Utility Optimization in a Brewery Process Based on Energy Integration Methodology

Monika Dumbliauskaite [a]**, Helen Becker** [a]**, François Maréchal** [a]

[a] *Industrial Energy Systems Laboratory (LENI), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*

Abstract: This paper presents a methodology aimed at improving the energy efficiency of a brewery applying process integration techniques. The different steps of the analysis are presented. The first step is the identification of the process energy requirements and the corresponding heat loads, which allows the definition of the process hot and cold streams. The Pinch Analysis of the brewery reveals a heat recovery potential of 36% by improving the heat exchanger system. In order to satisfy the minimum energy requirements, optimal energy conversion technology configurations are calculated, taking into account economic and environmental criteria. The integration of suitable utilities is considered (cogeneration engine combined with heat pumping and refrigeration systems) and the interaction between them is analyzed. In addition, a thermo-economic optimization is performed in order to determine the optimal heat pump operating temperatures. The results show the opportunity to reduce by 36% the brewery heating bill and by 44% the CO_2 emissions through the set up of an optimized utility configuration when compared to the current one. In addition, the optimal integration shows that the cooling water consumption of the refrigeration can be suppressed and appropriately be replaced by a heat pumping effect. The comparison between French and German conditions shows that contrasting results can be obtained due to the different economic and energy supply configurations. The process system analysis shows that when considering the recovery of the plant organic waste, bio-methane can be produced and valorized in the cogeneration engine. In that case, it is demonstrated that the process can become self sufficient in terms of energy.

Keywords: process integration, pinch analysis, brewery, thermo-economic optimization.

1. Introduction

Beer production (28Mt in 1999, EU-15) ranks 5th in European food industry and the European beer is widely exported. Breweries use significant amounts of water and energy to produce this fresh and tasty drink. In the current trend of high energy price, energy efficiency improvement of industrial processes represents an important way to reduce production costs. In addition, growing environmental concern encourages companies to consider innovative solutions not only to reduce the carbon footprint but also the water consumptions.

In the Top-Down approach developed by D. Muller et al. [9] for analyzing the energy efficiency of industrial processes in the food industry, Pinch Analysis is used to identify the possible heat recovery by heat exchange between the streams to be cooled down and the streams to be heated up. Pinch Analysis [6] targets the minimum heat requirement of a process through the graphical representation of

the process energy requirements, called *composite curves*, and describes how it is possible to achieve the determined energy targets with a correctly designed network of heat exchangers.

The systemic approach consists of the identification and characterization of the main Process Unit Operations (PUOs). The Top-Down approach [9] shows that more than 80% of the energy consumption can be explained by describing only 20% of the units of a factory. For these important PUOs, models are used to characterize the set of hot and cold streams that are needed to achieve the operation. The choice of the minimum approach temperature ΔT_{min} allowed by the heat exchangers enables the determination of the process Minimum Energy Requirements in heating and cooling. Grand composite curve analysis helps towards identifying opportunities for energy-efficient utility integration to satisfy the energy requirements, such as combined heat and power (CHP) systems or heat pumps (see for example [3]). Optimal utility inte-

gration can be achieved using a Mixed Integer Linear Programming (MILP) formulation, as described by Maréchal and Kalitventzeff [7].

This paper presents the implementation of the process integration methodology on a brewery. The results are presented based on two different scenarios in terms of equivalent CO_2 emissions according to the substitution options of the electricity mix. In addition the methodology will be used to assess renewable energy integration using bio-methanation of the process waste.

2. Pinch analysis of a brewery

2.1. Process Description

The brewery studied corresponds to a typical brewing process. The target temperatures of the streams and the proportions of ingredients are determined by the product recipe. The brewing house is associated with beer production and is split into two parts:

- **a hot part**(*mashing*), described by the block flow diagram of Figure 1, where the blend of water and malt (*Mash*) is firstly brewed at high temperature (76°C) so that the activated enzymes transform malt starch into sugar. The *Mash* is then filtered to obtain the wort, which is boiled with hops to develop beer flavors. Wort boiling is an energy intensive operation. The wort is clarified in a whirlpool to remove the hops and eventually cooled to the pitching temperature.

