Analysis of Ethanol production from biomass for transportation’s uses

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Semester Ma1 project, SGM
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Abstract

Since the earth faces global warming problems and future oil missings, we must find ways to replace Petroleum in energy production. In the transportation, Petroleum can be replace by Biofuels in a first stage. To fill in the gap between these 2 kind of fuels’ efficiencies, we must optimize the uses of energy in production of biofuels. The most available biomass in Switzerland is Sugar Beet. The Betalcool process is designed for production of Ethanol 95% in the medium size industry. The most important energy consumers are distillations (385 kW of heat) and electrical components (119kW). The contribution of other stages can be neglected. So optimization is reduced to increase efficiency of heat producers for distillation, and electrical components. The margin is really small! The progresses would not be so significant. Integration of a cogeneration engine is an interesting step, to improve both electricity and heat effectiveness.

The cost of one liter of ethanol is interesting, close but a bit lower than the current price of fuels, even in the worst configuration. Importation of Ethanol could be considered since it still presents interesting costs.

It is important to add that biofuels’ worse properties in combustion comparing with fossil fuels’ ones is a major handicap we do not talk about in this analysis, but that must be emphasize.
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Aan mijn grootvader,
voor alles dat hij me gegeven heeft
Introduction

"The climatic crisis even threatens the future of our civilization"¹

Al Gore

"What a planet are we leaving to our children? In this true question that we all wonder about, ecologists have found an amazing goodwill."²

J.P. Croizé

In this quotes is summarized what may be the 21st century’s biggest debate. Nowadays, all the new political programs and speeches have to contain a few paragraphs on ecology and environment while some countries still refuse to ratify Kyoto’s protocol. Scientists dispute themselves on either or not the Earth is unusually warming up. Behind these questions, are clashing thousands of interests. The polemic’s stakes includes the entire world Geopolitics. Every country whose economies are based on the petroleum industry could face an unbelievable drop off of their political influence. All the Middle East that already has difficult times may face a social and economical crisis. The huge Petroleum Companies that hold some complete national health could go bankrupt in a few years. From this few examples, it’s unbelievable that these institutions stay unconcerned to these problems and so on, we can’t deny that the debate is under influences.

But hidden behind this bustle subsists an even more worrying matter: we are running out of fossil energies! Some conflicts also persist for the same reasons. But the truth is that our increasing demand for fossil fuels is facing the worldly production peak. Before totally replacing petroleum, we have to reduce our consumption, and Biofuels are a first answer to it. This early solution also offers the possibility to reduce the pollution by carbon dioxide.

However, Biofuels are not a miraculous issue. Energetic efficiencies of its uses are lower than fossil energy’s. Here is why it asks for high developed technologies as well in production as in utilization.

We must note that this phenomenon is worldly, and that all the countries do not have same exposures to Biofuels. Considering Ethanol as the base of them, we can show that kinds of feeds are plentiful, and so are the technologies to get Ethanol. In this paper we will focus on Ethanol production in countries like Switzerland. But every feed is useful in order to produce Bio-fuels all over the world. Once a production process analyzed from an energetic view, we will focus on costs. The study of current energetic processes and their possibilities to be optimized will help us to realize what level of technical progresses can still be expected, and the economical analysis will emphasize the competitiveness of ethanol as a fuel. These 2 faces of production will offer us a good outline of the first part of Ethanol’s potential and so on of its future.

¹USA Senator / "An inconvenient truth" / Real. David Guggenheim
²French Scientific Journalist / "Ecologistes, petites esbroufes et gros mensonges" / ed. Broché
Part I
Choosing a biomass

1 How to get Ethanol

Ethanol is an alcohol obtained by fermentation of kinds of sugar. This operation is actually biological. Adding yeast to the mash of sugar collected from the plants, allows the conversion of sugars into ethanol and carbon dioxide. The most used molecule of sugar is Glucose and its fermentation is given by:

\[ C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \]  

or

\[ glucose \rightarrow 2ethanol + 2carbon dioxide \]

According to the Gay-Lussac’s theory (1815), based on this equation, the amount of ethanol produced by an ideal fermentation of 1 kg of glucose should be pretty much 0.511 kg. The remaining products are 0.489 kg of carbon dioxide. However the real quantity of ethanol produced depends on several parameters as temperature, pH, or sugar concentration into the mash. The amount of Ethanol really produced is about 0.484 kg, which represents an efficiency of 95.7. These losses are due to the creation of co-products like glycerol or succinic acids due to unexpected reactions of sugars.

2 Biomasses

2.1 Three kind of biomass

As we have seen before, producing Ethanol means transforming Glucose into alcohol. However all the kinds of biomass used for the Ethanol production, do not contain directly fermentable sugar. Indeed one can easily get glucose from other chemical molecules. For instance sugar can also be obtained from starch or cellulose, and even if these sources ask for one more step in the Ethanol production process, their efficiencies forced us to take them into account. Consequently we can now make out the 3 main biomasses we could use to produce ethanol:

- Sugar-containing plants
  As they offer directly sugar from crops, the production process of Ethanol from sugar-containing plants is straightforward. Sugars are partially extracted from the plant by diffusion, crushing or pressing. Then are the fermentation steps, and finally the distillation that takes apart Ethanol from the mash. The three main plants of this group are: Sugar Canes, Sugar Beets and Sweet Sorghums.
• Starch-containing plants

The transformation of starch into sugar (or glucose) is the main distinction between the sugar-containing and the starch-containing crops’ uses. Once the grains crushed, an hydrolysis of starch is made to obtain maltose. (Equation below)

$$2C_6H_{10}O_5 + H_2O \rightarrow C_{12}H_{22}O_{11} \quad (3)$$

The next step, called saccharification, split the oligosaccharides molecules (the starch) into monosaccharides ones (fermentable sugar) using enzymes. (Equation below).

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6 \quad (4)$$

Later on, one can normally proceed to the usual chemical operations of fermentation and dilution. The most known and used plants in this group are for sure corn, sweet-potatoes and barley.

• Lignocellulosic feedstock

Obtaining fermentable sugars from lignocellulosic feedstock asks for an hydrolysis of the cellulose’s polymer molecules to obtain glucose’s monomer. And then are following the traditional fermentation and distillation steps. This group is actually the most representative of the "renewable energy" concept, using mainly wastes from agriculture and forests.

2.2 Comparison of the biomasses

For our energetic study of the production process we shall have to choose one category of biomass, and afterward one feed of this category. To be able to compare our options and to select one of them, we would better define the main criterions we are looking for. Our goal is "to study the most efficient and the most widely realizable ethanol production process we could get". That’s why we will evaluate the alternative we have seen according the 3 following points:

• The total energy needed to produce a quantity of ethanol

This parameter is pretty logical. The aim of biomass’ utilization in energy is to reduce the pollution due to the energy processes we use nowadays and by the way to reduce the energy consumption. That’s why we could consider this point as the most important.

This table shows clearly that the production of ethanol from sugar-containing plants is the cheapest from an energetic point of view. This result can be easily explained by the need of one more step in the starch-containing and cellulosic plants’ transformation to ethanol. However, Cellulosic Plants can not be compared to the others simply like that. Indeed, the definition of an energetic cost for producing ethanol from cellulosic plants should take into consideration that these feedstock are usually wastes. It corresponds to a revalorization of an energy seen as "end of
Table 1: Net energy balance for Biomass-to-Ethanol production

<table>
<thead>
<tr>
<th></th>
<th>Corn</th>
<th>Sugar beets</th>
<th>Cellulosic feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel process energy</td>
<td>0,75</td>
<td>0,65</td>
<td>1,70</td>
</tr>
<tr>
<td>( E_{\text{used}}/E_{\text{recovered}} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total energy used to produce liter (kWh)</td>
<td>63225</td>
<td>54795</td>
<td>101160</td>
</tr>
</tbody>
</table>

Pipe" in its previous cycle. That’s why a pretty good energetic analysis of this kind of production should be done on all the successive life cycles, and not considering only the last process of transformation to Ethanol. Thus, we can not choose which one is better between cellulosic and sugar-containing plants, but in any case, we can affirm that sugar-containing are cheaper than starch containing.

- **The surface needed to cultivate the amount of biomass required to produce a quantity of ethanol.**

  The main problem we usually heard about using biofuels in our society is the lack of place we would have to produce enough biomass.

