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June 2007

LFEE 2007-02 RP

Massachusetts Institute of Technology
Laboratory for Energy and the Environment
77 Massachusetts Avenue,
Cambridge, MA 02139

http://lfee.mit.edu/publications/reports
Publication No. LFEE 2007-002 RP

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Incorporating Technological and Geographic Variability into the Evaluation of Alternative Ethanol Production Methods for Reducing Fossil Energy Use and Greenhouse Gas Emissions

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Current and future environmental impacts of potential bioethanol production pathways are examined by incorporating a Monte Carlo uncertainty analysis within a life cycle model to account for system variability. Compared to single-valued estimates, this range of energy and greenhouse gas impacts provides additional information to decision makers and brings greater clarity to the ethanol debate. The petroleum consumption, greenhouse gas emissions, and land impacts of an expanding and evolving ethanol industry are also evaluated. Corn and cellulosic ethanol production projections are evaluated over the next 20 years to determine the potential impacts of producing 130 billion liters, the current alternative fuels production goal.

The 2007 State of the Union address proposed more than a seven-fold increase in "alternative fuels" production from 18 to 130 billion liters per year by 2017 (*1, 2*). In the nearer term, ethanol is one of the more viable options for achieving this goal given current production scale and future capacity investment, although other alternative fuels, such as biodiesel and coal-to-liquids may also play a role. Current ethanol production in the United States is limited to corn as the only technically feasible high-volume feedstock. Recent efforts to develop and commercialize cellulosic ethanol are showing promising results. These efforts are expected to provide additional pathways to meeting the administration's proposed production targets in a manner that might substantially lower US petroleum consumption and greenhouse gas (GHG) emissions.

This analysis reports on the current and longer-term life-cycle assessment (LCA) of corn and cellulosic ethanol production. The model created evaluates the fossil fuel energy consumption, GHG emissions, and petroleum displacement potential of four biofuel production pathways and projects these results into the future. Previous corn and cellulosic LCA studies have focused on single-value system inputs and estimate net energy values (NEV) ranging from -3.2MJ/L to 9.0MJ/L as presented by Farrell (*3, 4*). The NEV is defined as the energy out of the total production system minus the direct fossil fuel energy consumption and the fossil energy consumed to product system inputs such as fertilizers (Supporting Material). This range in previous results is due in part to the system variability found within the agricultural sector, where seasonal effects, soil characteristics, and geographic locations significantly influence LCA analysis input values such as fertilizer application and yield as well as technological variability. The primary objective of this report is to compare potential future bioethanol production pathways, including this variability, and evaluate the energy and environmental benefits compared to current corn ethanol production.

We utilize a LCA approach which includes a Monte Carlo simulation of numerous normally distributed input parameters which together account for the combined agricultural and technological variability. This produces a probability density function (PDF) that represents a range of outcomes for the ethanol production systems fossil energy consumption and GHG emission values. This range of outcomes, rather than the single-value results provides new insights to the ongoing debate around ethanol's energy security and GHG reduction potential as an alternative fuel.

In the future, as ethanol production increases, biomass from different geographic regions will be utilized. Our study explores the impacts of obtaining biomass from less efficient producing land on system fossil energy consumption and GHG emissions. It is also assumed that in the near future ethanol will be the main contributor to achieving the administrations alternative fuels goal of 130 billion liters per year. Therefore, additional corn and cellulosic models were created to evaluate how agricultural and technological improvements over the next 20 or so years can improve bioethanol system fossil energy use and GHG emissions. Land availability and land use efficiency are discussed since they are critical factors in achieving the current administrations alternative fuels goal and future production levels.

The *Iowa Corn (Kernel) Ethanol* scenario represents the current best practice case for corn kernel ethanol production, as Iowa has the highest crop yields for the lowest agricultural inputs. The primary inputs for this analysis are summarized in Table S1 and are derived from the USDA ERS database and ethanol conversion reports (*5-7*). Evaluating the model using these input parameters results in a net energy benefit and standard deviation of 3.8±2.3 MJ/L and the emission of 90±13 gCO_2-equivalent/MJ (Figure 1 and S1). The application of the Monte Carlo LCA approach illustrates that the NEV is highly dependent on system assumptions and inputs resulting in both positive and negative NEV. This scenario does not include coproduct credits, though we discuss their affect on the NEV and GHG emissions later. Additionally, while mean values for *Iowa Corn (Kernel) Ethanol* production show moderate energy benefits, there is little to no GHG benefit when compared to gasoline consumption (Figure 1 and S1) (*8*). However, on an energy basis, *Iowa Corn (Kernel) Ethanol* does decreases petroleum consumption by 68%, since natural gas is the main fossil fuel input.

