Energy and economic assessment of bioethanol production by a dry milling process

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Ethanol production from corn is taken into account. The process known as Dry Grind is considered, assuming a 100000 t/y capacity. The energy consumption of such processes is mainly related to the pre-treatment step and the ethanol recovery section. The minimization of energy duties as well as water consumption is treated by using Pinch Technology Analysis (PTA). Bioethanol production will be assessed, by taking into account both operational and capital costs for a plant operated in Italy. A financial analysis to estimate the return on investment is carried out.

1. Introduction

The recent development on the international geopolitical scenery and the growth of the worldwide petroleum demand, makes the energy supply for transportation an increasing problem. As a consequence there is a strong need for additional primary sources. Bioethanol production from sugar cane, grain crops and, in the mid-long term, lignocellulosic materials is receiving more and more attention. One common feature in all biofuels processes is that their economics are very sensitive to local price and availability of crops, country legislation and energy incentives (Tiffany *et al*., 2004).
In this paper, a dry milling (or dry grind) process operated in Italy is considered. It is assumed that the plant can process 341281 t/y of corn. After rigorously modelling the plant unit operations, the minimisation of energy and heat consumptions is carried out by using Pinch Technology Analysis (PTA). The Aspen Plus™ process simulator and the Excel™ flowsheet are used. Different solutions in order to match the process energy consumption are taken into account. In particular, the possibility of making the process self-sufficient and/or utilizing other renewable resources is taken into account.
Finally, the different solutions are assessed through a financial analysis in order to compare the bioethanol and gasoline from oil economics: the different processes will be assessed in term of production costs and return on investment.

2. Bioethanol from corn grain: dry milling process

In conventional corn-based ethanol production, the most common processes are the so-called dry mill and wet mill. In particular dry milling process is the most performing in term of ethanol yield. As illustrated in Figure 1, dry milling process comprises the following sections (Kwiatkowski *et al.*, 2005):

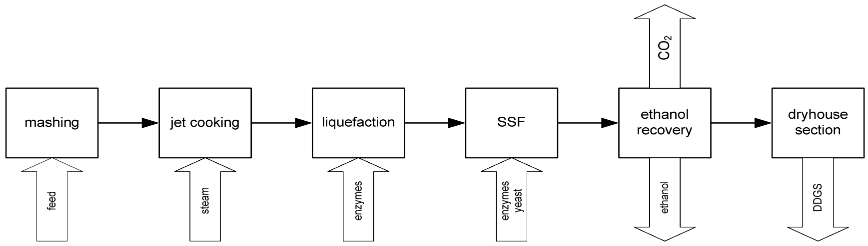

Figure 1. Process block diagram for the dry milling process.

– Mashing: after mechanical grinding, corn flour is mixed with water to form a homogeneous emulsion with relative low viscosity (the *mash*);
– Jet cooking: the mash is sterilized by high-pressure steam, which also has the effect to make the starch crystals available to enzymes;
– Liquefaction: it occurs a preliminary hydrolysis of starch in simplest sugar (oligosaccharides), by means of α-amylase enzymes, so to reduce mash viscosity;
– SSF: the *Simultaneous Saccharification and Fermentation* consists of the hydrolysis of oligosaccharides in glucose and fermentation of glucose in ethanol catalysed by yeast;
– Ethanol recovery: this section comprises *a)* the separation of SSF products (*beer*) to azeotropic ethanol; *b)* the dehydration of the azeotropic ethanol;
– Dryhouse section: the solid from the separation section (*thin stillage*) are concentrated so as to obtain a solid product with a high content of protein (DDGS), suitable for livestock feeding.

The simulation results show that the plant being investigated can produce 111258 t/y of ethanol and 105526 t/y of DDGS. In this work, the ethanol recovery section will be mainly been considered for optimisation purposes, as this is one of the most demanding steps in terms of energy consumption. The flowsheet considered in this paper is illustrated in Figure 2.

