot water may be produced in one section and condensed or cooled down in another section of the plant. The computer aided design methodology will help in defining the characteristics of the streams to be considered as an intermediate heat transfer fluid to indirectly exchange heat between the streams of the penalising restricted matches. The formulation proposed by Marechal and Kalitventzeff [24] uses a MILP formulation of the restricted matches to target the energy penalty of the restricted matches. The penalty is divided into two parts according to the position of the process pinch point. From the optimisation results, hot and cold restricted matches penalty composite curves are computed (figure 20). The hot curve represents as a function of the temperature the heat that can not be removed from hot streams involved in restricted matches by the allowed process streams. This heat has to be received by the cold streams of the heat transfer fluid system. The cold composite represents the temperature enthalpy profile of the heat that has to be sent back to the process by the heat transfer fluid in order to avoid the restricted matches energy penalty. The two composite curves have a pinch point temperature that is identical to the one from the MER calculation since no heat can be exchanged through the pinch point in the MER situation. Any combination of hot and cold streams of the utility system that is framed by the two curves will allow eliminating the penalty, provided that the temperature difference will be sufficient. The use of an intermediate streams imposes the use of two heat exchangers instead of one will double $\Delta Tmin$ value. One should note that the restricted matches composite curves are designed in order to preserve the possible combined heat and power production. (i.e. producing high pressure steam by the hot streams and sending back to the process at a lower pressure after expansion in a turbine. Once the utility streams characteristics are identified, restricted matches constraints are added to the optimal energy conversion system integration problem. The constraint formulation is an extension of the heat load distribution formulation [38] that complements the MILP problem definition. As a result, the complete list of hot and cold streams to be considered for the heat exchanger network design will be obtained and we know that there exists at least one feasible heat exchanger network configuration that satisfies the restricted matches constraints and the minimum cost of energy target.

0.5.8 Non linear optimisation strategies

The analysis of the Integrated composite curve help in interpreting the results of the optimisation and verifying (or optimising) the choice of the utility system operating conditions (temperature or pressure levels) that were supposed to be ”well chosen” for when stating the MILP problem.

In order to solve the non linear problems with a linear programming formulation, three strategies may be used : 1) the appropriate formulation of the problem constraints as it is explained for the gas turbine integration, 2) the piece wize linearisation and 3) the continuous search space discretization. The later consist in defining different operating conditions of a given technology as an option in which the optimisation will select using integer variables. The method presented here above has tackled the problem of non linearities by discretisation of the continuous variables search space.

Other authors have tackled directly the MINLP problem. These formulation use the alternative heat cascade formulation (**??**) because in this formulation is constraint is associated with one key temperature (stream inlet temperature) of the system. In this case, when the inlet temperature changes, the definition of the equation is not changed, but it may happen that some of the streams that were above the key temperature will be now below. This creates a discontinuity that is usually not acceptable for most of non linear programming solvers. In order to smooth the discontinuities, Duran and Grossmann [31] have defined a temperature enthalpy diagram of the streams that is continuous for the whole temperature range. For a cold stream, the enthalpy profile (figure **??** of a stream is defined by (42).

$$h(T) = 0 \qquad if \quad T < T_{in} \tag{42a}$$
$$= \dot{m}cp(T - T_{in}) \qquad if \quad T_{in} \leq T \leq T_{out} \tag{42b}$$
$$= \dot{m}cp(T_{out} - T_{in}) \qquad if \quad T > T_{out} \tag{42c}$$

A smoothing technique is then used to round the corners of the enthalpy profile. The difficulty being to tune the smoothing parameters to be compatible with the non linear solver criteria without introducing infeasibilities in the heat integration results. This technique has been first proposed by Duran and Grossmann. It has been used and extended by other authors [39], [40] for optimising simultaneously process performances and heat integration problems.

When isothermal streams are considered in the problem, the smoothing technique is not valid anymore fromthe mathematical point of view to smooth the discontinuities. In this case, it is necessary to use integer variables that will represent the contribution of the isothermal stream i in the heat balance above temperature j constraint. $y_{i,j}$ = 0 if $T_j < T_i$ and $y_{i,j}$ = 1 if $T_j \geq T_i$ is represented by the following equations :

$$T_j - y_{i,j}T_i \geq 0 \tag{43a}$$
$$(1 - y_{i,j})T_j - T_i \leq 0 \tag{43b}$$

This formulation is generic and may be used to represent all the situations even the situations solved by the smoothing approximation technique. The resulting MINLP problem will have a huge number of integer variables and will be solved by using outer-approximation algorithm or using disjunctive optimisation techniques.

0.6 Solving multiperiod problems

Even when the processes may be considered as being stationary, it is often necessary to consider multiperiod operations where the requirements of the processes are considered as being constant during a given period. The utility system is serving the different processes of the plant. It has therefore to answer the varying demands of the different processes. Two different problems have to be adressed in this case. What is the optimal design of the system and what is the optimal operating strategy.

0.6.1 Optimal design

In multiperiod problems, the goal of the optimal design task is to determine the best investment to be done in terms of energy conversion equipment, considering the varying demands of the processes. This implies to take into account the part load efficiencies of the equipment but also to determine in each period the best way to operate the system. The use of MI(N)LP problems for solving multi-period process synthesis problems has been reviewed by grossman et al. [41] and [42]. Multi-period optimisation is a well known problem that has been considered mainly in the heat exchanger network design: e.g. [43], [44],[38] . The generic problem is formulated as follows (44).

$$\underset{y_t,x_t,y,s}{Min} \sum_{t=1}^{n_t} t_t * c(x_t, s) + I(y, s) \tag{44}$$

Submitted to :

$$h_t(x_t, s) = 0 \qquad \forall t = 1, ..., n_t \tag{45a}$$

$$g_t(x_t, s) \geq 0 \qquad \forall t = 1, ..., n_t \tag{45b}$$

$$y_t \leq y \qquad \forall t = 1, ..., n_t \tag{45c}$$

$$y_t, y \epsilon \{0, 1\} \qquad \forall t = 1, ..., n_t \tag{45d}$$

where	$h_t(x_t, s)$	is the set of modelling constraints during the period t;
	$g_t(x_t, s)$	is the set of inequality constraints during the period t;
	x_t	is an array representing the operating conditions of the equipments during time period t;
	y_t	is an integer variable representing the use or not of an equipment during time period t;

s	is the array of the sizing parameters of the equipment sets, once an equipment is selected (see value of y), it is used throughout all the operating periods;
y	is the array of the integer variables representing the global selection of the equipment sets (i.e. the decision to invest or not);
$c(x_t, s)$	is the operating cost during the operating period i;
$I(y, s)$	is the total annualised cost of the equipments of size s;
t_t	is the operation time of period t;

In the general formulation, the set of constraints may be linear or non linear and it is assumed that the operating scenario in each period are independent and without heat exchange between periods. If this is not the case, the problem becomes an even more complex batch process synthesis problem. By generating the heat cascade constraints in each period, the model for integrating the energy conversion units presented above may be adapted for solving multiperiod problems [28]. The part load operation of some of the units have been introduced in the model. Shang et al. [45] have demonstrated that a transhipment model that accounts for part load efficiency of the the expansion turbines and the boilers. When using heat cascade contraints, it is assumed that it will be possible to make the heat exchanges required by the heat cascade representation in each time period. If this appears to be a restriction with respect to the heat exchange network structure, its impact may be limited when considering the utility system that will offer a greater flexibility in terms of process utility interface.

The multiperiod design formulation implicitly account for the optimal operating scenario. Iyers and Grossmann [46] proposed a MILP formulation for multiperiod problems where the design problem includes operational planning of the system in which the limited availability of the units is accounted for. To overcome the difficulties related to the size of the problem, the authors proposed a bilevel decomposition of the problem that reduces the size of the MILP problems and considerably reduces the computing time required.

0.6.2 Optimal operating strategy

Once the utility system structure is defined, an optimal operating strategy has to be established. Some authors [47], [48], propose a linear programming approach to solve this multiperiod problem in order to make the optimal scheduling of the system, considering the start up and shut down time as well as the unavailability of the equipment during the maintenance period.

The optimisation of the operating conditions of a utility system has been solved by Kalitventzeff et al. [49], [12] as a mixed integer non linear programming problem. The non linear models allows to account for effects of the pressure, temperature and the flowrates, and to consider the available heat exchanger areas. To solve the MINLP problem, the outer-approximation algorithm was applied [50]. Combined with data reconciliation techniques for process performance follow-up, this method has been applied with success for the optimal operation to complex industrial utility systems. The MINLP problem formulation assumed that each operating scenario may be optimised independently of the history. It has been demonstrated [12] that this MINLP formulation may be used to make the simultaneous optimisation of heat exchanger network integrated with a complex utility system. The method has been also applied to solve retrofit utility system problems where available equipment (e.g. an exchanger) are affected to operations (e.g. a heat exchange). Papalexandri et al. [51] proposed a MINLP strategy that solves the multiperiod optimisation problem and that accounts for uncertainties in certain parameters.

0.7 Example

Let us consider the system requirements defined on figure 15 that results from the hot and cold composite curves of figure 14. For the calculations, we assumed that all the possible process improvements were already implemented before analysing the Grand composite curve for the energy conversion technologies integration. In terms of energy, the requirements are given on table 11. From the Grand composite curve, several utilities may be proposed. The simplest solution is to integrate a boilerhouse using natural gas (with a LHV of 44495 kJ/kg) and to cool the process with cooling water. The refrigeration needs will be supplied with a refrigeration cycle using ammonia (R717). The operating conditions of the refrigeration cycle (table 12) have been obtained by simulation considering the temperature levels in the composite curve and the $\Delta Tmin$ to be reached in the heat exchangers.

The integrated composite curves presenting the results of the optimisation are presented on figure **??** and on table 14. The refrigeration cycle consumption is of 314 kW. In should be noted that the energy consumption is higher than the MER due to the losses at the boiler house stack (398 K). The solution accounts for the possibility of air preheating to valorise the energy excess available in the process. The heat load of air preheating is of 131 kW.

In order to valorise the exergy potential (figure 6), a steam network has been integrated. The steam network characteristics are given on table 13. The Grand composite curves obtained by the integration of the steam network is given on figure 16. This figure is not readable and even the integrated composite curves of the system (Figure 17) becomes difficult to read. Based on the same results the integrated composite curves of the steam network (figure 18) offer a better visualisation of the steam network integration. It should be mentioned that the choice of the process pinch point location as a reference for locating the temperature axis allows to verify the appropriate choice of the steam pressure levels. The energy balance of the hot and cold streams of the steam network is the net mechanical power production. when appropriately placed, it corresponds to a supplement of energy to be supplied to the process. The fact that it appears on the left of the temperature axis proves that the steam network characteristics are appropriate for the optimal production of mechanical power. The area between the to curves giving an indication of the quality of the exergy valorisation.

Applying the rules of the appropriate placement of heat pumping devices, 3 heat pumping cycles have been proposed and simulated (table 16). Using the optimisation tool, the optimal flowrates in the three cycles have computed together with the new value of the fuel in the boiler house. In the example considered, this lead to a situation where the whole heat requirement may be provided by the heat pumps. The integrated curves of the heat pump system integration are given on figure 21. When the steam network is considered the results are slightly different since in this case, an additional amount of energy is supplied to the system to produce mechanical power by expansion in the steam network.

The solution of heat pumping is than compared with a combined heat power production using a gas turbine.

The summary of the enegy conversion integration target is given on table 15. It is shown that a MER of 6854 kW for the heating requirement and of 1709 kW for the refrigeration requirement is finally supplied with an equivalent of 893 kW of fuel when considering the possibility of heating pumping and when valorising the exergy content of the process streams. Compared to the boiler house solution, the new situation corresponds to a reduction by a factor

8 of the fuel consumption. These data have been computed by considering a fuel equivalence of 55% for the electricity production.

The method applied here allows to quickly evaluate energy conversion alternatives and to quickly assess the impact of process modifications on the processes. Using the targeting method based on optimisation, the major advantage of the approach stands in the accounting of the energy savings in terms of cost or exergy rather than in terms of energy. The method allows to make a first selection of energy conversion options to be further analysed in more details using therrmo-economic optimisation tools. In this analysis, the cost of the energy conversion system will be considered together with the cost of the heat exchanger network in order to assess the profitability of the solutions.

0.7.1 Rational use of water in industry

In chemical process systems, water is often used as a processing support. The optimisation of the water usage concerns two aspects : the water savings (i.e. the resource usage minimisation) and the emissions (i.e. the level of contaminant in the waste water). Resulting from the mass balance and the process requirements, both objectives are antagonists since the mass of contaminant to be extracted from the process is constant, if the flowrate decreases, the concentration should increase. El-halwagi and Manousiouthakis [52] presented the analogy between the energy pinch analysis and the mass exchange networks : the concentration replaces the temperature and the water flow replaces the heat load. The method uses mathematical programming techniques where a constraints set defines the water cascade.

