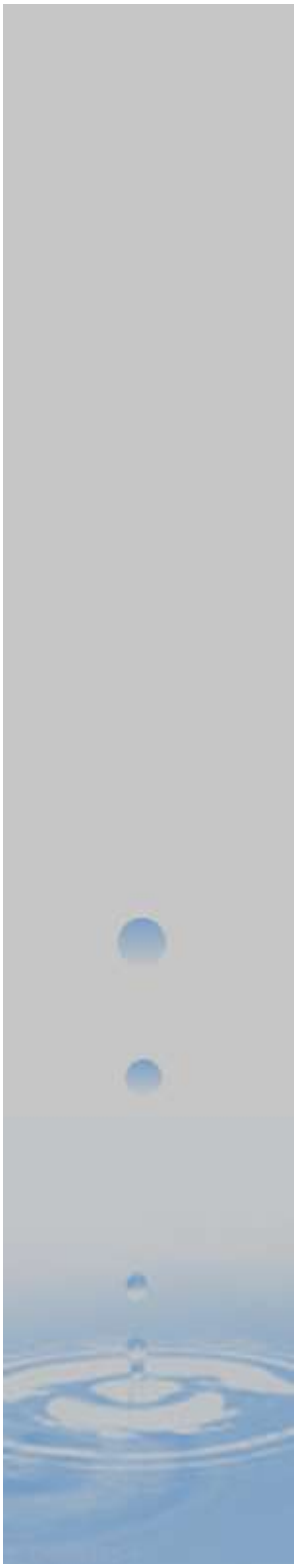
IEA Bioenergy Task 39 Commercializing 1st- and 2nd- Generation Liquid Biofuels from Biomass



Backgrounder:
Major Environmental Criteria of Biofuel Sustainability

A REPORT TO THE IEA BIOENERGY TASK 39

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EXECUTIVE SUMMARY

Sustainability has become one of the defining concepts of the current industrial era, and a recognized criterion of public and political acceptance. The term ‘sustainable,’ however, can mean different things depending upon one’s perspective. Sustainable alternatives to fossil-based liquid transport fuels are often defined as sustainable if they are sourced from renewable feedstocks, such as biomass, which are harvested in a sustainable fashion. Public and political support for biofuels is in part attributable to the perceived sustainability of these fuels; the industry’s ’License to Operate’ and continued level of political support (i.e. through funding and blending targets) hinges upon demonstrating positive environmental performance; it may no longer be sufficient to simply be better than the fossil alternative. As biofuels gain increasing share of the liquid transportation fuel market, the economic, environmental and social impacts at all points in the value chain are being increasingly scrutinized to verify that all externalities are accounted for in assessing the true sustainability of these products.

Life Cycle Analysis (LCA) models are often the basis for assessing sustainability of biofuels, as well as providing baseline data by which biofuels may be compared to fossil alternatives. Findings from LCA studies vary for seemingly identical systems due to several reasons. The results of environmental impacts analyses vary with parameters including feedstock type, cultivation practices, conversion technology, geographic scope, year of study, system boundary definition, numeric assumptions and co-product allocation. Comparing the varying results from the use of different assumptions employed by separate studies for identical biofuel systems is a challenge. There is an urgent need for life cycle assessment protocol that is sensitive to regional variations associated with biofuel production. It is also important that the various international bodies engaged in developing LCA methodology to work collaboratively in order to avoid duplicity of effort and enable third party verification.[1]

The report provides a general overview of biofuel sustainability topics, and examines four primary environmental performance indicators (net energy balances, GHG emissions (excluding land use change), water requirements and land use change). Studies published after 2006 have been reviewed to reflect the most current industry practices. The goal of this report is to provide an objective meta-analysis of the most prominent sustainability criteria, which can be used as a basis for subsequent comprehensive assessment of biofuel sustainability. This general report (Phase 1) will be followed by Phase 2 that will further explore each environmental criterion through a comparison of multiple indicators that collectively reflect upon the environmental performance of the various feedstocks and end-products.

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[1] For further information on LCA analyses please refer to IEA Bioenergy Task 38 http://www.ieabioenergy-task38.org/

The scope of Phase 1 (this report) is restricted to eleven feedstocks; however there are numerous emerging options (e.g. energy cane or Arundo donax) that can be grown as dedicated crops on marginal land often with positive environmental benefits. The authors recognize the potential of some of the emerging options and will further analyze these emerging options in Phase 2. While the scope of this report focuses on environmental performance, it is evident that sustainability analyses cannot be considered complete without incorporating social sustainability. Biofuel production, trade and consumption interfaces with the social dimension at all times; society's priorities have resulted in the development of policies that drive accelerated of biofuel deployment (R&D support, blending targets, etc.). While recognizing the importance of social sustainability, this subject requires a comprehensive analysis, best case scenario identification and provides policy guidelines that optimize economic activity which is fully aligned with societal goals. While the social dimension is not explored in depth within the scope of this report, it is acknowledged that all the issues discussed are closely related with the social sustainability.[2]

Another topic of increasing importance in biofuel sustainability discussions is biodiversity, and the need to fully explore the links between land-use, biodiversity and biofuels. Both social and environmental sustainability are increasingly important topics and the subject of significant academic and political discussions. The review of existing material highlighted the importance of four major sustainability criteria, related to energy use, greenhouse gas or GHG emissions, water requirements, and land use change. Data is currently not collected in a coordinated fashion to inform each of these criteria, however; in fact, most published analyses are limited to one or two of these measures, and thus cannot provide an overall assessment of the true sustainability of the system at hand. The amount of data available on each of these indicators varies. The literature is best informed by data on energy content of biofuel relative to gasoline, followed by GHG emissions, and water requirements; the least amount of data is available for land use change.

Energy use

The dominant factors influencing energy performance are the type of primary electricity source used in the bioconversion process, and allocation of co-products (e.g. animal feed or energy). Studies indicate that the energy balance of biofuels consistently improves as efficiency gains are made in both feedstock production and manufacturing processes ((S&T)^2 2009). The energy balance[3] of various feedstocks is inherently dynamic; efficiency gains are achievable for both 1st and 2nd generation biofuels through continued R&D efforts. For instance, the energy balance of corn ethanol improved from 1.2 to 1.4 between the years of 1995-2005; it is anticipated that this ratio will further increase to 1.9 by 2015.

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[2] For further information on social dimensions of bioenergy please refer to IEA Bioenergy Task 29 (Socio-Economic Drivers in Implementing Bioenergy Projects) http://www.task29.net/, and IEA Bioenergy Task 40 (Sustainable International Bioenergy Trade) http://www.bioenergytrade.org/

[3] The energy balance represents the amount of fossil energy consumed per unit energy delivered.

Estimates of the energy savings resulted to ranking biofuels (in decreasing order of net energy savings relative to fossil fuel) as: sugarcane (89%), wheat straw (88%), switch grass (85%), wood (82%), sunflower (72%), rapeseed (63%), beet (48%), soybean (45%), corn (43%), wheat (42%) and palm oil (36%) (Figure 1). With the exception of sugarcane, 1st-gen bioethanols have the lowest energy efficiency, biodiesel demonstrated better energy ratios, and 2nd gen fuels achieve the best energy savings. One strategy effective at increasing the energy input/output ratio is the co-location of biorefinery plants with power plants as a means of harnessing waste heat from the industrial facility. Policies supporting symbiotic partnerships with other industrial partners would significantly benefit the performance of the biofuels industry. Policy should continue to promote the increased production of sugarcane ethanol, wheat straw ethanol, switch grass ethanol, wood ethanol, sunflower biodiesel and rapeseed biodiesel.

Industrial symbiotic relationships have been employed in other industries to improve environmental performance. This can be achieved by co-locating biofuel industries and power plant; which leads to waste heat generated in the power plant to be used in the biofuel plant. This symbiotic partnership is currently practiced by Inbicon A/S (Denmark). The use of waste heat from the Asnæs Power Plant to meet the process steam and heating requirements in Inbicon A/S results in the elimination of natural gas (fossil fuel) as well as the heating infrastructure otherwise associated with a stand-alone biofuel plant. Policies to encourage industrial symbiotic partnerships involving the biofuel industry and other species in the industrial ecosystem need to be promoted aggressively to achieve high net energy savings.

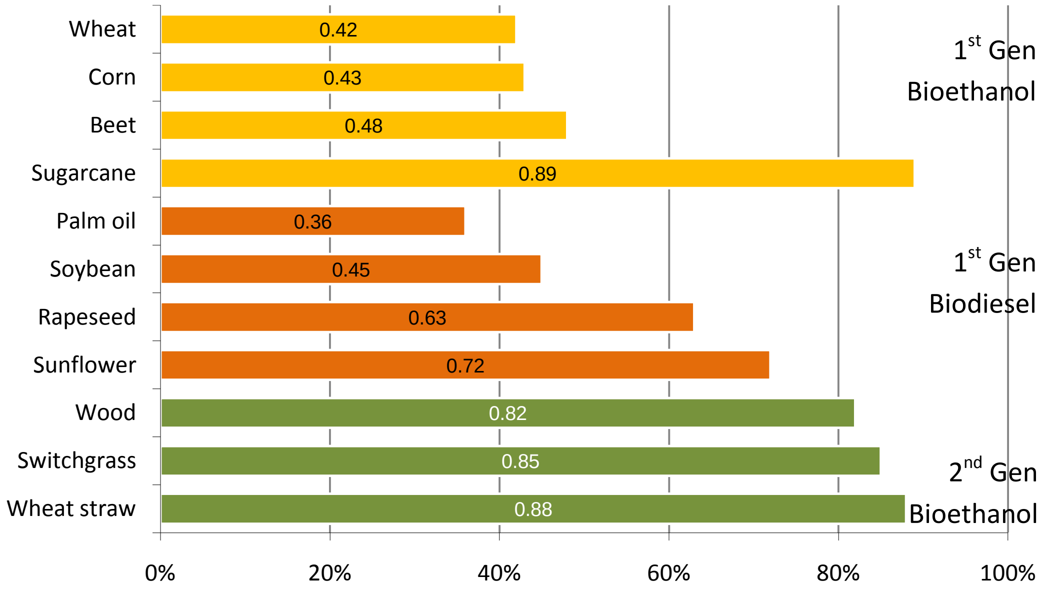

Figure 1. Reduction of fossil energy use, % total fossil energy savings relative to reference fossil systems.[4]

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[4] Source: Manichetti and Otto, 2009.

Greenhouse gas emissions

GHG emission reductions are closely linked to energy performance; however, some variability does exist and emissions analyses are therefore included in this study. Similar to findings in the energy efficiency criterion, GHG emission reductions are highly dynamic and have also demonstrated continuously improving performance over the last decade. In fact, GHG emission reductions associated with bioethanol production will have more than doubled between 1995 and the projected 2015 levels; this emphasizes the importance of basing policy decisions current as opposed to outdated, historical data ($(S\&T)^2$ 2009).

Nitrous oxide emissions embodied in fertilizer are the primary component of GHG emissions calculations for biofuels. One tonne of N_2O gas has the equivalent global warming impact as 298 tonnes of CO_2. The GHG intensity of electricity used during the conversion process of biofuels is another determinant of emissions reductions achievable through biofuels[5]. Policies aimed at improving the GHG emission savings of biofuels should encourage the use of:

- manure and biomass residues to substitute petro-chemical derived fertilizers;
- residue biomass for heat and electricity generation in natural gas fired co-generation systems;
- co-allocation of lignin (from wood) to substitute petro-chemicals, to eliminate high energy intensive manufacturing. The use of lignin for chemicals results in significant GHG emissions savings (compared to its utilization for heat).