Figure 1 illustrates the *Iowa Corn (Kernel) Ethanol* Monte Carlo LCA results compared to four published studies, all with the same system boundary, as reported by Farrell. This is used to validate the Monte Carlo approach and to clarify the debate over the energy benefits of corn kernel ethanol (Figure 1) (*3*). Results reported by Shapouri, Wang, and Farrell are within one standard deviation of the Monte Carlo models results, indicating that they are all roughly equivalent given the range of variation in key inputs (Figure 1). However, Pimentel's reported value is more than three standard deviations below the mean Monte Carlo NEV value, making it less than 1% probable. This is primarily a result of Pimentel's use of older information (*3*)

One key element of the corn ethanol energy debate focuses on the allocation of energy and greenhouse gas emissions between corn ethanol production, and the byproduct dried distillers grain with solubles (DDGS) used for livestock feed (*9*). During the fermentation processes, starch from the kernel is converted to ethanol while the remaining mass is used to produce DDGS (*4*). A 20% to 40% coproduct credit range has been used in literature (*9*). Using a 20% coproduct credit nearly doubles the *Iowa Corn (Kernel) Ethanol's* NEV value from 3.8 to 7.2±1.8 MJ/L, a 90% increase. When including their assumed coproduct credits, Shapouri, Wang, and Farrell are again within one standard deviation of the Monte Carlo LCA results. Pimentel did not include a credit.

Though there is an ongoing debate over the correct way to calculate the NEV of corn ethanol-with and without coproduct credits-our results using the Monte Carlo LCA method demonstrates that under the best case scenario for corn ethanol production (Iowa), bioethanol decreases petroleum consumption and yields moderately positive overall fossil energy benefits. Even so, it also showed little to no GHG abatement benefit when compared to gasoline. While evaluating *current* corn ethanol production provides insight into main system inputs, it also serves as a baseline for the comparison of improved corn ethanol processing, alternative cellulosic ethanol production scenarios, and greater geographic diversity.

With that in mind, three additional alternative bioethanol production scenarios were evaluated. Currently, some ethanol facilities are utilizing the energy value of DDGS to displace their fossil energy inputs (primarily natural gas). This scenario is represented by *Iowa Corn (Kernel) Ethanol Plus DDGS.* Approximately 70% of the DDGS can be gasified to produce all of the facility's process steam, or 77% of the DDGS could be consumed to provide all the facility's steam and electricity needs using combined heat and power (CHP) (*10, 11*). When the DDGS-CHP scenario is compared to *Iowa Corn (Kernel) Ethanol* scenario, fossil fuel consumption and GHG emissions decrease by 67% and 60%, respectively (Figure 1 and S1). Though utilizing the energy content of DDGS provides significant fossil energy and GHG savings, economic drivers such as the DDGS market price and natural gas prices are likely to determine the role that DDGS plays as a fuel in the corn ethanol production system.

As cellulosic conversion technology advances and becomes more cost-effective, producing cellulosic ethanol from agricultural wastes such as corn stover may be utilized.

Corn stover protects the soil from wind and water erosion and is also incorporated within the soil carbon cycle (*12*). It is estimated that 40%-50% of corn stover could be removed for ethanol conversion depending on local soil conditions and topography, without exceeding US recommended erosion rates (*12*). The *Iowa Corn Stover Ethanol* scenario represents this alternative (*13*).

Compared to *Iowa Corn (Kernel) Ethanol*, ethanol produced exclusively from corn stover decreases fossil energy use and GHG emissions by 80% and 70% respectively (Figure 1 and S1). This decrease in fossil energy use and GHG emissions is due to the use of lignin, the fraction of the corn stover biomass that cannot be converted to ethanol, as a fuel for on-site combined heat and power. While this analysis treats ethanol from corn kernels and corn stover separately, these two processes can be integrated at the biorefinery (*14*).

The next potential step in the evolution of ethanol production is the cultivation of dedicated energy crops, such as switchgrass, to meet increases in ethanol demand. Input values for this scenario were obtained from agricultural journals and cellulosic ethanol conversion reports(*5, 15-19*) The best cellulosic case scenario is represented by *Alabama Switchgrass Ethanol*. Compared to *Iowa Corn (Kernel) Ethanol*, *Alabama Switchgrass Ethanol* consumes approximately 93% less fossil energy, emits 94% fewer GHG emissions, and displaces 68% of petroleum on an energy basis (Figure 1 and S1). The primary reason for this significant decrease is the elimination of external facility fossil energy use during ethanol production since the lignin component of switchgrass is used to produce all of the facility's steam and electricity needs. Additionally, switchgrass over its ten year productive life requires only one-third the nitrogen fertilizer needed for corn: this fertilizer is the most highly energy intensive agricultural input.

We can also use the Monte Carlo LCA approach to evaluate the system fossil energy consumption and GHG emissions across a range of geographic locations as expanding ethanol production requires greater amounts of agricultural land. For example, corn grown in Georgia, a traditionally non-corn producing state, instead of Iowa, results in a

NEV that decreased from a positive 3.75 MJ/L to a negative 7.6 MJ/L and resulted in a 47% increase in GHG emissions (Figure 1 and S1). This is a result of increased fertilizer inputs, irrigation, and lower corn yields. For cellulosic ethanol from switchgrass, production is expanded from Alabama to Iowa, another potential switchgrass site. This results in a 5% decrease in the NEV and a 20% increase in GHG emissions (Figure 1 and S1). This is due to increased fertilizer use and lower yields due to Iowa's shorter growing season (*18*). Ultimately, overall environmental and petroleum displacement impacts depend on industry-wide bioethanol production scale, which may become constrained by either overall land availability and/or economic viability as less productive land is used.