Wang and Smith [2] proposed a graphical method based on the same analogy. In their approach, each unit utilising water is represented by a limiting water profile defined as a concentration/mass of contaminant profile. This profile represents the worst conditions (in terms of flowrate and concentration) that should have the support water entering and leaving the unit in order to realise the mass transfer required. This allows to draw a composite curve that may be assimilate to the utility profile in the energy domain and to which the fresh water curve (utility) will be integrated. The utility curve starts with a mass of contaminant of zero, its slope corresponds to the fresh water flowrate required for the system. The minimum flowrate is computed by activating the pinch point between the utility curve and the limiting profile. By balance the maximum concentration of water is determined. From this targeting procedure, it is then possible to design a water exchange network using a procedure similar to the pinch design method for the heat exchangers. An example of such curve is given on figure 23. The proposed method suffers from the drawbacks of being based on the limiting profiles of the mass transfer that does not allow for generic representation of the water usage in the chemical industry and on the difficulty of handling multiple contaminants even if the authors have proposed an adaptation of the method [53] [54]. Dhole et al. [55] proposed another representation of the water cascade considering the water units as being source and demand of water with a given level of purity. The advantage of this representation is the generalisation of the approach to represent all types of water usage units and not only the one based on the mass transfer profiles. This allows to draw the hot (source) and cold (demand) composite curves and the corresponding grand composite curve and to identify the pinch of the system. This approach suffers however of the problem of not being able to identify the purity changes that will result from the mixing of a high purity stream (above the pinch point) with a low purity stream (below the pinch point to produce water with a medium purity above the pinch point. Based on this representation, Hallale [56] proposed an algorithm that computes the possible recovery by mixing and that is based on the water surplus profiles. By analogy with the process integration techniques, the methods based on the graphical representations help to identify the possible integration of water regeneration equipment. The rules are similar to the one of the heat pumps integration.

The graphical representation are attractive to solve and explain water usage targeting, these methods becomes however difficult to apply when multiple contaminant are concerned. In this case, the use of mathematical programming appears to be more convenient. Several formulations have been used : after the formulation of El-halwagi [52], Alva-argaez et al. [57] proposed a transhipment formulation of the problem that allows to introduce multi contaminants constraints and balances in the system. Such methods solve simultaneously the water target and the mass exchange network.

Like in the case of energy conversion integration, the water usage minimisation will not only concern the minimisation of the water usage but as well the integration of water treatment or purification units that will concentrate the effluent and perhaps transfer the contaminant to an other phase (e.g. solid). In this case there is an interest to consider the combined integration of the water usage and the energy. This would become especially true in situations where waste water will be treated by concentration (cold stream) followed by a biomethanation to produce biogas (fuel).

Futhermore, when analysing the Grand composite curve of the water requirement profile (water surplus composite), one may suggest to introduce water regeneration units (e.g. filtration) that will change the shape of the water profile and will allow to futher reduce the water consumption. This approach will therefore be similar to the one used in the energy conversion technology integration. The mathematical programming approach [58] presented below is based on a multiple contaminants transhipment model. It may be combined with heat integration by summing up MILP problems. The link between the two models will be the value of the level of utilisation f_w that are related to water usage and to energy effects.

$$
\begin{aligned}
&\min_{\dot{m}_{s,d},f_w,y_w} \sum_{w=1}^{n_w} (C2_w * f_w + C1_w * y_w) + Cs, d * \dot{m}_{s,d} \\
&subjectto: \\
&\sum_{s=1}^{n_s} \dot{m}_{s,d} - \dot{m}_d * f_w(d) = 0 \qquad \forall d = 1, ..., n_d \\
&\dot{m}_s * f_w(s) - \sum_{d=1}^{n_d} \dot{m}_{s,d} \geqslant 0 \qquad \forall s = 1, ..., n_s \\
&\sum_{s=1}^{n_s} \frac{\dot{m}_{s,d}}{X_s} * x_{s,j} \leqslant \frac{\dot{m}_d}{X_d} * f_w(d) * x_{d,j}^{max} \qquad \forall j = 1, ..., n_j \qquad \forall d = 1, ..., n_d \\
&\sum_{s=1}^{n_s} \frac{\dot{m}_{s,d}}{X_s} * (1 - X_s \leqslant \frac{\dot{m}_d}{X_d} * f_w(d) * (1 - X_d^{max} \qquad \forall d = 1, ..., n_d \\
&X_d = 1 - \sum_{j=1}^{n_j} x_{i,j} \\
&f_w = 1 \qquad \forall w = 1, ..., n_{up} \\
&f_w^{min} * y_w \leqslant f_w \leqslant f_w^{max} * y_w \qquad \forall w = 1, ..., n_w \\
&y_w \in \{0, 1\}
\end{aligned}
\tag{46}
$$

with $\dot{m}_{s,d}$ the flowrate exchanged from source s to demand d

X_d^{max}	the purity required by demand d
X_s	the purity of source s
$f_w(d)(f_w(s))$	the level of usage of unit w corresponding to demand d (resp. source s)
$\dot{m}_d$	the flowrate in nominal conditions of demand d
$x_{s,j}$	the fraction of impurity j in source s
$x_{d,j}^{max}$	the maximum allowable fraction of impurity j in demand d
$C1_w, C"_w$	resp the fixed and the proportional cost of the unit w expressed as a function of its nominal flowrate
$C_{s,d}$	cost of exchanging one unit of flowrate from source s to demand d
n_w	number of utility units in the system
n_{up}	number of process units in the system
$n_d(n_s)$	number of demands (sources)
n_j	total number of impurities to be considered in the problem

By analogy with the energy integration technique, the use of the graphical representations will allow to represent the quality of the integration and suggest further process modifications.

It should be mentioned that the approach suggested for the water usage may be translated by analogy to the hydrogen networks in refineries. Both graphical techniques [59] and mathematical programming techniques [60] are transposed.

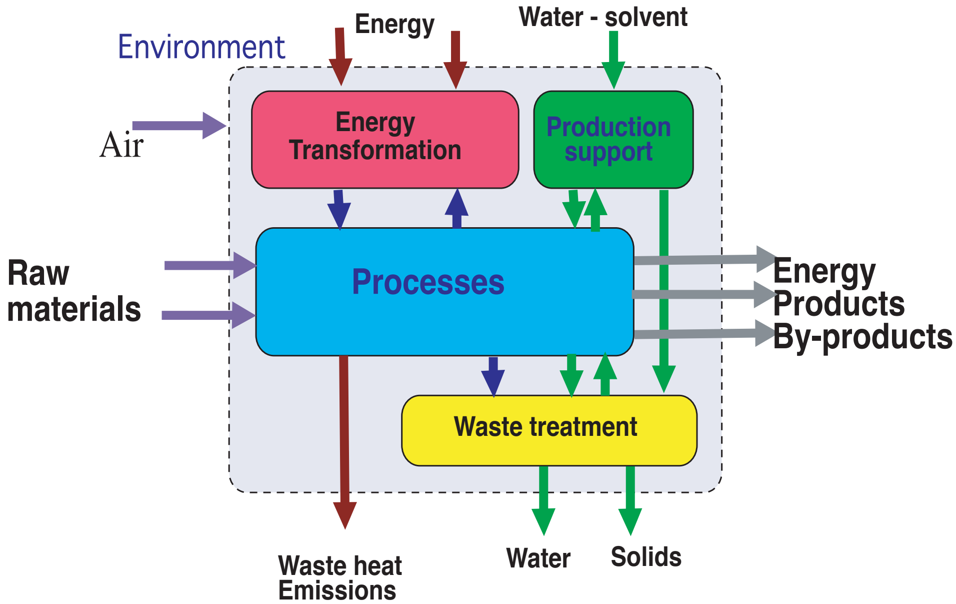


Figure 1: The process as a system that convert raw materials into products and by-products

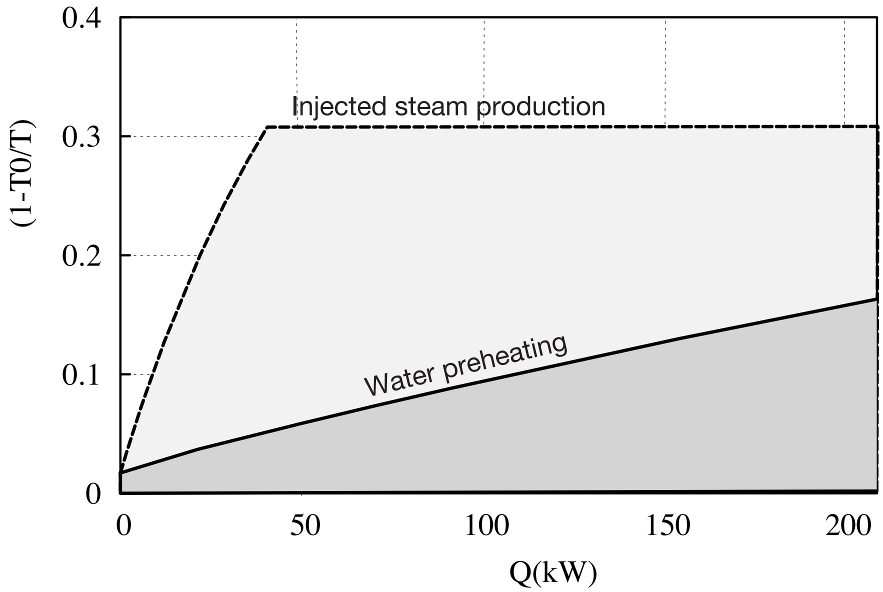


Figure 2: Dual representation of a heat requirement representing a stream heating by steam injection

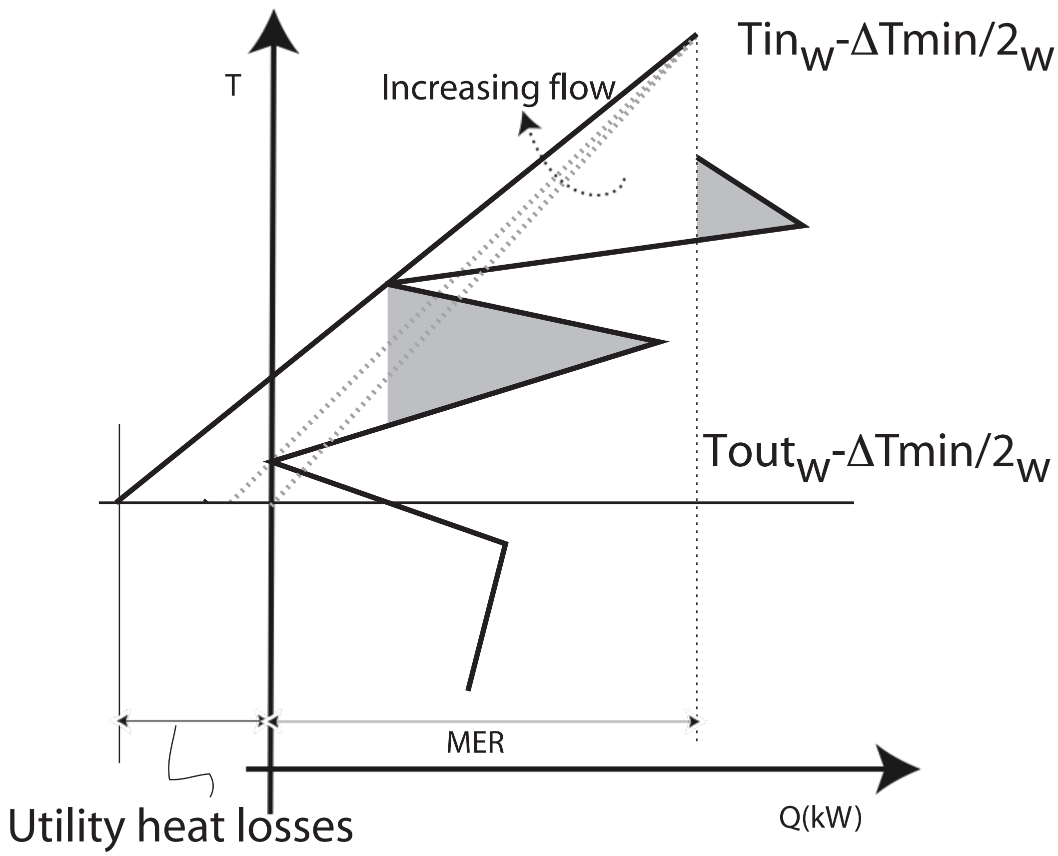


Figure 3: Computing the flowrate of the hot utility

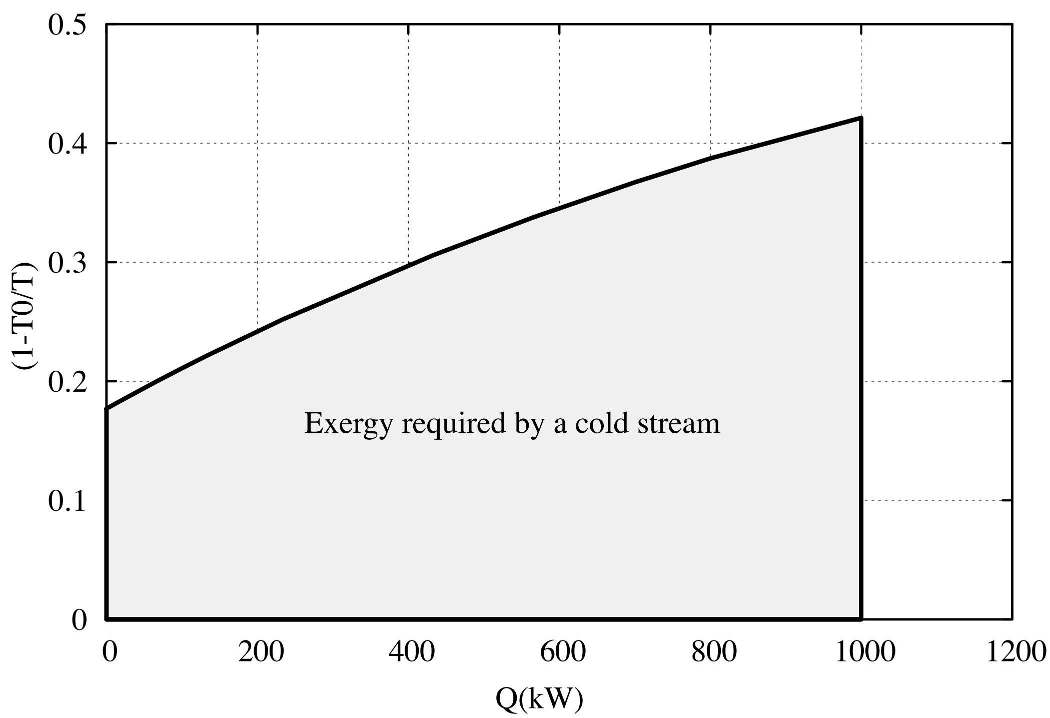


Figure 4: Exergy required by a cold stream heated up from 350 (K) to 500 (K)

