High efficiency Trigeneration systems in integrated energy systems

François Maréchal
Industrial Energy System Laboratory (LENI)
Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Abstract

A systematic method has been developed to study the integration of polygeneration systems in industrial processes and/or urban systems. Several aspects are analyzed with a holistic vision. For given system's boundaries, the energy services and energy requirements are first characterized. This requires the analysis of the different services and production operations needed. In an industrial process, the process requirements are considered by looking at therequirement of the process unit operations. Having identified the possible heat recovery by heat exchange using a pinch analysis, the Grand composite curve defines the energy services to be supplied. This defines a set of energy conversion units that are used to convert the energy resources into useful process energy.

The use of mixed integer linear programming techniques based on pinch analysis and mass integration constraints is used to model the optimal integration of the system. It selects the energy conversion unit options, optimizes the value of the flows in the system and optimizes the efficiency of the integrated energy conversion system. This leads to the definition of the overall system balance whose inefficiency is evacuated from the system in the form of heat that could be valorized.

Based on an example from the food industry, it is demonstrated how the combination of cogeneration, heat pumping and mechanical vapor compression can be used to increase the energy conversion efficiency of the process.

1 Introduction

In a given socio-economic and environmental context, energy is the driving force of the development. The role of the energy systems is to convert the available renewable and non renewable resources into useful products and energy services. The efficiency of the energy use highly relies on the amount and of the quality of energy requirement (i.e. the exergy), but also on the quality of the conversion system and its ability to satisfy the different energy requirements. Understanding the system's integration is therefore a critical issue when engineers have to design efficient systems.

In industrial systems, the energy is the main driver used to deliver the services. To do so the energy resources have to be converted into useful energy for the system. The useful energy is defined as heat, cold or electricity. In most of the systems, each requirement is produced by a specific unit like boiler, refrigeration cycle and the electrical grid.

Trigeneration systems aim at producing simultaneously more than one of the energy services required in a given system, the efficiency of such integration is therefore mainly defined by the quality of the system integration.

The design of trigeneration system is often based on the definition of the energy requirement. It is important to follow a systematic methodology in order to define the best system design. In the following example, we are discussing the integration of a trigeneration energy conversion system in a brewing process.

2 Process integration and trigeneration

The first step of the methodology is the definition of the energy requirement. In an industrial process, the energy requirement is defined by the set of streams to be heated up and cooled down. The definition of the requirement is obtained from a process model in which the process units are calculated in order to define the hot and cold streams enthalpy-temperature profiles. The details of the analysis are presented in [13], the focuss being here to comment on the integration of the trigeneration system. This analysis results in the definition of the hot and cold composite curve of the process (Figure 1) that allows one to calculate the possible heat recovery by heat exchange between process streams. Resulting from the heat balance of the process requirement, the hot and cold composite define also the heating and cooling requirement of the process. The calculation of the Grand composite curve (Figure 2) defines the enthalpy-temperature profile of the heating, cooling and refrigeration requirement. Resulting from the pinch analysis, the heat recovery potential corresponds to 1143 kW i.e. 45 % of the actual consumption. This also corresponds to more or less doubling the present heat exchange recovery.