Over the next two decades, ethanol will likely continue to dominate the alternative fuels market. Future improvements in corn and switchgrass production and conversion into ethanol were modeled and evaluated by projecting 20 years into the future, and determining the resulting impacts on fossil energy consumption and GHG emissions. Using historic trends, each system input value was extrapolated to estimate values for the year 2025 (Table S2). Compared to today's *Iowa Corn (Kernel) Ethanol* results, the NEV of a future corn ethanol system increases by 90%, while GHG emissions decrease 20% (Figure 1 and S1). When compared to the *Alabama Switchgrass Ethanol* scenario, the future switchgrass scenario results in a 40% increase in the NEV while GHG emissions decrease by 60%. These future scenarios also identified biomass yield, nitrogen fertilization rates, ethanol conversion efficiency, and ethanol facility fossil energy consumption as the main system inputs where achieving technological and other incremental advances would have the greatest impact in decreasing fossil energy consumption and GHG emissions.

Lastly, the 2025 future corn and switchgrass scenarios were analyzed to evaluate the overall petroleum displacement, GHG emissions reductions, and land impacts of producing 130 billion liters of ethanol. In 2006, 20% of the US corn acreage was utilized for corn ethanol production (*6*). Producing 130 billion liters of ethanol from corn or switchgrass would require 75% or 50% of the 2006 planted corn acreage land area, respectively (Table 1) (*20*). At this scale, corn and switchgrass scenarios each would displace 12% of expected 2025 petroleum consumption. Additionally, corn and switchgrass would displace 3.3% and 12% of transportation GHG emissions, respectively (Table 1). While corn ethanol directly competes with prime land for food production at this scale, switchgrass production can be planted on land not currently utilized for food production (*19, 21*).

The 2025 results in Table 1 represent a "best practice" scenario as optimal growing characteristics and yield were assumed. However in the future, biomass from geographic locations that have varying land use efficiencies will be utilized, increasing the land use impacts for a given amount of ethanol produced. Figure 2 represents this land use efficiency for the various ethanol production pathways, and is defined as the amount of ethanol that can produced for a given hectare of land.

This research has developed a model that incorporates the uncertainty in system inputs to investigate four ethanol production pathways, starting with current corn ethanol production, and moving towards cellulosic ethanol options such as corn stover and switchgrass. Results demonstrate that gasoline displaced by ethanol is not a one to one ratio, mainly due to the 30% difference in the fuels energy densities. Therefore, ethanol produced from either corn and/or switchgrass actually displaces 68% of petroleum. Additionally, the superiority of cellulosic ethanol to displace GHG emissions was also verified. These scenarios were then extended out 20 years to show how incremental system improvements further a decrease in system fossil energy consumption and GHG emissions.

This model was then applied to investigate the impacts of producing the administrations proposed alternative fuels goal of 130 billion liters in 2025, assuming it came from ethanol. In 2025, 130 billion liters of ethanol would displace 12% of petroleum consumption whether from corn, corn plus corn stover, or switchgrass. Additionally, light duty vehicle transportation GHG emissions would decrease by 3.3%, 5.6%, or 12% if produced by corn, corn plus corn stover, or switchgrass, respectively. Land availability proves to be a growth constraint for corn ethanol, since producing 130 billion liters would consume 75% of current corn acreage, while ethanol from switchgrass would require 30% less land and would not be constrained to the Corn Belt. These projections will start to define the impact that future large-scale bioethanol production will have on fossil energy use, GHG emissions, and petroleum displacement.

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Acknowledgments

This research was made possible by the support of BP. The authors thank Stephen Connors and Anup Bandivadekar for their assistance and valuable comments.

Figure 1 – Net energy value (NEV) of current (2006) and future (2025) ethanol production with various bioethanol production pathways. All the calculations have the same system boundary and use fuel's LHV. Ethanol's LHV is taken to be 21.2 MJ/Liter. The white symbol's represents the NEV without the allocation of coproduct credits, while the shaded symbol's includes coproduct credits. Each box represents the mean plus or minus one standard deviation (67% of the mean) and the whisker represents plus or minus 3 standard deviations (99% of the mean). Previous published results as reported by Farrell are compared with the Monte Carlo LCA model (*3*). The NEV for gasoline production is 6.7MJ per liter of gasoline, or 4.7 MJ per liter of ethanol (*22*).