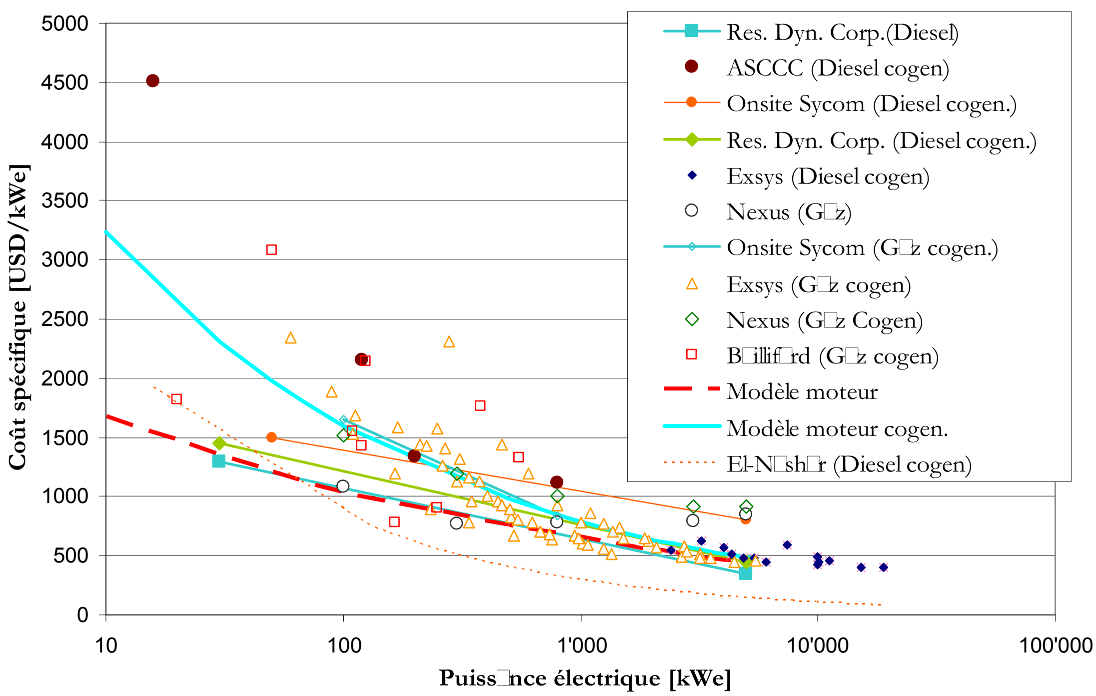


Figure 5: Comparison of different cost correlation for diesel engines in cogeneration applications

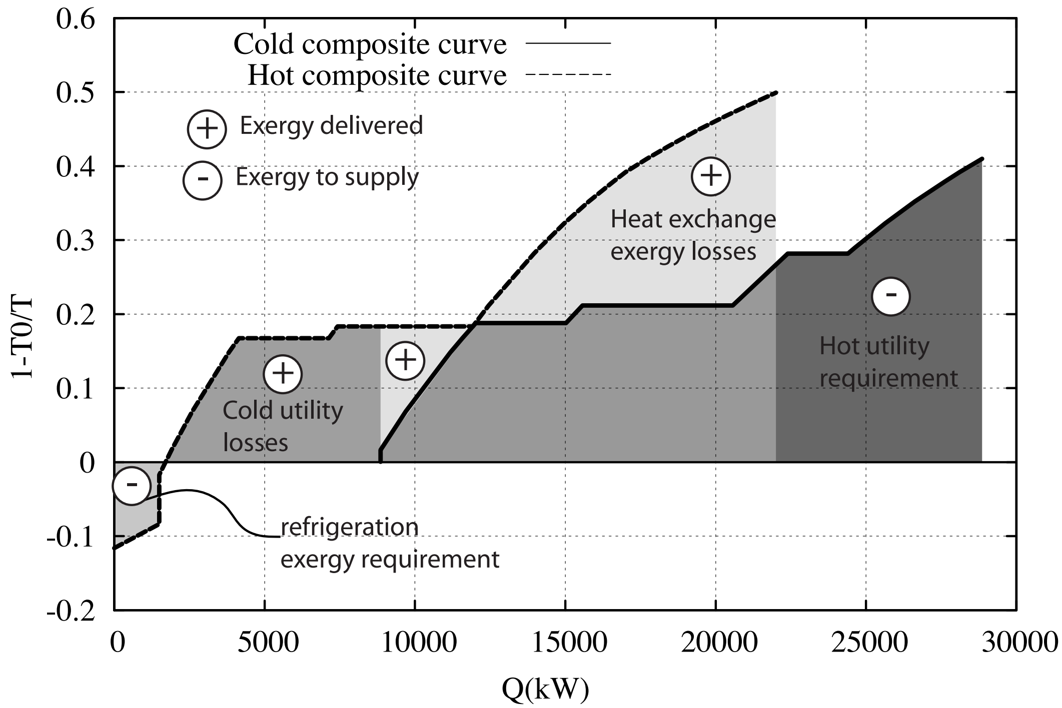


Figure 6: Exergy composite curves defining the process requirements

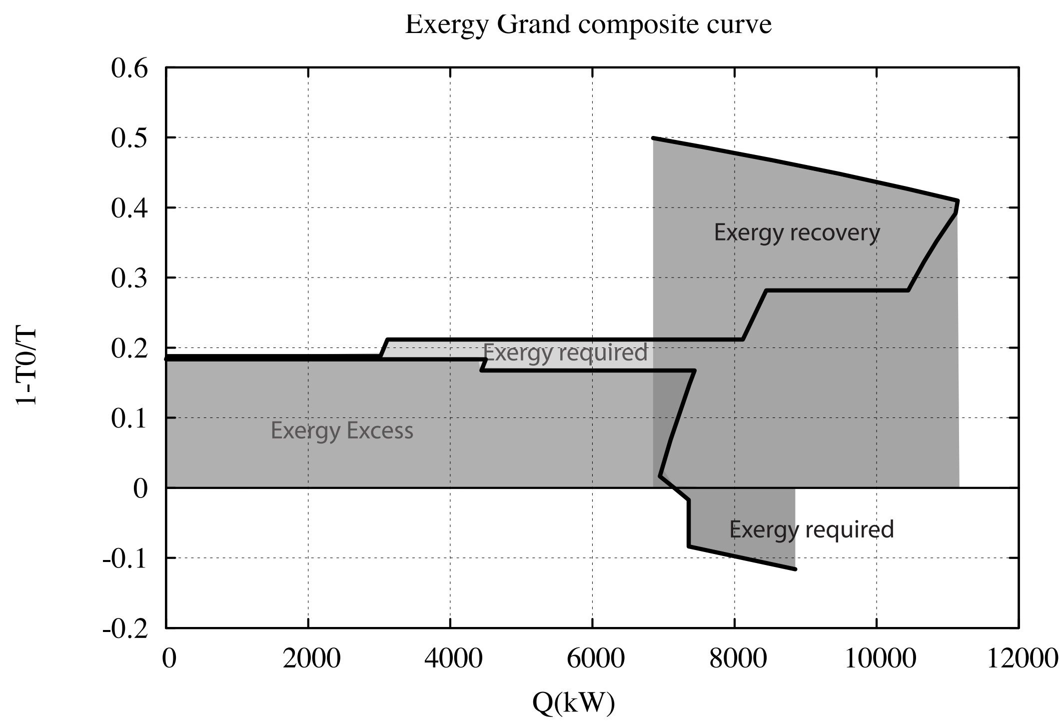


Figure 7: Exergy Grand composite curves of the process requirements

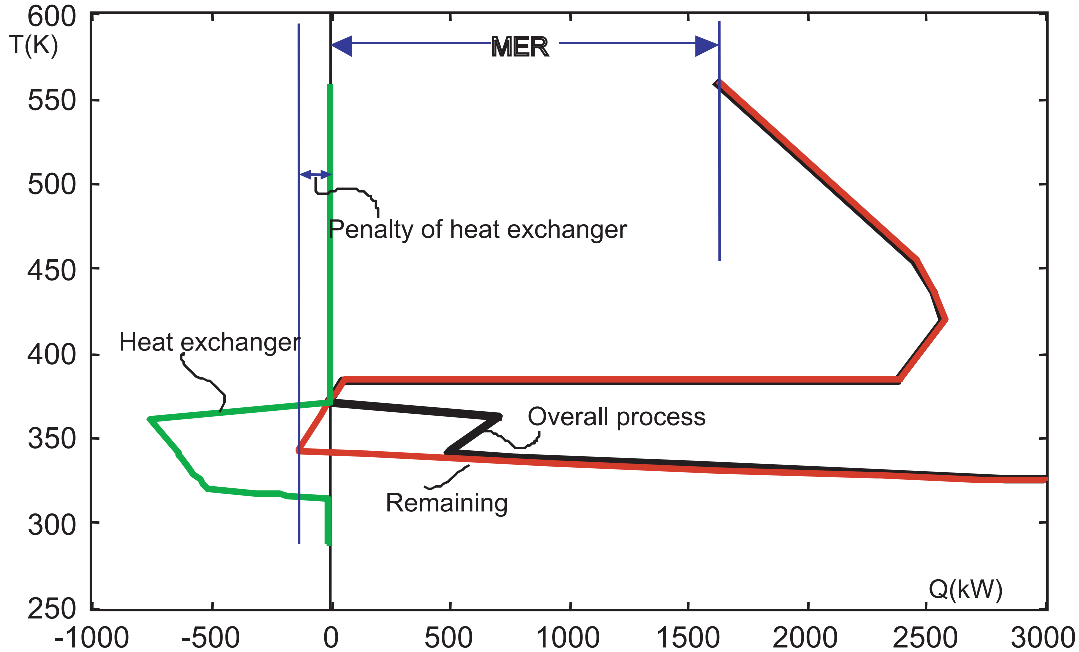


Figure 8: Integrated composite curves and remaining problem analysis

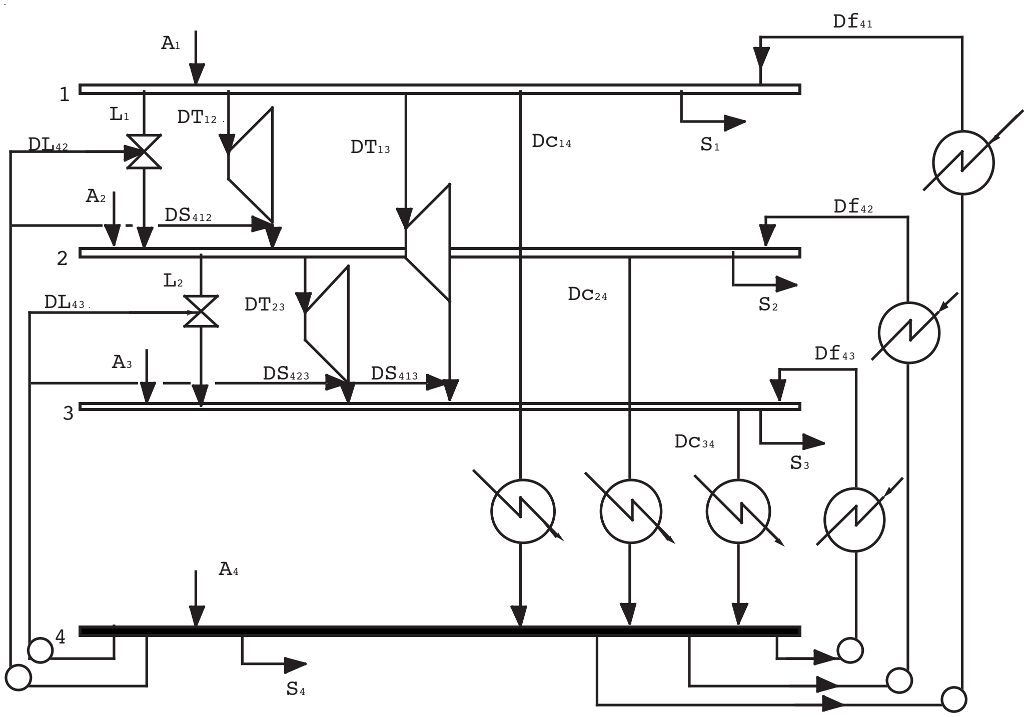


Figure 9: Superstructure of a steam network including 3 production/usage levels and one condensing level (deaerator)