- **a cold part**, illustrated in Figure 2, mainly consisting of the wort fermentation by yeast, at constant temperature (11°C), during 2 weeks. The beer is then chilled (-2°C) and clarified before being stored in insulated tanks where it ends its maturation.

The rest of the process consists of the beer packaging. In the process under study, four conditioning lines package the beer in new bottles, in kegs and in returnable bottles that are washed beforehand. The bottles filled with beer are then pasteurized.

A Cleaning in Place (CIP) system with effluent recovery, designed to wash the tanks, is also modeled in the study.
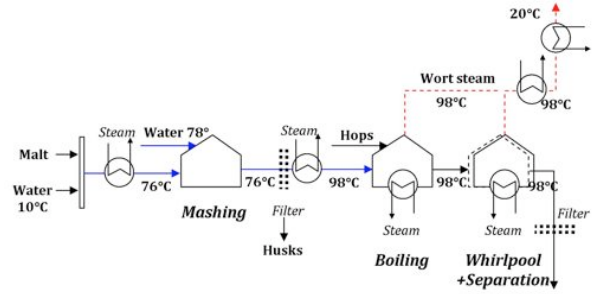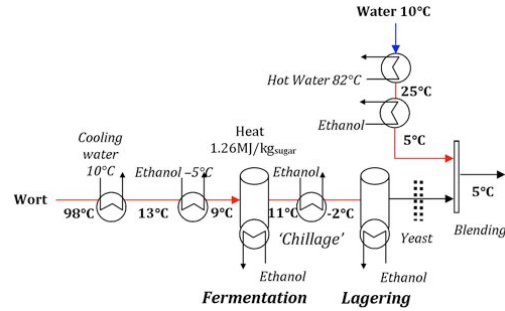

Figure 1: Block Flow Diagram of the Hot Part

Figure 2: Block Flow Diagram of the Cold Part

2.2. Process Integration Assumptions

Table 1: Chosen Values of $\Delta T_{min}/2$

Stream State	$\Delta T_{min}/2$ [Δ°C]
Liquid	2.5
Evaporating	0.8
Condensing	1.7

The Pinch Analysis of the brewery is performed using the following key hypotheses:

- Thermal losses during heat transfers are not taken into account.

- Despite the fact that the units are operated in batch mode, we consider a time averaging approach, where all the process operations are considered as being simultaneous. This is done by calculating the overall energy consumed per unit of product and dividing it by the mean hourly production. The yearly operating time of the brewery is 4992h.

- For each stream, the corresponding $\Delta T_{min}/2$ was chosen according to the existing equipments. The associated values of $\Delta T_{min}/2$ may not be optimal; however they are used in the study, as they correspond with the existing heat exchangers available in the factory.

2.3. Modeling of the Conditioning Lines

The opportunity of recovering heat from the conditioning lines is worth studying, since bottle washing and pasteurization devices represent important energy consumers in breweries. In the process under study, the conditioning lines account for more than 32% of the current heating demand, which reveals the importance of modeling and integrating these units when undertaking the Pinch Analysis of breweries.

As an example, the modeling of the bottle pasteurization device is presented in this paragraph. The device is considered as a sequence of soaking baths transferring their heat to the beer bottles passing through them. The bottles are successively heated and cooled; the baths thus require respectively heating and cooling supplies in order to keep a constant temperature level.

The model considers the different baths at their corresponding temperatures. This representation enables the determination of internal heat recovery potential, as well as between the baths and other process streams.

In the study, permanent regime is considered. The current bottle pasteurization device consists of ten baths maintained at constant temperature levels. The input and output temperatures of the bottles are respectively 8°C/281K and 30°C/303K. The main soaking bath is kept at 62°C/335K.

The computed heat loads of the different baths correspond to the sum of the bottle heat loads and the heat losses to the surroundings (from conduction-convection and from radiation). The composite curves associated with the device can thus be obtained and represented in a $(T - \dot{Q})$ diagram. Figure 3 shows the composite curves corresponding to the device operating on the production line n°4. 40000 bottles of 0.33L/unit are currently pasteurized per hour by the machine.