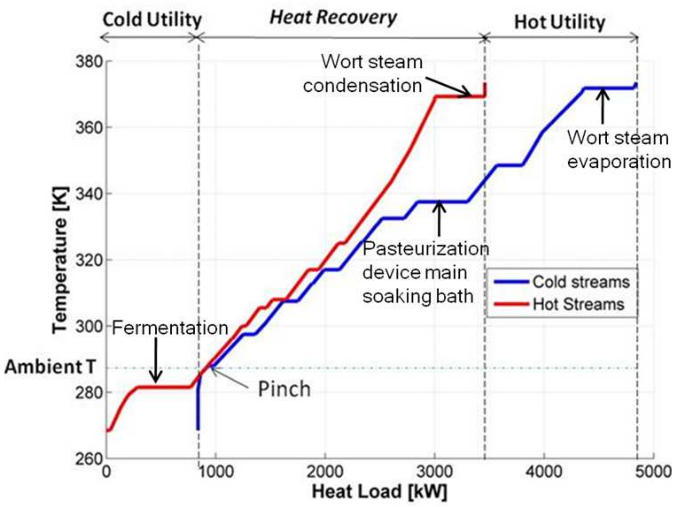

Figure 1: Hot and cold composite curves of the process

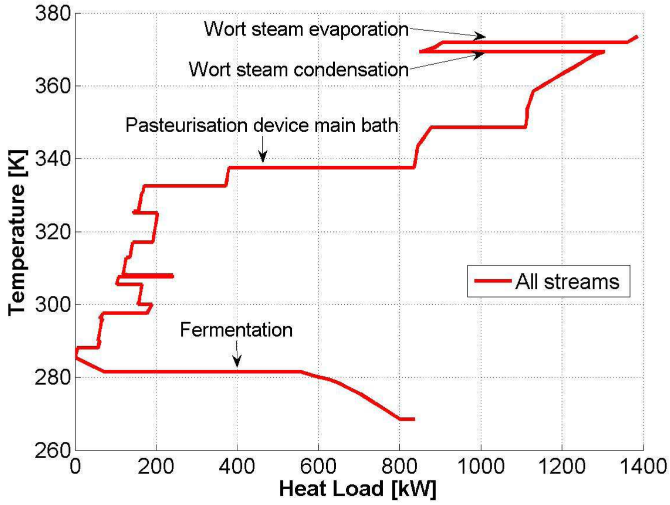

Figure 2: Grand composite curve of the process

The analysis of the energy requirement leads to the following conclusion

• The pinch temperature (T_{pinch} =12.5°C) corresponds to the inlet conditions of the process water and therefore also to the cooling water conditions. The pinch temperature therefore also defines the refrigeration temperature limit.

• A refrigeration system is needed below the ambient temperature to satisfy the refrigeration requirement

• The maximum temperature of the system corresponds to the evaporation of the wort a little bit above 100 °C.

• A self sufficient zone corresponds to the recovery of the evaporated steam to preheat the process water.

• The process could be fed by a cogeneration engine.

• The pinch location shows the possible integration of a heat pump system that could produce the refrigeration requirement and, in the same time, deliver useful medium temperature heat.

3 Integration of the utility system

Calculating the utility system integration aims at defining the best way to supply the process requirement using distributed energy resources. The calculation of the utility system is based on a MILP formulation ([16]) that will calculate the optimal flows of the utility streams.
The utility integration method proceeds in three steps :

• Based on the analysis of the Grand Composite curve, define the list of the possible utility streams and utility cycles and to calculate the properties (i.e. enthalpy-temperature profiles and the mechanical power production/consumption) that are associated with each utility stream.

• Using optimization model : select in the list of the utility streams the one that will at best satisfy the requirement and calculate the flows of each of the streams of the utility system in order to obtain the balanced composite curves with the lowest operating cost. This defines the complete list of streams in the system to design heat exchanger network that will concern not only the process streams but also the utility streams.

• Analyze the obtained composite curves to verify that the list of optional utility streams is complete and that the operating conditions of the utility streams is optimal. If not, go back to step 1. The integrated composite curves concept presented in [15] is an interesting way of visualizing and analyzing the integration the utility sub-systems. In additional, working with the Carnot factor dimension to draw composite curves ([12, 14]) allows to have an attractive indicator to graphically optimize the choice and the operating conditions in the utility system. When several option exist, choosing the refrigerant, the cycle configuration and the operating conditions may require the use of optimization techniques (e.g. [10]).

It should be mentioned that the utility integration method integrates the constraints of the heat cascade and therefore assumes that the process heat recovery will be realized together with the utility system integration. This is important since it allows to avoid oversized utility systems that would prevent further energy savings investment.