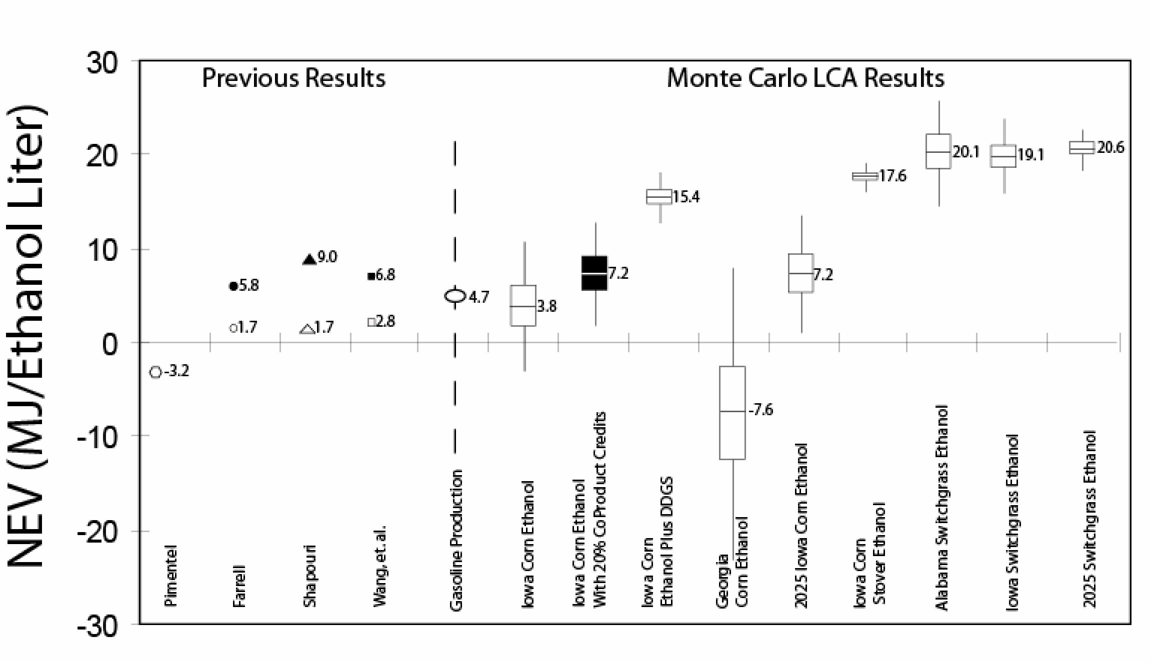

Table 1 – The impact of producing the Administrations proposed alternative fuels goal of 130 billion liters, assuming it comes from ethanol. Petroleum consumption was extrapolated to 2025 based on EIA projected US energy consumption. Ethanol displaces 68% of gasoline consumption on an energy basis per liter. A 30% corn stover removal rate was assumed.

	2006	**2025**[a]		
Feedstock	Iowa Corn Kernel	Iowa Corn Kernel	Iowa Corn Kernel + Corn Stover	Alabama Switchgrass
Ethanol Production	18 Billion Ethanol Liters (4.8 Billion Gallons)	130 Billion Ethanol Liters (35 Billion Gallons)		
% of US Gasoline Consumption	2.3% of 2006 Consumption	12% of 2025 Consumption		
% of US Gasoline GHG Emissions Displaced (without credit)	0%[b]	3.3%	6%	12%
% of 2006 US Corn Cropland[c]	20.4%	75%	60%	50%
% of 2006 US Cropland	3.6%	14%	11%	10%

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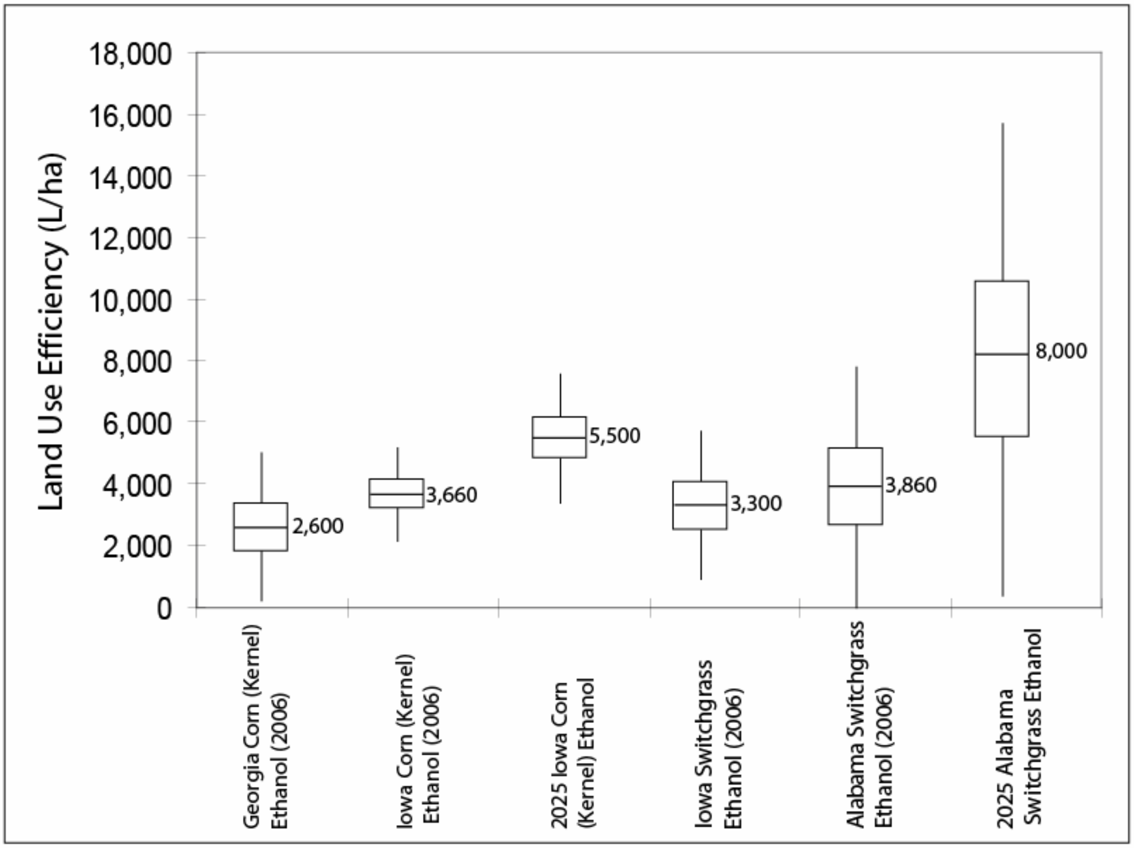
[a] Future 2025 values were assumed and are defined in Table S1.