<table>
<thead>
<tr>
<th>Sugar plants</th>
<th>Agricultural efficiency ( (t/\text{ha}) )</th>
<th>Ethanol efficiency ( (l/\text{t of plant}) )</th>
<th>Ethanol efficiency ( (m^3/\text{ha}) )</th>
<th>Energetic efficiency ( (\text{tep}/\text{ha}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar beet</td>
<td>70-75</td>
<td>92</td>
<td>6,5-7,0</td>
<td>3,3-3,5</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>80-90</td>
<td>85</td>
<td>7,0-8,0</td>
<td>3,5-4,0</td>
</tr>
<tr>
<td>Sugar sorghum</td>
<td>50-60</td>
<td>80</td>
<td>4,0-5,0</td>
<td>2-2,5</td>
</tr>
</tbody>
</table>

Table 2: Sugar plant efficiency and their alcoholic potential

<table>
<thead>
<tr>
<th>Cereals</th>
<th>Agricultural efficiencies ( (t/\text{ha}) )</th>
<th>Grain’s starch concentration</th>
<th>Ethanol efficiency ( (l/\text{t de grain}) )</th>
<th>Ethanol efficiency ( (m^3/\text{ha}) )</th>
<th>Energetic efficiency ( (\text{tep}/\text{ha}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>7,2-8,3</td>
<td>62-65</td>
<td>370</td>
<td>2,7-3,1</td>
<td>1,4-1,6</td>
</tr>
<tr>
<td>Corn</td>
<td>7,2-8,5</td>
<td>72</td>
<td>400</td>
<td>2,9-3,4</td>
<td>1,5-1,7</td>
</tr>
<tr>
<td>Orge</td>
<td>5,0-7,0</td>
<td>56-59</td>
<td>320</td>
<td>1,6-2,2</td>
<td>0,8-1,2</td>
</tr>
</tbody>
</table>

Table 3: Cereals culture’s efficiencies and their alcoholic potential

By comparing the two tables below we can quickly make out, from the columns "volume of ethanol produced by hectare", that the surface needed is up to 3 times more important for starch-containing than for sugar-containing. This parameter gives a serious advantage to the direct production from sugar!
Inside the sugar-containing category, the plant that needs the smallest surface is the sugar cane, closely followed by beets.

- **The process' technical and economical feasibility.**

  Even if this point will be difficult to analyze in a couple of lines, we will try to figure the main difficulties out for those processes. The first parameters we should look after is the conditions on weather the production of these plants imposed.

  Sugar cane can be cultivated between 10° C and 30° C. It needs a lot of water, and an heavy floor. This plant usually enjoys the tropical climate like in the north of Brazil. The sugar cane can not survive under 0° C, as the sugar starts to freeze.

  The Sugar Beet is cultivated in moderate climates. Since the temperature do not go down to −5° C, it does not really care about temperature. Below this critical level, the sugar also freeze just like it does for Sugar Canes. Beet is the most appropriate for countries like the Center Europeans or the North Americans.\(^3\)

  The culture conditions for potatoes, corn and barley are almost the same that beets'ones.

  Finally the lignocellulosic can be found worldwide, excepting Deserts.

  The cost for cultivating those feedstock can be seen as equal for each one. All of them need manures and labor to plant and collect.

  From a technical view, the main differences between the processes are the stages before fermentation. While Sugar Beets just ask for crushing and mixing, the Lignocellulosic feedstock also ask for a pre-treatment and an hydrolysis to transform Cellulose into Glucose. To transform Starch into Glucose, the processes based on starch-containing plants ask for a saccharification step instead of hydrolysis. So that Sugar Beets offer a simplified Ethanol production process, and by the way more economical.

3 Sugar beets at a Glance

From this quick overall analysis, we conclude that beets seem to be the most efficient plants to produce Ethanol. Nevertheless we must admit that cellullosic feedstock are, despite of the difficulties in analyzing its efficiency, a truly promising process since it can regenerate energy from sources considered as dead.

Beet produces sugar during the first year of growth that’s why it can be harvested in the middle of his development for the production of sugar. The largest amount of sugar is stored in the fleshy root. Their averaged chemical composition is given in figure 1.

In fact the composition of sugar beets can even change within plants harvested in same fields. This variations still increase with changes of climates.

\(^3\)All datas from the United Nations Conference on Trade and Development: www.unctad.org
To conclude this part, it is essential to note that the solution to the substitution of fossil energy do not consist in only one new source of energy. All the kind of biomass would have to be used, sometimes according to the country, sometimes also according to the seasons. The end of fossil energy can not happen slowly without the use of all the sources of renewable energy we have.
Part II
Analyzing production: Betalcool

4 The Betalcool process

The use of biofuels aims to reduce emissions of polluting gas from engines' combustion. But what would be the interests of biofuels if their productions were worst than usual fuels' ones? Thinking this way, Enest Badertscher and Manfred Steiner, two members of the ADER association, have developed a process for Ethanol production that decreases all the emissions to Nature.

The used method is based on the main principle of Industrial Ecology: the energetic symbiosis. It consists in a re-use, wherever it can be, of energy seen as "end of pipe" in traditional processes. For the 2 inventors, the goal was to use matter and energy in closed track between the production process and its environment. Therefore the "garbage" made by the process would have to be totally consumed by Nature and given back as raw materials. The key of such an idea is the optimization of the energies uses. And here is the specialty of Betalcool. The process is quickly presented by the figure below.

Beets are directly crushed from fields. No washing with water, and no peeling. This is the first huge economy of energy (up to 7 liters of water by kilos of beet). Afterward, juice of beet is mixed with yeast in severals tanks to ferment sugars. Then, residuary liquors are separated from fermented juice by centrifugation, and stocked into big containers to produce Methane. The gas will be used as a fuel to produce heat for distillation, and "rubbishes" as manure for fields. The distillation of fermented juice gives 95% Ethanol, and the separated liquors are put into the containers for methanisation. As results we have only the carbon dioxide produced by fermentation and combustion of Methane, and manures given by the methanisation step, that are returned to Nature; Carbon dioxide will be consumed by the photosynthesis of plants, and manures will feed the fields cultivated. Each stage will be described more deeply during its energetic analysis. The detailed flowsheets
are put in annexes at the end of this document. For the whole process' analysis we will admit several assumptions.

**Hypothesis:**

1. Temperature and pressure are similar for every stages’ input and output: 20°C and 1 bar
2. The mixing of feed by $CO_2$ is perfect in each tank so that we have homogeneous concentrations in there.
3. No Ethanol losses during Centrifugation and Distillation
4. Yeasts and enzymes don’t have mass
5. As the mixing CO2 is used in close track, we suppose that all CO2 produced is evacuated.

## 5 Analysis of individual stages

### 5.1 Fermentation

Betalcool’s fermentation is singular since it uses both enzymes and yeast to hydrolyze beets’ Cellulose and transform Glucose all together. Fermentation is a complex chemical process. From a thermodynamic point of view it can be quickly resumed by applying mass and energy conservation laws. In such an analysis we will see the fermentation tanks as one black box where chemical reactions take place. We can first calculate from flowsheets, the mass input and output of the process. Then we could get the energy exchanged and finally give a survey of the tanks’ size.

- **Mass balance**
  
  We know from the flowsheets that 4200 kg of beet are used per hour to produce 420 L/h of 95% Ethanol.
Input:
Data from figure 1:

100 kg of beets → 16,5 kg of Sucrose & 0,94 kg of Cellulose

If we suppose that cellulose hydrolysis is complete, using equations (3) and (4) we have:

100 kg of beets → 16,5 + MC₆H₁₀O₆ × 0,94 / MC₆H₁₀O₅ = 17,54 kg of glucose

With a 4200 kg/h sugar beet input flow, we get a total of 736,86 kg of glucose entering the process every hours.

Output:
As we know the rate of Ethanol at the end of the process from flow-sheets, we can easily calculate the concentration of ethanol leaving the fermentation tanks. As the concentrations are homogeneous we know, by the way, about concentrations in the last tank.

\[ \dot{M} \cdot c_{C_2H_5OH} = 420 \cdot 0,95 \cdot 0,805 \]

\[ \Leftrightarrow c_{C_2H_5OH} = \frac{420 \cdot 0,95 \cdot 0,805}{4200} = 7,55\% \]

So the Ethanol flow has to be 7,55 % of the total mass flow, and its concentration in the last tank is also about this amount of the total mass.

