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Life cycle greenhouse gas emissions, fossil fuel demand and solar energy conversion efficiency in European bioethanol production for automotive purposes

L. Reijnders [a,*], M.A.J. Huijbregts [b]

[a] IBED/EDDO, University of Amsterdam, Nieuwe Prinsengracht 166, NL 1018WV Amsterdam, The Netherlands
[b] Department of Environmental Science, Faculty of Science, University of Nijmegen, PO Box 9010, NL 6500GL Nijmegen, The Netherlands

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Abstract

Crop derived biofuels such as (bio)ethanol are increasingly applied for automotive purposes. They have, however, a relatively low efficiency in converting solar energy into automotive power. The outcome of life cycle studies concerning ethanol as to fossil fuel inputs and greenhouse gas emissions associated with such inputs depend strongly on the assumptions made regarding e.g. allocation, inclusion of upstream processes and estimates of environmentally relevant in- and outputs. Peer reviewed studies suggest that CO_2 emissions linked to life cycle fossil fuel input are typically about 2.1–3.0 kg CO_2 kg^{-1} starch-derived ethanol. When biofuel production involves agricultural practices that are common in Europe there are net losses of carbon from soil and emissions of the greenhouse gas N_2O. Dependent on choices regarding allocation, they may, for wheat (starch) be in the order of 0.6–2.5 kg CO_2 equivalent kg^{-1} of ethanol. This makes ethanol derived from starch, or sugar crops, in Europe still less attractive for mitigating climate change. In case of wheat, changes in agricultural practice may reduce or reverse carbon loss from soils. When biofuel production from crops leads to expansion of cropland while reducing forested areas or grassland, added impetus will be given to climate change.

Keywords: (Bio)ethanol; Fossil fuels; Automotive power; Agricultural practices; Greenhouse gases

1. Introduction

Concerns over oil prices and availability and greenhouse gas emissions stimulate interest in alternatives to mineral oil to provide for automotive power. So far this has mainly resulted in an increasing interest in biofuels derived from agricultural crops. Automotive fuels containing ethanol derived from starch or sucrose and vegetable oil esters are current examples thereof, whereas for the future, ethanol from lignocellulosic biomass, including crop residues, is being considered [1–13]. In the 1970s Brazil started with a large scale program for the use of sugarcane derived ethanol as a motor fuel, especially to decrease dependence on gasoline imports and to improve the balance of trade [12]. Ethanol may fully replace petrol, but it may also be used in ethanol/hydrocarbon blends and in the production of ethyl *t*-butylether (ETBE) an ingredient of petrol [5]. Ethanol is used in automotive fuel not only in Brazil, but also in the European Union, and North America. In the latter cases the ethanol is mainly produced from starch crops, such as corn and wheat. Crop derived fuels have been called climate neutral, as they release to the atmosphere carbon that was recently fixed by photosynthesis.

To cover demand for automotive power based on biofuels, large areas of agricultural land are necessary. For instance supposing that US demand for automotive power that is to be covered by corn based ethanol, more land is necessary than the current US agricultural area [5]. This raises the question whether there are ways to convert solar energy into automotive power that are more efficient, thus requiring less land.

* Corresponding author. Tel.: +31 20 5256269; fax: +31 20 5257431.
E-mail address: l.reijnders@uva.nl (L. Reijnders).

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Many authors have pointed out that there are often inputs of fossil fuels in the '*source to wheel*' life cycle of crop derived biofuels (e.g. [2,5,7,8,11,14–18]). This is at variance with climate neutrality. In industrial countries such fossil fuel inputs may be large. Indeed, in one of the early studies regarding ethanol, Chambers et al. [17] concluded that assuming the use of standard (US) production techniques and conventional distillation technology the net energy balance (lower heating value of ethanol minus fossil fuel energy input) was negative. Since then there have been improvements in the energy efficiency of converting carbohydrates into ethanol [19]. Also discussions about fossil fuel inputs have continued and branched out in studies about greenhouse gas emissions associated with the use of biofuels.