[b] This value does not include a coproduct credit.

[c] Land impact results assumed “best practice” for location and system inputs. Therefore, these results represent a minimum value for land use since as production volumes increase, less efficient land will have to be utilized for biomass.

Figure 2 - Land use efficiency for current (2006) and future (2025) bioethanol production options. Ethanol yield per unit of land is dependent on crop yield, geographic location, and ethanol yield. As ethanol production increases, crops from various geographic regions will be utilized. For example, land consumed to produce corn in Georgia compared to Iowa is 29% less efficient. This impact can be seen in the decreased NEV and increased GHG emissions (Figure 1 and S1). Future Iowa corn kernel ethanol scenarios project a 50% increase in land use efficiency, due to projected higher corn and ethanol yields in 2025. Currently, land required per unit of switchgrass ethanol is comparable to land required for corn ethanol. However, in the future required for switchgrass ethanol production outperforms future corn ethanol hectares by 45%.



Supporting Material for:

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June 2007

Data Analysis Methodology

A Monte Carlo approach was incorporated into a life cycle analysis for various bioethanol production pathways to evaluate system fossil energy consumption and greenhouse gas (GHG) emissions(*1*). Probability distribution functions (PDF) were created for each system input variable from collected data sets to account for system variability (*2*). Initially normal distributions were assumed for all input values. A sensitivity analysis determined the key system input parameters that affected the reported results the greatest. Different PDFs were then assumed for these key system input variables to determine the results sensitivity to varying PDFs. Varying key input PDFs resulted in a difference of less than 2% of reported fossil energy use and greenhouse gas (GHG) emissions.

Parameters such as the net energy value (NEV) are often defined to help evaluate the benefits of ethanol production. NEV is defined as follows (*3*):

$$NEV\,(MJ / L_{Ethanol}) = Output\ Energy\,(MJ_{Fossil\ Fuel} / L_{Ethanol}) - Input\ Energy\,(MJ_{Fossil\ Fuel} / L_{Ethanol})$$

If co-products are considered then the Output Energy is expressed as:

$$Output\ Energy\,(MJ / L_{Ethanol}) = Fuel\ Energy\,(MJ / L_{Ethanol}) + Coproduct\ Energy\,(MJ / L_{Ethanol})$$

Inputs included in the system boundary are described in the following section. Coproduct credits are the additional "credit" allotted towards fossil energy use and GHG emissions for producing multiple outputs for a given set of inputs. While such metrics are often stated and debated, more policy-relevant metrics are GHG emissions and petroleum displacement (*3*).

System Boundary

This section describes the system that was used in the corn and switchgrass ethanol Monte Carlo life-cycle analysis. The system boundary includes the agricultural sector, corn and switchgrass transport from the farm to the ethanol facility, and ethanol processing. Items such as building infrastructure, human labor, and embodied machine production energy were not included as these quantities are uncertain and relatively small when their long lifetimes are taken into account (*3*).

Iowa, being the top corn producing state, was chosen as the main corn case study. It was also assumed that switchgrass would be used as a cellulosic ethanol option. Experimental plots in Alabama, Tennessee, and Iowa were part of a US Department of Energy biomass research study to evaluate the optimal land use and best environmental crop management practices for switchgrass (*4*). Best switchgrass type was categorized by geographic location, which is based on soil type and climate (*4*). Alamo switchgrass in Alabama was determined to be the optimal variety and location for large-scale production. For the main cellulosic study, Alamo switchgrass grown in Alabama is analyzed. The following section describes what inputs were included and excluded within the current and future corn and switchgrass system boundary.

