BIOETHANOL REPLACING GASOLINE: GREENHOUSE GAS EMISSIONS REDUCTION, LIFE-CYCLE ENERGY SAVINGS AND ECONOMIC ASPECTS

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Abstract

Biofuels have been emerging as the main alternative to fossil fuels in the transportation market. However, because their production requires fossil inputs and may have significant environmental impacts, the actual benefits to which biofuels can displace fossil fuels and GHG emissions depend, crucially, on the efficiency with which biofuels are produced. In this paper the life cycle of alternative bioethanol chains is investigated to assess energy renewability, environmental performance and cost-effectiveness. GHG emissions and energy used throughout the life cycle have been calculated, using different allocation approaches, together with bioethanol production costs. The implications of bioethanol replacing gasoline are discussed based on our results, namely avoided GHG emissions, life-cycle energy savings and CO_2 abatement costs.

1. Introduction

Growing concerns about climate change, high-dependence on oil and increasing oil barrel prices have been promoting biofuels as the main option to displace fossil fuels in transportation. In particular, ethanol derived from biomass has the potential to substitute large amounts of gasoline. However, the actual benefits to which in practice bioethanol can displace fossil fuels and GHG emissions depend, crucially, on the efficiency with which biofuels are produced.

In this paper a life cycle approach is employed, allowing quantification of the bioethanol energy and carbon balances and demonstrating the relative magnitude of fossil fuel savings and avoided CO_2 emissions resulting from bioethanol use as an alternative to gasoline. Based on a systemic description of two alternative bioethanol chains in France (wheat and sugar beet), physical and economic production data have been combined to build a Life Cycle Inventory model and to calculate bioethanol production costs. Accumulated energy requirements have been calculated and it is shown that bioethanol produced in France is clearly favorable in terms of GHG mitigation and primary energy savings. However, bioethanol production costs rely highly on tax exemptions to be competitive. This motivated the calculation of CO_2 abatement costs to assess if increased use of bioethanol with the only goal of reducing GHG emissions is economically efficient. Section 2 presents the main aspects of the methodology. Section 3 briefly describes the bioethanol chains in France. Section 4 presents the main results. Section 5 concludes.

2. Methodology

The methodology used is based on the standardized Life Cycle Assessment (LCA) methodology, limited to fossil energy use and global warming potential (GWP), but extended to include new dimensions: economic costs and energy renewability. In particular, a novel *E*nergy *Ren*ewability *Ef*ficiency indicator (*ERenEf*) is used to assess the bioethanol renewability. *ERenEf* is defined by $\frac{Fuel\ energy\ content - Total\ fossil\ energy\ inputs}{Fuel\ energy\ content}$ and measures the fraction of final fuel energy obtained from renewable sources [1]. GHG emissions, energy use and ERenEf values have been calculated using four different allocation approaches (output weight, energy content, economic value and replacement value) and ignoring co-product credits, in order to understand the effect of allocation of co(sub)-products in the results. The functional unit chosen for this investigation is the use of 1MJ of fuel energy by vehicle engines, measured in terms of the lower heating value (LHV). The GHG gases covered are CO_2, CH_4 (methane) and N_2O (nitrous oxide). Other GHG were initially investigated but occur in negligible amounts in the system analyzed and, therefore, were not followed up.

3. Bioethanol Production Chains

Two alternative ways of producing bioethanol (from sugar beet and wheat) have been investigated. The life cycles are illustrated in Fig. 1.