In Figure 3, the hot streams are associated with the baths in heat excess and the cold ones with those requiring heat. The grand composite curve corresponds to the enthalpy (heat) difference between the hot and cold streams for each temperature interval. In Figure 4, the integration shows the possible heat recovery that can be obtained by transferring hot water from one cooling bath (hot stream at constant temperature) to a heating bath (cold stream at constant temperature).

Figure 3: Bottle Pasteurization Device (Line 4) Composite Curves
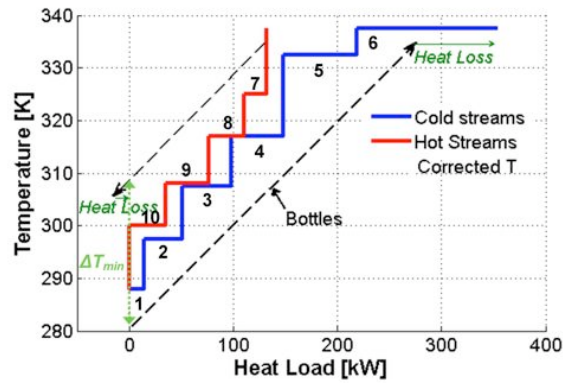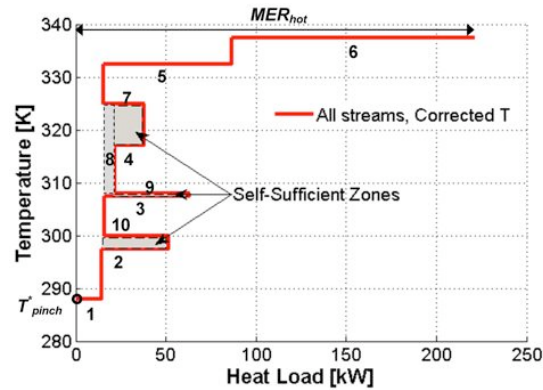

Figure 4: Bottle Pasteurization Device (Line 4) Grand Composite Curve

The chosen value of $\Delta T_{min}/2$ (2.5°C) leads to a pinch corrected temperature T^*_{pinch} =15°C (288.2K), which corresponds to the minimal bath temperature ($T_{pinch,cold}$ = 12.5°C= T^*_{pinch} − $\Delta T_{min}/2$). As a result, the device does not need external cooling, since it is possible to transfer all the heat excess from the hot streams to the cold ones. The chosen value of ΔT_{min} is an optimal one, since it is associated with the minimal MER feasible for the current device (220kW in heating and 0kW in cooling).

In addition, it can be noted that the device heat recovery potential is determined not only by the ΔT_{min}, but also by the number of baths and by their temperature levels. Thus, the bottling system design can be optimized using Pinch Analysis, in particular through the definition of the minimum number of baths and their corresponding volumes that can be expressed as a function of the speed of the bottle processing.

2.4. Process Integration

The process requirements identified for the PUOs are used to calculate the maximum energy recovery in the system. Figure 5 presents the brewery composite curves resulting from the definition of the hot and cold streams identified in the process.

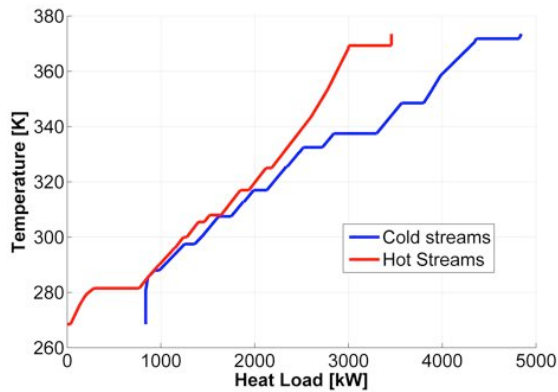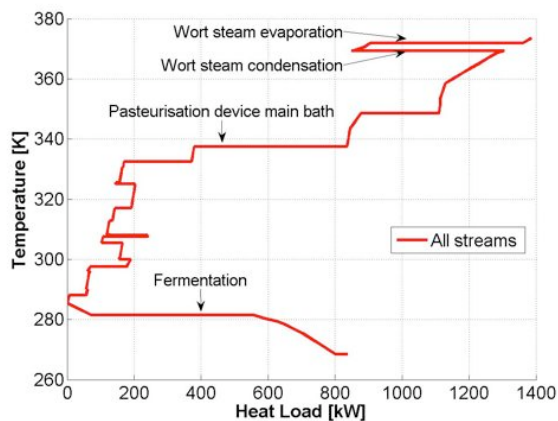Figure 5: Brewery Process Composite Curves

