ENERGY BALANCE OF BIOETHANOL: A SYNTHESIS

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ABSTRACT: While in recent years, the popularity of fuel bio-ethanol has increased significantly all over the World, energy policies aimed at promoting the use of biofuels are largely motivated by the will to reduce greenhouse gas emissions, preserve non renewable energy resources and improve energy security. Since the early 80's, extensive research was aimed at evaluating the so-called net energy balance and CO_2 balance of bio-ethanol through the life cycle assessment approach. Today, if there seems to be a general consensus about the energy balance of bio-ethanol, the utilization phase of the fuels is generally not taken into account in the evaluation of this indicator. Since the appropriate question should be 'how much non renewable energy use (resp. CO_2 emissions) can be avoided through the introduction of fuel bioethanol on the fuels market?', the comparison between fuel bio-ethanol and conventional fuels should really be based on a given distance travelled and thereby integrate their respective performances in terms of fuel economy. In the light of the various observations, an alternative approach is proposed to assess the non renewable energy use and greenhouse gas emissions actually avoided, in relation with the introduction of biofuels on the market.

Keywords: bio-ethanol, CO_2 emission reduction, life cycle assessment (LCA)

1 INTRODUCTION

Global climate change mitigation policies call for increasing use of biofuels as renewable substitutes to conventional fossil fuels. Quantified targets for biofuels introduction into the market exist in the European Union (EU), the United States (US), but also in a number of developing countries. In this context, mixing bio-ethanol with gasoline represents an attractive technical option, allowing for the preservation of non renewable energy resources, reduction of greenhouse gas (GHG) emissions and improvement of energy security.

Since the early 80's, extensive research was aimed at evaluating the so-called **energy ratio** (i.e. the ratio of the energy produced in the form of vehicle fuel to the non renewable primary energy consumed to produce the fuel) and **CO_2 balance** of fuel bio-ethanol through a life-cycle assessment (LCA) approach.

While one of the main purposes of the two indicators is to assess the capability of bio-ethanol to substitute non renewable energy resources and avoid GHG emissions, it comes out from the many studies and publications that results vary quite significantly and sometimes even lead to contradictory conclusions. If some differences can be explained by the type of feedstock, the technology and/or other characteristics specific to the system, the statement above also applies to cases presumably similar. The best example is undoubtedly the historic dispute between D. Pimentel and T. Patzek [1-9] on one side, and M. Wang, H. Shapouri and M. Graboski [10-16] on the other. The two parties, indeed, have been opposed for many years through media and publications, on the subject of corn-based bio-ethanol energy balance. Their last publications [7,16] date back to a couple of months.

The present article is neither aimed at nourishing the dispute nor at taking position in favour of one of the two parties. The objective is (1) to present a synthesis of the various works on bio-ethanol energy balance, and (2) to introduce an environmental assessment approach based on actual concerns about the introduction of biofuels on the vehicle fuels market, considering the entire life cycle of the fuels.

2 THE ENERGY BALANCE OF BIO-ETHANOL

The **energy ratio** (E/R) of a given fuel is defined as the ratio of the heat content of the fuel (in MJ/kg) to the non renewable primary energy consumed to produce 1 kg of that fuel (also often referred to as the Cumulative Energy Demand or CED), the latter being evaluated over the entire life cycle of the fuel. This ratio is one of the most documented indicators of the performance of fuel bio-ethanol production in the literature and references on the topic abound (see **Table I**).

Table I: Energy ratio (E/R) of fuel bio-ethanol

	Author(s)	Year	Ref.	E/R
Sugarbeet	Ecobilan	1996	[28]	1.18
	LASEN	2000	[30]	2.50
	L-B-Systemtechnik	2002	[25]	1.65
	Ecobilan	2002	[29]	2.05
	Woods & Bauen	2002	[26]	1.75
	Elsayed	2003	[33]	2.00
	EUCAR/CONCAWE	2003	[34]	1.65
Lignocellulosic	Lorentz & Morris	1995	[21]	2.62
	L-B-Systemtechnik	2002	[25]	4.30
	LASEN	2002	[31]	1.88-2.50
	Woods & Bauen	2003	[26]	1.80
	Elsayed	2003	[33]	5.60
	EUCAR/CONCAWE	2003	[34]	3.51
Cereals	Ecobilan	2002	[29]	2.05
	Woods & Bauen	2003	[26]	2.25
	Elsayed	2003	[33]	2.20
	EUCAR/CONCAWE	2003	[34]	1.55
	(S&T)2 Consultants	2003	[24]	1.45
	LASEN	2004	[32]	1.08
Corn	Ho	1989	[17]	0.95
	Pimentel	1991	[1]	0.69
	Marland & Turhollow	1991	[18]	1.28
	Keeney & DeLuca	1992	[19]	0.92
	Morris & Ahmed	1992	[20]	1.51
	Shapouri	1995	[10]	1.21-2.02
	Lorentz & Morris	1995	[21]	1.38-2.51
	Wang	1999	[13]	1.42-1.85
	Levelton Engineering	2000	[22]	1.60
	Graboski	2002	[15]	1.22
	Andress	2002	[35]	1.31-1.47
	Shapouri	2002	[11]	1.30-2.22
	Patzek	2003	[8]	0.99
	Shapouri	2004	[12]	1.67
	Pimentel & Patzek	2005	[7]	0.78

