Energy Demands and Other Environmental Impacts across the Life Cycle of Bioethanol Used as Fuel

Mary Ann Curran
US EPA
Office of Research and Development
Cincinnati, Ohio 45268 USA
curran.maryann@epa.gov

Abstract

Most assessments of converting biomass to fuels are limited to energy and greenhouse gas (GHG) balances to determine if there is a net loss or gain. A fairly consistent conclusion of these studies is that the use of bio-ethanol in place of conventional fuels leads to a net gain. However, the findings of a recent literature review indicate that basing fuel production policy on environmental sustainability studies that are life cycle based but that ignore other issues are likely to result in unintended, and possibly detrimental, shifting of environmental burdens. Human and ecological health impacts need to be weighed into the decision-making process along with climate change and resource depletion concerns. Acidification, human toxicity and ecological toxicity impacts, mainly occurring during the harvesting and processing of the bio-mass, were more often unfavourable than favourable for bio-ethanol.

This paper summarizes the findings of a literature search that was recently conducted and revealed 45 publications (1996-2005) that compare bio-ethanol systems to conventional fuel on a life-cycle basis, or using life cycle assessment. Feedstocks, such as sugar beets, wheat, potato, sugar cane, and corn, have been investigated in many countries, including Brazil, Canada, India, the Philippines, South Africa, the United States and several European nations. Studies are needed to fill the critical gaps, especially on ethanol from tropical sugar crops, cellulosic cropped feedstocks, particularly perennial grasses, and corn.

Keywords: bio-fuel, bio-ethanol, life cycle assessment, sustainable transportation

Introduction

Ethanol derived from bio-mass is often advocated as a significant contributor to possible solutions to our need for a sustainable transportation fuel. Kim and Dale [2003] estimated that the potential for ethanol production is equivalent to about 32% of the total gasoline consumption worldwide, when used in E85 (85% ethanol in gasoline) for a midsize passenger vehicle. Such a substitution immediately addresses the issue of reducing our use of non-renewable resources (fossil fuels) and the attendant impacts on climate change, especially carbon dioxide and the resulting greenhouse effect, but it does not always address the notion of overall improvement. For instance, it is well-understood that the conversion of bio-mass to bio-energy requires additional energy inputs, most often provided in some form of fossil fuel. The life cycle energy balance of a bio-fuel compared to conventional fossil fuel should be positive, but depending on the processing choices, the cumulative fossil energy demand might at times only be marginally lower or even higher than that of liquid fossil fuels (e.g., Pimentel, 2003, and von Blottnitz, et al, 2002). Also, ethanol in gasoline may result in decreased urban air quality, and be associated with substantive risks to water resources and biodiversity [Niven, 2005].

Bio-based systems have other possible ecological drawbacks. Agricultural production of bio-mass is relatively land intensive, and there is a risk of pollutants entering water sources from fertilizers and pesticides that are applied to the land to enhance plant growth. A very large number of researchers have recognized this conundrum and have attempted to analyze bio-ethanol systems in an effort to describe their environmental sustainability and to determine whether bio-based fuels, i.e. bio-fuels, are helping us achieve the goal of providing environmentally sustainable transportation. Two recent reviews have attempted to summarize the findings. One focused on ethanol alone and presents generally unfavorable recommendations [Niven, 2005]; the other review looked at bio-fuels more generally and presented more favorable results for ethanol but cautioned with respect to some of its environmental impacts [Quiran, et al, 2004]. It must be noted that a number of studies that looked specifically at the North American corn-to-ethanol route reported were very critical as to its environmental sustainability [Patzek, 2004], [Pimentel, 2003], [Berthiaume, *et al*, 2001].

Many authors have studied liquid bio-fuel production systems, both current and projected, with the aim of determining whether the currently accepted premise that such systems contribute to environmental sustainability is valid. While the issue of sustainability is complicated, one that encompasses human and environmental health as well as societal needs, it is clear that our efforts to identify solutions should be broad in scope to avoid shifting problems from one place to another [Curran, 2004a]. This study reviewed these studies that used life cycle thinking or life cycle assessment as the basis for comparing bioethanol to conventional fuels.

