

Application of Process Integration techniques in the brewing process

François Marechal, Anurag Kumar Sachan, Leandro Salgueiro
Industrial Energy Systems Laboratory
Ecole Polytechnique Fédérale de Lausanne - EPFL

September 4, 2012

Abstract

This chapter presents the application of Process Integration techniques to increase the energy efficiency of a typical brewery process. The example is chosen to illustrate the application of the Process Integration methodology and to demonstrate the steps towards the realisation of the Process Integration analysis. The chapter starts with a discussion on the definition of the process requirement and of the perimeters of the study. The heat cascade is then used to calculate the maximum heat recovery in the process. The integration of the refrigeration cycles and of the energy conversion technologies will then be studied to finally analyse the possible integration of heat pumping technologies as well as the integration of waste conversion units. We will discuss how the targeting energy consumptions of the process can then be reached in a real industrial process implementation. The data used for the study are based on a flowsheeting model and can therefore be considered as being generic.

Keywords

: Process Integration, Energy efficiency, Pinch analysis, Brewery process, Cogeneration, Heat pump, Thermo-economic optimization

1 Introduction

Any industrial process is a system (Figure 1) in which raw materials are converted into products and by products. In most of the case, the conversion is realised in a set of process unit operations or processing steps that require a production support like water or solvent. The driving force of the conversion step is energy that enters the system as energy resource flows being converted into useful energy form like heat, cold or work to realise the required processing steps. As the conversion of the raw materials as well as of the energy resources is not perfect, part of the mass and the energy entering the system is leaving the process as waste in form of solid, liquid or gaseous as well as waste heat that has to be treated and conditioned before leaving the system and released to the

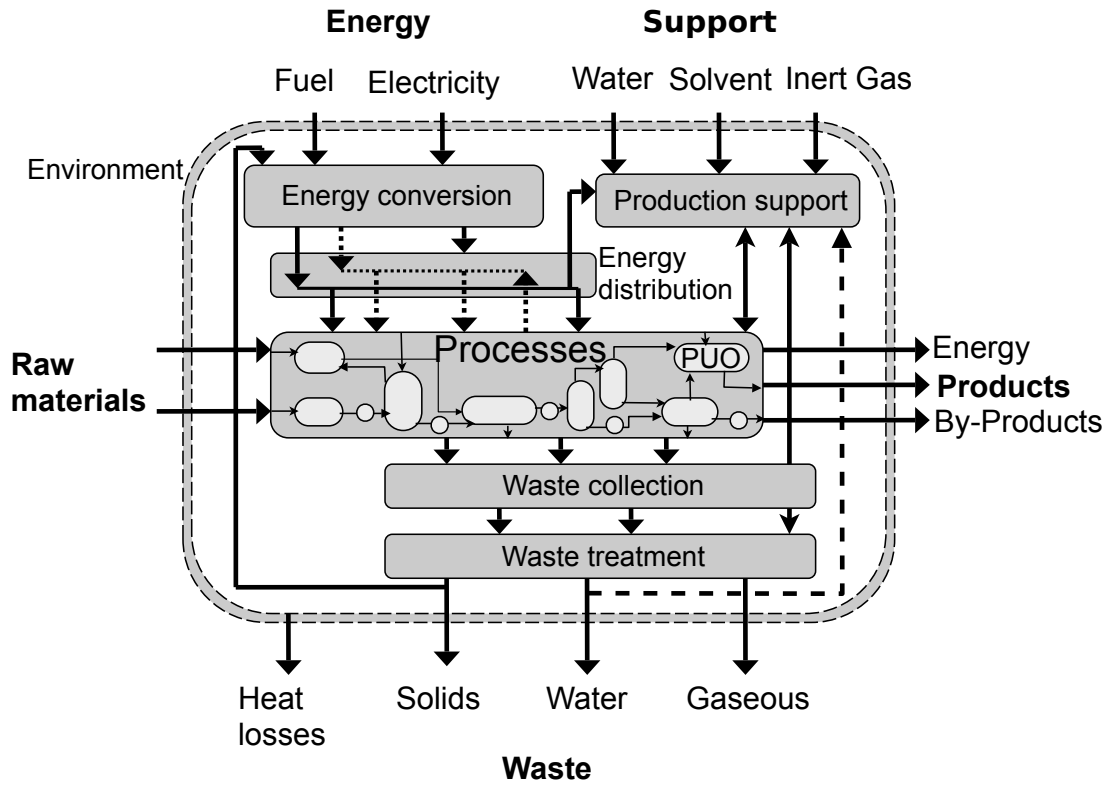


Figure 1: The industrial production system

environment. When considering Process Integration, the goal is to optimise the overall efficient of the process therefore considering to maximise the horizontal flows while minimising the vertical ones. Considering the system boundaries, the Process Integration will consider not only the processing steps maximising the process throughput but also the support streams management maximising the recycling and the reuse of materials as well as the waste management and treatment and the energy conversion. This results sometimes in the addition of new products in the form of by-products or energy servives.

The process used in this chapter is a beer production process . The block flow diagram describing the major processing steps is sketched on Figure 2. The beer production follows a recipe that converts a mixture of corn, water and hop (**raw materials**) into bottled beer (**product**) by a set of cooking, filtering and fermentation steps (**processing steps**). The process uses water as the **production support** both for the process itself and for the equipment and conditioning washing. The conversion process requires energy in form of **heat** for the cooking and **cold** during the fermentation and conditionning. **Waste** that results from the process is more or less humid, leaving the system as solid or liquid. In addition, the evaporation of a part of the water during the process also produces vapour that is typically vented on the roof.

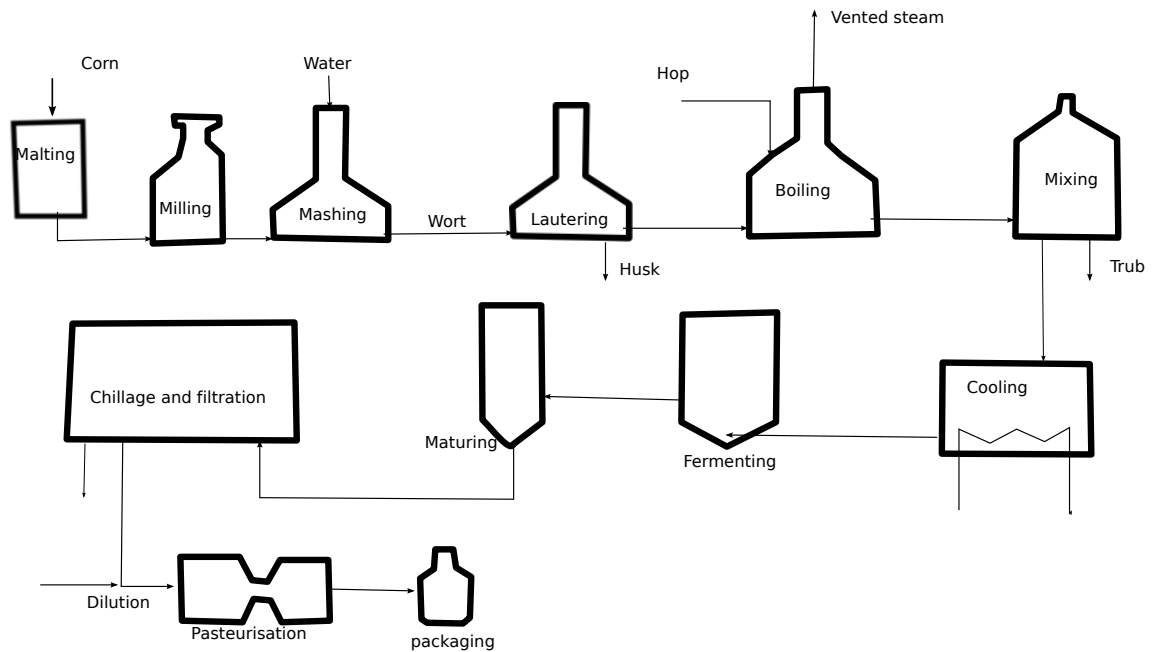


Figure 2: The brewery process block flow diagram

In the brewery, beer is produced from a mixture of water and malted corn. By volume, water is the main raw material. The different operations are described in more detail in order to characterise the use of energy in the beer processing.

Malting In this process, the barley grains are prepared for brewing by releasing the starches in the barley. In three step approach, the grain is added to a vat with water and allowed to soak for approximately 40 hours during steeping. Then, in germination, the grain is spread out on the floor for around 5 days and finally, the green malt goes through a very high temperature drying in the kilning step.

Milling In the process of milling, the grains are cracked so that they absorb the water. Water in result of this mixing extracts the sugar from the malt.

Mashing The milled barley grains and supplementary grains (corn, sorghum, rye and wheat) are mixed with water and then heated at 65°C in a vessel for approximately 2 hours in the process of mashing. During the mashing, the process of saccharification takes place with the mash, resulting into a sugar rich liquid called "Wort".

Lautering This wort is filtered from the mash in the process named "lautering". The remaining solid particles of the malt (brewing dregs) may be used as animal feedstock or biomethanized.

Boiling The wort then boiled at 105°C (under atmospheric pressure) for 1 hour in a tank. During boiling, hops are added to control the bitterness, flavour

and aroma; finally the mixture is sterilised. Approximately, 10% by mass of wort is evaporated in the form of vapour during the boiling, representing most of the evaporated mass of the total wort evaporated in the brewing process.

Mixing - Whirlpool The wort is then stirred and settles in a large tank before being purified of all the solid protein particles (Trub). Approximately 0.2% by mass of the wort is settled and removed in form of trub.

Cooling This is the last step of the hot part of the brewing process. The purified wort is cooled to 10°C to prepare it for the process of fermentation.

Fermentation Fermentation is the conversion of sugars to alcohols and carbon dioxide or organic acids using yeasts or bacteria under anaerobic conditions. For this purpose the wort is stored in fermentation tanks, maintained at a constant temperature of 10°C for 14 days. These chemical reactions are exothermic and thus, cooling is necessary during fermentation.

Maturing The wort is then maintained at 6°C for a period of 10 days for maturing. In this period, CO₂ concentration is controlled and kept constant.

Chillage and Filtration The wort is finally rapidly chilled to 1°C and the yeast is eliminated by filtration. Here a concentrated beer is obtained.

Dilution The de-gasified cold water is mixed to the concentrated beer to achieve the desired alcohol content in the beer. In our case, it is diluted by adding 25% water by mass to the concentrated beer.

Pasteurization The beer is pasteurised by heating up to 70°C and, after a stay, cooling the beer to 5°C; it is then stored in the insulated tanks to be filled in bottles or kegs.

Bottling After pasteurisation, the beer is bottled. This step requires the bottle or kegs washing as well as the packaging material preparation.

2 Process flowsheet analysis

2.1 Block flow process analysis

The flowsheet of Figure 3 presents the flow of various streams within the brewing plant with constraints of temperature and pressure as per the recipe of the beer. The conventional plants do not have direct process/process heat recovery and thus heat exchangers exist only between process streams and the utility streams including the hot water system.

The process flowsheet is divided in different sub-systems that are then allocated to process and utility sub-systems. The **process** sub-system refer to process units that are strictly related to the process unit operations. The units in this system define therefore the requirements of the process. The **utility** system includes the units that are related to the supply of the energy (heating and cooling) services that are needed by the process. The utility subsystem includes the flows that we would like to optimise in order to minimize the energy bill.

The process subsystem is defined into three major sub-systems :

Hot section The hot part (Figure 4) corresponds to the cooking part of the brewing process. The malt is first mixed with water in a big tank (MAT) and elevated to a temperature of 48°C with the addition of hot water. The malt is especially made of sprouted barley. When malt is heated, the enzymes decompose the starch into sugar. Later, this sugar will be transformed in alcohol during the fermentation. Another tank (MAK) filled with malt, corn and water if also preheated to 48 °C, the resulting flow is then heated to a temperature of 102°C, before being mixed with the MAT tank content reheated to 75°C. At this point, the mixture is called Maische. Maische then passes through a pressing filter which requires an additional amount of hot water at 80°C. The wastage is essentially compressed malt that can be considered as dry and called Dreche. After the filter, the liquid is mixed with hops and heated in the WOK to the temperature of 102°C for approximately one hour. It is assumed that during this time about 10% of the liquid mass flow is evaporated. While the vapour is vented, the outgoing liquid (wort) is mixed with an additional amount of hot water before being filtered by a centrifugal device to separate the 0.2 % of cooked proteins (Trub). The wort is then cooled down to 10°C in a heat exchanger to reach the cold section of the process. The heat recovered is sent to the hot water tank to feed the hot water needs of the next operation.

Cold section The cold section (Figure 5) concerns mainly the fermentation and the following beer conditioning operations. The wort is first fermented at a temperature of 10°C. The fermentation reaction is exothermic, the observed heat of fermentation is of 37.14 [kJ/ l_{wort}], it includes the heat gains from the ambience. Glycol water is circulated in the fermentation tanks to maintain the temperature at 10°C for a fermentation period of 14 days. The wort is then cooled and maintained at a temperature of 6°C to eliminate diacetyl residues that gives the beer an unwilling taste of butter. This maturation period is usually of 10 days, depending on the alcohol content required in the beer. The specific cooling requirement of the maturation is of 29.55 [kJ/ l_{wort}]. After the maturation process, the fresh beer is cooled down the liquid to 1°C in order to precipitate the yeast that is filter in the Chillage step. The specific heat for this step is observed as 29.70 [kJ/ l_{beer}]. The CO_2 concentration maintained during the maturation period is between 2.2-2.4 kg_{CO_2}/hl_{wort} . At the end of the process, the alcohol concentration is controlled by diluting the beer mixture with water @ 15°C. The beer is finally pasteurized by heating up the mixture to 70 °C and cooling it again to 5°C rapidly. This beer is now ready for packaging.

Washing The washing system (Figure 6) mainly aims at preparing the packaging materials (mainly bottles and kegs) before filling it up with beer. This process is considered as a continuous operation. The bottles are successively pre-rinsed, washed with soda and rinsed in successive baths again before being filled with beer. The temperature of the baths is maintained by steam injection. The final rinsing is done with the clear water at 15°C. Water of the final bath rinsing is recuperated and sent to the pre rinsing bath, recovering heat from the bottles that are cooled down in the last bath.