The present system

In the present system, a boiler fed with natural gas is currently generating steam at high pressure (8.5bar) that is distributed to the process at a lower pressure (2.2bar/123.3°C). The refrigeration requirement is satisfied by a NH_3-refrigeration cycle with two evaporation levels, at -4°C and -8°C. The cooling requirement is satisfied by cooling water. The integration results are presented on figure 3 using the integrated composite curve of the utility system. The utility streams are represented by the line “brewery_utility” and the process requirements correspond to the grand composite curve “Others”. The mechanical work supplied to compressors (heat pump and refrigeration cycle) is represented by the line “Mech. Power”. It can be observed that this situation in addition of realizing the process heat recovery already realizes heat recovery form the refrigeration system and therefore corresponds to an attractive energy saving. However, the major part of the refrigeration cycle hot streams is removed by the cooling water and evacuated to the environment. In the integrated solution, the refrigeration cycles consumes 184 kWe. This corresponds to a reduction of 225 kWe (56%) of the present mechanical power consumption of the refrigeration cycle. This is mainly explained by the fact that in the present situation, the refrigeration cycle is used in penalizing heat exchangers that use the refrigeration cycle to cool down stream above the cooling water temperature. Reaching the minimum cycle consumption requires therefore to identify the penalizing heat exchangers through the cooling water temperature.

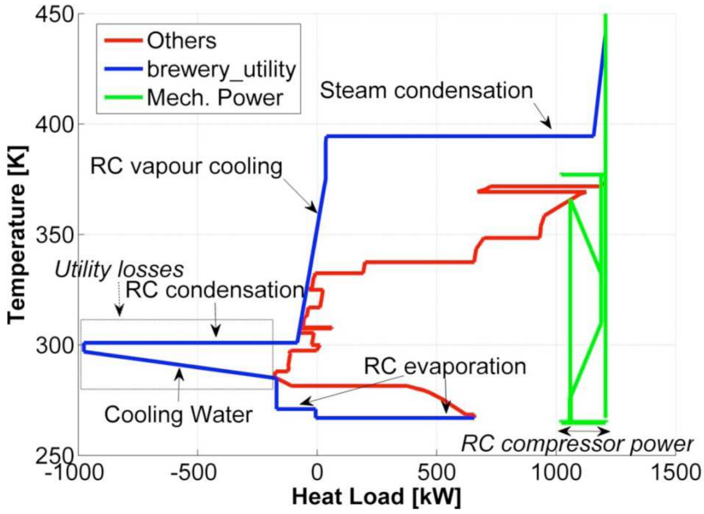

Figure 3: Current Utility Setup: Boiler & Refrigeration Cycle (RC)

Improvement of the utility system integration

The analysis of Figure 3 reveals that the current utility configuration could be improved by replacing the high temperature steam used in the process by a cogeneration unit that could supply heat at lower temperature while producing electricity. The analysis of the refrigeration cycle integration suggests that the temperatures at which the heat is removed could be optimized
by better staging the refrigeration requirement and by increasing the temperature of the -4 °C level to be closer from the 5 °C temperature of the requirement. In addition, applying the rules for the proper integration of heat pumps, it can be suggested to increase the condensation temperature of the refrigeration cycles in order to create a heat pumping effect. As the COP of the refrigeration cycle depends on the compression ratio and therefore of the temperature lift in the cycle, several condensation levels will be assessed. For each combination of condensation/ evaporation levels, the NH3 cycle is calculated and a collection of cycles is added in the utility sub-systems list.

Description	T_{in} [°C]	T_{out} [°C]	ΔTmin	Power [kW]	Efficiency[%]
M_{fuel} [kWe LHV]				2605	
W_e [kWe]				1063	40.8
Q_{th} [kW]				1190	46.0
Q_{Gas} [kW]	470	120	15	537	21.0
$Q_{Cooling}$[kW]	87	80	5	653	25.0

Table 1: Cogeneration unit characteristics based on GE-Jenbacher data, power range : 500-1100kW (http://www.gejenbacher.com)

Cogeneration system integration

A reciprocating engine appears to be an adequate technology : it has a attractive electrical efficiency and it is possible to recover heat from both exhaust gases and cooling water. Table 1 shows the characteristics of the cogeneration engine using natural gas as fuel. Figure 4 shows the result of the cogeneration engine integration, the exhaust gases enable wort evaporation (T^{sat}=373K), whereas the engine water cooling provides heat to the process streams below 360K. The power production corresponds to 1047 kWe in the integrated situation, the mechanical power will be used to drive the refrigeration cycle compressors (184 kWe). This results in a net production of electricity that can be exported to the grid or used for other usage in the process.