Scope of the Search

An online search of publicly-available papers and reports was conducted to find studies that have been published in the last ten years. The focus of the search was on ethanol from bio-mass for use as a transportation fuel (a gasoline replacement). The search included completed, published assessments that claimed to be life-cycle based and that were environmental in nature. Cost analyses were not part of the main focus of the study. Only those reports that are available in English were subjected to further analysis; 36 reports were included in the analysis (four reports in German and one in French were also found but not used in the study).

This area of research is still of significant interest worldwide and studies on biofuels continue to be conducted. Although additional studies have been published since the completion of the literature search, this paper includes the assessments that were available at that time.

Defining the Life Cycle

Life cycle management is quickly becoming a well-known and often used approach for environmental management. A comprehensive environmental assessment of an industrial system needs to consider both upstream and downstream inputs and outputs involved in the delivery of a unit of functionality. A life cycle approach involves a cradle-to-grave assessment, where the product is followed from its primal production stage involving its raw materials, through to its end use. The diagram in Figure 1 illustrates a generic bio-fuel life-cycle scheme; it shows the main sub-processes, and identifies the flows of importance for describing environmental performance.

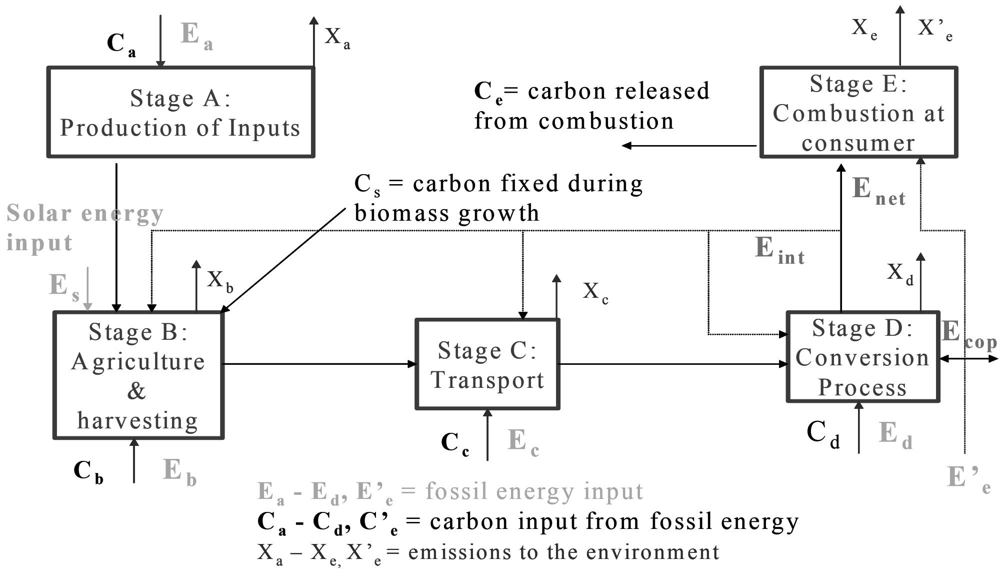

Figure 1. Material Flow and Environmental Interventions across the Life Cycle Stages in a Bio-Fuel System

The main stages A to E can be studied in order to determine the holistic performance of the system, depending on the goals of the study. It is at this point that differences in studies that are called life cycle assessments can be seen. Some studies include cradle-to-grave boundaries but limit input or output data. Most often studies on energy and carbon balances, as well as greenhouse gas emissions, are found in the literature. The goal of a life cycle assessment (LCA), on the other hand, is to model all potential impacts to human health and the environment across all media - air, water and solid waste (Curran, 2004b). A distinction can then be made between studies that are life-cycle based versus those that aim to be fuller life cycle assessments.