Figure 6: Brewery Process Grand Composite Curve

The first observation that can be established is related to the pinch, detected at the corrected temperature T^*_{pinch} =285.5K (or 12.5°C). The pinch point coincides with the temperature of cold water entering the process at ambient temperature. As a consequence, all the effluents (hot streams) leaving the process at a temperature above the ambient temperature must deliver their heat to the process cold streams.

The computation of the MER for the identified PUOs enables the identification of opportunities for energy saving. The results are shown in Table 2 and reveal a heat recovery potential of **1143kW**. The remaining heating requirements of the Non Identified

Process Units (NIPUs), i.e. 604kW_{th}, are added to define consistently the minimum heat requirement for the entire process. The targeted heating savings represent 36% of the total heat consumptions.

Table 2: Estimated minimum energy requirement for $\Delta T_{min,liquid}$ =5°C

Type	MER [kW]	Present [kW]	Savings [kW]	Savings
Hot Utility	1386	2529 $_{identified}$	**1143**	45%
	1990$_{total}$	3133 $_{total}$		**36%**
Cooling Water (>10°C)	**0**	NA	NA	NA
Refrigeration (<10°C)	**837**	NA	NA	NA

3. Energy conversion integration

The analysis of the energy conversion system integration is based on the energy costs [4] and the CO_2 emissions [1] of the French industrial sector in 2007 and will be compared to the German case (table 3).

Table 3: Energy Costs (without taxes) and CO_2 Emissions- France FR and Germany GER (2007)

	Cost	CO_2 Emissions
Electricity FR	54.1 €/MWh$_e$	55kg$_{CO2}$/MWh$_e$
GER	92.7 €/MWh$_e$	624kg$_{CO2}$/MWh$_e$
Nat. Gas FR	27.1 €/MWh$_{LHV}$	231kg$_{CO2}$/MWh$_{LHV}$
GER	41.7 €/MWh$_{LHV}$	231kg$_{CO2}$/MWh$_{LHV}$
Water	0.00657 €/m^3	-

3.1. Grand Composite Curve analysis

The analysis of the Grand composite curve (Figure 6) leads to the following observations:

- Heat is required at relatively low temperature levels which offers the opportunity to integrate combined heat and power (CHP) and heat pumping systems.

- The pinch temperature (T^*_{pinch} =12.5°C) corresponds to the ambient conditions. It allows for integrating the hot stream of the refrigeration system as a heat source for the process.

- Provided that a heat pumping system is used to satisfy the needs at medium temperature, an MVR system can be used to recover the condensation of wort steam at high temperature.

This would enable lower temperature heating requirements to be satisfied by the cooling water of a cogeneration engine. Thus, the size of the MVR system will be related with the heat delivered by the cogeneration system.

- A refrigeration utility with multiple levels of evaporation represents an appropriate solution in order to minimize the exergy losses below the pinch temperature.

Using a linear programming formulation [7] the flows of the utility streams are calculated to satisfy the process requirements at minimum cost.

3.2. Improving the conversion system

Currently, a natural gas boiler generates steam at high pressure (8.5bar) that is distributed and condensed after expansion at 2.2bar and 123.3°C. For the cooling supply, the factory uses cold water and an NH_3-refrigeration cycle with two levels of evaporation, at -4°C and -8°C.