While the large majority of studies tend to indicate a net energy balance greater than 1, Pimentel and Patzek [7] conclude that energy outputs from ethanol production are less than fossil energy inputs. This statement sounds particularly worrying when bio-ethanol benefits from a large support from authorities all around the World (EU, US, Brazil, China, India, etc.). Pimentel's controversial findings have always given rise to stormy debates, but also bring to light major issues about the environmental evaluation of bio-ethanol and more generally biofuels.

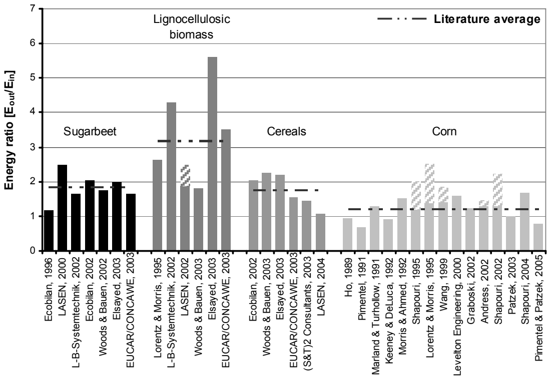

Figure 1: Energy ratio (E/R) of fuel bio-ethanol

As it can be noticed on **Figure 1**, the energy ratio of bio-ethanol depends very much on the nature and type of the feedstock considered. In practise, even for a given feedstock, the net energy balance will differ from a study to the other, as there are indeed various reasons why the outcome of similar studies should give different results. Although the fuel and the feedstock may be identical, variations between two studies can occur at each of the stages of a LCA study, namely (1) the system definition, (2) the life cycle inventory, (3) the evaluation of impacts and (4) the interpretation and analysis of results. Typical sources of differences are indicated in **Table II**.

Table II: Sources of deviations between LCA studies

	System definition	Life cycle Inventory	Impact evaluation	Interpretation
Time scale		X		
Geographic situation (climate resources)	X	X		
Agricultural practise		X		
- Mechanisation		X		
- Type of fertilisation (organic, mineral)		X		
Yields (crops, ethanol)		X		
Quality of feedstock	X	X		
- Type (sugar / strach / lignocellulosic)		X		
- Nature (dedicated crop / waste)	X	X		
Delivery of feedstock (distances, modes)	X	X		
Nature of the production plant	X	X		
- Scale (commercial, pilot, model)	X	X		X
- Technology, use of by-products		X		
Structure of the energy system		X		
- Power generation		X		
- Energy agents		X		
Quality of LCI data		X		X
- Reliability		X		X
- Coherence		X		X
Nature of the study (partiality)		X	X	X
Allocation of environmental burdens	X			X
Method of impact evaluation			X	X

Amongst the most influent parameters, are the types of fertilisers, the performance of the fertiliser industry, the crop and bio-ethanol yields, the fate of by-products, the allocation method, and more generally, the quality of LCI (life cycle inventory) data (reliability, coherence). Because the supply of feedstocks usually represents over 50% of the total non renewable primary energy use, all data relating to the agricultural phase (or more generally the biomass supply) including the delivery to the ethanol plant are key elements in the global energy balance. The allocation issue also can have a significant effect on the entire inventory and consequently on the energy balance and the energy ratio.

Based upon a study carried out by the Laboratory of Energy Systems (LASEN) of the Swiss Federal Institute of Technology of Lausanne in 2004 [32], the influence of the allocation method on the energy ratio was evaluated. The study describes the manufacture of bio-ethanol from wheat in a plant with a production capacity of 50 Ml/yr, in the Swiss context. The stillage water, resulting from the distillation stage, is converted to distiller's dried grains with solubles (DDGS) by drying and granulation (see **Figure 2**), and is sold as animal feed.

