Energy and Greenhouse Gas Budgets for Biomass Fuels

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Biomass Fuel Energy Budgets

Much attention has been given to the potential of biofuels to replace fossil fuels, but the extent to which liquid biofuels, especially ethanol, do so is controversial. Analysis of this question requires that fossil fuel energy used in the whole biofuel production chain be determined and used to calculate the net energy benefit associated with the biofuel. The energy gain from the biofuel is usually expressed as a ratio of biofuel energy output to fossil energy input. Part of the controversy in determining this ratio is over estimates of fossil energy use in crop production and conversion to biofuels and part is whether or not to include co-products as credits. When co-products are credited, both their energy value and the proportional costs of their production are factored into the energy output-input ratio calculation. We believe that the USDA/DOE estimates of fossil energy costs of ethanol and biodiesel production are the best (See http://www.iogen.ca/issues_environment/resources/net_energy_balance_2004.pdf and http://www.nrel.gov/docs/legosti/fy98/24089.pdf). But, we are ambivalent about factoring co-products into calculations of fossil fuel replacement value unless their use also replaces fossil fuel. Given that the primary co-products are animal feeds it is perhaps more appropriate to calculate the energy output-input ratio without co-products. On the other hand, the economic value of the co-products, together with various subsidies and tax incentives associated with ethanol and biodiesel, are clearly part of the economic feasibility of biofuel production by farmers and others.

Fuel Type	Energy Output -Input Ratio	Energy Output-Input Ratio with Co-Product Credits
Petroleum Gasoline	0.85[1]	
Ethanol	1.06[2]	1.67 with DDG[2]
Petroleum Diesel	0.83[1]	
Biodiesel		
from oilseed rape (UK)	1.98[3]-2.29[4]	3.36 with meal[3] 3.45 with meal + glycerin[3]
from soybean (USA)	1.84[5]	3.2 when production energy partitioned between oil and meal[6]

[1] **The energy cost of producing a gallon of gasoline and diesel from oil is 15 and 17% of the energy contained in the fuel**
[2] **Shapouri et al. 2001, see http://www.iogen.ca/issues_environment/resources/net_energy_balance_2004.pdf; DDG is distillers grains**
[3] **Shell Global Solutions, 2002; see www.fas.usda.gov/pecad/highlights/2003/09/biodiesel3/index/html**
[4] **Elsayed et al., 2003; www.shu.ac.uk/rru/reports/scp21-3.pdf**
[5] **Calculated by Duxbury using soybean production energy cost data from West and Marland, 2002 and process costs from NREL[6]**
[6] **NREL report "Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus", see http://www.nrel.gov/docs/legosti/fy98/24089.pdf**

In comparing biofuels with petroleum fuels it is important to recognize that there is some fossil fuel cost with extraction, transport and refining of petroleum fuels. This cost is 15 and 17% of the energy contained in gasoline and diesel, respectively, which can be expressed by using an energy output-input ratio of 0.85 and 0.83, respectively. Without considering co- products, it is clear that ethanol, with an energy output-input ratio of 1.06, will not replace fossil fuel, while biodiesel, with an energy output-input ratio of 1.8-2.3 will. Relative to petroleum diesel, the effective energy output for biodiesel is 2.2-2.6 times the energy input. The widely quoted ratio of 3.2:1 for biodiesel produced from soybean in the USA is derived by partitioning the cost of soybean production between the soybean oil and the soybean meal.

The attention given to production of liquid biofuels has masked the fact that other energy uses of agricultural products, and also of wood, provide very favorable energy output-input ratios. This is especially true when solid biofuels are used directly for heat with the high efficiencies (80-85%) of modern stoves and furnaces using these fuels. Thus, combustion of corn grain for heat, where the energy output is 6.5-7.7 times the energy input, is a more effective energy choice than making ethanol from corn because all of the intrinsic energy in the corn is utilized as fuel. Grass and wood pellets and wood chips can provide an even better return, with estimated energy outputs of 10 to 14 times the energy inputs. Conversion of biomass to electricity in large generation plants generally reduces the energy output to between 3 to 4 times the energy input.

Fuel Type	Energy Output-Input Ratio
Corn Grain for heat	6.5-7.7[1]
Grass Pellets (switchgrass @10 t/ha)	13.8[2]
Wood Chips (small scale)	
heat	10.5[3]
combined heat and power (CHP) by gasification	9.8-10.8[3]
Co-firing biomass for electricity generation	3.2-4.2[2,3]

[1] Calculated by Duxbury using corn energy production costs from West and Marland, 2002; lower value includes drying of corn
[2] REAP, Canada, see report no. 14 on "The use of switchgrass….." at http://www.reap-canada.com/library.htm
[3] Elsayed et al., 2003; www.shu.ac.uk/rru/reports/scp21-3.pdf; includes short rotation woody biomass such as willow

Solid biomass fuels generally replace oil, natural gas and electric heating at the household level, and coal at industrial and electricity generation scales. Thought should be given to using biomass energy sources in the most effective manner. Perhaps the best choice would be to use these fuels to replace desirable fossil fuels, especially heating oil and natural gas. Using biomass fuels to replace natural gas in distillation of ethanol from corn would improve the energy output-input ratio of ethanol production considerably but it can be argued that this is a poor choice as it perpetuates production of a biofuel that is marginal in energy terms. But, we should recognize that the market for ethanol and biodiesel is likely to be driven by their use in combination with petroleum products. Ethanol will be used as an oxidant substitute for MTBE in petroleum gasoline at a level of 5.8%. Similarly, biodiesel, which contains long-chain fatty acid esters, will be used as a lubricant at the 2% level as sulfur is removed from petroleum diesel. At current levels of fuel consumption in the USA, the ethanol and biodiesel required would utilize one-third and one-quarter of total USA production of grain corn and soybeans, respectively.