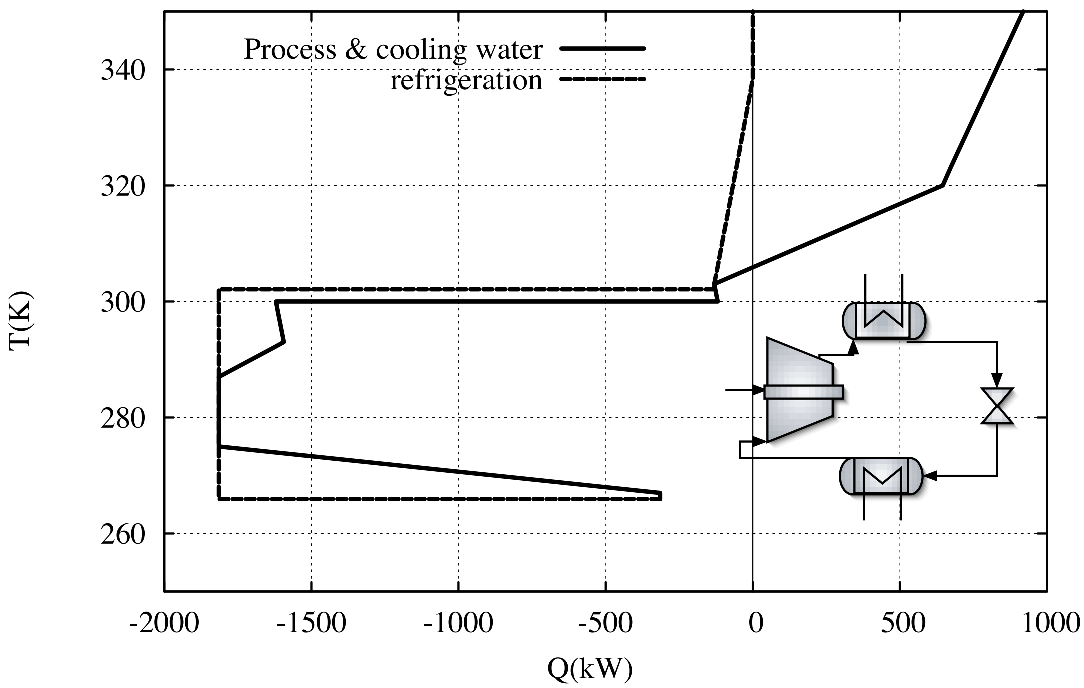


Figure 10: Integrated composite curve of a single stage refrigeration cycle

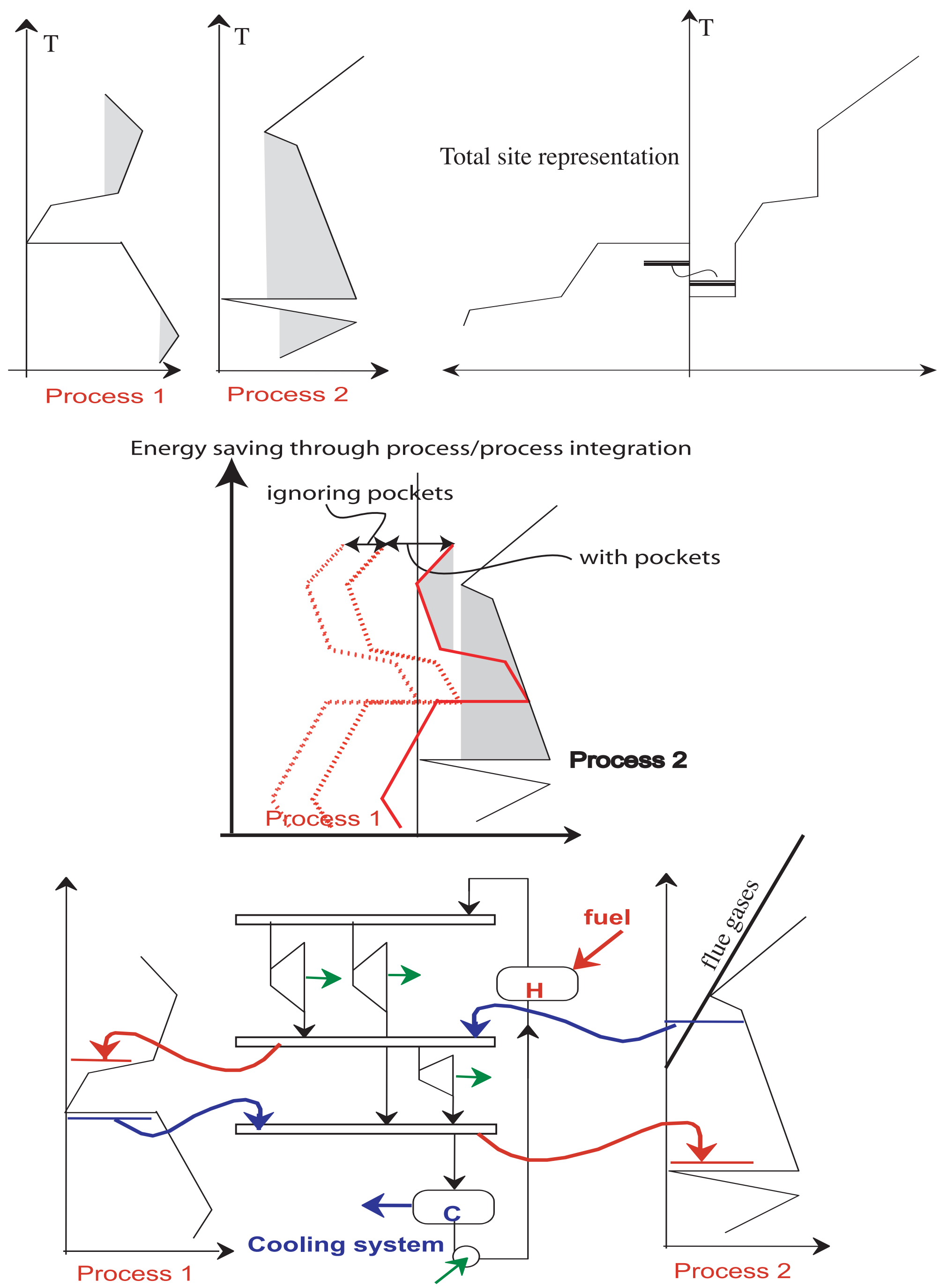


Figure 11: Total site integration and steam network

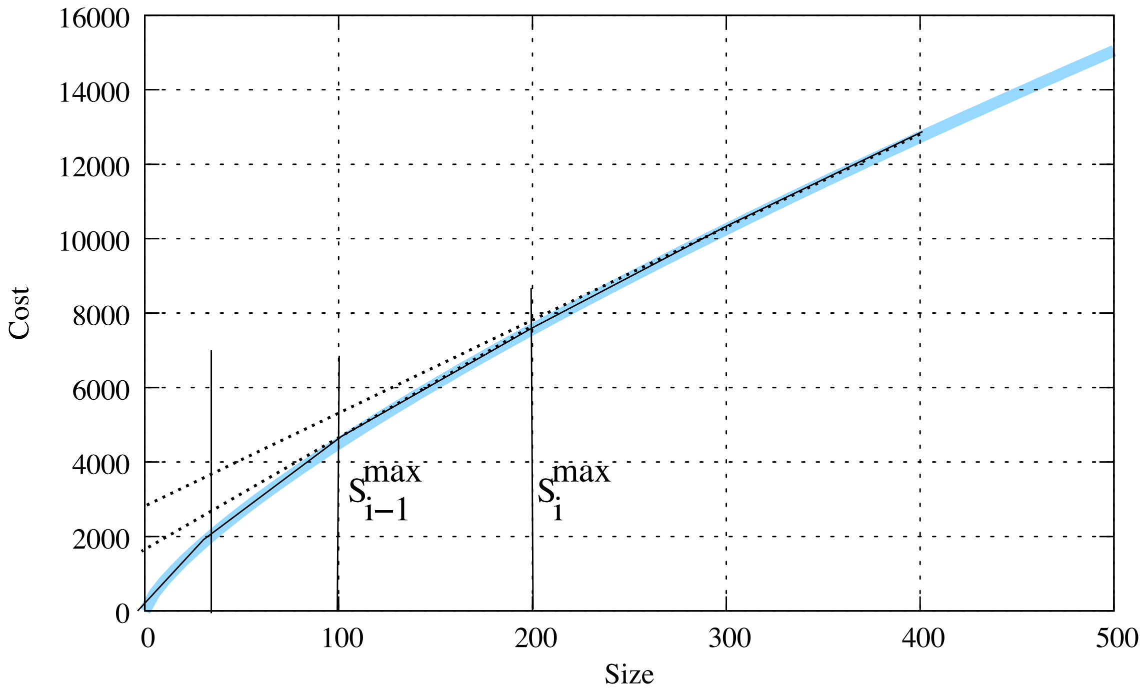


Figure 12: piece wize linearisation of cost function (exponent 0.75)