Estimates of average GHG emission savings achievable from biofuels, are as follows: Switchgrass (93%), sugarcane (92%), wheat straw (87%), wood (77%), sunflower (67%), beet and wheat tied (48%), soybean and palm oil tied (44%), rapeseed (38%), and finally corn (27%) (Figure 2). The GHG performance of the identified biofuels categories parallel the energy performance (ranked lowest to best GHG emission reductions: 1st gen ethanol, 1st gen biodiesel and 2nd generation biofuels). Beside fuels wheat, corn, soybean, sunflower and rapeseed based biofuels value chains produce high quantities of high grade animal feed. Policies aimed at maximizing the GHG benefits associated with biofuels should promote co-location of biorefineries with existing power infrastructure and the use of natural fertilizers. Additionally, “no till” and “no till with crop cover” and sustainable agricultural practices should be widely promoted to minimize GHG emissions associated with biofuels. Industrial symbiotic relationships and the use of waste heat from power generation to offset fossil fuel requirements in biofuel plant also results in significant GHG emission reduction savings.

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[5] Electricity can be produced from a variety of sources (e.g. coal, natural gas, and renewables) and therefore contains varying amounts of embodied GHG emissions. The matter is further complicated by electricity trade which then necessitates GHG record-keeping to account for the GHGs embodied in the electricity as it moves from one jurisdiction to another. There are numerous methods used calculate a weighted average of the GHG intensity of electricity consumed; these include and account for emissions embodied in imported electricity in addition to the GHGs resulting from power production within a jurisdiction.

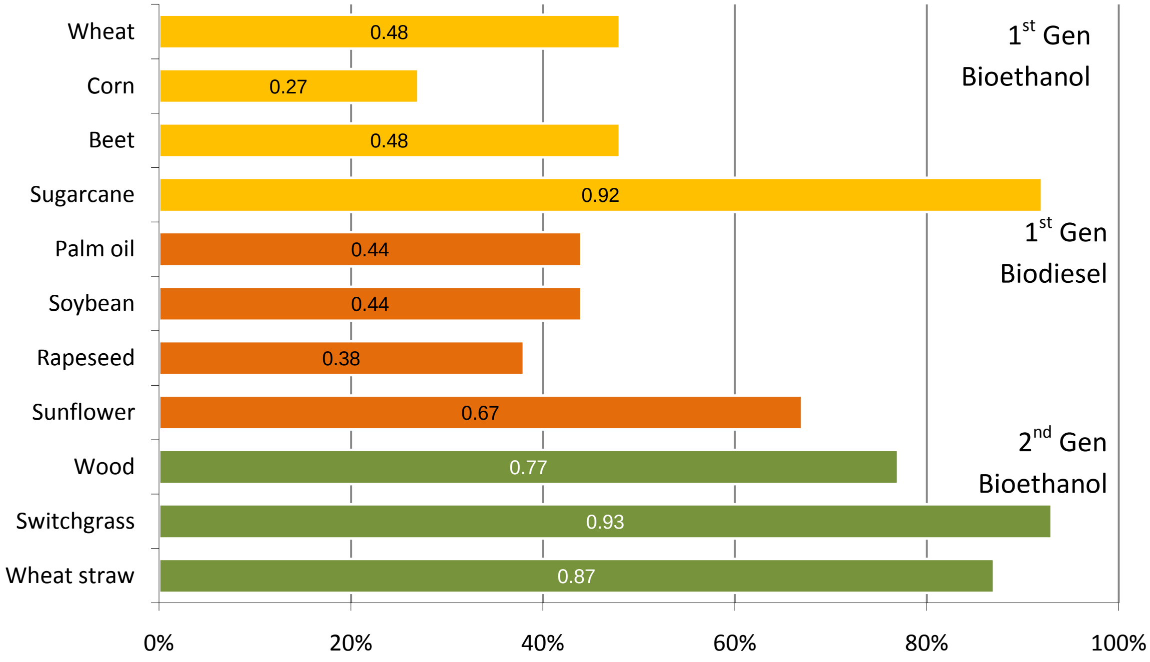

Figure 2. Reduction in GHG emissions, % CO_2-equivalent relative to reference fossil systems.[6]

Water use

Some biofuel production chains require significant amounts of water relative to other energy production processes. Biofuel production in climatic conditions with high evapo-transpiration rates often rely on surface and ground water for irrigation. The water challenge is exacerbated when biofuel production occurs in a dry climatic region that is also highly populated as that result in water use conflicts for human and fuel. Effective policies aim to minimize the water impact of biofuels by encouraging rain-fed biofuel production. Today's biofuel production is not suitable in regions with dry conditions, high population densities; increased water consumption may place excessive pressure on the resource.[7]

Biofuel policies should promote the combined use of food, feed and fuel as well as the use of biological nutrients as substitutes for petro-chemically derived fertilizers in crop cultivation. This will significantly reduce the food versus fuel conflict as well as the amounts of nitrate, nitrite, atrazine and phosphorus loadings in streams that are already impacted by the intensification of the agriculture and agro-fuel industries. Strategic relationships could be developed by siting new biofuel plants close to waste water treatment facilities meeting water quality standards; this could increase access to water required during

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[6] Source: Manichetti and Otto, 2009.

[7] Innovative feedstock options with low water demand are being investigated

the biofuel conversion process. If feasible, sterilizing the treated waste water with heat from the power facility provides clean process water for bioconversion processing.

Land use change

Indirect land use change (ILUC) impacts remain the most controversial in the biofuel sustainability discussions. The biofuel production value chain interacts with the global economic, natural and climatic systems. For example, indirect land use change occurs when pressure from market forces leads to land conversion from food crop production to biofuel cultivation which consequently result in land use change in other regions of the world in order to make-up for the loss in food production (Kim *et. al.,* 2009). Complexities arise when we attempt to quantify these effects and re-distribution of agreeable land, and the methods used to estimate the impacts are still under development. The method employed in the Renewable Fuel Standard 2 (RFS2) developed by the US Environmental Protection Agency is an example of the more successful means of quantifying ILUC.

Policy formulation should promote the increased use of forest residues, agricultural residues and coupled products, bagasse, urban waste, sugarcane cultivation on former grazing lands and perennial prairie grasses from abandoned cropland for power, heat and transport fuel production. The use of renewable-derived fertilizers as substitute for petro-chemical fertilizers and utilization of biomass in highly integrated systems along the whole value chain improves the land use change emission reductions. Biofuel policies targeted at mitigating land use change impact should encourage the allocation of co-products to animal feed which will result in decreased amount of crops cultivated for animal feed.[8] Finally (but not the least), the application of “no till” and “no till with crop cover” and sustainable agricultural practices should be widely promoted. Harmonizing the various LCA results using different assumptions for similar biofuel systems is a challenge, and it is therefore imperative to establish a locally and internationally recognized LCA protocol specifically designed for biofuels that also recognize regional variations of environmental impacts.

This report represents Phase 1 of a more comprehensive analysis of biofuel sustainability issues; the intent is to introduce the four outlined environmental criteria for discussion, to solicit insights from the various country representatives and provide an in-depth analysis of sustainability trends.

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[8] However a paradox exists co-product allocation of energy production (which is the way to maximise GHG emission reduction) and using these as animal feeding ingredients (minimization of land use change impact).

CONTENTS

1 INTRODUCTION

Biofuels derived from sustainably-produced feedstocks are considered to be among the most appropriate alternatives to substitute petroleum-based transportation fuels. Petroleum-based fuels account for 57% of global anthropogenic GHG emissions (WWI, 2009). Emissions resulting from fuel combustion including carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, have been linked to anthropogenic climate change as well as the depletion of the earth's ozone layer. Biofuels are compatible with existing distribution infrastructure and engine design and are therefore considered as an appropriate alternative to petroleum-based transportation fuels. Shifting society's reliance on petroleum-based fuels to sustainably derived biomass resources is essential to sustaining modern civilization and achieving GHG emission reductions (Ragauskas *et. al.,* 2006).

There has however been an intense and growing debate about the sustainability of biofuels, particularly with regards to environmental and socio-economic externalities of a growing biofuel industry. While the debate continues the most recent available studies using current data and realistic assumptions have confirmed environmental benefits achieved by the industry (Liska et.al., 2009; $(S\&T)^2$ 2009).

This report provides a meta-analysis of biofuel sustainability topics, namely net energy balances, GHG emissions (excluding land use change), water requirements and indirect land use change. We reviewed biofuel sustainability studies published after 2006 to reflect the most current industry practices. Our goal was to produce an objective meta-analysis of the most prominent sustainability indicators.

1.1 Study Objectives

The main study objectives of this review are to:

- Identify the most relevant sustainability performance indicators
- Conduct a meta analysis of biofuels sustainability literature
- Determine trends in the sustainability 1st and 2nd generation biofuels

1.2 Scope

The scope of this study includes 1st and 2nd generation biofuels and focuses on 4 main sustainability indicators. Due to the greatest data availability, regions of the United States were chosen case studies illustrating noteworthy messages in the document. California, Iowa and Georgia states were chosen to highlight different regional conditions (they represent the west, Midwest and eastern regions of the US, respectively. While information from the US is referenced extensively due to the availability of data; it is anticipated that as data sets become available in other regions that these will be incorporated in subsequent reports further exploring the regional variability of sustainability impacts.

1.3 Report Structure

The Executive Summary provides basic conclusions and the 'best case' policy recommendations to assist the biofuel industry and policy makers towards improving the sustainability performance of the industry. The first chapter introduces biofuels sustainability issues and describes the study objectives and scope. The second chapter provides a review on net energy balances, GHG emissions (without land use change), water requirements and land use change; it provides information a global scale and illustrates trends using three United States case studies.

The four selected sustainability criteria were ranked based on environmental relevance and the amount of data available on each indicator. Industry's knowledge on the amount of energy gain obtainable from each biofuel conversion route is relatively well established and this is also primarily the case for direct GHG emissions. However, the level of understanding about water quantity and quality impacts are less defined, particularly for 2nd generation biofuels. A research area with the least amount of available data is ILUC, which is a phenomenon that was only recently added as a biofuel sustainability criterion – this dimension requires immediate additional attention and increased understanding.

There is an urgent need for harmonized, third party verifiable, life cycle assessment protocols specifically designed for biofuels. The International Standards Organization (ISO) is presently developing the ISO 13065 standards for biofuels, and it is anticipated that this process will yield a harmonized approach to LCA protocols. The European Platform for Life Cycle Assessment (created by the European Commission and the Life Cycle Initiative (crafted by the United Nations Environment Program - UNEP) are also pursuing LCA efforts in general product chains, however, these are not specific to biofuels (Lampe, 2008). The goal of the various LCA analyses is to identify the environmental tradeoffs of biofuel production, which are inherently tied to the region in which the biofuels were produced and processed. Based on these findings, environmentally and socially responsible biofuel policies can be developed that displace our society's dependence on fossil fuels and provide a truly sustainable alternative our current transportation methods.

2 BIOFUEL SUSTAINABILITY CRITERIA

2.1 Net energy balance

Many studies have investigated the net energy investments in biofuels globally. As the 1st and 2nd generation biofuel technologies reach increased levels of market adoption, efficiency increases and learnings result in a more favourable energy balance (ratio of energy consumed per unit energy delivered). For instance, the corn ethanol balance continues to improve as efficiency gains are made both with feedstock production and ethanol manufacturing; this trend is expected to continually improve biofuels' energy output ((S&T)^2 2009). This trend is reflected in numerous other industries that transition from pre-commercial stages to market and technological maturity (Table 1).

Table 1. Total Energy Balance Improvement of Corn Ethanol

Year	**1995**	**2005**	**2015***
	Joules consumed / Joules delivered		
Fuel dispensing	0.0037	0.0038	0.0036
Fuel distribution and storage	0.0147	0.0150	0.0154
Fuel production	0.6402	0.5208	0.3650
Feedstock transmission	0.0127	0.0130	0.0135
Feedstock recovery	0.1061	0.0950	0.0681
Ag. Chemical manufacture	0.1295	0.1144	0.1035
Co-products credits	-0.0616	-0.0572	-0.0500
Total	0.8452	0.7048	0.5192
Net Energy Ratio (J delivered/J consumed)	1.1831	1.4189	1.9262

Source: (ST&T)^2 2009 * Projected values

Selected studies were reviewed on a "well to wheel" basis for first generation bioethanol, first generation biodiesel and second generation bioethanol. For both first and second generation bioethanol, estimates were based on the energy balance in the production of one litre of ethanol (using the higher heating value, HHV of 23.6MJ/litre ethanol) and the associated fossil fuel energy input. Similarly, the net energy balance estimates for biodiesel were based on energy balance in the production of one litre of biodiesel (using the higher heating value of 35.7MJ/litre biodiesel) and the associated fossil fuel energy input (with reference to petroleum diesel). Life Cycle Analysis (LCA) models are often the basis for these sustainability discussions, however, the there are large variations within the findings of the LCA analyses, sometimes even in systems with identical or similar study parameters. The results of environmental impacts analyses vary with parameters such as: feedstock type, cultivation practices, conversion technology, geography, year of study, system boundary definition, numeric assumptions and co-product allocation.