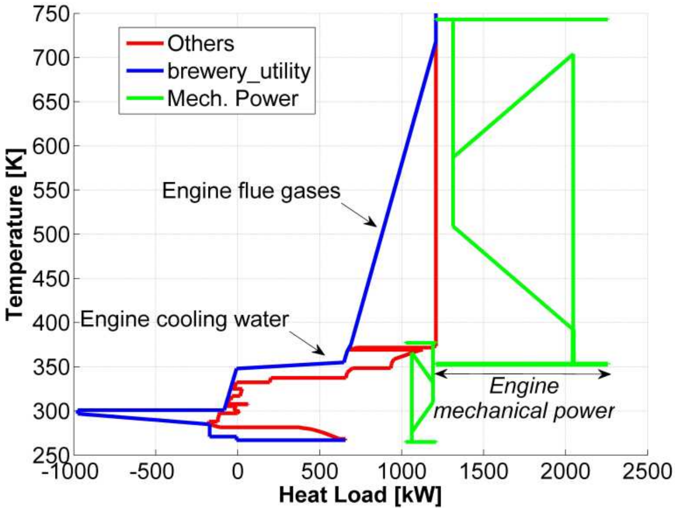

Figure 4: Boiler Replaced with a CHP System

Heat pumping system integration

Below the ambiance, it can be seen that the refrigeration cycle temperature could be optimizedin order to better use the intermediate refrigeration level. From the analysis of the Grand composite curve (Figure 2), it appears also important to try to create a heat pumping effect by the integration of the refrigeration cycle. This is realized by increasing the condensation temperature of the cycle. However as the flow of the combustion gases of the cogeneration engine creates a utility pinch point (Figure 4) that defines the fuel flow, an MVR system using the steam produced during the wort evaporation will allow for a better system integration. The scheme of the mechanical vapor recompression is schematized on figure 5. This will allow to reduce the high temperature heat requirement and therefore reduce the size of the cogeneration engine, allowing for high temperature heat pumping by recovering the condensation heat of the refrigeration cycle for process preheating.

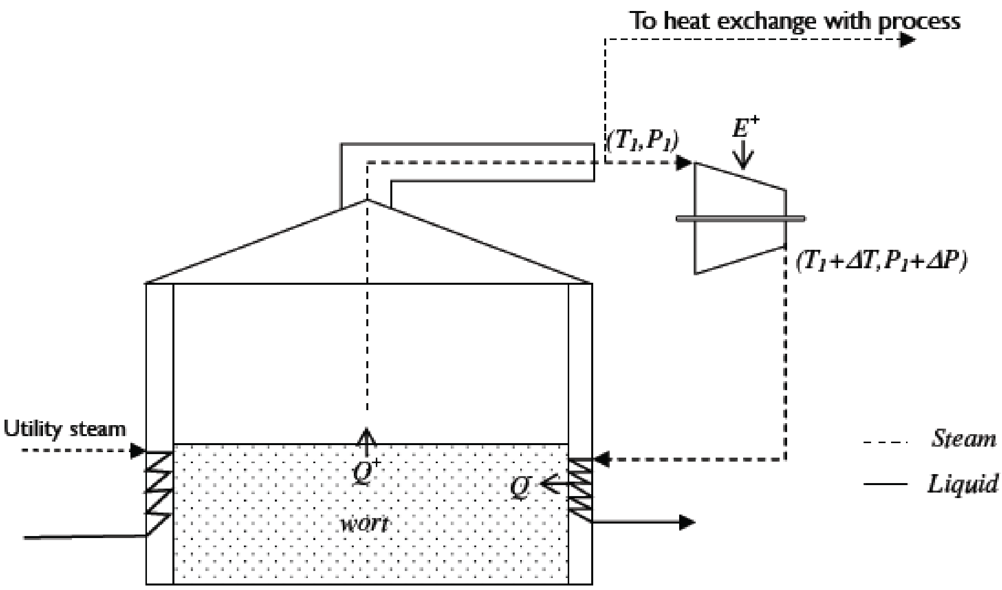

Figure 5: Mechanical vapor on the wort evaporation

As the heat of the vapor condensation is a priori also useful to satisfy process needs (self sufficient zone on figure 2), only the useful part of the MVR has to be calculated. This is done by introducing a decision variable that represents the amount of recompressed vapor.