The flows in the utility system are computed to minimize the yearly operating costs. In practical terms, the stream heat loads of the energy conversion technologies are optimized and added to the process hot and cold streams

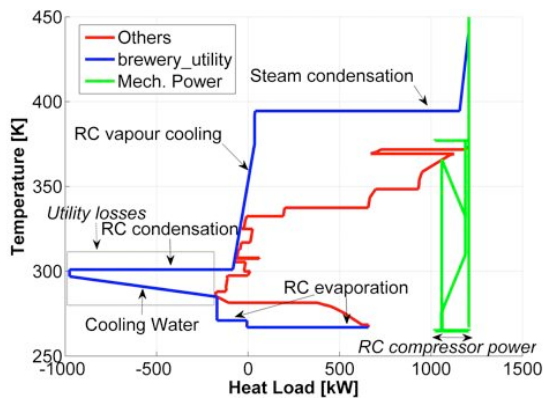Figure 7: Current Utility Setup: Boiler & Refrigeration Cycle (RC)

Figure 7 shows the integrated composite curves 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". The analysis of Figure 7 reveals that the current utility configuration does not prove optimal for multiple reasons. On the one hand, the use of steam at high

pressure and temperature generates exergy losses, since the process requires heat at lower temperatures. On the other hand, it can be seen that below the condensation temperature of the refrigeration cycle, the process heating requirements are lower than the heat provided by the condensation of the refrigerant. This excess of heat must be evacuated by cooling water. It is therefore necessary to consider solutions allowing the improvement of the current utility configuration.

In order to reduce the exergetic losses due to the use of high pressure steam, the integration of a cogeneration internal combustion engine is considered as an alternative to the boiler currently in operation. It appears to be the most relevant technology, as it is possible to recover heat from both exhaust gases and cooling water, which can be used in low temperature processes like breweries. Natural gas is firstly considered. As can be seen in Figure 8, the exhaust gases enable wort evaporation (T*=373K), whereas the engine cooling water provides heat to the process streams below 360K. Fuel conversion leads to the generation of 1047kW of mechanical power. Part of this power can be used to drive the refrigeration cycle compressors, which represents an important reduction in process electricity bill.

Figure 8: Boiler Replaced with a CHP System
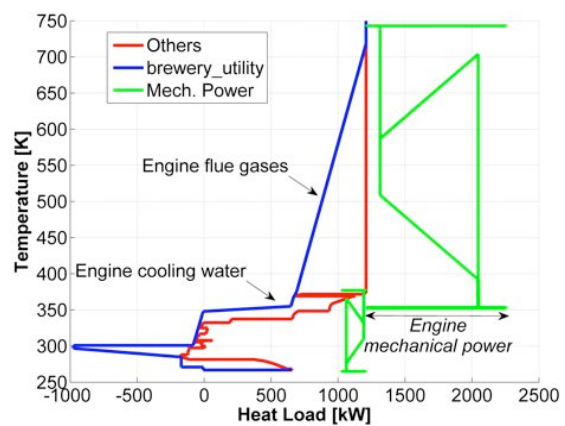
However, the size of the CHP system can still be optimized and the losses caused by refrigeration cycle condensation remain a problem that has not been solved yet. The integration of heat pumps is eventually considered. The mechanical vapor recompression (MVR) of the wort vapor can assist the evaporation and will reduce the CHP system size. In addition, this high temperature heat pump is

making the condensation of the refrigeration cycle useful for process water preheating.

The heat pump operating conditions may influence the flows and the sizes of the other utility systems. In order to determine the optimal heat pump operating temperatures, a multi-objective thermo-economic optimization is performed. Three decision variables are considered: the heat pump condensation temperature, the refrigeration cycle condensation and high pressure evaporation temperatures. Using the evolutionary algorithm *QMOO* ([5],[8]) a set of Pareto-optimal points is obtained, representing the trade-off between investment costs and operating costs. The Pareto-optimal set of figure 10 is divided into two distinct clusters, characterized by a single value of the heat pump condensation temperature (see Figure 9), namely 66.5°C for cluster 1 and 77.5°C for cluster 2, which corresponds to the maximal temperatures of the conditioning line units.