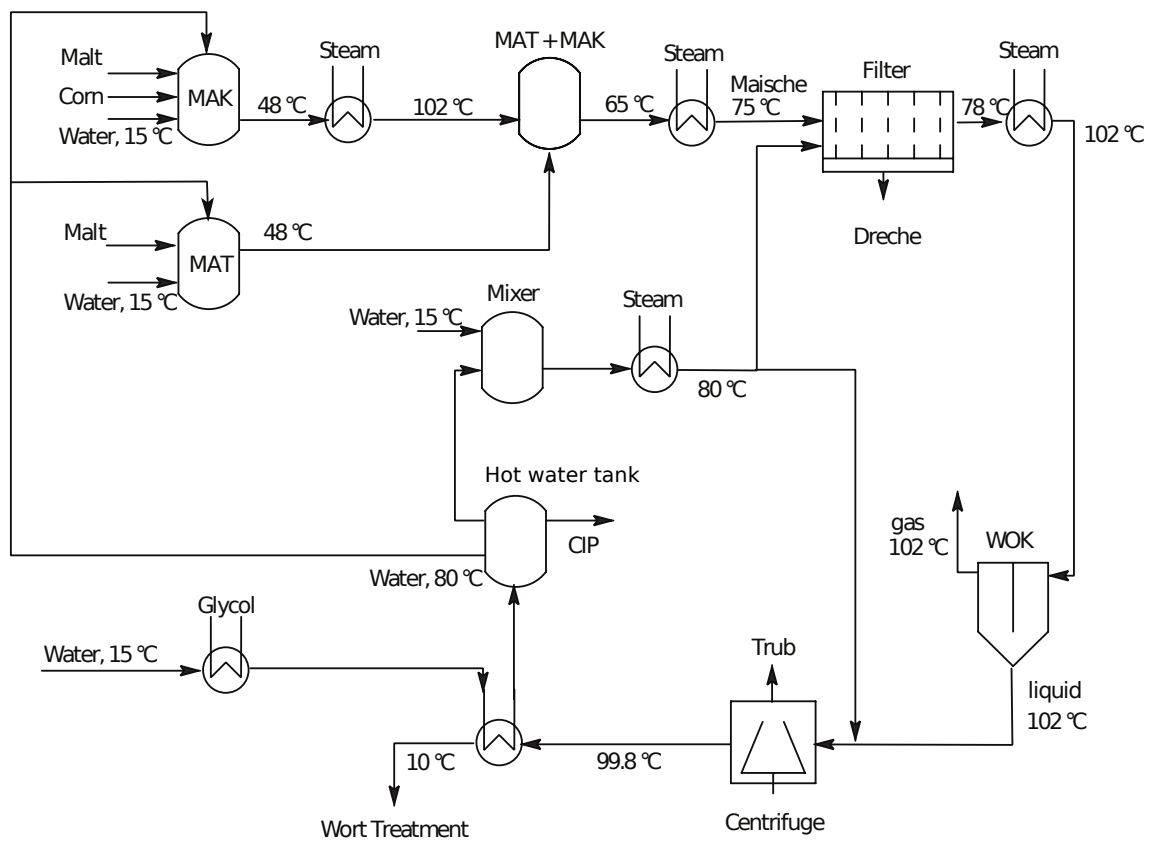


Figure 4: Brewing process : Hot section

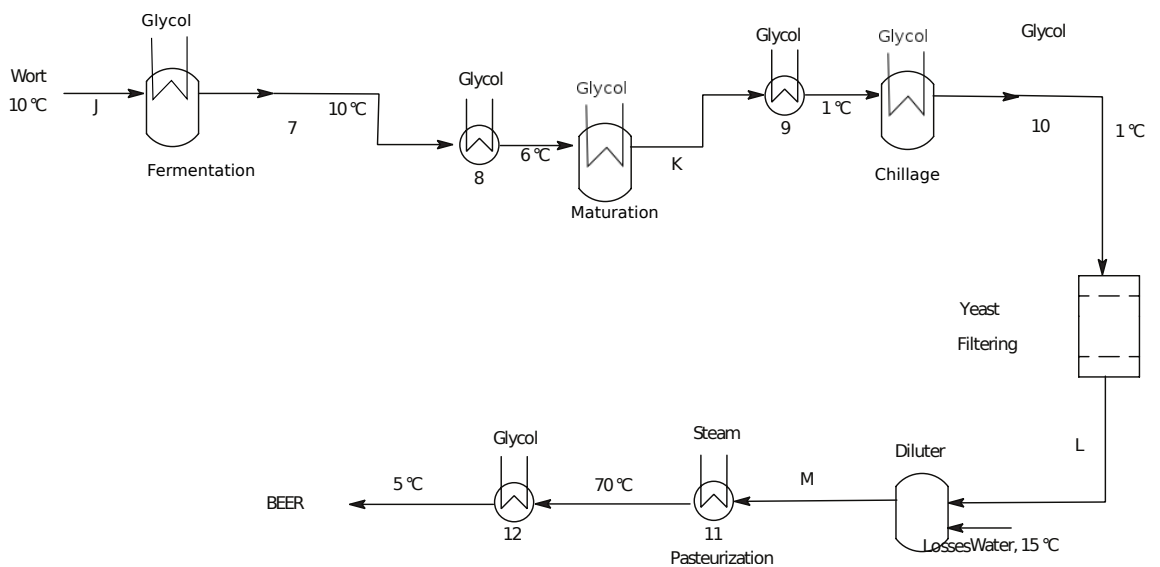


Figure 5: Brewing process : Cold section

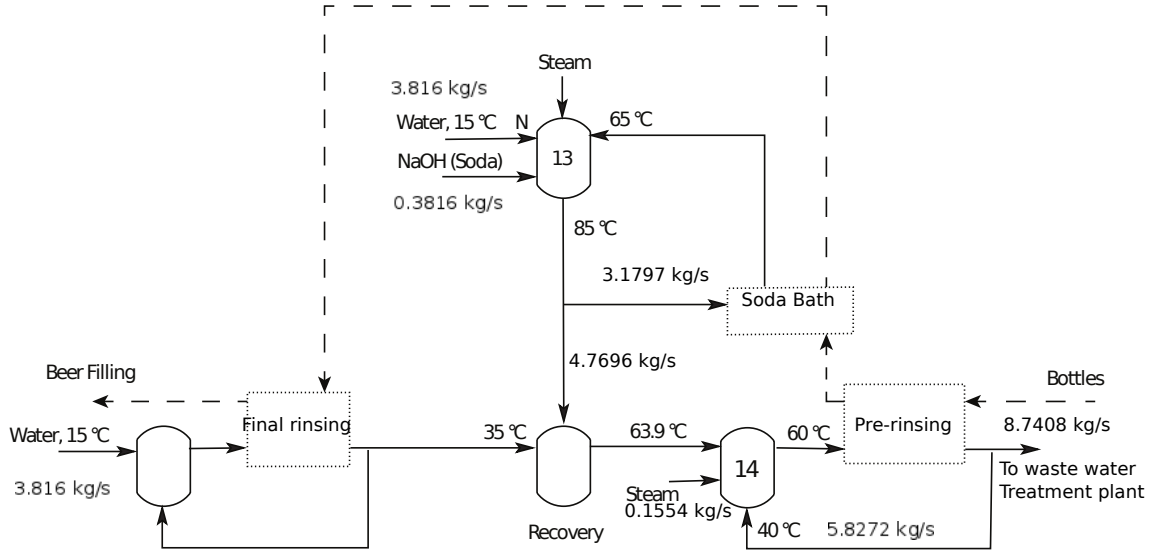


Figure 6: Brewing process : Cleaning in place section

It is assumed that the amount of water used for the third rinsing cycle is about 20% of the amount of beer produced. The fraction of NaOH/water for the bath rinse supply water is equal to 1/10. The whole cleaning system is proceeding at atmospheric pressure. Details on the temperature set points and the energy losses in the different baths are given on Figure 6.

The utility system includes the following sub-sections :

Hot Utility system The process heat is supplied conventionally by steam produced in a boiler. Hot water is also used in the process. It is stored in an intermediate hot water tank that also serves as a heat recovery system.

Refrigeration system Cooling requirement are supplied by distributing cold glycol-water mixture that is produced in an ammonia refrigeration cycle.

2.2 Time average approach

The beer production is a priori described as a succession of batch reactors. However in industrial plants, although the processing operation are batch, the overall process can be considered as a nearly constant process by realising the operation in different batch reactions that are operated with a certain dephasing. The heat recovery being made possible by introducing hot water buffer tanks. It is therefore possible to apply the time average approach [Linnhoff et al., 1988] to represent the process operation by replacing the instantaneous flows or power by the mean energy needed per unit flows multiplied by the mean unit flow per product flow (Eq. 1).

$$\dot{m}_s[kg/s] = m_s[kg/kgproduct] \cdot \tilde{M}_p[kgproduct/s] \quad (1)$$

Table 1: Inlet and outlet flows of the process

Input		
Malt	0.135	kg/kg
Corn	0.0115	kg/kg
Water	1.029	kg/kg
Demineralised Waster	.051	kg/kg
Cleaning Water	0.391	kg/kg
Soda	0.02	kg/kg
Natural Gas	748.9	kJ_{LHV}/kg
Electricity	69.3	kJ_e/kg
Cooling water	9.47	kg/kg
Output		
Beer	1.0	kg/kg
Brewing dregs	0.0397	kg/kg
Waste water	0.458	kg/kg
Vapour	0.081	kg/kg
CO2	0.0373	kg/kg

where the mean flow of product is calculated by Eq. 2

$$\tilde{M}_{product}[kg_{product}/s] = \frac{\dot{M}_p[kg_{product}/year]}{t_p[s/year]} \quad (2)$$

In the following, all the flows and power that will be presented will refer to mean flows and power.

2.3 Inventory of flows entering and leaving the system boundaries

Following the definition of the system 1, the first step is the identification of the flows entering and leaving the system. The flows entering the system are the raw materials (water, corn, malt (barley) and hops), the energy (natural gas in the boiler and electricity), the support materials (water, soda,...) and the packaging materials. The cleaning of bottle requires the water and soda as input flows. The waste water leaves the cleaning system. The total water required at the third rinsing is 20% of the total beer produced and same for the bath rinsing step as well. The amount of soda is 10% of the water added to the bath rinse. It leaves the system as the part of waste water flow. The streams leaving the system are the products (bottled beer) and the waste streams. The bio waste of husk (dregs) accounts for 30% of the initial malt added. In addition, evaporated water and CO_2 from the fermentation is leaving the system and released to the environment.

The Figure ?? summarise the major flows entering and leaving the systems. Table 1, gives the specific major flows using the unit of bottled beer produced.

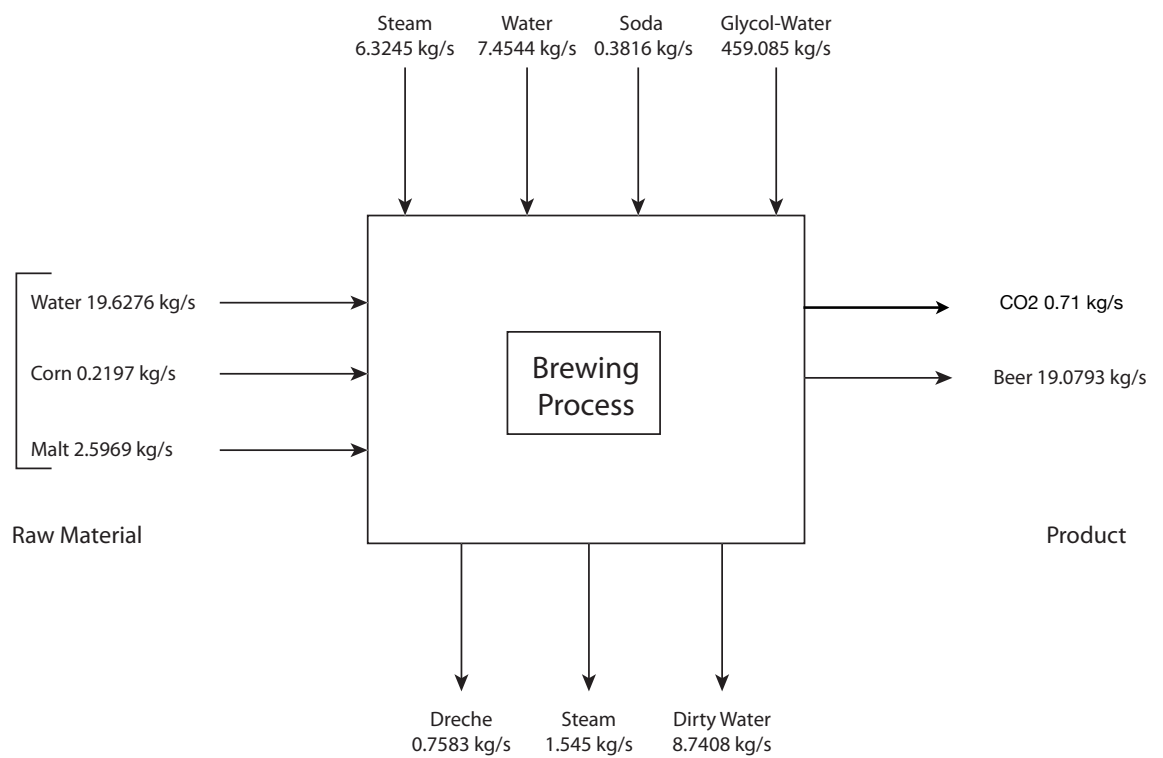


Figure 7: Block Flow Diagram representation of the Brewing Process

	Electricity	Natural Gas	Water	Demineralized Water
Spec. cost	0.136 [€/kWh]	0.048 [€/kWh]	0.07 [€/m ³]	1.0 [€/m ³]
Flows	1322 [kWe]	17062 [kW_{LHV}]	0.31 [m^3/s]	0.001 [m^3/s]
Op. Cost	1470.9 [k€/y]	6699.2 [k€/y]	630.0 [k€/y]	35.0 [k€/y]

Table 2: Current Energy bill

Table 3: Current utility requirements with no heat recovery

Hot Utility	Cold Utility	Electricity
17062.0 kW_{LHV}	7,555.9 kW	1,322.2 kWe

2.4 Energy conversion and distribution system

A boiler is used to produce the steam, thus natural gas is burned as primary fuel to generate the heat and converting the water into steam. Electricity is also required in small amount for the pumping power for the water in the boiler unit. The waste stream from the boiler is the flue gasses which exhaust at 200°C in the chimney. The overall boiler efficiency is 89 % accounting for 2% of radiation losses and 9% in the flue gases.

In most of the conventional bottle cleaning systems, some steam is directly injected to heat up the water. This will require makeup water (demineralized water) to be added to compensate the losses.

Glycol-water is produced by a refrigeration unit which consumes electricity as resource to drive its compressor. In nominal operation there is no requirement of makeup glycol-water until there is leakage in the system. The refrigeration unit works with ammonia as the refrigerant fluid in our case.

2.4.1 Defining the energy bill

The Table 2 presents the cost of the various resources and the current energy bill of the process.

With no internal heat recovery in the conventional brewing process, consumes 17062 kW_{LHV} of primary energy in form of lower heating value of natural gas. This corresponds therefore to a heat supply to the process of 15252.51 [kW]. The cooling load is of 7555.9 [kW], which is provided by refrigeration unit, whereas 1322.2 [kWe] of electricity is required to drive the necessary pump and compressor. We find the natural gas consumption as 0.3595 [kg/s], which results into natural gas bill of 6699.2[k€/y]). The electricity cost in this case is 1470.9[k€/y]). The net yearly operating cost including water and demineralised water is of 8837.1[k€/y] (see Table ??).