Using equation (1) from Gay-Lussac theory, we can get the sugar and CO₂ concentrations at the end of the fermentation process by applying the mass conservation.

\[ c_{C_6H_{12}O_6}_{out} = \left( c_{C_6H_{12}O_6}_{in} - \frac{1}{2} \cdot \frac{c_{C_2H_5OH}_{out}}{\tilde{m}_{C_2H_5OH}} \cdot \tilde{m}_{C_6H_{12}O_6} \right) = 2,78\% \]

\[ c_{CO_2}_{out} = \frac{c_{C_2H_5OH}_{out}}{\tilde{m}_{C_2H_5OH}} \cdot \tilde{m}_{CO_2} = 7,216\% \]

We can check that mass is conserved! Those flows come down to figure 3.

Energy balance
Ethanol fermentation reactions are exothermic! Referring to the first hypothesis, both flows entering and leaving the process are at atmospheric temperature, that’s to say 20°C. As we consider steady state conditions, the all Energy released by fermentation has to be transferred to Nature. We take, \( \Delta h^0 = 871.1 \text{ J/kg}^4 \) as an average value of massic enthalpy for Ethanol

\[^4Ullmann’s Encyclopedia of Industrial Chemistry^ / J. Wiley & Sons (2005)\]
fermentation from Glucose, with standard conditions and pH 7. Applying first principle conservation laws to our model of fermentation, we get:

\[
\dot{Q}^- = (M_{C_6H_{12}O_{6in}} - M_{C_6H_{12}O_{6out}}) \cdot \Delta h^0
\]

\[
\Leftrightarrow 2400 \cdot (0.1754 - 0.0278) \cdot 871,1 = 85,71W
\]

- **Effectiveness**

\[
\epsilon_{ferm} = \frac{\dot{Q}^-}{\Delta h^0} = 0 = 0
\]

Since we admit that all the Energy released by the chemical reaction is directly given to the Atmosphere, this operation has no sense from an energetic point of view. It has nothing but chemical interests.

- **Efficiency**

\[
\eta_{ferm} = \frac{(1 - \frac{T_a}{T}) \cdot \dot{Q}^-}{\Delta k^0} = 0 = 0
\]

From the precedent calculus, we normally find this result.

### 5.2 Centrifugation

In all the fermentation process, Mash is liquid thanks to the enzymes we added for Celluloses’ hydrolysis. This allows us to pump it from a tank to another one. When the fermented feed leaves the ultimate tank, CO₂ is released, and the liquid go straight to the centrifugal machine. There is usually from 5 to 9% of the feed mass that is mud. In our analysis we will take the average value, so 7%.

- **Mass balance**

  - The mass flows entering the centrifugation process:

\[
\dot{M}_{in} = \dot{M}_{Glucose} + \dot{M}_{Ethanol} + \dot{M}_{Other} = (3,1 + 8,8 + 96,9) \cdot 10^{-2} = 1,08kg/s
\]

- Mud mass recovered by centrifugation:

\[
\dot{M}_{Mud} = 0,07 \times \dot{M} = 7,66 \cdot 10^{-2}kg/s \Rightarrow \dot{M}_{liquid} = 1,004kg/s
\]

According to hypothesis 3 which involves no Ethanol losses during centrifugation and distillation, mud is exclusively composed by unfermented Glucose and Others. This gives us the following flows leaving the centrifugal machine.

- Mass flows to Methanogenesis:

Let us consider the entering feed without Ethanol. It contains, 3,1 \cdot 10^{-2} kg of Glucose/s and 96,9 \cdot 10^{-2} kg of others products/kg. It gives a mass concentrations of 3,125% for Glucose and 98,875% for the remainder. As a flow of 7,66 \cdot 10^{-2}kg/s of this feed go to methanisation, it gives:
* Glucose flow: $2,41 \cdot 10^{-3}$ kg/s
* Others flow: $73,78 \cdot 10^{-3}$ kg/s

- Mass flows to Distillation:
  Ethanol simply "go through" the process so that its flow going to distillation is equal to the one coming from fermentation's tanks. For Glucose and all the others feed's components, their flows to distillation are simply the ones entering the machine minus the ones leaving for methanogenesis.

  * Ethanol flow: $8,8 \cdot 10^{-2}$ kg/s
  * Glucose flow: $(3,1 - 0,24) \cdot 10^{-2} = 2,86 \cdot 10^{-2}$ kg/s
  * Others flow: $96,9 - 7,378 \cdot 10^{-2} = 89,52 \cdot 10^{-2}$ kg/s

**Energy balance**

The centrifugal machine is an electrical one and its power is about 15 kW. It does not make sense to calculate efficiencies for this step as it is useless on the energetic view. It only affects the mass balance. However let's note that its energy consumption will be take into account into the overall energetic bill.

5.3 Methanogenesis

**Mass balance**

Analyzing the production of methane from organic matter can be done easily thanks to the Chemical Oxygen Demand (COD) concept. It represents the mass of oxygen needed to transform 1 kg of organic matter into methane. Indeed when this quantity is known we deduce the amount of methane produced according to the law: $1$ kg of COD $\rightarrow 250$ g of methane$^5$.

In our case, we consider Glucose as the only organic matter within the muddy feed. Its reaction with $O_2$, which is its methanogenesis' first step, is given by the following chemical equation:

$$C_6H_{12}O_6 + 6 \ O_2 \rightarrow 6 \ CO_2 + 6H_2O$$

So that stoichiometry gives 6 mol of $O_2$ for 1 mol of $C_6H_{12}O_6$. From a massic point of view we have:

$$\tilde{m}_{C_6H_{12}O_6} \Leftrightarrow 6 \tilde{m}_{O_2}$$

180 kg of $C_6H_{12}O_6$ $\Leftrightarrow$ 192 kg of $O_2$

1 kg of Glucose $\Leftrightarrow$ 1.07 kg of COD

Using the flows calculated earlier for Glucose within the mud, we get:

$$COD = 1.07 \cdot 2.41 \cdot 10^{-3} = 2.57 \cdot 10^{-3}$$

And according to the relation between COD and methane we have:

$$\dot{M}_{CH_4} = 0.250 \cdot COD = 6.4 \cdot 10^{-4} kg/s$$

• Energy balance

The biomethanation or methanogenesis, is an endothermic reaction. We will use an average value of $\Delta h^\circ = 4,681 kJ/kg$ for the heat of formation. It gives for our case a need of 2.99 W. It is a ridiculous amount, less than 4% of what the Fermentation releases. That’s why no modification of the process can be planned for recovering such a little quantity of Energy, and trying to use it somewhere else would have no sense.

5.4 Distillation

Distillation includes 2 main heat exchanges we can’t avoid. They have to take place in order to realize the chemical operation; the recycled hot water has to be totally evaporated, and the Ethanol 95% has to be condensate and then cool down to atmosphere temperature. To calculate the heat powers needed, we must consider a few hypothesis: vapor/liquid equilibrium is respected anywhere inside the column, so the higher stage only has gas 95% Ethanol and the lower has pure water. Furthermore we don’t admit losses to atmosphere. Then as we know the boundary conditions for every flows entering or leaving the column, we can calculate the 2 needed powers, by simply applying the first law of thermodynamic. It gives us:

$$\dot{Q}^-_{eth} = \dot{M}^-_{eth}(c_{peth} \cdot \Delta T + \Delta h_{eth}) = 82.9 kW$$

$$\dot{Q}^+_{wat} = \dot{M}_{H_2O_{out}}(c_{pH_2O_{out}} \cdot \Delta T + \dot{Q}^-_{eth}) = 363 kW$$

$$\dot{M}_{wat} = \frac{\dot{Q}^+_{wat}}{\Delta h_{H_2O}} = .136 kg/s$$

Since we know what the distillation column asks for, we must find utilities to bring it, or to take it away.

The heat is produced by a boiler in the current version of Betalcool. We suppose it

---

uses Natural Gas as a fuel. This choice will allow us to stay ecologist, and to burn the Methane produced by the biomethanation. Referring to traditional values used in one of our references on Distillation\(^7\) we will arbitrarily choose values of 200 \(^\circ\)C for \(T_{out}\) and 1 kg/s for \(\dot{M}_{vap}\). Afterward Energy Conservation laws gives us \(T_{in}\) of 113, 2 \(^\circ\)C.