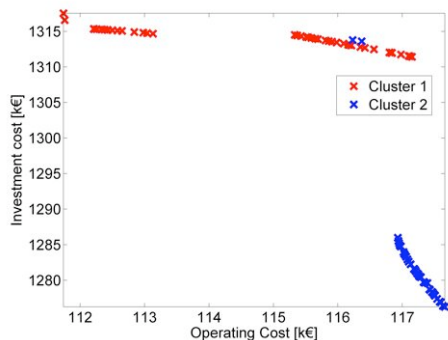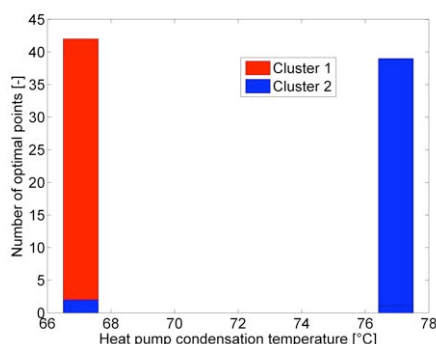*Figure 9:* Pareto Front (84 Pareto-optimal points after 2000 iterations)

Figure 10: Two Pareto-Optimal Clusters of Heat Pump Condensation Temperatures

The high pressure evaporation temperature of the refrigeration cycle is converged at 6°C. The condensation temperatures are preferably distributed between 45°C and 50°C.

Two optimized configurations, including the integration of MVR and heat pump systems, are presented in Figures 11 and 12. 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 the energy losses: for the case where the heat pump condenses at 77.5 °C (351K), external cooling water requirement is close to zero. Table 4 presents the results associated with the different utility setups. It is considered that the remaining heating needs of the NIPUs can be fulfilled by the use of the current boiler (efficiency 85%), fed by natural gas. The French case is compared with the German case where the electricity supply is sensibly different : higher electricity price when compared to natural gas cost and electricity being mainly produced by coal power plants (Table 3). One can observe that in France, from both an economic and an environmental point of view, the most interesting utility setup consists of using heat pumping systems. The best configuration feature a decrease by 36% of the operating costs and 18% of the total costs when compared with the current utility setup. It shows a drastic reduction in CO_2 emissions (44%) and in water consumption. On the contrary, in Germany, the higher electricity to gas price ratio favors cogeneration systems, which in turn enables important reductions in operating costs and CO_2 emissions. It is important to note that only energy costs are taken into account in the yearly operating costs. If carbon taxation was considered, the most environment-friendly setups would be associated with an increased economic savings.

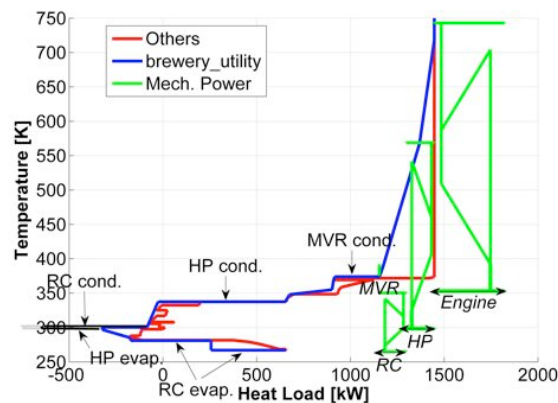*Figure 11:* CHP System+MVR, Heat Pump Condensing at 66.5°C, COP=5.37

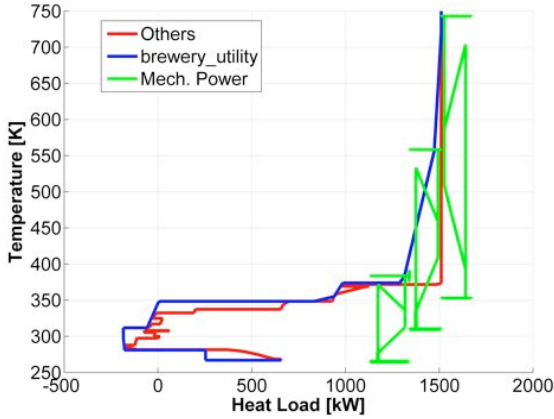*Figure 12:* CHP System+MVR, Heat Pump Condensing at 77°C, COP=5.71