2.5 Defining the process heat transfer requirements

The definition of the heat transfer requirement of the process aims at analysis the role of heat transfer in each of the process unit operation. The unit operation in the flowsheet are therefore analysed with regard to their role in the beer production recipe. From this analysis, one has then define the heat transfer requirement to be used for Process Integration, i.e. define the enthalpy-temperature profile of the heat transfer demand including the corresponding ΔT_{min} contribution.

For defining the heat transfer requirement, the main take home messages are :

Process unit analysis : analyse the role of the process unit operation and understand what are the inlet and output flows and what are the principles of the unit operation in order to identify the role of energy (i.e. heat and electricity) in the operation.

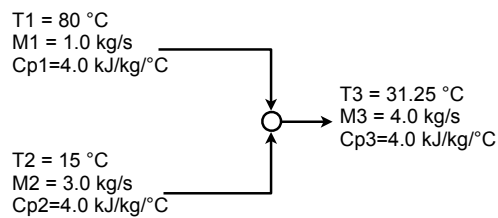
Hot stream definition : for this the key message is cool down the hot streams with the higher possible temperature. This means looking at the process unit operation and try to define a process unit scheme that maximises the temperature of the fluids that will enter to be cooled in a heat exchange operation.

Cold stream definition : when heat is required the goal is to define the minimum temperature at which the heat has to be supplied.

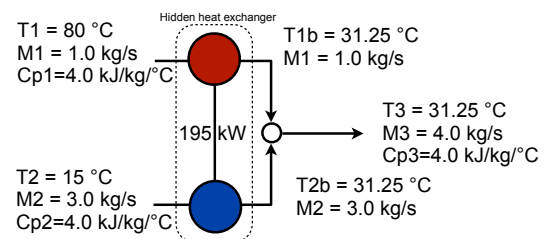
Non isothermal mixing are heat exchangers : The non isothermal mixing of Figure 8, defines two heat transfer requirement , one hot stream from 80 [°C] to the mixing temperature and one cold streams from 15 [°C] to the mixing temperature (31.25 [°C]). If the pinch point temperature is 40 [°C] (i.e. 45 [°C] for the hot stream) at total amount of 140 kW over other 195 kW of the heat exchange in the mixing could be recovered for streams above the pinch while the same amount would be recovered from below the pinch to heat up the cold stream. In such a case, the mixer is a heat exchanger that transfers 140 kW across the pinch. It is therefore important, at the level of the targeting stage to define all the non isothermal mixing as heat exchangers and to deduce, once the pinch points are identified if the non isothermal mixing can still be realised or if part of the heat exchange has first to be realised in heat exchangers before realising mixing. In the given example, the final configuration would be the one described in Figure 8.

Let us analyse the process requirement of the first unit (MAK) on the process flowsheet. Referring to Table 9, there exist several ways of defining the heat transfer requirement of the unit. First, it has to be observed that the heat requirement of the unit is in fact hidden in the hot water tank that supplies the MAK unit with hot water. The hot water tank is not really related to the process, it serves in reality as an intermediate stream for the process. The requirement of the MAK unit has therefore to be related to the injection of hot water that defines the way the MAK requirement is satisfied today. However, an alternative way of defining the requirement could be also to decide to heat the vessel after mixing the ingredient or better to preheat the streams entering the vessels to a temperature of 48 deg C. In order to calculate the respective heat load of the different streams one has first to consider that the total amount of water is imposed, therefore the water flow is the flow of the fresh water + the flow of hot water. In this situation, the heat load of the three heat transfer requirement will be the same but the defined cold streams will be different. The solution with feed preheating being the one with the lower exergy requirement (see Table 2.5) and as well the highest possible level for heat recovery. This is explained on Figure 9 and illustrated with the case where the process pinch point is at 40 [°C]. The heat recovery potential is in fact much higher when one defines

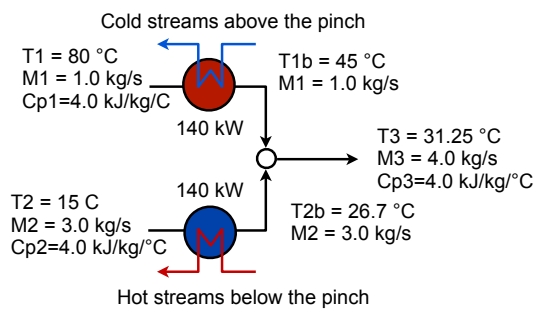
Flowsheet representation



Heat transfer requirement



Heat exchange after pinch identification



Hot and cold streams of the mixer

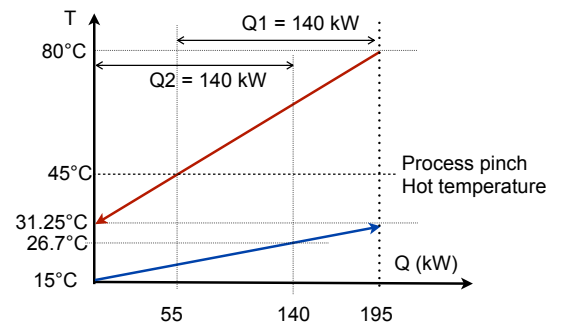


Figure 8: Non isothermal mixing heat transfer requirement and heat recovery if the pinch temperature is at $45\text{ }^{\circ}\text{C}$ for the hot streams

	Exergy [kW]	Heat @40 [°C] [kW]
Hot water from 15 to 80 [°C]	11.40	38.46
Vessel heating at 48 [°C]	11.84	0.00
Heat feed streams from 15 to 48 [°C]	6.97	75.76

Table 4: Exergy demand of 100 kW heating for the different heat requirement of the same unit operation (MAK), possible heat recovery if the pinch is at 40 [°C].

the requirement considering the feed preheating. The feed preheating would however require a heat exchange between the corn, malt and water mixture and another process stream. Considering that this counter current heat exchange could be difficult to realise, we have considered that only the water will be heated to a temperature such that the mixture reaches the required 48 [°C].

The same kind of analysis will be realised for the different process unit operations.

2.6 Analysing the streams leaving the systems

The streams leaving the system have to reach their system's boundary state. For the products, they have to be brought to their "ideal" distribution state. The flows released to the environment have to reach a state that is in equilibrium with the environment. This can be done by heat exchange and therefore define a heat recovery opportunity. When setting up the heat recovery target, it is important to list and analyse all the heat exchange opportunities that are available from the streams leaving the system. In order to maximise the heat recovery, the enthalpy-temperature profile will be established following the rules presented above for the process streams and defining as a target the conditions that are the closest of the environment conditions. The target state is however a *soft* target since it does not necessarily have to be reached.

For the waste streams, it is important to study if the waste treatment system is part of the system boundaries or not.

1. Beer – Beer leaves the system as the final Product and will be stored to be filled later in the beer bottles.
2. Flue Gasses – Flue gasses exhaust from the chimney of the boiler system (Steam Cycle) at almost 200°C. It is possible to treat these gasses to cool down to optimal temperature to pre-heat the fresh air going to the burner. This in turn increases the exergy level of the hot gasses in the burner and thus reducing the consumption of natural gas for the same amount of steam production.
3. Steam Condensate - Flash Vessel is used to improve the efficiency of condensation of the condensate return in the boiler system. This steam exhaust is usually lost and not recovered.
4. Husk (Dreche) - Malt waste in form of husk is extracted during the filtration of maische before boiling process. The amount is approximately 30% by mass of the initial added barley. In our case it is around 0.7583 Kg/sec

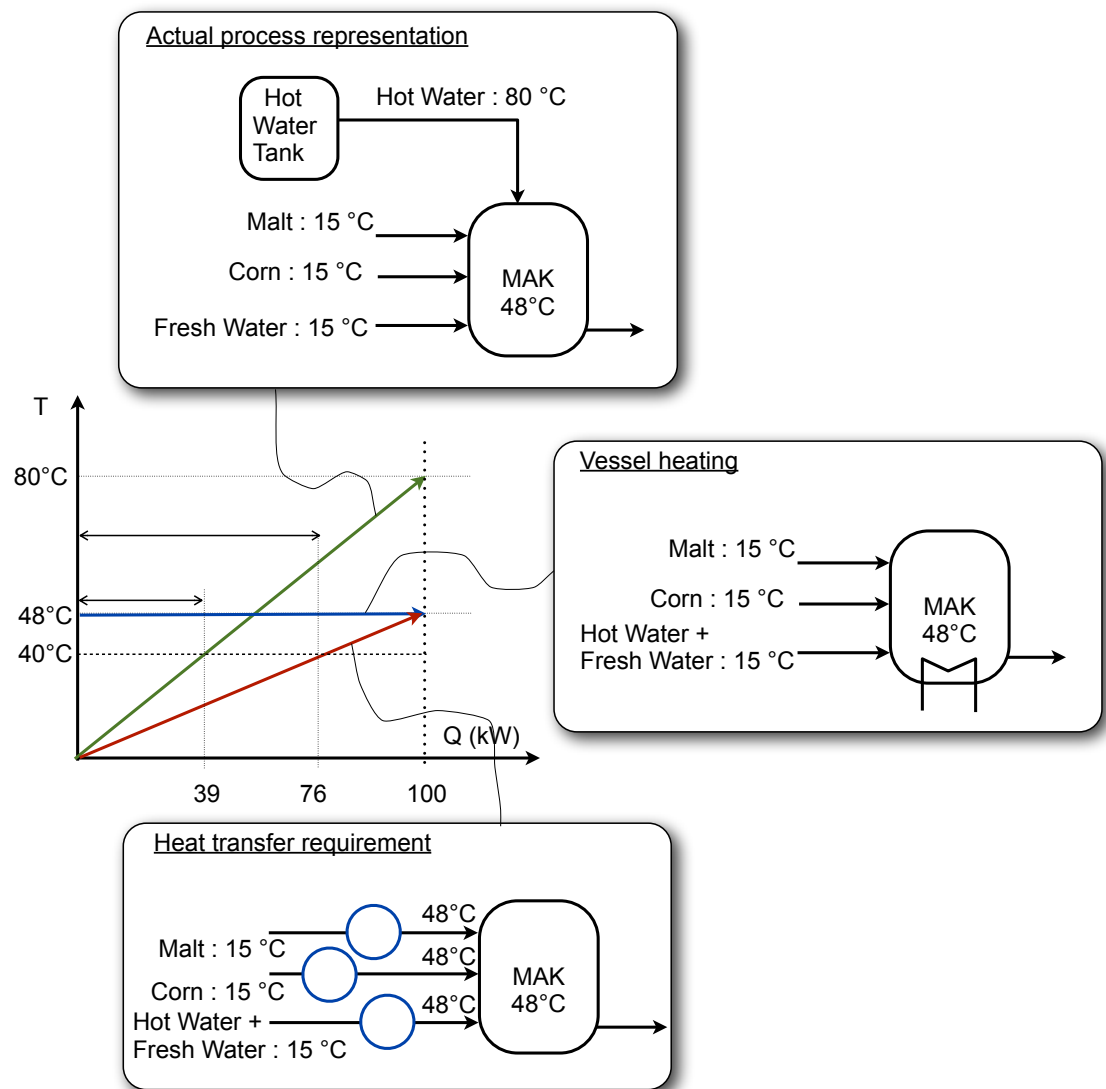


Figure 9: Process Unit : heat transfer requirement analysis, heat recovery if the pinch point is at 40 [°C]

or 2.73 t/h. This husk usually feeded to the animals but there is a possibility to convert this into the methane (bio-gas) through bio-methanation process.

5. Steam evaporation at WOK – 10% by mass of the working wort is evaporated during the boiling and energy is recovered from this vapour by cooling it down to the ambient temperature.
6. Trub - 0.2% by mass of wort is lost during the centrifuge step to finally remove any proteins from the wort.
7. Dirty water – A significant amount of dirty water leaves the bottle cleaning system. This water includes soda, dirt and impurities cleaned during the process and usually send to the water treatment plant to be used for other purposes.
8. Water – CIP – A part of water heated to 80°C in the hot section is going out of the system to be used for the cleaning purposes for the tanks and other devices. This energy is not recoverable and lost in the cleaning purposes necessary for maintaining the hygiene at the production line.

2.7 Overall process requirement definition

The hot and cold streams defined for the whole process are given in Table ?? . We give here some hints on the hot and cold streams definitions for the different sections.

MAT and MAK tanks : the water is preheated to heat up the corn and malt streams and reach the required temperature in the different tanks. It is also assumed that the first preheating to 102[°C] is not necessary and that a temperature of 75 [°C] has to be reached.

Evaporation in the launter tun The evaporation takes place at 105 [°C]. The vapour condensation is considered as a hot stream with a condensation at 100 [°C] considering pure vapour. After condensation the liquid is still sub cooled to reach the 25 [°C] target temperature. This is a *soft* temperature.

Centrifuge A water make up is added and has to be heated to 80 [°C].

CIP Hot water used for Cleaning In Place is produced at 80 [°C]. It is assumed that after its usage the hot water can not be recovered and is sent cold to the water treatment plant.

Trub Trub could be added as a hot stream if heat exchange can be realised with the solid flow. The flow is however small when compared to the major flow

Fermentation The feed is first cooled down to the fermentation temperature, then the temperature is maintained. Note that we consider the temperature in the tank and not the temperature of the glycol water mixture used to maintain the temperature in the tank.

Process Unit	Name - Process	$\dot{M}$ [kg/s]	T_{in} [C]	T_{target} [C]	$\dot{Q}$ [kW]	$\Delta T_{min/2}$
Hot Section 1	Water-MAK	2.4415	15	51.5	369.9	2
	MAK-Heating	2.9971	48	65	188.6	2
	Water-MAT	4.9652	15	54.5	823.6	2
	MAT-Heating	7.2982	48	65	420.1	2
Hot Section 2	MAT+MAK	10.2953	65	75	368.4	2
	Water-Filter	5.9130	15	80	1608.9	2
	CIP	6.767	15	80	1841.1	2
	WOK - Boiling	15.4500	78	105	1662.9	2
	WOK - Evaporation	15.4500	105	105	3319.8	2
	Vapour - Recovery	1.5450	105	100	17.2	1
	Vapour - Recovery	1.5450	100	100	3487.9	
	Vapour - Recovery	1.5450	100	25	482.8	2
	Centrifuge	1.3890	52	80	857.9	2
	Wort-Cooling	15.2634	102.5	10	5434.6	2
Cold Section 1	Fermentation	15.2634	10	10	534.8	2
Cold Section 2	Cooling	15.2634	10	6	233.8	2
	Maturing	15.2634	6	6	425.5	2
Cold Section 3	Chilling	15.2634	6	1	714.5	2
	Chillage	15.2634	1	1	427.7	2
Cold Section 4	Beer preheating	15.26	1	15	822.05	2
	Pasteurization heating	19.0793	15	80	4854.05	2
	Pasteurization cooling	19.0793	70	5	4858.4	2
Cleaning	Soda Bath Temperature	3.1797	65	85	251.9	2
	Pre Rinse Bath Temperature	5.8272	40	60	472.8	2
	Soda make-up	0.3816	15	85	39.8	2
	Water to soda tank	3.816	15	85	1287.1	2
	Pre-rinse make up	0.1554	15	60	29.3	2
	Final Rinse Water make up	3.816	35	60	399.34	2
	Soda Bath Rinse - Out	4.7696	85	60	472.7	2
	Pre Rinse - Out	8.7408	40	20	713.7	2

Table 5: List of Streams in Brewing Process

Minimum Heating Requirement	4904.0	[kW]
Minimum Cooling Requirement	0	[kW]
Minimum Refrigeration Requirement	3089.1	[kW]

Table 6: Minimum heating and cooling requirement target for the process

consider the fresh water as defining the cooling water temperature. From our analysis, the pinch point is at the ambient temperature. Which means that the overall cooling requirement is fact to be realised below the ambient temperature and has to be realised using a refrigeration cycle.