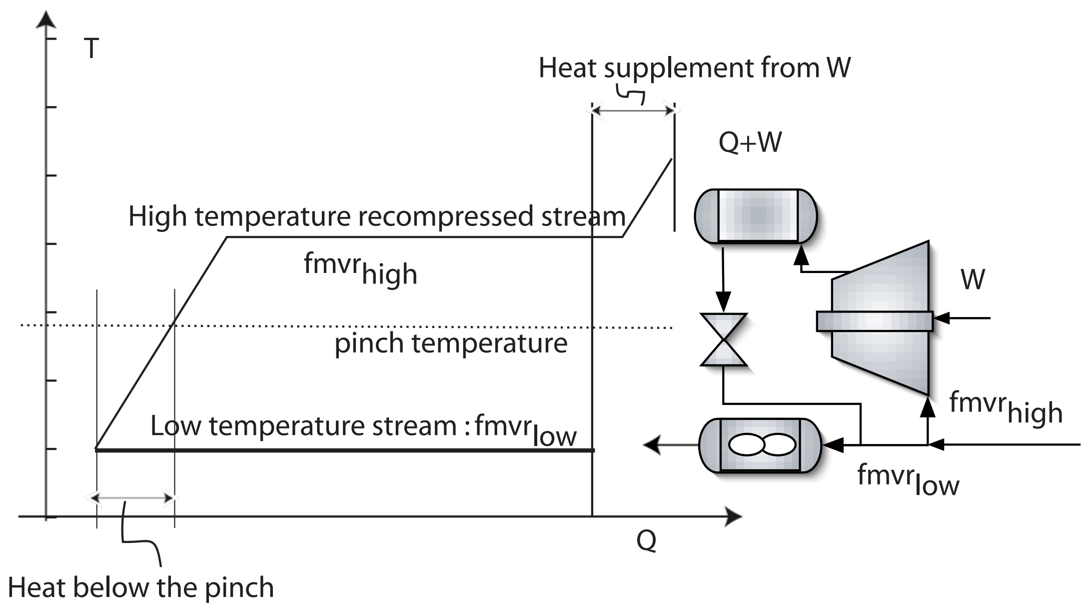


Figure 13: Mechanical vapour recompression

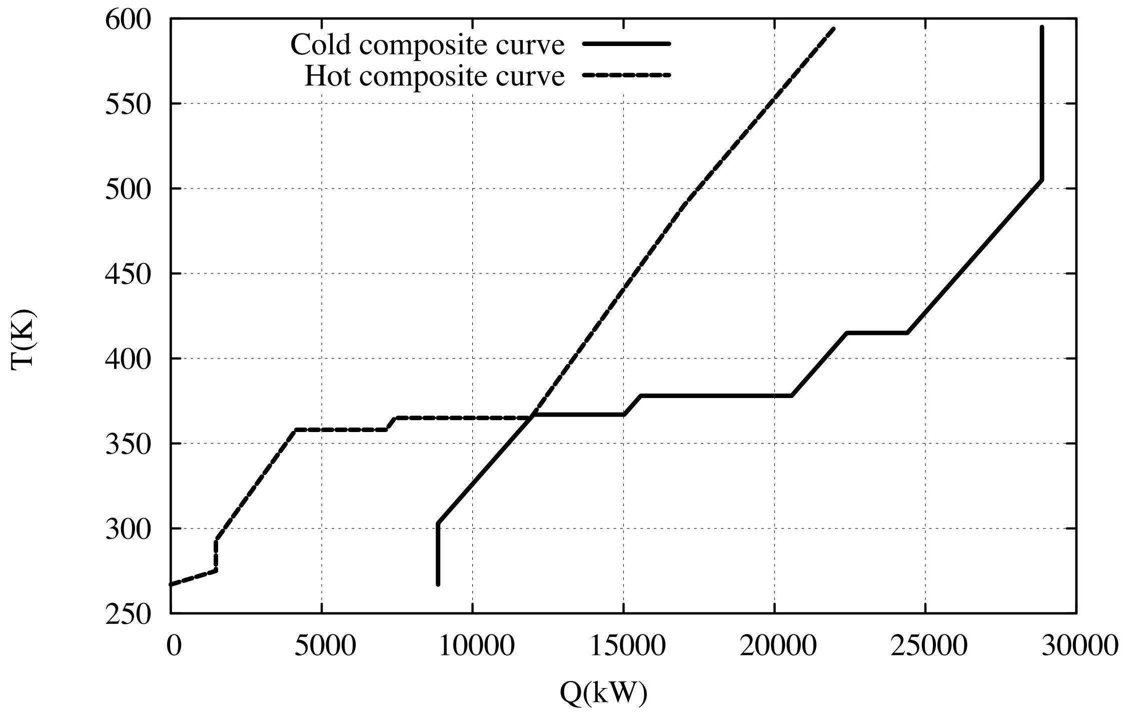


Figure 14: Hot and cold composite curves of the process

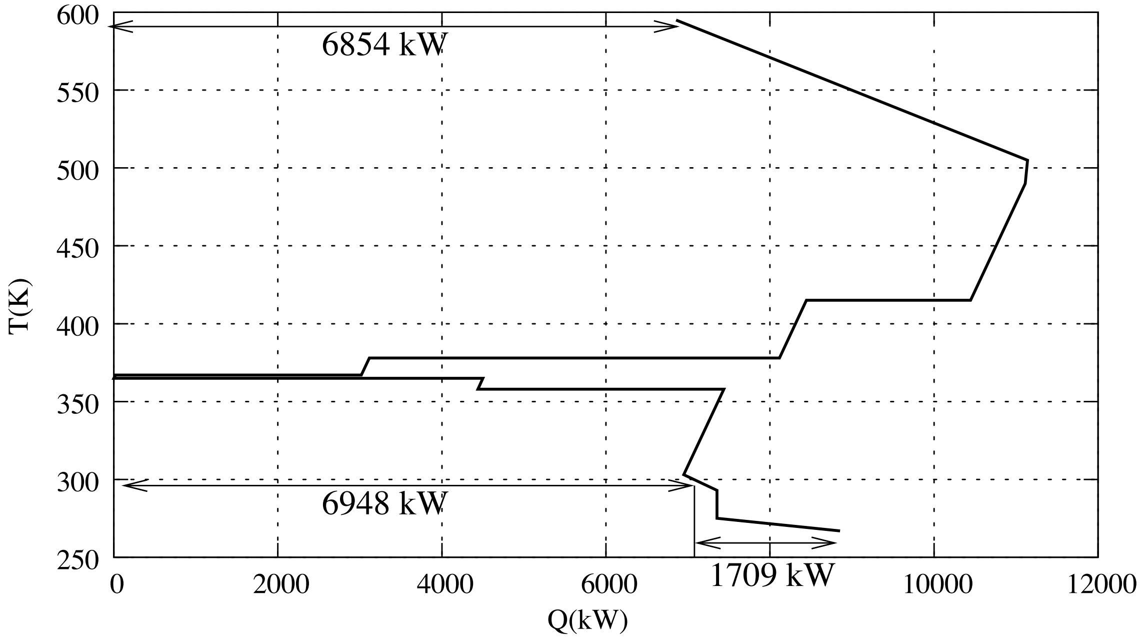


Figure 15: Grand composite curves of the process

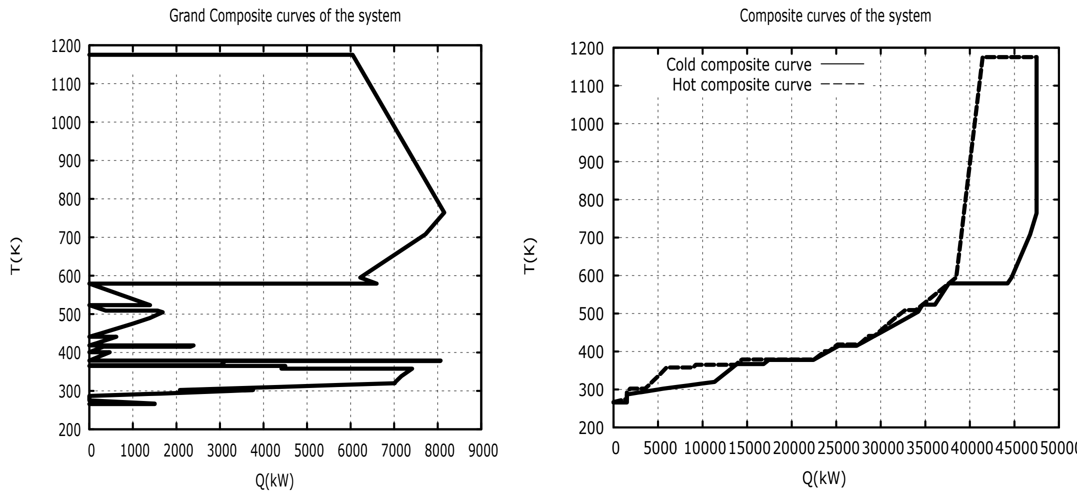


Figure 16: Balanced composite curves of the process with boiler, steam and cooling system

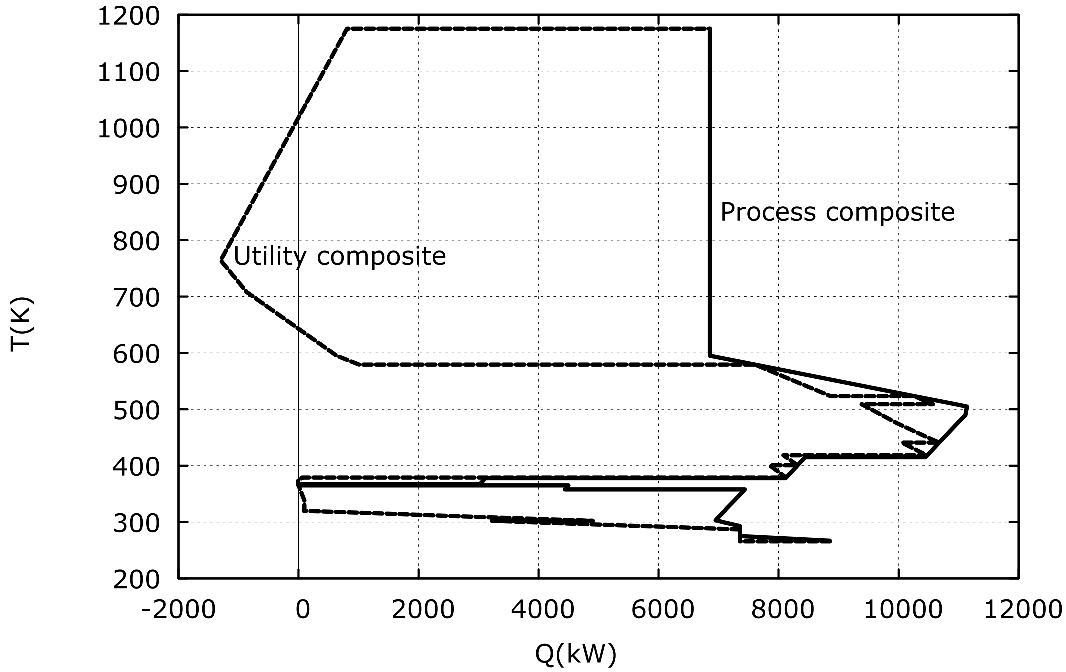


Figure 17: Integrated composite curve of the utility system : boiler, steam, refrigeration and cooling water

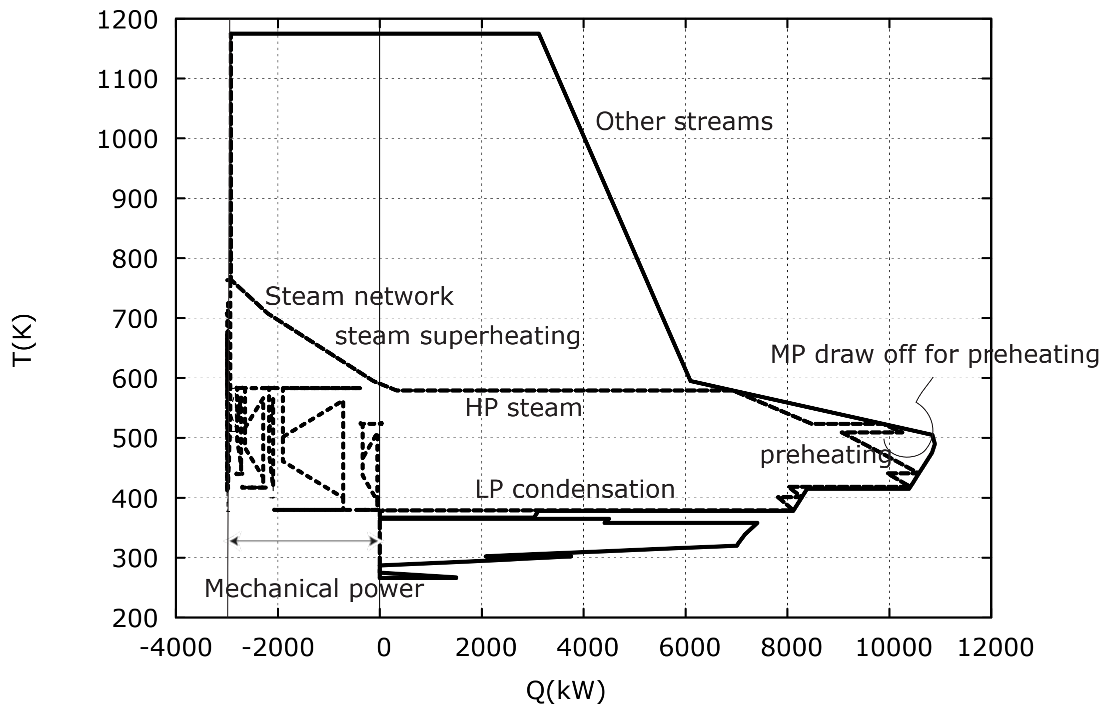


Figure 18: Integrated composite curve of the steam network : boiler, steam network, refrigeration and cooling system