The ethanol will be cold by water from "rivers", it means entering at 115 \(^\circ\)C and leaving at not much than 45 \(^\circ\)C. By taking these two values, we would need a 0,66 kg/s flow.

We can now calculate efficiencies and effectivenesses.

---

- **Effectiveness**

  \[
  \epsilon_{comb} = \frac{1}{\frac{\Delta H_{comb}}{T_{in}}}
  \]

  This value is due to the heat insulation hypothesis, for the whole distillation, that prohibits losses!

- **Efficiency**

  \[
  \eta_{comb} = \frac{\dot{E}_{products}^+ + \dot{E}_{heating}^+}{\dot{E}_{heating}^{-}}
  \]

  We can calculate the entropy variation using:

  \[
  \Delta s = cp \cdot \ln\left(\frac{T_{out}}{T_{in}}\right) - r \cdot \ln\left(\frac{P_{out}}{P_{in}}\right) = cp \cdot \ln\left(\frac{T_{out}}{T_{in}}\right)
  \]

  So that we have

  \[
  \eta_{comb} = \frac{30,31 \, kW + 1,30 \, kW}{615 \, kW} = 5,14\%
  \]

It is not amazing to find such a bad result knowing that distillation is based on heat exchanges, and so on create important losses. The efficiency of this process could only be increased by having boiler that accept higher flow. It would reduce the fall of temperature. However on a more general view the improvement of distillation would be counter by a degradation of the boiler’s efficiency, since they share the same flow.

5.5 Combustion

In our process combustion, methane is burned in a boiler.

\[ CH_4 + 2 O_2 \rightarrow CO_2 + 2 H_2O \]  \hspace{1cm} (6)

with \( \Delta h_i^o = 50'018 \text{ kJ/kg} \)

and \( \Delta k_i^o = 51'757 \text{ kJ/kg} \)

However to simplify once more the study of combustion we consider it as complete. We can now easily analyze the process.

- Mass balance

The system is in steady state conditions so that no heat is accumulated by the heating vapor. Thus all the water given to distillation has to come from the heat exchange within the boiler. Taking an insulated boiler, to apply the first thermodynamic law to a volume fixed and open, gives:

\[
\frac{dU_{cz}}{dt} = \sum \dot{M}_F \cdot \Delta h_i^o + \sum \dot{Q}^+ + \sum \dot{M} \cdot \hat{h}
\]  \hspace{1cm} (7)

As we consider steady state conditions, and a same standard temparture for input and output \(\dot{q}\) we obtain:

\[
0 = \sum \dot{M}_F \cdot \Delta h_i^o + \sum \dot{Q}^+
\]

So we get:

\[
\dot{M}_{CH_4} = \frac{\dot{Q}_{\text{water}}^+}{\Delta h_i^o} = \frac{363}{50'018} = 7,25 \cdot 10^{-3} \text{ kg/s}
\]
The real quantity me must buy is 7,25 - 0,64 = 6.61 g/s. The Methane produced by biomethanation saves about 8.8% of the total consumption.

Now taking $\lambda = 1$ as the air factor, we use the stoichiometry to find all the molar and mass flows.

- **Input**
  * $\dot{M}_{CH_4} = 7,25 \cdot 10^{-3}$ kg/s
  $\dot{N}_{CH_4} = \frac{\dot{M}_{CH_4}}{\bar{m}_{CH_4}} = 4,53 \cdot 10^{-4}$ mol/s
  * $\dot{M}_{O_2} = 2 \cdot \dot{N}_{CH_4} = 9,06 \cdot 10^{-4}$ mol/s
  $\dot{M}_{O_2} = \dot{N}_{O_2} \cdot \bar{m}_{O_2} = 1,45 \cdot 10^{-2}$ kg/s
  * $\dot{N}_{Air} = \frac{\dot{N}_{O_2}}{0,21} = \frac{1,45 \cdot 10^{-3}}{0,21} = 6,9 \cdot 10^{-3}$ mol/s

- **Output**
  * $\dot{N}_{CO_2} = \dot{N}_{CH_4} = 4,53 \cdot 10^{-4}$ mol/s
  $\dot{M}_{CO_2} = \dot{N}_{CO_2} \cdot \bar{m}_{CO_2} = 3,98 \cdot 10^{-2}$ kg/s
  * $\dot{N}_{H_2O} = 2 \cdot \dot{N}_{CH_4} = 9,06 \cdot 10^{-4}$ mol/s
  $\dot{M}_{H_2O} = \dot{N}_{H_2O} \cdot \bar{m}_{H_2O} = 1,16 \cdot 10^{-2}$ kg/s

**Energy balance**

As we already calculated the amount of energy exchanges in the distillation’s section, we can directly find the effectiveness and efficiencies:

- **Effectiveness**
  $$\epsilon_{comb} = \frac{\dot{M}_{vap} \cdot c_{pH_2O} \cdot \Delta T}{\dot{M}_F \cdot \Delta k_i^0} = 1$$

  This is, once more, due to the heat insulation hypothesis that prohibits losses!

- **Efficiency**
  $$\eta_{comb} = \frac{\dot{M}_{vap} \cdot (k_{cz_fin} - k_{cz_ini})}{\dot{M}_F \cdot \Delta k_i^0} = \frac{\dot{M}_{vap} \cdot (\Delta k_{cz} - T_a \cdot \Delta s)}{\dot{M}_F \cdot \Delta k_i^0}$$

  We still can calculate the entropy variation using:
  $$\Delta s = cp \cdot ln \left( \frac{T_{out}}{T_{in}} \right) - r \cdot ln \left( \frac{T_{out}}{T_{in}} \right) = cp \cdot ln \left( \frac{T_{out}}{T_{in}} \right)$$

  And we get:
  $$\eta_{comb} = \frac{\dot{M}_{vap} \cdot (\Delta h - T_a \cdot cp \cdot ln \left( \frac{T_{out}}{T_{in}} \right))}{\dot{M}_F \cdot \Delta k_i^0} = 93,19 \cdot \frac{375,2}{375,2} = 26,8\%$$
6 Overall analysis

We are now able to do the overall mass and energy balances. In a first time we will summarize quickly the mass balance for the whole betalcool factory and its energy consumption. Then we will try to have a look at the global production supply chain, from fields to consumers. To normalize our results, we will always refers them to our final product, 1L of Ethanol 95%.

6.1 Factory’s mass and energy balances

- **Mass balance**
  In our process there are only one Input but four different Outputs. The beets enter the process from the beginning, directly into the crushing machine, fermentation releases $CO_2$, biomethanation releases $CO_2$ and fertilizers for agriculture, combustion releases $CO_2$ as well, and distillation releases the Ethanol and useless wastes.

  - Beets
    We use 4200 kilograms of beets per hour, and we add yeast and enzymes. However their mass is neglected. We only consider the sugar beet as input.

  - Ethanol
    It is the main product of the process. We get 420 liters of 95% Ethanol per hour.

  - $CO_2$
    According to the mass balances already done for Fermentation, Biomethanation and Combustion, we know that the two first steps releases respectively $CO_2$ flows of 0,084 kg/s and 0,0212, and that stoichiometry gives 6 moles of $CO_2$ produces for 1 moles of Glucose consumed! Taking the Glucose mass flow of $2,41 \times 10^{-3}$ kg/s, we find a $CO_2$ mass flow of $3,54 \times 10^{-3}$ kg/s.
    As this flows refer to a Ethanol production of 420 L/h, we have a $CO_2$ emission of
    \[
    \frac{0,084 + 0,0212 + 0,00354 \cdot 3600}{420} = 0,932kg/L.
    \]

  - Fertilizers
    They are included inside the mud resulting of biomethanation. As the study of the conservation of each atoms is complicated during this step, we trust the ADER’s result to find their concentration. We get 0,019 kg of Nitrogenize, 0,009 kg of Phosphorus and 0,019 kg of Potassium by liter.

- **Energy balance**
  As we have seen in the step by step analysis, each exchange of energy outside the process is done with atmosphere. So the production only consumes
energy (electricity and natural gas), but did not produce from an exergy point of view. Indeed, the whole amount of heat released is seen as losses. However with another process structure, we could imagine using this losses somewhere else in the factory, but Fermentation happens at a temperature very close of the atmospheric one (difference less than 1 for a thermal conductivity of \(1.5\, \text{kW/m}^2\,\text{K}\) and the temperatures where this energy could be used (Vapor track of distillation) is pretty high. Furthermore the amount of energy released is ridiculous in comparison with what combustion produces! The only available transfer would be from Fermentation to Methanation.