Overview of Published Studies

The on-line literature search led to a recent review study that was conducted by the Institute for Energy and Environmental Research (IFEU) with a similar objective [Quiran, et al, 2004]. IFEU analyzed and compared all international, publicly-accessible publications about bio-fuels that are currently used for transportation (e.g., bio-diesel and bio-ethanol as well as those potential fuels like biomass-to-liquid, BTL). The literature search uncovered additional references that were not part of the IFEU review. The integration of these efforts resulted in 45 publications, in English, that address bio-ethanol (see References). Note that while several studies encompassed the entire life cycle as depicted in Figure 1, many studies did not extend beyond ethanol production, i.e. they excluded fuel distribution, storage and combustion (in use) and were not considered further in the current study.

Health and Environmental Impact Assessments

Only six of the collected studies evaluated impacts that are more expansive in scope than the studies described in the previous sections. While these studies all account for energy (as resource demand), CO_2 and greenhouse gas emissions, they go beyond these measures and include additional impact indicators. The six studies are summarized below and in Table 1. Full citations can be found in the reference section.

Kadam (2002). Environmental Benefits on a Life Cycle Basis of Using Bagasse-Derived Ethanol as a Gasoline Oxygenate in India.
Feedstock: Bagasse
Location: India
Basis: 1 dry tonne of bagasse to produce 10% by volume ethanol in gasoline (E10).
System Description:
The study compares the conventional practice of burning bagasse in the field and using conventional fuel (Scenario 1) to a hypothetical process of converting bagasse into ethanol for use in E10 (Scenario 2). Boundaries include bagasse transport, ethanol production, use and excess electricity.
Impacts:
- Nonrenewable resource depletion
- Greenhouse effect
- Air acidification
- Eutrophication
- Human toxicity
- Waste generation
- Air odor

Findings:
The author claims that there are significant benefits in diverting excess bagasse to ethanol production as opposed to the current practice of open-field burning. Scenario 2 leads to a decrease in carbon monoxide, hydrocarbons, SO_x, NO_x, particulates, carbon dioxide, methane and fossil fuel consumption. COD (from ethanol raw material production) is significantly higher. Non-methane hydrocarbons are from ethanol production. Lime, ammonia & sulphuric acid occur only in Scenario 2. Electricity credits result in negative CO_2 and CH_4 emissions and lower solid waste.

Kaltschmitt, Reinhardt & Steltzer (1997). Life Cycle Analysis of Bio-Fuels under Different Environmental Aspects.
Feedstock: Sugar beet, wheat, and potato
Location: Germany
Basis: 1 hectare
System Description:
This study compared bio-based systems, including cultivation and harvesting of raw materials, through energy use, to fossil systems, including mining and processing of raw materials through energy use.
Impacts:
- Finite energy
- Global warming potential (CO_2 equivalents)
- Nitrous oxide
- Acidification potential
- Sulphur dioxide
- Nitrogen oxide

Findings:
The study shows some clear ecological advantages of bio-ethanol over fossil fuels, such as conserving fossil energy sources and reducing global warming potential, but bio-ethanol also has some definite disadvantages; in particular N_2O and NO_X emissions are higher. SO_2 emissions and, correspondingly, acidification potential show no discernible change.

Puppan (2001). Environmental Evaluation of Bio-Fuels.
Feedstock: Sugar beet, winter wheat, and potato

Location: Germany
Basis: Summary of a German study on E5 fuel versus gasoline (Steltzer et al, 1999).
System Description: Not provided
Impacts:
- Depletion of abiotic resources
- Climate change
- Stratospheric ozone depletion
- Acidification
- Human & Ecotoxicity

Findings:
Puppan cites a German study (Steltzer 1999) that shows that E5 fuel (5% ethanol) has lower impacts for depletion of abiotic resources and climate change, but higher impacts for stratospheric ozone depletion (acidification and human toxicity impacts were mostly unchanged). Puppan states that the LCA study proved the environmental benefit of biofuels during the combustion in the engine, but also emphasized the environmental drawbacks that occur during the agricultural phase, such as pollution of ground and groundwater by fertilizers and pesticides as well as the creation of monocultures. Puppan concludes that the net environmental impact depends on the agricultural conditions.

