ADVANCED POWER PLANT DESIGN METHODOLOGY USING PROCESS INTEGRATION AND MULTI-OBJECTIVE THERMO-ECONOMIC OPTIMISATION

Raffaele Bolliger, Francois Maréchal*, Daniel Favrat
Laboratory for Industrial Energy Systems
École Polytechnique Fédérale de Lausanne
Switzerland - 1015 Lausanne

ABSTRACT

Thermo-economic modelling techniques are well known techniques to optimise power plant designs. These methods are usually based on the definition of a superstructure that includes the major options of the design. If this approach has proved to be appropriate for the optimisation of several conventional NGCC (Natural Gas Combined Cycles), it reveals some weaknesses when dealing with particularly complex systems where heat integration leads to a lot of possible heat exchange configuration. This is for example the case in advanced cycles in zero emission plants where numerous heat exchanges between the gas turbines, the steam network and the CO_2 capture units can be considered. In this situation, the superstructure approach is not anymore practical and new modelling techniques are needed. In this paper, we present a new modelling technique developed to be used in the context of a multi-objective optimisation framework. This method uses a thermodynamic model of the energy flows of the energy conversion units. The results of the model allow the calculation of the hot and cold streams to be considered in the heat exchanger network. A heat cascade model using the ΔT_{min} concept is used to compute the optimal integration of the heat exchange in order to maximise the energy conversion. In this model, a special steam cycle model has been developed to represent all the possible heat exchange interactions and to compute the optimal flowrates in the system with a minimum of structural information. The third part of the model is the thermo-economic estimation of the system cost to deduce the performances of the system. An optimisation method, based on a multi-objective evolutionary algorithm is then used to identify the most important system configurations. The method is illustrated on an AZEP (Advanced Zero Emission Plant) combined cycle design.

Keywords: process integration, heat cascade, multi-objective optimisation, thermo-economic, advanced power plants, AZEP

NOMENCLATURE

C_x	cost of equipment x
$C_{x,r}$	reference cost of equipment x
V	sizing variable
V_r	reference value for sizing
n	size factor
$f_{M\&S}$	Marshall & Swift actualisation factor
Π_x	Pressure ratio of x
$\dot{m}$	Mass flowrate
$\dot{\tilde{m}}$	Molar flowrate
T	Temperature (K)
A	Area (m^2)
P	Pressure (bar)
R	Universal gas constant (8.314 J/K mol)
$\dot{E}$	Power (kW)
AZEP	Advanced Zero Emission Plant
OTM	Oxygen Transfert Membrane
MER	Minimum Energy Requirement
GA	Genetic Algorithm
HRSG	Heat Recovery Steam Generator

*Corresponding author: Phone: +41 21693 3516 Fax: +41 21693 3502 E-mail: francois.marechal@epfl.ch

BACKGROUND

The conventional process simulation approach [8], [15] is based on the idea of scenario: a model is built according to a given structure, in order to meet mass and energy balance. All the elements of the process are connected together to form a superstructure. For each heat exchange, one has to choose between which units it is performed. From here the idea of scenario: each heat exchangers network design corresponds to a well defined structure. When the network is not trivial, i.e. when there is more than one way to exchange heat between units, it is necessary to build several scenarios in order to evaluate the performance of all the possible combinations. When modelling a very complex superstructure composed by several units, the possible scenarios for heat exchangers network become too large to be entirely taken into account. At this point, it is necessary to eliminate some possible solutions and to select only the most interesting ones. The major drawback of this approach is that, when handling with non-linear models, the optimal solution is not known a priori. So, eliminating some possible solutions could lead to the loss of some good solutions. The same topological problem is met when analysing several technological alternatives for a given process. For each unit it is necessary to create the streams and energy connections with the rest of the model, which means creating a scenario. The pinch technology [9] has been widely used in industrial processes to encompass the difficult task of the optimal heat exchanger network design. The method has been adapted to consider streams with unknown flowrates [10] and optimise the combined production of heat and power in a process. It has been demonstrated that the method may be adapted to tackle the optimal integration of steam cycles in power plants [11].