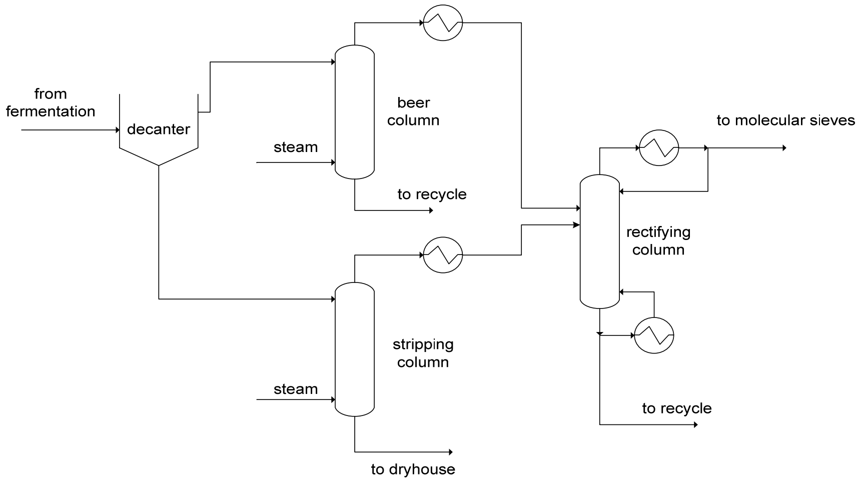

Figure 2. Process flowsheet of the ethanol recovery section in the dry milling process.

A decanter splits the fermentation outlet into two substreams: *i)* a flow stream rich in solids, which is fed to a stripping column (operating at 5 bar) recovering 99 % of the product in the distillate (composition: 41.4 % ethanol by weight); *ii)* a flow stream with no solids, sent to a column (beer column, operating at 3.7 bar) which distillate an overhead product with an ethanol content of 54.2 % by weight. In each column, direct steam is used (at 10 bar) as thermal vector and the overhead products feed the final rectifying column. This last unit is designed to obtain at least a 92.5 % purity in the distillate stream so that molecular sieves can dehydrate ethanol up to fuel grade 99.8%. The bottom products of the beer and rectifying columns are basically made of water, which is partially recycled as process fluid. The bottoms of the stripping column are fed to thee dryhouse section to obtain the DDGS.
If no optimisation step is carried out a steam consumption of 5.30 kg/kg ethanol is obtained. In the literature (Sudiro *et al*., 2006), a steam requirement of 3.15 kg/kg ethanol is reported. An analytical procedure in order to reduce energy duties as well as water consumptions has been carried out.

3. Energy Optimisation

In particular this problem has been treated by using the Pinch Technology Analysis. PTA is a procedure that allows the reduction in the energy duties, through a systematic design of the heat exchangers network. A preliminary thermal integration has been realised in advance by operating the distillation columns at different pressures: thus, it is possible to use the condenser of the stripping column (operating at 5 bar) working as reboiler for the beer column (operating at 3.7 bar) and the condenser of beer column working as pre-heater for the first stage of the evaporators train.

Table 1. Result of PTA: energy requirements.

	Case Study		**PTA**	
	t/y	**kg/kg$_{eth}$**	**t/y**	**kg/kg$_{eth}$**
steam (10 atm)	589785	5.3	308246	2.77
cooling water	21369120	192.3	9614600	86.4
n. of heat exchangers	19		17	

The application of Pinch Technology Analysis leads to the results reported in Table 1. It can be seen that significant decrease in steam and cooling water consumptions is obtained (and that further improves the data in the literature). In this case (base case) it is assumed that steam and electricity are bought from external sources. The electricity consumption is taken as 0.288 kWh/L ethanol (Morey *et al*., 2006). Furthermore, a natural gas consumption is considered in order to dry the DDGS (kg CH_4/kg DDGS).
The next step is to find the most convenient solution to produce the electricity and steam required by the plant. Three different alternatives have been analysed, each one based on a combined heat and power generation.