Table 4: Results with maximum heat recovery

1. Boiler, 2. CHP, 3. CHP+MVR +HP(T_{cond}=66.5°C), 4. CHP+MVR+HP(T_{cond}=77.5°C)

	Unit	1.	2.	3.	4.
Fuel consumption	[kW_{LHV}]	2088	3279	1677	1140
Electricity	[kW_e]	184	-863	-80	142
Operating Costs FR	[k€/year]	332	210	205	212
Saving potential	*[%]*	*0*	*-37*	*-38*	*-36*
Operating costs GER	[k€/year]	520	283	312	336
Saving potential	*[%]*	*0*	*-46*	*-40*	*-35*
TOTAL COSTS FR[4]	[k€/year]	**332**	**308**	**274**	**274**
Saving potential	*[%]*	*0*	*-7*	*-17*	*-18*
TOTAL COSTS GER	[k€/year]	**520**	**380**	**381**	**398**
Saving potential	*[%]*	*0*	*-27*	*-27*	*-24*
CO_2 (EDF mix)	[tons/year]	**2459**	**3544**	**1912**	**1372**
Saving potential	*[%]*	*0*	*+44*	*-22*	*-44*
CO_2 (GER mix)	[tons/year]	2987	1094	1686	1976
Saving potential	*[%]*	*0*	*-63*	*-44*	*-34*
Cooling water	[kg/s]	17.1	17.1	3.0	0.1
Saving potential	*[%]*	*0*	*0*	*-82*	*-99*

3.3. Husk Bio-Methanation

Breweries offer the opportunity of recovering energy through husk bio-methanation. The recovered biogas can be used as an alternative to natural gas to feed the cogeneration engine. Knowing the amount of husk produced per year, it is possible to calculate the primary energy that can be recovered :

$$Q_{LHV} = \frac{M_{husk} \times \widetilde{M}_{CH_4} \times v_{CH_4} \times LHV_{CH_4}}{\widetilde{v}}$$

75 Nm^3 of methane can be recovered from 1 ton of husk [2], which represents, for the brewery studied, 8287MWh$_{LHV}$/year=**1660kW$_{LHV}$**, corresponding to a combined production of 677kW$_e$ of electricity and the corresponding heat load. The organic matter is blended and its transformation into biogas by microorganisms requires a specific operating

---

[4]Total Yearly Costs = Operating Costs+Annualized Investment (interest rate=5%, payback time=15 years)

temperature (35°C) [2], which results in additional electricity and heat consumptions.

Table 5: Results Bio-Methanation integration with maximum heat recovery

1. Boiler, 2. CHP, 3. CHP+MVR +HP(T_{cond}=66.5°C), 4. CHP+MVR+HP(T_{cond}=77.5°C)

	Unit	1.	2.	3.	4.
Biogas Engine Size	[kW_e]	0	-1232	-677	-677
Process Identified Elec.	[kW_e]	184	184	295	379
Digester Elec.	[kW_e]	80	123	80	80
Total Elec.	[kW_e]	264	-925	-298	-219
Biogas Extra Heat	[kW_{th}]	39	0	196	434
Boiler (NIPU)	[kW_{LHV}]	664	711	480	200
Operating Costs FR	[k€/year]	161	-31	-16	-32
Operating Costs GER	[k€/year]	260	-280	-38	-60
Invest. Bio-methanation	[k€]	895	2030	1418	1418
Invest. Heat Pumps	[k€]	0	0	198	290
TOTAL COSTS FR	[k€/year]	**238**	**145**	**124**	**115**
Savings /ref.	*[%]*	*-28*	*-56*	*-63*	*-65*
TOTAL COSTS GER	[k€/year]	**338**	**-105**	**101**	**88**
Savings /ref.	*[%]*	*-35*	*-120*	*-81*	*-83*
CO_2 (EDF mix)	[tons/year]	**839**	**566**	**471**	**170**
Savings /ref.	*[%]*	*-66*	*-77*	*-81*	*-93*
CO_2 (GER mix)	[tons/year]	**1588**	**-2060**	**-377**	**-452**
Savings /ref.	*[%]*	*-47*	*-169*	*-113*	*-115*

Table 5 presents the comparison between the different options when converting the biogas. The calculated energy consumptions include the NIPU heat loads that are satisfied by the current boiler supplied with biogas. The reference investment cost of a biogas installation is 450k€(digester+cogeneration of 100kW$_e$) [2].