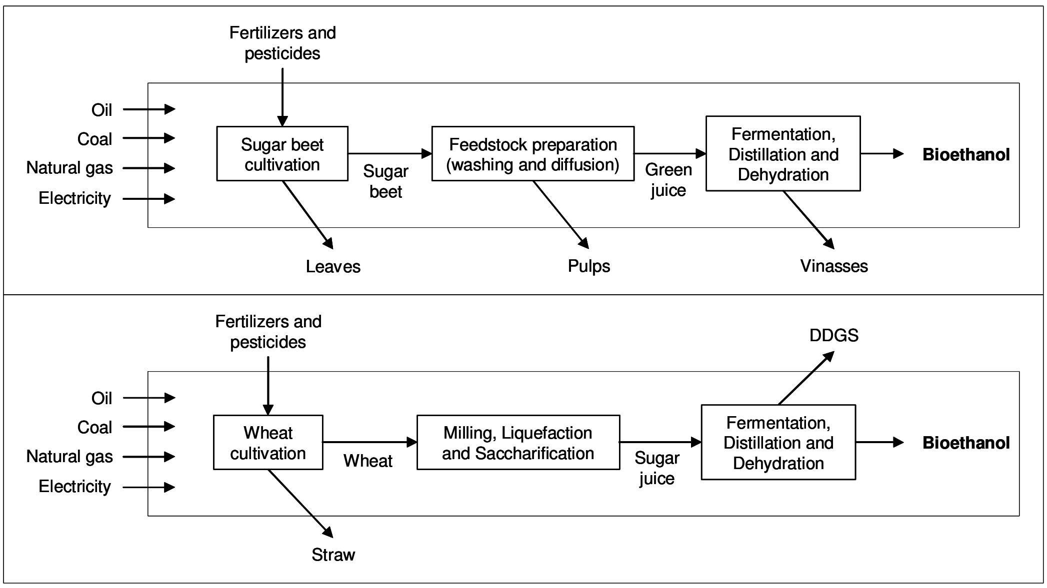

Fig. 1. Flow chart illustrating the bioethanol production chain from a) sugar beet and b) wheat.

The production of ethanol from sugar beet comprises two main steps. Firstly, feedstock preparation, including washing to remove mud, stones and other waste material, beet slicing and diffusion to obtain green/diffusion juice. Secondly, juice fermentation, distillation to increase ethanol concentration and dehydration to obtain anhydrous ethanol. Sugar beet pulp is recovered from the diffusion step and can be used in several alternative ways, namely in animal feed or as fuel. Vinasses, other co-product of the chain, are concentrated and spreaded on agricultural land. Details concerning the technological description and the mass and energy balances of these steps can be found in [1, 2]. Also note that there are other ways of producing bioethanol from sugar beet, *e.g.* sugar production, which are not considered here.

The production route of ethanol from wheat can be divided in two main stages. Firstly, feedstock processing, including grinding of grains, liquefaction and saccharification, where enzymes are introduced to break down the starch into sugar. Secondly, fermentation of sugar juice, distillation and dehydration to obtain anhydrous ethanol [3]. The leftover residue from the first stage (Distiller's Dried Grains with Solubles, DDGS) is the wheat equivalent of pulps from sugar beet, but with higher protein content. Data for the production of bioethanol from sugar beet and wheat has been collected from agricultural and industrial reports for France and from commercial databases.

4. Results and Discussion

The energy renewability efficiency and GHG emissions of bioethanol (sugar beet and wheat, allocation approach) and gasoline are compared in Fig. 2. Ethanol from wheat is more sensitive to allocation than sugar beet based ethanol. Results obtained for both chains exhibit higher ERenEf values than gasoline, which clearly indicates that considerable reductions in fossil fuel depletion would be achieved by replacing gasoline with bioethanol. GHG emissions[1] are calculated as 40,2 and 26,8 kg CO_2eq for sugar beet and wheat, respectively, which are considerably low than gasoline emissions. In this comparison, it is assumed that CO_2 emissions from bioethanol combustion are neutral, being balanced by the CO_2 absorbed from the atmosphere during biomass growth, which does not occur for gasoline. Sensitivity analysis shows that ethanol from wheat GHG balances are more sensitive to allocation (varying up to 34%) than sugar beet based ethanol (12%).

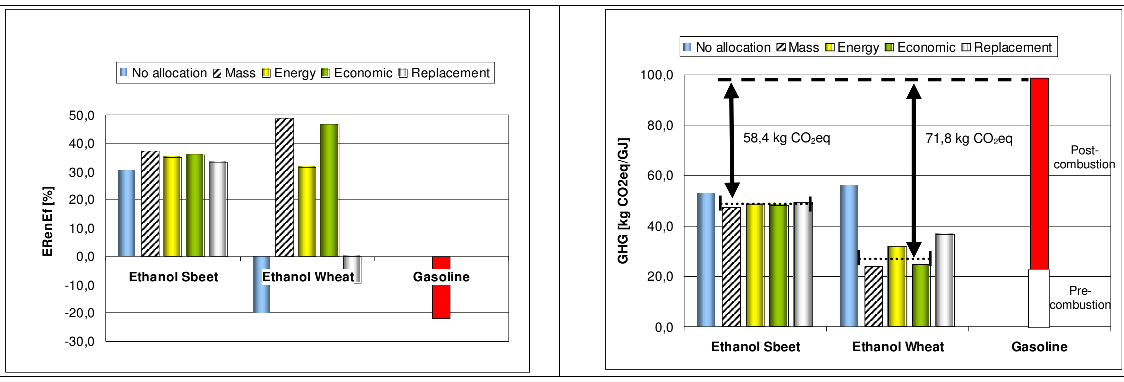

Fig. 2. Comparative ERenEf values and GHG emissions: Bioethanol versus gasoline.

