Biomass to Ethanol: Potential Production and Environmental Impacts

by

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the
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Abstract

This study models and assesses the current and future fossil fuel consumption and greenhouse gas impacts of ethanol produced from three feedstocks; corn grain, corn stover, and switchgrass. A life-cycle assessment approach with an integrated Monte Carlo uncertainty analysis is applied to each of these three bioethanol pathways. Incorporating a Monte Carlo uncertainty analysis within a life-cycle model enables one to account for system variability within the agricultural, technological, and geographic arenas. This results in a range of energy and greenhouse gas impacts rather than previous single-valued estimates. This uncertainty analysis brings greater clarity to the ethanol debate through evaluating the probability of previously published life-cycle assessment net energy results, from reports such as Farrell, Wang, Shapouri, and Pimentel. Life-cycle assessment net energy results show corn grain ethanol to have a positive value when DDGS coproducts are included within the assessment boundary and a slightly negative value when they are not. The system net energy value and GHG emissions are also sensitive to system input assumptions and geographic location. For lignocellulosic ethanol produced from corn stover and switchgrass, a positive net energy value and reduced GHG emissions are seen when compared to gasoline. In addition to net energy results and system GHG emissions, the petroleum displacement and land use impacts for an expanding and evolving ethanol industry are also evaluated.

Corn grain, corn stover, and switchgrass-based ethanol potential production levels are also analyzed. It was determined that 55-65 billion liters per year of corn grain ethanol could potentially be produced in the next 10 years, consuming 30% of future US corn grain production. Corn stover and switchgrass have the potential to produce 25-35 and 10-20 billion liters per year of ethanol, respectively. These ethanol production results were then applied to assess the feasibility and environmental impact of achieving the new Renewable Fuels Standard, of producing 136 billion liters of renewable fuels by 2022. This study concluded that while the scale is potentially feasible from these three feedstocks, the timeline to achieve this scale would be very challenging given the cellulosic ethanol technological and economic advances that are still needed.

Thesis Supervisor: John B. Heywood
Title: Sun Jae Professor of Mechanical Engineering

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Conversion Tables

Ethanol Conversions	
Ethanol Density @ 20°C	789 kg/m^3
Liter of ethanol	2.7 kg

Biomass Conversions	
1 bushel of corn	56 lbs
1 bushel of corn	25.25 kg
Lignin Energy Content	29.54 MJ/kg
Switchgrass Energy Content	17.4 MBTU/Mg (dry)
Switchgrass Energy Content	14.8 MBTU/Mg (15% moisture)
Switchgrass Energy Content	18.3 MJ/kg (dry)
Cellulose Molecular Weight	162.14 g/mole
Xylan Molecular Weight	132.1 g/mole
Ethanol Molecular Weight	46 g/mole

Carbon Emission Factors

Fuel	Factor	
	Metric tons of Carbon / MMBTU	*grams of Carbon / MJ*[1]
No 2 Oil (gasoline)	0.0225	19.6
No 6 Oi (diesel)	0.0225	20.8
Natural Gas	0.01633	15
Coal	0.0265	
Propane	0.01951	

Source - Emission Factors - www.cleanair-coolplanet.org
Stationary Emission Factors

Fuel	Higher Heating Value	Lower Heating Value	Units
Gasoline	120,000	115,000	BTU/gal
Diesel	140,000	130,500	BTU/gal
Natural Gas	1040	930	BTU/scf
Ethanol	84,000	76,000	BTU/gal

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[1] Based on fuels LHV

Fuel	Higher Heating Value	Lower Heating Value	Units
Gasoline	33	32	MJ/L
Diesel	39	36	MJ/L
Natural Gas	1.09	0.98	MJ/scf
Ethanol	23.4	21.2	MJ/L

Conversions

SI Units	English Units
1kW-hr	3413 BTU
1 gal	3.785 liters
1 gal	0.1337 scf
1 barrel of oil	6.3 MMBTU
1 barrel or oil	42 gal
1 kg	2.2046 lb
1 m^3	264.17 gallons
1 ton	2,000 lbs
1 mton	Mg

Other GHG Emission Factors

	Methane (CH4)	Nitrous Oxide (N2O)	Methane (CH4)	Nitrous Oxide (N2O)
	Stationary Sources		Electric Utilities	
Fuel	Factor		Factor	
No 2 Oil	0.7	0.357	0.91	0.36
No 6 Oi	0.7	0.357	0.91	0.36
Natural Gas	1.1	1.1	1.1	1.1
Coal	0.75	0.298	0.75	0.298
Propane	1.08	4.86	-	-

Emission Factors Units - g / MMBTU, Stationary Emission Factors, Transmission Losses = 8%

Source - Emission Factors - www.cleanair-coolplanet.org

Global Warming Potential (GWP)

Methane	21
Nitrous Oxide	310

Source - Emission Factors - www.cleanair-coolplanet.org

GWP Units - kg of CO2/kg pollutant

1,000 kg = 1 metric ton

Chapter 1: Introduction and Background

Project Motivation

When looking into the future, world oil demand is projected to increase more than 40% by 2030 [1]. This increase is mainly from Asian countries like China and India, whose transportation industries are rapidly expanding. Currently, the United States consumes approximately 20 million barrels of oil per day (531 billion liters per year), with two-thirds of this consumption coming from the transportation sector [1]. Petroleum consumption from transport accounts for 25% of the nations greenhouse gas (GHG) emissions [2]. In the next 20 years, US gasoline consumption is expected to grow 30%, to a level of 700 billion liters per year [1]. Unlike the power generation sector, where there is a portfolio of energy generation options, the light duty vehicle transportation sector currently only has one choice, petroleum. That inflexibility makes the US's transportation system vulnerable to fluctuations in the oil market, which may be caused by natural disasters like hurricane Katrina, unstable governments, and increased world oil demand. Biofuels provide the US an opportunity to diversify its transportation fuel mix, bringing greater stability to our growing energy needs, decreasing dependence on foreign resources, and decreasing the environmental impact of our energy consumption. Though, not all biofuels are equal in their ability to facilitate these goals. Depending on the source of biomass, conversion technology, and life-cycle energy requirements, biofuels production can have varying results and impacts.

In the US, ethanol has been the recent renewable transportation fuel of choice due to the maturity of its technology, feedstock availability, and the ease of infrastructure scalability. Ethanol was also chosen to help combat high oil prices and increase national security by displacing petroleum consumption. In 2006, ethanol accounted for nearly the entire biofuels market in the US, producing 18 billion liters (4.8 billion gallons) [3]. While ethanol is produced from sugarcane in Brazil; in the US it is produced from corn grains. Ethanol produced in the US and Brazil represents 70% of the world's ethanol production, though countries like China are increasing their production capacity rapidly [3]. In Brazil, ethanol accounts for as much as 20% of their total transportation fuel use (by volume) [4]. In the US market, ethanol only represents 2.5% of motor gasoline consumption (Figure 1-1) [4]. This difference is due to the US transportation fuel consumption is 9 times that of Brazil's. So therefore, while the US and Brazil produce approximately the same amount of ethanol, the oil displacement impact it has on each of our transportation markets is very different due to their magnitudes.

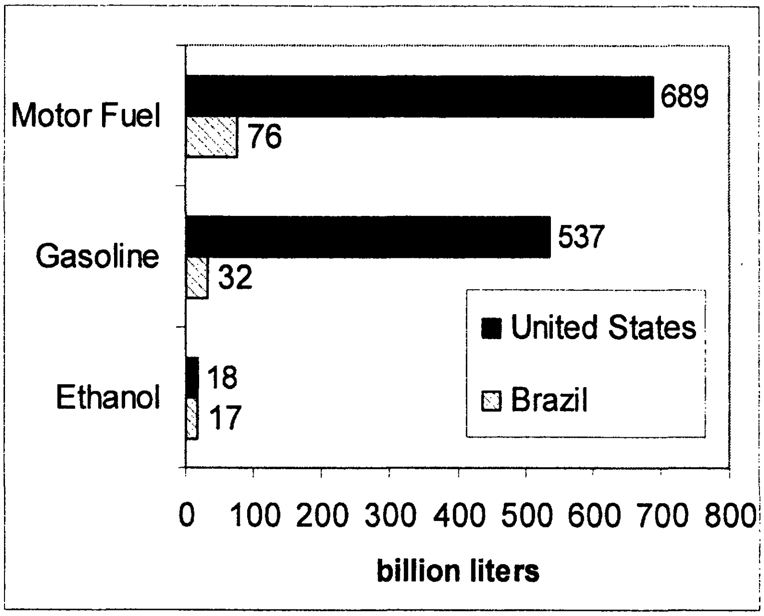

Figure 1- 1 – 2006 Transportation Fuel Consumption in the United States and Brazil [3]

Ethanol produced in the United States is expected to increase to 23 billion liters by 2009 [3]. This is based on projections for capacity additions to existing facilities and the addition of 73 new facilities [3]. The US ethanol industry is mainly located within the Corn Belt, however facilities are also being built in New York, Arizona, and California.

Ethanol has been produced in the US since the early 1800s [5]. Historically, ethanol production mainly increased during times of war, such as World War 1, or in times of high oil prices, as in the 1980s (Figure 1-2). Since 2000, ethanol production has increased 3 fold due to two major events; the first being the phase-out of methyl tertiary-butyl ether (MTBE) and the second being the adoption of the Renewable Fuels Standard

(RFS) in 2007. MBTE is a fuel oxygenate that is added to gasoline to promote cleaner engine combustion [6]. After reports in 2006 of groundwater contamination from leaking underground storage tanks, MBTE begun to be phased out of gasoline blending practices. Ethanol, also being a fuel oxygenate, was then used as a replacement for MBTE in gasoline. A second policy that promoted ethanol production was the 2007 Renewable Fuels Standard (RFS). The 2007 RFS was a government mandate that boosted the production of ethanol, by requiring 28 billion liters of renewable fuel to be blended with gasoline by 2012. There is also a blender's tax credit of \$0.13/L (\$0.51/gal) which made producing/purchasing ethanol economically feasible. State government policies mandating blending have also boosted the demand for ethanol. In total, production levels have increased so rapidly that the 2007 RFS is expected to be met by 2009, three years early [3].

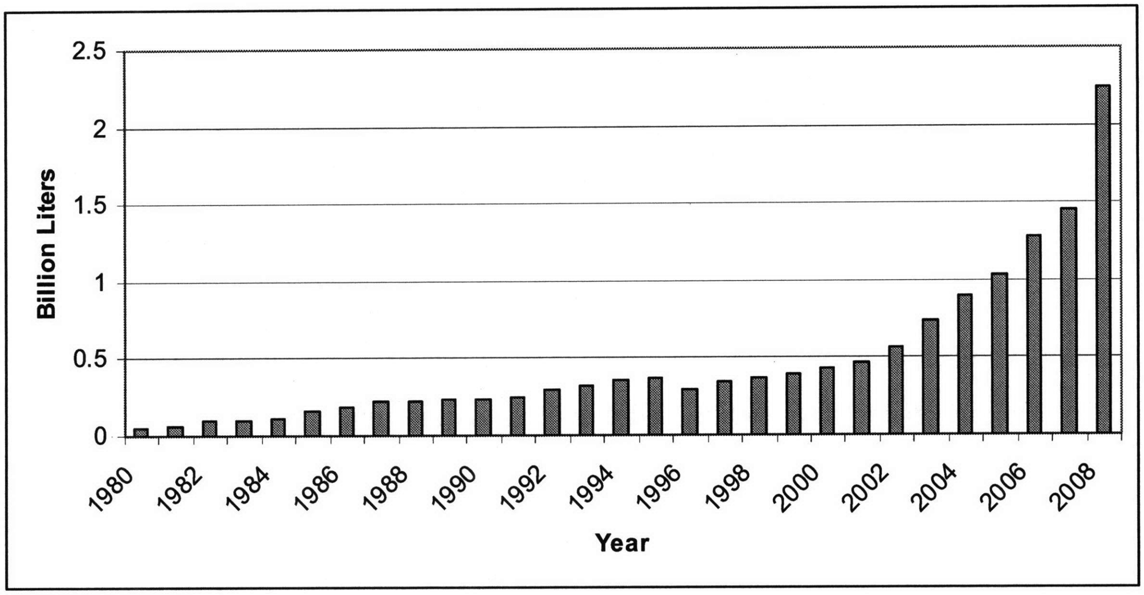

Figure 1- 2 – United States Ethanol Production (1980-2009). Production levels from 2007 to 2009 are based on expected increases in ethanol production from new facilities and from the expansion of existing facilities [3].

This rapid scaling up of production is sited as a reason for the recent glut of ethanol in the marketplace and the accompanying 30% drop in the market price since May 2007 [7]. This surplus is partly due to a saturation of local markets and infrastructure bottleneck to transporting ethanol to coastal markets. Some see this as only a short-term problem, while others are looking for longer-term solutions, such as retrofitting existing pipelines and creating dedicated ethanol pipelines. Policy makers have reacted by passing a new RFS in January of 2008 that has increased the required amount of renewable fuels production from 28 billion liters to 136 billion liters [8]. Their hope is to promote the additional development of biofuels, and specifically second generation cellulosic based biofuels, as a way to further decrease our nation's petroleum consumption and greenhouse gas emissions. Additionally, this increase in the RFS would help alleviate the production surplus, as blenders are now required to purchase an increase amount of ethanol.

Current gasoline engines can use fuel blends of up to 10% ethanol without engine modification. Vehicles called flex-fuel vehicles are produced for higher ethanol blends such as E85. While flex-fuel vehicles are currently sold in the marketplace, they only represent 0.3% of the actual light-duty vehicle fleet, and therefore do not create a large market demand for higher ethanol blends[2] [9]. The EPA is currently working to create policies to support fuel blends slightly higher than E10, such as E20. This would provide additional markets in states that have minimal ethanol blending policies and provide blending options for when then the E10 market is saturated at around 57 billion liters. Currently, vehicle testing is being preformed to determine if current gasoline vehicles could use higher ethanol fuel blends, and if not what engine modifications would be needed and at what cost.

In the near-term corn production is expected to increase to meet the demands of an expanding ethanol industry. This growth in both the agriculture industry and ethanol producing industries comes at an economic and environmental cost that is already starting to be seen. For example, since 2006 the market price of corn has surged from $1.86 per bushel to around $4 per bushel [10]. This is due to the ethanol industry consuming 20% of the 2006 corn grain crop. This increase in corn prices has had both a local and world affect. In the US, this has had a large affect on livestock producers, who have seen their feed costs' increase. Additionally, the prices of other commodities are expected to

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[2] (674,678 E85 cars http://www.eia.doe.gov/cneaf/alternate/page/datatables/atf14-20_04.html)

increase as expanding corn acreage is often displacing other crops such as soy beans, wheat, and cotton. Increased corn production also has unintended environmental consequences, such as increased runoff from nitrogen fertilizers and decreasing ground water levels. Also, as corn production expands, a loss of biodiversity could result from new land use practices. Though some of these issues should prove to be problems in the short-term, the long-term global ramifications of increased corn prices remain to be seen.

Project Introduction

As the bioethanol system continues to expand the need to model and analyze its production from a life-cycle perspective has become increasingly important. To address this issue, this study has focused on modeling and evaluating the life-cycle impacts of current and the longer-term production of ethanol from starch and lignocellulosic-based biomass. The impacts considered are fossil energy consumption, petroleum displacement, and greenhouse gas (GHG) emissions emitted during the production life-cycle of corn grain, corn stover, and switchgrass-based ethanol. Debate over these impacts continues today as previous LCA analysis treated the system as if it were in steady-state, not taking into account natural variations in system inputs. For example, previous studies have taken an average fertilizer application rate to characterize the entire industry, rather than a range of possible values which more accurately represents the variability that occurs from farm to farm. Unlike previous LCA's, this study incorporates a Monte Carlo approach to include the variability of each system input. This results in a range of probable outcomes for the fossil energy consumption and GHG emissions of the entire system. These results are then compared to previous single valued results, as a way to validate the model and to determine the probability that previous results will occur. A review of previous studies, in section 1.3, highlights the main differences between previous analyses and demonstrates why a Monte Carlo analysis incorporated within a LCA more accurately characterizes the system.

In addition to environmental impact, this analysis assesses the potential scale that ethanol production could attain if produced from corn grain, corn stover, and switchgrass. The scale of production is assessed for today and into the future assuming certain economic and technological advances. This analysis pinpoints the constraints that can limit the production scale in the short-term and that can ultimately limit the scale of production of the entire system in the long-term. Estimating the scale of ethanol production allows us to determine the potential future impact ethanol may have on displacing petroleum consumption and improving light-duty vehicle GHG emissions.

Review of Previous Corn Grain Ethanol Life-Cycle Assessments

Many studies over the past decade have attempted to answer the question of whether bioethanol production results in a net energy gain and reduced GHG emissions when compared to gasoline. The net energy of this production system is defined as the energy content of ethanol minus the fossil energy consumed during its production. The system boundary defined for corn grain ethanol production includes corn grain production, corn grain transport, and ethanol production.

This section will discuss the approach, conclusions, and differences of previous life-cycle assessments. Previous studies have preformed LCA's based on single value inputs, which result in a single valued output that has lead to both positive and negative results. This section will demonstrate that even when system boundaries and assumptions are uniform one still needs to account for the systems inherent variability within the agricultural, ethanol processing, and technological sectors. While reviewing previous published work, the following discussion will address the following questions:

1) What are the major differences between the main corn grain ethanol studies?
2) How do these differences affect the final results and conclusions of these studies?
3) What additional benefits does incorporating a Monte Carlo analysis within a LCA provide?

Four studies were compared in this analysis. They were chosen for their availability, publication date, and the accessibility of their system input values.

1) Wang, M. (1999) *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions* (Argonne National Laboratory, IL) [11].
2) Shapouri, H., Duffield, J. A. & Wang, M. (2002) *The Energy Balance of Corn Ethanol: An Update.* USDA Study [12]
3) Pimentel (2003), *Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative* [13]
4) Farrell, A. E., Plevin, R. J., Turner, B. T. & Jones, A. D. *Ethanol Can Contribute to Energy and Environmental Goals,* (2006) *Science* **311,** 506-508 [14].