Table 5 reveals that bio-methanation on site is the most economic and environmental solution. Indeed, the investment in a bio-methanation installation is highly profitable and makes the process self-sufficient. In France, bio-methanation allows the yearly total energy bill to be reduced by 65% and 2'289tons of CO_2/year to be saved (93% with respect to reference). The results are also very different between France and Germany. The higher cost and CO_2 content of German grid electricity promotes the cogeneration operated with biogas, which results in important economic and environmental profits.

4. CONCLUSION

A methodology based on process integration techniques has been applied to improve the energy efficiency of a brewery.

The definition and the modeling of the identified process units allows the determination of the heat recovery potential between process streams using Pinch Analysis. The analysis of the process composite curves enables a first identification of the utilities that can be used to fulfill the determined Minimum Energy Requirements.

A multi-objective optimization method is applied to define the best utility setup and the corresponding operating conditions that minimize the operating and investment costs. It has been shown that integrating combined heat and power system together with heat pumps can be profitable from both an economic and an environmental point of view. A special focus is made on the dependance on the electricity cost and production mix. The comparison between France and Germany is presented: the contrasted electricity economic and environmental costs with respect to gas result in a solution promoting heat pumps in France whereas in Germany cogeneration systems prove more profitable.

The opportunity of recovering energy from brewery organic waste through bio-methanation has been studied. A quantitative analysis shows that the production and use of biogas on site leads to a drastic reduction in the total costs for both cases. However, the reduction in CHP system operating cost is not sufficient to substitute heat pumps by cogeneration if the brewery studied was located in France.

The energy requirements of the brewery are evaluated considering a continuous process functioning, which limits the accuracy of the results presented. Indeed, the identified units may not operate simultaneously, hence the interest of performing a multi-period analysis, which would require additional information on instantaneous material flows. The quantitative results presented are specific to the brewery studied and it is important to keep in mind that any process has singularities that can hardly be transposed into another case study, without prior verification.

Nomenclature

COP Coefficient Of Performance [-]

$\dot{Q}_{th}$ Heat Load [kW]

LHV Lower Heating Value [MWh/kg]

M Mass[kg]

MVR Mechanical Vapor Recompression

v_{CH_4} Methane Content of Brewery Waste [m^3/kg]

MER Minimum Energy Requirement [kW]

$\widetilde{M}$ Molar Mass [kg/kmol]

$\widetilde{v}$ Molar Volume of Perfect Gases [m^3/kmol]

$NIPU$ Non Identified Process Unit

PUO Process Unit Operation

T Temperature [K]

References

[1] ADEME. Note de cadrage sur le contenu co$_2$ du kwh par usage en france, 2005.

[2] ADEME. La méthanisation à la ferme, 2006.

[3] H. Becker, F. Marechal, and A. Vuillermoz. Process integration and opportunity for heat pumps in industrial processes. In *Proc. 22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, 2009.

[4] Observatoire de l´ Energie. Prix du gaz et de l'électricité en europe au 1er janvier 2007, 2007.

[5] G.B. Leyland. *Multi-Objective Optimisation applied to Industrial Energy Problems*. Ph.d. dissertation, Lausanne: EPFL-STI, Industrial Energy System Laboratory, 2002.

[6] B. Linnhoff et al. A user guide on process integration for the efficient use of energy. *Institution of Chemical Engineers, IChemE; Revised Sub-Edition*, 1994.

[7] Kalitventzeff B. Marechal, F. Energy integration of industrial sites: tools, methodology and application. *Applied Thermal Engineering*, 18:921–933, 1998.

[8] A. Molyneaux. *A Practical Evolutionary Method for the Multi-Objective Optimisation of Complex Energy Systems, including Vehicle Drivetrains*. Ph.d. dissertation, Lausanne: EPFL-STI, Industrial Energy System Laboratory, 2002.

[9] D. Muller. *Web-based tools for energy management in large companies applied to food industry*. Ph.d. dissertation, Lausanne: EPFL-STI, Industrial Energy System Laboratory, 2007.