Reinhardt & Uihlein (2002). Bio-Ethanol and ETBE (Ethyl Tertiary Butyl Ether) versus other Bio-Fuels for Transportation in Europe: An Ecological Comparison.
Feedstock: Sugar beet, wheat and potato
Location: Europe
Basis: Per kilometer
System Description:
The study includes fertiliser, fuel, and pesticide production; cultivation; sugar extraction; ethanol production; and consumption (use in the vehicle).
Impacts:
- Resource demand (natural gas, mineral coal, brown coal, uranium ore)
- Greenhouse gas emissions (CO_2, CH_4, N_2O)
- Acidification
- Eutrophication
- Photochemical smog (N_2O)
- Human toxicity (reported as LCI)
- Eco toxicity (reported as LCI)

Findings:
For all life cycle comparisons, resource demand and greenhouse gas effect are in favour of bio-fuels, whereas most of the other parameters are in favour of the fossil fuels. Ethanol from sugar beets has advantages over wheat and potato.

Sheehan et al. (2004). Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol.
Feedstock: Corn stover
Location: USA (Iowa)
Basis: 1 hectare of land and 1 kilometer travelled using 85% ethanol in gasoline (E85) versus gasoline.
System Description:
Sheehan describes a hypothetical system of using corn stover to make E85. The processes include stover production & collection; transport; ethanol production; distribution; and use. The system also includes the gasoline system, with which the ethanol is blended, from crude oil extraction through use.

Impacts:
- Fossil energy use
- Greenhouse gas emissions
- Air quality (ozone precursors; CO; NO_x)
- Land use (soil health)
- Cost

Findings:
Findings are presented in the paper for a few key metrics:
- Fossil energy use is 102% and greenhouse gas emissions are 113% lower for E85.
- 2.91 MJ/km avoided non-renewable energy.
- Air quality impact is mixed with emissions of CO, NO_X, and SO_X substantially higher. NO_X emissions result mainly from farm soil. SO_X emissions result from the combustion of lignin residue at ethanol plants. Hydrocarbon ozone precursors are reduced.
- Stover can be removed from the field while maintaining or increasing soil carbon.

Tan & Culuba (2002). Life-Cycle Assessment of Conventional and Alternatives Fuels for Road Vehicles.
Feedstock: Cellulosic agricultural waste using enzymatic hydrolysis and fermentation
Location: Philippines
Basis**:** Per kilometer
System Description:
The LCA encompasses extraction of raw materials and energy resources; conversion of these resources into the desired product; the utilization of the product by the consumer; and the disposal, reuse, or recycle of the product after its service life.
Impacts:
- Resource depletion (oil, coal, natural gas)
- Human toxicity potential (PM10)
- Nutrification
- Photochemical ozone
- Acidification
- GWP (CO_2, CH_4, N_2O)
- Air emissions (VOC, CO, NO_X, PM10, SO_X)

Findings:
For Scenario A (using Philippine Department of Energy projections for the year 2009), the use of bio-ethanol in place of gasoline is expected to yield significant gains particularly with respect to fossil fuel depletion and greenhouse gas emissions. The total impacts for bio-ethanol are significantly lower than those of gasoline, primarily due to sharp reductions in CO_2 emissions (and global warming potential) and fossil fuel consumption. Tan & Culuba stat that impacts of bio-fuels in other impact categories remain roughly comparable to those of conventional fuels (Table 1 of the report shows acidification, nitrification and human toxicity potentials that are slightly larger and photochemical oxidation potential slightly less than conventional fuel).

Table 1 summarizes the findings of these six LCA studies by indicating for 13 impact categories whether the study reports an increased or decreased impact for bio-ethanol compared to conventional fuel. As one scans across the lines of this table, it becomes evident that there is not much consensus on the environmental benefits of fuel bio-ethanol beyond the broad agreement that they do avoid to some extent the use of fossil energy carriers, and consequently also reduce GHG emissions.