The rest of energy we need is given to the process by both combustion of natural gas (for combustion within the boiler), and electricity for all the intermediary electronic components! The quantity of additional natural gas is evaluated at 25,416 kg for 420 liter of Ethanol 95%, and the electricity amount is pretty much 119 kWh. It finally gives 0.064 kg of methane and 0.298 kWh by liter, what represents respectively 3184.2 kJ and 1073 kJ from fuel and electricity, so a global need of 4,257.2 kJ/L.

The overall mass and energy balance are summarized in the figure below.

<table>
<thead>
<tr>
<th>Consommation</th>
<th>4200 kg of beet</th>
<th>L of ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>25,416</td>
<td>0.064</td>
</tr>
<tr>
<td>Electricity</td>
<td>119</td>
<td>0.298</td>
</tr>
<tr>
<td><strong>Matter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermentable sugar</td>
<td>739.2</td>
<td>1.852</td>
</tr>
<tr>
<td>Water</td>
<td>3213</td>
<td>8.048</td>
</tr>
<tr>
<td>Other solids</td>
<td>247.8</td>
<td>0.621</td>
</tr>
<tr>
<td></td>
<td>4200</td>
<td>10.52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production</th>
<th>4200 kg of beet</th>
<th>L of ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat (kJ)</td>
<td>308,556</td>
<td>0,772859314</td>
</tr>
<tr>
<td><strong>Matter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol 95%</td>
<td>338.10</td>
<td>0.805</td>
</tr>
<tr>
<td>CO2</td>
<td>391.44</td>
<td>0.932</td>
</tr>
<tr>
<td>H2O</td>
<td>67.55</td>
<td>0.161</td>
</tr>
<tr>
<td>Nitrogenize</td>
<td>7.59</td>
<td>0.019</td>
</tr>
<tr>
<td>Phosphate</td>
<td>3.59</td>
<td>0.009</td>
</tr>
<tr>
<td>Potassium</td>
<td>9.28</td>
<td>0.025</td>
</tr>
<tr>
<td>Waste</td>
<td>3381.66</td>
<td>8.052</td>
</tr>
<tr>
<td></td>
<td>4200</td>
<td>10.00263213</td>
</tr>
</tbody>
</table>

Figure 4: Mass and Energy Balances
6.2 Global supply chain’s mass and energy balances

- **Mass balance**
  Here we only consider the 2 most interesting products, \( CO_2 \) and fertilizers. The fuel will be studied in the energy part.

  - \( CO_2 \)
    Concerning released \( CO_2 \), we must take into account the amount produced by transportation of beet from fields to factories and from factories to customers. We can divide this transportation in 3 categories: trucks, trains and ships. By taking into account these 3 categories of transport, we guarantee the possibility of studying any importation profile! Let’s analyze trucks and boats (Trains are neglected).

    * **Trucks**
      If we take for instance trucks that used to work at an average power of 140 kW and at an average speed of 40 km/h, the Euro III legislation for trucks allows a \( CO_2 \) emission of 2.1 g/kWh. It is equivalent to an emission rate of
      
      \[
      \frac{0.0021 \cdot 140}{40} = 0.0735 \text{ kg/km}
      \]

      If we consider that the trucks going from fields to factories have a capacity that allows to consider the same number journey by liter of Ethanol 95% than the tanker that will bring Ethanol from factories to customers, and using the definitions: \( T_{f-f} \) for distance done by trucks between fields and factory, \( T_{f-d} \) for distance from factory to docks, and \( T_{d-c} \) for distance from docks to customers, the total amount of \( CO_2 \) released is:

      \[
      \dot{M}_{CO_2} = 0.0735 \cdot (T_{f-f} + T_{f-d} + T_{d-c}) \cdot 2
      \]

      The coefficient 2 is due to the way back that we must consider!

    * **Ships**
      According to a study done by the Hamburg Institute for International Economics, a medium size tanker releases about 0.024 kg/tkm of \( CO_2 \). Its weight is estimated at 3000 tons, so that if we called \( S \) the distance between the 2 harbors (or docks), we have the following amount of \( CO_2 \) released:

      \[
      \dot{M}_{CO_2} = 0.024 \cdot 3000 \cdot S \cdot 2 = 1440 \cdot S
      \]

      Let’s note that to compute the amount of \( CO_2 \) released by liter of Ethanol 95% we have to divide this values by the capacity of each transportation. To calculate the global emissions by year for example, we just have to multiply it by the number the number of journeys needed!

  - **Fertilizers**
    The only additional products we need to realize the analysis of mass
balance from fields to consumers, are the fertilizers used in agriculture. Referring to ADER’s data for agriculture needs, we need 120 kg of Nitrogenize, 110 kg of Phosphorus and 350 kg of Potassium to cultivate one hectare of beets. As this surface represents an average amount of 80 tons of beets, we easily deduce that 10 kg of beets (and so 1L of Ethanol 95%) asks for 0.015 kg of Nitrogenize, 0.014 kg of Phosphorus and 0.044 kg of Phosphates.

As we produce those fertilizers during the biomethanation of muds, we can remove the quantity produced to the quantity needed and we find for the global supply chain, the following results: We still need 0.0057 kg of Phosphor and 0.0171 kg of Potassium but we have an excess of 0.0032 kg of Nitrogenize.

- Energy balance

On the contrary, the additional amount of energy needs brought by transportation is relevant. Indeed, even if the supply chain does not affect a lot the global CO₂ emission rate, it increases significantly the global Energy consumption. Once more, we will evaluate the part of each transports by analyzing them, one by one.

- Trucks

In this part the only characteristic we must find to solve our problem, is the Energy Consumption of standards Trucks by kilometer and liter of Ethanol. However it is important to separate the Trucks we use into 2 categories, as the final liquid product is much more concentrated than the raw materials. So we first have the traditional containers Trucks that bring beets to factory. Its consumption is evaluated at 0.18 mL/km.kg by ADER’s studies, or also 1.08 mL/km.L, or finally 46.14 kJ/km.L. The tanker Trucks’ consumption is about 0.5 L/km for a 12'000 L capacity (Average value from Truck manufacturers). That gives us a consumption of 0.042 mL/km.L or 1.48 kJ/km.L, what is, by liter of Ethanol, up to 50 times less than containers.

- Trains

Supposing we are ecologists and all our trains are electrical ones, the average of the 2 advanced studies realized by the canadian manufacturer Bombardier and by the Swiss Railroad Company SBB-CFF-FFS gives an interesting value of 1.53 kJ/km.kg. So for beets’ transportation, we would have a consumption of 15.30 kJ/km.L, and for Ethanol 1.23 kJ/km.L.

- Ships

For a medium size tanker, such as the one we take earlier as reference, we know from different cases\(^8\) that the usual consumptions is 6 tons/day for full ships, and 4 tons/day for empty ships. As we also learn from

---

\(^8\) www.alibaba.com section tanker manufacturer
this source, the cruise speed of medium tanker is 12.2 noms, so that the consumption is finally close to $3.1 \times 10^{-3} \text{ mL/km.L}$ for full ships, and $2.4 \times 10^{-3} \text{ mL/km.L}$ for empties.

So, to finally calculate the total needs of any production profile, we need to know how many kilometers we do with every transportation.

By the way, an interesting data to study would be the ratio Energy used/Energy received. It would give us an idea of the energetic efficiency of the fuel. In one liter of 95\% Ethanol, we estimate that the energy density is about 20425 kJ/L.

All the datas we have got here will be used to calculate the mass and energy balances in our computational program. Since we know the consumption in matter and energy of each element of our supply chain, we will be able to compute these balances in any situations. The second part of our program, based on the current Betalcoool version, is "costs" that we will evaluate in the fourth part. Before we will try to study where and how we could improve the system, to see what is its evolution margin.
Part III
Process Integration: Can we do better?

As we studied the existing process, we never wondered if there were anyway to make it more efficient. Now that we have all the data we wanted on traditional processes’ efficiencies, we can focus on the optimization of the energy’s uses. By applying the process integration method, we will try to enhance the quality of heat transfer, and the use of energy in general. The first step of this approach is the block flow diagram. It shows all the flows, temperatures or physical properties implied in the calculation of every energy exchanges. To make it right, we now have to calculate the real needs of the process, it means the energy amounts that are necessary for the main physical or chemical transformations on which is based the process and not only the total energy expenses. We should enter into details when they are relevant for the process’ goals.