2.1.1 First generation bioethanol

Energy savings of first generation bioethanol relative to fossil fuels varied from 16%-70% for corn ethanol; 23%-61% for wheat ethanol; 78%-100% for sugarcane ethanol and 23%-73% for beet ethanol (Table 2, Figure 3).

Table 2. Range of energy balance improvements for 1st generation bioethanol relative to fossil-fuels.

Author	Feedstock	Year	Scope	Energy Balance Improvement*
Farrell et al.[9]	Corn	2006	USA	34%; 16.6%[10]
Grood & Heywood	Corn	2007	USA	68%[11]
Unnash & Pont	Corn	2007	USA	33%-64%
Wang et al.	Corn	2007	USA	36% (30-70%)[12]
Zah et al.	Corn	2007	USA, China	37%[13]
Edwards et al.	Wheat	2007	Europe +	42% (22-115%)[14]
S&T Consultants	Wheat	2006	Canada	61%
Edwards et al.	Beet	2007	Europe +	48% (24-73%)[15]
Zah et al.	Beet	2007	China	73%[16]
De Castro	Sugarcane	2007	Africa, Brazil	90%
Smeets et al.	Sugarcane	2006	Brazil	>90%
Edwards et al.	Sugarcane	2007	Europe +	>90-100%+
Unnash & Pont	Sugarcane	2007	USA	86%
Zah et al.	Sugarcane	2007	Brazil, China	89%[17]

Source: Menichetti and Otto, 2009

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[9] Values reported are for "ethanol today" and "CO2 intensive" scenarios, respectively.

[10] The savings are 95% if calculated as a ratio of petroleum (MJ) per MJ of ethanol only.

[11] Reflects current best practices in Iowa.

[12] Results differ with energy source used (min value for coal, max for biomass). Wang indicates range of 15-40%.

[13] On a Well-to-Wheel (WTW) basis.

[14] 42% is the average best case based on use of natural gas for processing & straw CHP with DDGS used as fuel.

[15] 25% if pulp to fodder, 65% if pulp to heat.

[16] On a Wheel-to-Tank (WTT) basis.

[17] Non-renewable energy from Wheel-to-Tank (WTT).

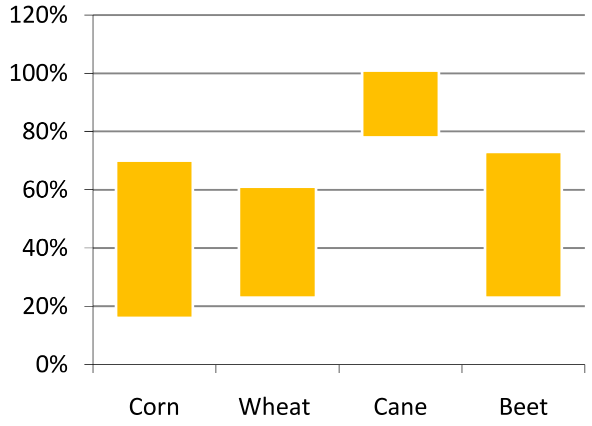

Figure 3. Reduction in fossil energy use - % total fossil energy savings relative to reference fossil systems[18].

Corn ethanol

Based on six recent studies based in North America, the net energy savings (relative to gasoline) for corn-based ethanol ranged from 16% to about 70%. These studies indicate that the use of corn stover as an energy source can dramatically improve the energy output to input ratio: the use of corn stover and/or Dried Distillers Grain with Solubles (DDGS) for heat production. The use of DDGS allows the industry to offset fossil fuel demand and contributes to a net energy savings of 70%, while DDGS can also be utilized as feed for livestock due to its high protein content. This process is sometimes preferred due to financial advantages. CHP use economics are sensitive to factors such as geographic location, electricity source and price, the demand and supply dynamics for DDGS derived animal feed and competing products. Additionally, the use of DDGS for animal feed has the potential to offset the cultivation of crops specifically for livestock feed which in turn leads to reduction in fertilizer usage and overall reduction in energy consumption.

Bioethanol plants located in regions where electricity is derived from coal are associated with the lowest net energy savings of 16% relative to gasoline (Wang et.al, 2007; Menichetti and Otto, 2009). However, authors suggest that most corn ethanol plants (>80%) in North America make use of natural gas powered electricity ((S&T)^2 2009).

The decision to use DDGS for either animal feed or heat production (or both), depends on a combination of factors including (but not limited) to local legislative and federal mandates, economics, grid electricity source (coal, heating oil, natural gas, or cogeneration with biomass), policy direction, and industry partnerships. This study's findings indicate that the average net energy savings achievable from corn ethanol are about 43%.

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[18] Sources used for this graph include Menichetti and Otto, 2009; Farrell et al., 2006; Grood & Heywood, 2007; Wang et al., 2007; Zah et al., 2007; Unnasch & Pont, 2007; (S&T)2, 2009.

Wheat ethanol

Net energy savings (relative to gasoline) ranged from 23% to about 61% (Edwards et al. 2007; (S&T)^2 consultants, 2006). The use of wheat straw and DDGS for heat production offsets fossil fuel demand and leads to the 61% net energy savings associated with wheat ethanol. Similar to corn ethanol, DDGS derived from wheat ethanol is also utilized as feed for livestock due to its high protein content. Utilization of DDGS from wheat for animal feed can lead to significant reductions in energy utilization, not only in the bioethanol production industry, but rather in the overall agro-fuel sector. The average net energy savings of wheat ethanol (relative to gasoline) are about 42%.

Sugarcane ethanol

Sugar cane ethanol provides the best energy savings relative to gasoline. The net energy savings from sugarcane ethanol production are at least 78%, and can reach up to 100% in Brazil due to co-product allocation and credits for co-products (Menichetti and Otto, 2009). The Brazilian sugarcane industry produces ethanol and sugar in addition to electricity from the sugarcane bagasse. Unlike other first generation ethanol industries, bagasse, a co-product from sugarcane ethanol, is not suitable for animal feed. There is therefore no competition between animal feed and electricity generation. The generated electricity is used internally by the industry and excess electricity is sold by the sugarcane ethanol industry to the grid.

Studies reviewed for this report suggest that the average savings are 89%. It should be noted that regional variations will affect the above described results. The integration of sugar and ethanol production with electricity generation by the Brazilian sugarcane ethanol industry provides the best example for first generation ethanol production and energy security within the biofuels industry.

Beet ethanol

Global beet ethanol production occurs predominantly in Europe. Energy balance on a well to wheel basis for beet ethanol shows 23% -73% energy savings relative to gasoline (Edwards, *et. al.* 2007; Zah, *et. al.* 2007). The high 73% net energy savings are achieved by allocating beet pulp co-products to heat production, thereby offsetting the heat that would otherwise be derived from fossil fuels. The use of beet pulp leads to higher energy savings even though its diversion to heat might not be the most economic option. Conversion of beet pulp for animal feed production is more economical but this leads to a lower net energy savings (23%).The decision to allocate the beet pulp to either animal feed or heat production or both depends on a combination of factors similar to those for corn and wheat ethanol. The average energy savings achieved by the beet ethanol industry is about 48%.

Co-product allocation

Co-product allocation to either animal feed or heat production has a significant impact on the net energy balance of 1st generation biofuels in LCA analyses; in other words, energy savings are highly sensitive to how LCA analyses allocate energy uses of co-products.

Presently, there is no standardized approach to the methodological challenges associated with co-product allocation (Winrock International 2009). However several techniques have been adopted in various LCA models and tools to help streamline the difficulties associated with co-product allocation. Four co-product treatment approaches have been employed in LCAs including: (1) system expansion, (2) allocation by market price, (3) allocation by market value, and (4) allocation by mass (Bauen et al, 2008).

- **Net Energy Savings:** Net energy savings in this report were obtained from studies using the system expansion approach. System expansion is utilized by the following tools: GREET, EBAMM, JEC, UK RTFO, and ISO 14040 (recommended). ISO14040 has been reported to provide the best assessments of environmental impacts associated with co-products (Winrock International 2008). Limitation for this option is the lack of information or uncertainties on market reaction to the new product.

- **Market Value**: The allocation using the market value approach utilizes market values of co-products to establish corresponding environmental impacts. Spatial and temporal variations in co-products market prices are the main limitation of this approach. In the absence of site specific data of co-products in the system expansion approach is a disadvantage, so the market value approach is the second best method.

- **Energy Content**: The energy content approach allocates environmental impacts to co-products based on their energy required for their production. This approach is less cumbersome. However, the limitation is that it omits environmental burdens associated with the production of the co-products; the energy content approach does not account for environmental impacts of co-products outside the system boundary through product displacement (Bauen et al, 2008).

- **Mass Content:** The mass content approach allocates environmental burdens to co-products based on their mass. Similar to the energy content approach, determining the mass of co-products is relatively simple. This approach however omits the environmental burdens associated with the production of the co-products (process heat and electricity used in the production of co-products cannot be allocated by mass).

In summary, three major factors influence the net energy performance of 1st generation biofuels: (1) the development of co-products, (2) utilization of agricultural stover as a means to offset heat demand, and (3) the carbon content of electricity used in the conversion process. Ranking the four 1st generation bioethanol feedstock based on their average energy savings leads to sugar cane ethanol providing the best energy investment, followed by beet, corn and wheat.

2.1.2 Net energy balance of corn ethanol: Case studies

US Federal and State government incentives have contributed to an enabling environment for Iowa to become the largest bioethanol production state in the US. Iowa was also found to be the state with the highest net energy balance of 17.3 MJ fossil fuel/litre ethanol. In Iowa, corn ethanol achieves 36% energy savings relative to fossil fuel. The use of the dry milling and natural gas powered electricity contributed to Iowa's high net energy balance.

Georgia had the lowest net energy balance of 0.82 ethanol/MJ fossil fuel. The percent energy deficit for corn ethanol produced in Georgia relative to fossil fuels is -18%. The net energy deficit observed in Georgia is due to low soil productivity which results in greater fertilizer applications during crop production and long transportation distances ethanol processing plants. Shifts in electricity generation from coal to natural gas and cogeneration, as well as establishing ethanol processing facilities in Georgia would help improve Georgia's corn ethanol net energy balance.

The net energy balance for the state of California is not available.

2.1.3 First generation biodiesel net energy balance

First generation biodiesel production involves low temperature and low pressure processes and is less energy intensive than first generation ethanol (Edwards et al, 2007). Energy savings of first generation biodiesel production varied from 46%-79% for rapeseed; 10%-79% for soybean; 67%-76% for sunflower and 7-64% for palm oil (Table 3, Figure 4).

Table 3. Range of energy balance improvements of 1st generation biodiesel feedstocks

Author	**Feedstock**	**Year**	**Scope**	**Energy Balance Improvement**
Edwards et al.	Rapeseed	2007	Europe/Brazil	56-61%
Lechon	Rapeseed	2006	Spain	79%
Zah et al.	Rapeseed	2007	Europe/Switzerland	46-54%[19]
Edwards et al.	Soybean	2007	Europe/Brazil	67%
Unnash and Pont	Soybean	2007	NA	10%
Lechon	Soyean	2006	NA	79%
Zah et al.	Soybean	2007	Various	27% (BR) - ~40%
Edwards et al.	Sunflower	2007	Europe/Brazil	67%
Lechon et al.	Sunflower	2006	Spain	76%
Reinhardt et al.	Palm Oil	2007	Various	7%
Unnasch and Pont	Palm Oil	2007	NA	10%
Lehin et al.	Palm Oil	2006	Thailand/Spain	64%
Zah et al.	Palm Oil	2007	Malaysia/China	64%

Source: Menichetti and Otto, 2009

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[19] Energy improvement is for non-renewable energy Wheel-to-Tank (WTT) basis. 46% is for Europe, 54% is for Switzerland.