A NEW APPROACH FOR COMPLEX SYSTEMS

The approach developed combines the use of thermo-economic modelling and process integration concepts. In the first step, the process is divided into subunits according to the material flows. Each subunit of the process is modelled independently from the others using a thermo-modelling package. The heat exchanges between the units considered as hot or cold sources. In a second step, an energy integration is performed to model the heat exchange contribution to the final layout of the superstructure. By this way, all the units are correctly sized according to the thermodynamic of heat exchanges, as shown in Figure 1. With this approach the heat exchangers network is a part of the solution of the optimisation problem. The main advantage is that it is possible to build a model without taking care of the heat exchangers network layout, avoiding therefore the creation of scenarios. The same reasoning can be applied to the choice of process alternatives: in the process modelling all the alternatives are programmed; the energy integration will choose the one which best satisfies the objective functions. Alternatively, the use of integer variables allows the direct control of the alternatives during the optimisation. After the application of the energy flows and the process integration model, all the necessary data for computing the system cost estimation is available.

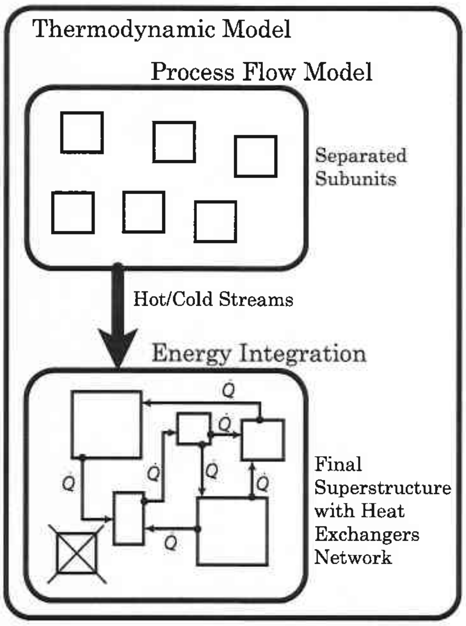

Figure 1: Detail of the thermodynamic model

HOW IT WORKS

The approach can be split into two parts: modelling and optimisation. As shown in figure 2, the optimiser sends the values of the decision variables to the model. Its performance is then evaluated and the values of the objective functions are returned to the optimiser. Decision variables can be sent to all

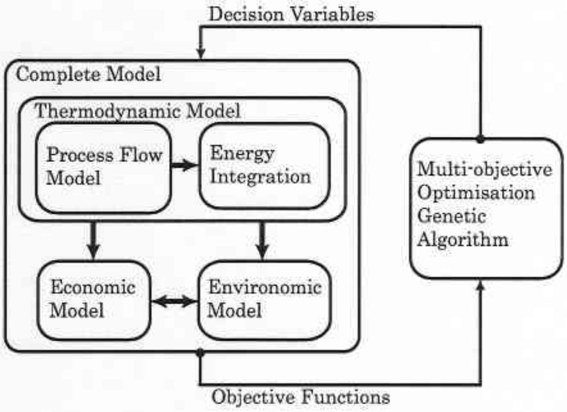

Figure 2: Schematic view of the process integration approach

subparts of the model, in particular, to the process flow, to the energy integration model, to the economic model, to the environomic model or to any sub-model developed for the simulation.

Integrating models

The Laboratoire d'Energétique Industrielle (LENI) is developing a MATLAB® routine called OSMOSE allowing to apply the approach presented in this paper. The details of the modelling and energy integration software called by OSMOSE can be found in [12]. The first sub-model to be run is the process flow. Here the thermodynamics of the material and energy transformation for each sub-unit in the process is computed. Then, the table of cold and hot streams is established. The list can be completed with some units which can be entirely defined in the energy integration model, like the steam network, described later. The process is then perfectly integrated and sized by solving the energy integration as an optimisation [10]. The information coming from the thermodynamic model are then passed to the thermo-economic performance evaluation model in order to compute the objective functions of the global optimisation. At this stage, the values of the objective functions are returned to the optimiser, and the cycle can restart.

Process Flow Model

The process flow model is built with a process modelling software, BELSIM [2]. Each sub-unit of the process is modelled as if it was energetically independent from the others. All the heat exchanges are performed between streams and imaginary sources, assumed to be available at the required temperature. Two types of units are defined: process units and utilities. First ones are the units with fixed flow, which will be used to compute the Minimum Energy Requirement (MER) of the process. Utilities are units with a well defined structure (temperature levels, pressures,...), but with unknown level of utilisation. They are built in the process flow model with a nominal size and the best size is defined to reach the optimal energy integration.