- BLOCKFLOW DIAGRAM

We find now the following block flow diagram where we do not represent the boiler as it is a utility, and not a fundamental stage of the process. It helps us to calculate each amount of heat exchanged within the process, as well as the temperatures where they happen. We can then compute them in our program (EXSYS II), to obtain our cold and hot composite curves and the grand composite curve. We take a DTmin value of 10°C.

![Block Flow Diagram](image)

Figure 5: Block flow diagram
• Composite curves

The program has plotted the curves below. So the chemical nature of the process prohibits any heat recovery! As we could expect, no heat exchange could happen in our actual process. Indeed, the energy is needed at 100°C to evaporate the re-used water, but the stages releasing energy are colder; the condensation and cooling of Ethanol go from 78.15°C to 25°C, and fermentation from 25°C to 24.94°C. Putting aside fermentation, the temperature levels can not be changes in the process as they make part of the chemical properties of the reactions. The fermentation could happen at an higher temperature. It could even increase the Yeasts’ productivity. But to be usable, the energy must be released at more than 100°C, it means the mud should be warm up by 109 kW. So we would use 109 000 W to be able to recover 85.71 W, it sounds amazing! Furthermore the most efficient temperatures for any Yeasts are only between 35 and 50°C, and it would ask for 25% of the energetic expenses whereas the goal would be saving less than 1/1000 of them.

So the chemical nature of the process prohibits any heat recovery, excepting maybe by using heat pumps!

• Integration of utilities

Here we need to find the best way to bring heat to water’s evaporation, and to cool down the Ethanol 95%. According to the discussion we had in the item before, we will not consider heat consumed and released by the fermentation and biomethanation steps.

It is also interesting to take here into account the 119 kW electric power needed in the whole process to run the installation.

So we will try to integrate a cogeneration engine. Thanks its high efficiency, we will try to produce both heat and electricity and then compare it to the boiler(next item).

We will integrate a standard cogeneration engine, and to allow a comparison
with the boiler and to stay ecologist, we will take Natural Gas as a fuel. The characteristic of the engine we use are presented in the following table.

<table>
<thead>
<tr>
<th>Type</th>
<th>$P$ (kW)</th>
<th>$M_{GN}$ (kg/s)</th>
<th>$T_{Win}$ (K)</th>
<th>$T_{Wout}$ (K)</th>
<th>$Q_W$ (kW)</th>
<th>$T_{f-in}$ (K)</th>
<th>$T_{f-out}$ (K)</th>
<th>$Q_{fin}$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNC</td>
<td>145</td>
<td>29.49</td>
<td>360.1</td>
<td>353</td>
<td>118.7</td>
<td>743.6</td>
<td>393.1</td>
<td>86.7</td>
</tr>
</tbody>
</table>

Table 4: Cogeneration Engine

The cooling system is water from river, it enters $15^\circ C$ and cannot leave at a temperature higher than $45^\circ C$.

- **RESULTS FOR COGENERATION** The flows involved in heat transfers are shown in the table below. We can see that the engine’s flows are separated since the fumes transfer heat from high temperatures, and cooling water from lower ones (GN1 and GN2). Heat transfers from fumes are more difficult so we define bigger $dT_{min}$ than for water.

---

<table>
<thead>
<tr>
<th>Name in -&gt;Name out</th>
<th>Temp-in</th>
<th>Heat load</th>
<th>Temp-out</th>
<th>Energy Flow</th>
<th>$dT_{min}$/2</th>
<th>$h_{thm}$</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq FERM. -&gt;STEA1</td>
<td>296.00</td>
<td>0.85710E-01</td>
<td>297.84</td>
<td>-0.86297E-05</td>
<td>1.00000</td>
<td>5000.00</td>
<td>ALL</td>
</tr>
<tr>
<td>Cq BOM. -&gt;STEA1</td>
<td>373.00</td>
<td>383.00</td>
<td>371.60</td>
<td>72.396</td>
<td>-5.0000</td>
<td>5000.00</td>
<td>ALL</td>
</tr>
<tr>
<td>Eq ETHWA. -&gt;STEA1</td>
<td>296.15</td>
<td>11.420</td>
<td>296.00</td>
<td>0.63240</td>
<td>1.00000</td>
<td>5000.00</td>
<td>ALL</td>
</tr>
<tr>
<td>Eq GN1 -&gt;GN1</td>
<td>351.15</td>
<td>75.000</td>
<td>351.15</td>
<td>11.352</td>
<td>1.00000</td>
<td>5000.00</td>
<td>ETHV</td>
</tr>
<tr>
<td>Eq GN2 -&gt;GN2</td>
<td>373.00</td>
<td>378.50</td>
<td>373.15</td>
<td>171.09</td>
<td>4.00000</td>
<td>0000.00</td>
<td>GN</td>
</tr>
<tr>
<td>Eq COOLU. -&gt;COOLU</td>
<td>290.00</td>
<td>93.205</td>
<td>290.00</td>
<td>0.38990</td>
<td>4.00000</td>
<td>19710.00</td>
<td>COOLU</td>
</tr>
<tr>
<td>Cq COOLU. -&gt;COOLU</td>
<td>350.00</td>
<td>86.058</td>
<td>354.70</td>
<td>-1.6700</td>
<td>4.00000</td>
<td>15710.00</td>
<td>COOLU</td>
</tr>
<tr>
<td>Cq COOLU. -&gt;COOLU</td>
<td>294.60</td>
<td>89.059</td>
<td>299.30</td>
<td>-0.59154</td>
<td>4.00000</td>
<td>19710.00</td>
<td>COOLU</td>
</tr>
<tr>
<td>Cq COOLU. -&gt;COOLU</td>
<td>302.35</td>
<td>84.058</td>
<td>304.00</td>
<td>1.03445</td>
<td>4.00000</td>
<td>19710.00</td>
<td>COOLU</td>
</tr>
<tr>
<td>Cq COOLU. -&gt;COOLU</td>
<td>306.67</td>
<td>86.059</td>
<td>313.33</td>
<td>5.5587</td>
<td>4.00000</td>
<td>19710.00</td>
<td>COOLU</td>
</tr>
<tr>
<td>Cq COOLU. -&gt;COOLU</td>
<td>313.33</td>
<td>89.059</td>
<td>316.00</td>
<td>4.6149</td>
<td>4.00000</td>
<td>19710.00</td>
<td>COOLU</td>
</tr>
</tbody>
</table>

Figure 7: Process Flows from integration

The graph in figure 8 come from Exsys II. It contains the composite curves

Figure 8: Utility integrated composite curve
of utilities (in Green) and process (in red). It is easy to locate the 2 flows from the engines and the water one. It is interesting to note that only the heat from fumes is used to warm up the distillation water at 100°C, so that most of the cooling system is used to cool down hot water from engine, and not the ethanol 95%. The system needs 4 times the engine in its nominal state. We also know how much electricity and heat it produces and what is released.

- Comparing cogeneration engine and boiler
  If we want to compare the cogeneration engine and the boiler, we must notice that by choosing vapor between 189°C and 200°C in the boiler’s study, all the $\Delta h_i^p$ has been considered as available whereas the cogeneration study has shown that pretty much half of the energy is lost (in the engine cooling water) at such a level of temperature.
  The thermal restrictions for the engine forces us to take low temperature cooling waters and so on to waste an important part of the heat.
  That’s why we find such differences between the two systems in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Cogen.</th>
<th>Boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{CH4}$</td>
<td>32.7 g/s</td>
<td>7.06 g/s</td>
</tr>
<tr>
<td>Heat production</td>
<td>874 kW</td>
<td>385 kW</td>
</tr>
<tr>
<td>Heat used</td>
<td>363 kW</td>
<td>385 kW</td>
</tr>
<tr>
<td>Electricity produced</td>
<td>615.01 kW</td>
<td>0</td>
</tr>
<tr>
<td>$M_{CO2}$</td>
<td>90 g/s</td>
<td>19 g/s</td>
</tr>
<tr>
<td>Net Energy used</td>
<td>258.99 kW</td>
<td>385 kW</td>
</tr>
<tr>
<td>Direct Cost</td>
<td>-69.43 CHF/s</td>
<td>29.66 CHF/s</td>
</tr>
</tbody>
</table>

Table 5: Comparison of cogeneration and boiler

So thanks to Electricity production, the cogeneration system offers the best costs and the lowest energy consumption. However, has it needs much more Natural Gas (4.6 times), it releases much more $CO_2$ by the way. On a more general view we should look at pollution by considering also what would be the carbon dioxide used to produce the 615 kW in a classic situation, and had it to the boiler’s emission.
So finally the choice of a system depends on what we are looking for, but let’s say in general that financial and energetical interests asks for a cogeneration engine while ecology may prefer the boiler. Furthermore if it was possible to use some hotter cooling water for the engine (higher than 100°C), the cogeneration would be significantly better.
Part IV

Economical analysis of production

7 Identifying costs

7.1 Pricing a Factory

The evaluation of the Factory’s installation has been done by Betalcool’s engineers. In this study we won’t define every components, but we’ll aggregate costs according to their nature and behavior. In a first group, we have the buildings, in a second one we have all the building equipments (the ones that allow the building to accommodate any process), in a third one we have the technical equipments (the ones directly uses to produce), and finally we have the vehicles (Cars and Trucks).