Higher levels of ethanol and biodiesel can also be used in fuels and production of ethanol from cellulose in plant residues and woody materials is being actively researched (see Burtis overview of biofuels). With current technology, use of all USA production of grain corn and soybeans for biofuels would meet only 15% of our transportation fuel demand.

Greenhouse Gas Mitigation through Use of Biofuels

There is not much analysis of the mitigation of greenhouse gas (GHG) emissions by use of biofuels. Most people might intuitively expect that there is a direct 1:1 relationship. However, this is not necessarily so, due to the fossil energy costs in biofuel production which lead to emissions of N_2O and CH_4 in addition to CO_2.

Greenhouse Gas Budget for Ethanol from Corn Grain

Savings in CO_2 emissions associated with ethanol production are calculated for ethanol energy output:fossil energy input ratios of 1.06:1 and 1.67:1 for the scenarios where no-energy credit and full energy credit are given to the distillers grains co-product, respectively. The CO_2 emission savings for these scenarios are 224 and 1862 lbs ac^{-1}. Emissions of N_2O associated with fertilizer manufacture and use, plus loss of CH_4 (from gas pipelines) used in the Haber process of N fixation, were calculated to be equivalent to 934 lb CO_2 ac^{-1} for conventional tillage corn production. Therefore, ethanol from corn only reduces greenhouse gas emissions when credit is given to co-products. This analysis does not include any emissions of N_2O and CH_4 during the conversion of corn grain to ethanol. Natural gas (CH_4) is currently used to distill ethanol so there are at least pipeline loss costs.

A. CO_2 savings

- 144 bu corn/acre[1] and 2.6 US gal EtOH/bu corn yields 374 gal EtOH/acre

Ethanol Energy Output: Fossil Energy Input	Net Ethanol Yield & (Gasoline Equiv) gal ac^{-1}	Savings in CO_2 Emissions lb CO_2 ac^{-1}
1.06 (no co-product credit)	22 (12)	***224***
1.67 (inc. co-product credit)	150 (100)	***1862***

B. N_2O and CH_4 emissions associated with corn production

lb CO_2e/lb N fertilizer applied

N_2O 0.947 during fertilizer manufacture[2]
5.474 from field emission[3]
CH_4 0.767 from pipeline gas leaks[4]

[1] Average corn yield in USA 2001-2005 from USDA (http://www.nass.usda.gov:8080/QuickStats/index2.jsp)

[2] Associated with production of nitric acid that is used to manufacture NH_4NO_3; release of 4.68 g N_2O/kg NH_4NO_3 (Kramer et al.,1999). Ammonium nitrate accounts for 22% of the fertilizer N consumption in US agriculture (Brady and Weil, 1999) and it was assumed that this proportion was used on maize. Conversion to CO_2e using a factor of 310.

[3] For a N fertilizer application rate of 130 kg N/ha and the IPCC formula of 1.25% released as N_2O from 90% of applied N.

[4] From Kramer et al., 1999; conversion to CO_2e using a factor of 21.

Greenhouse Gas Budgets for Other Biofuels

Total GHG emissions for biodiesel from oilseed rape in the UK are estimated to be 30-60% higher than carbon dioxide emissions, and are 39-47% of emissions from petroleum diesel. Only fossil CO_2 emissions have been calculated for biodiesel from soybean in the USA and this is based on partitioning fossil energy used in soybean production between the oil and meal fractions. The lowest GHG emissions are associated with use of solid biomass fuels directly for heat or in CHP applications, although emissions may not have been completely quantified.

Fuel Type	Fossil C emissions g CO_2/MJ	Total GHG emissions g CO_2 equiv/MJ	Biofuel GHG % of fossil GHG
Petroleum gas/diesel/heating oil	81-87[1]	81-87[1]	
Biodiesel			
from oilseed rape (UK)	25[1]-36[3]	41[1]-47[3]	39-47
From soybean (USA)	19[3]	?	?
Grass Pellets (switchgrass @10 t/ha)	5[4]	?	
Wood Chips (small scale)			
heat	5[1]	7[1]	8
combined heat and power (CHP) by gasification	4-7[1]	4-8[1]	5-9

[1] **Elsayed et al., 2003; www.shu.ac.uk/rru/reports/scp21-3.pdf**
[3] **Shell Global Solutions, 2002; see www.fas.usda.gov/pecad/highlights/2003/09/biodiesel3/index/html**
[4] **REAP, Canada, see http://www.fcpp.org/pdf/FB039ThePotentialforGrassBiofuelPelletsJan2706.pdf**

Summary

- Energy returns from biofuels are expressed as the ratio of biofuel energy output to fossil fuel energy input
- There is no energy return with ethanol from corn unless co-products are given credit
- The energy return for biodiesel is about 2 without co-products and 3.5 with co-products
- Including co-products in biofuel energy calculations obscures actual fossil fuel replacement values
- Energy returns from direct combustion of solid biomass fuels for heat, including corn grain, grass pellets and wood, are between 6.5 and 14
- Production of ethanol from corn grain does not mitigate greenhouse gas emissions, whereas biodiesel is estimated to reduce emissions by 50-60% compared to an equivalent amount of petroleum diesel
- Use of solid biofuels is estimated to reduce greenhouse gas emissions by up to 90%, but it is probable that analyses are incomplete

References

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