Table 1. Life Cycle Assessments of Bio-Ethanol Found in Recent Literature (1996-2004)

	Agricultural Feedstocks			Waste Feedstocks		
	Kaltschmitt 1997 Sugar beet Wheat Potato	Puppan 2001 Sugar beet Winter wheat Potato	Reinhardt 2002 Sugar beet Wheat Potato	Kadam 2002 Waste Bagasse	Sheehan 2004 Corn Stover	Tan & Culuba 2002 Agricultural Cellulosic Waste
	Germany	Germany	Europe	India	USA	Philippines
Resource Depletion	↓	↓	↓	↓	↓	↓
Global Warming	↓	↓	↓	↓	↓	↓
Ozone Depletion	↑ **(N2O; NOx)**	↑	**NA**	**NA**	↑ **(N2O; NOx)**	**NA**
Acidification	**--**	**--**	↑	↓	**(SO2)** ↑	↑
Eutrophication	**NA**	**NA**	↑	↓	**NA**	↑
Human Toxicity	**NA**	**--**	**NA**	↓	**NA**	↑
Ecological Toxicity	**NA**	**--**	**NA**	**NA**	**NA**	**NA**
Photochemical Smog	**NA**	**NA**	↓ **(N2O)**	**NA**	↑ **(CO; NOx)**	↓
Solid Waste	**NA**	**NA**	**NA**	↓	**NA**	**NA**
Land Use	**NA**	**NA**	**NA**	**NA**	**--**	**NA**
Water Use	**NA**	**NA**	**NA**	**--**	**NA**	**NA**
Odor	**NA**	**NA**	**NA**	↓	**NA**	**NA**

Notations in parentheses (XX) indicate interpretation of inventory data as an increase, decrease or no change.

NA Not Assessed ↑ Increased Impact for Bio-Ethanol ↓ Decreased Impact for Bio-Ethanol -- No Significant Difference

Findings

To date, the emphasis in life cycle based studies of bioethanol has been on North America and Europe, and the few LCAs that have been completed do not cover the full range of possible options (see Table 2). Published life cycle based assessments of bio-ethanol systems have investigated a wide variety of feedstocks. An array of different metrics has been used to convey their results, sometimes complicating comparisons. Methods have varied from simple energy and carbon accounting to attempts to be more inclusive in addressing sustainability. Much of the focus has been to determine if the use of bio-mass to make fuel is a net loss or a net gain regarding energy input versus output.

Table 2. Studies of Biomass to Fuel Ethanol Categorized by Feedstock, Location and Scope of the Evaluation (Energy/GHG or Multiple Criteria/LCA)

		Farmed Feedstock		Waste Feedstock	
		Energy/GHG	**Multiple Criteria/LCA**	**Energy/GHG**	**Multiple Criteria/LCA**
Corn:	N America	Pimentel 2003 IEA 2003 Graboski 2002 USDA 2002 Berthiaume 2001 Pimentel 2001 GM 2001 Schneider 2001 Levelton 2000 Wang 1999		Levelton 2000 (corn stover)	Sheehan 2004 (corn stover)
	Europe	JRC 2003 Jungmeier 2003 Schmitz 2003 TU München 2003			
Wheat:	N America	IEA 2003 $(S\&T)^2$ 2003		Elsayed 2003 (wheat straw) Levelton 2000 (wheat straw)	
	Europe	Elsayed 2003 EUCAR 2003 JRC 2003 Jungmeier 2003 LowCVP 2004 Schmitz 2003 TU München2003 Thrän 2004 ADEME 2002 CONCAWE 2002 Rosenberger 2001 Levington 2000 Hanegraaf 1998 ETSU 1996	Kaltschmitt 1997 Steltzer 1999 IFEU 2002		
	Australia	CSIRO 2001			
Potatoes:	Europe	JRC 2003 Schmitz 2003	Kaltschmitt 1997 Steltzer 1999 IFEU 2002		
Lignocellulose:	Australia			CSIRO 2001 (wood)	
	N America	IEA 2003			
	Europe	EUCAR 2003 (wood) IEA 2003 (unknown) Jungmeier 2003 LBST 2003 CONCAWE 2002 (wood & grass) EST 2002 (wood) GM 2002 (various) JRC 2002 (wood & grass) Fromentin 2000 (in French) Levelton 2000 (switchgrass & hay)		GM 2002 (crop residue) EUCAR 2003 (wood & straw) LBST 2002 (wood)	
	Philippines		Tan & Culuba 2002 (agricultural)		
Sugarcane:	N America	Bastianoni and Marchettini 1996			