The goal of this study is to evaluate the indirect costs that the Factory cause in the total costs of 1 L of Ethanol 95%. We don’t really care about the ground since it’s the only good that doesn’t have any depreciation. If we consider that we build our factories without any loans, the ground does not cost anything! However, as far as all the groups we defined earlier are concerned, depreciation do exists. In accounting we take it into account through financial amortisation. It consists in attributing a percentage of losses per year to every goods, in order to consider its aging!

The importance of the separation in groups, lies in the difference of amortization rate for each kind of goods. Indeed, a building as a much longer lifetime than cars or boilers etc... These rates are defined by rules according the countries. Basing our study on the International Accounting Systems, we get the costs and rates shown in the table below.

<table>
<thead>
<tr>
<th></th>
<th>Cost (CHF)</th>
<th>Lifetime (yr)</th>
<th>Amortisation rate</th>
<th>Depreciation (CHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings</td>
<td>350'000</td>
<td>50</td>
<td>2%</td>
<td>7'000</td>
</tr>
<tr>
<td>Build. Equip.</td>
<td>1'025'000</td>
<td>20</td>
<td>5%</td>
<td>51'250</td>
</tr>
<tr>
<td>Tech. Equip.</td>
<td>2'245'000</td>
<td>10</td>
<td>10%</td>
<td>224'500</td>
</tr>
<tr>
<td>Vehicles</td>
<td>180'000</td>
<td>5</td>
<td>20%</td>
<td>36'000</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3'800'000</strong></td>
<td></td>
<td></td>
<td><strong>318'750</strong></td>
</tr>
</tbody>
</table>

Table 6: Factory financial amortisation

Since we know the indirect costs due to the global factory, we can now focus in the next part on the direct costs due to raw materials, energies and outsourcing. Let’s note that we consider the factory as the only item of property of the company owns! It means that it outsources all the others stage of the supply chain. This parameter does not affect in any kind the final cost per liter, but it helps significantly the calculations of costs.
7.2 Operating Costs

The principle of direct costs (such as Operating costs) is that they always have a similar amount in a unit cost, no matter the volume produced. Finding the amount of the global expenses due to direct costs consists in multiplying the direct cost per unit by the total volume produced! So we only have to find what are the necessary quantities of materials and energies needed to produce a unit product (1L of Ethanol 95%), and then multiply them by their costs. Operating costs are divided into 2 categories: the cost of production, and the costs of transportation! The firsts depend directly of the mass balance through the factory, and the seconds depend of the energy needs for importation/exportation as well as the chartering costs. Let’s study both!

- **Cost due to production**
  We know exactly from figure 4 what 1L of Ethanol asks for! The remaining step is computing the costs of the following materials:
  
  - Natural Gas (CHF/L)
  - Electricity CHF/kWh
  - Beets and enzymes (CHF/kg)

  And then to multiply by the volume we produce per year. Let’s note that we consider the beets as outsourced, and its costs is officially close to 8 CHF/kg with the amount of enzymes corresponding. In our program that comes with this paper we consider this price as constant, whereas we allow the user to select the price of Natural Gas and Electricity he wishes. This is due to the relevant variance of Energy’s price all over the world in comparison to the stability of agriculture products such as beets.

- **Cost due to transportation**
  The main costs in transportation are caused by fuels! Once we know the kilometers done by every transports, as well as its consumption, we simply have to multiply them all together with volume price. As fuels’ prices can easily change from a country to an other, it could be possible to take into account 2 different prices for a same fuel, according to the country where the journey happens. The chartering costs can often be neglected for train and trucks but not for ships. It’s important to notice that it has to be considered as direct cost since the cost of a charter is constant but the volume transported as well! We globally evaluate the costs of chartering a medium size tanker at 50'000.-\(^{10}\). The costs we need are the followings:

  - Diesel(s) (CHF/L)
  - Electricity CHF/kWh

\(^{10}\)"Etude sur les transports maritimes-Trafic et marchées des frets"/ United Nations Conference on Trade And Development/ Geneva 2002
The total cost of a year production is then given by the formula above.

\[ C = \text{Fixed Costs} + \text{Variable costs} \cdot \text{Production} \]  
(8)

\[ C = \text{Factory amortisation} + (\sum \text{Direct costs}) \cdot \text{Production} \]  
(9)

8 Comparing different production profiles

8.1 Producing in the USA (Kansas)

Kansas is one of the most Sugar Beet-oriented states in the USA. Sugar beet farms are plenty, and production conditions are close to Swiss’ ones. In Kansas, to establish a factory really close to fields is easy, so that we can consider an average 5 km distance between fields and factories. To export to Switzerland, we suppose we transport the Ethanol up to the Port of South Louisiana (Worldly number 4, and one of the closest), that means 1360 km by truck. Then we ship from Louisiana to the French port of Bordeaux, it represents pretty much 8000 km. Finally we transport ethanol up to Switzerland (VD) by truck: 780 km. The case is resumed by the following print-screen. According to those values we find some acceptable results, as shown above. We can see that the production cost of the Ethanol 95% liter isn’t excessive.
That’s let us imagine that importation could be an interesting issue if the Ethanol consumption would increases in order to reduce the petroleum uses. As we expected the part of transport in the Energy expenses diagram become the most important. However we should note the bad ratio Energy used/Energy received of 69,4%.

Figure 9: Results Kansas
8.2 Producing in Ukraine

Ukraine is one of the world’s biggest producer of Sugar Beet and sweet potatoes. Its economy is mainly based on agriculture, but it also as important energetic resources. That’s why the standard of living isn’t high, what means cheap comparing with any industrialized country, and it keeps very competitive price for Energy. That’s why, even if we imagine buying a factory for a price similar to Swiss’s ones, the low cost of energy offers very interesting operating costs! Furthermore, there are also big differences in Sugar Beets’ prices and labor’s costs that we do not take into account!

In our study we import Ethanol from Middle Ukraine to Switzerland. We sup-
pose we do it by truck but if it increases, having a train transportation would bring Ukraine’s production still more efficient. $CO_2$ pollution is decreased by 10% compared to Kansas’ case. However the Energy ratio is still really bad, with a 70,9% value. It is even worse than the America’s one, due to the worst organization of Agriculture that made us consider a longer trip from fields to factory. This part of the transportation is critical for Energy consumption whereas shipping generates the most important $CO_2$ rate.