The current energy requirements are found to be 15185.18 [kW_{LHV}] for the heating load and 7555.9 [kW] for the refrigeration load to be compared with the minimum target values of 4904.0 [kW] and 3089.1 [kW] of refrigeration load. The energy savings corresponds therefore to 67.71 % of savings for the hot utility and 57.57 % of savings for the refrigeration load.

3.1 Identification of the penalising heat exchangers and the heat recovery potentials

The penalising heat exchangers are heat exchangers that transfer heat across the pinch point. The definition of the penalising heat exchangers has however to be completed by the existence of pseudo pinch point as the one created by the heat recovery of the evaporated vapour.

One major penalty is created by the refrigeration system that is cooling down the beer product after pasteurisation. This is a heat exchanger crossing the pinch point. The heat recovery penalty is of 3957.9 [kW], i.e 38.50 %. This saving is realised both above the pinch i.e. reduction of the heating requirement and below the pinch i.e. reduction of the refrigeration requirement where it explains 88.61 % of the savings.

The additional saving is coming from the heat recovery from the evaporation and the bottle cleaning system. Considering that the pinch point is created by the fresh water input temperature, the overall amount of heat available could be recovered in the process leading to an additional saving of 4701.6 [kW] explaining 45.7 % of the energy penalty.

It is also interesting to analyse the integration between sections. For this analysis, the Integrated Composite Curve representation is interesting. As an example, the Figure ?? shows the Integrated Composite Curve of the bottle cleaning section. One can see from this analysis that the minimum heat requirement can be divided in two major parts that could be solved dependently one from the other : the process hot section that receives 3723 [kW] the high temperature heat while 1189 [kW] are sent to the bottle cleaning sub system. 285 [kW] will be recovered from the waste heat of the bottle cleaning system to preheat the streams of the other sections while the 400 [kW] will be supplied from the higher temperature waste heat of the hot section to the bottle cleaning section.

From the analysis of the Grand Composite Curve and the Integrated Composite Curve, it is also important to notice that most of the steam used in heat exchangers or steam injection to supply heat to the process at a tempera-

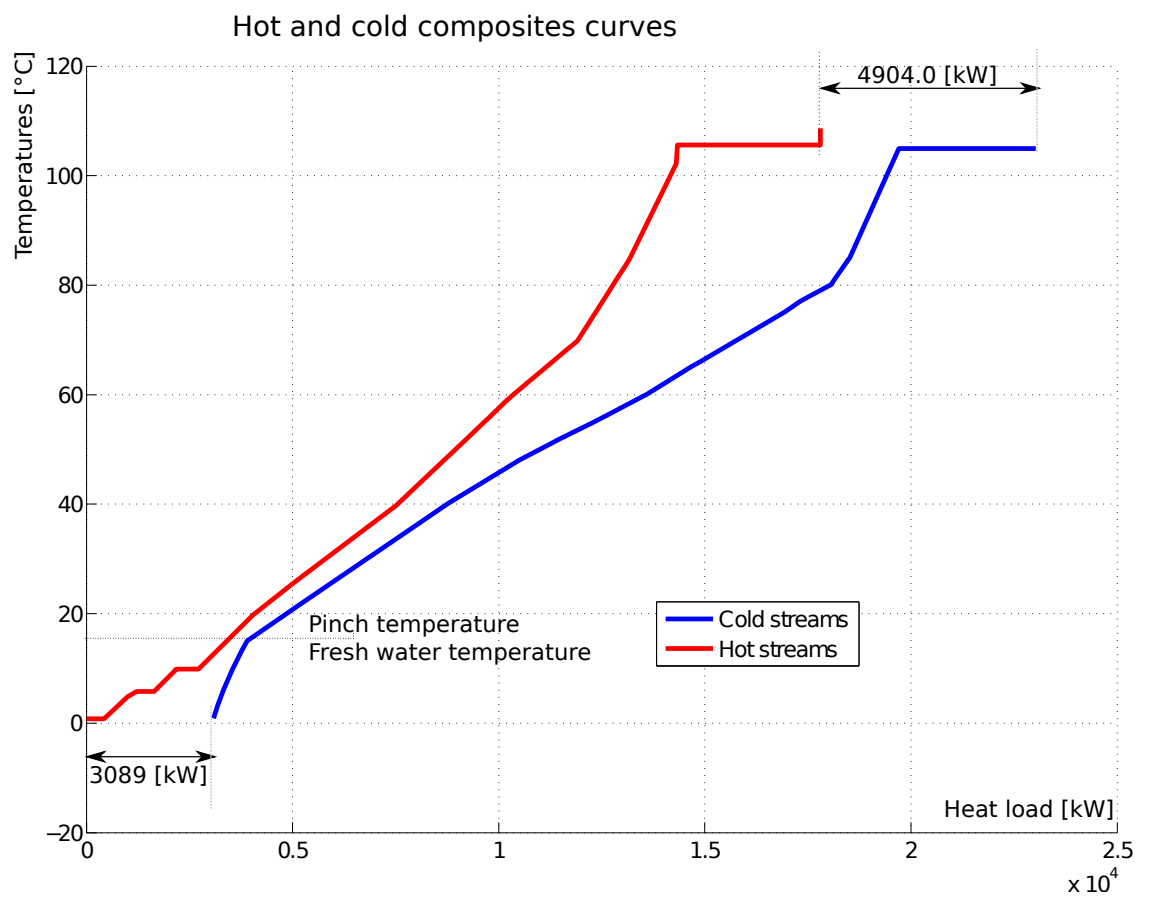


Figure 11: Hot and cold Composite Curves of the process

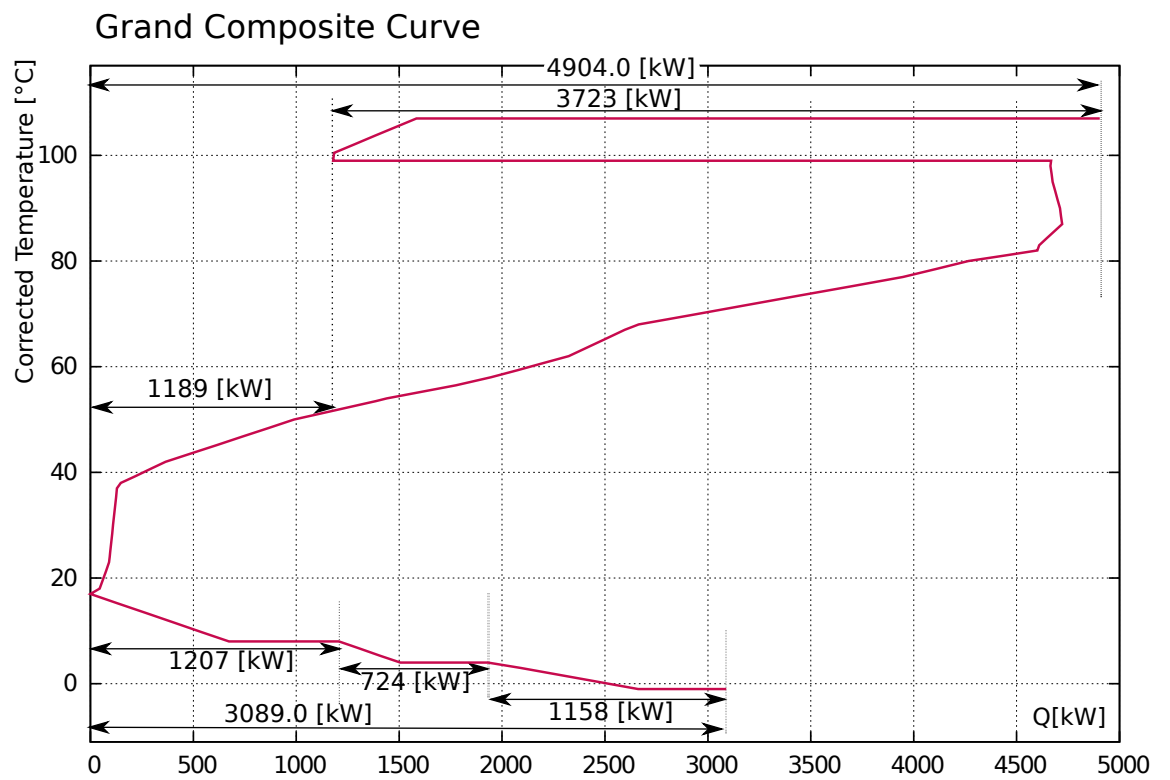


Figure 12: Grand Composite Curve of the brewing process

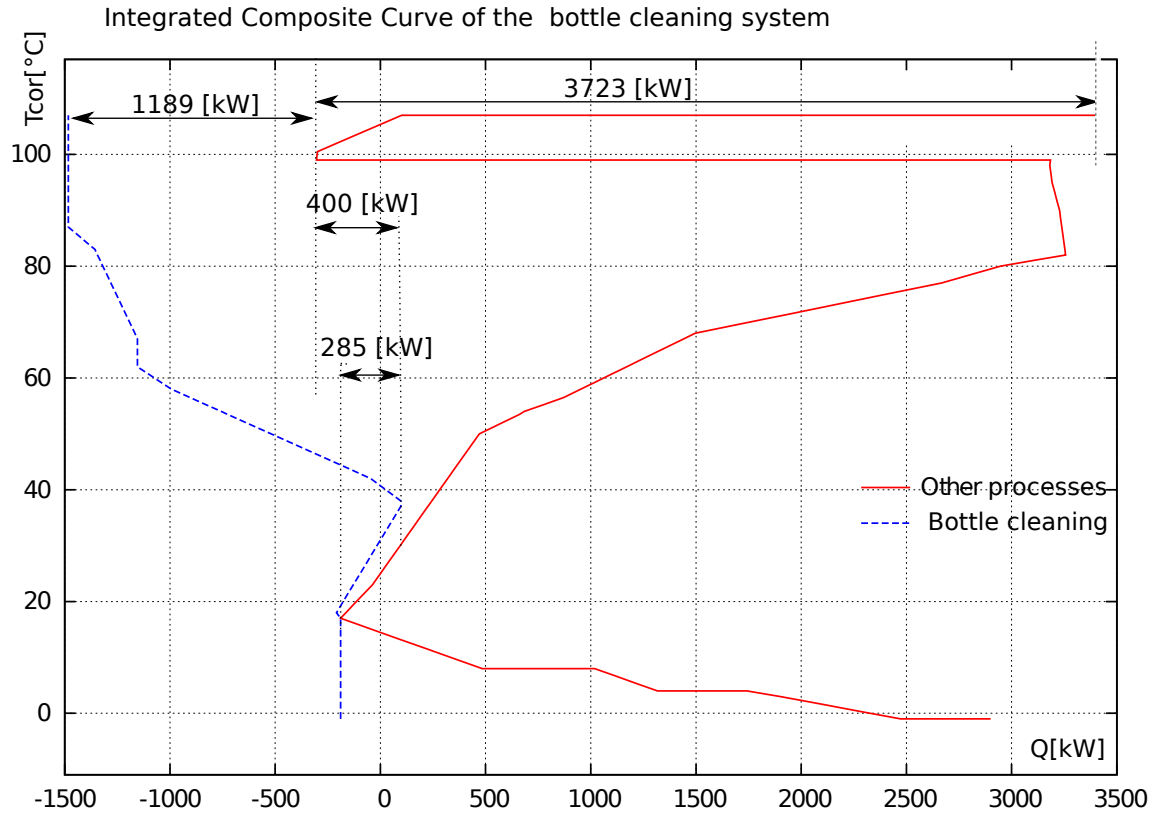


Figure 13: Integrated Composite Curve of the bottle cleaning section

ture below 96 [°C] will have most probably be changed into heat recovery heat exchangers.

4 Defining the energy conversion system

Before design the heat recovery heat exchanger network system, it is important to first analyse the integration of the energy conversion system.

Conventionally, a boiler is used to provide steam for the heating requirements and a glycol-water system powered by a refrigeration unit is used to provide the refrigeration requirements. It is however important to analyse also the possibility of integrating heat pumps and cogeneration units in order to reduce the energy bill of the process.

4.1 Grand composite analysis

The analysis of the Grand Composite Curve (Figure 12) gives already some indications of the possible energy conversion opportunities.

Above the pinch the temperature, the heat requirement can be divided into 2 different zones :

Above 105 [°C :] 3723 [kW] have to be supplied to the process mainly for the beer evaporation above 105 [°C].

from 20 to 60 [°C :] 1189 [kW] can be supplied mainly for water preheating. This could indicate the opportunity for working with a lower temperature in the boiler chimney realising flue gas water condensation for preheating process water. From this analysis it can also be concluded that air preheating would not be a valid option for the recovery boiler. Introducing condensation in the boiler and considering cooling down the gas to 40 [°C] could increase the boiler efficiency to a value of 104 % based on the lower heating value of the natural gas leading therefore to a consumption of 4715.4 [kW_{LHV}] or a gas bill reduction of 72.4 %.

Below the pinch, the overall amount of refrigeration has to be supplied by a single refrigeration cycle. In the present situation the refrigeration cycle is working with an COP (Coefficient of performance) of 5.80 [kW_{cold}/kWe]. This leads to a cost of 0.023 [€/kW_{h_{cold}}]. Assuming that the efficiency of the refrigeration cycle will not be affected by the reduction of the demand, the expected electricity consumption for the refrigeration cycle can be estimated to 532.42 [kW].

From the analysis of the Grand Composite Curve, the refrigeration demand could be divided in 3 parts :

from ambient (19 [°C]) to fermentation (10 [°C]) This corresponds to 1207 [kW] or 39.07 % of the demand.

from fermentation (10°C) to Maturation (6 [°C]) this corresponds to 724 [kW] or 23.44 % of the demand.

from maturation (6°C) to the lowest temperature (1 [°C]) corresponds to the rest of the supply, i.e. 1158 [kW] (37.49 %).