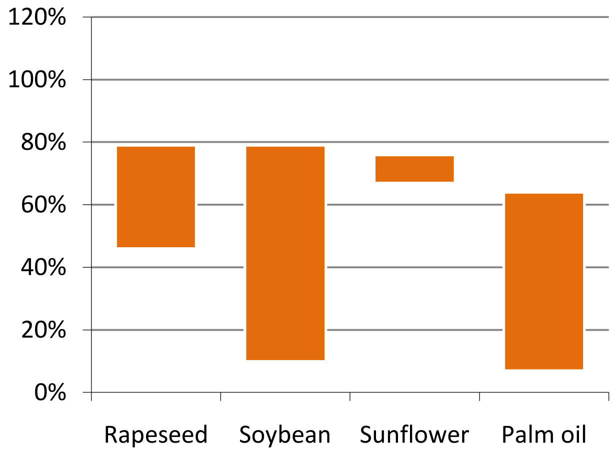

Figure 4. Net energy improvements of 1st generation biodiesel (relative to petroleum diesel)[20].

Rapeseed biodiesel net energy balance

Based on four studies, rapeseed biodiesel uses between 46% -79% less fossil energy relative to biodiesel (Edwards, *et. al.* 2007; Zah, *et. al.* 2007; de Castro, 2007; Lechon et.al. 2006). Although rapeseed methyl ester (RME) is usually produced using methanol, rapeseed ethyl ester (REE) could also be produced using ethanol. Net energy savings of 79% (relative to diesel) can be achieved through co-product allocation of glycerine, and energy co-generation from the press cake in natural gas fired and biomass systems.

Soybean biodiesel net energy balance

The energy balance analysis of soybean biodiesel showed 10% -79% net energy savings relative to petroleum diesel. In the production of soybean methyl ester, glycerine is generated as a by-product. Glycerine has economic uses either for animal feed production or as a chemical. The use of fossil fuel powered electricity and utilization of petroleum derived methanol in the esterification process led to the 10% net energy savings of soybean biodiesel relative to diesel.

On the other hand, allocating the high energy content glycerine to heat and power production resulted in the 79% net energy savings relative to petroleum diesel, which is substantially higher that in the uses described above.

Sunflower biodiesel net energy balance

The net energy balance on a well to wheel basis sunflower biodiesel shows a relatively narrow range of net energy savings relative to diesel, namely 67% -76% (Edwards, *et. al.* 2007; Lechon et.al. 2006). Sunflower requires minimal fertilizer use for its cultivation (Edwards et. al. 2007), which accounted for the relatively high net energy savings.

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[20] Sources used for this graph include: Menichetti and Otto, 2009; Edwards et al, 2007; Lechon et al, 2006; Zah et al, 2007; Unnasch & Pont, 2007; Reinhardt et.al., 2007.

Palm biodiesel net energy balance

The energy balance for palm biodiesel ranges from 7% -64% of net energy savings relative to petroleum diesel (Reinhardt et.al., 2007; Zah, *et. al.* 2007; Menichetti and Otto, 2009; Lechon et.al. 2006; Unnasch and Pont, 2007). The use of fossil fuel powered electricity and petroleum derived methanol in the esterification process resulted in the 7% net energy savings (relative to petroleum diesel). Greater net energy savings (64%) relative to petroleum diesel are achieved by using natural gas and biomass fired co-generation electricity and methanol from renewable energy sources. It has been reported that the palm biodiesel industry could be energy self-sufficient by using the press fibre and palm nut shells as fuel sources in steam boilers and using it to run turbines for electricity generation (Yusoff, 2006).

Ranking the four 1st generation biodiesel feedstock based on their average percent energy savings led to sunflower biodiesel providing the best energy investment(72%), followed by rapeseed (63%), soybean (45%) and palm oil (36%).

2.1.4 Second generation bioethanol net energy balance

Presently, there are no commercial scale cellulosic ethanol plants, therefore new data and studies are expected to be released as 2nd generation biofuels reach commercializing. This review shows that second generation bioethanol has a better energy balance than first generation bioethanol and biodiesel (Figure 5). Cellulosic ethanol bioconversion process result in the production of co-products namely lignin and other chemicals. Percent net energy improvement for 2nd generation bioethanol ranged from 76%-93% (switch grass); 76%-100% (wheat straw) to 73%-91% (wood).

Figure 6Figure 5. Energy balance improvements of 2nd generation

Table 4. Energy balance improvements of 2nd generation bioethanol.

Author	Feedstock	Year	Scope	Energy Balance Improvement
Farrell et al.	Switchgrass	2006	USA	93%
Edwards et al.	Wheat straw, wood	2007	Europe/Brazil	76-91%
Grood and Haywood	Switchgrass	2007	USA (AL, IA)	76%
Wang et al.	Various	2007	USA	93%
Veeraraghavan & Riera-Palou	Wheat straw	2006	UK	78-102%
Zah et al.	Grass and wood	2007	Swiss +	73-79%

Source: Menichetti and Otto, 2009

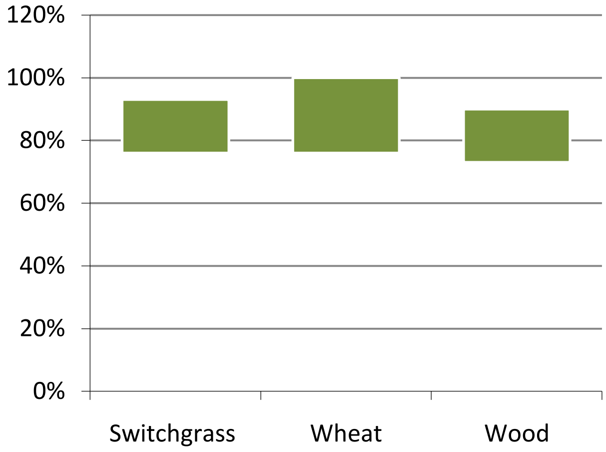

Figure 6. Net energy improvements of 2nd generation bioethanol with reference to gasoline.[21]

Switchgrass ethanol

Switchgrass achieves 76%-93% net energy savings compared to gasoline (Farrell, 2006; Grood and Haywood, 2007). Utilization of biomass in co-generation applications to offset fossil fuel accounts for the significant energy savings relative to gasoline.

Wheat straw ethanol

Among 2nd generation ethanol feedstocks and wheat straw exhibited a great variability with regards to the percent net energy savings (relative to gasoline). The energy balance for switch grass ethanol showed 76%-100% net energy savings compared to gasoline (Edwards et.al., 2007; Veeraraghavan and

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[21] Sources include: Menichetti and Otto, 2009; Farrell et.al., 2006; Grood & Heywood, 2007; Edwards et al, 2007; Veeraraghavan and Riera-Palou, 2006.

Riera-Palou, 2006). Using a biomass integrated gasification combined cycle power system can help to achieve the high net energy savings for wheat straw ethanol.

Wood ethanol
The energy balance for wood ethanol achieves 73%-91% net energy savings compared to gasoline (Edwards et.al., 2007; Zah et.al. 2007). Offsetting fossil fuel energy through the utilization of residue biomass for heat and electricity generation in natural gas fired co-generation systems resulted in the high net energy savings for wood ethanol (relative to gasoline).

Co-allocating the lignin from wood to substitute petro-chemicals usually yields high net energy savings. This is due to the fact that chemicals derived from petroleum require energy intensive manufacturing processes (this is explained further in Section 2.2 GHG emissions (without land use change).

Ranking the three 2nd generation bioethanol feedstocks based on their average energy savings values led to wheat straw providing the best energy investment (88%), followed by switch grass (85%) and wood (82%). The net energy improvements for 2nd generation bioethanol were at least 73% more energy efficient than gasoline. These findings provide incentive to further investigate cellulosic ethanol through enabling policies and increased investment in the RD&D in the sector.

2.2 Greenhouse gas emissions (without land use change)

GHG benefits of biofuels have reached increased attention due to Indirect Land Use Change (ILUC). Numerous authors argue that ILUC should be included in calculations because an increase in land use for biofuels does unquestionably lead to increased GHG emissions elsewhere. However, it can be argued that the effect can doesn't have to be attributed to biofuels alone (also without biofuels these effects would occur, a bit later possibly, and inefficiencies in our agricultural policies with land being unused or used ineffectively are the main cause for deforestation and other GHG emitting land use change to occur). ILUC can (strongly) affect and even decrease the biofuel GHG performances that are mentioned in the section below.

While GHG emission reductions of biofuels (relative to their fossil counterparts) are highly sensitive to location, the biofuel industry has achieved significant advances. For instance, over the course of 10 years (1995-2005), the emission reductions of corn ethanol have increased from 26 to 39%; furthermore, it is anticipated that this trend will continue to increase to 55% by 2015 ((ST&T)^2 2009) (Table 5) .

Table 5. Comparison of GHG Emission Reductions of Corn Ethanol

Year	**1995**	**2005**	**2015**[*]
		gCO_2 eq/GJ (HHV)	
Fuel dispensing	185	181	142
Fuel distribution and storage	1,107	1,109	1,124
Fuel production	35,012	28,294	19,085
Feedstock transmission	1,004	1,009	1,031
Feedstock recovery	12,012	10,550	7,348
LUC, cultivation	21,827	20,987	20,369
Fertilizer manufacture	8,261	7,033	6,215
Emissions displaced	-18,490	-17,934	-17,219
Sub-total	60,919	51,229	38,095
Combustion emissions	3,058	2,237	1,973
Grand Total	63,977	53,466	40,068
% Reduction	26.2	39.0	54.9

Source: $(ST\&T)^2$ 2009 * Projected values

Net greenhouse emissions (without land use change) of biofuel production have been widely studied Several studies published from 2006 to 2009 were reviewed on a well to wheel basis to assess the GHG emissions reductions of first generation bioethanol, first generation biodiesel and second generation bioethanol.[22] For both first and second generation bioethanol, GHG emissions savings associated with the production and utilization of one megajoule of ethanol was compared to the equivalent emissions associated with gasoline. Similarly, GHG emissions savings in the production and utilization of one megajoule of biodiesel were compared to the equivalent emissions associated with petroleum diesel.

There were great variations in the GHG emission reductions of 1st generation bioethanol. N_2O emissions (even in minute quantities) emanating from fertilizer production and emissions have a more significant GHG emissions impact compared to fossil fuel-based electricity used in the bioconversion process and co-product allocation of DDGS. Nitrous oxide emissions from agriculture are estimated either from individual field measurements or based on IPCC guideline calculations; the results from the two approaches have significant error margins (Edwards, et.al. 2007; Lampe, 2008). However a recent method that employs soil and crop distribution data based on 1070 regions in Europe reduces this error of margin to about 30% in the European context (Edwards et.al, 2007). The percent GHG emissions for 1st generation bioethanol ranged from -5%-58% for corn ethanol; 32%-48% (wheat ethanol); 84%-100% (sugar ethanol) and 30%-65% (beet ethanol) (Table 6, Figure 7).