[1] Average from the four allocation procedures, except the replacement method in the case of wheat, which presents a large deviation due to a strong assumption related to DDGS replacement.

Bioethanol production costs present a wide range of values due to different critical variables, such as biomass yields, conversion technologies, co-product evaluation. Recent ethanol costs presented in the literature for Europe vary from 38 to 60€/hl [4,5,6]. Regarding the life cycle cost structure of bioethanol in France, data has been analyzed in detail (Table 1). The industrial conversion of biomass has the greatest impact in the final cost of bioethanol, with co-products' selling having an important share in total revenue (10-20%).

Table 1. Life cycle costs for bioethanol in France.

	Life Cycle Costing of bioethanol [€/hl]					
	Sugar beet			Wheat		
	[7]	[8]	[9]	[7]	[8]	[9]
Cultivation of biomass	16,5	16	20,7–23,1	15	24,7	19,1–21,2
Production of bioethanol (operacional costs + investments)	27	29	24,7	31	34,9	33,2
By-product selling (revenue)	– 6,5	– 5,5		– 6,5	– 12,6	– 8,5
TOTAL	**37**	**39,5**	**45,4–47,8**	**39,5**	**47**	**43,8–45,9**

Assuming a range of bioethanol costs from 37€/hl to 47€/hl of ethanol, the bioethanol costs have been calculated per GJ and per hectoliter of gasoline equivalent (Table 2) – substitution ratio of 1,5 liter of ethanol per 1 liter of gasoline, based on different lower heating values and densities.

Table 2. Bioethanol costs compared with gasoline tax free prices (2004-2005).

	Bioethanol	**Gasoline**
€/hl	37,0 – 47,0	29,7 – 33,5
€/hl of gasoline–equivalent	55,5 – 70,5	29,7 – 33,5
€/GJ	17,4 – 22,1	8,3 – 9,3
Cost difference [€/GJ]	8,1 – 13,8	

Table 3 presents avoided GHG emissions and primary energy savings per tonne and GJ of bioethanol replacing gasoline and per hectare of cultivated land. GHG abatement costs are also presented in Table 3 with wheat based ethanol showing the most favorable values, due to lower GHG emissions (per ton and GJ). However, it should be noted that sugar beet based ethanol presents more efficient values per ha with considerably higher avoided GHG emissions, due to higher yields of bioethanol per ha of cultivated land.

Table 3. Implications of bioethanol replacing gasoline.

	GHG abatement costs	**Avoided GHG emissions [ton CO_2eq]**						**Primary energy savings [GJ]**					
	[€/ton CO_2eq]	per ton		per GJ		per ha		per ton		per GJ		per ha	
Sugar beet	139 – 236	1,56	+0,06 -0,06	0,0584	+0,0021 -0,0024	9,08	+0,33 -0,37	15,38	+0,51 -0,59	0,574	+0,019 -0,022	89,2	+3,0 -3,4
Wheat	113 – 192	1,92	+0,08 -0,13	0,0718	+0,003 -0,005	4,10	+0,17 -0,29	17,23	+1,72 -2,87	0,643	+0,064 -0,107	36,7	+3,7 -6,1

5. Conclusions

A life cycle approach was used to calculate avoided greenhouse gas emissions, primary energy savings and GHG abatement costs for bioethanol (sugar beet and wheat) replacing gasoline. The results were calculated using four allocation procedures (and ignoring co-product credits) showing that the use of bioethanol as a gasoline substitute avoids GHG emissions and saves energy (reducing fossil fuel depletion). However, bioethanol production costs are considerably higher than gasoline and bioethanol relies highly on tax exemptions to be competitive. GHG abatement costs calculated for bioethanol from sugar beet (139–236 €/ton CO_2eq) and wheat (113–192€/ton CO_2eq) cannot compete with other GHG reducing measures, assuming the benchmark of 30€/ton CO_2. It can be concluded that increased use of bioethanol with the only goal of reducing greenhouse gas emissions is currently economically inefficient. However, it should be emphasized that bioethanol has positive effects beyond climate change. In fact, biofuels are currently the main alternative to fossil fuels in the transportation market, contributing to a greater security of energy supply in Europe.

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