Corn Ethanol System Boundary

Agricultural Sector Includes (*5*):

1. Corn Seed Production
2. Nitrogen, Phosphate, and Potash fertilizer production and application
3. Lime production and application
4. Herbicide and Insecticide production and application
5. Farm machinery fossil fuel consumption
6. Farm electricity consumption

Corn Transport Sector Includes:

1. Diesel fuel consumption assuming a 100-mile roundtrip from the farm and corn storage station to the ethanol processing plant
2. Semi-trailer truck capacity 875-100 bu/truck
3. Semi-trailer truck loaded engine efficiency (5 miles/gal) and unloaded engine efficiency (8 miles/gal) (*6*)

Ethanol Processing Sector Includes:

1. Natural gas and electricity inputs are the energy inputs utilized by the ethanol processing plant to convert corn to ethanol (*7*)
2. Enzyme, chemical, and yeast production energy are excluded

Switchgrass Ethanol System Boundary

Agricultural Sector Includes:

1. Nitrogen fertilizer production and application
2. Herbicides production and application
3. Farm machinery fossil fuel consumption

Switchgrass Transport Sector Includes:

1. Switchgrass bales and transport capacity information was modeled with respect to hay cultivation and transport (*8*).
2. Diesel fuel consumption assuming a 100-mile roundtrip from the farm location to the ethanol processing plant
3. Semi-trailer truck capacity 23.5 ton/truck (*8*)
4. Semi-trailer truck loaded engine efficiency (5 miles/gal) and unloaded engine efficiency (8miles/gal) (*6*)

Ethanol Processing Sector Includes:

1. All process energy is obtained through the burning of lignin (*9, 10*)
2. Additional electricity may be produced from excess process energy that can then be sold to the gird. This is considered a co-product of this process. For this analysis coproduct credits are not included as the amount of electricity sold to the grid depends on facility's schematic (*9*).
3. Ethanol yield is calculated from the mass fractions of cellulose and hemicellulose in switchgrass.
4. Enzyme, chemical, and yeast production energy are excluded

Additionally Excluded Variables

Only fossil energy was considered when accounting for energy needed during the production life cycle of corn and cellulosic ethanol. Therefore, the contribution of solar energy during feedstock production was not included. Carbon sequestered in biomass left on the field after cultivation was also not included as a sink in GHG calculations.

Crop Input Data and Characteristics

Table S1 and S2 displays the current (2006) and future (2025) key corn and switchgrass model inputs and assumptions.

Corn Ethanol Input Data

USDA and ERS state-specific agricultural data sets from 1995-2004 were used to characterize the PDFs for variables such as yield, fertilizer application, and farm machinery fuel consumption (*5*). The ethanol processing energy distributions were created using reported plant natural gas and electricity consumption values in *USDA's 2002 Ethanol Cost-of-Production Survey*, July 2005 (*7*).

Corn is composed mainly of starch, a six carbon carbohydrate, which is broken down to glucose, and then fermented to produce ethanol. Dried distillers grain with solubles (DDGS) is an additional product of dry-milling ethanol plants. DDGS is produced from the remaining mass, such as protein, that is not converted into ethanol (*11*). Currently, a majority of ethanol facilities sell DDGS to animal feed producers, but as natural gas prices increase facilities are finding it economical to burn it to displace facility natural gas consumption (*12*). The ethanol conversion efficiency of corn-based ethanol is determined by the amount of starch in a kernel of corn, the effectiveness at which that starch can be exposed to enzymes during the pretreatment process, and the efficiency of the fermentation process. The current *Iowa Corn (Kernel) Ethanol* and *Iowa Corn (Kernel) Plus DDGS* models assumed an ethanol conversion efficiency of 435 L/Mg.

Switchgrass Ethanol Input Data

The Southern Plains of the United States have been reported as having the greatest potential for growing Alamo switchgrass (*4*). Switchgrass agricultural data was gathered from a variety of published papers, government and national laboratory reports, and university publications (*4, 13-23*). Databases from the Energy Efficiency and Renewable

Energy division of US DOE[d] were used to gather physical properties and cellulose, hemicellulose, and lignin mass fractions for modeling Alamo switchgrass (*10, 19, 24, 25*). Switchgrass crop management, yearly yield, and growing characteristics were gathered from (*4, 15, 17-20, 22-24, 26*).

Unlike a single planting and cultivation season for corn, switchgrass is planted once and cultivated over a ten-year period. The first year is dedicated to plant establishment and weed control and only 30% of the maximum yield is expected, a two-thirds yield is assumed the second year with continuing weed management practices and minimal fertilizer application. Full yields are assumed for years three through ten with fertilizer application (*4, 15, 26*). While corn ethanol results represent a single planting year, switchgrass ethanol results are represented by a ten-year average crop yield. This incorporates the varying inputs over the lifetime of the crop.

Harvesting switchgrass at optimal time periods can decrease the amount of fertilizer needed in the following year. For example, throughout the growing season nitrogen and other nutrients accumulate in the above-surface mass of the plant. However, in preparation for winter the nutrients relocate from the shoots to the roots (*27*). Therefore, harvesting switchgrass after a killing frost when nutrients are in the roots reduces the amount of nutrient application needed the following year, as nutrients within the roots are retained (*27*).

Switchgrass cultivation and transport was modeled based on current hay agricultural practices. It is assumed that switchgrass can be cultivated using similar hay cultivation techniques and therefore no additional machinery will need to be developed (*8, 28*). For this analysis a transport distance of 100 miles round trip was assumed with a trailer capacity 23.5 ton/truck (*8*).

Ethanol processing information and conversion efficiencies were characterized utilizing published reports (*9, 10, 29-32*). Ethanol produced from cellulosic sources, such as switchgrass, undergoes different pretreatment and conversion steps than corn ethanol due to its different molecular structure and mass components. Switchgrass has three main components, cellulose, hemicellulose and lignin. Both cellulose and hemicellulose can be converted to ethanol, while lignin can be burned to provide all the thermal energy needed by the ethanol processing facility. In some cases excess heat can be used to produce electricity that can be used on site or sold to the grid. In this case, electricity sold to the grid would be considered a coproduct.