Energy integration - pinch technology

The list of the hot and cold streams of the process is built. Other units can be added to complete the model. The energy integration of the process allows to build the composite curves, in order to determine the MER and to integrate the utilities. The steam network model is embedded in the approach allowing the calculation of the optimal flows in the steam cycle that maximises the power production using the exergy delivered or required by in the process streams. Heat exchanges are computed according to the pinch technology [10], allowing the design of the heat exchangers network, which becomes a solution of the optimisation problem,

Thermo-economic model

Thermo-economic modelling allows predicting the cost of the units used in the process. The thermo-economic costing model used in this paper is using the concepts proposed by Turton [16]:

$$C_x = C_{x,r}(\frac{V}{V_{ref}})^n$$

where V is the sizing variable representing a technical characteristic of the process unit treated. It can be an area (typically for heat exchangers), a mechanical power, a pressure ratio or a temperature.

Hybrid Multi-objective optimisation method

The approach presented in this paper can use both genetic (GA) and conventional semi-Newton optimisation algorithms. GA's are very useful to explore an extremely large solution space, since they can

easily handle first degree discontinuities and multiple local minimums. Their weakness is that they ask a lot of computational time and they can't ensure convergence, since they don't compute objective function's first derivative. Conventional optimisation methods based on semi-Newton algorithm offer the guarantee of convergence (if there is one) with a limited number of iterations. Unfortunately, these algorithms are extremely sensitive to the slope of the objective and they are limited to the research of local minima.
Coupling GA with conventional optimisation allows reducing computational time and ensures convergence. In our work we used advanced GA developed at LENI (MOO) [7],[13] exploiting clustering and multi-objective functions. The usage of integer variables allows studying several technological alternatives leading to the creation of different solution's families. The optimisation of several objectives functions like exergetic efficiency, cost, environmental impacts, leads to the generation of a Pareto curve which is a powerful information support for decision making considering mature and new technologies. In the hybrid approach, the members of the Pareto curve are optimised along the two objectives (the other being considered as a constraint) so that the Pareto curve is pushed to its frontier.

CASE STUDY - ADVANCED NGCC WITH CO_2 CAPTURE

For demonstration purposes, we choose to study the performance of an advanced natural gas combined cycle based on the zero-emission gas turbine (AZEP) developed by Alstom [6]. This cycle combines a conventional 3-stage steam turbine with reheat and a modified gas turbine allowing CO_2 capture. Modifications concern the combustor: the conventional combustion chamber has been substituted with a system composed of two heat exchangers and an oxygen separation membrane (OTM) [6]. Figure 3 shows the concept. After compression, air is preheated to the membrane working temperature (between 800 and 900°C) and oxygen is partially captured. The remaining air is then heated and finally expanded in the turbine. Since depleted air does not participate in the combustion, there is no additional water in the flue gases and therefore it can be cooled down to the ambient temperature. The separated

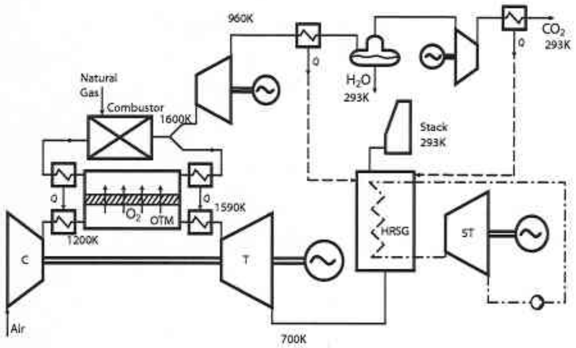

Figure 3: AZEP combined cycle layout

oxygen is recovered in a recirculation loop containing CO_2 and steam and burned with methane. The combustion in the absence of N_2 eliminates concerns about NO_x formation. Combustion gases are partially recycled in the loop and partially sent to the CO_2 capture system. The latter flow is expanded in a turbine down to ambient pressure and then cooled down in order to almost completely condense water. Since the gas phase is composed of CO_2 and water, it is possible to separate the CO_2 by condensation and recover it by pressurising it to about 100 bars and cooling it down to 25°C in order to be transported to its storage place [1].
This cycle is very interesting from the point of view of energy integration, because there are several hot streams that can be used to heat up steam in the heat recovery steam generator (HRSG). Since the network structure is not known a priori, energy integration allows creating the optimal one.