All of these studies conducted a life-cycle analysis including corn grain farm inputs, the transport of corn grains to an ethanol facility, and the ethanol conversion facility. Our analysis was done applying the lower heating value (LHV) of different fuels and therefore any study that was based on the higher heating value (HHV) of fuels has been adjusted. The heating value of a fuel is defined as the amount of heat released during the combustion of a fuel [6]. The main difference between these studies was the system boundary definition. The system boundary is a selected boundary that defines which energy inputs are included and excluded from the life-cycle analysis.

Figure 1-3 is a bar graph of the total energy input included for each of the four studies. Each studies inputs were categorized by the three main sectors; corn grain production, corn transport, and ethanol production. Each study encompasses different inputs for each of the three categories which are expanded and discussed in Figure 1-3.

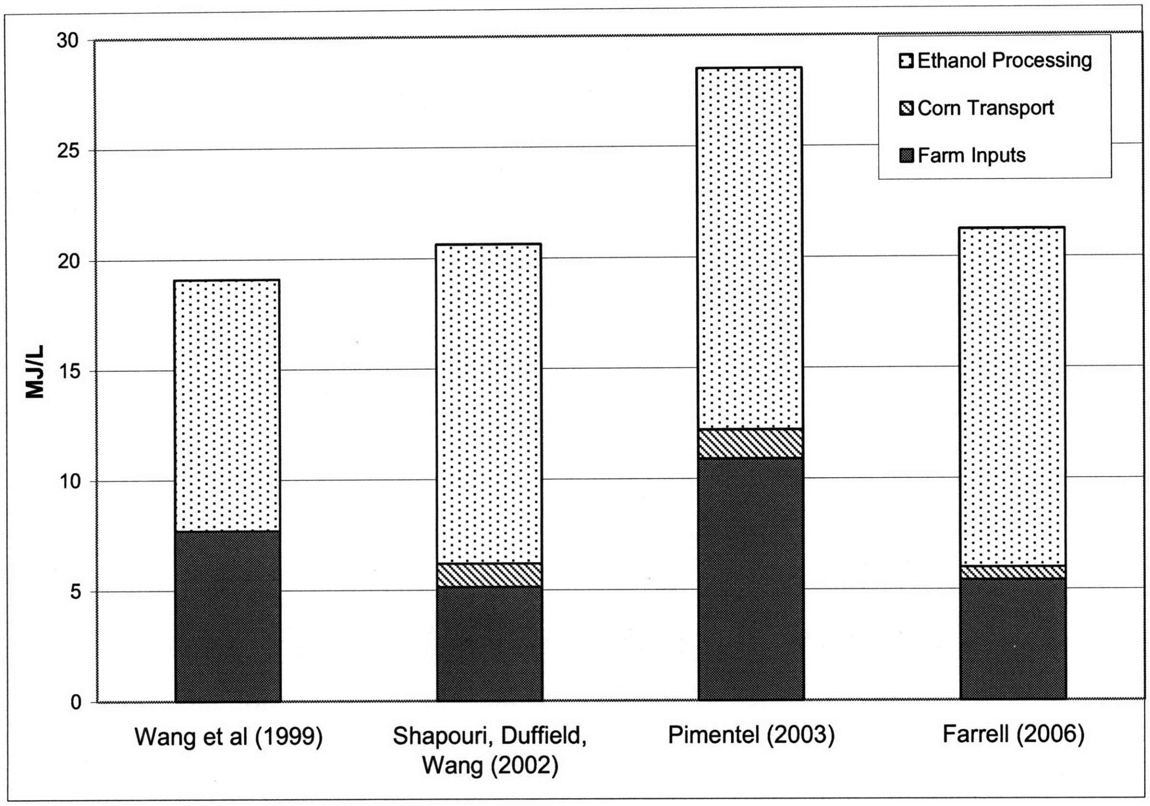

Figure 1- 3 - Total Corn Grain Ethanol Life-Cycle Production Energy Use. These results are presented with no coproduct credits ([11-14]

There are two main reasons these studies vary. First, is the definition of the system boundary, which is different for each of these studies. Secondly, the values chosen for input variables vary depending on source, date, and geographic location. Comparing across studies without modification, Pimentel is approximately 40% higher in estimating the total energy input to produce a liter of ethanol compared to the other studies. This is due to Pimentel's assumptions and system boundary choices. Figure 1-4 demonstrates this through a break down of all farm inputs included in each study. The study by Wang et al (1999) did not have a break down for specific farm inputs, but instead used one value to represent farm inputs due to farm machine energy use and chemical use; this is represented by the light yellow category "Wang Other". From Figure 1-4 the majority of the farm energy is in two main categories: fertilizer production and use (mainly nitrogen fertilizer) and farm machinery energy use, which is comprised of diesel fuel, gasoline, liquid propane gas, natural gas, and electricity (Figure 1-4).

When comparing across studies, Pimentel's farm inputs are approximately 80% higher than the other studies. This is mainly due to his assumptions in the system boundary and system input values.

Pimentel includes additional farm inputs such as the embodied energy in farm machinery and labor, which accounts for 16% of his total farm value.[3] Another major difference is that Pimentel also includes the energy to construct an ethanol facility, along with the energy it takes to extract, manufacture, and transport the construction plant materials. These types of inputs are excluded from the other studies as they are said to be difficult to estimate and minimal due to the long life span of these machines and facilities. Pimentel also uses higher input values for the energy used in fertilizer production and fertilizer application rates. These major differences in both the system boundary and data values are the main reasons Pimentel's study gives different results.

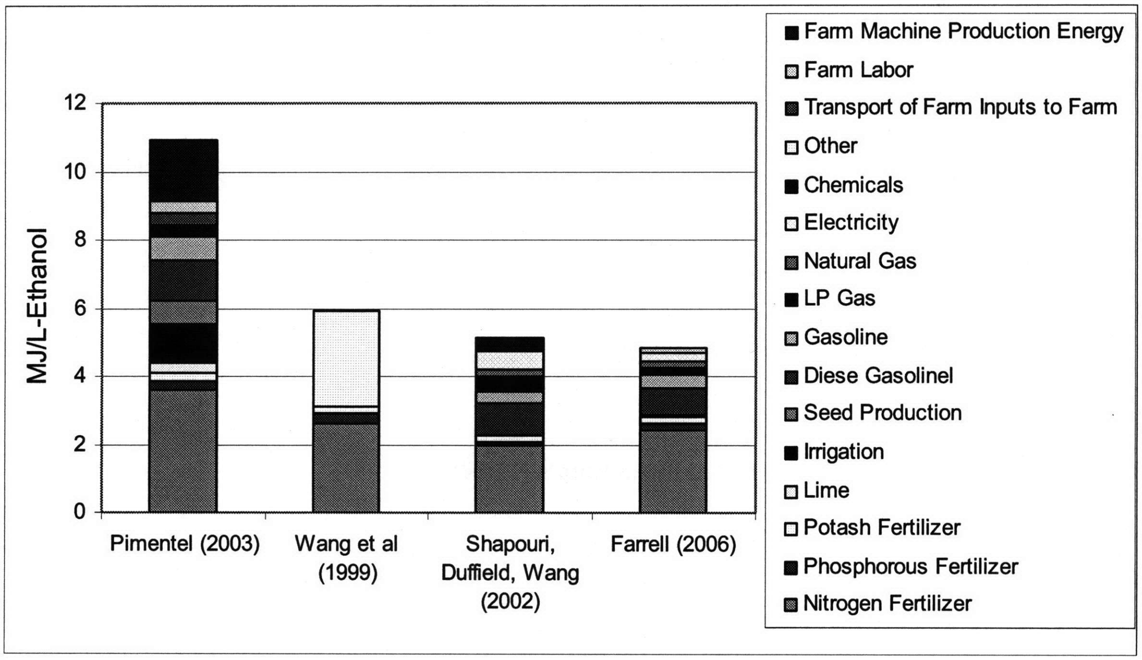

Figure 1- 4 – Corn Grain Agricultural Production Inputs [11-14]

Figure 1-5 compares only farm fossil energy inputs that were included in all studies to equalize system boundaries. This makes it possible to examine how values for a specific input vary between studies and the impact this has. The study by Wang et al (1999) is

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[3] Pimentel assumes an average person works 2,000 hrs per year and utilizes an average of 8,000 liters of oil equivalents per year

excluded since the numbers that were provided by Wang were not separated into the same categories as the other authors. When applying a uniform farm system boundary there is still a 30% difference between Pimentel and the two other studies. Comparing within specific categories there are obvious differences in input values. For example Pimentel's nitrogen fertilizer inputs is 45% higher than the Shapouri study. Farm fuel energy is highest in the Shapouri study, which is 20% higher than the lowest value, which is in Pimentel's analysis. All studies have values for corn seed production energy but only Pimentel's is large enough to see on the graph.

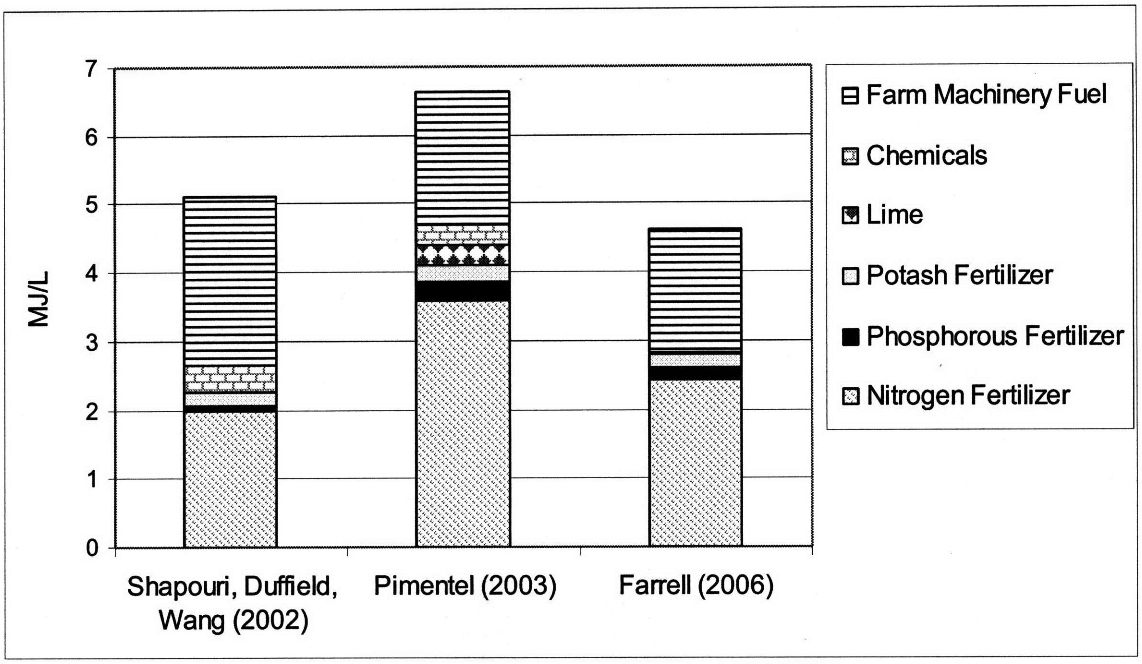

Figure 1- 5 – Uniform Corn Grain Agricultural Inputs [12-14]

Figure 1-6 represents the total system fossil energy consumption per liter of ethanol produced of all four studies with a uniform system boundary, without coproduct credits. Coproduct credits represent the assignment of an energy credit from the production of ethanol coproducts, such as distiller's grains, to improve ethanol's net energy balance. The dashed lines represent the total energy into the system once the assumed studies coproduct credits are taken into account. Even before considering the effects of energy credits due to coproduct production, Shapouri and Farrell show a moderate net positive energy gain, based on an ethanol LHV of 21.2 MJ/L. When the coproduct credit assumption is included, Pimentel's net energy value breaks even while the other three studies both result in a net energy gain.

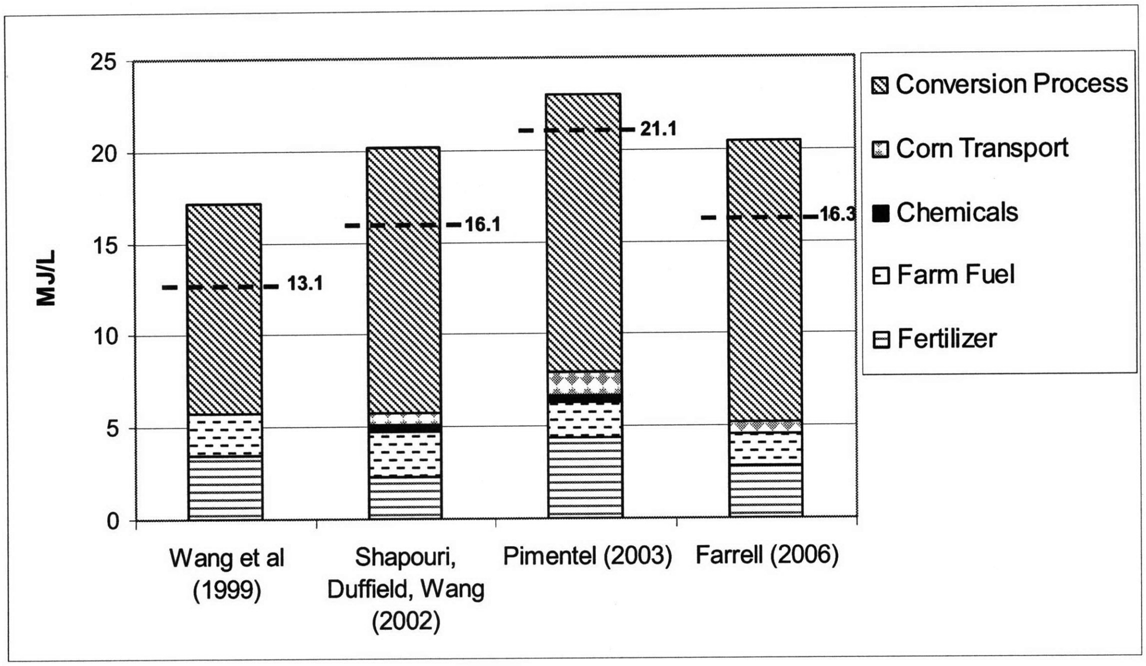

Figure 1- 6 – Total Corn Grain Ethanol Production Energy Consumption (Uniform System Boundary's) [11-14]

Even when uniform system boundaries and assumptions are applied, there are still differences in previously published results. This is due in part to the system variability found within the agricultural and ethanol processing as well as the input data used in individual studies, all of which comes from a wide range of sources. The range of possible values within agricultural inputs is created by seasonal effects, soil characteristics and geographic locations. Even when comparing across ethanol facilities, there are differences in fuel use type, fossil fuel consumption amounts, and ethanol conversion efficiencies. Historically within LCA's, a single value was used to represent each input. This approach would miss the variability in the input data itself. This has resulted in what was just seen; single valued results that range in value leading to different conclusions. This study's approach differs in that it utilizes a LCA approach that includes a Monte Carlo simulation assessment. Rather than a single value, each system input is represented by a probability density function (PDF) or a range or probably values. This produces a probability density function (PDF) that represents a range of outcomes for the ethanol production systems fossil energy consumption and GHG emissions. This range of outcomes, rather than the single-value results enables us to account for the system's variability which provides new insights to the ongoing debate over ethanol's fossil energy use and GHG reduction benefits. This method is also applied to cellulosic ethanol production. Here uncertainty in inputs is even higher since cellulosic ethanol production processes have yet to be commercialized. A complete description of this study's scope, methodology, and limitations is given in Chapter 2.

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Chapter 2: Thesis Scope & Methodology

Overall Project Goal and Scope

The goal of this research is to determine the fossil energy, GHG emissions, and petroleum displacement impacts of ethanol production from three feedstocks; corn grain, corn stover, and switchgrass. Additionally, this study assesses the biomass availability and scalability of ethanol produced from these three biomass sources. Models were created to evaluate these impacts and the scale of ethanol production in the near and long-term given the potential for economic and technological advances. Corn grain ethanol was chosen to represent current day ethanol conversion practice as well as a benchmark for comparing other feedstocks. Agricultural residues are seen as the first feedstocks to be utilized for cellulosic ethanol production. Corn stover was chosen as an example of an agricultural residue that has the greatest potential for being the first major cellulosic ethanol feedstock. A major reason for this is its abundance within the Corn Belt where ethanol production facilities and distribution networks are already located. Companies like POET, formally known as Broin, provide an example of a corn grain ethanol facility expanding production to second generation biofuels [1]. POET is co-locating their pilot cellulosic facility with their corn grain ethanol plants to utilize corn stover, a local feedstock [1]. Crops dedicated to energy production, known as energy crops, have also been cited as a longer-term option for biofuels production. In this study, switchgrass is analyzed as an example of an energy crop. It was chosen as it was sighted as an optimal bioenergy crop by the Biomass Development Feedstock Program [2]. The attractiveness of an energy crop like switchgrass is that it can be grown in a wide range of climates and soil conditions. Therefore, unlike corn grain or stover that is concentrated in the Corn Belt, switchgrass can be grown in variety of regions within the country, providing a more decentralized biorefinery and distribution network.

To assess the environmental impacts of these different bioethanol pathways, a life-cycle assessment (LCA) or cradle-to-grave analysis was conducted for each of these three bioethanol systems; corn grain ethanol, corn stover ethanol, and switchgrass ethanol. The environmental impacts evaluated are the current and long-term fossil energy consumption, GHG emissions, petroleum displacement, and land use impacts of producing ethanol from these three biomass sources. The scale of ethanol production is also assessed for each of these three feedstocks. The short and long term impact of a growing and evolving ethanol industry is evaluated based on current and future projections of inputs such as agricultural requirements, biomass productivity, and ethanol conversion yields. These projections can provide insight into which bioethanol production pathways have the greatest scalable potential and which have minimal environmental impacts.

This thesis is divided into three main analysis sections that are discussed further in the following sections. The first is the LCA of bioethanol from corn grains, corn stover, and switchgrass, which is discussed in Chapters 3, 4, and 5. The second section is the scalability of each of these bioethanol pathways, which is discussed in Chapter 6. The final section is in Chapter 7, which applies the LCA and ethanol scale of production results to assessing the feasibility and environmental impact of the new 2008 Renewable Fuels Standard (RFS), which increased the alternative fuels production standard from 28 billion liters to 136 billion liters by 2022 [3].