The ethanol conversion efficiency is mainly determined by four things: first, the mass fraction of cellulose and hemicellulose, second, the efficiency of the pretreatment process to expose the cellulose and hemicellulose to enzymes, third, the efficiency of the enzymatic breakdown of cellulose and hemicellulose, and lastly, the efficiency of the fermentation process.

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[d] Energy Efficiency and Renewable Energy (EERE), Alternative Fuels Comparison Chart, Biomass Feedstock Composition and Property Database
http://www1.eere.energy.gov/biomass/feedstock_databases.html

The following equations represent the chemical conversion steps. Additionally, the cellulosic ethanol conversion efficiency was modeled based on published switchgrass mass fractions and demonstrated ethanol conversion yields (*9, 10, 33*).

Cellulose To Ethanol

Step 1: Cellulose to Glucose, 63.5% conversion efficiency assumed

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$$

Step 2: Glucose to Ethanol, 95% conversion efficiency assumed

$$C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$$

Hemicellulose to Ethanol

Step 1: Hemicellulose modeled as Xylan to Xylose, 67.5% conversion efficiency assumed

$$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$$

Step 2: Xylose to Ethanol, 90% conversion efficiency assumed

$$3C_5H_{10}O_5 \rightarrow 5C_2H_6O + 5CO_2$$

Table S2 – Table of current (2006) corn and switchgrass ethanol production system inputs

Key Bioethanol Assumptions & Input Values[e]			
	Corn Ethanol		
	Units	***Average***	***Standard Deviation***
Farm Input Values			
Corn Yield[f]	Mg/ha	9.1	1.4
Nitrogen Fertilizer Application Rate	kg/ha	142	5.7
Corn Ethanol Processing			
Natural Gas	MJ/L	9.0	1.9
Electricity	MJ/L	1.1	0.4
Ethanol Conversion Efficiency	L/Mg	402	30
	Switchgrass Ethanol		
	Units	***Average***	***Standard Deviation***
Farm Input Values			
Switchgrass Yield[g]			
Year 1, 10	Mg/ha	4.5	4.6
Year 2,9	Mg/ha	9.9	4.6
Year 3 – 8	Mg/ha	14.9	4.6
Nitrogen Fertilizer Application Rates			
Year 3 – 10	kg/ha	76	37
Switchgrass Mass Fractions[h]			
Cellulose	%	33.6	1.3
Hemicellulose (Xylan)	%	26.2	1.0
Lignin	%	18.7	1.6
Ethanol Processing[i]			
Xylan to Xylose Yield	%	67.5	-
Cellulose to Glucose Yield	%	63.5	-
Xlyose to Ethanol	%	90.2	-
Glucose to Ethanol Yield	%	95.0	-

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[e] Main inputs for Iowa Corn Ethanol and Alabama Switchgrass Ethanol models for the year 2006. Future inputs are in Table S2

[f] 1 bushel of corn = 56lbs = 25.4kg

[g] Assumed a switchgrass 10 year growing cycle. Assumed a 30% yield in the first year, 67% yield in the second year, and max yield for years 3-10.

[h] Mass fractions were obtained from Biomass Feedstock Composition and Property Database from the EERE. Though hemicellulose is made up of Xlyan, Arabinan, Galactan, Mannan, it was assumed that all the hemicellulose mass fraction is Xylan as that accounts for over 80% of the hemicellulose mass fraction.

[i] Assumed 2035 conversion values were 90% for both xylan to xlyose and cellulose to glucose yields

Future Corn and Switchgrass Scenarios

Additional corn and switchgrass ethanol production scenarios were created to represent the nearer term future for these industries. For Iowa corn ethanol production, each system input value was extrapolated using historic trends to estimate values for the year 2025. A sensitivity analysis showed yield, nitrogen application rate, ethanol conversion efficiency, and ethanol process as the four key most sensitive input variables.

Since switchgrass does not have historic trends for input values to project from, yield and conversion efficiency values were assumed for the year 2025 using published projections. A 2% yearly yield increase was assumed resulting in a yield of 24.4 ± 6.8 Mg/ha in the year 2025 (*4*). A 2% yearly yield increase is appropriate as yields in corn grains initially increased 3-5% per year (*4, 34*). Additionally, the largest experienced yield obtained is 47Mg/ha; the assumed 2025 yield value is 53% of this value. The ethanol conversion rate was assumed to increase from the current demonstrated levels of approximately 65% to the future projected levels of 90% (*9, 10*).

Table S2 represents the future input values and assumptions for corn and switchgrass future ethanol scenarios.