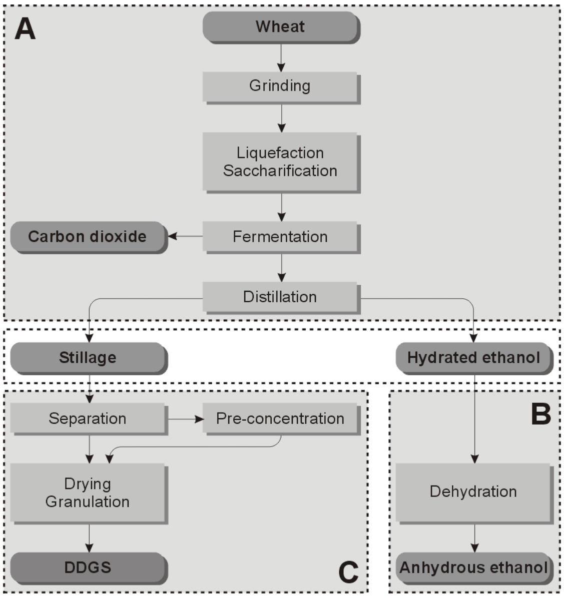

Figure 2: Simplified flow diagram of the process

The allocation of non renewable primary energy use was applied to stillage and hydrated ethanol (at the point of separation), according to the acknowledged practise. The results of this sensitivity analysis are presented in **Table III**. The two figures in brackets show the results when the allocation is done between anhydrous ethanol and DDGS (encountered, although wrong practise). The results show that the allocation method may indeed have a significant influence on the calculated energy ratio. It is essential, therefore, to clearly discuss the choice of the applied allocation method. When this is possible, a study should always include such a sensitivity analysis, within the interpretation stage of a serious LCA.

Just like this allocation issue has an influence on the energy ratio of bio-ethanol, it will have the same effect on the carbon or CO_2 balance. The methodology applied in LCA studies should be all the more rigorous as they are actually required in the frame of most CDM projects.

Table III: Influence of the allocation method on the E/R

Allocation method		Energy use [MJ/l]	Allocation % Ethanol	Allocation % Stillage	E/R [MJ/MJ]
Without allocation	A	19.35	100	0	0.70
	B	1.93	100	0	
	C	8.95	100	0	
Economic value	A	19.35	95	5	1.08 (0.83)
	B	1.93	100	0	
	C	8.95	0	100	
Energy content	A	19.35	61	39	1.54
	B	1.93	100	0	
	C	8.95	0	100	
System extension	A	19.35	81	19	1.21
	B	1.93	100	0	
	C	8.95	0	100	
Mass	A	19.35	12	88	5.01 (1.56)
	B	1.93	100	0	
	C	8.95	0	100	

Although the energy ratio is one of the most widely used indicators of the performance of ethanol production and of its capability to substitute non renewable energy, it does not take into consideration the entire life cycle of the fuel.

Bio-ethanol, indeed, can be used as a fuel in various ways, i.e. (1) as a neat fuel in specially designed engines (hydrated ethanol) or (2) as a blend with gasoline, up to 20-25% in standard engines or up to 85% in flexible fuel vehicles or FFVs (anhydrous ethanol). The performance of fuel ethanol (which can be expressed as the volume of gasoline it replaces) is very much dependant on the rate of incorporation, and will generally vary from about 1 l/l at 5-10% to almost 1.5 l/l at 100% (due to the difference in the heating values of the two fuels, i.e. 21.3 MJ/l for ethanol and 32.0 MJ/l for gasoline).

These considerations mean to show that taking into account the use of the fuels is essential when evaluating the capability of fuel bio-ethanol to save non renewable energy sources. An alternative approach is proposed here to avoid such limitations.

3 AN IMPROVED APPROACH

The substitution of fossil energy and more generally of non renewable energy represents, with the mitigation of GHG emissions, one of the main motivations towards a larger introduction of biofuels on the vehicle fuels market. Therefore, although the energy ratio introduced before is indeed widely used, it only describes a part of the issue. Beyond the specific energy balance and/or energy ratio of bio-ethanol production, it is indeed in the comparison with conventional fuels (in this case, gasoline) that lies the actual capability of fuel bio-ethanol to substitute non renewable energy.