Life-Cycle Assessment Methodology and Scope; Focus of Chapters 3,4,5

The environmental impacts of bioethanol production have been debated since before the 1980s. Previous corn and cellulosic life-cycle assessments have resulted in differing conclusions over the fossil energy consumption and environmental benefits of bioethanol. The disparity between prior studies is mainly caused by differences in system boundary choices, data choices, and system input value variability. The system boundary defines which fossil fuel inputs in the life-cycle are included or excluded from the analysis.

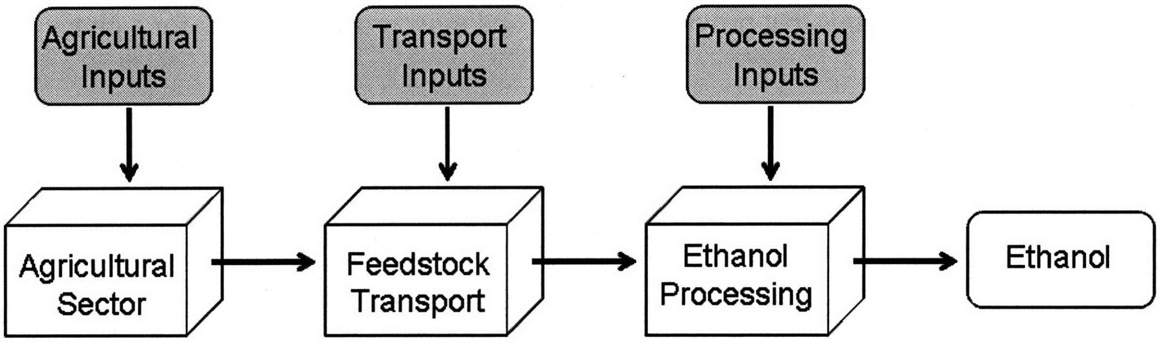

Figure 2- 1 –LCA System Boundary of Bioethanol - Each sector is discussed in detail in chapters 3 & 4.

The system boundary evaluated for all LCA scenarios in this analysis includes the growing of biomass within the agricultural sector, biomass transport from the farm to the ethanol facility, and ethanol processing. Data choice disparities come from acquiring data across different sources, different time frames, and different geographic regions. Even when system boundaries and data sources are equivalent, the system itself still has variability as it is not in steady state. System inputs, such as fertilizer application rates, farm fuel use, biomass yield, and ethanol conversion rates vary by year and location. Previous studies have not been able to capture this inherent system variability as they have used a single value to characterize each input variable. This approach has resulted in a wide range of single valued results that often lead to varying conclusions. Therefore, to incorporate this type of natural system variability, this study utilizes a LCA model that incorporates a Monte Carlo simulation approach.

Monte Carlo simulation uses an iterative problem solving technique to analyze uncertainty propagation [4]. This helps determine how probable an output is: in other words what the reliability of the calculated value is [4]. The Monte Carlo method is categorized as a sampling method, because the inputs are randomly generated from probability density functions [4]. Input variability is captured in a probability density function (PDF), which represents the probabilistic range of values an input can have [4]. The model then runs through a given number of trials where multiple results are generated for each output. The final results can then be presented as probability distributions or histograms that provide the range and most probable values for a given output [4].

To model these systems, a LCA software program called Umberto was used. Umberto is a tool that enables the modeler to visualize the material and energy flows throughout the system [5]. LCA scenario-specific data is discussed in Chapters 3 and 4. The LCA scenarios were both modeled and evaluated in Umberto using the Monte Carlo simulation tool embedded within the program. Each Monte Carlo simulation ran through 2000 iterations. Results were then exported from Umberto to Excel where further data analysis was preformed. A sensitivity analysis determined that the defined values for three inputs; nitrogen application rates, ethanol conversion rate, and ethanol facility fossil energy consumption values, affected the reported results the greatest. Different PDFs were then assumed for these key system input variables to determine the sensitivity of the results to varying types of PDFs. Varying key input PDFs resulted in a difference of less than 2% of reported fossil energy use and greenhouse gas (GHG) emissions. Therefore, normal distributions were assumed for all inputs defined by the inputs average and standard deviation from a given data set. Unlike previous studies, this LCA approach results in a probabilistic distribution for the fossil energy consumption, GHG emissions, and land use impacts rather than a single point. This distribution of outcomes was then used as a comparison between previously stated single point values to provide new insights to the ongoing debate around ethanol's fossil energy use and GHG reduction potential as an alternative fuel.

To assess these different bioethanol production pathways, metrics such as the net energy value (NEV), GHG emissions, and land use efficiency (L/ha) are used. The net energy value is used to determine if more fossil energy is consumed during the production of a biofuel than is produced by the biofuel itself. The NEV is often used to evaluate the energy benefits of ethanol production. NEV is defined as

$$NEV(MJ / L_{Ethanol}) = Output\ Energy\,(MJ / L_{Ethanol}) - \sum_{i=1}^{n} Fossil\ Input\ Energy_i\,(MJ_{Fossil\ Fuel} / L_{Ethanol}) \qquad (2-1)$$

The *Output Energy* is defined as the lower heating value of ethanol, 21.2 MJ/L. Within the LCA of bioethanol the idea of coproduct credits are often discussed and debated. Coproduct credits are the assignment or allocation of an energy and/or GHG credit for the co-production and selling of another product from the same energy input. Examples of coproducts are dried distiller's grains with solubles (DDGS), an animal feed produced during corn grain ethanol production, and electricity sold to the grid produced from the burning of lignin. DDGS is the remaining mass that is sold after corn grains are fermented and the ethanol is distilled. Lignin is the remaining mass after cellulosic ethanol is produced, that can be burned to provide process heat and electricity for the ethanol facility. Electricity produced in excess can be sold to the grid, making it a coproduct to cellulosic ethanol production. There are a variety of methods to assess the coproduct credit amount that can be taken to reduce the total amount of energy consumption and GHG emissions attributed to ethanol production. Methods such as process energy, market value, energy displacement, and weight have been used to assess this credit. If coproducts are considered then the *Output Energy* in equation 2-1 is expressed as:

$$Output\ Energy\,(MJ\,/\,L_{Ethanol}) = Ethanol\ \ LHV\,(MJ\,/\,L_{Ethanol}) + Coproduct\ \ (MJ_{Fossil}\,/\,L_{Ethanol}) \qquad (2-2)$$

Greenhouse gas (GHG) emissions were calculated for all considered fossil energy flows within the system boundary. 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[4] [7]. Fossil fuel emission factors were taken from the DOE and EIA [8]. Soil nitrous oxide emissions associated with nitrogen fertilizer use were included within the GHG calculation as recommended by the IPCC [9]. Photosynthetic carbon in ethanol is excluded from this study as carbon dioxide released during ethanol combustion is assumed to be absorbed from the atmosphere during photosynthesis during the re-growth of the feedstock [10].

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[4] Global warming potential is a measure of how much a given mass of greenhouse gas is estimated to contribute to global warming 6. (EIA), E.I.A., *Updated State-level Greenhouse Gas Emission Coefficient for Electricity Generation 1998-2000*, ed. DOE. 2002.

GHG emissions associated with bioethanol processing are based on fossil fuel type and purchased electricity. To determine the total fossil fuel energy use and GHG emissions associated with purchased electricity the EIA recommended US electricity emission factors for the year 2000 and an 8% transmission loss were applied [6, 11]. No energy or GHG credit was given for additional electricity that may be sold to the grid during cellulosic ethanol production as this depends on the design of the facility.

The main starch and cellulosic ethanol production pathways modeled and evaluated are *Corn Grain Ethanol, Corn Stover Ethanol*, and *Switchgrass Ethanol*. Within each pathway there are additional scenarios that are analyzed to evaluate how different aspects of the system affect the results. For example, scenarios that represent different geographic regions or alternative uses of coproduct credits are considered as well. These three main scenarios are then projected into the future some 20 years to evaluate how improving aspects of the system can impact future fossil energy consumption and GHG emissions.

Below is a description of the life-cycle scenarios that were modeled and assessed for ethanol produced from corn grain, corn stover, and switchgrass. A complete description of the LCA scenarios are discussed in their respective chapters. State specific studies are evaluated to demonstrate the importance and affect that geographic location can have on the impacts being evaluated.

Corn Grain Ethanol (Chapter 3)

- **Iowa Corn Grain Ethanol** – This scenario looks at corn grain ethanol production in Iowa. Agriculture characteristics of Iowa are used to represent a corn grain ethanol scenario from a high corn yield state from the Corn Belt. This scenario is intended to represent the most efficient option as Iowa is the state with the highest average corn yield [12]. No coproducts are assumed for this scenario.

- **Georgia Corn Grain Ethanol** – Corn grown in Georgia was analyzed to illustrate the affect of growing corn for ethanol production in a traditionally low corn producing state outside the Corn Belt. This scenario was chosen to demonstrate the affects of using different geographic regions for corn production. Understanding this will become increasingly important as the entire ethanol system expands and new lands are utilized for corn production. In this scenario it is also assumed that the corn produced would be shipped to an ethanol conversion facility in the Corn Belt initially. In the future, if enough of the feedstock was locally available, a facility could be built closer to the feedstock. No coproducts are assumed for this scenario.

- **Iowa Corn Grain Ethanol Plus A <u>20%</u> Coproduct Credit** – This scenario adds onto the *Iowa Corn Grain Ethanol* scenario by incorporating the assumption that a "credit" should be given for the sale of dried distillers grains with solubles. A 20% to 40% coproduct credit range has been used in the literature [13]. This means that 20%-40% of the process energy and thus GHG emissions are not counted for in the final result. This scenario assumes a 20% coproduct credit to show how this assumption affects the energy and GHG emission results.

- **Iowa Corn Grain Ethanol Plus DDGS** – This scenario looks at corn grain ethanol production in Iowa and considers the use of DDGS as a facility fuel source rather than selling it as an animal feed. Burning the DDGS can be used as a fuel source to offset an ethanol facilities natural gas and electricity consumption [14]. Currently, DDGS is sold within the animal feed market resulting in a second economic source for the ethanol facility. A variety of changes to the system may make the use of this product as a fuel source more economical. For example, under high natural gas prices or a low DDGS market price, DDGS could be burned to offset facility fuel costs [14]. DDGS may also be used a fuel source, if facility sites expand to regions where there either is no animal feed market or the transport costs are too high to ship DDGS to market. In this scenario, burning DDGS would offset the total corn grain ethanol fossil energy use and GHG emissions [14].

- **Iowa Coal Powered Corn Grain Ethanol** – Facing high natural gas prices, some ethanol conversion facilities are being approved that utilize coal as their fuel source.

This scenario considers corn grain ethanol produced in Iowa by a coal powered, rather than natural gas powered, ethanol conversion facility. This scenario was developed to look at the fossil energy and GHG impact of producing corn grain ethanol when the conversion facility utilizes coal instead of natural gas for its energy needs. No coproducts are assumed for this scenario.

- **2025 Iowa Corn Grain Ethanol** – This scenario projects the Iowa Corn Grain Ethanol scenario to the year 2025 to evaluate the potential future system NEV and GHG emissions. This scenario is used to identify which aspects of the system, if improved could reduce the overall fossil energy consumption and GHG emissions the greatest. Iowa historic agricultural data is used to project each input into the future some 20 years. No coproducts are assumed for this scenario.

Corn Stover Ethanol (Chapter 5)

- **Corn Stover Ethanol** – This scenario looks at ethanol produced from corn stover. The location of the stover is assumed to be within a 50 mile radius of an ethanol conversion facility. The agricultural inputs to produce the corn are traditionally allocated to the grains and not the stover, as stover is a residue of corn production [15]. A laboratory demonstrated cellulosic ethanol conversion rate of 67% (238L/dry ton) is assumed [16]. In practice initially this value would be lower. Corn stover LCA results from a MIT PhD thesis by Jeremy Johnson will be used [15]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design.

- **2025 Corn Stover Ethanol** – This scenario projects corn stover ethanol production into the future some 20 years. The main assumption that changes in this scenario is the cellulosic feedstock to ethanol conversion efficiency rate, which improves from 67% to 90% (328L/dry ton) [16]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [16].

Switchgrass Ethanol (Chapter 5)

- **Alabama Switchgrass Ethanol** – This scenario examines the use of Alamo switchgrass as a bioenergy crop. This scenario considers switchgrass that would be grown in Alabama, as an example of a high biomass yield state. Through previous experimental field testing, Alabama has been shown to have the potential of producing high switchgrass yields [17]. As in the corn stover scenarios, the location of switchgrass is assumed to be within a 50 mile radius of a conversion facility. Currently, demonstrated cellulosic ethanol conversion yields of 67% (238L/dry ton) are assumed [16]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [16].

- **Iowa Switchgrass Ethanol** – This scenario represents Cave-In-Rock switchgrass produced in Iowa. This state was chosen to evaluate whether geographic variation affects the systems fossil energy consumption and GHG emissions. The location of switchgrass is assumed to be within a 50 mile radius of a conversion facility due to economic constraints. Currently, demonstrated cellulosic ethanol conversion yields of 67% (238L/dry ton) are assumed [16]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [16].

- **2025 Alabama Switchgrass Ethanol** – This scenario projects Alabama switchgrass grown in Alabama into the future some 20 years. The location of switchgrass is assumed to be within a 50 mile radius of a conversion facility. This scenario examines the systems fossil energy consumption and GHG emission impacts of improved system inputs such as biomass yield and ethanol conversion efficiency. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [16].

Scalability of Ethanol Production; Focus of Chapter 6

To determine the impact that ethanol can have at displacing petroleum and reducing GHG emissions, the long term potential scale of production is evaluated. This study assesses the potential scale of ethanol production from three different feedstocks; corn grains, corn stover; and switchgrass. For each feedstock option six factors were assessed that were determined to affect scale: land availability, technological feasibility, economic viability, development and synergy of industries, policy, and environmental impact. Each of these factors is discussed in detail for each bioethanol production option to identify the main barriers that will need to be overcome to increase biomass availability and ethanol production. Below are brief descriptions of each of the six factors:

- **Land Availability** – Land availability to either grow traditional and/or bioenergy crops, as well as harvesting agricultural residues will limit the scale at which domestic ethanol production can grow. Current US agricultural land and land within the USDA's Conservation Reserve Program (CRP) is considered as potential site for agricultural residue removal and bioenergy crop production. CRP land, today estimate at 14.6 billion hectares (36 billion acres), is degraded agricultural land that has been taken out of production for environmental reasons or due to its low productivity. This analysis, under a defined set of criteria, examines the potential biomass production from CRP land.

- **Technological Feasibility** – This relates to the technological challenges that need to be overcome throughout bioethanol's life-cycle. For example, within the agricultural sector biomass yields, crop management practices, and biomass collection techniques need to be improved. Additionally, biomass storage needs to be developed along with increased cellulosic ethanol conversion rates.

- **Economic Viability** – This discusses which factors affect the economic competitiveness of bioethanol relative to gasoline. Factors such as oil and ethanol prices, feedstock and transport costs, cellulosic ethanol facility costs, and ethanol distribution costs are discussed.

- **Development & Synergy of Industries** – This addresses how the need for initial and further development of the key industries affect both further scale-up of corn grain ethanol production and the need to create cellulosic ethanol production industry. Industries that need to be either further developed or created include: farmers, biomass transport infrastructure, biomass storage facilities, cellulosic ethanol facilities, and ethanol distribution infrastructure. Within the corn grain ethanol industry, development mainly relates to ethanol distribution bottlenecks as the feedstock and conversion facilities are already developed. Within the cellulosic ethanol industry this relates to all aspects of development such as, feedstock availability and certainty of a cellulosic market, biomass transport, storage, facility development, and ect.

- **Policy** – This relates to the policy role that national and state governments play in both initiating and motivating the increase in bioethanol production from both starch and cellulosic sources. Particularly this study assess the feasibility of the new 2007-2008 H.R. 6 RFS that increased alternative fuel production targets from 28 billion liters to 136 billion liters [3].

- **Environmental Impact** – This assesses the fossil energy consumption and GHG emissions as the scale of ethanol production increases from each of the three biomass sources. It also considers the most effective use of land for biofuels production by examining the land use efficiency, defined as the liters of ethanol produced for hectare of land. Additionally, other environmental impacts such as soil erosion and ground water use are discussed as potential barriers to increased bioethanol production.

The potential scale of corn grain ethanol is based on the *USDA Agricultural Projections to 2016 Baseline [18].* This report projects corn grain acreage and production to the year 2016 and discusses its production and economic impacts on other crops. It was also assumed that in the future, corn grain ethanol conversion efficiencies would only incrementally increase as this is a mature technology. The scale of ethanol produced from corn stover is directly related to corn grain production as an agricultural residue. Therefore, ethanol produced from corn stover is also dependent on *USDA Agricultural Projections to 2016 Baseline [18].*

Ethanol produced from switchgrass is dependent on the availability of land and its productivity. As there is currently not a market for switchgrass, a modeled called POLYSYS was used to assess switchgrass production from agricultural land based on net returns to the farmer and feedstock farm gate price. POLYSYS is an agricultural policy simulation model developed by the USDA, ORNL, and the University of Tennessee [19, 20]. POLYSYS includes the eight major crops (corn, grain, sorghum, oats, barley, wheat, soybeans, cotton, and rice), and a livestock sector (beef, pork, lamb and mutton, broilers, turkeys, eggs, and milk). The model was modified to also include hay and pasture land [19, 20]. POLYSYS runs on a ten year time frame and is based on the *USDA Agricultural Projections to 2016 Baseline.* Within POLYSYS, the United States is divided into 305 agricultural districts that do not cross state lines. Switchgrass growing characteristics, yields, and costs were added to the model to determine where in and what amounts agricultural crop land would shift from current production given various switchgrass farm gate prices. A constraint of the model is that food and export demands as defined by the USDA 2006 baseline still need to be met.

When the model starts, switchgrass is introduced as an option to farmers with a user defined farm gate price. The farmer's decision to change from their current cropping practice to growing switchgrass is based on the net returns to the farmer, or in other words the farmer's profit. The net return depends on factors such as farm gate price and cost of production.