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[22] Reviewed studies include Menichetti and Otto, 2009; Farrell et.al., 2006; Grood & Heywood, 2007; Veeraraghavan and Riera-Palou, 2006; Wang et.al. 2007; Zah et al, 2007; Unnasch & Pont, 2007; Edwards et.al., 2007; Smeets et.al. 2006; (S&T)2, 2006; (S&T)2, 2009; Liska, 2009; Plevin, 2009; Anex and Lifset, 2009; Lechon et.al. 2006

Table 6. Range of GHG emission reductions associated with 1st generation bio-ethanol feedstocks

Author	Feedstock	Year	Scope	GHG Improvement
Farrell et al.	Corn	2006	USA	13%; -2%[23]
Grood & Heywood	Corn	2007	USA	20% (-47%, 58%)[24]
Unnash & Pont	Corn	2007	USA	-5%, + 30%[25]
Wang et al.	Corn	2007	USA	19% (-3%, +52%)[26]
Zah et al.	Corn	2007	USA, China	18%
Edwards et al.	Wheat	2007	Europe +	32%[27]
S&T Consultants	Wheat	2006	Canada	48%
Smeets et al.	Beet	2007	NA	~35-55%
Edwards et al.	Beet	2007	Europe +	48% (32-65%)[28]
Zah et al.	Beet	2007	China	65%
De Castro	Sugarcane	2007	Africa, Brazil	>100%
Smeets et al.	Sugarcane	2006	Brazil	85-90%
Edwards et al.	Sugarcane	2007	Europe +	~87%
Unnash & Pont	Sugarcane	2007	USA	84%
Zah et al.	Sugarcane	2007	Brazil, China	85%

Source: Menichetti and Otto, 2009

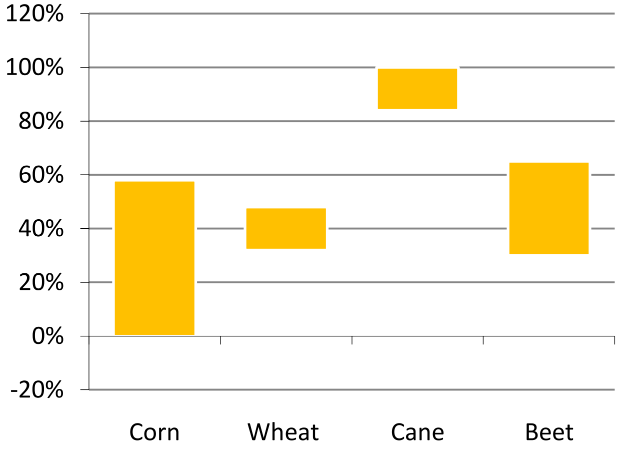

Figure 7. GHG emission reductions of 1st generation bioethanol (relative to fossil fuel).[29]

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[23] As reported in the Excel workbook dated 25 December 2005. More favorable results are found in the updated version of the supporting online material issued on 13 July, 2006, reflecting EBAMM 1.1 calculations.

[24] Average value for Iowa corn ethanol with 20% credits fro co-products. Range from -47% for Georgia corn without allocation to co-products to +58% for Iowa corn with credit allocated to DDGS production.

[25] Mid-west corn with co-product allocation. -5% if coal is used. California corn = -30% to +50%.

[26] Current average reported in table. Results range from -3% if coal is used to +52% if biomass (i.e. woodchips) is used as process fuel.

[27] Values reported are for conventional gas boilers; a wider range is found wit other energy sources (i.e. coal or straw CHP). Range in brackets includes lignite vs. straw CHP, both with DDGS.

[28] 32% if pulp to fodder, 65% if pulp to heat.

Corn ethanol GHG emissions
GHG emission reductions of corn ethanol ranged from 58% in the best case to an emissions deficit of -5% in the worst case (Farrell et.al., 2006; Grood & Heywood, 2007; Wang et.al. 2007; Zah et al, 2007; Unnasch & Pont, 2007; (S&T)^2, 2009; Liska, 2009; Plevin, 2009; Anex and Lifset, 2009) (Figure 7) The GHG emissions deficit resulted from fossil fuel-based electricity being used in the ethanol bioconversion process, N_2O emissions from fertilizer use, and the allocation of credits of DDGS. The use of corn stover and other biomass residues in biomass-based integrated gasification combine cycle (BIGCC) power systems resulted in significant GHG emission reductions (58%) relative to gasoline.

GHG emissions reductions achieved by the corn ethanol industry are accelerating, and have resulted in a twofold reduction compared to previous years (Anex and Lifset 2009; de Oliveira et.al., 2005). Greenhouse gas emissions reductions of 54.9% have been predicted for corn-ethanol by 2015 as a result of efficiency gains and learning in the industry ((S&T)^2, 2009).

Wheat ethanol GHG emissions
GHG emissions reductions for wheat-ethanol ranged from 32 to about 48% (Edwards et al. 2007; (S&T)^2 consultants, 2006) (Figure 8). The use of wheat straw for soil nutrient enrichment coupled with crop residue and DDGS in BIGCC power systems led to the 48% GHG emission savings. However, the combination of use of synthetic fertilizers (containing nitrous oxice) coupled with the utilization of the DDGS for animal feed result in lower emission reductions (32%).

Sugarcane ethanol GHG emissions
Sugar cane ethanol provides the best GHG emission reductions (84%)(Figure 7). 100% GHG emission reductions are achievable by the sugarcane ethanol industry due to electricity self-sufficiency. The sugarcane industry generates excess electricity from bagasse in excess of its own needs and then sells additional production sold to the grid further improving the industry's cost-effectiveness.

The integration of sugar, ethanol production, and electricity generation by the Brazilian sugarcane ethanol industry provides the best example of first generation ethanol production and GHG emission reductions in the industry.

Beet ethanol GHG emissions
GHG reductions on a well to wheel basis for beet ethanol are 30% -65% (Edwards, et. al., 2007; Zah, et. al. 2007; Smeet et.al., 2006; Menichetti and Otto, 2009). Conversion of beet pulp for animal feed production is more economical, but also leads to lowered GHG emissions reductions (30%) compared to the relatively high GHG emissions reductions (65%) associated with the use of the beet pulp co-products for heat production.

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[29] Sources for this graph include Menichetti and Otto, 2009; de Castro et.al, 2007; Farrell et.al., 2006; Grood & Heywood, 2007; Wang et.al. 2007; Zah et al, 2007; Unnasch & Pont, 2007; Edwards et.al., 2007; Smeets et.al. 2006; (S&T)^2, 2006; (S&T)^2, 2009; Liska, 2009; Plevin, 2009; Anex and Lifset, 2009).

Ranking the four 1st generation bioethanol feedstock based on their average percent GHG emissions reduction values led to sugarcane ethanol providing the best GHG emissions reduction investment (92%),, followed by beet ethanol (48%), wheat ethanol (40%), and finally corn ethanol (27%).

Based on their percent GHG emissions reduction, all the 1st generation feedstocks qualify under the European Union current minimum GHG emission savings mandate of 35%, with the exception of corn ethanol[30]. Using current data on efficiency gains and improvements in GHG reductions by the bioethanol industry, the United States Environmental Protection Agency (US EPA) concludes that new ethanol plants will achieve the renewable fuels standard (RFS2) mandate of 20% GHG emission reductions. This is great development considering the fact that the US EPA RFS2 standards incorporate indirect GHG emissions resulting from land-use changes by the corn ethanol industry.

2.2.1 Greenhouse gas emission reductions for corn ethanol: Case studies

Georgia was found to be the state with the highest greenhouse gas emissions. Georgia's GHG emissions per MJ ethanol were 139.5 gCO_2eq compared to Iowa's 89 gCO_2eq. Percent GHG reductions of corn ethanol produced in Iowa and Georgia were calculated using CARBOB GHG intensity value of 95.86 gCO_2eq/MJ. The CARBOB GHG intensity value takes into consideration the proportion of tar sands in the US gasoline mix to provide the most current reference for the United States (2008). The percent GHG emissions reductions of corn ethanol produced in Iowa (CARBOB) are 7%, compared to the -46% GHG emission reduction deficit for Georgia. Dry milling and electricity generation from natural gas in Iowa result in the state's low GHG emissions. Georgia, on the other hand, uses coal fired electricity and also has low soil productivity which leads to greater need for fertilizer application, and long-distance transportation to ethanol processing plants. The greenhouse gas emission for corn ethanol production in the state of California was not available.

2.2.2 First generation biodiesel greenhouse gas emissions (without land use emissions)

Wide variations in GHG emissions reductions were observed for 1st generation biodiesel relative to petroleum diesel. Percent GHG emissions reductions for 1st generation biodiesel ranged from 20%-64% (rapeseed); 10%-78% (soybean); 66%-67% (sunflower) and 8%-80% (palm oil) (Table 7, Figure 8).

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[30] As noted before, average percent GHG emission reduction values for corn ethanol can exceed the EU minimum mandate through the minimum use of synthetic fertilizers via substitution with biologically derived nutrients/biomass residues and biomass-based integrated gasification combine cycle (BIGCC) power systems to drive the bioconversion process.

Table 7. GHG emission reductions of various biodiesel feedstocks

Author	Feedstock	Year	Scope	Energy Balance Improvement
De Castro	Rapeseed	2007	Brazil/Africa	~20-40%
Edwards et al.	Rapeseed	2007	Europe/Brazil	41-47%
Lechon	Rapeseed	2006	Spain	56%
Zah et al.	Rapeseed	2007	Various	64%
De Castro	Soybean	2007	Brazil/Africa	53%-78%
Edwards et al.	Soybean	2007	Europe/Brazil	67%
Unnash and Pont	Soybean	2007	NA	10%
Lechon	Soyean	2006	NA	56%
Zah et al.	Soybean	2007	Various	-17%% (BR) - ~40% (USA)
Edwards et al.	Sunflower	2007	Europe/Brazil	67%
Lechon et al.	Sunflower	2006	Spain	66%
Reinhardt et al.	Palm Oil	2007	Various	31%
Unnasch and Pont	Palm Oil	2007	NA	8-12%
Lehin et al.	Palm Oil	2006	Thailand/Spain	40%
Zah et al.	Palm Oil	2007	Malaysia/China	70%
Beer et al.	Palm Oil	2007	NA	~80% (-868% w rainforest conversion; 2070% w peat forest conversion

Source: Menichetti and Otto, 2009

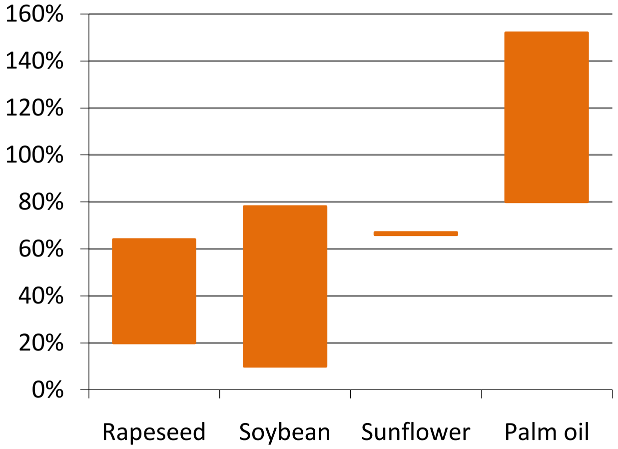

Figure 8. Greenhouse gas emissions of 1st generation biodiesel with reference to fossil fuel.[31]

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[31] Source: Menichetti and Otto 2009; de Castro et.al, 2007; Zah et al, 2007; Unnasch & Pont, 2007; Edwards et.al., 2007; Unnasch & Pont, 2007; Beer et.al. 2007; Lechon et.al. 2006.

Rapeseed biodiesel GHG emissions

GHG emission reductions for rapeseed biodiesel ranged from 20% -64% relative to biodiesel (Menichetti and Otto, 2009; Edwards, *et. al.* 2007; Zah, *et. al.* 2007; de Castro, 2007; Lechon et.al. 2006). GHG emission reductions of 64% were achieved in regions with minimal fertilizer utilization and allocation of glycerine for chemical as a substitute for fossil fuel derived chemicals. The use of synthetic fertilizers and petroleum derived ethanol and methanol results in decreased GHG emissions reductions.

Soybean biodiesel GHG emissions

GHG emissions reductions of soybean biodiesel ranged from 10% to about 79%. Petro-chemical substitutes for glycerine require energy-intensive processes for their manufacture. Allocating glycerine co-products as a biologically derived chemical substitute for petroleum based products, use of residue biomass in BIGCC power (natural gas) systems and minimal fertilizer utilization in soybean cultivation resulted in high GHG emissions reductions of 79%. Nitrous oxide emissions from synthetic fertilizer production and emissions, allocation of glycerine for animal feed and use of fossil fuel derived electricity resulted in the 10% GHG emission reductions relative to petroleum diesel.