Advanced zero-emission power plant (AZEP) gas turbine

The AZEP gas turbine developed for this study is extremely simplified (Figure 3): the compressor has an isentropic efficiency of 88%, the turbine 93%, combustion is assumed complete, natural gas is composed by pure methane and air is 78%N_2 and 22%O_2. Heat exchangers have a global heat exchange coefficient of 1 kW/°C$/m^2$. The oxygen separation membrane is assumed ideal, i.e. it is possible to separate as much oxygen as needed; membrane area and cost are backward calculated. Stack temperature is fixed at 25°C. Heat exchanges performed in the membrane zone are directly computed in the process flow model, i.e they are not considered for energy integration.

CO_2 capture system

Combustion gases which are not recycled are expanded in a turbine and then cooled down to 25°C in order to condense water, which is separated in a liquid/gas separator. The gas phase, composed by more than 99% of CO_2 is then pressurized with a compressor up to 100 bar, and then cooled down to 25°C in order to be liquified. Turbine efficiency is 90% and compressor efficiency is 80%.

Steam network

The steam network model is entirely developed in the energy integration model, using the technique explained in [11]. The concept is related to the definition of a superstructure made by combining Rankine cycles that define one hot stream, one cold stream, one mechanical power by steam expansion and one mechanical power consumption for liquid pumping. Both counter pressure and condensing pressure turbines are considered. Knowing the temperature and pressure levels, the thermodynamic state of the hot and cold streams are computed as well as the mechanical power productions and consumptions. There are two types of streams: steam production and steam condensation. The former can be represented as cold streams by choosing steam pressure and starting/ending temperature. the latter are modelled in the same way as headers, but they are hot streams, since they need to be cooled down. Finally, a steam network can be modelled in the energy integration software by using an assembly of three elements: steam headers (for collecting and distributing steam), extraction ports (to extract steam form the turbines) and one condensation level (representing the return to the deaerator), each one being associated with an integer variable. The superstructure being built to represent all the possible interconnections between the headers.
The main advantage of this way of modelling the steam network is that it is possible to build a very complex steam network by assembling the base elements and to let the software choose the optimal configuration. At each model evaluation, the software performs a MILP (Mixed Integer Linear Programming) optimisation over all the streams appearing in the process and will choose the configuration that best fits the objective function. In this way, the optimal flowrate of each stream of the steam network is computed and some of the headers or extraction ports will be turned off (flowrate equal to zero) and the complex initial configuration will be simplified. The mathematical modelling of the steam network is based on the definition of one or more steam headers and one or more condensate headers. Steam headers can receive steam from four different sources: from an external source (e.g. from the process), from a previous steam header (i.e. from an header with higher pressure), from a condensate header or from an expansion turbine placed between the actual header and a previous one. Symmetrically, a steam header can distribute steam to four kinds of outlets: the exterior of the steam network (e.g to the process), to one of the downstream steam headers, to one of the following condensate headers or to an expansion turbine. Since an header is defined by a pressure and a temperature, it is possible that an expansion from a header A to the pressure of a header B will not provide the corresponding temperature defined for the header B. In order to maintain consistency in the steam network model and to valorize the expansion (which allows extraction of mechanical power from the turbine), the temperature difference is compensated by injecting into header steam coming from either the previous steam header or the condensate header which follows. with this procedure the solution of the MILP optimisation consist in the choice of the headers to be used (integer variables) and their flowrates. The steam network developed for the model presented in this paper is composed by three steam headers, and five steam condensing levels. Steam can be extracted from one of the steam headers, superheated and re-injected in the steam network. This is equivalent to a reheat system. The corresponding steam turbine is a three-stage turbine with one reheat and four extractions. This is the most complex configuration that the energy integration software can select.

Thermo-economic model

The thermo-economic model is based on the investment cost functions of the following equipment: air compressor and turbine, combustion chamber, combustor heat exchangers, oxygen transport membrane, CO_2 compressor and turbine, HRGS heat exchangers and steam turbines system.