For a given farm gate price, POLYSYS delivers yearly district-specific data on the amount of land in production for each crop, its productivity, and how their market price changes over the ten years. This data is then exported and analyzed by Excel. Overall switchgrass production as calculated by POLYSYS can then be used to determine the amount of ethanol produced at today's and future conversion rates. The amount of switchgrass produced and thus ethanol production ultimately depends on the farm gate price. As the farm gate price increases, so does the amount of land shifting from current agricultural practices to switchgrass production. The maximum farm gate price is limited by the economics of the cellulosic ethanol facility that would be purchasing the feedstock. Therefore, to determine the appropriate farm gate price range that should be analyzed, the minimum and maximum expected farm gate price is discussed. This study also looks at where geographically traditional agricultural land shifts to switchgrass production. This provides insight as to where a cellulosic industry based on switchgrass might be located.

While POLYSYS is used to analyze the potential for switchgrass production on current agricultural land, switchgrass can also be grown on degraded land in the Conservation Reserve Program (CRP). CRP land is often sited as land that is potentially available for switchgrass production [21]. To consider this option, this study also examines the scale of production that could be obtained from switchgrass grown on CRP land.

Currently, there is 36 million acres enrolled in CRP [21]. Land is enrolled within 3 potential areas within CRP; general sign-up, continuous sign-up, and farmable wetlands [21].

Definition of CRP Sign-up Categories [21]
General – Landowners and operators apply for acceptance based on an environmental benefits index (EBI) during specific enrollment periods.

Continuous – Landowners and operators may enroll certain high priority conservation practices and/or to address specific environmental objectives.

Farmable Wetlands – Landowners and operators can apply to enroll small non-flood plain wetlands

This analysis does not consider utilizing land enrolled in the continuous and farmable wetland sign-up category for switchgrass production as the environmental reasons for CRP enrollment are too grave. This analysis considers three different scenarios for utilizing general sign-up CRP land for switchgrass production.

- **Switchgrass Production Based on General Sign-Up** – This considers growing switchgrass on all of the land within the general sign up category. Ethanol production is calculated based on switchgrass biomass yields representing current potential yields of 3 dry tons/acre and future potential yields of 6 dry tons per acre.

- **Switchgrass Production Based On Erodibility Index (EI)** – Often land is enrolled within CRP for erosion control purposes. Switchgrass, due to its large rooting system, is a crop that is often used to decrease erosion. Therefore, this scenario considers switchgrass production on land enrolled within general sign-ups with an EI between 1 and 8, and a EI between 1 and 15 [21]. Land that is enrolled with an EI greater than 15 should not be used for crop production due to the environmental damage that can be caused. For an EI between one and eight, 2.7 million acres are available for switchgrass production. For an EI between eight and fifteen, 361,102 acres are potentially available for switchgrass production.

- **Switchgrass Production Based On Conservation Practice** – Land is enrolled within in CRP based on 33 conservation practice categories. This scenario determines the approximate amount of CRP land that can be utilized for switchgrass production based on these conservation practice categories within the general sign-ups. Conservation categories considered applicable to switching to switchgrass production are labeled as "grasses". Land that is categorized as trees, wetlands, buffers, and erosion control are not included. This results in 25 million acres that could potentially be used for switchgrass production [21].

Feasibility and Impact of the New Renewable Fuels Bill, 136 Billion Liters (36 Billion Gallons) by 2022; Focus of Chapter 7

In December of 2007, a new renewable fuels standard was passed that increased the alternative fuels production target from 28 billion liters to 136 billion liters by 2022 [3, 22, 23]. In the nearer term, ethanol is seen as one of the more viable options for achieving this goal given current production scale and future capacity investment. Other alternative fuels, such as biodiesel, gas-to-liquids, and tar sands may also play a role. To assess the feasibility and environmental impact of achieving this standard of 136 billion liters by 2022 the results and conclusions from the bioethanol life-cycle assessment models and the evaluation of ethanol's scale of production were applied. This assessment will also identify the main areas where advances would have the greatest impact at achieving this production level target.

Thesis Limitations

This study covers a range of feedstock options, conversion technologies, and system scenarios to evaluate the impact of various potential bioethanol pathways. While this study spans a range of topics and issues there are still limitations to the scope and depth to which this study can go. The following are the main limitations of this research:

1. **Feedstock Crop Selection** - Though this study analyzes three potential feedstocks (corn grain, corn stover, and switchgrass), it recognizes that there are numerous agricultural residue and potential woody and herbaceous crop options [2]. This study chose three biomass sources to represent the current practice, and two potential cellulosic feedstocks. Other crops such as wheat residue, willows,

poplars, and miscantus, have been cited as additional bioenergy crops that could also be used for biofuels production [2].

2. **Feedstock Use In Biofuels Production**– Biomass is scene as an opportunity to diversify the transportation fuel mix to reduce national dependence on a foreign oil imports, and decrease GHG emissions to combat global warming. While biomass could also be used as a fuel source for electricity generation, the power sector already utilizes other renewable options such as, hydropower, solar, and wind. Biomass can be converted to liquid fuel either through a Fisher Tropshe process or processed biochemically. This research only considers the biochemical conversion of biomass to ethanol, as that is current industry standard and Fisher Tropshe is often not economically competitive.

3. **Ethanol As A Biofuel** – This study only considers the production of ethanol as the biofuel option produced from these biomass sources. While other biofuel options, such as butanol (butyl alcohol) and biodiesel, might be produced from biomass and may have superior properties for transporting and blending, this research only considers ethanol. Ethanol is seen as a biofuel option that is readily available due to its existing infrastructure and easily scalable in the short term as it is a mature technology.

4. **System Boundary** – The system boundary considered includes three main sectors; agriculture, biomass transport, and ethanol processing. The system boundary for this analysis is more specifically defined in each of the respective chapters based on feedstock choice. The embodied energy in machinery or building infrastructure was not included as their long life-times minimize their impact on the overall energy consumption [24]. The embodied energy is the fossil energy consumed during the manufacturing of machinery and building infrastructure.

5. **Environmental Impacts Considered** – For each LCA and bioethanol scale of production scenario the environmental impact was determined. The unit of measures that define the environmental impact is the fossil energy consumption (MJ/L), GHG emissions (gCO_2-equ/MJ), and land use efficiency (L/ha). Only fossil energy was considered when accounting for energy needed during the production life-cycle of corn grain and cellulosic ethanol. Therefore, the contribution of solar energy during feedstock production was not included. The GHG's considered are carbon dioxide, methane, and nitrous oxide. Carbon sequestered in biomass left on the field after cultivation was also not included as a sink in GHG calculations. The GHG impact to land use changes were also not included within this analysis.

   Large-scale agricultural and ethanol production potentially consume large amounts of water and affect the local soil and water body conditions. While these environmental impacts are important and need to be analyzed especially as the scale of production increases, they were not analyzed in this research. These conditions are often farm plot specific and require detailed water resource knowledge, as well as appropriate soil and nutrient models which are beyond the scope of this project.

6. **Scale Of Ethanol** – This analysis only considers ethanol produced from corn grains, corn stover, and switchgrass. The projected scale of ethanol produced can be increased if one includes additional agricultural residues, such as wheat straw, forest waste, and other potential energy crops. Additionally, this study only considered switchgrass produced in a market environment that did not have an agricultural subsidy. If a subsidy is applied in the future, it could increase the number of acres shifted into production, thereby increasing the amount of switchgrass produced and thus total ethanol production.

7. **Economics** – It was outside the scope of this study to perform a detailed economic analysis of ethanol produced from each of these three feedstocks. This

study recognizes that the economics of the system are critical to determining which biofuel pathway will be pursued and optimized. Future work focused on this aspect would greatly complement and add to this analysis.

8. **Data Availability** – The results of this study are dependent on the availability and accuracy of the data used. For corn grain ethanol, corn production data collected from the USDA Economic Research Service (ERS) database was available in detail. For switchgrass production a national data base on yield and agricultural inputs is not available. Therefore, data from journals and reports was collected and used. This data had a wide range in inputs and yield values. Though this variation was captured in the model, the results reflect the high level of uncertainty in switchgrass system inputs. In the future, as increased amounts of switchgrass data become available, an updated analysis should be performed.

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Chapter 3: Corn Grain Ethanol Life-Cycle Assessment

Currently in the United States, ethanol is primarily produced from corn grains [1]. In 2006, 18 billion liters (4.8 billion gallons) of ethanol was produced, consuming 20% of the 2006 corn crop production, and displacing 2.5% of light duty vehicle gasoline consumption [2, 3]. Utilizing an agricultural crop to produce liquid fuels has created an intense debate around two issues; first, analyzing the energy it takes to produce a liter (or gallon) of ethanol and second, consuming food for fuel production. This study focuses on modeling and analyzing the first issue through conducting a life-cycle analysis of corn grain ethanol production. This analysis focuses on the fossil energy consumption, GHG emissions, petroleum and natural gas consumption, and land use impacts of producing ethanol from corn grains in the United States. (Ethanol produced from corn stover and switchgrass are discussed in chapter 4.) Unlike previous LCA studies, this analysis integrates a Monte Carlo approach within a life-cycle assessment capturing the system input variability. This results in a range of probable outcomes rather than a single point value as previous published reports have presented. To demonstrate the importance of regional geographic assumptions two states were analyzed, Iowa and Georgia. Iowa is assumed to represent a corn grain ethanol scenario from a state in the Corn Belt with high corn yields. To illustrate the effects of geographic variation on system fossil energy use, greenhouse gas emissions, and land use efficiency, ethanol produced from corn grown in Georgia, a traditionally low corn yielding state was also analyzed.

As ethanol production expands to regions outside the Corn Belt and as fossil energy costs increase, corn grain-based ethanol facilities may chose two paths to either decrease fossil energy consumption and GHG emissions or reduce operating costs. The first pathway analyzed is the facility's option to burn the dried distiller grains to offset facility fossil energy consumption and fuel operating costs. A second potential pathway is burning coal instead of natural gas as a primary fuel source. Both these pathways are modeled as a potential future step in this industry, and therefore is analyzed and compared to current corn grain ethanol facilities based on fossil energy consumption and GHG emissions. Additionally, as current renewable fuels standards are cementing the production of corn grain ethanol in the future, a scenario representing the year 2025 is analyzed to help focus current policy and research efforts to have the greatest impact at reducing fossil energy consumption and GHG emissions in the future.

This chapter is broken up into three sections; corn grain agriculture, corn grain transport, and corn grain ethanol processing. Each section describes they system boundary for the sector, system inputs, and presents fossil energy and GHG emission results. The end of the chapter integrates all three sections to provide a systems perspective and to discuss the overall fossil energy and GHG impact of producing corn grain ethanol.

Corn Grain Agriculture

History of US Corn Grain Production

Corn production in the United States is centered within the Corn Belt where approximately 83% of 2007 corn grain production was produced from 10 states (Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, South Dakota, Wisconsin, Missouri, and Minnesota) [4, 5]. Figures 3-1, 3-2, and 3-3 display the historic harvested corn acreage, US total corn grain production, and average corn yield from 1925 to 2006 [4, 5].

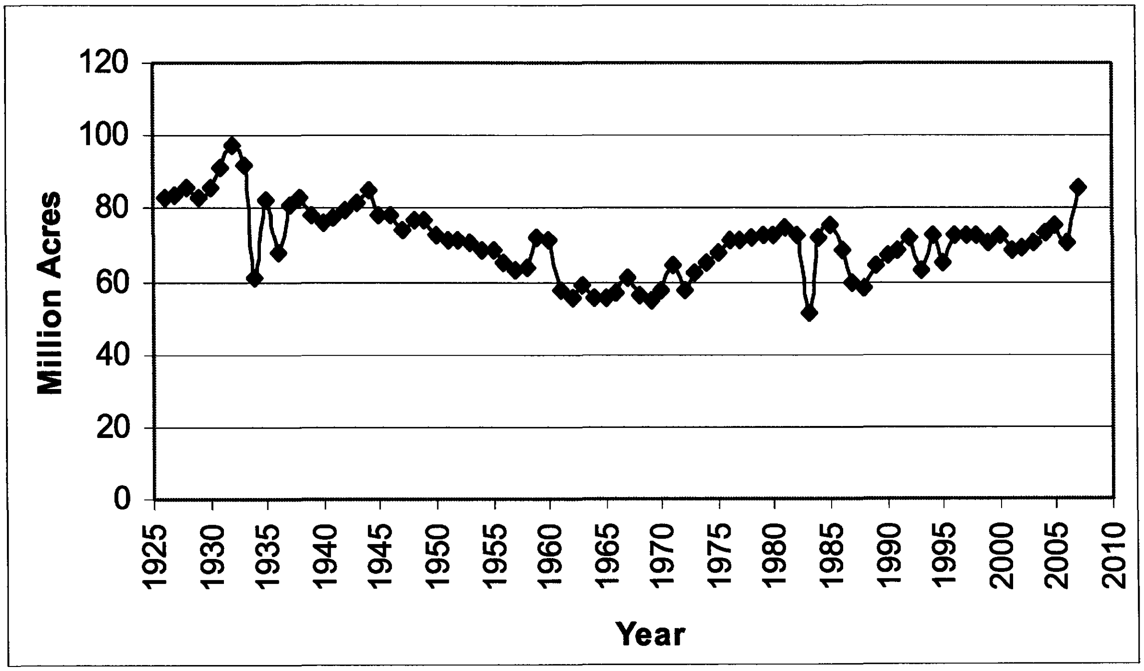

Figure 3-1 – US Corn Grain Harvested Acreage (1925-2006) [4, 5]

In the past few years acreage dedicated to corn production has increased due to increased demand from the ethanol industry. From 2006 to 2007, harvested corn acreage increased 20%, coming mainly from soybean acreage which is in rotation with corn grain [4, 5]. Soybeans are often rotated with corn as a mechanism to decrease corn grain fertilization requirements and increase soil quality. As farmers increasingly grow corn without rotating the land with soybeans, additional fertilizer will be needed as the soil nutrient benefits of crop rotations are not realized. This increased fertilizer application increases the amount of overall energy the system consumes as well as magnifies the current environmental impact that fertilizers already have.

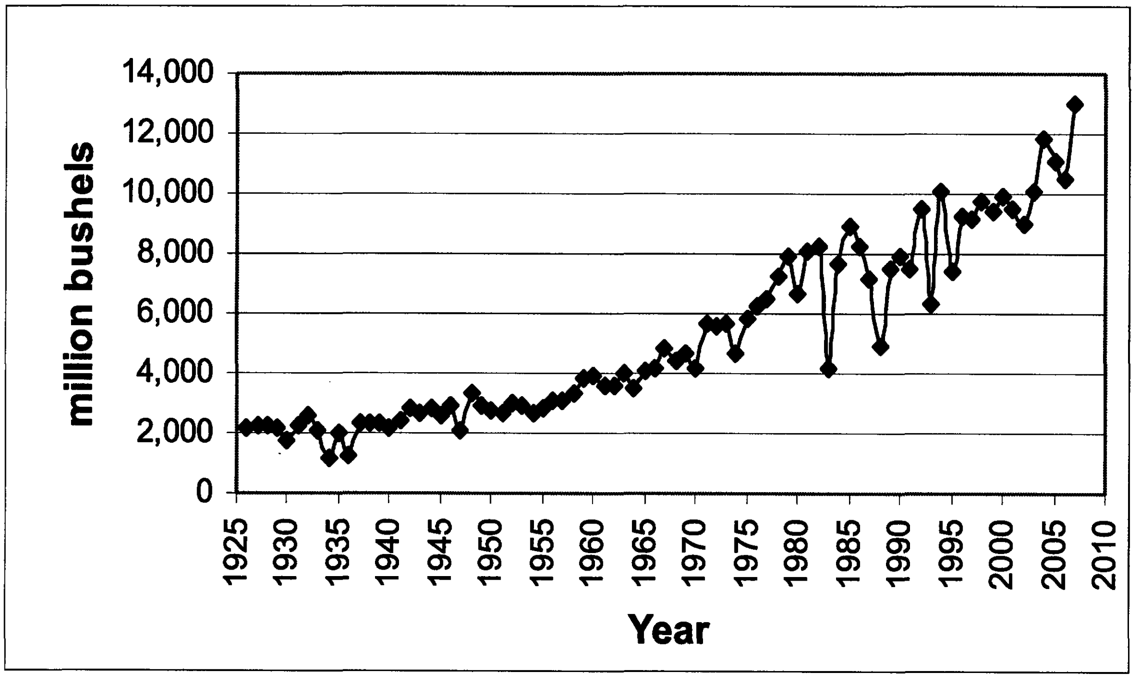

Figure 3-2 – US Corn Grain Production (1926-2007) [4, 5]

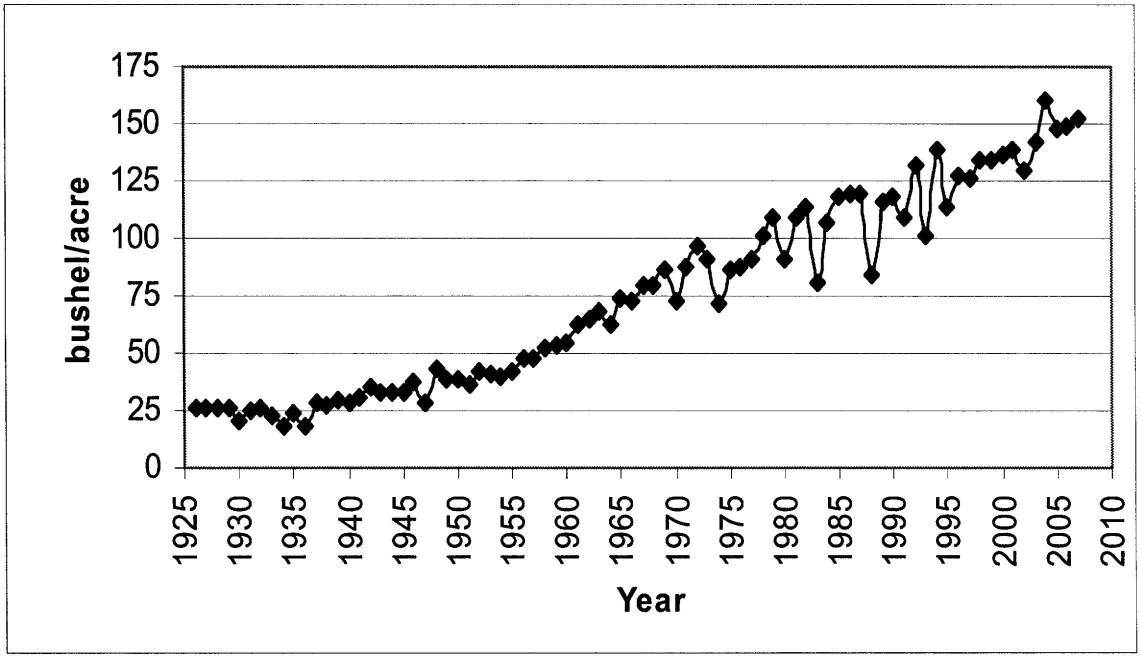

Figure 3-3 – US Average Corn Grain Yield per Harvested Acreage (1926 to 2007) [4, 5]

From 1926 to 1955 corn grain yields per acre nearly doubled from 25 bu/acre to 50 bu/acre. Then between 1955 and 1985 a 10% increase in corn yields was seen, and from 1985 to 2007 corn yields doubled again to the current day average of 152 bu/harvested acre. Yields have increased over the years due to fertilization, genetic engineering, and improved crop management practices. Corn is fertilized with nitrogen, phosphorus, and potassium. Figure 3-4 displays the historic application of these three fertilizers during corn production. Initially there was a large increase in the application of nitrogen fertilizer, while in the past 20 years the application rate has stayed within 123-136 lb/acre. Agricultural input quantities such as seeding rate, fertilizers, and irrigation, depend on the local soil and climate conditions and therefore can vary greatly depending on geographic location.