This paper first addresses '*source to wheel*,' solar energy conversion efficiencies for the biofuel ethanol and alternative ways to provide for automotive power. Then the matter of fossil fuel inputs and greenhouse gas emissions associated with the use of bioethanol in industrialized countries is considered. In the context of the latter, emissions of greenhouse gases from agricultural soils, optimum levels for the return of crop residues to agricultural soils and the impact of expanding agricultural land for biofuel production are discussed.

2. '*Source to wheel*,' solar energy conversion efficiencies

'Source to wheel,' solar energy conversion efficiencies are calculated here using system boundaries that exclude infrastructural upstream processes such as the production of power trains or the building of factories that convert carbohydrates into ethanol. Source to wheel solar energy conversion efficiencies for different ways to provide for automotive power are given in Table 1. When conversion efficiencies are better less land is needed for the provision of automotive power. Ethanol based on sugarcane is considered. So are the use of lignocellulosic biomass for conversion into electricity and the use of solar cells (silica-based with a lifetime of about 25 years) to power an electric vehicle. Solar energy conversion efficiencies are assumed to vary between 10 and 20% for electricity from solar cells and between 0.1 and 3% for (lignocellulosic) biomass [5,22–27]. Sugarcane does relatively well in converting solar energy into biomass: it is probably the highest yielding major land-based crop [5].

Column 2 of Table 1 gives conversion efficiencies from solar radiation to the automotive power sources electricity and ethanol, if necessary corrected for fossil fuel inputs in the life cycle. In this Table 1 the production of sugarcane based ethanol is assumed to be powered by harvest residues [5], but a substantial correction for fossil fuel inputs is necessary for solar cells [23].

Table 1 suggests that conversion of lignocellulosic biomass into electricity to power an electric vehicle may do better than the use of sugarcane derived ethanol in converting solar energy to automotive power. Solar cell based automotive power is, according to Table 1, over two orders of magnitude more efficient in converting solar energy in automotive power than sugarcane based ethanol. Including storage of solar cell derived electricity [20] will lower the difference in efficiencies to about two orders of magnitude.

3. Source to wheel inputs of fossil fuels

In the calculation given in Table 1 it is, as pointed out before, assumed that energy inputs in producing ethanol from sugarcane are derived from harvest residues of the sugarcane production itself. In industrialized countries, however, it is common to use large fossil fuel inputs in the process of producing ethanol. Many assessments of biofuels have focussed on these fossil fuel inputs [2,5,7,8,11,14–16,27–32]. Such assessments vary dependent on crop and the assumptions used. Assumptions refer in part to the allocation, whereby environmentally relevant inputs and outputs are allocated to products, by-products and (in some cases) non-product outputs (wastes) of production processes [27]. Such allocation can be done on the basis of monetary values or physical aspects of outputs (such as energy or weight). System expansion in which outputs substitute for other inputs in the economy is also used (e.g. [30,31]). Most '*source to wheel*,' assessments have such allocations but Patzek [14] has argued that there should be no allocation to by-products or wastes as these should be returned to cropland to maintain fertility. Assumptions regarding the use of land if the energy crop would not have been cultivated or crops replaced by by-products also matter [30]. Other assumptions that impact outcomes of source to wheel assessments of fossil fuel inputs concern selection (inclusion or exclusion) of upstream production processes, estimates of environmentally relevant inputs and outputs, the 'energy content' (lower or higher heating value) of biofuel and the extent to which biofuels and conventional fuels are equivalent in their automotive performance.

Table 1
Typical conversion efficiencies for solar energy to car-kilometers

Type of energy supply	Conversion efficiency solar radiation to automotive power source (ethanol, electricity); corrected for fossil fuel inputs; in percent (%)	Efficiency drive train (%)	Overall efficiency conversion solar radiation to automotive kilometers (not including storage of electricity) (%)
Ethanol from sugarcane (Brazil) for Otto motor	0.16 [5]	18 [20]	0.029
Electricity from lignocellulosic biomass for electromotor	0.038–1.14 [5,21,22,24–26]	∼70 [20]	0.027–0.80
Electricity from solar cells for electromotor	4.5–10.2 [23,26]	∼70 [20]	5.2–10.5