Staging the supply of the refrigeration would allow to increase the efficiency of the refrigeration system and therefore reduce the price of supplying the refrigeration load. It is possible to approximate the impact of staging the refrigeration load by using the concept of the carnot factor. For a refrigeration load $\dot{Q}_c$ at a temperature T_{cold} supplied to a source with a temperature T_{amb} , the theoretical mechanical power $\dot{E}_{ref}$ required is calculated by Eq. 3. Knowing the present consumption, one could calculate an efficiency η by Eq. 4 and consider that this efficiency will stay constant. The new consumption can therefore be calculated by Eq. 5. Table 7 gives the estimated mechanical power for the 3 levels identified. In the calculation we have considered a temperature difference of 9 [°C] between the refrigeration requirement and the supply considering the possible use of an intermediate fluid.

$$\dot{E}_c(T_c) = -\dot{Q}(T_c) \cdot \left(1 - \frac{T_{amb}}{T_c}\right) \quad (3)$$

$$\eta = \frac{\dot{E}_c(T_{ref})}{\dot{W}_c(T_{ref})} \quad (4)$$

$$\dot{W}_c(T_c) = \frac{-\dot{Q}(T_c) \cdot \left(1 - \frac{T_{amb}}{T_c}\right)}{\eta} \quad (5)$$

Temperature	Load [kW]	$\dot{W}(T = -8C)$ [kW]	$\dot{W}(T)$ [kW]
10 [°C]	1207.0	208.0	146.3
6 [°C]	724.0	208.0	103.9
1 [°C]	1158.0	208.0	199.6
Total	3089.0	532.4	449.8

Table 7: Expected mechanical power for the refrigeration loads with a reference temperature of 25 [°C](298 K)

	Annual Bill	%ref
Natural Gas	1851.45 [k€/y]	28 %
Electricity	500.44 [k€/y]	34 %
Water	3132.72 [k€/y]	497 %
Total	5484.61 [k€/y]	62 %

Table 8: Estimated new energy bill after heat recovery

Using the approximation of the exergy efficiency, one could approximate the mechanical power required to 449.8 [kW]. The staging corresponds to an expected refrigeration efficiency increase of 15.51 % and a new COP of 6.9 [kW_{cold}/kW_e]. This will also reduce accordingly the use of cooling water by 1.52 [m^3/s] which corresponds to a reduction of 0.60 %.

With this first analysis, one could therefore estimate the new energy bill after heat recovery and integration with the present energy conversion system (Table 8)

One could however realise at this stage that we assumed that the heat of the refrigeration cycle is directly sent to the cooling water and not reused in the process.

4.2 Defining the possible energy conversion technologies

4.2.1 Existing Energy conversion system

Steam boiler

As mentioned before, a boiler is used to produce steam and thus to provide the heat requirements to the brewing process. A detailed diagram is given on Figure 14. Steam is produced at a temperature of 193 [°C] and a pressure of 8.5 [bar] it is then expended to 6 [bar] in the distribution system. The condensates return at 3 bars in saturated conditions. It is then flashed to a pressure of 1.5 [bar] in a deaeration tank where it is mixed with the demineralized water make-up required to compensate the steam used in direct injections in the process. A pump (efficiency 90%) is necessary to raise the pressure of the returned condensate before it enters in to burner for heat transfer.

Refrigeration Cycle

The refrigeration needs are supplied by a ammonia refrigeration cycle (Figure 15) operating between 3.2 [bar] (-8 [°C]) and 10 [bar] (25 [°C]). The compressor

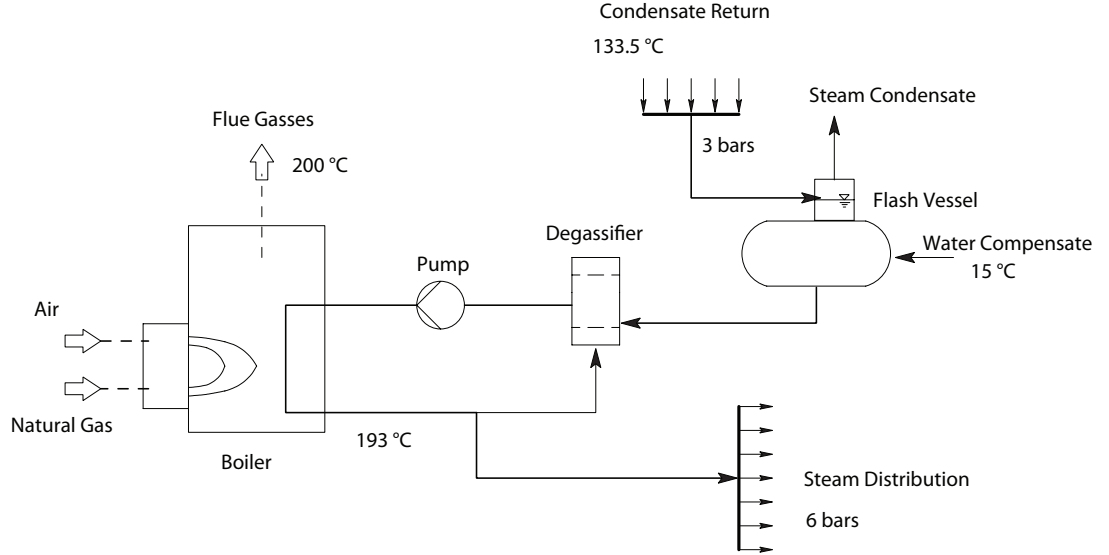


Figure 14: Steam Distribution system of the process

isentropic efficiency is 85 %. The cycle is cooled using cooling water and supplies a glycol-water distribution loop operated between -5 [°C] and -1 [°C].

4.2.2 Alternative energy conversion units

Cogeneration engine

A cogeneration engine could be used to replace the boiler system. Internal combustion engines have an attractive electrical efficiency and it is possible to recover heat from both exhaust gases and cooling water. Table 9 shows the characteristics of a typical cogeneration engine using natural gas as fuel.

According to the optimal placement of a cogeneration unit, the hot streams of the cogeneration unit should be above the pinch point. From the analysis of the Grand Composite Curve, however, one may expect problems in integrating the cogeneration unit since the temperature of the water cooling system is not high enough to supply the evaporation heat load in the process. However, based on the Grand Composite Curve analysis, one could also suggest to use water condensation in the recovery boiler in order to supply the low temperature heat.

Waste treatment and energy conversion

The husk leaving the process is hot and is rich in Carbon and Hydrogen species. The husk has a lower heating value of approximately 14.3 [MJ/kg] and that can be converted into a mixture of CH_4 and CO_2 by bio-methanation in anaerobic conditions. This reaction generally requires a specific operating temperature of 35°C that defines an new cold stream in the process.

Based on the report published by the French agency ADEME [ADEME, 2011],

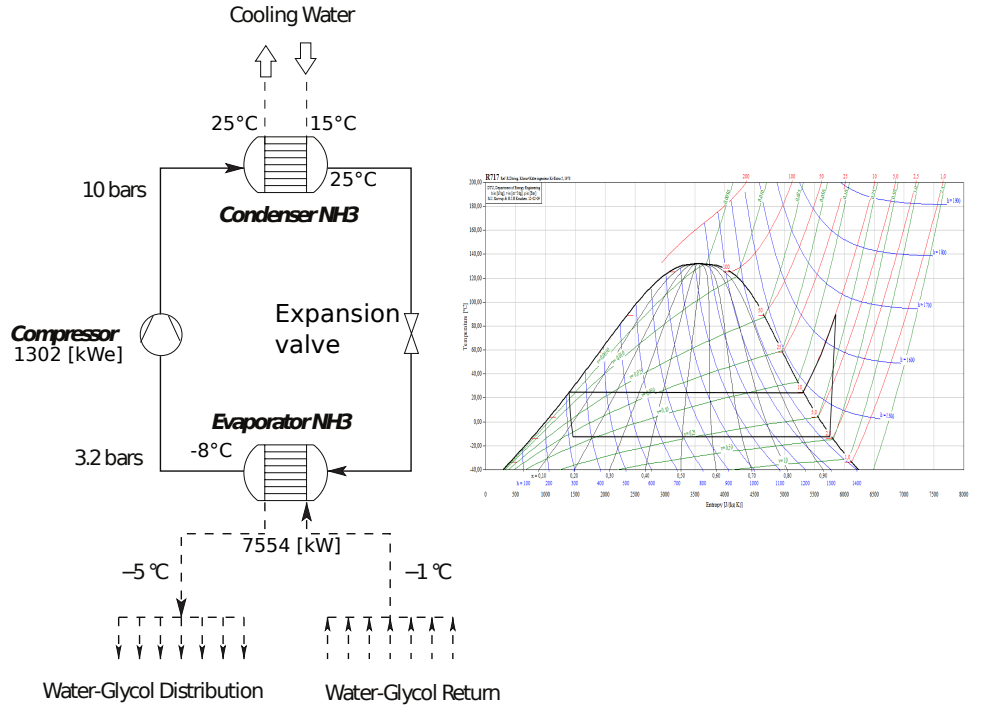


Figure 15: Ammonia cycle for producing the glycol-water cold loop

Description				Power [kW]	Efficiency [%]
$\dot{M}_{fuel}$ [kWe LHV]				2605	
$\dot{W}_e$ [kWe]				1063	40.8
Without water condensation in the flue gases					
	T_{in} [°C]	T_{out} [°C]	$\Delta T_{min}/2$	Power [kW]	Efficiency [%]
$\dot{Q}_{Gas}$ [kW]	470	120	15	537	21.0
$\dot{Q}_{Cooling}$ [kW]	87	80	2	653	25.0
$\dot{Q}_{th}$ [kW]				1190	46.0
With water condensation in the flue gases					
	T_{in} [°C]	T_{out} [°C]	$\Delta T_{min}/2$	Power [kW]	Efficiency [%]
$\dot{Q}_{Cooling}$ [kW]	87	80	5	653.	25.07
$\dot{Q}_{Gas}$ [kW]	470	60	15	632.	24.26
$\dot{Q}_{Gas}$ [kW]	60	40	15	209.	8.02
$\dot{Q}_{th}$ [kW]				1494	57.35

Table 9: Cogeneration unit characteristics based on GE-Jenbacher data, power range : 500-1100kW (<http://www.gejenbacher.com>)

Description				Power [kW]	Efficiency [%]
$\dot{M}_{fuel}[kW_{LHV}]$				2030.3	
$\dot{W}_e[kWe]$				609.1	30.0
	T_{in} [°C]	T_{out} [°C]	$\Delta T_{min}/2$	Power [kW]	Efficiency [%]
$\dot{Q}_{Cooling}[kW]$	87	80	5	424.1	20.89
$\dot{Q}_{Gas}[kW]$	470	90	15	631.7	31.11
$\dot{Q}_{Gas}[kW]$	34	35	2	351.2	17.30

Table 10: Cogeneration unit based on the biomethane produced on the process husk

75 [Nm³] of biomethane with a lower heating value of 35.7 [MJ/Nm³] can be recovered from 1 ton of husk, which represents 22430 tonnes of husk for this brewery study resulting in to the 1,674,781 m³ of possible methane production. With the proper calculations by using the lower heating value of methane we may produce 16,608 MWhLHV/year or an available mean power of 2030.3 [kW]. This production requires about 4% (81.2 [kWe]) of lower heating value as electricity for the biomethane production as well as a 20 % (406.1 [kW]) as heat to maintain the temperature in the methanation vessel. This defines a cold stream to be added in the list of the streams to be heated. The heat available in the husk is at 75 [°C] to be cooled down to 35 [°C] this makes a heat load of 54.8 [kW] (i.e. $0.762 \cdot 1.8 \cdot (75-35)$). If the biomethane produced is used in a cogeneration unit for combined heat and power production, we may expect an electrical efficiency of 34% and a thermal efficiency of 52% . Table 10 defines the resulting hot and cold streams of the biomethane production and its combustion in a gas engine.

4.3 Heat pumping

4.3.1 Refrigeration cycles integration

As the pinch point is also at the ambient temperature, the hot stream of the refrigeration cycle can also be used to supply heat to the process. The operating conditions of the refrigeration cycle have therefore to be adjusted, not only for the evaporation temperature but also for the condensation temperature. We have therefore to optimize the operating conditions of the refrigeration cycle. As the refrigeration system is using a glycol-water mixture to distribute the cold to the process, the solution will be to reuse the existing system and to reorganise the glycol water distribution system with three different temperature levels.

The operating conditions will change the amount of heat that can be recovered and therefore affect the flow of the other refrigeration cycles to be used.

The final operating conditions considered for the refrigeration cycle are given on Table 12. It would be still possible to optimize the operating conditions of the cycles if needed.

4.3.2 Mechanical Vapour recompression

The theory of the heat pump integration recommends the integration of the heat pump to raise heat from below to above the pinch point. If from the Grand Composite Curve analysis, the mechanical vapour recompression appears not

	Evaporation [C]	Condensation [C]	$\dot{Q}_c$ [kW]	$\dot{W}_{mec}$ [kW]
Conditions 1	1.0	50.0	1000.0	355.1
Conditions 2	-3.0	38.3	1000.0	312.6
Conditions 3	-8.0	26.7	1000.0	276.6

Table 11: New operating conditions for the three refrigeration cycles

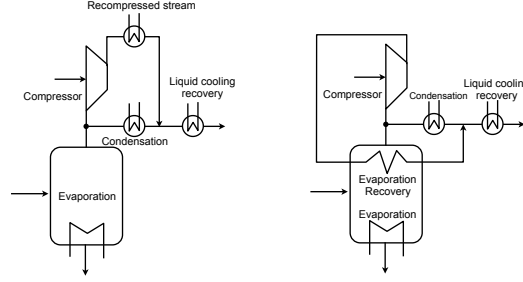


Figure 16: Mechanical vapor recompression scheme for vapour recovery

to be interesting, it will be shown that the mechanical vapour recompression is justified when the energy conversion system integration is considered. In fact the heat pumping effect of the refrigeration cycle will introduced utility pinch points that will justify the use of the mechanical vapour recompression. The mechanical vapour recompression will also help the integration of the cogeneration engine since the heat of the engine cooling water is available below the high temperature pinch point.

The mechanical vapour recompression system is described on Figure 16. It should be noted that only part of the recovered vapour will be compressed, the rest of the flow being recovered without recompression since it has already the required temperature level. It should be mentioned that the representation of the mechanical vapour recompression is identical to a close cycle. This always to visualise the evaporation heat load and the exchange with the condensing vapour. In reality, there will be no heat exchanger at the evaporation temperature, the evaporation being directly replaced by a reduction of the condensation heat load.

It has also to be highlighted that for the two streams (recompressed and not), the condensed water will be cooled down to the system limits.