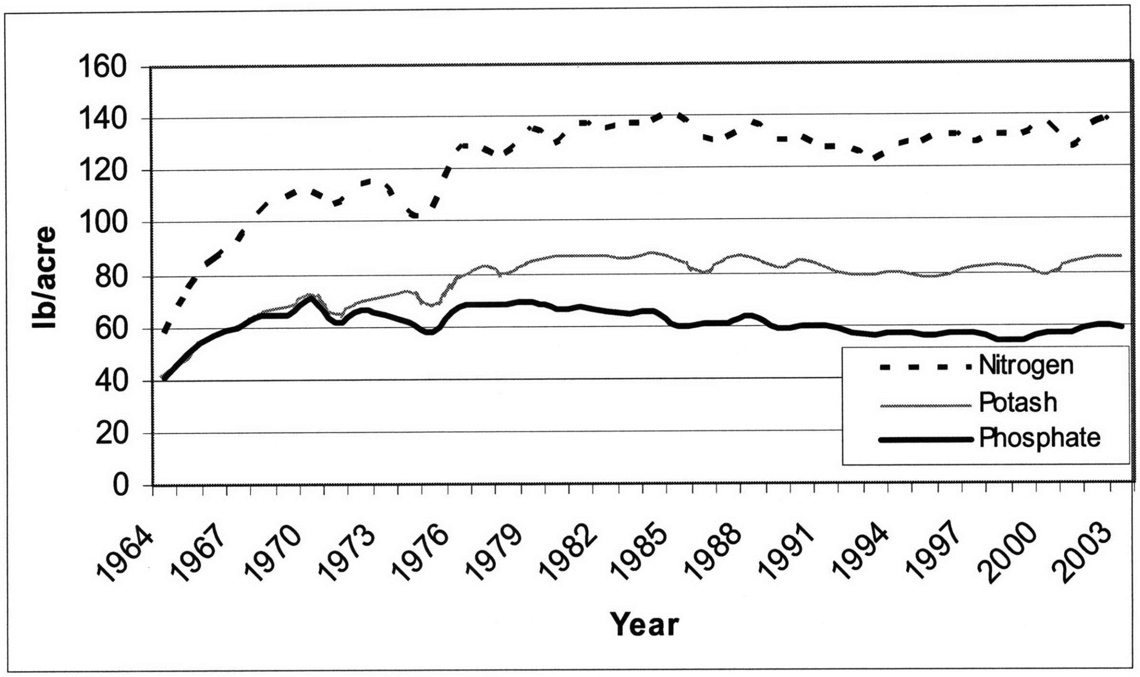

Figure 3-4 – US Corn Grain Average Fertilizer Application Amounts (1965-2004) [4]

Genetically engineered crops which came into use in the late 80s and early 90s made crops insect and herbicide resistant and further increased corn yields [5]. Additionally, corn has been modified for the production of hybrid crops which are often taller and have greater yields [6]. Figure 3-5 represents the percent of corn acreage from 2000 to 2005 that is growing genetically engineered corn grains [7]. Figure 3-6 represents the total acreage planted with genetically engineered corn hybrids[6, 7].

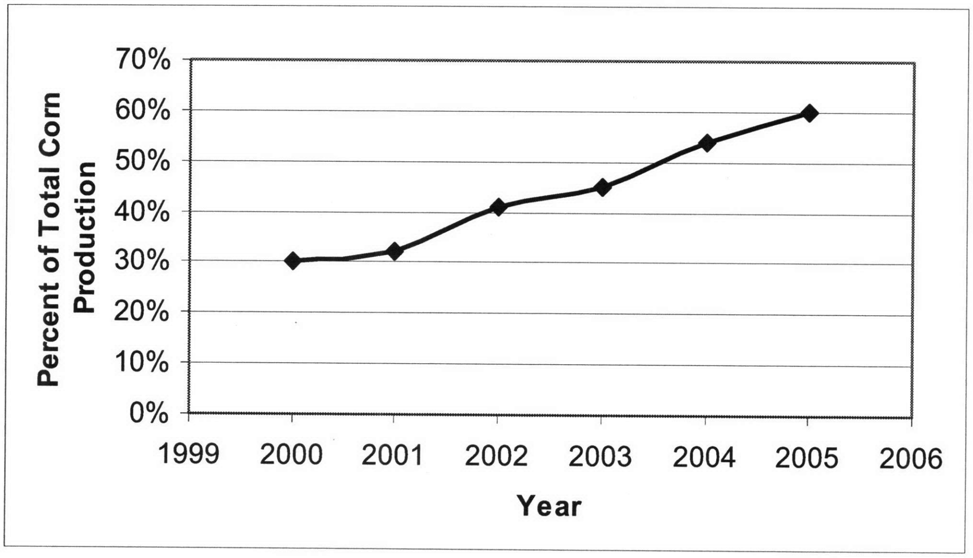

Figure 3- 5 – Percent of Genetically Engineered Corn in the United States. [5] Sources: 2000-2001: U.S. Dept. of Agriculture, National Agricultural Statistics Service (NASS), Acreage. June 29, 2001.

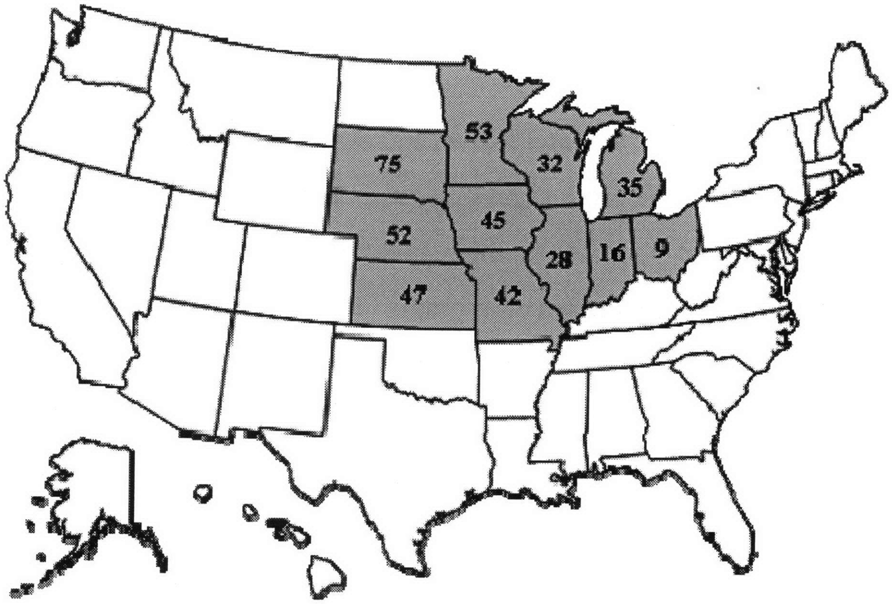

Figure 3-6 - Statewide percentage of total corn acres planted with genetically engineered corn hybrids in major corn producing states in 2005. Corn produced in these states represents 81% of US corn production. Source: http://www.geo-pie.cornell.edu/crops/corn.html

As ethanol production has increased so has the demand for corn grains. This increase in demand for corn has also resulted in increased corn prices which have seen record highs. Figure 3-7 displays the average monthly national price of corn from 1960 to 2006.

Between the late 1990s and today, corn grain prices have almost doubled from increased ethanol demand. This increase has negatively affected the cattle market as their feed prices have increased, and other corn-based products. High corn prices are causing farmers to plant additional corn acreage which is often displacing other crops such as soy beans, wheat, and cotton. As these other crops become displaced their prices are also expected to rise. Though some of these economic issues are in the short term the global ramifications of increased corn prices in the long run still remains to be seen.

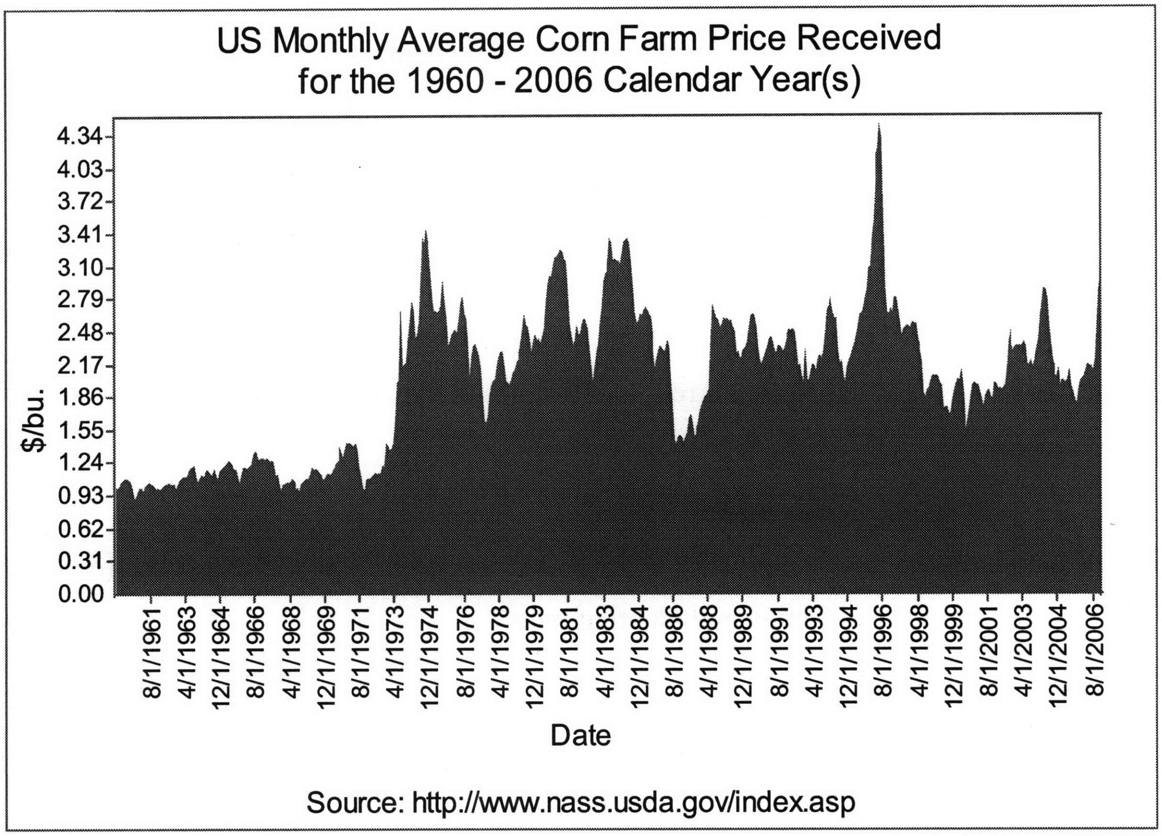

Figure 3- 7 – US Monthly Average Corn Farm Price Received (1960 to 2006)
http://www.farmdoc.uiuc.edu/manage/pricehistory/PriceHistory.asp

Corn production will continue to increase as ethanol capacity in the US expands and greater amounts of corn grain are required [1]. This growth in both the agricultural and ethanol producing industries comes at an environmental cost when current practices are used. Analyzing this current system and projecting it into the future can provide insights that can be used to limit this impact. Historic trends for system inputs, such as the ones discussed above, were projected to the year 2025 to create future models that assessed the potential of this improvement. Historic trends also allow one to see when and how improvements occurred, providing insight that can be applied to alternative systems, such plants grown for cellulose.

Corn Grain Agriculture Life-Cycle Assessment Inputs

This section describes the assumptions, system boundary, and input variables for current and future corn grain production in the United States. To minimize system variability and to demonstrate the impact of geographic variation, state specific data was used to model each system scenario. Iowa is used to represent a high corn yielding state within the Corn Belt, and is the main focus for this study as it characterizes today's best case scenario. Georgia is analyzed to show how the results are affected by geographic location, which is important as feedstock and ethanol production are expanding to traditionally less productive lands outside the Corn Belt. To determine where within the agricultural sector, system improvements would have the greatest impact on fossil energy consumption and GHG emissions, a future corn production model was also created. Historic data was used to project current input values to the year 2025 as inputs for this future scenario.

The system boundary for the agricultural sector of corn grain production includes [8]:

1. Corn seed production and planting rates
2. Nitrogen, phosphate, and potash fertilizer production, transport and application rates
3. Lime production, transport, and application rates
4. Herbicide and insecticide production, transportation, and application rates
5. Farm machinery fossil fuel consumption
6. Farm electricity consumption

USDA and ERS state-specific agricultural data sets from 1995-2004 were used to characterize the probability density functions (PDFs) for variables such as yield, fertilizer application, and farm machinery fuel consumption [8]. The model inputs for Iowa and Georgia corn production are shown in Table 3-1 and Table 3-2. Each main system input variable is either modeled as a probability density function characterized by a normal distribution.

Only fossil energy was considered when accounting for energy needed during the production life-cycle of corn grain 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. System inputs that were applied to the 2025 future corn ethanol scenario are presented in Table 3-3.

Corn Grain Ethanol System Inputs

Direct System Input Values		**Iowa**		**Georgia**	
	Units	*Average*	*Standard Deviation*	*Average*	*Standard Deviation*
Farm Input Values					
Corn Yield[5]	bu/acre	145	21.7	100	32.3
Corn Yield	bu/ha	358	53.6	247	79.8
Corn Yield	Mg/ha	9.1	1.4	6.3	2
Nitrogen Fertilizer Application Rate[6]	kg/ha	141.7	5.6	142.3	11.2
Phosphate Fertilizer Application Rate	kg/ha	70	5.3	59.4	5.6
Potash Fertilizer Application Rate	kg/ha	86.5	6.1	88.5	5.6
Lime Application Rate[7]	kg/ha	280	-	280	-
Herbicide Application Rate[8]	kg/ha	8.2	1.6	8.6	1.34
Insecticide Application Rate	kg/ha	0.86	0.34	0.36	0.17
Seed Production Planting Rate[9]	kernel/ha	67,431	-	67,431	-
Corn Seed Production Energy Input	MJ/ha	0.002	-	0.002	-
Farm Machinery Electricity[10]	kW-hr/ha	41.5	16.3	73.1	53.8
Farm Machinery Gasoline	liters/ha	11.2	0.65	23.4	12.7
Farm Machinery Diesel	liters/ha	43	2.7	138.4	32.4
Farm Machinery LP Gas	liters/ha	67.3	6.9	4.7	2.4
Corn Transport					
Distance (roundtrip)	km	161	-	161	-
Loaded Engine Fuel Efficiency	km/liter	2.1	-	2.1	-

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[5] Corn yield is state specific and gathered from the USDA ERS and NASS database. Iowa's average corn yield is based on a country average corn yields from 1995-2005. Georgia's average corn yield is based on county average corn yields from 1996-2005

[6] Fertilizer application rate data is gathered from the USDA ERS and NASS database. Iowa's average fertilizer application rates were averaged from 1996-2001. Georgia's average fertilizer application rate is from 1996-2003.

[7] 9. Shapouri, H., J.A. Duffield, and M. Wang, *The Energy Balance of Corn Ethanol: An Update*, ed. USDA. 2002.

[8] Herbicide and insecticide state specific date was gathered from the USDA ERS and NASS database

[9] 10. Graboski, M.S., *Fossil Energy Use in the Manufacturing of Corn Ethanol*. 2002: Colorado School of Mines.

[10] All farm machinery was based on the USDA ERS database

Unloaded Engine Fuel Efficiency	km/liter	3.4	-	3.4	-
Trailer Capacity	Mg/trailer	22-25	-	22-25	-
Ethanol Processing[11]					
Natural Gas	scf/liter	8.9	1.8	8.9	1.8
Natural Gas	MJ/liter	1.1	0.4	1.1	0.4
Electricity	kW-hr/liter	0.3	0.1	0.3	0.1
Electricity Generation Efficiency	%	32.5%	-	32.5%	
Ethanol Conversion Efficiency[12]	gallon/bu	2.7	0.2	2.7	0.2
Ethanol Conversion Efficiency	Liter/ha	3,686	273	3,686	273
Ethanol Conversion Efficiency	Liters/Mg	405	30	405	30

Table 3-1 – Corn Grain Ethanol Life-Cycle Assessment System Input Values for Iowa and Georgia. Inputs are modeled as either a normal distribution or a single point value. Data is from the USDA ERS and NASS agricultural databases. The electricity generation efficiency and transmission and distribution losses are included to determine the actual amount of energy consumed for a delivered amount of purchased electricity. All energy values are based on the LHV of the fuel. Ethanol's LHV is assumed to be 21.2 MJ/liter. All values are converted values from Table 3A-1

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[11] The natural gas and electricity consumption for an average corn grain ethanol facility was based on 11. Shapouri, H. and P. Gallagher, *USDA's 2002 Ethanol Cost-of-Production Survey*, ed. USDA. 2005.