3.1 Gas Turbine

The first solution is to use a gas turbine cogeneration plant capable of generating all the steam required by the plant (about 32.3 t/h corresponding to 24.3 MW). Such a plant would produce about 25 MW (www.rolls-royce.com) of electric energy (5 MW are used by the plant, while the remaining power is sold to the grid). The stack gases can be exploited to dry the DDGS. The natural gas feed is about 6622 kg/h (about 55000 t/y). This solution determines an increase in the natural gas consumption and additional capital costs. On the other hand, new revenues are generated by selling the electricity.

3.2 Oil Engine

Another available solution could be a vegetable oil power station, designed to meet electric power requirements and part of the heat power needs. A lot of commercial solutions are available. An engine capable of producing 8 MW of electric power and 3,2 t/h of steam at 12 bar has been chosen (www.wartsila.com). The oil consumption is about 13145 t/y. In this case, an additional gas-fed boiler is needed. Assuming a thermal efficiency of 80 %, the natural gas consumption is equal to 27205 t/y. The main advantage in choosing this technical solution is due related to the promotion of Green Credits (subsidies for electricity production from renewable sources) by the Italian Government, in relation with the Kyoto Protocol. The following price has been assumed for the Green Credits: 125,28 €/MWh (Oct. 31st, 2006).

3.3 DDGS power and heat generator

Finally, the chance of using the entire DDGS production as fuel to provide both process heat and electricity has been taken into account. This solution allow to produce 20 MW (Morey *et al.*, 2006) of electric power and all the heat power required by the ethanol production and the DDGS drying section. Once again, it is important to underline that burning DDGS for power generation may represent a very profitable solution because of the great income due to Green Credits.

4. Financial Analysis

In order to assess the profitability of bioethanol production, it has been developed a financial model capable of evaluating both capital and operational costs for the base case (where steam and electricity are bought from an external supplier) and for the alternative solutions proposed. The first goal of such analysis is to evaluate the production costs and compare them to those for gasoline production. The pie charts in Figure 3 show the cost allocations for the different cases. Note that in the base case about 70 % of total costs are due to raw materials while about 15 % to energy needs. A similar allocation of the costs occurs for a combined cycle with either a gas turbine or an oil engine. On the contrary, note that when all the process energy requirements are supplied by a DDGS heat and power station, the power supply costs are nearly negligible, while the capital costs (depreciation) become quite significant.
Table 2 summarises the final results. A first remark is that, except for a gas turbine system, electricity generation is potentially an important contributor to the annual energy cost savings and returns and represents an effective investment in a dry milling process. On the other hand, it emerges that only if the crude oil price is above 60 $/barrel, then bioethanol is advantageous with respect to gasoline and for oil 60 $/barrel only the dry milling process combined with a DDGS generation unit makes the bioethanol advantageous with respect to gasoline.