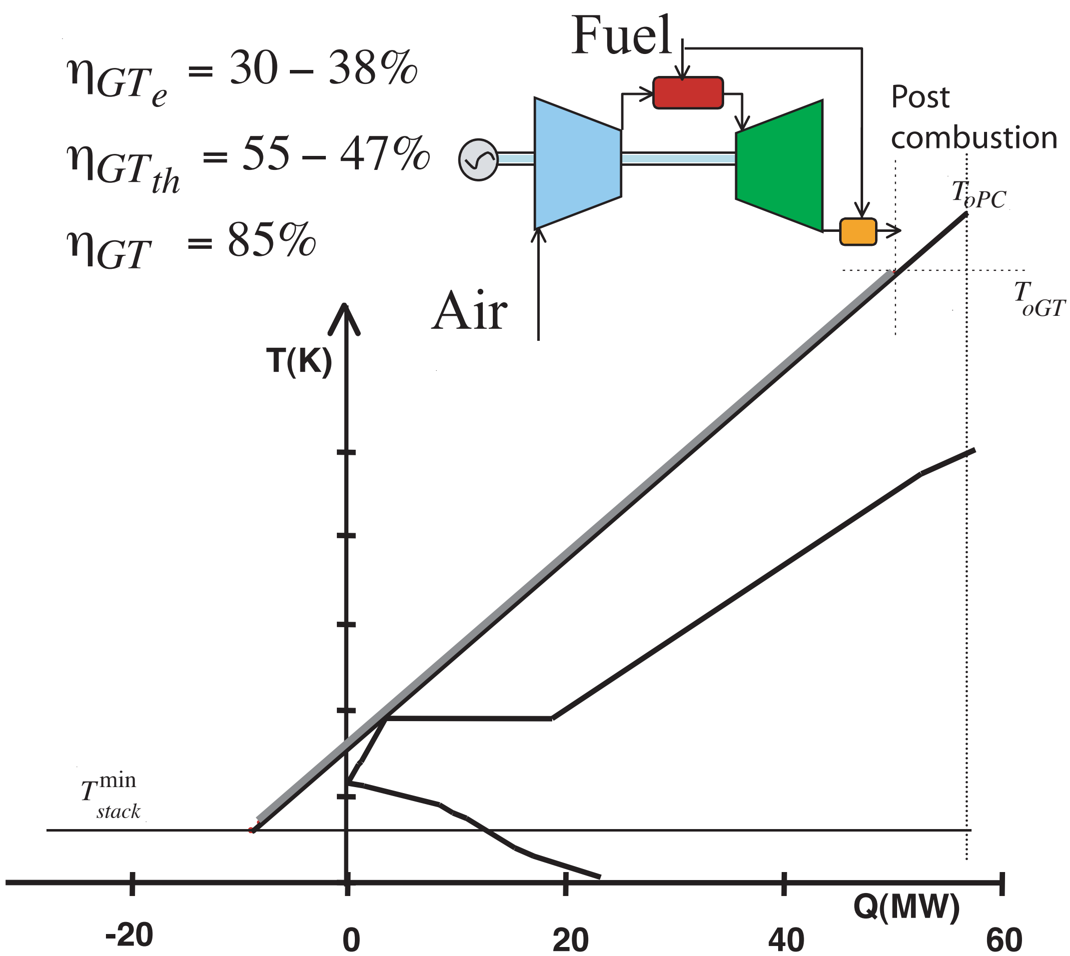


Figure 19: Integration of a gas turbine with post combustion to a process

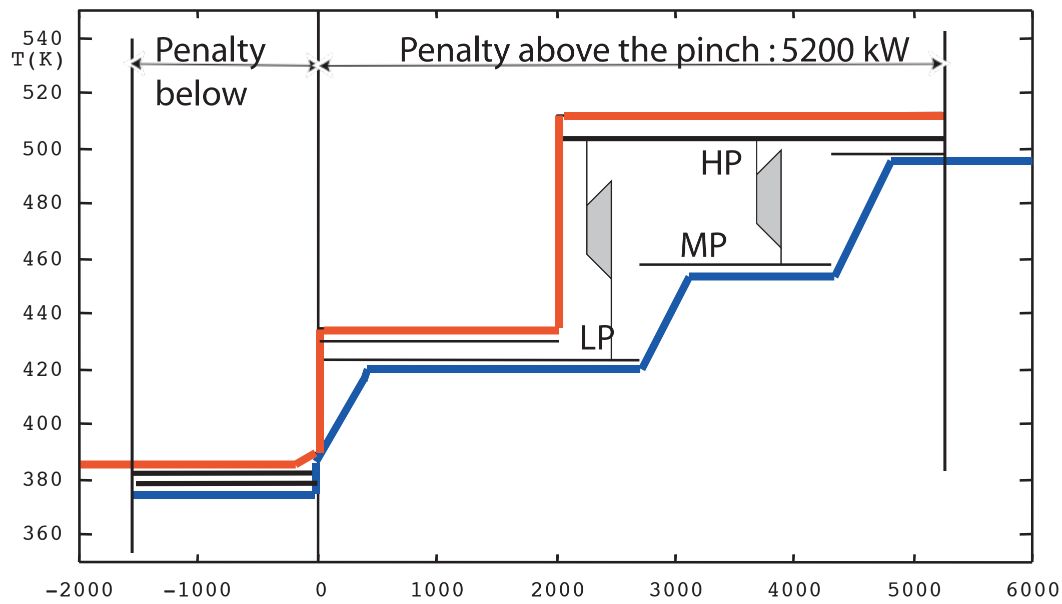


Figure 20: Restricted matches penalty composite curves

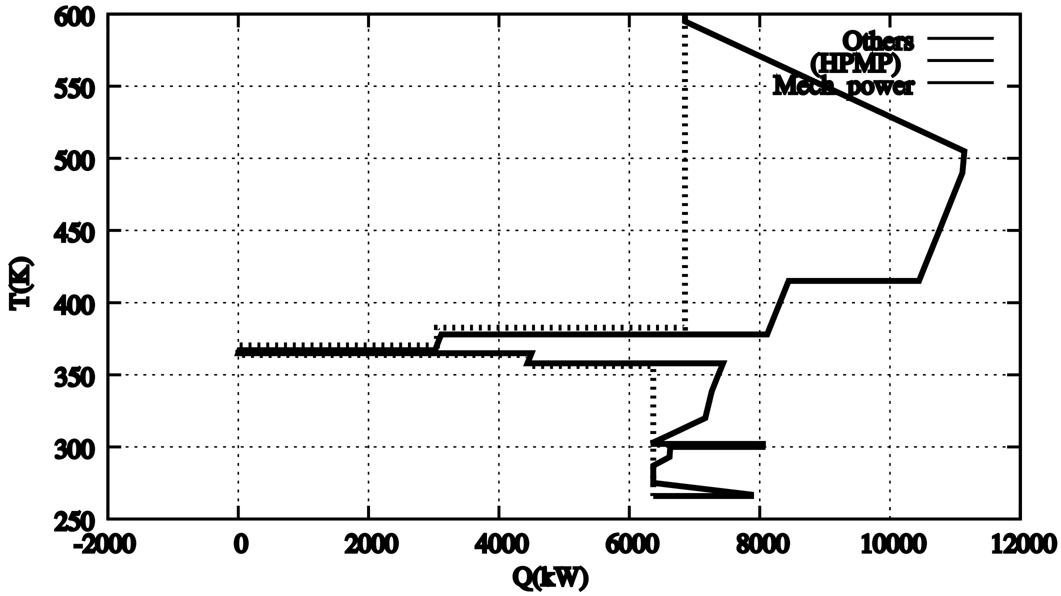


Figure 21: Integrated composite curve of the heat pump system :boiler, refrigeration and cooling system

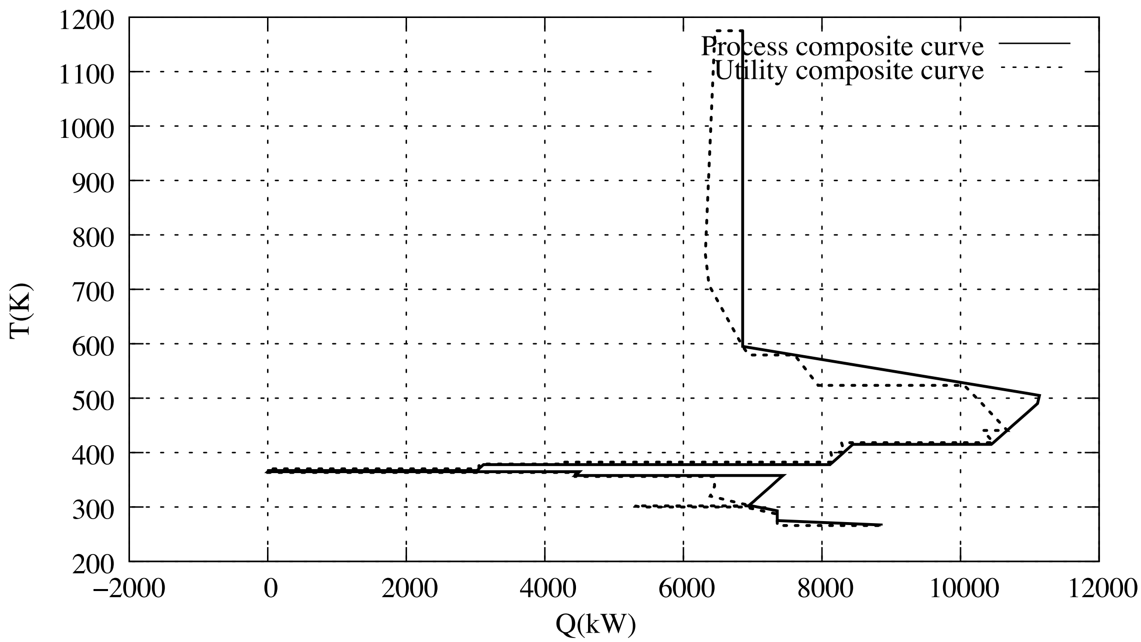
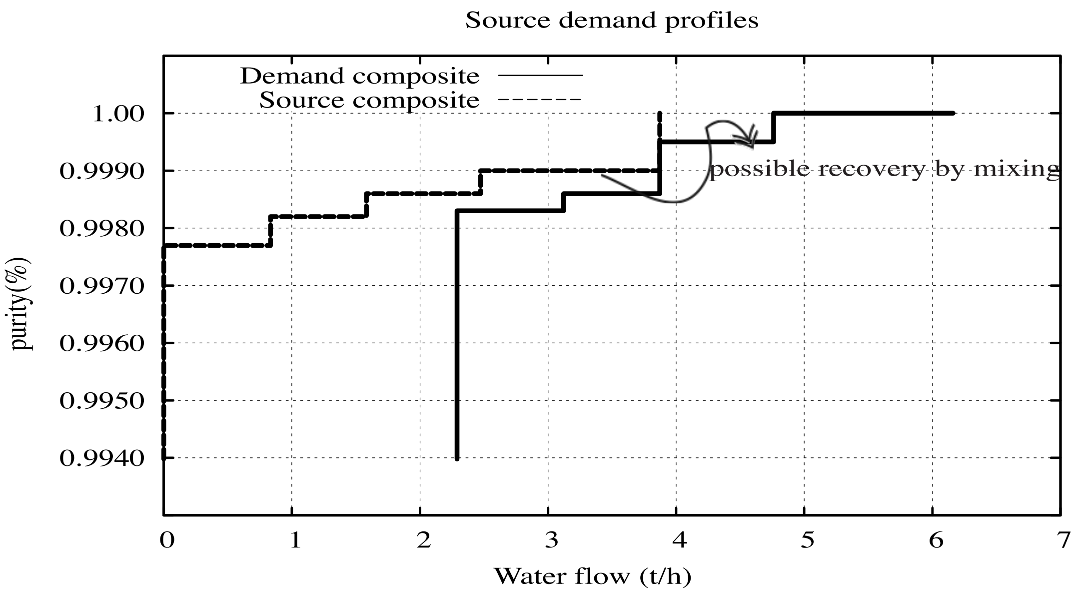
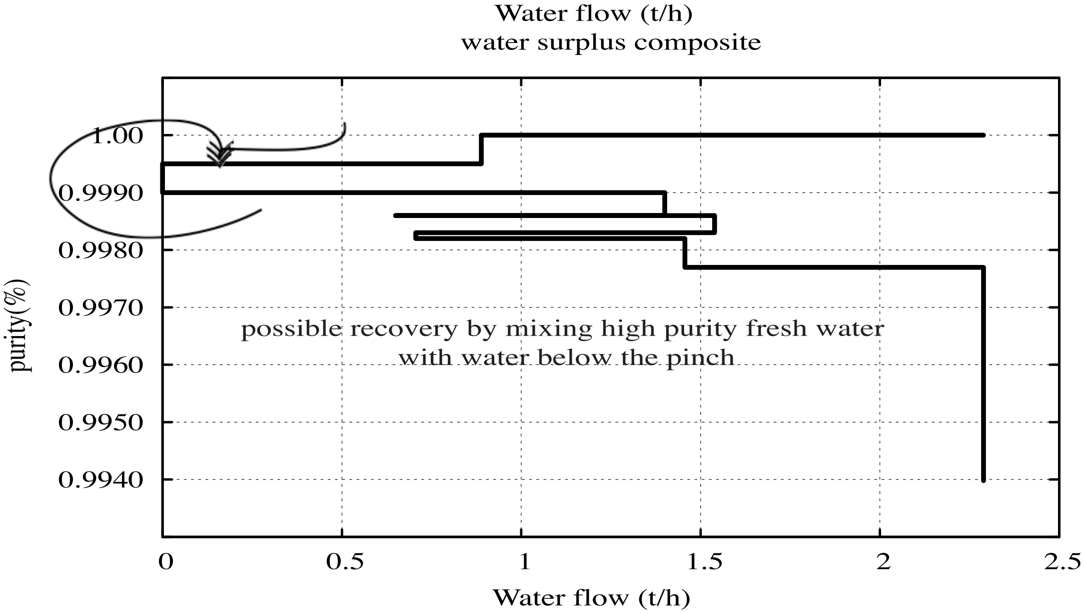
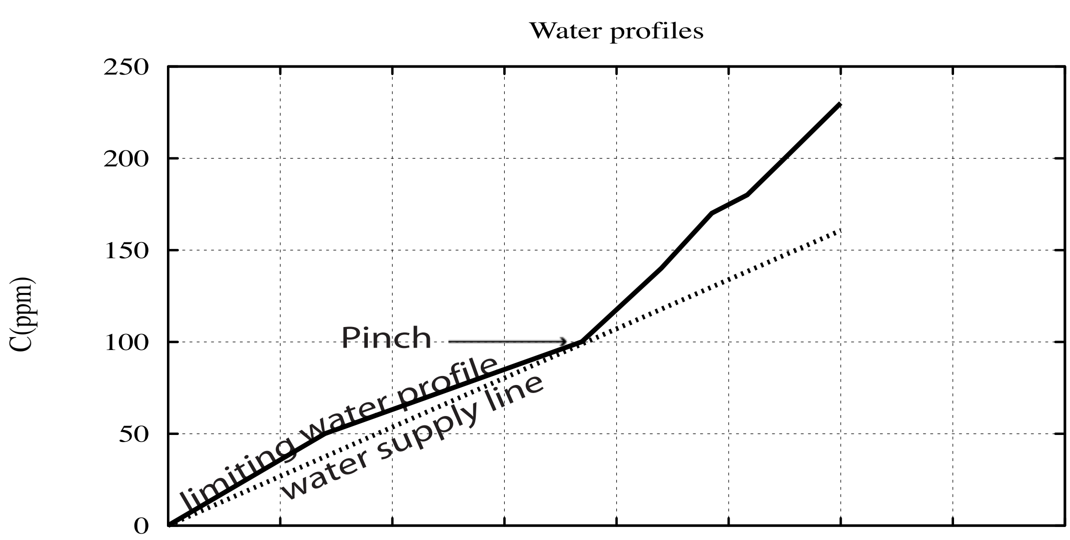