Sunflower biodiesel GHG emissions

GHG emission reductions on a well to wheel basis for sunflower biodiesel show a relatively narrow range of reductions (66% -67%) compared to rapeseed, soybean and palm biodiesel (Edwards, *et. al.* 2007; Lechon et.al. 2006). Sunflower crops require minimal fertilizer in its cultivation (Edwards, et. al. 2007), which leads to significant reductions in nitrous oxide emissions associated with fertilizer production and emissions. The authors recognize that as is the case with other crops that there is a large variability of potential reductions depending on the specific circumstances under which the crop is grown and processed. More detailed analyses such as Chiaramonti and Reccia's work (2010) will be explored in subsequent reports further exploring the regional nature of the emission savings ranges.

Palm biodiesel GHG emissions

GHG emissions reduction for palm biodiesel showed a wide range of emissions reductions ranging from 8% -80 relative to petroleum diesel (Reinhardt et.al., 2007; Zah, *et. al.* 2007; Menichetti and Otto, 2009; Lechon et.al. 2006; Unnasch and Pont, 2007; Beer et.al., 2007). The increased use of fertilizers, fossil fuel electricity and petroleum derived methanol in the transesterification process resulted in the 8% GHG emissions reduction.

The relatively low temperatures associated with 1^{st} gen biodiesel production (relative to 1^{st} gen bioethanol) imply lower fossil fuel usage and consequently larger GHG emissions savings. Comparison of the four 1st generation biodiesel feedstock based on their percent GHG emissions reduction midpoint values show that sunflower offers the best GHG emissions reductions (67%), followed by a tie between palm oil (44%) and soybean (44%), and finally rapeseed (38%). However, sunflower biodiesel production provides greater certainty with regards to GHG emissions reduction compared to soybean which ranged from 10%-78% in GHG emissions reductions relative to petroleum diesel.

2.2.3 Second generation bioethanol greenhouse gas emissions (without land use emissions)

The review showed that 2nd gen bioethanol is anticipated to have better GHG performance than 1st gen bioethanol and biodiesel. Greenhouse gas emission reductions of 2nd gen bioethanol fuels were at least 65% better than gasoline. Relatively high GHG emission reductions are due to 2nd gen feedstocks being primarily derived from residues and often use portions of the biomass as a fuel source in BIGCC power systems. GHG emissions from enzyme production were not taken into account in the reviewed studies. Further work should incorporate these calculations since enzyme production is anticipated to have a substantial impact on the GHG emission savings of2nd generation bioethanol (Table 8, Figure 9).

Table 8. GHG emission reductions of 2nd generation bioethanol.

Author	**Feedstock**	**Year**	**Scope**	**GHG Emission Reductions**
Farrell et al.	Switchgrass	2006	USA	88%
Edwards et al.	Wheat straw, wood	2007	Europe/Brazil	76-88%
Grood and Haywood	Switchgrass	2007	USA (AL, IA)	93-98%
Unnash and Pont	Switchgrass, poplar, residues	2007	USA (CA) +	10-102%
Wang et al.	Various	2007	USA	86%
Veeraraghavan & Riera-Palou	Wheat straw	2006	UK	88-98%
Zah et al.	Grass and wood	2007	Swiss +	65%

Source: Menichetti and Otto, 2009

Figure 9. Greenhouse gas emissions of 2nd generation bioethanol relative to gasoline.[32]

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[32] Source: Menichetti and Otto 2009; Farrell et. al., 2006; Grood & Heywood, 2007; Wang et.al. 2007; Edwards et al, 2007; Veeraraghavan and Riera-Palou, 2006).

Switchgrass ethanol

GHG emission reductions of switch grass ethanol range from 88%-98% relative to gasoline (Farrell, 2006; Grood and Haywood, 2007). The absence of fertilizer utilization in cultivating switchgrass resulted in significant reductions of N_2O emissions from fertilizer production and utilization resulted in high (98%) GHG emission reductions.

Wheat straw ethanol

Greenhouse gas emissionsof wheat straw ethanol ranged from 76% in the pessimistic scenario to 98% in the optimistic (Edwards et.al. 2007; Veeraraghavan and Riera-Palou, 2006). The use of biomass in the biomass integrated gasification combined cycle to offset fossil fuel energy resulted in improved GHG emission savings.

Wood ethanol

Greenhouse gas emission of wood ethanol range from 65%-88% reductions compared to gasoline (Edwards et.al., 2007; Zah et.al. 2007). Offsetting fossil fuel energy through the use of residue biomass for heat and electricity generation in natural gas fired co-generation systems resulted in improved energy savings for wood ethanol. Co-allocating the lignin from wood to substitute petro-chemicals (as opposed to combustion of the lignin) yielded higher greenhouse emission reductions because the carbon is sequestered in the solid materials and since equivalent chemicals derived from petroleum require high energy intensive manufacturing.

Ranking the three 2nd generation bioethanol feedstock based on their average GHG emission reduction values led to switch grass providing the best GHG emission reductions(93%), followed by wheat straw (87%) and wood (77%). All 2nd generation bioethanol fuels achieved a minimum threshold of least 65% reductions relative to gasoline.

2.3 Water requirements

Compared to net energy balances and greenhouse gas emissions, fewer life cycle assessment studies have investigated the global water requirements of biofuels. Biofuel water requirements have been studied in Spain, Greece, Italy and the United States. However, the country with the most robust studies on water requirement for biofuel production is the United States, and this is particularly the case for first generation bioethanol.

California, Iowa and Georgia were selected as case studies to represent the west, mid west and east regions of the US respectively for year 2008. Data utilized for the water requirement case study were obtained from Chiu *et. al.,* (2009).

2.3.1 Water quality and quantity

Biofuel production requires significant amounts of water, which varies with the different energy production processes. The water requirements for fossil energy production range from 10-190 L/MWh for oil extraction and refining. The amount of water required to irrigate corn and soybean crops also varies: corn requires 2.3 – 8.7 million L/MWh, while soybean crops require 13.9-27.9 million L/MWh (Table 9). Open loop cooling systems require more water than their closed loop counterparts. This provides important implications for policy formulation regarding efficient water utilization for energy generation. With respect to biofuels, the water requirements for soybean biodiesel of 13.9-27.9 million L/MWh are at least 60-220% higher than that of corn ethanol, which consumes 2.3 - 8.7 L/MWh.

Table 9. Water requirements of energy production processes.

Production process	**Water use (L/MWh)**
Petroleum extraction	10 - 40
Oil refining	80 - 150
Oil Shale surface retort	170 - 681
NGCC* power plant, closed loop cooling	230 - 300,300
Coal integrated gasification combined-cycle	~900
Nuclear power plant, closed loop cooling	~950
Enhanced oil recovery	~7,600
NGCC, open loop cooling	28,400 - 75,700
Nuclear power plant, open loop cooling	94,600 - 227,100
Corn ethanol irrigation	2,170,000 - 8,670,000
Soybean biodiesel irrigation	13,900,000 - 27,900,000

Source: USDOE, 2008; Dominguez-Faus et.al. 2009. (* Natural Gas Combined Cycle)

When considering the overall lifecycle of biofuel production, almost all of the water consumption occurs during agricultural activities necessary to produce the feedstocks; these can range from 500 to 2000 litres of water per litre of biofuel produced (Powers et al. 2010). Table 10 outlines the range of water consumption in bioethanol production. The wide range of water requirements for biofuels depends on how the water demand is defined, the type of feedstock used and soil and climactic variables; differentiation is also required between agricultural water withdrawals and agricultural water consumption, the impact of which is investigated in greater details in work by Powers et al. (2010).

Table 10. Water use for selected US biofuel crops (L water per L ethanol)

Feedstock	**Evapotranspiration**[33]	**Irrigation**[34]
Sugar beet	812	1080 +/- 590
Corn grain	1260	566 +/- 340
Sugarcane	1270	1680 +/- N/A
Switchgrass[35]	1400	N/A
Sorghum	2020	1520 +/- 422
Soybean[36]	4190	1260 +/- 401

Source: Powers et al 2010

Water utilization for ethanol production on a "corn field-to-fuel pump basis" in the US (2005 to 2008) showed that the irrigation practices vary from state to state (Chiu *et. al.,* 2009). The study found an increase in consumptive water appropriation of 246% over the 4 years, from 1.9 x 10^{12} litres (2005) to 6.1 x 10^{12} litres (2008). This increased consumption was almost twice the percent increase of corn production (of 133%) from 15 x 10^{9} litres in 2005 to 34 x 10^{9} litres in 2008 (Chiu *et. al.,* 2009) Figure 10 illustrates a snapshot of ethanol production and embodied water for the year 2007 . These observations suggest an imminent debate regarding water requirements issues associated with corn ethanol production, especially if corn for biofuel production expands into regions associated with high consumptive water practices. As can be seen in Figure 10, traditional corn ethanol production states such as Iowa, Illinois, Minnesota, South Dakota have the least water appropriation, while states producing the least amount of ethanol (e.g. California, New Mexico etc) are associated with a much larger water footprint. Corn ethanol production in Iowa relies on rainfall or abundant surface water in comparison to California which has a higher population and drinking water supply shortages. It can also be concluded from Figure 9 that policies designed to increase bioethanol production in the EISA 2022 mandate should address the potential competition between water used for fuel and other societal needs.

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[33] Based on UNESCO report 'The water footprints of nations' except for switchgrass.

[34] Irrigation estimates represent the average only of that fraction of the crops that are irrigated based on 2003 NASS statistics.

[35] Data for switchgrass from a variety of literature sources.

[36] Soybean for biodiesel: denominator in terms of energy equivalent volume of ethanol (0.64 J ethanol/BC).

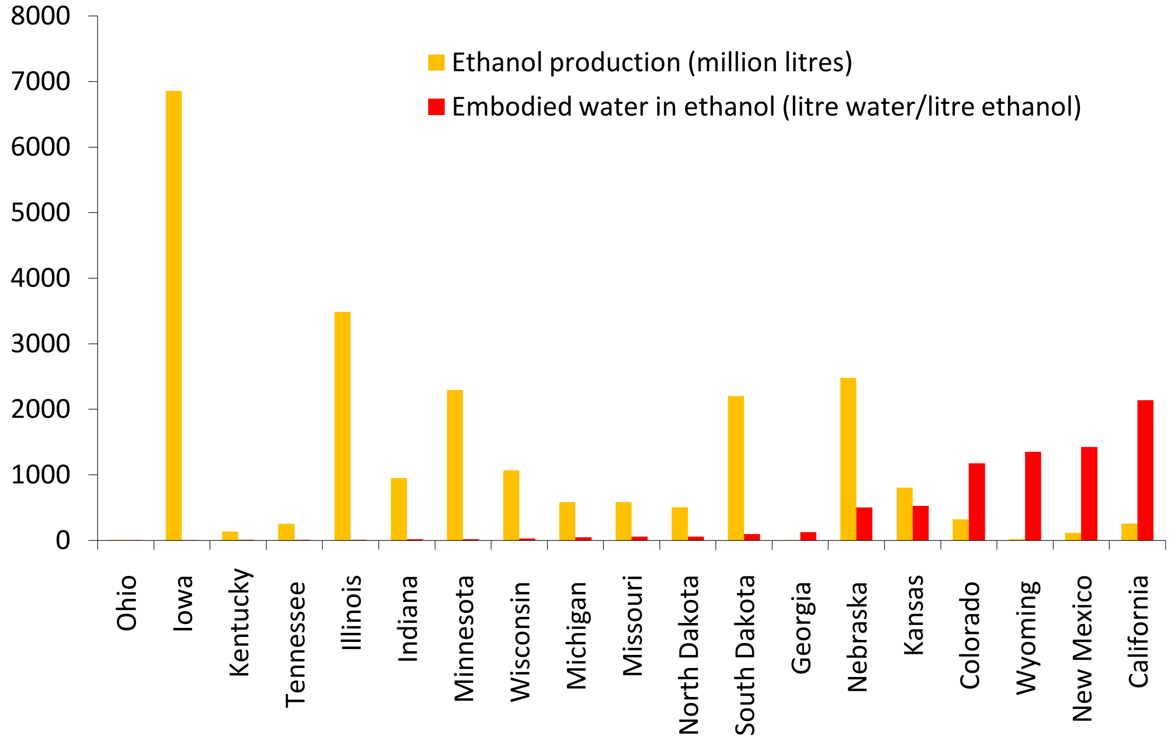

Figure 10. Ethanol production and embodied water in ethanol in the ethanol producing states in the USA (for year 2007) (Chiu et.al. 2009).