Table S3 - Table of future (2025) corn and switchgrass ethanol production system inputs

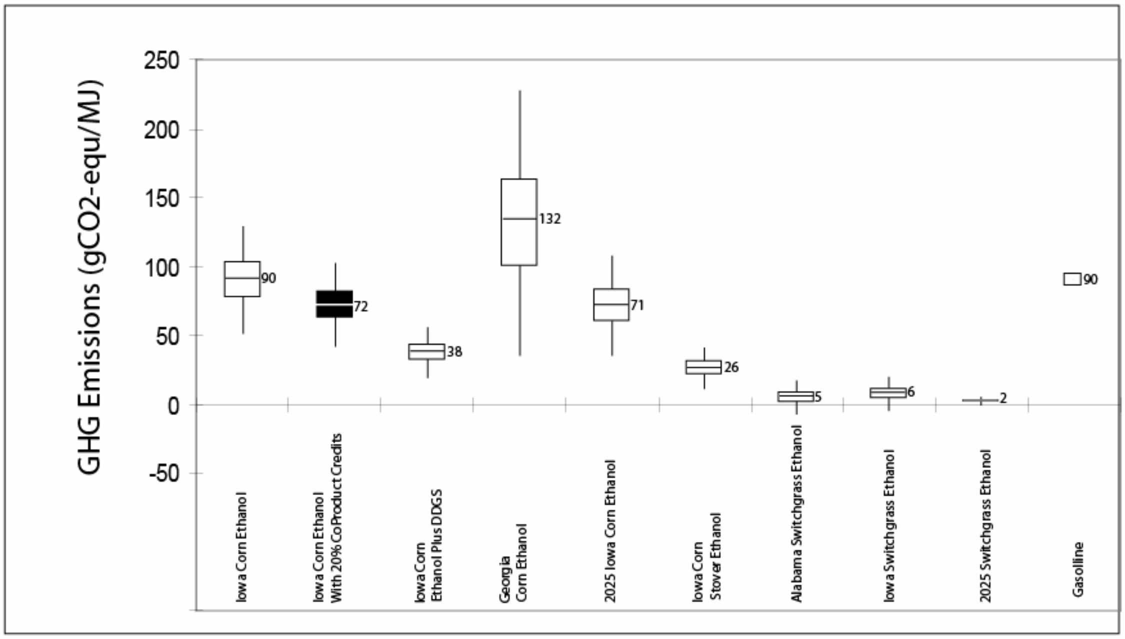
2025 Key Bioethanol Assumptions & Input Values		
	Corn Ethanol	
	Units	***Average***
Farm Input Values		
Corn Yield	Mg/ha	13.0
Nitrogen Fertilizer Application Rate	kg/ha	159
Corn Ethanol Processing		
Natural Gas	MJ/L	7.5
Electricity	MJ/L	0.9
Ethanol Conversion Efficiency	L/Mg	435
	Switchgrass Ethanol	
	Units	***Average***
Farm Input Values		
Switchgrass Yield		
Year 1	Mg/ha	7.3
Year 2	Mg/ha	16.3
Year 3 – 10	Mg/ha	24.4
Nitrogen Fertilizer Application Rates		
Year 3 – 10	kg/ha	76
Switchgrass Mass Fractions		
Cellulose	%	33.6
Hemicellulose (Xylan)	%	26.2
Lignin	%	18.7
Ethanol Processing		
Xylan to Xylose Yield	%	90
Cellulose to Glucose Yield	%	90
Xlyose to Ethanol	%	90
Gluclose to Ethanol Yield	%	95

System Greenhouse Gas Emissions and Assumptions

Greenhouse gas (GHG) emissions were calculated for all considered fossil energy flows within the system boundary (Figure S1). Carbon dioxide, methane, and nitrous oxide were included. GHG emissions were aggregated on a carbon dioxide equivalent basis using EPA global warming potential (GWP) emission factors (*35*). Fossil fuel emission factors were taken from the DOE and EIA website (*36*). Soil nitrous oxide emissions associated with nitrogen fertilizer use were included within the GHG calculation as recommended by IPCC (*37*). Photosynthetic carbon in ethanol that comes from feedstocks is excluded from this study as carbon dioxide released during ethanol combustion is assumed to be absorbed form the atmosphere during photosynthesis during the feedstocks life cycle (*38*).

GHG emissions associated with ethanol processing is based on fuel type and purchased electricity. A 8% transmission loss was assumed and the US electricity energy portfolio in 2000 was used to determine total fuel energy use and GHG emissions associated with purchased electricity (*39*). EIA recommended US electricity emission factors were applied (*39, 40*). No energy or GHG credit was given for additional electricity that may be sold to the grid during cellulosic ethanol production. The total fossil energy consumed for corn-based ethanol is divided into natural gas (82%), purchased electricity (12%), and petroleum consumption (6%). Natural gas is consumed to produce nitrogen fertilizer and to provide energy for ethanol processing. Fossil energy use and GHG emissions related to gasoline production and consumption were gathered from (Figure S1) (*6*).

Figure S3 – The greenhouse gas emissions for various corn and switchgrass ethanol production scenarios. All the calculations have the same system boundary and use fuel's LHV. Ethanol's LHV is taken to be 21.2 MJ/Liter. The white symbol's represents the NEV without the allocation of coproduct credits, while the shaded symbol's includes coproduct credits. Each box represents the mean plus or minus one standard deviation (67% of the mean) and the whisker represents plus or minus 3 standard deviations (99% of the mean).



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