The correct question is not to determine whether the production of bio-ethanol consumes more or less energy than it produces, but really to ensure that the use of bio-ethanol as a vehicle fuel leads to a non renewable energy consumption less than that of the fossil fuel it replaces, over the entire life-cycle of the fuels.

It is therefore essential to take into consideration the performance of the fuels, which depends on the strategy of bio-ethanol introduction, as discussed previously. An example of a practical application is shown below, based on the results presented in Table III. Bio-ethanol is here considered to be incorporated at a rate of 10% (vol.) into conventional gasoline. The blend, also often referred to as "gasohol" in the United States or E10, is considered to have similar performances as conventional gasoline in terms of the fuel consumption. Note, however, that this hypothesis would not be correct at higher incorporation rates. The specific consumption is taken as 10 l/100 km for reasons of convenience. The equivalence ratio (e/r) is defined to characterise the volume of gasoline equivalent corresponding to 1 litre of ethanol, for a given distance travelled (the actual 'service' provided by the fuels), and is given by the formula:

$$e/r = \frac{c_{\text{gasoline}} - (1 - ir) \cdot c_{\text{blend}}}{ir \cdot c_{\text{blend}}}$$

where c_{gasoline} is the specific consumption of gasoline (in l/100 km), c_{blend} is the specific consumption of the blend (in l/100 km) and ir is the incorporation rate of ethanol (in % vol.). The equivalence ratio is expressed in l_{gasoline} per l_{ethanol}. In the example considered, 1 litre of bio-ethanol replaces exaclty 1 litre of gasoline and e/r is equal to 1.

With heat content of 21.3 MJ/l and an energy ratio of 1.08 (see Table III), the consumption of non renewable energy in the production of fuel bio-ethanol is 19.7 MJ/l. According to the ecoinvent LCI database [33], the value for low-sulphur gasoline is 43.4 MJ/l (corresponding to an energy ratio of 0.74). According to these figures and the calculated e/r, the variation in non renewable energy consumption (per litre of bio-ethanol) is equal to:

$$19.7\ \left[\text{MJ}/l_{\text{eth}}\right] - e/r\ \left[l_{\text{gasoline}}/l_{\text{eth}}\right] \cdot 43.4\ \left[\text{MJ}/l_{\text{eth}}\right]$$

that is -23.6 MJ/$l_{\text{bio-ethanol}}$. This results is a function of e/r and therefore is dependant upon the incorporation rate of ethanol and the respective performances of the blend and gasoline. If we consider that 1 ton of crude oil represents 42'500 MJ and given the density of ethanol (0.79 kg/l), for each ton of bio-ethanol incorporated at a rate of 10%, we save 0.70 t of crude oil equivalent (toe).

If we reproduce the calculations by using Pimentel's energy ratio of 0.78 (see Table I), we obtain a net saving of 0.47 toe per ton of bio-ethanol incorporated at a rate of 10%.

The same exact approach can be applied to the CO_2 balance. In the example considered above, the emissions of GHG avoided amount to 1.8 t $CO_{2\ \text{eq.}}/t_{\text{bio-ethanol}}$. When related to an estimate of the cost difference with respect to the reference fossil fuel, for the same service, such an indicator allows comparing different biomass-to-energy pathways, which is one of the principles behind certified emissions reduction (CER).

4 CONCLUSIONS

Although the energy ratio is possibly one of the most documented indicators of the environmental performance of fuel bio-ethanol, it is limited to the production of the fuel and omits a significant part of the problem, i.e. the efficiency of the fuel compared to its fossil equivalent. The approach introduced in the present article considers the entire life cycle of the fuels, including the utilisation phase. The everlasting disputes about the energy ratio of bio-ethanol being more or less than 1 do not really make sense when half of the problem is not considered.

For instance, when ethanol is blended with gasoline at a rate of 10% (with identical performances compared to gasoline), its energy ratio would have to fall below 0.5 before the effect in terms of non renewable energy use is negative.

The example considered in the present article leads to the conclusion that, even with a relatively pessimistic energy ratio of 1.08 (wheat-based ethanol in the Swiss context, used as E10), the avoided non renewable energy use reaches 0.7 toe per ton of bio-ethanol. Similarly, the reduction of GHG emissions amount to 1.8 t $CO_{2\ eq.}$ per ton of bio-ethanol. The values will remain positive even with the most pessimistic results found in the literature.

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