	Evaporation [C]	Condensation [C]	$Max\dot{Q}_c$ [kW]	$Max\dot{W}_{mec}$ [kW]	COP
MVR 1	98.0	109.0	3434.2	150.9	23.8

Table 12: Operating conditions for the mechanical vapour recompression

4.4 Mathematical formulations

From the analysis of the Grand Composite Curve and the proposed set of energy conversion units, we can conclude that there will be more than one option for supplying the requirement of the process. In addition, one can also see that the different energy conversion systems will be interconnected or interrelated.

When looking at the energy conversion units, one can see that each one is related to hot and cold streams as well as to a cost or a resource consumption and to mechanical power consumption or production. At the difference with the process streams, the flows in the utility systems have to be optimised in order to minimise the cost of supplying the energy requirement.

Following the theory of the Process Integration, this means to maximise the flow of the cheapest utility first. If this works for simple systems, this is not anymore the case for the system under study since both hot and cold streams of the refrigeration cycles are used and that the combined heat and power production units will interact and or compete with the heat pumps and the mechanical vapour recompression.

It is therefore easier to calculate the flows by using mathematical programming techniques. The Mixed Integer Linear Programming (MILP) formulation proposed by [Marechal and Kalitventzeff, 1998b] solves the heat cascade and calculates the maximum heat recovery together with the optimal integration of energy conversion units by minimizing the operating cost (Eq. (6)) of supplying the heat and cold requirements of the process while satisfying the heat cascade constraints (Eq. 7) as illustrated in Figure 17. Introducing the electricity balances for import (Eq. 9) and export (Eq. 9), the combined heat and power production is therefore optimised considering the possibility or not of export electricity to the grid. In the formulation, the bold text corresponds to variables of the problem to be defined by the optimisation algorithm, while normal text refers to problem parameters that will not be affected by the optimisation procedure.

When temperatures are fixed, the problem is a linear programming problem since the objective function and the constraints are all linear with respect to the problem variables. The use of integer variables allows engineers to select the best utility system and to propose more than the only best selection.

Solving the MILP problem will calculate the best flows in the system considering the possible interactions between the process streams and the utility system but also considering the heat exchange interactions between two utility flows.

As this is a linear problem, the optimal solution is identified by the activation of inequality constraints. In our case, two major categories can be activated :

The pinch points correspond to the activation of $\dot{R}_k \geq 0$ constraints and will define pinch points between the Hot and Cold Composite Curves.

The maximum flow corresponds to the maximum usage allowed for a utility stream.

It has to be highlighted that, due to the heat cascade constraints (Eq. 8) it is assumed that the proposed utility system is chosen with the appropriate conditions to satisfy the process requirement. As a consequence no "magic" heating or cooling duty will be added to the system and the resulting Hot and Cold Composite Curves will be balanced.

$$\min_{\dot{E}_{el}^-, \dot{E}_{el}^+, \mathbf{f}_u, \dot{\mathbf{R}}_k, \mathbf{f}_u} F_{obj} = \sum_{f=1}^{nf} (c_f^+ \sum_{u=1}^{nu} \mathbf{f}_u \dot{E}_{f,u}^+) + c_{el}^+ \dot{E}_{el}^+ - c_{el}^- \dot{E}_{el}^- + \sum_{u=1}^{nu} \mathbf{f}_u c_u \quad (6)$$

$$\sum_{h_k=1}^{ns_{h,k}} \mathbf{f}_u \dot{Q}_{h,k,u} - \sum_{c_k=1}^{ns_{c,k}} \mathbf{f}_u \dot{Q}_{c,k,u} + \dot{\mathbf{R}}_{k+1} - \dot{\mathbf{R}}_k = 0 \quad \forall k = 1, \dots, nk \quad (7)$$

$$\dot{\mathbf{R}}_1 = 0 \quad \dot{\mathbf{R}}_{nk+1} = 0 \quad \dot{\mathbf{R}}_k \geq 0 \quad \forall k = 2, \dots, nk \quad (8)$$

$$\dot{E}_{el,process} + \sum_{u=1}^{nu} \mathbf{f}_u \dot{E}_{el,u}^+ + \dot{E}_{el}^+ - \sum_{u=1}^{nu} \mathbf{f}_u \dot{E}_{el,u}^- \geq 0 \quad (9)$$

$$\dot{E}_{el,process} + \sum_{u=1}^{nu} \mathbf{f}_u \dot{E}_{el,u}^+ + \dot{E}_{el}^+ - \dot{E}_{el}^- - \sum_{u=1}^{nu} \mathbf{f}_u \dot{E}_{el,u}^- = 0 \quad (10)$$

$$\dot{E}_{el}^+ \geq 0 \quad \dot{E}_{el}^- \geq 0 \quad (11)$$

$$\mathbf{y}_u \cdot f_u^{min} \leq \mathbf{f}_u \leq \mathbf{y}_u \cdot f_u^{max} \quad (12)$$

c_{el}^+	the purchase cost of electricity
c_{el}^-	the selling price of electricity.
$\dot{E}_{el,process}$	the electricity consumed by the process
$\dot{E}_{el}^+$	the overall electricity purchased for the process
$\dot{E}_{el}^-$	the overall electricity exported from the process
c_f^+	the fuel price
$\dot{E}_{f,u}^+$	the nominal energy (or heating value) delivered to unit u by the fuel (e.g. natural gas)
$\dot{E}_{el,u}$	the nominal electricity demand $(+)$ or excess $(-)$ of unit u
c_u	the nominal operating cost per hour of unit u (excluding the fuel and electricity costs of unit u)
with C_u	fixed cost related to the use of unit u .
$\mathbf{f}_u$	level of usage of unit u . This is a multiplication factor that is applied to all the streams and flows of the unit u .
f_u^{min}	the minimum level of usage of unit u
f_u^{max}	the maximum level of usage of unit u
$\mathbf{y}_u$	an integer variable defining the use ($\mathbf{y}_u = 1$) or not ($\mathbf{y}_u = 0$) of unit u .
$\dot{Q}_{h/c,k,u}$	the nominal heat load of hot or cold stream h/c in temperature interval k and belonging to unit u .
$\dot{\mathbf{R}}_k$	the cascaded heat from the temperature interval k to the lower temperature intervals.

Based on a formulation originally presented by Papoulias et al. ([Papoulias and I.E.,]), the MILP formulation presented here can be easily extended to introduce additional constraints like restricted matches [Becker and Maréchal, 2012a] or multi-period problems [Marechal and Kalitventzeff, 2003]. It can also be used to solve combined heat and water problems [Marechal and Kalitventzeff,] as well as to optimise the operating conditions of complex systems like integrated steam networks [Marechal and Kalitventzeff, 1999] or site scale problems [Marechal and Kalitventzeff, 1998a].

Table 13: Detailed results

Case	frg1	frg2	frg3	MVR	Cog	Bcog	combcond	comb
SA	215.7	153.8	173.0	0.0	-0.0	-0.0	0.0	4726.1
SB	368.1	224.0	208.4	0.0	-0.0	-0.0	0.0	3804.4
SC	215.7	153.8	173.0	0.0	-0.0	-0.0	4234.9	0.0
SD	346.4	211.9	202.3	0.0	-0.0	-0.0	3784.4	0.0
SE	531.6	289.6	237.7	69.0	-0.0	-0.0	1676.8	0.0
SF	531.6	289.6	237.7	0.0	6272.1	-0.0	0.0	0.0
SG	531.6	289.6	237.7	0.0	5120.3	609.1	0.0	0.0
SH	480.0	244.1	312.5	107.1	1353.4	-0.0	0.0	0.0
SI	486.5	265.9	289.6	101.3	455.9	609.1	0.0	0.0

4.4.1 Comparison of energy conversion system

In this chapter we will compare different options for the supply the heat to the process. We will consider the following scenarios of integration of energy conversion units.

Scenario A Boiler + Refrigeration

Scenario B Boiler + Heat pumping from the refrigeration cycle

Scenario C Condensation Boiler + Refrigeration

Scenario D Condensation Boiler + Heat pumping from refrigeration cycle

Scenario E Condensation Boiler + Heat pumping from refrigeration cycle and Mechanical Vapour Recompression

Scenario F Cogeneration engine + Heat pumping from the refrigeration cycle

Scenario G Cogeneration biogas engine and natural gas + Heat pumping from the refrigeration cycle

Scenario H Cogeneration biogas engine and natural gas + Heat pumping from the refrigeration cycle and Mechanical Vapour Recompression

The table ?? presents the results of the energy conversion system integration including the heat recovery options identified by the process integration analysis.

Table 14 compares the energy consumption results of the different scenarios. Primary energy is calculated by considering an efficiency of 56% for the electricity production (this is the efficiency of a natural gas combined cycle) and accounting only for fossil fuel (i.e. the biogas produced from the waste is not accounted as a primary energy resource). In this table, the scenario S0 refers to the present situation without heat recovery.

The Table 16 presents the overall results obtained for the different scenarios. For the electricity, we only consider the electricity needed by the energy conversion system without considering the electricity needed by the process itself. For calculating the operating cost, we consider the yearly operation time and do not distinguish between selling or purchasing electricity. The values of table ?? are considered to estimate the investment. Only Cogeneration and Mechanical vapour recompression are considered for the investment, for the other units as

Table 14: Energy consumption of solutions

Case	Nat. Gas [kW]	Cool. Water [kW]	El. out [kWe]	El. In [kWe]	Primary Energy [kW]	% [%]
S0	17062.0	0.0	8878.0	1322.2	19423.0	100.0
SA	4726.1	3141.6	0.0	579.7	5761.3	29.7
SB	3804.4	2539.0	0.0	834.2	5294.2	27.3
SC	4234.9	3141.6	0.0	579.7	5270.1	27.1
SD	3784.4	2890.3	0.0	797.4	5208.5	26.8
SE	1676.8	1061.2	0.0	1150.0	3730.3	19.2
SF	15680.1	8063.3	5058.3	0.0	6647.4	34.2
SG	12800.8	7148.4	4530.3	0.0	4710.9	24.3
SH	3383.4	1232.3	172.2	0.0	3076.0	15.8
SI	1139.7	674.6	0.0	107.3	1331.3	6.9

Table 15: Data for the investment estimation

Cogeneration	1.100	[k€/kWe]
Cogeneration Maintenance	0.015	[€/kWhe]
Mechanical Vapour Recompression	$4.000 * (\dot{E}_{el})^{0.9}$	[k€]
Mechanical Vapour Recompression Maintenance	0.02	[€/kWhe]
Estimated Life time of equipment	15	[y]
Interest Rate	6	[%]

well as for the investment of the heat recovery heat exchangers, the calculations have not been considered. It could be mentioned that the reuse of the existing refrigeration system should be analysed in more detail to confirm that the new compression ratio can be realised with the existing system. The operation with different operating temperature in the refrigeration implies the reorganisation of the glycol water system adding more tanks and defining a new operating strategy. It has also to be mentioned that the staging the heat recovery from the refrigeration cycle, profiting from the heat pumping effect will mean to retrofit the hot water recovery system, introducing 1 hot water storage tank per utility pinch point introduced in the system. This will require the development of a more detailed simulation model.

We give below some comments on the different scenarios.

Scenario A & B – Boiler + Refrigeration

These two scenarios allow to show the benefit of the heat recovery from the refrigeration cycle. By increasing the temperature level of the refrigeration cycle, one can see that $922.0 [kW_{LHV}]$ can be saved by the heat pumping solution. The additional mechanical power consumed is $254.5 [kWe]$ which feature an overall COP of 3.6.

The Integrated Composite Curve of the energy conversion system for the two solutions are compared on Figures 18 and 19.

Table 16: Total Cost Calculation of with investment

Case	Nat.Gas [k€/y]	El. [k€/y]	Opex k€/y]	Maint. k€/y]	Inv. [k€]	Total [k€/y]	% [%]
S0	6699.2	1405.8	8105.0	0.0	0.0	8105.0	100.0
SA	1855.7	616.5	2472.1	0.0	0.0	2472.1	30.5
SB	1493.8	887.1	2380.9	0.0	0.0	2380.9	29.4
SC	1662.8	616.5	2279.3	0.0	0.0	2279.3	28.1
SD	1485.9	848.0	2333.9	0.0	0.0	2333.9	28.8
SE	658.4	1222.9	1881.3	1.0	75.9	1889.1	23.3
SF	6156.7	-5379.0	777.6	94.1	6899.3	1488.0	18.4
SG	5026.1	-4817.5	208.5	85.9	6302.3	857.4	10.6
SH	1328.5	-183.1	1145.4	21.9	1606.5	1310.8	16.2
SI	447.5	114.1	561.6	17.5	1283.0	693.7	8.6

4.4.2 Scenario C & D – Condensing Boiler + Refrigeration

Introducing a condensing boiler could save 491.2 [kW] or 10.39 % of the Natural gas consumption in the minimum energy requirement conditions. By increasing the temperature level of the refrigeration cycle, one can see that 451.0 [kW_{LHV}] can be saved by the heat pumping solution. The additional mechanical power consumed is 217.7 [kWe] which feature an overall COP of 2.1. It is interesting to note that the saving from the condensing boiler is not anymore significant and most of the condensing heat is finally released in the cooling system.

The analysis shows therefore that although a real benefit is observed from the condensing boiler integration, the benefit is set to zero when the heat pumping from the refrigeration system is considered. The difference between scenario B and scenario C, is explained by a small reduction of the heat pumping temperature in the refrigeration cycle that leads to an increase of the efficiency of the refrigeration cycle.

4.4.3 Scenario E – Condensing boiler, refrigeration and mechanical vapour recompression

When the mechanical vapour recompression is introduced, the utility pinch point observed in scenario B and D is moved in order to reduce the flow of natural gas. The use of the mechanical vapour recompression is optimised together with the temperature of the refrigeration cycle heat recovery to profit from the heat pumping effect. The natural gas saving corresponds to 2559.0 [kW] or 60.42 % of the Natural gas consumption in the minimum energy requirement conditions. This is obtained with an increase of 570.3 [kWe] spent in the refrigeration cycles and in the mechanical vapour recompression. The COP of this scenario is of 4.49 when compared with the solution using the the condensing boiler with heat pumping.

4.4.4 Scenario F and G– Cogeneration and Refrigeration

In the scenario F and G, we compare the cogeneration systems, with and without biogas production. From the figures 23 and 24, we can see that the system is not favourable for the cogeneration unit mainly because the heat load of the

engine cooling is only partly used to satisfy the process heat load. There is also a competition with the refrigeration cycles that can not be used anymore as a heat pump.

The system becomes however a net electricity producer. When compared with scenario A, one can calculate the marginal efficiency of the electricity production by Eq. 13. For scenario F, we obtain a marginal efficiency of the electricity production of 51.47 %. The efficiency can also be observed when considering the difference in the cooling water usage that increases from 3141.6 to 8063.3 [kW] (i.e. 4921.7 [kW]).

The biogas is used to reduce the amount of natural gas consumed and contributes also to the production of mechanical power.