Figure 22: Integrated composite curve of the utility system: boiler, steam network, refrigeration and cooling system


Source demand profiles
Demand composite
Source composite
possible recovery by mixing
purity(%)
Water flow (t/h)


water surplus composite
possible recovery by mixing high purity fresh water
with water below the pinch
purity(%)
Water flow (t/h)


Water profiles
Pinch
limiting water profile
water supply line
C(ppm)

Gas engines, lean burn		
Generator eff.	$[-]$	$\eta_{gen} = 0.015 \cdot \ln(P) + 0.8687$, $P \leq 845$ $[kW]$ $\eta_{gen} = 0.0013 \cdot \ln(P) + 0.9611$, $P > 845$ $[kW]$
Mechanical eff.	$[-]$	$\eta_{mec} = 0.2419 \cdot P^{0.0653}$
Engine cooling @ 90C	$[-]$	$\eta_{th,refr} = 0.7875 \cdot P^{-0.1682}$
Heat from combusiton gases	$[-]$	$\eta_{th,echap} = 0.1556 \cdot P^{0.0513}$
NO_x emissions	$[mg/m^3N]$	250
CO emissions	$[mg/m^3N]$	650
Installed cost	[?]	$C_{inst} = -0.0266 \cdot P^2 + 578.84 \cdot P + 208174$
Catalysts cost	[?]	$85 \cdot P^{0.8}$
Maintenance cost	$[?/kWh]$	$C_{maint} = 0.0407 \cdot P^{-0.2058} + 0.0034$
Life time	$[hours]$	48000

Table 2: Gas engine, lean burn configurations. P : power in (kW)

Diesel engines		
Generator eff.	$[-]$	$\eta_{gen} = 0.015 \cdot \ln(P) + 0.8687$, $P \leq 845$ $[kW]$ $\eta_{gen} = 0.0013 \cdot \ln(P) + 0.9611$, $P > 845$ $[kW]$
Mechanical eff.	$[-]$	$\eta_{mec} = 0.0131 \cdot \ln(P_{mec}) + 0.3452$
Engine cooling @ 90C	$[-]$	$\eta_{th,refr} = 0.2875 \cdot P_{mec}^{-0.0139}$
Heat from combusiton gases	$[-]$	$\eta_{th,echap} = 0.5433 \cdot P_{mec}^{-0.1026}$
NO_x	$[mg/m^3N]$	100
CO	$[mg/m^3N]$	400
Installed cost	[?]	$C_{inst} = -0.0266(\frac{3}{4}P)^2 + 578.84\frac{3}{4}P + 208174$, $P \leq 1000$ $[kW]$ $C_{inst} = 1147.62 \cdot P^{0.9009}$, $P > 1000$ $[kW]$
Catalyst	[?]	$136 \cdot P$
Maintenance	$[?/kWh]$	$C_{maint} = 0.0407 \cdot P^{-0.2058}$
Lifetime	$[hours]$	48000

Table 3: Diesel engines

Aeroderivative gas turbines		
$\eta_{generator}$	$[-]$	$\eta_{gen} = 0.015 \cdot \ln(P) + 0.8687$, $P \leq 845\ [kW]$ $\eta_{gen} = 0.0013 \cdot \ln(P) + 0.9611$, $P > 845\ [kW]$
$\eta_{elec.}$	$[-]$	$\eta_{el} = 0.0439 \cdot \ln(P) - 0.0684$
η_{heat}	$[-]$	$\eta_{th,echap} = 0.838 \cdot P^{-0.0587}$
NO_x	$[mg/m^3N]$	80
CO	$[mg/m^3N]$	50
Turbine	[?]	$C_{ach} = 1516.41 \cdot P^{0.8503}$
Reference cost	[?]	$ref = \frac{C_{ach}}{(0.0503 \cdot \ln(\frac{P}{1000})+0.3208)}$
Recovery boiler	[?]	$C_{chaud} = (0.1255 - 0.0004 \cdot \frac{P}{1000}) \cdot ref$
Connection Charges	[?]	$C_{conn} = (0.09318 - 0.00011 \cdot \frac{P}{1000}) \cdot ref$
Instrumentation	[?]	$C_{ins} = (0.0494 - 0.0047 \cdot \ln(\frac{P}{1000})) \cdot ref$
Civil engineering	[?]	$C_{G.C.} = (0.1232 - 0.0005 \cdot \frac{P}{1000}) \cdot ref$
Engineering	[?]	$C_{eng} = (0.1211 - 0.000735 \cdot \frac{P}{1000}) \cdot ref$
Others	[?]	$C_{div} = (0.1403 - 0.0142 \cdot \ln(\frac{P}{1000}) \cdot ref$
Installed	[?]	$C_{inst} = \sum_i C_i$
Maintenance	$[?/kWh]$	$C_{maint} = 0.085 \cdot P^{-0.3081}$
Lifetime	$[hour]$	48000

Table 4: Aeroderivative gas turbines

Heavy duty gas turbines		
$\eta_{generator}$	$[-]$	$\eta_{gen} = 0.015 \cdot \ln(P) + 0.8687$, $P \leq 845\ [kW]$ $\eta_{gen} = 0.0013 \cdot \ln(P) + 0.9611$, $P > 845\ [kW]$
$\eta_{elec.}$	$[-]$	$\eta_{el} = 0.0187 \cdot \ln(P) + 0.1317$
η_{heat}	$[-]$	$\eta_{th,echap} = 0.7058 \cdot P^{-0.0315}$
NO_x	$[mg/m^3N]$	50
CO	$[mg/m^3N]$	50
Turbine	[?]	$C_{ach} = 4786.5 \cdot P^{0.7338}$, $P \leq 50'000$ $C_{ach} = 2977.0 \cdot P^{0.7791}$
Reference cost	[?]	$ref = \frac{C_{ach}}{(0.0503 \cdot \ln(\frac{P}{1000})+0.3208)}$
Recovery boiler	[?]	$C_{chaud} = (0.1255 - 0.0004 \cdot \frac{P}{1000}) \cdot ref$
Connection Charges	[?]	$C_{conn} = (0.09318 - 0.00011 \cdot \frac{P}{1000}) \cdot ref$
Instrumentation	[?]	$C_{ins} = (0.0494 - 0.0047 \cdot \ln(\frac{P}{1000})) \cdot ref$
Civil engineering	[?]	$C_{G.C.} = (0.1232 - 0.0005 \cdot \frac{P}{1000}) \cdot ref$
Engineering	[?]	$C_{eng} = (0.1211 - 0.000735 \cdot \frac{P}{1000}) \cdot ref$
Others	[?]	$C_{div} = (0.1403 - 0.0142 \cdot \ln(\frac{P}{1000}) \cdot ref$
Installed	[?]	$C_{inst} = \sum_i C_i$
Mantenance	$[?/kWh]$	$C_{maint} = 0.085 \cdot P^{-0.3081}$
Lifetime	$[hour]$	55000

Table 5: Thermo-economic model of the heavy duty gas turbines

Type	ΔT_{lift} C	Tc_{max} C	Power kW	a $/kW_{th}$	b	Carnot eff. %
Electric compression heat pump	45	110	10-3000	814	-0.327	45%
Mechanical vapour recompression	30	200	250-50000	663.5	-0.3925	45%
Absorption Heat pump NH_3	50	150	5-60000	810.2	-0.3154	1.4
Absorption Heat pump $liBr$	50	150	5-60000	810.2	-03154	1.6
Absorption heat transformer $LiBr/H_2O$	50	150	250-4000	1164.8	-0.288	0.45
Thermal Vapour recompression	20	180	15-50000	268.56	-0.4832	-

Table 6: Thermo-economical characteristics of industrial heat pumps systems, The sizing parameter is the heat delivered Q_{th} in kW_{th}, the cost is expressed in $/kW_{th}$ computed by $Investment = a*(Q_{th})^b$, source contribution of TNO in [9]

PAFC		
η_{el}	$[-]$	0.35-0.4 [61]
η_{th}	$[-]$	0.25
NO_x	$[ppm]$	0 [62]
CO	$[pppm]$	0 [62]
Installed cost	$[/kW]$	4000[61]
Maintenance	$[cts/kWh]$	1 [61]
Life time	$[h]$	40000 [63]

Table 7: Phosphoric acide Fuel Cells

SOFC		
η_{el}	$[-]$	$\sim$ 0.5 [61]
η_{th}	$[-]$	0.35
NO_x	$[ppm]$	¡ 0.2 [64]
CO	$[pppm]$	0 [64]
Installed cost	$[/kW]$	450 (long term) - 1500 [65]
Maintenance	$[cts/kWh]$	1[61]
Life time	$[h]$	¿ 20000 [66]

Table 8: Solid Oxide Fuel cells

PEMFC		
η_{el}	$[-]$	$\sim$ 0.3 - 0.4 [61]
η_{th}	$[-]$	0.5-0.45
NO_x	$[ppm]$	-
CO	$[pppm]$	-
Installed cost	$[/kW]$	$\sim$ 500 (long term) [67] - 1000[61]
Maintenance	$[cts/kWh]$	1 [61]
Life time	$[h]$	87600 [67]

Table 9: Proton Exchange Membranes

Table 10: Values for some typical fuels

	LHV kJ/kg	UHV kJ/kg	T_{ad} K	T_{stack} K	O_2 kg_{O_2}/kg	Cost ϵ/GJ_{LHV}	CO_2 kg_{CO_2}/kg	Remarks
CH_4	50001.2	55784.1	2646.5				2.74	Pure metha
Natural Gas	39680		2270	374			2.18	87% CH
Light fuel oil	45316		2425	440			3.40	
Heavy fuel oil	44500		2423	441			3.38	
Coal (lignite)	25450		2111	438			2.03	
Wood	18900		2185.43		1.4112			
Wood (oak)	17769		4059.52		1.35		1.81	
Biogas	13358		4069.9		1.07		1.47	50%CO_2 and 50

- Natural Gas composition: 87% Methane, 13% N_2
- Light Fuel Oil: C-86.2% mass, H-12.4% mass, S-1.4% mass
- Heavy Fuel Oil: C-86.1% mass, H-11.8% mass, S-2.1% mass
- Lignite: C-56.52%, H-5.72%, O-31.89%, N-0.81%, S-0.81%, Ash-4.25%
- Wood (oak) composition:

$$
\begin{aligned}
C\ 49.5\%w &= C_1 \\
H\ 6\%w &= H_{1,4} -> C_1 H_{1,4} O_{0,7} \\
O\ 44.6\%w &= O_{0,7}
\end{aligned}
$$

Table 11: Minimum energy requirements of the process

Heating requirement	6854	kW	Above 365 K
Cooling requirement	6948	kW	Between 365 K and 298 K
Refrigeration requirement	1709	kW	Below 298 K (lowest T =267 K)

Table 12: Refrigeration cycle characteristics

Refrigerant	R717	Ammonia			
Reference Flowrate	0.1	kmol/s			
Mechanical power	394	kW			
	P (bar)	T_{in} (K)	T_{out} (K)	Q kW	$\Delta Tmin/2$ (K)
Hot stream	12	340	304	2274	2
Cold stream	3	264	264	1880	2

Table 13: Steam cycle characteristics

	P (bar)	T (K	Comment
HP2	92	793	superheated
HP1	39	707	superheated
HPU	32	510	condensation
MPU	7.66	442	condensation
LPU	4.28	419	condensation
LPU2	2.59	402	condensation
LPU3	1.29	380	condensation
DEA	1.15	377	deaeration

Table 14: Results of the energy conversion system integration for different options

Option	Fuel kW_{LHV}	GT kWe	CHP kWe	Cooling kW	Heat Pump kWe
Boiler	7071	-	-	8979	-
Boiler+ steam	10086		2957	9006	-
GT+steam	16961	5427	2262	9160	-
Boiler+ heat pump	-	-	-	2800	485
Boiler + steam + heat pump	666	-	738	2713	496

Table 15: Overall energy consumption of the different options based on 55% fuel equivalent for electricity

Option	Fuel kW_{LHV}	Net Electricity kWe	Total consumption kW_{LHV}
Boiler	7071	371	7746
Boiler+ steam	10086	-2481	5575
GT+steam	16961	-7195	3879
Boiler+ heat pump	-	832	1513
Boiler + steam + heat pump	666	125	893

Table 16: Characteristics of the heat pump system, based on R123 as working fluid

Option	P_{low} (bar)	T_{low} (K)	P_{high} (bar	T_{high} (K)	COP -	kWe
Cycle 3	5	354	7.5	371	15	130
Cycle 2	6	361	10	384	12	323
Cycle 0	6	361	7.5	371	28	34

Bibliography

[1] Boland P. Hewitt G.F. Thomas B.E.A. Guy A.R. Marsland R.H. Linnhoff B., Townsend D.W. A user guide on process integration for the efficient use of energy. *The Institution of Chemical Engineers*, 1982.