Compressors [14]:

$$C_C = \frac{f_{M\&S}}{1069.9}\frac{C_{C,r}}{0.95-\eta_C}\dot{m}_{C,r}(\frac{\dot{m}_C}{\dot{m}_{C,r}})^{0.7}\pi_{C,r}\ln(\pi_C)$$

Turbines [14]:

$$C_T = \frac{f_{M\&S}}{1069.9}\frac{C_{T,r}}{0.94-\eta_T}\dot{m}_{T,r}(\frac{\dot{m}_T}{\dot{m}_{T,r}})^{0.7} \cdot \ln(\pi_T)(1+e^{0.025(T_T-1570)})$$

Combustion Chamber [14]:

$$C_{CC} = \frac{f_{M\&S}}{1069.9}\frac{C_{CC,r}}{|0.995-\pi_{CC}|}\dot{m}_{CC,r}(\frac{\dot{m}_{CC}}{\dot{m}_{CC,r}})^{0.7} \cdot (1+e^{0.015(T_{CC}-1540)})$$

Heat exchangers [3]:

$$C_{HX} = \frac{f_{M\&S}}{1069.9}\cdot C_{HX}(A_{HX})^{0.7948}$$

The energy integration of the process computes the overall area of the heat exchangers network and gives the minimum number of heat exchangers to respect the minimum energy requirements. With these two values it is possible to estimate the average area and the minimum number of the heat exchangers. The cost of the heat exchangers is then estimated by assuming identical heat exchangers.
Oxygen Transport Membrane [5],[4]:

$$C_{OTM} = \frac{C_{OTM,r}\cdot \dot{m}_{O_2}}{0.0022(P_{O_2})^{0.25}e^{-72000/RT}}$$

The membrane cost (c_{OTM}) is estimated on the basis of a guest future commercial price. For this reason $f_{M\&S}$ is not used.

Steam Turbine with alternator [14]:

$$C_{ST} = \frac{f_{M\&S}}{1069.9}1.15\dot{E}_{ST}\cdot C_{ST,r}(\frac{\dot{E}_{ST}}{\dot{E}_{ST,r}})^{0.7}$$

Multi-objective optimisation

The optimiser used for this case study is MOO (Multi-objective Optimiser, [7], [13]), developed at LENI. Two objectives are defined for the problem: maximising the efficiency of the combined cycle and minimising the specific cost of the installation ($\$/kWe$). Twenty decision variables have been defined. They are resumed in Table 1.

Decision variable	Range
Gas turbine press. ratio	15 - 45
OTM inlet temp.[1]	1050 - 1200 K
Oxygen sep. ratio[2]	0.2 - 0.6
OTM outlet HX ΔT[3]	30 - 100 K
Combustor outlet temp.	1500 - 1600 K
Steam head. press.	1 - 100, 1 - 50 100 - 160 bar
Steam head. superheating	0 - 400, 0 - 500 100 - 400 K
Condensate head. press.	2x 1 - 10, 1x 1 - 100 1x 0.020 - 0.025, 1x 0.020 - 1
ΔT multiplication factor[4]	1 - 3

[1]Inlet temperature of the air entering the OTM's heat exchanger

[2]Ratio of of oxygen molar flowrate captured by the OTM

[3]Temperature difference between air entering the OTM heat exchanger and recycling gases entering the combustor (See fig. 3)

[4]ΔT is defined for each stream depending on its thermodynamic state (liquid, gas,two-phase). The multiplication factor optimised here allows amplifying the ΔT_{min} defined by default.

Table 1: Definition of the decision variables and their range

Results

Pareto curve

The Pareto curve allows showing the relationship between the two objectives of the optimisation. It represents the frontier of the solution space, separating feasible and infeasible solutions. In the application, it defines the best specific cost for a given efficiency or, symmetrically, the best efficiency which can be obtained for a given specific cost. The Pareto curve obtained for the optimisation of the AZEP combined cycle is shown in Figure 4. Since clustering has been used to keep local minima alive, the different markers in Figure 4 represent the different families of solutions obtained. It is possible to see that the cluster represented by the square marker is performing a little bit worse in terms of efficiency than the other clusters.
The best performance that can be obtained with the AZEP combined cycle is about 62%, which puts the cycle in direct competition with the best conventional combined cycles and with the new CC's, like gas turbines with fuel cells.

Solutions analysis

Two solutions are detailed in Table 2 : solution A represents the lower specific cost configuration; solution B is the one which gives the best efficiency.