The Integrated Composite Curves of the two scenarios are given on Figure 23 and 24

$$\eta_{marg,i} = \frac{\dot{E}_i - \dot{E}_{SA}}{L\dot{H}V_{Si} - L\dot{H}V_{SA}} \quad (13)$$

4.4.5 Scenario H and I – Cogeneration, Refrigeration and mechanical vapour recompression

The scenario H and I consider in addition the use of the mechanical vapour recompression. Changing the temperature level of the vapour recovery allows to One can see the big advantage of doing the recompression. Without using the biogas the solution obtained corresponds to net production of mechanical power while reducing the natural gas consumption by 28.42 %. The marginal efficiency can not be calculated anymore expect if we take as a reference the scenario E. In this case, the marginal efficiency of the electricity production is of 77.46 %. Much higher than the one obtained without mechanical vapour recompression.

In both scenario, the mechanical vapour recompression concerns 70.97 % of the vapour available. The remaining vapour is directly useful to heat up process streams.

From the investment point of view, the engine of solution H is 4.6 times smaller than in scenario F without mechanical vapour recompression.

Scenarios H and I are the one the represents the lowest primary energy consumption. When comparing with starting point, i.e. 17062 [kW_{LHV}] and 1322 [kWe] corresponding to 19422.7 [kW], the primary energy saving corresponds to 84.16 % of the present consumption. When considering the use of the biogaz produced from the waste streams the saving is even more attractive with a saving of 93.15 %.

For the primary energy point of view, one should realise that the solution with combustion and mechanical vapour recompression (Scenario E) features similar results from the primary energy point of view with a saving corresponding to 80.79 %.

Considering the price of electricity and natural gas, one should realise that the solution with the lowest operating cost is the one with a maximum production of electricity. The operating cost difference has however to compensate the investment of a bigger engine.

The Integrated Composite Curves of the two scenarios are given on Figure 25 and 26

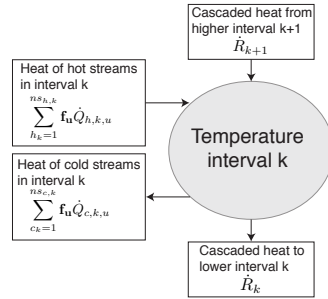


Figure 17: Graphical heat cascade representation for MILP formulation without heat exchange restrictions

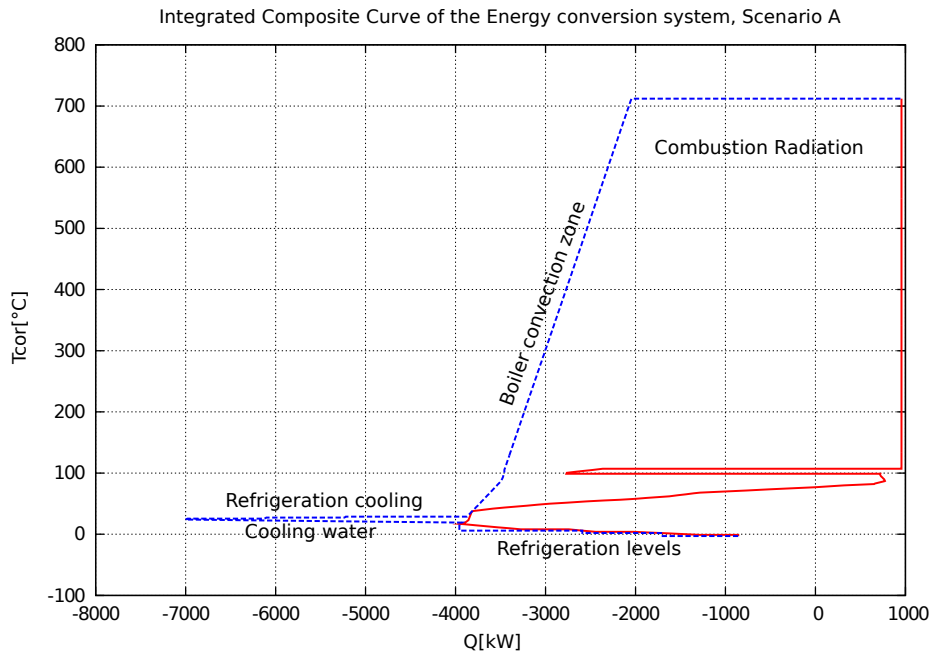


Figure 18: Integrated Composite Curves of energy conversion system for scenario A

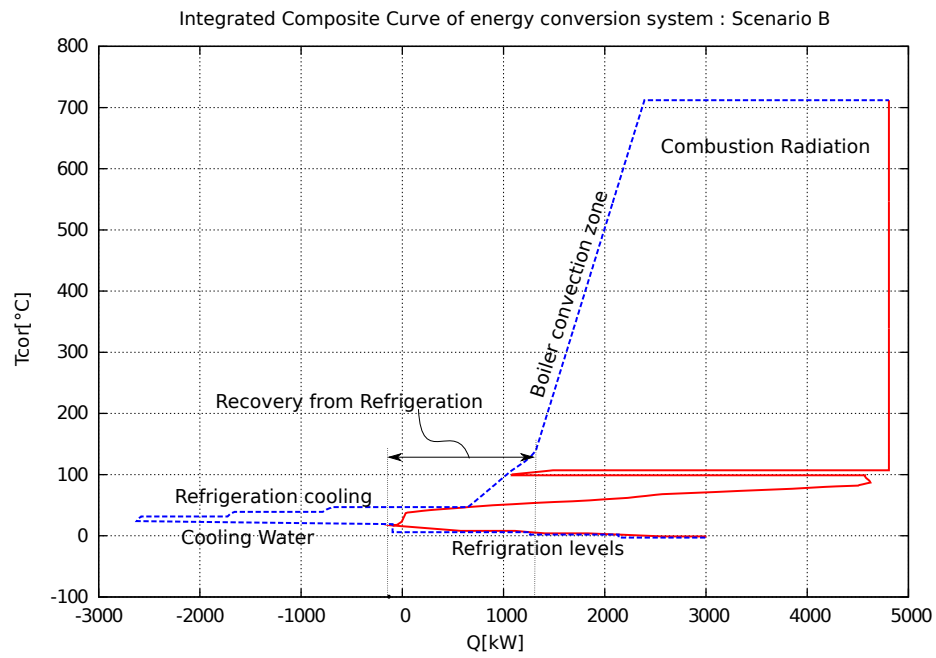


Figure 19: Integrated Composite Curves of energy conversion system for scenario B

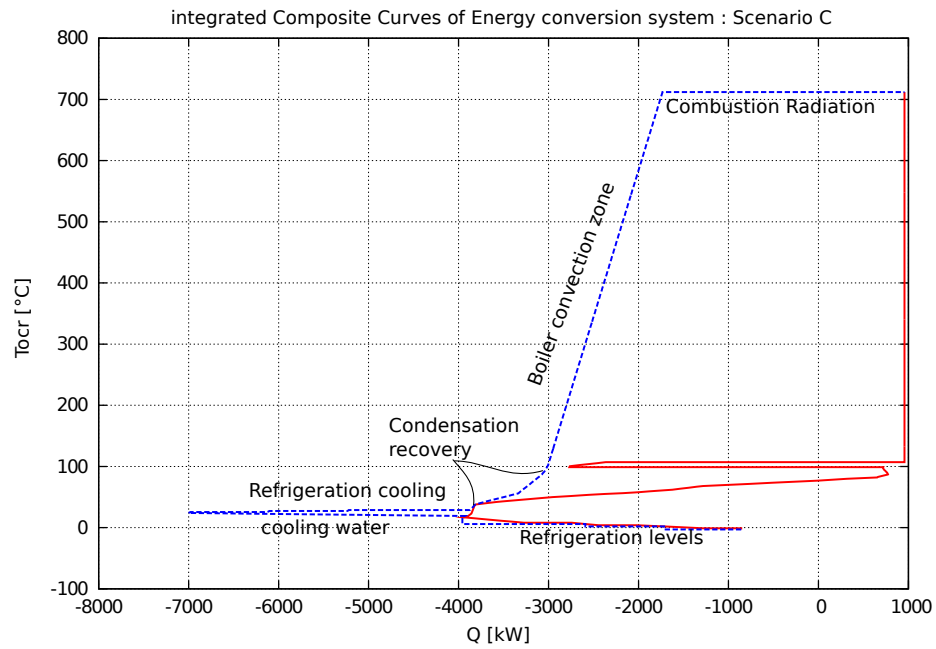


Figure 20: Integrated Composite Curves of energy conversion system for scenario C

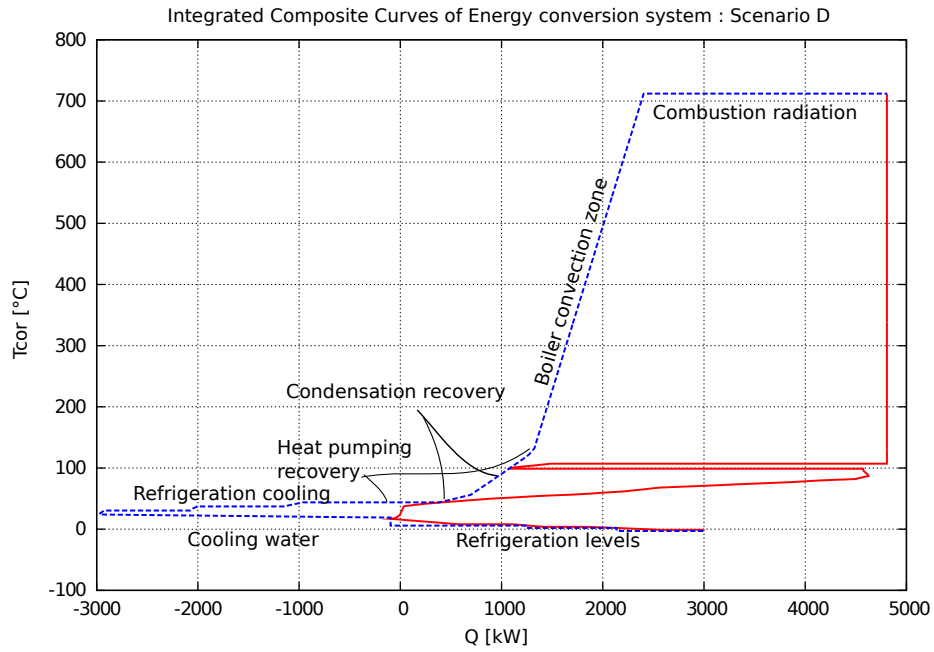


Figure 21: Integrated Composite Curves of energy conversion system for scenario D

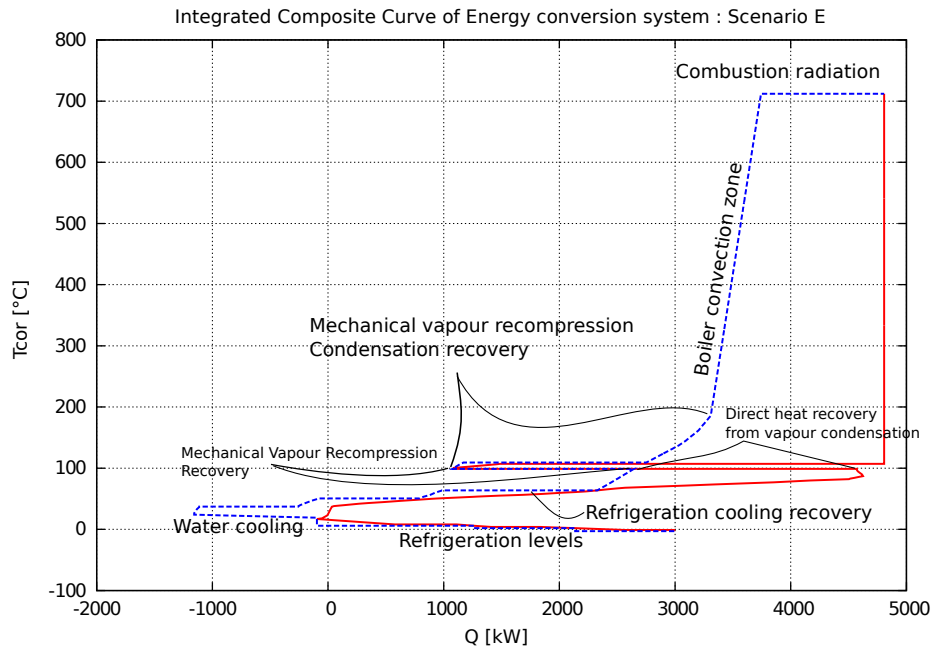


Figure 22: Integrated Composite Curves of energy conversion system for scenario E

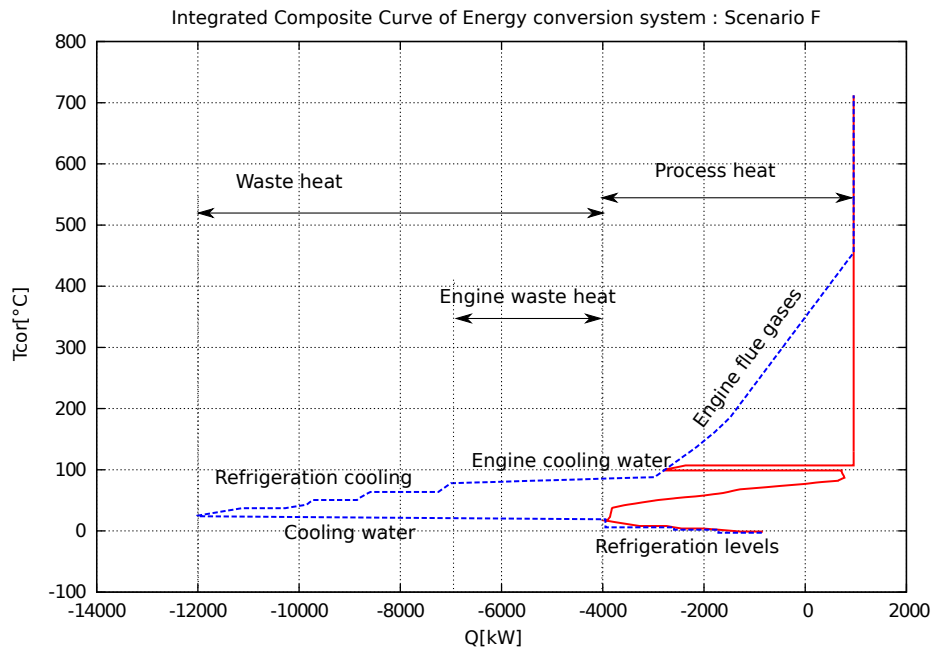


Figure 23: Integrated Composite Curves of energy conversion system for scenario F