[12] Based on an average of reported corn grain ethanol conversion values

Upstream Farm Inputs Production Energy

Inputs[13]	Units	Average
Nitrogen Fertilizer Production		
Natural Gas	scf/kg	37
Electricity	kW-hr/kg	1.7
Phosphate Fertilizer Production		
Natural Gas	scf/kg	12
Electricity	kW-hr/kg	0.6
Potash Fertilizer Production		
Natural Gas	scf/kg	2.4
Electricity	kW-hr/kg	0.5
Herbicide Production		
Natural Gas	MJ/kg	9.8
Electricity	kW-hr/kg	20.2
Distillate Fuel	MJ/kg	14.3
Naphtha	MJ/kg	72
Insecticide Production		
Natural Gas	MJ/kg	117.7
Electricity	kW-hr/kg	26
Distillate Fuel	MJ/kg	9.9
Naphtha	MJ/kg	63.3
Lime Production		
Electricity[14]	kW-hr/kg	355

Table 3-2 – Upstream Energy Consumption for the Defined Agricultural Inputs (All values are converted values from Table 3A-2)

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[13] Fertilizer, herbicide, and insecticide production energy is from: 10. Graboski, M.S., *Fossil Energy Use in the Manufacturing of Corn Ethanol.* 2002: Colorado School of Mines.

[14] 12. West, T.O. and G. Marland, *A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States.* Agricultural Ecosystems and Environment, 2002. **91**: p. 217-232.

2025 Iowa Corn Grain Ethanol System Inputs

Direct System Input Values	*Units*	*Average*	*Standard Deviation*
Farm Input Values			
Corn Yield[15]	bu/acre	203	21.7
Corn Yield	bu/ha	501	54
Corn Yield	Mg/ha	1237	1.4
Nitrogen Fertilizer Application Rate[16]	kg/ha	158.8	5.6
Phosphate Fertilizer Application Rate	kg/ha	73.5	5.3
Potash Fertilizer Application Rate	kg/ha	90.9	6.1
Lime Application Rate[17]	kg/ha	280	-
Herbicide Application Rate	kg/ha	8.2	1.6
Insecticide Application Rate	kg/ha	0.9	0.3
Seed Production Planting Rate	kernel/ha	67,431	-
Corn Seed Production Energy Input	kJ/ha	1.59	-
Electricity	kW-hr/ha	41.5	16.3
Gasoline	liter/ha	11.2	0.65
Diesel	liter/ha	43	2.7
LP Gas	liter/ha	67.3	6.9
Corn Transport[18]			
Distance (roundtrip)	km	161	-
Loaded Engine Fuel Efficiency	km/liter	3	-
Unloaded Engine Fuel Efficiency	km/liter	4.3	-
Trailer Capacity	Mg/trailer	22-25	-

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[15] Based on an assumed 1.2% yearly increase in corn yields. 13. JP Morgan Securities, I., *Investing in Ethanol*. 2006, North American Corporate Research.

[16] Fertilizer application rates fluctuate between 5-8% of the average between 1996-2002. This study therefore, assumed a 5% increase in fertilizer application rates from 2002 levels in the year 2025. An increase was assumed as increase soil erosion and corn expanding to less productive land, will in the future require more fertilizer.

[17] Lime, herbicide, and insecticide application rates were assumed to stay constant

[18] Engine fuel efficiency was assumed to increase as engine efficiency is continually increasing

Ethanol Processing[19]			
Natural Gas	scf/liter	7.6	1.8
Natural Gas	Mg/liter	7.5	1.9
Electricity	kW-hr/liter	0.25	0.1
Electricity Generation Efficiency	%	32.5%	-
Ethanol Conversion Efficiency[20]	gallon/bu	2.9	0.1
Ethanol Conversion Efficiency	liters/Mg	435	15
Ethanol Conversion Efficiency	liters/ha	5,476	189

Table 3-3 – 2025 Iowa Corn Grain Ethanol LCA System Inputs (All values are converted from Table 3A-3)

Corn Grain Agriculture Life-Cycle Assessment Fossil Energy Consumption and GHG Emission Results

Figure 3-8 and Figure 3-9 display the fossil energy consumption and GHG emission PDFs of the agricultural inputs for Iowa corn production. Each variable is represented by a white box symbol with whiskers. The white box represents the mean plus or minus one standard deviation. This represents the probability that 67% of the time the results will be within this range [15]. The whisker represents plus or minus 3 standard deviations, this represents the probability that 99% of the time the results will be within this range [15]. When considering all the corn grain agricultural inputs in Iowa, 7,405 MJ/acre or 51.2 MJ/bu of fossil energy is consumed. Nitrogen fertilizer accounts for 43% of this agricultural input energy, due to its high production energy intensity and high application rates. Nitrogen fertilizer, farm machine fuel consumption, and herbicides account for 84% of the total agricultural energy consumption from this sector. Due to the transport of nitrogen by both wind and soil erosion to nearby water bodies a phenomenon known as nitrification can occur. This lowers the waters oxygen level affecting animal life and the overall balance of the ecosystem.

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[19] Assumed a 7.5% decrease in facility fossil fuel consumption. I was assumed that improvements in machinery efficiency would occur. These values also correlate to the lower numbers being reported today for a corn grain ethanol facility 14. Wang, M., *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions*. 1999, IL: Argonne National Laboratory.

[20] Current ethanol facilities are reporting ethanol conversion efficiencies of 2.9 gal/bu. It was assumed that in the future this value would be the industry average.

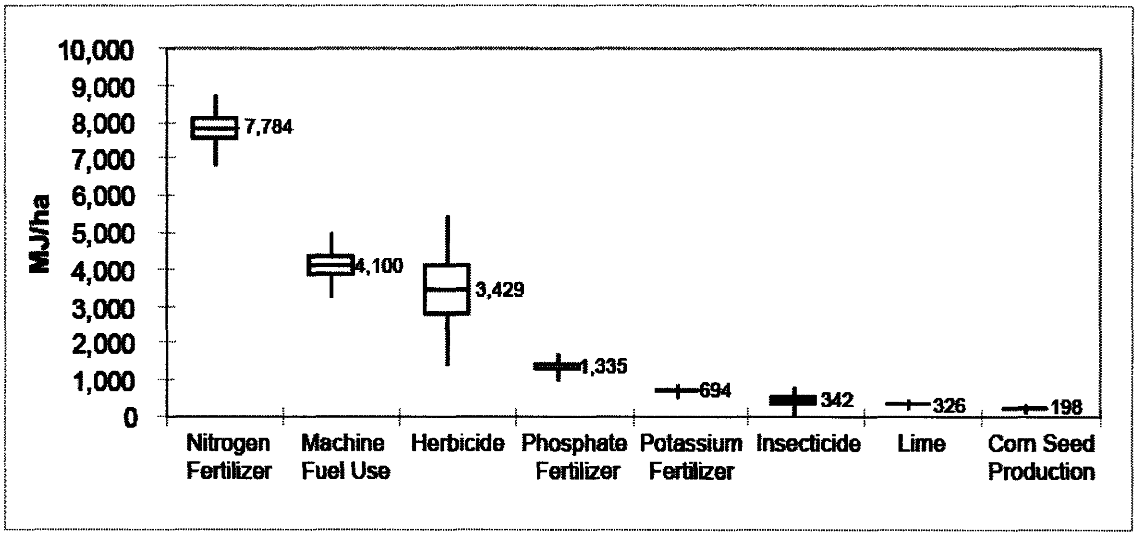


Figure 3-8 – Iowa Corn Grain Agricultural System Inputs Energy Consumption

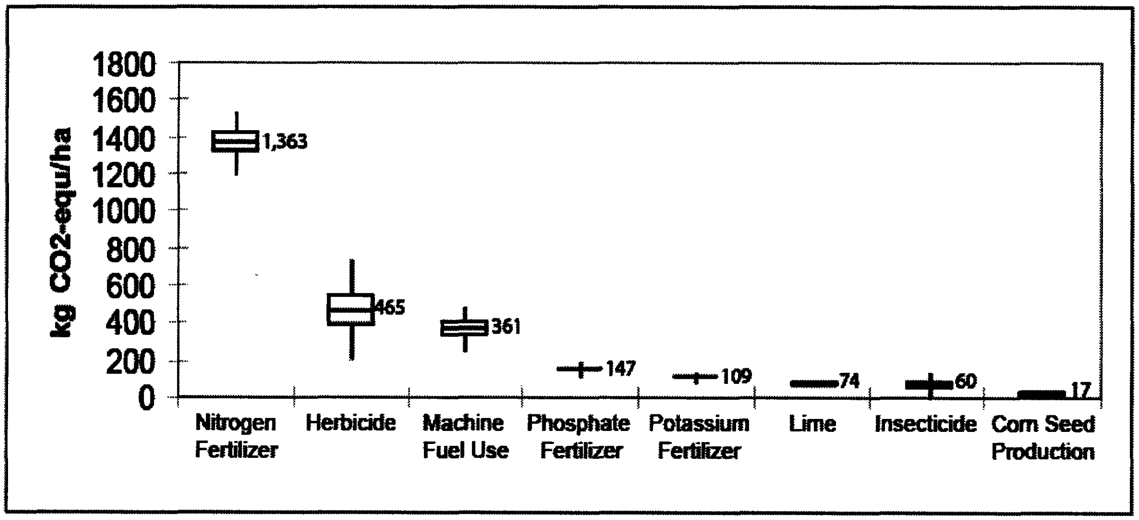


Figure 3-9 – Iowa Corn Grain Agricultural System Inputs Greenhouse Gas Emissions

Within the agricultural sector there are GHG emissions due to the fossil energy consumed to produce the agricultural inputs, the direct fossil energy consumption by farm machinery, and the emission of nitrous oxide by the application of nitrogen fertilizer. For this analysis a soil nitrous oxide emission factor of 1.25% of the applied nitrogen fertilizer use was included within the GHG calculation as recommended by IPCC [16]. The total GHG emissions attributed to the production of corn in Iowa is 1.05 Mg CO_2-

equ per acre or 7,291gCO_2-equ per bushel of corn produced. The production of nitrogen fertilizer accounts for 53% of the total agricultural GHG emissions.

Comparing the magnitude and GHG impact of each input enables one to focus potential future efforts towards areas that would have the greatest impact. Additionally, it identifies the input variables whose values and variability most affect the results. For example, focusing efforts to decrease nitrogen application rates, either through improved crop management practices or genetic engineering, would have a greater impact than decreasing phosphate or potassium fertilizer use. It is also important to remember that these input values represent a high corn-yielding state. Corn produced in other states such as Georgia, have higher input values, irrigation requirements, and lower yields which result in increased fossil energy use and GHG emissions.

Corn Grain Transport

Corn Grain Transport System Boundary

From the farm, corn grain at 15% moisture content is transported to the local elevator or ethanol facility. Ethanol facilities receive corn grain either directly from a farmer or through contract or spot purchase from a local elevator [10]. Ethanol facilities typically have enough corn grain storage to receive corn shipments every month. The average total distance radius from the farm to an ethanol facility is assumed to be 50 miles. This is a fixed number and not represented by a PDF because it accurately represents the current state of the industry and the impact of the biomass transport is minimal. Additionally, while there are multiple types of transportation vehicles such as wagons, and single and tandem axle trucks; a majority of corn is moved in semi trucks [10].

The system boundary for the corn grain transport sector includes:

1. Semi-trailer truck capacity of 875-100 bu/truck
2. Diesel fuel consumption assuming a 100-mile roundtrip from the farm and corn storage station to the ethanol processing facility
3. Semi-trailer truck loaded fuel consumption of 5 miles/gal and unloaded fuel consumption of 8 miles/gal [17].

Corn Grain Transport Fossil Energy Consumption and GHG Emission Results

Corn grain is assumed to be transported by trailer from the farm gate to the elevator and/or ethanol facility. A 100 mile round trip travel distance was assumed. This results in the consumption of 0.3 MJ of petroleum energy consumed per liter of ethanol produced and the emission of approximately 1gCO_2-equ/MJ-Ethanol. This value depends on the transport distance, the trailer capacity, and the assumed engine efficiencies. The transport of corn grains to the ethanol facility accounts for less than 2% of the total life-cycle assessment energy consumption. Even if the round trip travel distance was increased to 200 miles the corn grain transport energy consumption would be 0.57MJ/L, a small fraction of the total system energy consumption. The limiting factor in the transport distance generally is not its environmental impact but its cost. The transport cost of shipping corn grain greatly depends on trailer capacity, transport distance, and diesel fuel prices.

Corn Grain Ethanol Processing

In the past 7 years the production of ethanol has more than tripled, mainly due to the phasing out of Methyl Tertiary Butyl Ether (MTBE), new policy, and government incentives (Figure 1-2). In 2000, the EPA recommended the phase out of MTBE, a fuel oxygenate, due to its presence in drinking water from leaking holding tanks [18]. Ethanol production also increased due to the Renewable Fuels Standard (RFS), which took affect in 2007 mandating the production of 28 billion liters of renewable fuel by 2012 [19]. At the current capacity expansion rate this production level is expected to be reached by 2009, three years early [2].

Though there is a current debate surrounding the environmental benefits of ethanol, it is not a new one. Throughout the 70's and into the 80s, researchers and environmentalist were analyzing the fossil energy consumption and GHG emissions associate with the production of corn grain ethanol in the United States. Figure 3-10 summarizes eighteen studies that analyzed the ethanol facilities fossil energy consumption from the mid 70s till today [9, 10, 14, 20-31].

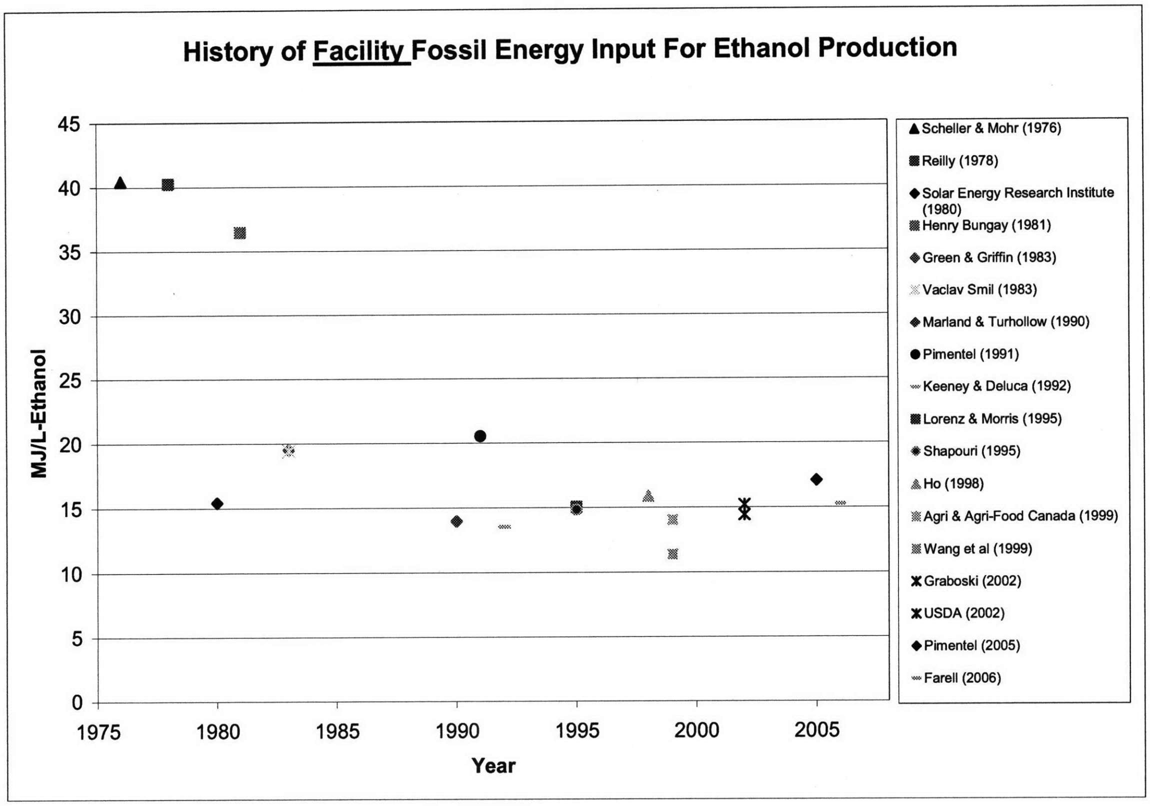


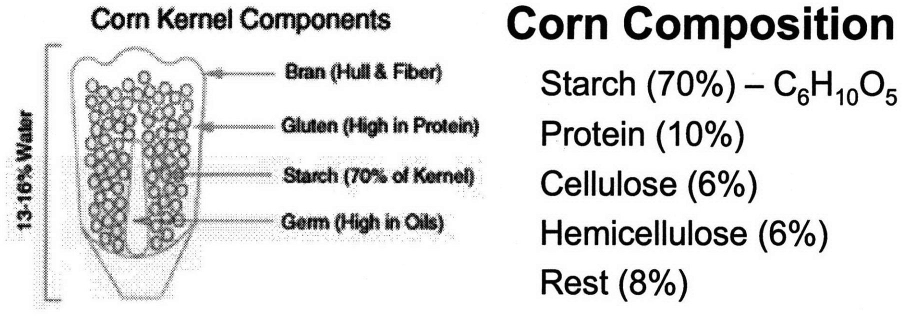
Figure 3-10 – Historic facility fossil energy requirement to produce a gallon of ethanol [9, 10, 14, 20-31] .

The average fossil energy consumption to produce a gallon of ethanol has decreased by 60%. This is due to increases in the efficiency of thermal mechanical processes and increased ethanol conversion rates. Throughout the 70s ethanol facilities were mainly powered by coal, while today the majority of facilities are powered by natural gas and have higher thermal efficiencies [32, 33].

Corn Grain Ethanol Processing Overview

This section describes the general corn grain to ethanol conversion process as well as the main steps in a dry mill ethanol conversion facility. Ethanol facilities are categorized as dry or wet mills depending on the pretreatment of the corn kernel before fermentation. In a dry mill ethanol facility the entire corn kernel is first ground into a flour called "meal" and then converted to ethanol via fermentation without separation [34, 35]. In a wet mill facility, the corn kernel is separated into starch, protein, germ and fiber in an aqueous medium prior to fermentation [2, 35]. Currently dry mill ethanol facilities account for 82% of the ethanol production as they get higher rate of returns on their investment [2, 36]. For this analysis a dry mill ethanol facility is assumed.