The choice of the heat pump operating conditions defines the temperature at which the heat will be made available and therefore the amount of heat that will be useful for the process. As a function of the selected level, the other utility flows will be updated by optimization.

Two heat pumps with an evaporation at 6°C(299K) and with respectively 66.5°C(340K) and 77.5°C (351K) condensation temperature are proposed and compared.

The second refrigeration cycle produces cold at -6 °C(299K) and optional condensing temperatures at 45 °C(318K) and 50 °C(323K) are considered.

The results of the optimised configurations, including the integration of MVR and heat pumping systems, are presented in Figures 6 and 7.

It can be seen a clear reduction of exergy losses: utility temperatures are as close as possible to the temperatures of the process energy requirements. One can also observe a drastic reduction in utility losses: for the case where the heat pump condenses at 77.5 °C (351K): the external cooling water requirement is close to zero, indicating that the overall refrigeration heat is used as a source for satisfying the process heat.

Table 3 presents the results of the different utility integration solutions. The economical performances are calculated considering the value of energy and the CO2 emissions for the electricity data given on table 2.

Combined with the heat recovery, the advanced trigeneration system offers an energy saving of up to 60 %, while reducing the electricity import by the same amount. It is important to realize that the optimal solutions depends on the equivalent CO2 content of the electricity mix. In a country like Germany with heavy loaded electricity, the solutions with cogeneration only

Energy / Resource	Unit Cost 2007 (Without taxes Taxes)	CO_2 Emission
France		
Electricity	0.0541 €/kWh_e	55$g_{CO2/kWhe}$
Natural Gas	0.0271 €/kWh_{LHV}	231$g_{CO2/kWhLHV}$
Water	0.00657 €/m^3	-
Germany		
Electricity	0.0927 €/kWh_e	624$g_{CO2/kWhe}$
Natural Gas	0.0417 €/kWh_{LHV}	231$g_{CO2/kWhLHV}$

Table 2: Cost data and CO2 emissions for the electricity mix

	0	**1**	**2**	**3**	**4**
Natural Gas [kW]	3133	2088	3279	1677	1140
Electricity [kWe]	465	184	-863	-80	212
Water [kg/s]	32.0	17.1	17.1	3.2	0.2
Run. Cost FR [kd/yr]	580	332	210	205	212
Run. Cost GER [kd/yr]	910	520	283	312	336
TOTAL Cost FR [kd/yr]	580	332	308	274	274
TOTAL Cost GER [kd/yr]	910	520	380	381	398
TOTAL CO_2 FR [ton/yr]	3767	2459	3544	1912	1372
TOTAL CO_2 GR* [ton/yr]	5277	2987	1094	1686	1976

Table 3: Summary of the results

0:reference
1:Heat recovery and boiler
2:Heat recovery and cogeneration engine
3:Heat recovery, cogeneration, mechanical vapor recompression and heat pump at Tcond=66.5°C
4:Heat recovery, cogeneration, mechanical vapor recompression and heat pump at Tcond=77.5°C
Total Yearly Costs = Operating Costs+Annualised Investment (interest rate=5%, payback time=15 years)

appears to be the best solution. Thisjustifies by the substitution of the exported electricity from the grid. In a country like France, in contrary, the best solutions are the one integrating the heat pumps allowing to reduce the CO2 emissions by 64%. It is important to realize that the heat pumping and MVR solutions only justifies when these are considered together with the cogeneration unit. Adopting a holistic vision is therefore important since it may be related to considerable different investment. For example, the size of the cogeneration unit of solution 2 is of about 1400 kWe, while in the solution 5 with heat pumping, the cogeneration engine has only 467 kWe, i.e. 30% of solution 2.