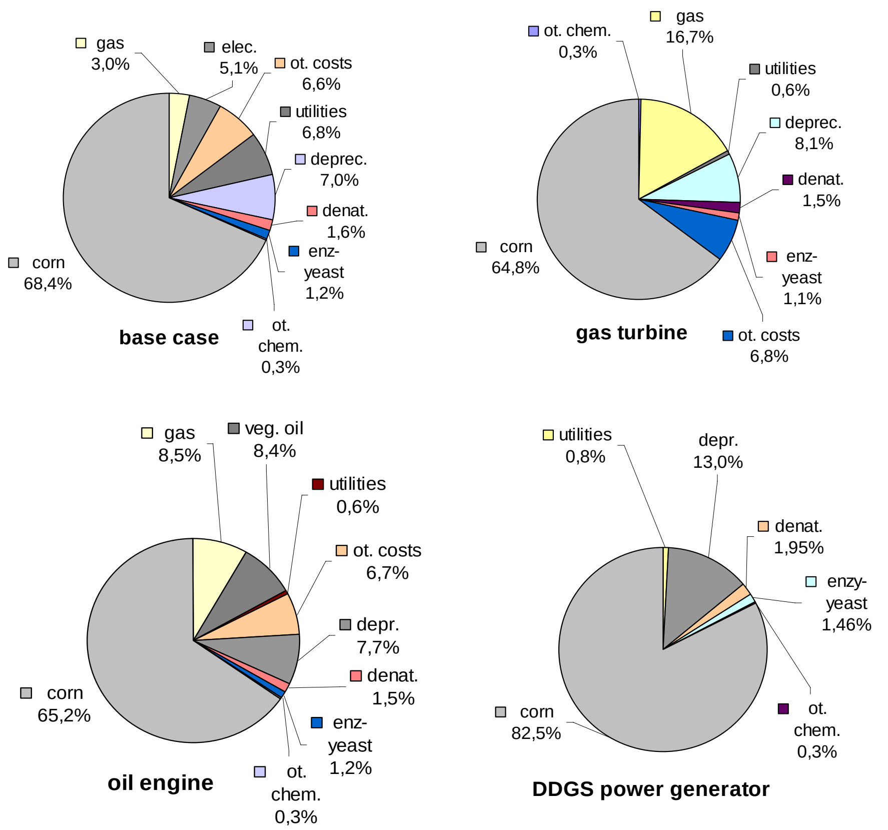

Figure 3. Costs allocation for the four different process cases.

Table 2. Bioethanol versus gasoline production costs.

dry milling process	**€/L**	**€/10^6kJ**
Base case	0,350	16,4
Gas turbine	0,370	17,3
Oil engine	0,338	15,8
DDGS generator	0,318	14,9
gasoline process	**€/L**	**€/10^6kJ**
Oil price: 40 $/barrel	0,324	10,1
Oil price: 60 $/barrel	0,486	15,2
Oil price: 80 $/barrel	0,648	20,3

Another important evaluation concerns the financial analysis of a standard process when compared to the alternatives proposed so as to determine which one represent the most profitable solution for a new investor. It is assumed that all the ethanol can be sold: this rather strong hypothesis makes sense in the present Italian market where in 2007 regulations compel the refineries to incorporate the nationally produced ethanol within the gasoline blend as ETBE up to a 1 % percentage (in terms of heating value). If the market were saturated (but it is far from that), then the financial analysis is reliable only when ethanol is competitive with respect to gasoline. The selling price for ethanol is taken as 0.55 €/L. Note that no additional incentives (such as a reduction on the fuel excise) are not been included in the analysis.

It is necessary to compare a range of financial indexes (Douglas, 1988), in particular the IRR (*International Rate of Return*), the ROI (*Return On Investment*), the NOPAT (*Net Operating Profit After Tax*). Their values are reported in Table 3.

Table 3. Comparison of financial indexes.

	payback	**IRR**	**ROI**	**NOPAT**
Process	**years**	**%**	**-**	**10^6 €/y**
Base case	3	46,01	0,775	65,06
Gas turbine	3,5	37,47	0,635	56,50
Oil engine	3	40,32	0,681	60,7
DDGS generator	3	41,38	0,691	84,81

From the financial point of view each solution appears to be very advantageous, especially in relation to both IRR indexes, whose limiting value is set to below 15 %; the payback time is substantially lower than 5 years.

5. Final remarks

A corn dry milling ethanol production process has been modelled and optimised in terms of the energy requirements. Technical solutions to provide for process heat and electricity at corn dry milling ethanol plants have been evaluated. A financial analysis to compare both capital and operating costs has been carried out.

The analyses show that the bioethanol production process from corn starts being competitive with respect to gasoline from oil when the oil price is at least 60 $/barrel. The most convenient solution is to burn the DDGS to produce steam and electricity: although a valuable co-product is lost, that is compensated for by the revenues obtained through the exploitation of the Green Credits. In any case, the financial analysis show that nowadays investing on such processes is always advantageous, because of the very favourable regulations that create a market nearly independently of the ethanol price.

6. References

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