Corn is approximately 70% starch, 10% protein, 5% oil, and 15% other materials such as fiber, ash and water (Figure 3-11) [37]. Starch is a polymer of sugar called a polysaccharide which is comprised of two types of carbohydrates, amylase (20%) which is water-soluble and amylopectin (80%). Starch is the part of corn that can be hydrolyzed by acids and enzymes to fermentable sugars. Examples of fermentable sugars are D-glucose, D-mannus, D-fructose, D-galactose and maltose[38]. To produce ethanol, the starch first needs to be converted to sucrose, a type of sugar. This step is called saccharification. Sucrose is then broken down further to simpler and fermentable sugars called glucose and fructose. These sugars are then fermented with yeast to produce ethanol and carbon dioxide. Equations 3-1 through 3-3 represent the three main overall reactions that occur when converting starch to ethanol [38].



Corn Composition

Starch (70%) – $C_6H_{10}O_5$
Protein (10%)
Cellulose (6%)
Hemicellulose (6%)
Rest (8%)

Figure 3- 11 - Corn Grain Composition

Saccharification Step

$$\underbrace{(C_6H_{10}O_5)_n}_{Starch} + \frac{n}{2}H_2O \rightarrow \xrightarrow{Diastase\ Enzyme} \frac{n}{2}\underbrace{C_{12}H_{22}O_{11}}_{Sucrose} \qquad Equation(3-1)$$

Fermentation Step

$$\underbrace{C_{12}H_{22}O_{11}}_{Sucrose} + H_2O \xrightarrow{Maltase\ Enzyme} 2\ \underbrace{C_6H_{12}O_6}_{Glu\cos e\ \&\ Fructose} \qquad Equation(3-2)$$

$$\underbrace{C_6H_{12}O_6}_{Glu\cos e\ \&\ Fructose} \xrightarrow{Yeast\ \&\ Zymase\ Enzyme} 2\underbrace{C_2H_5OH}_{Ethanol} + 2CO_2 \qquad Equation(3-3)$$

The amount of ethanol that can be produced is dependent on the starch content in the corn kernel and the tolerance of the yeast to high ethanol concentrations. During fermentation there is a maximum alcohol concentration of 14% after which the process becomes self-inhibitory and the metabolic activity of the yeast ceases [38]. Two main coproducts are also produced in this process, an animal feed known as dried distiller's grains with solubles (DDGS) and carbon dioxide. DDGS is produced from the kernel protein content that is not fermentable and carbon dioxide is produced during fermentation. These coproducts can often be sold for an additional profit. The conversion process of corn to ethanol and the production of these coproducts will be discussed in the following section.

Process Flow Description of a Dry Mill Corn Grain Ethanol Facility

Figure 3-12 represents a process flow diagram of a typical dry mill corn grain ethanol conversion facility. Initially, the corn kernel is mechanically broken down in a hammer mill to expose the starch cell walls since the bonds between starch molecules are not very strong [34]. High temperature water (95°C) is then added in a slurry tank and jet cooker to additionally help in the break down of the material. This mixture is now called "slurry". The starch cell walls need to be exposed and broken down so that enzymes called alpha-amylase and gluco-amylase when added can break down the starch into simpler fermentable sugars [34]. When the enzymes are added the substance is called "mash". Once the starch is converted to sugar it needs to be cooled to the fermentation temperature (30°F) [34, 38].

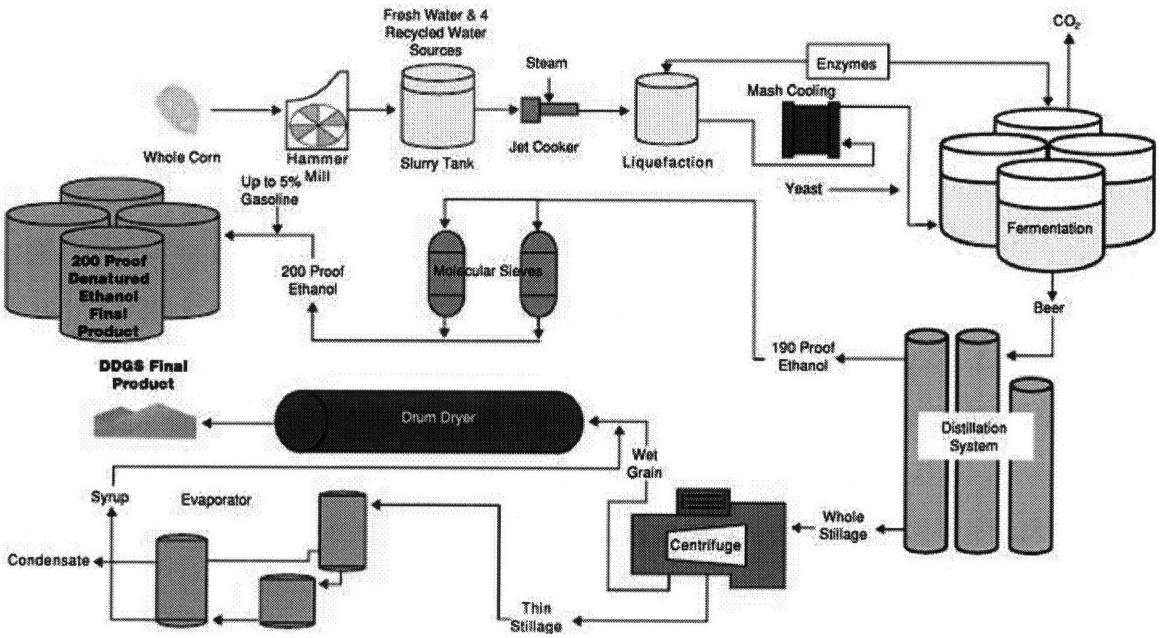


Figure 3- 12 – Typical Dry Mill Corn Grain Ethanol Processing Facility. www.midwestethanol.com

The two most important parameters in the fermentation process are temperature and pH level. Fermentation is an exothermic reaction and therefore cooling water is needed to keep the container temperature constant at 30°F [34]. Additionally the pH needs to be maintained between 3 and 5 [34]. There are two types of fermentation; continual or batch. During a continual fermentation process the mash is pumped from one container to another. For a batch fermentation process the mash stays in the same container for 2 days with continuous mixing [34]. At the end of the fermentation process the mixture that exits the container, called "beer", is approximately 10% by volume ethanol and contains all the solids from the original feedstock [34].

The beer is then distilled resulting in 190 proof or a 96% ethanol mixture. This mixture then goes through a dehydration step where the remaining water is removed by passing the mixture through a molecular sieve resulting in 200 proof ethanol called anhydrous ethanol [34]. The 200 proof ethanol is then denatured by adding 5% gasoline to prevent human consumption [34]. Corn grain ethanol's conversion efficiency is approximately 2.5-2.8 gal/bu depending on the age of the facility and the processes [35]. The theoretic maximum conversion rate for corn grain ethanol is around 2.9-3.1 gal/bu depending on the starch content of the kernel [39]. If all the starch and cellulose in the kernel are converted to ethanol, the yield can reach 3.35 gal/bu [39]

The residue remaining at the end of distillation is referred to as "stillage" and is pumped from the distillation columns to the coproduct processing sector. The stillage is sent through a centrifuge to remove excess liquid, which can be reused in the liquefaction step [34]. The remaining solids are referred to as wet distillers grain (WDG) and can be sold as animal feed. Depending on the shipping distance WDG may need to be dried further due to its short storage life and high shipping cost from the excess water weight. If additional drying is required, the WDG is put through a dryer to remove additional water until the final product has a 10% moisture content [34]. This product is now called dried distillers grain with solubles (DDGS) [34, 38]. During the production of ethanol, 17-18 lbs of DDGS are produced per bushel of corn [1, 35]. In the United States the majority of DDGS is fed to ruminant feedstock (beef and dairy cattle) with some also being fed to pork and poultry [1]. While selling DDGS provides additional income, it can also be used as a fuel source by the facility to displace fossil fuel consumption in times of high fuel prices. As an example, Corn Plus of Winnebago Minnesota is utilizing the energy content of DDGS to displace the facilities natural gas consumption [40]. This alternative use of DDGS can also be applied in geographic regions where an animal feed market is not available or transport is to costly. The consumption of DDGS as a fuel source rather than a feed source provides corn grain ethanol facilities with an additional economic alternative. The path DDGS takes will ultimately be determined by economics, which depend on transport distance costs, the DDGS market, and fossil fuel costs.

Corn Grain Ethanol Processing: Fossil Energy Consumption and GHG Emission Results

The system boundary for the corn grain ethanol processing sector includes:

1. Natural gas and electricity inputs as the energy inputs utilized by the ethanol processing plant to convert corn to ethanol [11]. The electricity transmission and distributions losses, as well as the power plant's thermal efficiency and fuel mix are also included with the system boundary.
2. The values for the fossil energy inputs are defined in Table 3-1

3. Enzyme, chemical, and yeast production energy are excluded
4. The embodied energy in construction materials was excluded

A corn grain ethanol facility selling DDGS consumes on average 12 ± 2.1 MJ of fossil energy per liter of ethanol produced (43,250 ± 7,550 MBTU/gal Ethanol). Facility's consuming 12 MJ/L of fossil energy result in the emission of 54 ± 11 gCO_2-equ/MJ. In the future, it is assumed that through mechanical and thermal efficiency gains, that the fossil energy consumed by an average ethanol facility could decrease by 17% to 10 MJ/L (35,870 MBTU/gal) (Table 3-3). This would translate to a 15% decrease in GHG emissions.

Grain Ethanol Energy Consumption and GHG Emission Results

The total system boundary for corn grain ethanol production is summarized below:

For Corn Grain Production [8]:

7. Corn seed production and planting rates
8. Nitrogen, phosphate, and potash fertilizer production, transport and application rates
9. Lime production, transport, and application rates
10. Herbicide and insecticide production, transportation, and application rates
11. Farm machinery fossil fuel consumption
12. Farm electricity consumption

For Corn Grain Transport:

13. Semi-trailer truck capacity of 875-100 bu/truck
14. Diesel fuel consumption assuming a 100-mile roundtrip from the farm and corn storage station to the ethanol processing facility
15. Semi-trailer truck loaded fuel consumption of 5 miles/gal and unloaded fuel consumption of 8 miles/gal [17].

For Corn Grain Ethanol Processing:

16. Natural gas and electricity inputs as the energy inputs utilized by the ethanol processing plant to convert corn to ethanol [11]. The electricity transmission

and distributions losses, as well as the power plant's thermal efficiency and fuel mix are also included with the system boundary.

17. The values for the fossil energy inputs are defined in Table 3-1
18. Enzyme, chemical, and yeast production energy are excluded
19. The embodied energy in construction materials was excluded

This section presents and discusses the fossil energy consumption and GHG emissions for the entire corn grain ethanol life-cycle assessment. Five different scenarios were evaluated to examine the sensitivity of the results to system inputs and to evaluate the impacts of a growing ethanol industry. These scenarios were also used to analyze the environmental impact future bioethanol producing pathways may have. The first scenario represents today's current best practices in corn production and ethanol processing in Iowa. This scenario is called *Iowa Corn Grain Ethanol.* As corn grain ethanol production expands, other geographic regions may need to be utilized for corn production. This geographic shift will lead to different agricultural inputs and values. Sensitivity to geographic location is examined by considering corn grown outside the Corn Belt in Georgia a typically low yield corn producing state. This scenario is called *Georgia Corn Grain Ethanol.* Additionally, as ethanol production expands beyond the Corn Belt, and as fuel prices continue to increase, a new role for DDGS as a fuel source may emerge. The use of DDGS as a fuel source in a corn grain ethanol facility is represented by *Iowa Corn Grain Plus DDGS.* Additionally, as natural gas prices increase, new facilities powered by coal, less expensive energy option, are being considered. This scenario is represented by *Iowa Coal Powered Corn Ethanol.* It is also assumed that in the near future ethanol will be the main contributor to achieving the administrations alternative fuels goal of 136 billion liters per year. Therefore, an additional corn grain ethanol model was created to evaluate how agricultural and technological improvements over the next 20 or so years can improve the bioethanol system fossil energy requirements and GHG emissions. This scenario is called *2025 Iowa Corn Grain Ethanol.*

This analysis was initially separated into three sectors; agricultural, corn grain transport, and ethanol processing, to compare the relative magnitude of each sector and to identify the system inputs that have the greatest impact on fossil energy consumption and GHG emissions. Figure 3-13 and 3-14 present the average fossil energy consumption and GHG emissions for each of the three sectors for the five scenarios. The ethanol processing sector is the major contributor to the system's energy consumption and GHG emissions. For example, the ethanol processing sector represents 70% and 60% of the total *Iowa Corn Grain Ethanol* systems fossil energy and GHG emissions respectively. When this input is displaced, as in the DDGS scenario, the total fossil energy consumption decreases between 70%-76%. The fossil energy consumption and GHG emissions of the Iowa corn transport sector accounts for less than 2% in all scenarios, expect Georgia, where it is assumed that corn would be transported to a facility in the Corn Belt. Georgia, being an example of a low corn yield producing region, consumes more than double the fossil energy of Iowa during corn production. This is due to lower production yields and higher values for agricultural inputs such as fertilizer. In the future, corn grain ethanol facilities could be built in Georgia which would decrease the corn grain transport distance. If the corn grain transport distance was decreased to 100 miles roundtrip, the as assumed for the Iowa scenario, corn ethanol produced in Georgia would consume 23.3 MJ/L of fossil energy consumption and emitted 126 gCO_2/MJ.

When the ethanol conversion facility is powered by coal instead of natural gas, the facility fossil energy consumed and GHG emitted increase by 42% and 30% respectively. The future scenario shows a potential to decrease agricultural and ethanol processing fossil energy consumption by 30% and 15% respectively. Examples of potential system improvements are improved crop management practices, crop yield per acre, increased farm machine fuel efficiency, and increases in corn grain ethanol conversion rates.

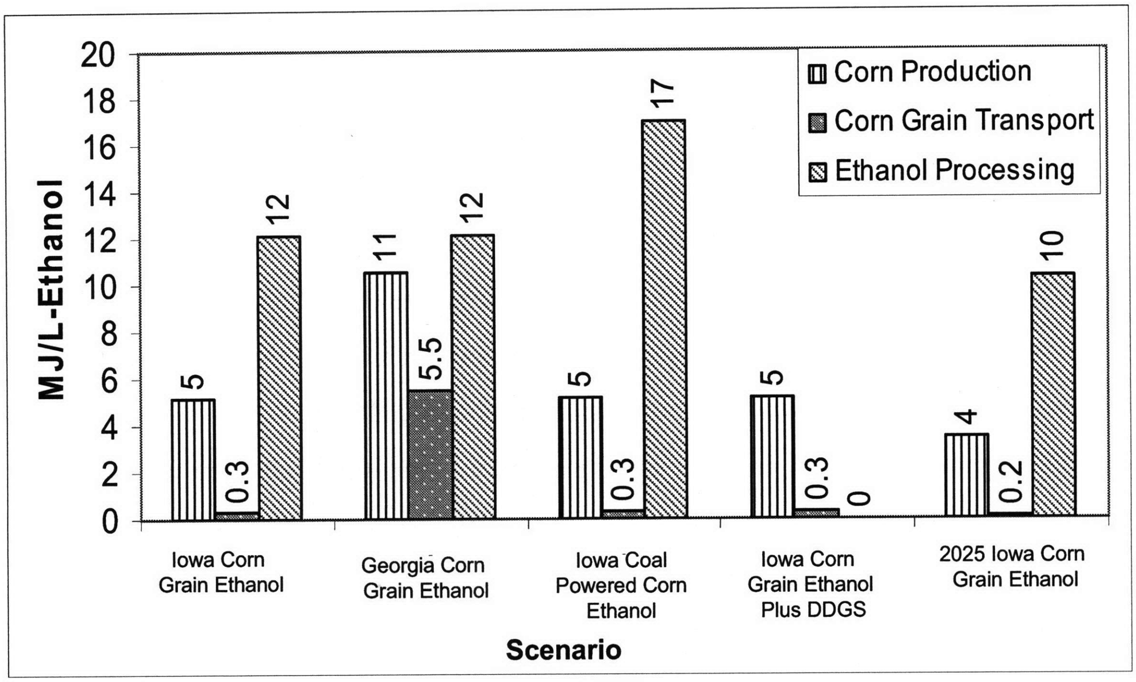


Figure 3-13 – Corn Grain Ethanol LCA Fossil Energy Consumption by Sector

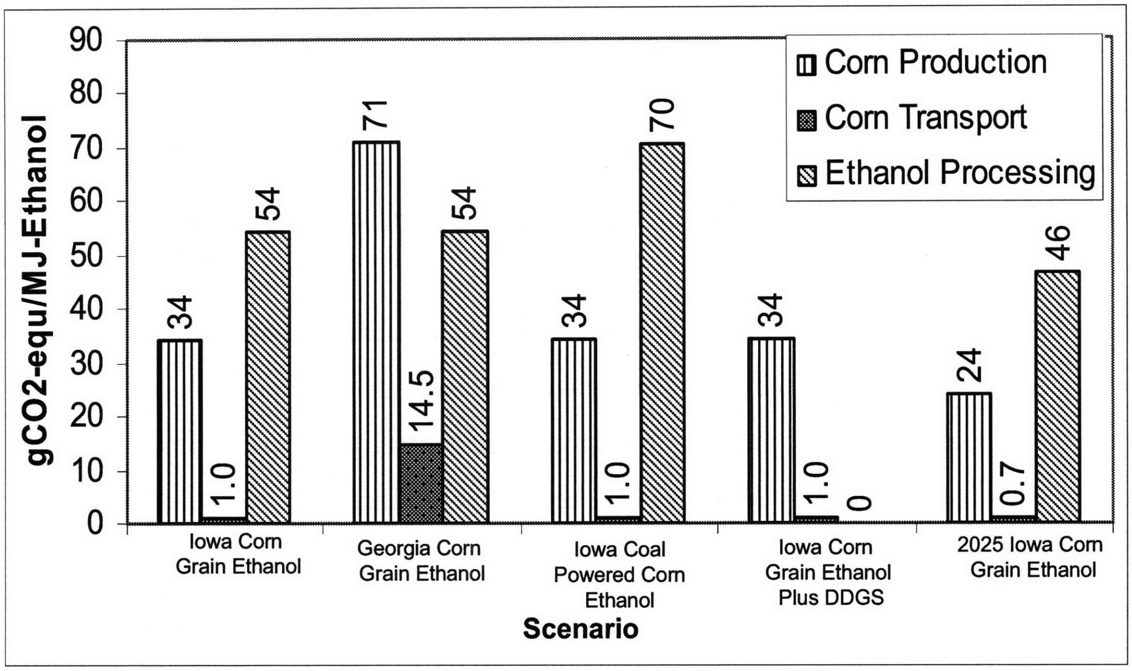


Figure 3-14 – Corn Grain Ethanol LCA GHG Emissions

Figure 3-15 presents the net energy value (NEV) of corn grain ethanol production compared to four previous published reports, all with the same system boundary, as reported by Farrell [23]. The NEV is defined as the energy content in a liter of ethanol minus the total fossil energy consumed to produce it (Equations 2-1 and 2-2). *Iowa Corn Grain Ethanol* is used as a comparison to validate the Monte Carlo approach and to clarify the debate over the energy benefits of corn grain ethanol [23]. The white symbol's represents the NEV without the allocation of coproduct credits, while the shaded or black 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) [15].