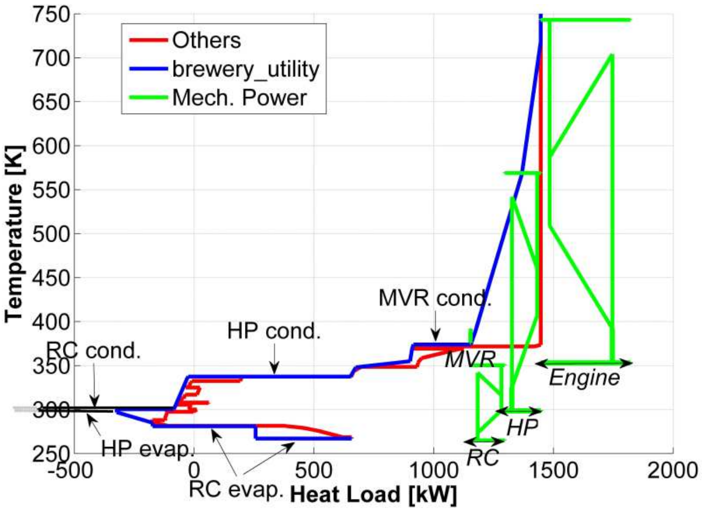

Figure 6: CHP System+MVR, Heat Pump Condensing at 66.5°C, COP=5.37 (solution 4)

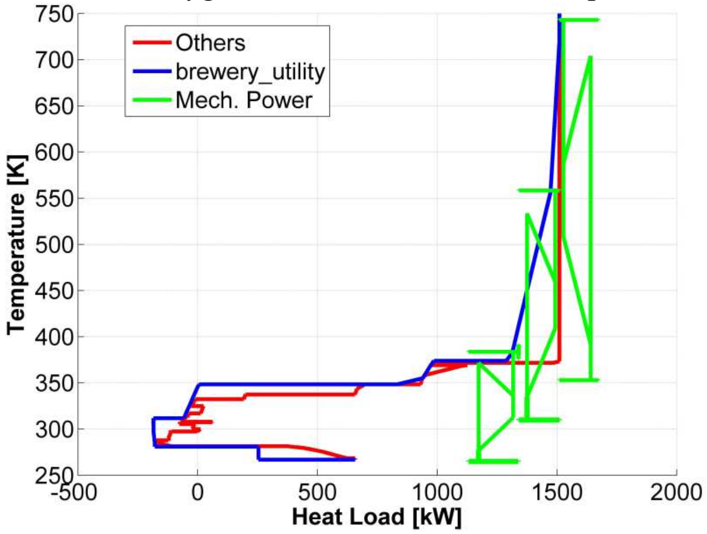

Figure 7: CHP System+MVR, Heat Pump Condensing at 77°C, COP=5.71 (solution 5)

4 Perspectives of the integration of the trigeneration system

The approach presented above is based on the time averaging approach that allows to consider that all the streams are simultaneous. Considering the batch operation dimension requires the adaptation of the approach to integrate in the analysis the calculation of the storage tanks that are required to make the heat recovery feasible. When studying the trigeneration system integration, it will be necessary to size the tanks not only to allow the heat recovery but also to take opportunities from the electricity market. The trigeneration system is indeed a way of storing electricity from the grid in the form of heat or cold. The heat or cold storage also allows the cogeneration unit to play the role of the peak shaving. The final configuration is presented on figure 8. The optimization method based on a multi-objective optimization strategy presented by Weber et al. ([17]) allows to design the trigeneration system and the storage tanks considering the use of a predictive optimal management strategy. In addition, methods like the one proposed by Collazos et al. ([11]) can be used to implement the predictive optimal management strategy in a control system.