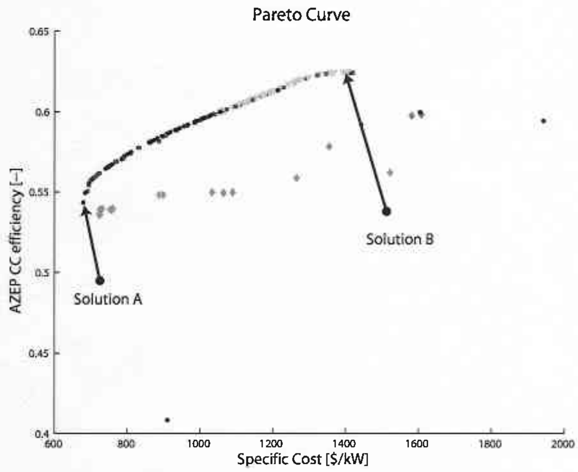

Figure 4: Pareto curve of the multi-objective optimisation

	Solution A	Solution B
Gas Turb. press. ratio	18	41
OTM inlet temp.	1200 K	1200 K
Oxygen sep. ratio	21.8%	31.2%
OTM outlet HX ΔT	100 K	97 K
Combustor out. temp.	1600 K	1600 K
Steam head. press.	101 bar	102 bar
	14 bar	13 bar
	2 bar	1 bar
Steam head. superh.	357 K	365 K
	311 K	214 K
	283 K	290 K
Condensate head. press.	0.021 bar	0.020 bar
ΔT multiplication factor	1	1
Specific Cost	690 US$/kW	1404 US$/kW
Efficiency	55.1%	62.5%

Table 2: Best solution of the optimisation

The layout of the two solutions is extremely similar. The only consistent difference is given by the gas turbine pressure ratio and the oxygen separation rate. Higher ratios lead to better performances but also to higher specific cost. A comparison between Table 1 and Table 2 shows that some variables (OTM inlet temperature, OTM outlet heat exchanger ΔT and combustor outlet temperature) are pushed to their upper bounds, which means that performances will increase when the ceramic technology will accept higher temperatures. The steam network resulting from the optimisation is very simple: 3-stage steam turbine. Reheat is not selected. Compared to conventional steam network, where several steam extractions and reheat are necessary to ensure a good performance, this simplified configuration allows money saving, which compensate the cost of the OTM. Figure 5 shows the integrated composite curve of the steam network. The slope change of process streams at high temperature (around 700 K) is due to the difference of temperature between the expanded CO_2-steam stream and the depleted air from the turbine (the first temperature is 260K higher). It is ideal to integrate steam superheating and to minimize exergy losses. Cooling down streams to 25°C ensures heat availability to preheat water and avoids low pressure steam extractions. From the figure, it can be seen that heat remains available from 75°C to 25°C for district heating, if necessary.

It should be noted that the excellent efficiencies obtained with our model can be partly explained with the following assumptions: the default ΔT_{min} defined for the HRSG (16K for gas-gas heat exchanges, 8K for liquid-gas and 4K for liquid-liquid) allows to increase the efficiency of the plant by 1-2%; the steam superheating of 365K for the high pressure steam header is also critical for conventional HRSG.

The method presented in this paper shows nevertheless that the integration of the hot streams of condensing water are extremely useful to improve the combined cycle performances: taking Solution B as reference, we obtain 62.5% of efficiency. If the temperature at stack is limited to 120°C, the performances are limited to 61.9%. If the heat recovery of the CO_2 separation system is limited to 120°C, the efficiency goes down to 60.9%, because it becomes necessary to introduce steam extraction in the cycle. Finally, if the CO_2 separation system is not integrated in the HRSG, performances fall to 56%. If the steam network is not implemented, the efficiency of the AZEP gas turbine plus the CO_2 system is 46%, and the efficiency of the AZEP gas turbine alone is 37%. The latter value is similar to the results published in [6], where the CO_2 capture system is not considered for power production.