Regions with existing water constraints are not suitable for the long-term success of a biofuel industry heavily relying on cheap and accessible water for irrigation and processing.

Distinctions can also be made based on groundwater vs. surface water use. For example, Nebraska and Kansas have relatively low embodied water. Ground water irrigation is a big component of their corn production practice which puts stress on the Ogallala Aquifer that lies underneath the states of Nebraska, Wyoming, Kansas, Colorado and New Mexico (Figure 11). Wyoming on the hand has relatively high embodied water content and makes use of surface water. Since surface water is the places less pressure on depleting aquifers, states using surface water are the preferred locations for bioethanol crops (i.e. New Mexico, Colorado, California).

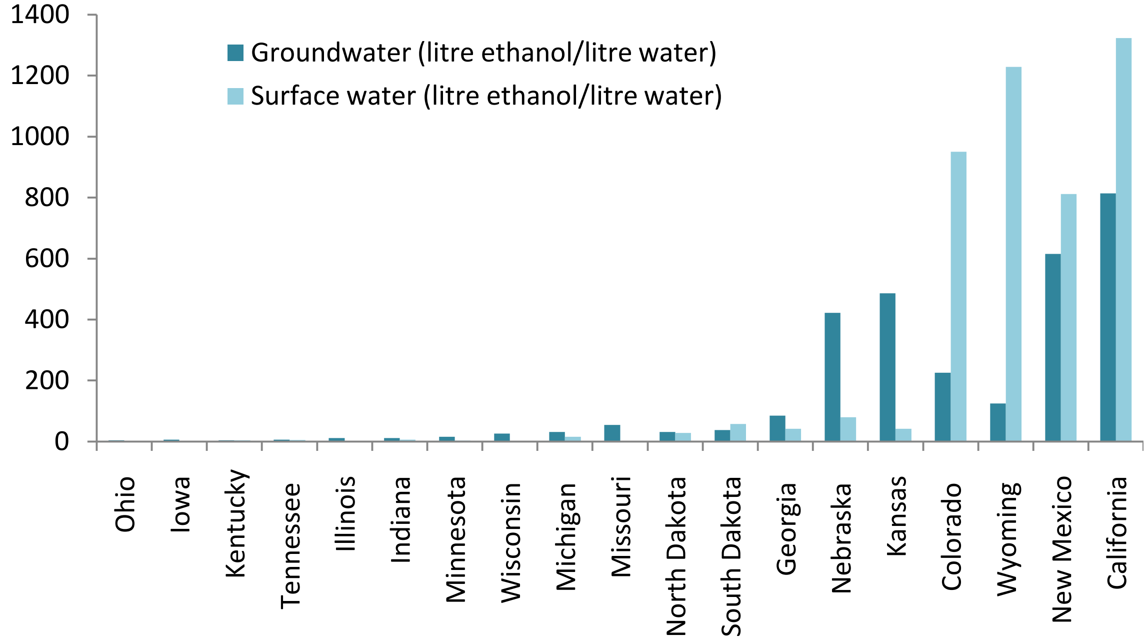

Figure 11. Ground water and surface water amounts in embodied in ethanol

Water quality issues are becoming very prominent in bioethanol sustainability discussions, especially in areas where freshwater is scarce. Increased nutrient levels in US water bodies, particularly into the US Gulf of Mexico from the Mississippi river, have been cited as a classic example of how agricultural fertilizers contribute to an ecological dead zone known as a hypoxic zone.

The hypoxic zone in the Gulf of Mexico is a seasonal dead region that covers approximately 14 600 km^2 and was first detected in 1970 (Mascarelli, 2009; Williams, 2007). Nutrient runoff from the US Corn Belt fields and urban sewage flow into the Mississippi river along its source in Minnesota through several US states and finally into the Gulf of Mexico (Williams, 2007). The high nutrient levels discharged into the Gulf Coast result in eutrophication during the summer period. Eutrophication results from the decay of large algal populations which deplete of oxygen as they decay. Low oxygen can then no longer sustain marine life such as fish, crab, shrimp etc. The dead zone of the Gulf of Mexico is the biggest hypoxic zone in the US and one of the largest in the world.

Recent studies indicate reductions in fertilizer utilization per unit tonne of corn in the US. It has been shown that corn production increased 75% from 171 million tonnes in 1995 to 300 million tonnes in 2007, the amount of fertilizer (nitrogen, phosphorus and potash) applied per tonne of corn production decreased 23% from 39.6 kg/tonne in 1995 to 30.4 kg/tonne in 2007 respectively (Figure 12). However, despite this per unit decline, the absolute amount of fertilizer disposed in the Gulf of Mexico remains high.

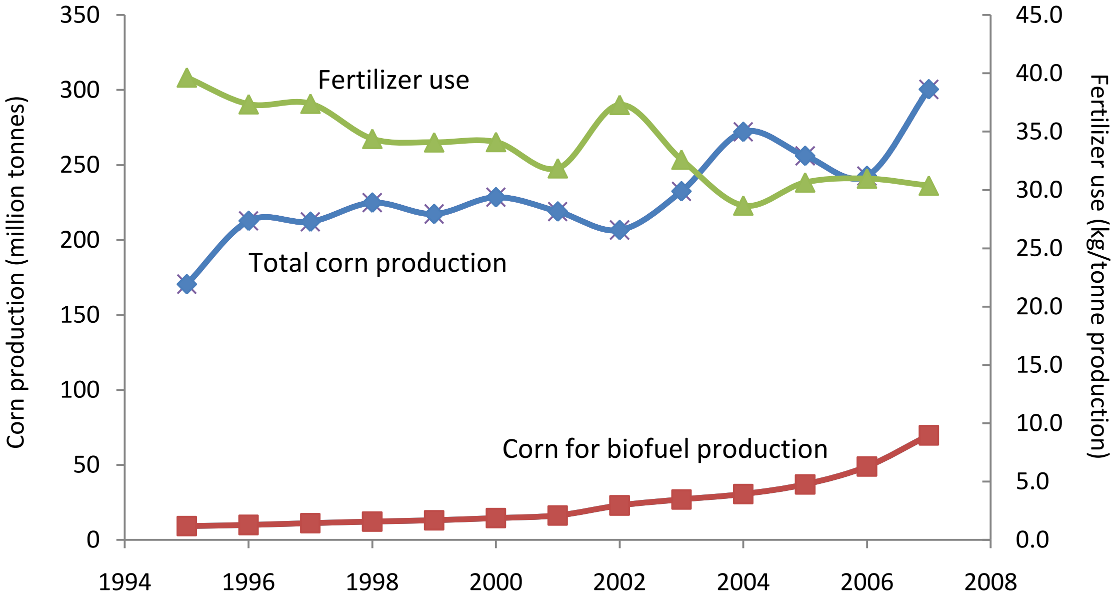

Figure 12. US corn production, proportion used for ethanol and fertilizer use.

Knowledge gained over time from genetic engineering of corn crops accounts for the overall decline in water requirements for corn-ethanol production. Within 9 years, corn ethanol requirements for water decreased by 13%: from 112 L water/L ethanol in 1998, to 98 L water/L ethanol in 2006. However, it has been estimated that a US biofuels mandate could result in an increase demand of approximately 5.5 trillion litres per year.

The new EPA RFS2 provides guidelines on nitrogen and phosphorus application amounts used in crop production. Growing genetically improved corn species or cellulosic crops that require minimal amounts of fertilizer would help the industry to be prepared in advance against any future potential farm bills mandating specific fertilizer utilization targets in agriculture. Growing crops and livestock on the same land plots has been suggested as a strategy to reduce nitrate runoff to the Mississippi river and the Gulf of Mexico. This is because rotating livestock and crops on the same plot results in more efficient management of less expensive and more natural nutrients compared to conventional fertilizers (Mascarelli, 2009). Additionally, it is imperative for the biofuel industry to continue to demonstrate achievements, such as declined fertilizer utilization per tonne of corn produced. While the fertilizer application intensity has declined, corn production for food and ethanol continues to increase. Maintaining or reducing the amount of overall fertilizer released as effluent into the Mississippi will help build confidence in investors, policy makers and the public regarding the environmental footprint of the biofuel industry.

2.3.2 Corn ethanol water requirement: Case studies

The reliance on rain-fed corn production in Iowa was responsible for the state's minimal water usage of 6 litres water/ liter ethanol compared to California (2138 litres water/liter ethanol) and Georgia (128 litres water/liter ethanol). However, fertilizer application linked to corn ethanol production in Iowa posed a significant sustainability concern and is partly responsible for hypoxia in the Gulf of Mexico. Leaching of fertilizers from corn fields into the Upper Mississippi River has also been reported to account for the growing amounts of nitrate, nitrite, atrazine and phosphorus loadings in drinking water sources recorded in the mid west regions of the US. The greatest sustainability concern for California emanates from the state's high water requirements for corn ethanol production. Primarily due to the dry climatic conditions and high evapo-transpiration rates, relatively large quantities of surface and ground water sources are appropriated per unit ethanol production in California. This sustainability challenge is exacerbated by California's high population density in California and the growing need for quality water to satisfy other competing human needs.

2.4 Land use change and emissions

Land use change impacts have become the most recent focal point of biofuel sustainability discussions. A number of studies have investigated land use change and associated emissions from biofuel production in the US and globally (Searchinger et.al. 2008; Fargione et. al., 2008; Gallagher et.al., 2008; Kim *et.al.*, 2009; Melillo et.al., 2009; Ros et. al., 2010). As in previous sections, California, Iowa and Georgia were selected for the case studies to illustrate developments in the biofuels industry in the west, mid west and east regions of the US, respectively. Data utilized for this case study were obtained from the Biofuel Energy Systems Simulator (BESS) model developed by the University of Nebraska.

2.4.1 Direct land use change and emissions

Direct land use change impact of biofuels can be linked directly to the biofuel value chain. For example, when new land is cleared for biofuel production (such as the conversion of forest lands to crop production for biofuels), the transformation is referred to as direct land use change. The conversion of existing agriculture lands as fallow fields can also be classified as land use change. Direct land use change leads to changes in the dynamics of soil carbon stocks. It has been reported that conversion of agricultural lands to grasslands leads to increase in soil organic carbon at rates of 0.2-1.0 t C/hectare (Cherubini *et. al*. 2009). The 2007 US Energy Independence and Security Act (EISA), holds biofuel industries accountable for GHG emissions emanating from both direct and indirect land use change (Kim *et.al,* 2007). Recent EPA standards (RFS2) at require biofuels to achieve at least 20% improvement in overall greenhouse emission reductions (including both direct and indirect land use emissions) for any new biofuel plant established within the United States from December 2009.

2.4.2 Indirect land use change and emissions (ILUC)

Indirect land use change remains the most controversial topic in the biofuel sustainability discussions (Liska and Perrin, 2009; Matthews and Tan, 2009). Indirect land use change effects can be categorized and investigated under environmental, economic and social impacts (Ros, et. al. 2010). The biofuel production value chain interacts with the global economic, natural ecosystems and climatic systems thereby resulting in indirect effects. Compounding complex interactions in these dynamic systems are constantly evolving, which makes attainment of a final equilibrium a challenge (Ros, et. al. 2010). Our study, however, reviews only the environmental aspects of indirect land use change associated with biofuels. The first paper that urged scientists to extend the LCA system boundary to incorporate indirect land use GHG emissions associated with biofuels was published in 2008 (Searchinger, et.al. 2008). Though a number of methodological challenges and uncertainties were associated with key variables employed, scientists recognized the importance of accounting for indirect impacts. Indirect land use change occurs when pressure from market forces results in land conversion from prevailing feed/food crop production to biofuel cultivation, which consequently can lead to land use change in other regions of the world in order to make-up for the loss in feed/food production (Kim *et. al.,* 2009).