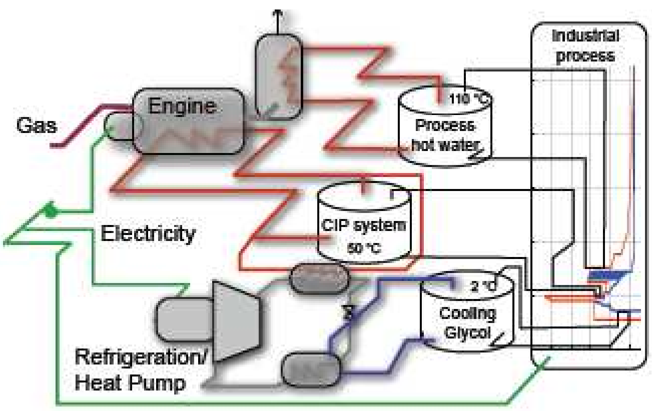

Figure 8: Storage tank system configuration

5 Conclusion

The optimal integration of trigeneration systems is realized in several steps. The first step is the definition of the requirement followed by the definition of the heat recovery potential between the hot and the cold streams of the process. This step is mandatory since it allows to define the heating and cooling requirement to be satisfied by the trigeneration system. Other approaches based on the use of the present utility system would lead to bigger systems and unnecessary investment that would in addition prevent the future energy savings options. The trigeneration system is sized by first identifying the possible trigeneration options based on the analysis of the Grand composite curve of the system. The configuration of the system is then defined by applying an optimization model that calculates the best flows in the system. It has been demonstrated that the proper analysis of the trigeneration system requires to account for the possible integration, not only at the level of the process, but also at the level of the possible integration inside the trigeneration system. The example presented shows that the combination of a refrigeration cycle where the condensation heat is used as a heat pump to preheat the process streams with a mechanical vapor recompression system that allows for utilizing the heat of the cogeneration unit by removing a utility pinch point, allows to reach an energy saving of about 60 %, as well as the corresponding CO2 emissions. The configuration of the trigeneration system is influenced by the value of the electricity mix in equivalent primary energy or of the CO2 emissions. In countries with high value of electricity and high CO2 content, the preferred solution corresponds to the use of cogeneration due to the benefit of the substituted grid electricity. In countries with more attractive electricity prices, highly integrated heat pumping solutions combined with smaller cogeneration units will be preferred.

6 Acknowledgment

The author recognizes here the contribution of Helen Becker and Monika Dumbliauskaite for contributions in [13].

References

[1] ADEME, january 2005, Note de cadrage sur le contenu CO2 du kWh par usage en France.

[2] BECKER, H., MARECHAL, F. and VUILLERMOZ, A., september 2009, Process Integration and Opportunity for Heat Pumps in Industrial Processes, Proc. ECOS 2009: 22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.

[3] LEYLAND, G.B., 2002, Multi-Objective Optimisation applied to Industrial Energy Problems, PhD thesis n°2572, Lausanne: EPFL-STI, Industrial Energy System Laboratory.

[4] LINNHOFF, B., TOWNSEND, D.W. et al., 1994, A User Guide on Process Integration for the Efficient Use of Energy, Institution of Chemical Engineers, IChemE; Revised Sub Edition.

[5] MARECHAL, F., KALITVENTZEFF, B., 1998, Energy integration of industrial sites: tools, methodology and application, Applied Thermal Engineering, 18:921-933.

[6] MOLYNEAUX, A., 2002, A Practical Evolutionary Method for the Multi-Objective Optimisation of Complex Energy Systems, including Vehicle Drivetrains, PhD thesis n°2636, Lausanne: EPFL-STI, Industrial Energy System Laboratory.

[7] MULLER, D., 2007, Web-based tools for energy management in large companies applied to
food industry, PhD Thesis n°3785, Lausanne: EPFL-STI, Industrial Energy System Laboratory.

[8] Observatoire de l´ Energie, august 2007, Prix du gaz et de l'électricité en Europe au 1er janvier 2007, Energies & Matières Premières, Paris.

[9] Umweltbundesamt, april 2009, Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2007, FG I 2.5.

[10] H. Becker, G. Spinato, and F. Maréchal. A Multi-Objective Optimization Method to integrate Heat Pumps in Industrial Processes. In Computer Aided Chemical Engineering series European Symposium on Computer Aided Process Engineering-21, 2011.

[11] A. Collazos, F. Marechal, and C. Gaehler. Predictive Optimal Management Method for the control of polygeneration systems. Comput .Chem. Eng., 33(10):1584–1592, Oct. 2009.

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

[13] M. Dumbliauskaite, H. Becker, and F. Marechal. Utility Optimization in a Brewery Process Based on Energy Integration Methodology. In 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2010), 2010.

[14] F. Marechal and D. Favrat. Combined Exergy and Pinch Analysis for Optimal Energy Conversion Technologies Integration. In ECOS 2005, 18th International Conference on Efficiency, Cost,Optimization, Simulation and Environmental Impact of Energy Systems, Trondheim, Norway, volume 1 of ECOS 2005, pages 177–184, 2005.

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

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

[17] C. Weber, F. Marechal, D. Favrat, and S. Kraines. Optimization of an SOFC-based decentralized polygeneration system for providing energy services in an office-building in Tokyo. Applied Thermal Engineering, 26:1409–1419, 2006. 11