CONCLUSIONS

The optimisation framework based on the coupling of process flow modelling and energy integration, is extremely useful to study complex superstructures and identify promising process configuration at early stage of design. The multi-objective optimisation performed with genetic algorithms combined

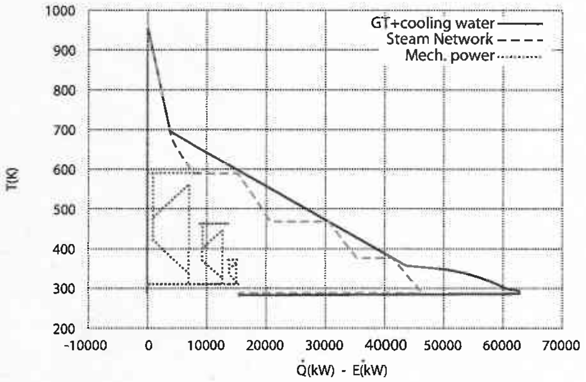

Figure 5: Optimal steam network for the AZEP combined cycle

with conventional optimisation method is ideal to handle multiple decision variables generating non-linear objective functions. Clustering techniques allow the simultaneous study of several promising solutions. The approach is very useful to explore new energy conversion technologies and combined cycles and to generate complex superstructures with unknown heat exchangers network. This is the case of fuel cells, thermal solar energy, organic Rankine cycles, biomass conversion or hydrogen production, to cite a few examples. In this approach, the heat exchangers network is a solution of the optimisation and its structure can be optimally designed thanks to energy integration when optimised configuration and operation of the other energy conversion units are decided.

In the application, the CO_2 capture, which represents a cost increase for conventional NGCC, becomes an interesting option for AZEP combined cycles: the availability of heat down to the ambient temperature allows an significant simplification of the steam network with an increase of performance of the combined cycle. When OTM technology will be mature enough to be commercially competitive, AZEP combined cycles will become a valid alternative in the energy conversion market.

REFERENCES

[1] S. Anderson and R. Newell. Prospects for carbon capture and storage technologies. *Annual Review of Environment and Resources*, 29:109–142, 2004.

[2] Belsim. http://www.belsim.com.

[3] R. Bolliger. Développement d'une méthodologie pour la conception et l'optimisatin thermo-économique de cycles thermodynamiques avancés. Master's thesis, Ecole Polytechnique Fédérale De Lausanne, 2004.

[4] H. Bouwmester and A. Burggraaf. *The CRC handbook of solid state electro-chemistry*, chapter Dense ceramic membranes for oxygen separation, pages 481–553. CRC, Boca Raton, 1997.

[5] R. Bredesen and J. Sogge. A technical and economic assessment of membrane reactors for hydrogen and syngas production. In *Seminar in the Ecological Applications of Innovative Membrane Technology in the Chemical Industry, Cetraro, Calabria (Italy)*, 1996.

[6] T. Girffin and et al. Advanced zero emission gas turbine power plant. In *ASME Turbo Expo*, June 2003.

[7] G. Leyland. *Multi-objective optimisation applied to industrial energy problems.* PhD thesis, Ecole Polytechnique Federale de Lausanne, 2002.

[8] H. T. Li, M. Burer, Z. P. Song, D. Favrat, and F. Marechal. Green heating system: characteristics and illustration with multi-criteria optimization of an integrated energy system. *Energy*, 29(2):225–244, 2004.

[9] B. Linnhoff, D. Townsend, and et al. A user guide on process integration for the efficient use of energy. *The Institution of Chemical Engineers*, 1982.

[10] F. Marechal and B. Kalitventzeff. 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.

[11] F. Marechal and B. Kalitventzeff. Targeting the optimal integration of steam networks: Mathematical tools and methodology. *Computers and Chemical Engineering*, 23:S133–S136, 1999.

[12] F. Marechal, F. Palazzi, J. Godat, and D. Favrat. Thermo-economic modelling and optimisation of fuel cell systems. *Fuel Cells : From Fundamentals to Systems*, 2004. In Press.

[13] A. Molyneaux. *A practical evolutionary method for the multi-objective optimisation of complex integrated energy systems including vehicle drivetrains.* PhD thesis, École Polytechnique Fédérale de Lausanne, 2002.

[14] S. Pelster. *Environomic Modeling and Optimization of Advanced Combined Cycle Cogeneration Power Plants including CO_2 Separation options.* PhD thesis, École Polytechnique Fédérale de Lausanne, 1998.

[15] S. Pelster, M. von Spakovsky, and D. Favrat. 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, 2001.*, Vol.123(4):pp.717–726, 2001.

[16] R. Turton. *Analysis, Synthesis, and Design of Chemical Proceses.* Prentice Hall, 2003.