Estimates on the ILUC of biofuels are sensitive to several variables, including biofuel type and the geographic location of production (Searchinger *et.al*. 2009). Recent studies acknowledge the challenges of determining the optimum balance between cropland extensification (expansion) and cropland intensification (i.e. increased production on current farmlands); however, valid methodologies suitable to estimate these variables have not yet been determined due to data availability constraints.

Using the Center for Agricultural and Rural Development (CARD) and the Food and Agricultural Policy Research Institute's (FAPRI) non-spatial econometric models and partial equilibrium models, Searchinger *et. al.* (2008) estimated the carbon payback periods resulting from ILUC for biofuels (Mathews and Tan, 2009). The estimates were based on a surge of 56 billion litres in ethanol consumption, which was assumed to occur by 2016. The authors assumed the consumption growth to occur as the direct result of the biofuel mandate set by the US congress by 2016, and would lead to the diversion of 12.8 million hectares of US cropland from corn-feed production to corn ethanol production. Consequentially, this diversion would result in the cultivation of additional 10.8 million hectares globally, which in turn result in soil and vegetative carbon emissions of 351 tonnes of CO2-eq. per converted hectare, or a total of 3.8 billion tonnes of CO_2-eq (Searchinger et. al. 2008; Mathews and Tan, 2009).

Table 11. Carbon debt associated with biofuels.

Biofuel	Former ecosystem	Location	Carbon debt, years	Source
Corn ethanol	Grassland	USA	93	Fargione *et.al.* 2008.
	Abandoned cropland	USA	48	Fargione *et.al.* 2008.
	Mixed forest/ grasslands	USA	167	Searchinger *et.al.* 2008.
Prairie biomass	Abandoned cropland	USA	1	Fargione *et.al.* 2008.
Sugarcane ethanol	Forest	Brazil	17	Fargione *et.al.* 2008.
	Forest	Brazil	15-39	Gallagher *et. al.* 2008.
	Grazing land	Brazil	4	Searchinger *et.al.* 2008.
	Grassland	Brazil	3-10	Gallagher *et. al.* 2008.
	Rainforest	Brazil	45	Searchinger *et.al.* 2008.
Switchgrass ethanol	Cropland	USA	52	Searchinger *et.al.* 2008.
Wheat ethanol	Grassland	United Kingdom	20-34	Gallagher *et. al.* 2008.
	Forest	United Kingdom	80-140	Gallagher *et. al.* 2008.
Palm biodiesel	Tropical rainforest	Indonesia/ Malaysia	86	Fargione *et.al*. 2008.
	Peatland rainforest	Indonesia/ Malaysia	423	Fargione *et.al.* 2008.
Soybean biodiesel	Tropical rainforest	Brazil	319	Fargione *et.al.* 2008.

Source: Modified from CBO, 2009.

Using the assumptions outlined above, Searchinger (2008) estimated the payback period associated with ILUC for corn ethanol grown on a mixed of former grasslands and forests in the US to be 167 years (Table 11). Sugarcane ethanol cultivated in Brazil was estimated to have payback a period of 4 years if the feedstock is grown on land previously occupied by grasslands and a payback period of 45 years when the sugarcane replaces rainforest ecosystems. Ethanol from switchgrass has been estimated to have a carbon debt of 52 years if it displaces croplands in the US.

A related study by Fargione (2008) also showed that the ILUC carbon debt associated with corn ethanol grown on a former U.S. grassland and abandoned croplands to be 93 years and 48 years, respectively. (Table 11). Ethanol produced from Prairie biomass cultivated on former abandoned cropland had the best GHG payback period of just 1 year. Among all the biofuel types investigated, biodiesels had the biggest carbon debt. For example, soybean biodiesel cultivated on former tropical rainforest ecosystem in Brazil has a carbon payback period of 319 years. Biodiesel grown on peatland and tropical rainforests has been estimated to have 423 years and 86 years, respectively. The payback period for sugarcane ethanol grown on former Brazilian forests is estimated to be 17 years and 4 years if cultivated on former grazing lands. Similar payback periods have been estimated by Gallagher *et. al.* (2008) for sugar cane ethanol produced on former forest and grasslands in Brazil. Studies on the ILUC carbon debt for wheat have been estimated to be 20-34 years when grown on former grasslands in the United Kingdom, and 80-140 years when cultivated on previous forest lands (Gallagher *et. al.* 2008).

Utilizing the Massachusetts Institute of Technology's (MIT) global economic and terrestrial biogeochemistry models, Melillo et.al. (2009) estimated the environmental impacts of an increased global biofuel program. Their findings showed the overall GHG emissions associated with cellulosic biofuels to be lower when assessed over longer periods (e.g. 100 years). Because their model relies on unused arable land and agriculture intensification, food versus fuel impacts were minimized. Their paper however calls for increased fertilizer application, primarily to improve crop productivity. Though the Melillo et.al. (2009) study did account for some aspects of the environmental impacts associated with the increased fertilizer utilization including N_2O emissions, it did not address broader environmental impacts including leakage into streams and aquifers and therein resulting hypoxic zones. The paper argues biofuel production in sub-Sahara Africa and South America could bring immense economic wealth to the region. However, this can only occur if citizens of the respective countries become stakeholders of this initiative. Potential environmental impacts including biodiversity loss, fertilizer overuse must be minimized so that biofuel production does not exacerbate already existing problems such as lack of access to clean water in these regions.

Several policy implications can be drawn from Table 11. In order to achieve the established bioethanol targets by 2022, the US biofuel needs to increase the use of forest residues, agricultural stover (Perlack, et. al., 2005), and perennial prairie grasses from abandoned cropland. Additionally, R&D activities would be necessary to investigate the potential of producing cane sugar on former grazing lands in the US (with a carbon payback period of 4 years).

A study by Kim *et.al.* (2009) has shown that the carbon repayment period of corn-ethanol from converted grassland could potentially be reduced from 93 years as reported by Fargione et.al. (2008) to only 3 years. Additionally, corn ethanol production from mixed of forests and grasslands could be reduced from 167 years, as reported in Searchinger *et.al.* (2008) to 14 years (Kim *et.al.*, 2009). These low carbon repayment periods can be achieve by practicing "no-till" and "no-till with crop cover" agricultural techniques (Kim, *et.al.*, 2009; $(S\&T)^2$, 2009). Corn farms on former grasslands and forests employing this cropping practice can achieve much higher soil organic carbon (SOC) levels than the SOCs in the initial ecosystems assuming that these grasslands and forests were left undisturbed.

The US Environmental Protection Agency (EPA) has recently developed a robust technique that is acknowledged to provide the most up-to-date estimates available. The technique uses improved satellite data to determine the ecosystem conversion trends, crop yield increases, and cost data(US EPA, 2010). Reductions are relative to a 2005 fossil fuel (gasoline or diesel) baseline:

- Corn ethanol production will meet the 20% GHG emission reduction (including indirect emissions) threshold
- Sugarcane ethanol will satisfy the 50% reduction threshold for advanced biofuels Biodiesel and renewable diesel will meet the 50% GHG threshold for biomass-based diesel
- Cellulosic ethanol will meet the 60% GHG reduction threshold for cellulosic biofuels. The use of marginal, degraded and abandoned agricultural lands could help satisfy the global biofuel target. The appropriation of marginal, degraded and abandoned agricultural land for biofuel production has sustainability benefits.

Marginal lands include all non-agricultural lands having very low primary productivity for commercial agricultural purposes; these lands have been investigated for energy crop cultivation in different studies (Bringezu, *et.al.* 2009). The reviewed studies suggest (Figure 13) that:

- Global marginal land areas range from 100-1000 million hectares (WWI, 2006) to 250 - 800 million hectares (FAO 2008)
- Global abandoned land areas range from 450 million hectares (Field *et.al*. 2008) to 385-472 million hectares (Campbell *et.al.* 2008).

In summary, a significant amount of marginal, degraded and abandoned lands (from 100-1000 million hectares) could potentially be available for biofuel production globally.

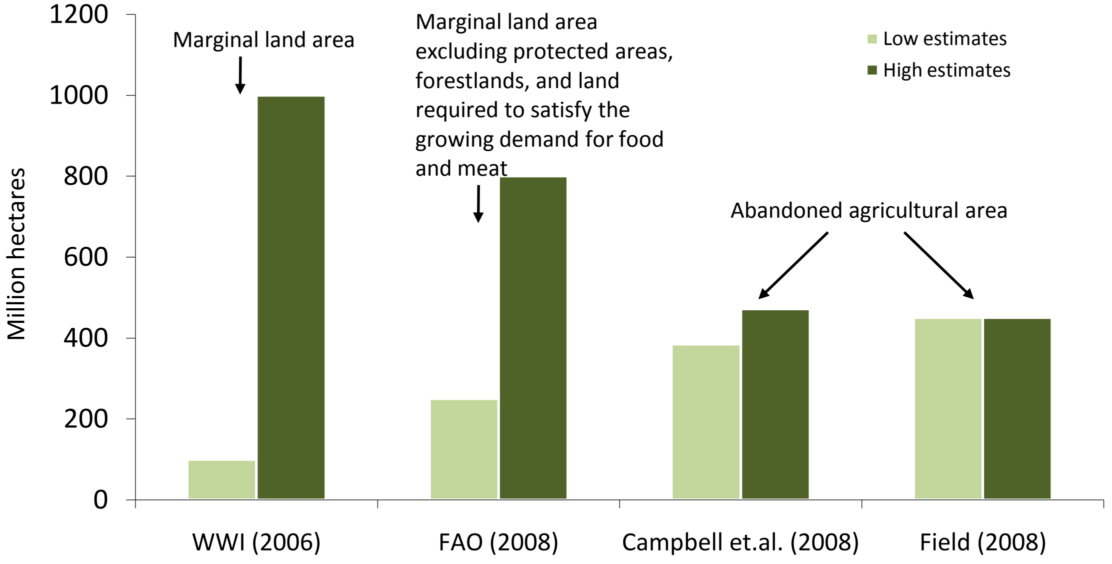

Figure 13. Marginal and abandoned agricultural lands potentially available for biofuel production.

The estimated 100-1000 Mha marginal, degraded and abandoned lands represent 24-27% (or 3099-3486 Mha) of the global terrestrial net primary productivity (NPP) appropriated by society (Metzger and Huettermann, 2008; Marland and Obersteiner, 2008). The key challenge in using marginal, degraded and abandoned land for biofuel crop cultivation is the soil's low productivity and yield. A number of lignocellulosic biomass species have been investigated for their potential to reclaim these lands. For example, *Albizia lebbek* and *Dendrocalamus strictus* are two tropical plant species that have been found to produce high biomass productivity yields of 20t/ha and 32 t/ha respectively on marginal, degraded and abandoned lands. However, it is recommended that only native perennial species are cultivated for biofuel production due to previously reported problems of invasive species affecting natural ecosystems.

Cellulosic ethanol production from *Albizia lebbek* is estimated to have a yield of 120-300 litres of ethanol per bone dried wood feedstock (Sim et.al. 2009). Only approximately 85% of biomass from *Albizia lebbek* is high quality (white wood) and therefore useful for ethanol production. It should be noted that the proportion of high quality white wood may vary with climactic, soil and other conditions.

Several conclusions about land use can be drawn from the investigated case studies. Iowa was also found have the highest soil productivity yields of 50.5 GJ/ha compared to 33.8GJ/ha for Georgia. There were no productivity values for corn ethanol production in California. The high productivity of Iowa's soils enables more ethanol to be produced per unit hectare. However, fertilizer application in Iowa posed significant sustainability concern as already discussed. Policy intervention could encourage the use of forest and agricultural residues as well as cultivating native energy crops on the estimated 60 million ha marginal agricultural lands in the US (Heaton et.al. 2007).

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