<table>
<thead>
<tr>
<th>CASE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
</tr>
<tr>
<td>Production</td>
</tr>
<tr>
<td><strong>Production profile</strong></td>
</tr>
<tr>
<td>Distance by truck</td>
</tr>
<tr>
<td>Distance by train</td>
</tr>
<tr>
<td><strong>Importation profile</strong></td>
</tr>
<tr>
<td>Distance by load</td>
</tr>
<tr>
<td>Distance by truck (Producer country)</td>
</tr>
<tr>
<td>Distance by truck (User country)</td>
</tr>
<tr>
<td><strong>Energies price</strong></td>
</tr>
<tr>
<td>Litter of Natural Gas Cost</td>
</tr>
<tr>
<td>Electricity kWh’s Cost</td>
</tr>
<tr>
<td>Litter of diesel’s price (Producer country)</td>
</tr>
<tr>
<td>Litter of diesel’s price (User country)</td>
</tr>
<tr>
<td><strong>Economics</strong></td>
</tr>
<tr>
<td>Total de change ($CHF</td>
</tr>
<tr>
<td>Unit sale price ($/L)</td>
</tr>
</tbody>
</table>
8.3 Producing in Switzerland (VD)

This is case for which the Betalcool process has been designed. It considers a maximum distance field-factory of 15 km, and the consumers are located at maximum 80 km. The Energy prices are the swiss’ ones, and more precisely the Vaud’s ones for electricity. Here we consider the prices in January 2007, while the oil barrel’s price is abnormally low. The ratio Energy used/Energy received is interesting with 28.5%, which is pretty efficient.
### CASE

- **Quantity**
  - Production: 4250000 L of ethanol a year

- **Production profile**
  - Distance by truck: 15 km
  - Distance by train: 0 km

- **Importation profile**
  - Distance by boat: 0 km
  - Distance by truck (Producer country): 50 km
  - Distance by truck (User country): 50 km

- **Energy price**
  - Liter of Natural Gas Cost: 1 $
  - Electricity kWh’s Cost: 0.14 $
  - Liter of diesel’s price (Producer country): 1.15 $
  - Liter of diesel’s price (User country): 1.15 $

- **Economics**
  - Tax de change $/CHF: 1.2 CHF
  - Unit sale price (DL): 1.5 $

### RESULTS

- **Energetic cost**
  - Energetic need by liter of ethanol: 587.5 kJ
  - Total energetic need: 24720/120007 kJ

- **Products rejected**
  - CO2: 3961310.016 kg
  - Nitrogen: 91872.5 kg
  - Phosphate: 38250 kg
  - Potassium: 106250 kg

- **Price by ethanol liter**
  - Agriculture direct costs (subcontracting): 0.70 $
  - Energy direct cost: 0.1001 $
  - Importation direct costs: 0.0009 $
  - Factory fixed costs: 0.27155 $
  - **TOTAL**: 1.04 $
  - 1.25 CHF

- **Savings due to fertilizers sales**
  - Phosphate: 0.00485 $
  - Potassium: 0.005375 $
  - Coke: 0.01232 $
  - **Total savings**: 0.0067 $

- **FINAL COST**: 1.03 $
  - 1.23 CHF

Figure 11: Results Switzerland
Conclusion

Throughout this project, we manage to make a quick overview of the biomass sectors, to compare the different kinds according a couple of properties, and finally choose one for our case, the Sugar Beet. The interests of lignocellulosic feedstock have been underlined, and the study of this biomass is a complement of our work. It has been done by a classmates, Hussein Dhanani.

As far as Sugar Beet is concerned, we had to find an existing process to be able to have a look at what can be done nowadays, and at its performance. Betalcool has been chosen here for its originality and its fullness. To find trustworthy outlines of performance, we have chosen to analyse the process in its classical version, with no change yet. We have finally got mass and energy balances for each steps and their efficiencies. Here two main notices had been done: first of all the energy produced or consumed by fermentation and biomethanation are ridiculous comparing with the amount needed by distillation. Then the amount of $CO_2$ released by fermentation is huge! It represents the big majority of the emissions even in studies that includes transportations from field to consumers.

Our first conclusion in this part is that $CO_2$ released by the process is much more than what we could expected, and it is difficult to understand how such an amount can be absorbed by the beets' photosynthesis. One third of the total pollution by $CO_2$ is done by the production. The second conclusion is that the energetic optimization of the process can be restricted to distillation, and since its temperature are imposed by the chemical process, only the heat production and heat exchanges can be modified.

This shows the limited progression margin the industry has.

In a last part we tried to analyze the economical statement of such an industry. By identifying costs we manage to find a formula to calculate the price per liter. It is important to notice that by basing the study on Betalcool we focus on medium size factors so we can take our values as average for the global industries. The two main conclusions here are: the liter of ethanol 95% is not so far from the nowadays price of fossil fuels on markets, and that importation can be pretty competitive since its impact on cost is limited, even cheaper sometimes.

From all these datas we were able to create a Program that calculate as well energetic and massic datas as economical ones for any profile of production. It resumes the two parts of our study on Betalcool, it means the energy and the economy.

The missing part of this study is the characteristics of biofuels in vehicles' combustion, and its strength and weakness against fossil fuels. It would also be interesting to make the comparison between fossil fuels, and biofuels from beets and lignocellulosic feedstock. Here is a point we would have enjoyed to do but we didn’t have enough time.
Future projects on this subject could be:

- Analysing biofuels’ combustion, its properties and its performances in engines
- Comparing the fossil fuels’ production to biofuels’ production from its 2 main feedstock: sugar-containing and cellulosic
  This projects would be able to base themself on the 2 studies done this semester, using mainly the programs for production computations.
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Annexes
Transport et pesage

Broyage

Levures et enzymes

Recirculation

Broyage

Fermentation alcoolique et hydrolyse continue

Centrifuge

Déchets

Débit: 4'200 kg/h

betteraves à sucre
ou pommes de terre

Stockage intermédiaire

Stockage pour épandage

Corr. du pH
Inocc.

Biogaz, fermentation continue

Biogaz pour chaudière à vapeur

Alcool 95° 420 l/h

Vapeur

Distillation rectification

ADER Flow-sheet du procédé Betalcool

Avant projet pour estimation des coûts.
Responsables du projet : Ernest Badertscher et Manfred Steiner
Orbe, le 22.08.2005 024 441 35 50 021 808 64 59
**PROCEDE DE FABRICATION DE BETALCOOL**

*Flow-sheet 1* Réception, dosage, broyage, inoculation et mise en cuve

<table>
<thead>
<tr>
<th>1) Tableau commande</th>
<th>5) Balance doseuse</th>
<th>9) Pompe doseuse</th>
<th>13) Recirculation de jus fermenté</th>
</tr>
</thead>
<tbody>
<tr>
<td>2) Réception pesée</td>
<td>6) Moulin broyeur</td>
<td>10) Pompe Mono</td>
<td></td>
</tr>
<tr>
<td>3) Stock intermédiaire</td>
<td>7) Cuve de mélange</td>
<td>11) 1re cuve de fermentation</td>
<td></td>
</tr>
<tr>
<td>4) Tapis d’alimentation</td>
<td>8) Cuves levures et enzymes</td>
<td>12) Pompe Mono</td>
<td></td>
</tr>
</tbody>
</table>

EBa 09.05
**PROCEDE DE FABRICATION DE BETALCOOL**

*Flow-sheet 2*  Fermentation, hydrolyse, centrifugation débourbage, méthanisation (biogaz)

11) Cuves de fermentation
12) Pompes Mono
13) CO2 et brassage pneumatique au CO2 avec compresseurs
14) Débourbeuse continue
15) Pompe Mono avec vis d’alimentation
16) Digesteurs pour méthanisation
17) Pompes Mono
18) Méthane

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EBa 09.05
**Projet Betalcool de l’ADER**

**Resp. du projet:** Ernest Badertscher

**Orbe**
e-mail: ernest.badertscher@bluewin.ch 024 441 35 50

---

**Flow-sheet 3** Distillation, récupération de chaleur, stockage de l’alcool et des effluents neutres.

- 19) Méthane vers chaudière
- 20) Gazomètre à méthane
- 21) Récupérateur de chaleur
- 22) Colonne de rectification
- 23) Pompe à alcool
- 24) Stock d’alcool 95%
- 25) Stockage des effluents pour l’agriculture
- 26) Pompe à vinasses
**PROCEDE DE FABRICATION DE BETALCOOL**

Réception, dosage, broyage, inoculation et mise en cuve

*Flow-sheet 1Bis  Pour alcool de pommes de terre ou de céréales hydrolysées*

---

1) Tableau commande  
2) Réception pesée  
3) Stock intermédiaire  
4) Tapis d’alimentation  
5) Balance doseuse  
6) Moulin broyeur  
7) Cuve de mélange  
8) Cuves amylase  
9) Pompe doseuse  
10) Pompe Mono  
10A) Injection de vapeur \(64^\circ C\)  
11) Cuve d’hydrolyse (liquéfaction)  
11A) Cuve d’hydrolyse (liquéfaction)  
12) Pompe Mono  
13) Recirculation de jus hydrolysé  
13A) Refroidissement

( les levures sont ajoutées à la 2\(^e\) cuve, après hydrolyse et refroidissement à 30 °C )

et suite de la ligne comme pour les betteraves.