	S America	Moreira 2002 Macedo 1998			
	India			Prakash 1998 (molasses)	Kadam 2002 (bagasse)
	Australia			Enerstrat 2003 (molasses) CSIRO 2001 (molasses)	
	S Africa			Theka 2003 (molasses)	
Sugar Beet:	Europe	Elsayed 2003 EUCAR 2003 IEA 2003 JRC 2003 Jungmeier 2003 Schmitz 2003 Thrän 2004 TU München 2003 ADEME 2002 CONCAWE 2002 GM 2002 LBST 2002 Fromentin 2000 FfE 1999 Hanegraaf 1998	Steltzer 1999 Kaltschmitt 1997 IFEU 2002		
	Australia	CSIRO 2001			

The popular conclusion of the studies that looked at energy balances was that the use of bio-ethanol in place of conventional fuels, or as an additive, leads to a net gain. The prevailing data indicate that it takes less energy to make and distribute ethanol than can be delivered by the fuel, although how much less varies across studies. The studies that evaluated other environmental impact categories beyond energy and greenhouse gases gave mixed results. Acidification, human toxicity and ecological toxicity impacts, mainly occurring during the harvesting and processing of the bio-mass, were more often unfavorable than favorable for bio-ethanol. The IFEU study had similar findings and concluded that for all life cycle comparisons resource demand and GHG effect are in favor of bio-fuels, whereas most of the other parameters they evaluated are in favor of fossil fuels (Reinhardt & Uihlein, 2004).

Recommendations for future sustainability assessments of bioethanol are:

1. It is not necessary to repeat detailed energy and GHG assessments. Depending on crop and geographical location, in many cases it will be possible to obtain a sufficiently reliable estimate from previous work.
2. Studies should be selected to fill the critical gaps: full life cycle assessments on ethanol from tropical sugar crops and cellulosic cropped feedstocks, particularly from perennial grasses, are needed.
3. The assessments must be cradle to grave, as significant air quality impacts may be associated with the bio-ethanol used in internal combustion engines.
4. Attention must be paid to gathering the data needed for the disputed environmental categories of acidification, eutrophication, photochemical smog, human and eco-toxicity, as well as land use and its effects on biodiversity. Human and ecological health need to feature more prominently next to those of climate change and resource depletion concerns.
5. The data gap for life cycle assessments of corn to bio-ethanol in the United States should be addressed and filled.

Conclusion

Moving toward sustainability requires a re-thinking of our systems of production, consumption and waste management and an increased awareness of the need to avoid shifting of problems, as often occurs with isolated measures. The ecological advantages should outnumber, or outweigh, the disadvantages to the environment and human health. Numerous studies have been done in recent years evaluating the life cycle impacts of bio-ethanol. However, while over 40 studies have been life cycle based, only six were identified which could be said to be life cycle assessments. These six studies do not, of course, cover the full range of possible feedstocks and geographies, and their results in the standard impact categories diverge. Future assessments should undertake evaluations of locations outside Europe and North America and pay more attention to the safeguard subjects of human and ecological health. Environmental sustainability studies that are life cycle based in the sense of extending from the crop to the wheel, but that ignore issues other than fossil fuel depletion and GHG emissions lead to limited results and are likely to result in detrimental shifting of burdens.

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