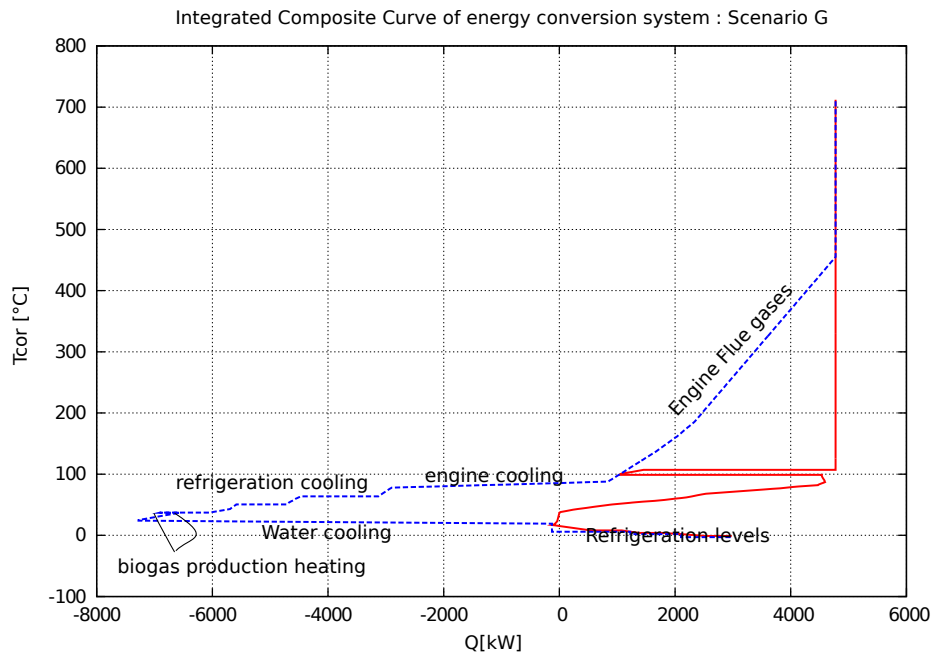


Figure 24: Integrated Composite Curves of energy conversion system for scenario G

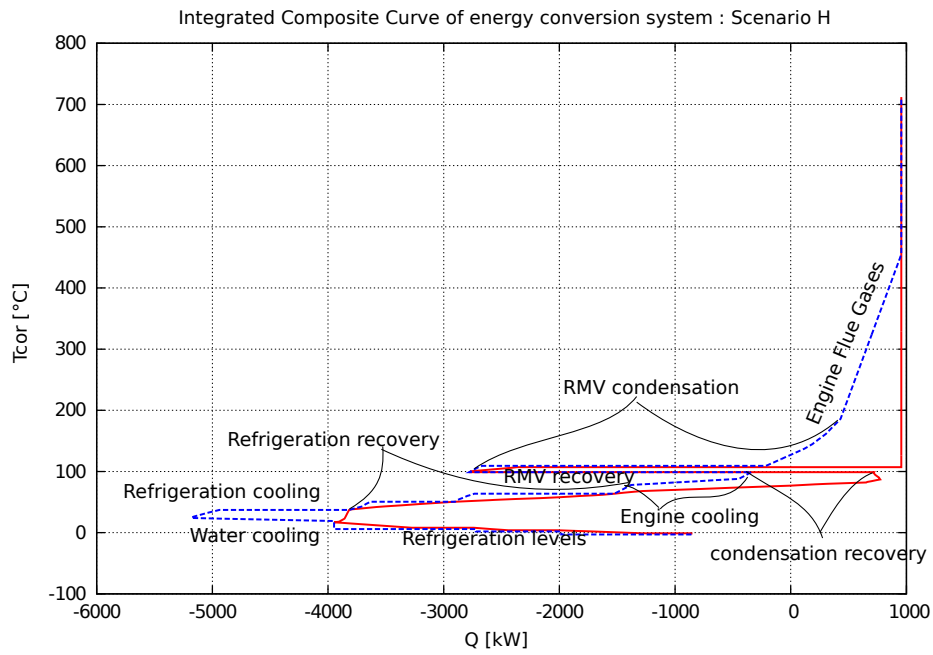


Figure 25: Integrated Composite Curves of energy conversion system for scenario H

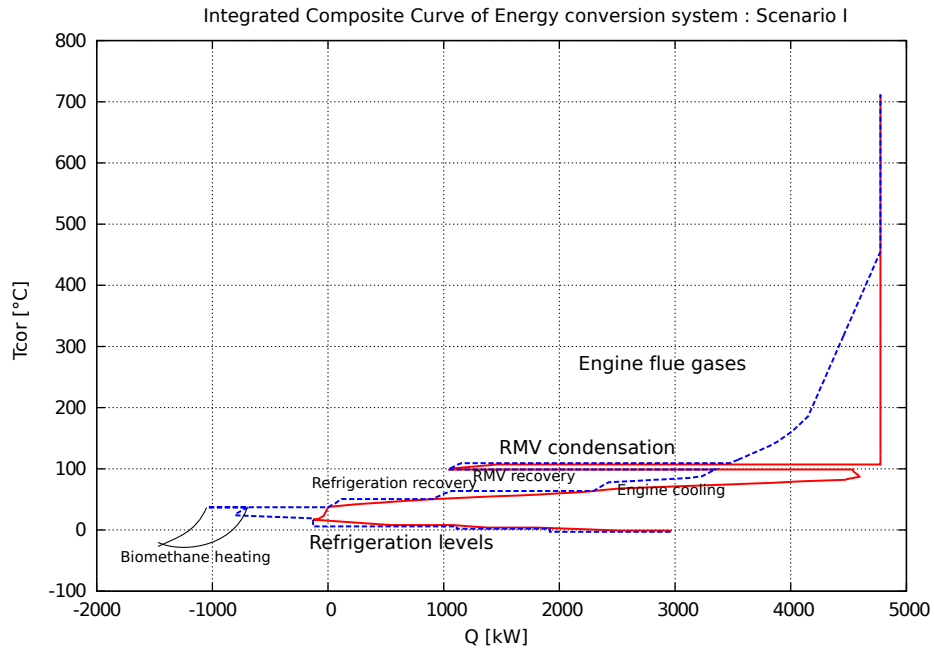


Figure 26: Integrated Composite Curves of energy conversion system for scenario I

5 Conclusion

As a result of the energy conversion system integration, the complete list of streams is defined and can be used to design the heat exchanger network design (the resulting list of hot and cold streams is given in annex). Before starting the heat exchanger network design however, one has to analyse again the list of streams, and identify in particular the streams that are related to the use of hot water. Indeed, we have first defined the needs of the units, in order to define the hot and cold streams requirement, once the energy target is set and the process and utility pinch points are identified, the list of streams to be considered in the heat exchanger network has to be defined by analysing the use of the hot water in the system.

The first step in this analysis would be to identify the conditions of the water tanks to be considered in the system. From this first analysis the water usage network has to be designed to result into a smaller number of streams to be finally considered for the heat exchanger network design. This approach could be performed by a simple examination or by applying mathematical programming models considering multi-period operation [Becker and Maréchal, 2012b] and combined mass and heat integration [Renard et al., 2012].

6 Annexes

1. Specific heat capacity of material streams

Material Stream	Specific Heat Capacity – Cp (KJ/KgK)
Water	4.18
MAK	3.75
MAT	3.43
MAT + MAK	3.52
Soda (NaOH)	1.49
Sprouted Barley / Corn	1.8

LHV Natural gas	47460	[kJ/kg]
Cost Natural gas	0.048	[€/kWh]
Boiler efficiency	89	[%]

1. $\Delta T_{min}/2$ for streams

Streams	$\Delta T_{min}/2$
Liquid	2
Liquid – Vapour	1
Gas	4

1. Brewing operation data

Description	Value
Operation Time	8180 Hours/Yearly
Daily Operation Time	24 Hour
Plant Life-time	12 Years
Maintenance Time	10 Days/Year
Failure Time	5%
Interest Rate	5%
Beer Production (68.7 Tonnes/Hour)	561.85 Thousand Tonnes / Year

1. Timeline of the batch processes in the Brewery

Stream	Process	Starting Time (Minutes)	End Time (Minutes)	Total Duration (Minutes)
1. Hot Part				
MAK	Heating 15°C to 65°C	0	60	60
MAT	Heating 15°C to 65°C	0	60	60
MAT + MAK	Heating 65°C to 75°C	60	130	70
Filtrate	Filter	130	250	120
WOK	Evaporation	250	320	70
Wort	Centrifuge	320	380	60

Wort	Cooling	380	420	40
		1. Cold Part		
Wort	Fermentation @ 10°C	14 Days		
Wort + Yeast	Maturing @ 6°C	10 Days		
Beer Chilling	Chillage @ 1°C	6-7 Hours		
Beer	Filtration + Dilution + pasteurization	2 Hours		
1. Bottle Cleaning		Continuous		

List of streams for the heat exchanger network design

Name	Temp:in [C]	Heat load [kW]	Temp:out [C]	DTmin/2 [K]	Unit
A	15.00	369.90	51.50	-2.00	MAK
B	48.00	188.60	65.00	-2.00	MAK
C	15.00	823.60	54.50	-2.00	MAK
D	48.00	420.10	65.00	-2.00	MAK
E	65.00	368.40	75.00	-2.00	MATMAK
F	15.00	3450.4	80.00	-2.00	MATMAK
G	78.00	1662.9	105.00	-2.00	MATMAK
H	105.00	3319.8	105.00	-2.00	MATMAK
L	52.00	857.90	80.00	-2.00	MATMAK
M	102.50	-5434.6	10.00	2.00	MATMAK
I	105.00	-17.200	100.00	10.00	RECOV
J	100.00	-3487.9	100.00	1.00	RECOV
K	100.00	-482.80	25.00	2.00	RECOV
N	10.00	-534.80	10.00	2.00	FERM
O	10.00	-233.80	6.00	2.00	FERM
P	6.00	-425.50	6.00	2.00	FERM
Q	6.00	-714.50	1.00	2.00	FERM
R	1.00	-427.70	1.00	2.00	FERM
S	1.00	822.05	15.00	-2.00	FERM
T	15.00	4854.0	80.00	-2.00	FERM
U	70.00	-4858.4	5.00	2.00	FERM
V	65.00	251.90	85.00	-2.00	CIP
W	40.00	472.80	60.00	-2.00	CIP
X	15.00	1326.9	85.00	-2.00	CIP
Y	15.00	29.300	60.00	-2.00	CIP
Z	35.00	399.34	60.00	-2.00	CIP
AA	85.00	-472.70	60.00	2.00	CIP
AB	40.00	-713.70	20.00	2.00	CIP
E1	470.00	-271.10	58.00	15.00	ENG

E1C	58.00	-89.835	40.00	15.00	ENG
E2	90.00	-280.06	80.00	2.00	ENG
BE1	87.00	-424.06	80.00	2.00	BENG
BE2	470.00	-631.71	90.00	15.00	BENG
BE3	35.00	351.22	35.00	-2.00	BENG
FRG1-	65.00	-62.913	55.00	1.85	FRG1
	65.00	-1229.2	65.00	1.16	FRG1
	190.85	-436.07	65.00	5.00	FRG1
FRG1_	1.00	1241.6	1.00	-5.00	FRG1
FRG2-	51.67	-37.352	41.67	1.85	FRG2
	51.67	-802.01	51.67	1.16	FRG2
	166.55	-231.13	51.67	5.00	FRG2
FRG2_	-3.00	804.57	-3.00	-5.00	FRG2
FRG3-	38.33	-44.886	28.33	1.85	FRG3
	38.33	-1042.7	38.33	1.16	FRG3
	142.18	-245.28	38.33	5.00	FRG3
FRG3_	-8.00	1043.3	-8.00	-5.00	FRG3
RMV-	110.00	-4.4050	109.00	1.36	RMV
	110.00	-2322.2	110.00	0.85	RMV
	148.56	-81.933	110.00	3.67	RMV
RMV_	98.00	2307.2	98.00	-1.00	RMV
COOLW	17.00	674.62	22.00	-2.00	COOLW

7 Further Readings

Handbook of Water and Energy Management in Food Processing edited by University of Pannonia Hungary R Smith J Kleme? EC Marie Curie Chair and U K J-K Kim University Of Manchester. Woodhead Publishing Ltd, 2008.

Thermodynamic and Energy System Analysis , L. Borel, D. Favrat, EPFL Press, Lausanne, Switzerland 2010, 399.

Computer Aided Process and Product Engineering – CAPE , edited by Luis Puigjaner and Georges Heyen. WILEY-VCH, ISBN-10: 3527308040, ISBN-13: 978-3527308040, 2005.

Improving Process Performances Using Pinch Analysis by Francois Marechal, In UNESCO Encyclopedia of Life Support Systems, edited by Christos Frangopoulos and Georges Tsatsaronis. EOLSS Publishers Co Ltd., 2008.

Pinch Analysis by Francois Marechal In UNESCO Encyclopedia of Life Support Systems, edited by Christos Frangopoulos and Georges Tsatsaronis. EOLSS Publishers Co Ltd., 2008.

8 Bibliography

References

- [ADEME, 2011] ADEME (2011). à la FERME Guide pratique. Technical report.
- [Becker and Maréchal, 2012a] Becker, H. and Maréchal, F. (2012a). Energy integration of industrial sites with heat exchange restrictions. *Computers and Chemical Engineering*, 37:104–118.
- [Becker and Maréchal, 2012b] Becker, H. and Maréchal, F. (2012b). Targeting industrial heat pump integration in multi- period problems. *Proceedings of the 11th International Symposium on Process Systems Engineering*, (July):415–420.
- [Linnhoff et al., 1988] Linnhoff, B., Ashton, G., and Obeng, E. (1988). Process integration of batch processes. *ICHEME Symposium Series*, 109:221–237.
- [Marechal and Kalitventzeff,] Marechal, F. and Kalitventzeff, B. *Computer Aided Process and Product Engineering – CAPE*, chapter Utilities. WILEY-VCH, ISBN-10: 3527308040, ISBN-13: 978-3527308040.
- [Marechal and Kalitventzeff, 1998a] Marechal, F. and Kalitventzeff, B. (1998a). Energy integration of industrial sites: tools, methodology and application. *Applied Thermal Engineering*, 18(11):921–933.
- [Marechal and Kalitventzeff, 1998b] Marechal, F. and Kalitventzeff, B. (1998b). Process integration: Selection of the optimal utility system. *Computers and Chemical Engineering*, 22(Supplement 1):S149—S156.
- [Marechal and Kalitventzeff, 1999] Marechal, F. and Kalitventzeff, B. (1999). Targeting the optimal integration of steam networks. *Computers and Chemical Engineering*, 23:s133–s136.
- [Marechal and Kalitventzeff, 2003] Marechal, F. and Kalitventzeff, B. (2003). Targeting the integration of multi-period utility systems for site scale process integration. *Applied Thermal Engineering*, 23:1763–1784.
- [Papoulias and I.E.,] Papoulias, S. A. and I.E., G. A structural optimization approach in process synthesis - I. Utility systems. *Computers and Chemical Engineering*, 7(6):695–706.
- [Renard et al., 2012] Renard, L., Périn-levasseur, Z., Salgueiro, L., and Savulescu, L. (2012). Combined heat and mass integration : A benchmarking case study. (June):17–20.