[2] Smith R. Wang Y.P. Wastewater minimisation. *Chemical Engineering Science*, 49(7):1981–1006, 1994.

[3] Paris J. Brown D., Marechal F. A dual representation for targeting process retrofit, application to a pulp and paper process. *Applied Thermal Engineering*, Accepted for publication, 2004.

[4] Marechal F. Kalitventzef B. Optimal insertion of energy saving technologies in industrial processes : a web based tool helps in developments and coordination of a european r&d project. *Applied Thermal Engineering*, 20 (15-16)(276):1347–1364, 2000.

[5] Pelster S. *Environomic Modelling and Optimisation of Advanced Combined Cycle Cogeneration Power Plants Including CO_2 Separation Options*. PhD thesis, Ph. D Thesis, LENI, EPFL, 1998.

[6] Von Spakovsky M.R. Pelster S., Favrat D. The thermoeconomic and environomic modeling and optimization of the synthesis, design, and operation of combined cycles with advanced options. *Journal of Engineering for Gas Turbines and Power*, 123(4):717–726, 2001.

[7] Frangopoulos C.A. Comparison of thermoeconomic and thermodynamic optimal designs of a combined-cycle plant.

[8] Pelet X. *Optimisation de systèmes énergétiques intégrés pour des sites isolés en considérants les paramètres économiques, d'émissions gazeuses, de bruit et de cycles de vie.* PhD thesis, Laboratory for Industrial Energy Systems, Swiss Federal Institute of Technology Lausanne, 2004.

[9] Arpentinier et al. Exsys ii: an expert system for optimal insertion of intensified energy saving technologies (iest) in the industrial processes. - publishable final report of project joe3-ct97-0070
. Technical report, EU commission, 2001.

[10] Marechal F. Kalitventzeff B. Optimal insertion of energy saving technologies in industrial processes : a web based tool helps in developments and coordination of a european r&d project. *Applied Thermal Engineering*, 20(15-16):1347–1364, 2000.

[11] Whiting W. Shaeiwitz J. Turton R., Bailie R. *Analysis, Synthesis and Design of chemical processes*. Prentice Hall, NJ,, 1998.

[12] Marechal F. *Méthode d'analyse et de synthèse énergétiques des procédés industriels*. PhD thesis, Laboratoire d'analyse et de synthèse des systèmes chimiques, Faculté des Sciences appliquées, Univesité de Liége, 1995.

[13] Barthel Y. Raimbault C. Arlie J.P. Chauvel A., Leprince P. Manuel d'évaluation économique des procédés, avant-projets en raffinage et pétrochimie, nouvelle édition revue et augmentée. *Ed. Technip*, 2001.

[14] Linnhoff B. Townsend D.W. Heat and power networks in process design. part 1: Criteria for placement of heat engines and heat pumps in process networks. *AIChE Journal, Vol. 29, no 5, september 1983.*, 29(5):742–748, 1983.

[15] Kotas T. J. *The Exergy Method of Thermal Plant Analysis*. Krieger, 1995.

[16] Favrat D. Staine F. Energy integration of industrial processes based on the pinch analysis mathod extended to include exergy factors. *Applied Thermal Engineering*, 16:497–507, 1996.

[17] V. Lavric D. Baetens V. Plesu De Ruyck, J. Broadening the capabilities of pinch analysis through virtual heat exchanger networks. *Energy Conversion and Management*, 2003.

[18] Linnhoff B. Dhole V.R. Total site targets for fuel, co-generation emissions, and cooling. *Computers and Chemical Engineering, vol. 17, pp s101-s109*, (161), 1992.

[19] Kalitventzeff B. Marechal F. Identify the optimal pressure levels in steam networks using integrated combined heat and power method. *Chemical Engineering Science*, 52(17):2977–2989, 1996.

[20] Kalitventzeff B. Marechal F. Targeting the minimum cost of energy requirements : a new graphical technique for evaluating the integration of utility systems. *Computers chem. Engng*, 20(Suppl.):S225–S230, 1996.

[21] B. Kalitventzeff Marechal F. Heat and power integration a milp approach for optimal integration of utility systems. *Proceedings Proceedings of the 22nd Symposium of the working party on use of computers in chemical engineering, COPE'91 (Barcelona)*, 1991.

[22] Kalitventzeff B. Marechal F. Process integration : Selection of the optimal utility system. *Computers and Chemical Engineering, Vol 22, Suppl.,*, (200):S149–S156, 1998.

[23] Kalitventzeff B. Marechal F. Targeting the optimal integration of steam networks,. *Computers and Chemical Engineering*, 23:s133–s136, 1999.

[24] Kalitventzeff B. Marechal F. Restricted matches and minimum cost of energy requirements: tools and methodology for producing practical solutions. *PRES'99 : 2nd conference on process integration, modelling and optimisation for energy saving and pollution reduction*, pages 433–438, 1999.

[25] B. Kalitventzeff Marechal F. A tool for optimal synthesis of industrial refrigeration systems. *Computer Aided Chemical Engineering, ed. R. Gani, S.B. Jorgensen, Ed. Elsevier*, 90:457–463, May 2001.

[26] Kalitventzeff B. Pierucci S. Closon H., Maréchal F. Energy integration: Application to an olefins plant. *ICHEAP 4 : Fourth Italian Conference on chemical and process engineering*, (277):131–134, 1999.

[27] Kalitventzeff B. Marechal F., Favrat D. A methodology for the optimal insertion of organic rankine cycles in industrial processes. *2nd International Symposium on Process Integration, Halifax (2001)*, 2001.

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

[29] Kalitventzeff B. Marechal F. Study of the insertion of the partial oxidation gas turbine to satisfy high temperature requirements of industrial processes using energy integration techniques. *Proceedings of ESCAPE 10, ed. Elsevier Science b.v.*, pages 679–684, 2000.

[30] Maréchal F. Kalitventzeff B., Dumont MN. Process integration techniques in the development of new energy technologies : application to the isothermal gas turbine. *Keynote lecture, paper F3.1, Proceedings of CHISA 98, 13th International Congress of Chemical and Process Engineering, Praha, 23-28 August 1998*, (205), 1998.

[31] Duran M. A. and Grossmann I.E. Simultaneous optimization and heat integration of chemical processes. *AIChE Journal, Vol. 32, no1, January 1986.*, (55), 1986a.

[32] Grossmann I.E. Papoulias S.A. A structural optimization approach in process synthesis - i. utility systems. *Computers and Chemical Engineering*, 7(6):695–706, 1983a.

[33] Dhole V.R. Linnhoff B. shaft work targeting for subambient plants. *Aiche Spring Meeting, Houston, Paper 34d*, April 1989.

[34] Seider W.D. Colmenares T.R. Synthesis of cascade refrigeration systems integrated with chemical processes. *Computers and Chemical Engineering*, 1989.

[35] Grossmann I.E. and Sargent R.W.H. Optimum design of heat exchanger networks. *Computers and Chemical Engineering*, 2:1–7, 1978.

[36] Mason D. Linnhoff B. Cerda J., Westerberg A.W. Minimum utility usage in heat exchanger network synthesis. a transportation problem. *Chemical Engineering Science*, 38(3):378–387, 1983.

[37] Grossmann I.E. Papoulias S.A. A structural optimization approach in process synthesis - ii. heat recovery networks. *Computers and Chemical Engineering, vol. 7, No 6, pp. 707-721*, (53), 1983b.

[38] Kalitventzeff B. Marechal F. Synep1 : a methodology for energy integration and optimal heat exchanger network synthesis. *Computers chem. Engng*, 13(4/5), 1989.

[39] Glavic P. Kravanja, Z. Cost targeting for hen through simultaneous optimisation approach: a unified pinch technology and mathematical programming design of large hen. *Computers and Chemical Engineering*, 21:833–853, 1997.

[40] Kravanja Z. Sorsak A. Grossmann I. Hostrup M., Gani R. Integration of thermodynamic insights and minlp optimization for the synthesis, design and analysis of process flowsheets. *Computers chem. Engng*, 25:73–83, 2001.

[41] Santibanez J. Grossmann I.E. Applications of mixed-integer linear programming in process synthesis. *Computers and Chemical Engineering, vol. 4, pp 205-214*, (69), 1980.

[42] Grossman I.E. Mixed interger programming approach for the synthesis of integrated process flowsheets. *Computers and Chemical Engineering, vol. 9, No 5, pp 463-482*, (68), 1985.

[43] Grossmann I.E. Floudas C.A., Ciric A.R. Automatic synthesis of optimum heat exchanger network configuration. *AIChE Journal , vol 32, no 2, pp 276-290*, (119), 1986.

[44] Grossmann I.E. Floudas C.A. Automatic generation of multiperiod heat exchanger network configuration. *Computers and Chemical Engineering, vol. 11, No 2, pp 123-142*, (120), 1987.

[45] Kokossis A. Shang Z. A transhipment model for the optimisation of steam levels of total site utility systems for multiperiod operation. *Computers chem. Engng*, 28:1673–1688, 2004.

[46] R. R. Iyer and I. E. Grossmann. Synthesis and operational planning of utility systems for multiperiod operation. *Computers and Chemical Engineering*, 22(7-8):979–993, 1998.

[47] Grossmann I.E. Iyer R.R. Optimal multiperiod operational planning for utility systems. *Computers chem. Engng*, (8):787–800, 1997.

[48] Hui C-W Cheung K-Y. Total-site scheduling for better energy utilisation. *Journal of cleaner production*, pages 171–184, 2004.

[49] Kalitventzeff B. Mixed integer non linear programming and its application to the management of utility networks. *Engineering optimization*, 18:183–207, 1991.

[50] Grossman I.E. Duran M.A. A mixed-integer nonlinear programming algorithm for process systems synthesis. *AIChE journal,vol 32, no4,pp 592-606*, (70), 1986b.

[51] Kalitventzeff B. Dumont MN. Papalexandri K.P., Pistikopoulos E.N. Operation of a steam production network with variable demands, modelling and optimisation under uncertainty. *Computers and chemical engineering, Vol. 20, Suppl.*, (207):S763–S768, 1996.

[52] Manousiouthakis V. El-halwagi M.A. Automatic synthesis of mass exchange networks with single component targets. *Chemical Engineering Science*, 45(9):2813–2831, 1990.

[53] Smith R. Kuo W-C. J. Effluent treatment system design. *Chemical Engineering Science*, 52(230):4273–4290, 1997.

[54] Smith R. Doyle S.J. Targeting water reuse with multiple contaminants. *Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers*, 75(3):181–189, 1997.

[55] Tainsh R.A. Wasilewski M. Dhole V.R., Ramchandani N. Make your process water pay for itself. *Chemical Engineering*, 103(1):100–103, 1996.

[56] hallale N. a new graphical targeting method for water minimisation. *Advances in environmental research*, 6:377–390, 2002.

[57] Kokossis A. alva-argaez A., Vallianatos A. A multi-contaminant transhipment model for mass exchange networks and wastewater minimisation problems. *Computers chem. Engng*, pages 1439–1453, 1999.

[58] Paris J. Brown D., Marechal F. Mass integration of a deinking mill. *Prétirés 90ième conf. ann. PAPTAC*, 2004.

[59] Liu F. Hallale N. Refinery hydrogen management for clean fuels production. *Advances in Environmental Research*, 2001.

[60] Towler G.P. Zhang J., Zhu X.X. A simultaneous optimisation strategy for overall integration in refinery planning. *Ind. Eng. Chem. Res.*, 2001.

[61] California Energy Commission : www.energy.ca.gov.

[62] Taylor W.R. Holcomb F.h., Binder M.J. Reduced emissions from cogeneration, applications of dod fuel cell power plant fleet. *DoD fuel cell (www.dodfuelcell.com (29/06/2004))*, 2004.

[63] Cropper M. Why is interest in phosphoric acid fuel cells falling. *Fuel cell today*, 8 october 2003.

[64] Crawley G. Operational experience with siemens-westinghouse cogeneration experience. *Fuel cell today*, 17 october 2001.

[65] Teagan P. Yang Y. Carlson E.J., Srimamulu S. Cost modelling of sofc technology. *1rst International conference on fuel cell Development and deployement*, www.ctfuelcell.uconn.edu/fcic/pdf/fcic-program-oral-4a.2.pdf, 2004.

[66] Colson-Inam S. Solid oxide fuel cells - ready to market ? *fuel cell today*, 07 January 2004.

[67] Thomas C.E. Cost analysis of stationary fuel cell systems including hydrogen co-generation. Technical report, Directed Technologies, December 1999, available online at www.directedtechnologies.com, 1999.