Results reported by Shapouri, Wang, and Farrell are within one standard deviation of the Monte Carlo models results, indicating that they are roughly equivalent given the range of variation in key inputs. However, Pimentel's reported value is more than three standard deviations below the Monte Carlo mean NEV value, making it less than 1% probable. This is primarily a result of Pimentel's use of older information [23].

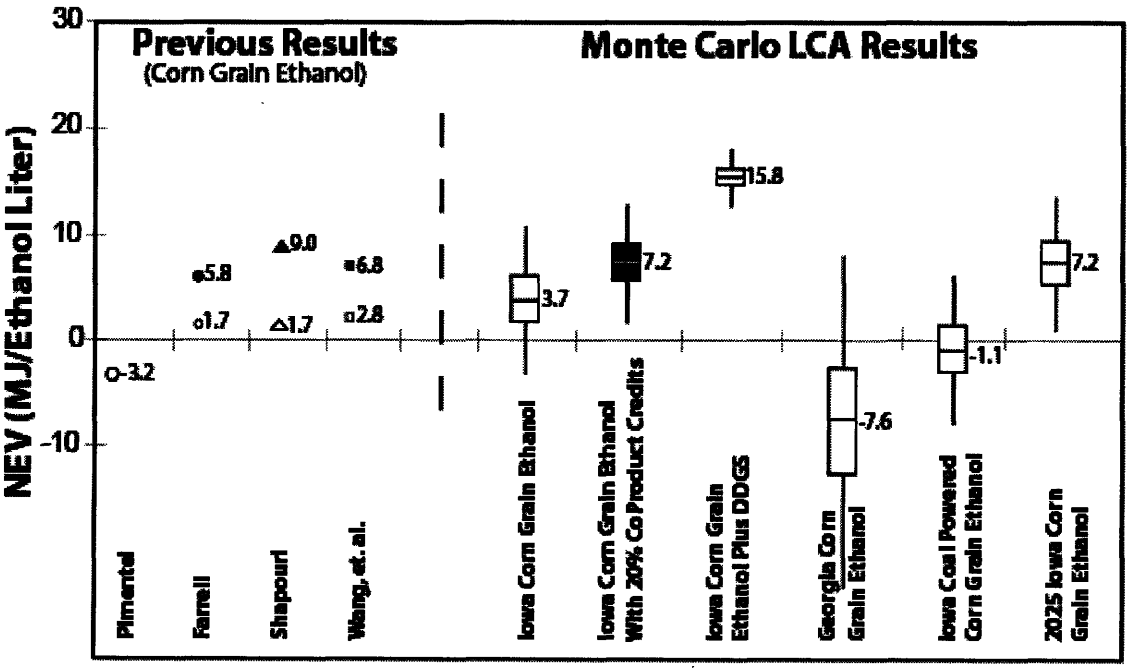


Figure 3- 15 – Corn Grain Ethanol Production LCA Net Energy Value [23]

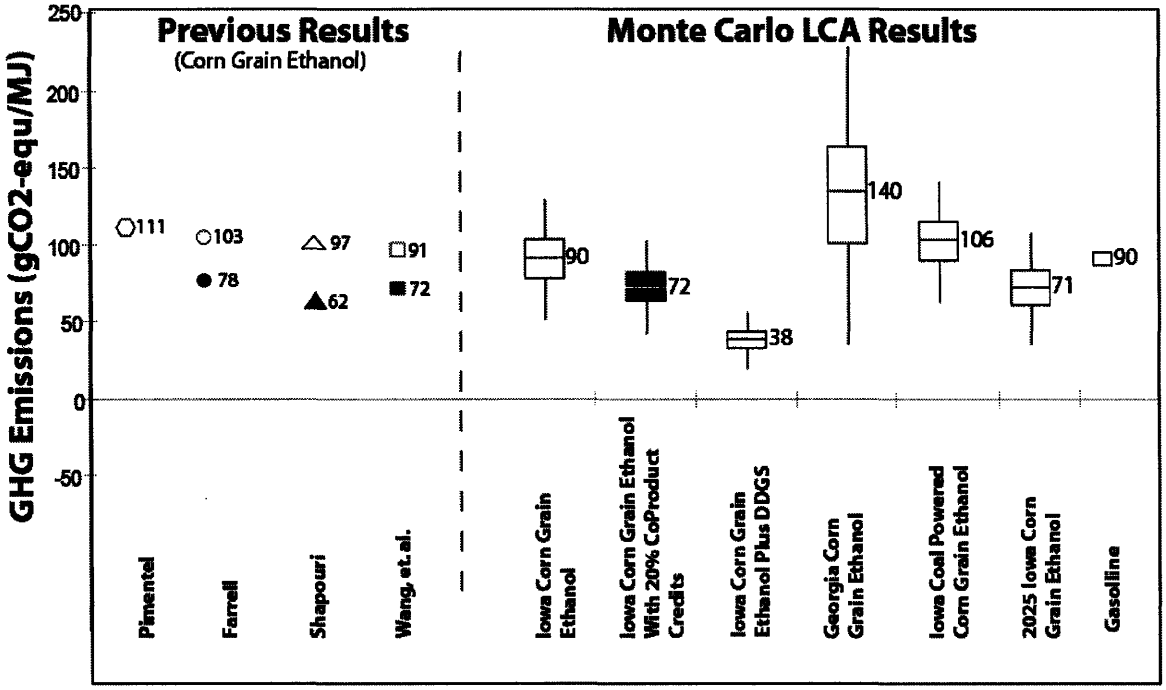


Figure 3- 16 – Corn Grain Ethanol Production LCA Greenhouse Gas Emissions [23]

One key focus of the corn grain ethanol energy debate is the allocation of energy and greenhouse gas emissions between corn ethanol production and the coproduct DDGS [41]. A 20% to 40% coproduct credit range has been used in the literature [41]. Using a 20% coproduct credit nearly doubles the *Iowa Corn Grain Ethanol's* NEV value from 3.8 to 7.2±1.8 MJ/L, a 90% increase. This scenario is represented by *Iowa Corn Grain Ethanol Plus DDGS.* 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.

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 results in a 47% increase in GHG emissions (Figure 3-15 and 3-16). This is a result of increased fertilizer inputs, irrigation, lower corn yields, and the transport of corn grains to the Corn Belt for ethanol processing. In the future, the number of ethanol facilities in Georgia may increase decreasing the corn grain transport distance. If this happens the NEV and GHG emissions for corn grain ethanol produced entirely in Georgia would decrease to a negative 2.1 MJ/L and 126 gCO_2/MJ. This demonstrates how geographic variation can impact the overall fossil energy consumption and GHG emissions.

Additionally, due to high natural gas prices, facilities are choosing two alternative facility fueling paths that have very different impacts. In one path, ethanol facilities are investing in technologies that burn DDGS as a fuel source for their facility energy demands, displacing a portion of their fossil fuel consumption. This path is represented by *Iowa Corn Grain Ethanol Plus DDGS* scenario. 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) [42, 43]. When the DDGS-CHP scenario is compared to *Iowa Corn Grain Ethanol* scenario, fossil fuel consumption and GHG emissions decrease by 67% and 60%, respectively (Figure 3-15 and 3-16). This option would depend on many market drivers such as fuel prices and the market price for DDGS. In another case some new facilities are being designed to be powered by coal instead of natural gas. These facilities would consume 27% more energy and produces 18% more GHG emissions. This option depends on natural gas prices, the proximity to coal, and the assumptions of future GHG regulation policy.

Over the next two decades, ethanol will likely continue to dominate the alternative fuels market in the US. To evaluate the impact of future improvements in corn production and ethanol conversion technology on fossil fuel consumption and GHG emissions, a model was created projecting 20 years into the future. Using historic trends, each system input value was extrapolated to estimate values for the year 2025 (Table 3-3). Compared to today's *Iowa Corn Grain Ethanol* results, the NEV of a future corn ethanol system increases by 90%, while GHG emissions decrease 20% (Figure 3-15 and 3-16). This future scenario also identified biomass yield, nitrogen fertilization rates, 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.

From an energy security perspective, the amount of petroleum that is consumed to produce a liter of ethanol is important. During the production of a liter corn grain ethanol, natural gas, purchased electricity use, and petroleum consumption represent 82%, 12%, and 6% respectively of the total direct fossil energy consumed. Approximately 73% of the natural gas is consumed by the ethanol-processing step, while the remaining amount is mainly consumed during fertilizer production. 58% of the electricity purchased is consumed by the ethanol-processing step, while the remaining amount is consumed while producing corn production inputs, such as fertilizer, and by farm machinery. To determine to what extent will corn grain ethanol use displace petroleum, the amount of petroleum consumed during ethanol's production life-cycle and the amount displaced during the use phase is needed. During the production of a liter of ethanol, an average value of 0.03 liters of petroleum is consumed. On an energy and volume basis 1 liter of ethanol is equivalent to 0.7 liters of gasoline. Therefore, the consumption of 1 liter of ethanol displaces 0.67 liters of gasoline. This does not include the transport of ethanol from the processing facility to the vehicle.

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 at best modest GHG abatement benefit when compared to gasoline.

While evaluating *current* corn ethanol production provides insights concerning the major system inputs, it also serves as a baseline for evaluating improved corn ethanol processing, alternative cellulosic ethanol production scenarios, and the impact of greater geographic diversity which is expected as the system grows. To truly have an impact on decreasing the US's petroleum consumption and GHG emissions, biofuels from cellulosic sources needs to become a reality. Chapter 4 examines the life-cycle fossil energy consumption, petroleum displacement, and GHG emissions of ethanol produced from an agricultural residue, corn stover, and a bioenergy crop, switchgrass. Even within these systems, understanding the main system inputs and their impact on the environment is necessary as a variety of feedstock and conversion options can still be adopted.

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Appendix 3A

Tables 3A-1 through 3A-3 are the actual numbers used in the LCA models. Tables 3-1 to 3-3 are values converted from these tables.

Corn Grain Ethanol System Inputs

Direct System Input Values		**Iowa**		**Georgia**	
	Units	***Average***	***Standard Deviation***	***Average***	***Standard Deviation***
Farm Input Values					
Corn Yield[21]	bu/acre	145	21.7	100	32.3
Nitrogen Fertilizer Application Rate[22]	lbs/acre	126.5	5	127	10
Phosphate Fertilizer Application Rate	lbs/acre	62.5	4.77	53	5
Potash Fertilizer Application Rate	lbs/acre	77.2	5.4	79	5
Lime Application Rate[23]	lbs/acre	250	-	250	-
Herbicide Application Rate[24]	lbs/acre	7.3	1.4	7.7	1.2
Insecticide Application Rate	lbs/acre	0.77	0.3	0.32	0.15
Seed Production Planting Rate[25]	kernel/acre	27,300	-	27,300	-
Corn Seed Production Energy Input[e]	BTU/acre	0.609	-	0.609	-
Farm Machinery Electricity[26]	kW-hr/acre	16.8	6.6	29.6	21.8
Farm Machinery Gasoline	gallon/acre	1.2	0.07	2.5	1.36
Farm Machinery Diesel	gallon/acre	4.6	0.29	14.8	3.74
Farm Machinery LP Gas	gallon/acre	7.2	0.74	0.5	0.26
Corn Transport					
Distance (roundtrip)	miles	100	-	100	-

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[21] Corn yield is state specific and gathered from the USDA ERS and NASS database. Iowa's average corn yield is based on a country average corn yields from 1995-2005. Georgia's average corn yield is based on county average corn yields from 1996-2005

[22] Fertilizer application rate data is gathered from the USDA ERS and NASS database. Iowa's average fertilizer application rates were averaged from 1996-2001. Georgia's average fertilizer application rate is from 1996-2003.

[23] 9. Shapouri, H., J.A. Duffield, and M. Wang, *The Energy Balance of Corn Ethanol: An Update*, ed. USDA. 2002.

[24] Herbicide and insecticide state specific date was gathered from the USDA ERS and NASS database

[25] 10. Graboski, M.S., *Fossil Energy Use in the Manufacturing of Corn Ethanol.* 2002: Colorado School of Mines.

[26] All farm machinery was based on the USDA ERS database

Loaded Engine Fuel Efficiency	miles/gallon	5	-	5	-
Unloaded Engine Fuel Efficiency	miles/gallon	8	-	8	-
Trailer Capacity	bu/trailer	875-100	-	875-100	-
Ethanol Processing[27]					
Natural Gas	scf/gallon	34	6.76	34	6.76
Electricity	kW-hr/gallon	1.14	0.38	1.12	0.38
Electricity Generation Efficiency	%	32.5%	-	32.5%	
Ethanol Conversion Efficiency[28]	gallon/bu	2.7	0.2	2.7	0.2

Table 3A- 1 – Corn Grain Ethanol Life-Cycle Assessment System Inputs for Iowa and Georgia

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[27] The natural gas and electricity consumption for an average corn grain ethanol facility was based on 11. Shapouri, H. and P. Gallagher, *USDA's 2002 Ethanol Cost-of-Production Survey*, ed. USDA. 2005.

[28] Based on an average of reported corn grain ethanol conversion values

Upstream Farm Inputs Production Energy

Inputs[29]	*Units*	*Average*
Nitrogen Fertilizer Production		
Natural Gas	scf/lb	16.9
Electricity	kW-hr/lb	0.75
Phosphate Fertilizer Production		
Natural Gas	scf/lb	5.48
Electricity	kW-hr/lb	0.29
Potash Fertilizer Production		
Natural Gas	scf/lb	1.11
Electricity	kW-hr/lb	0.23
Herbicide Production		
Natural Gas	BTU/lb	46,210
Electricity	kW-hr/lb	9.18
Distillate Fuel	BTU/lb	6,165
Naphtha	BTU/lb	31,015
Insecticide Production		
Natural Gas	BTU/lb	50,729
Electricity	kW-hr/lb	11.76
Distillate Fuel	BTU/lb	4,248
Naphtha	BTU/lb	27,276
Lime Production		
Electricity[30]	kW-hr/lb	161.56

Table 3A- 2 – Production Energy for Upstream Farm Inputs for Corn Production

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[29] Fertilizer, herbicide, and insecticide production energy is from: 10. Graboski, M.S., *Fossil Energy Use in the Manufacturing of Corn Ethanol*. 2002: Colorado School of Mines.

[30] 12. West, T.O. and G. Marland, *A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States.* Agricultural Ecosystems and Environment, 2002. **91**: p. 217-232.

2025 Iowa Corn Grain Ethanol System Inputs

Direct System Input Values	*Units*	*Average*	*Standard Deviation*
Farm Input Values			
Corn Yield[31]	bu/acre	203	21.7
Nitrogen Fertilizer Application Rate[32]	lbs/acre	141.75	5
Phosphate Fertilizer Application Rate	lbs/acre	65.6	4.77
Potash Fertilizer Application Rate	lbs/acre	81.1	5.4
Lime Application Rate[33]	lbs/acre	250	-
Herbicide Application Rate	lbs/acre	7.3	1.4
Insecticide Application Rate	lbs/acre	0.77	0.3
Seed Production Planting Rate	kernel/acre	27,300	-
Corn Seed Production Energy Input	BTU/acre	0.609	-
Electricity	kW-hr/acre	16.8	6.6
Gasoline	gallon/acre	1.2	0.07
Diesel	gallon/acre	4.6	0.29
LP Gas	gallon/acre	7.2	0.74
Corn Transport[34]			
Distance (roundtrip)	miles	100	-
Loaded Engine Fuel Efficiency	miles/gallon	7	-
Unloaded Engine Fuel Efficiency	miles/gallon	10	-
Trailer Capacity	bu/trailer	875-100	-
Ethanol Processing[35]			
Natural Gas	scf/gal	28.9	6.76

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[31] Based on an assumed 1.2% yearly increase in corn yields. 13. JP Morgan Securities, I., *Investing in Ethanol*. 2006, North American Corporate Research.

[32] Fertilizer application rates fluctuate between 5-8% of the average between 1996-2002. This study therefore, assumed a 5% increase in fertilizer application rates from 2002 levels in the year 2025. An increase was assumed as increase soil erosion and corn expanding to less productive land, will in the future require more fertilizer.

[33] Lime, herbicide, and insecticide application rates were assumed to stay constant

[34] Engine fuel efficiency was assumed to increase as engine efficiency is continually increasing

[35] Assumed a 7.5% decrease in facility fossil fuel consumption. I was assumed that improvements in machinery efficiency would occur. These values also correlate to the lower numbers being reported today for a corn grain ethanol facility 14. Wang, M., *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions*. 1999, IL: Argonne National Laboratory.

Electricity	kW-hr/gallon	0.95	0.4
Electricity Generation Efficiency	%	32.5%	-
Ethanol Conversion Efficiency[36]	gallon/bu	2.9	0.1

Table 3A- 3 – 2025 Iowa Corn Grain Ethanol LCA System Inputs

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[36] Current ethanol facilities are reporting ethanol conversion efficiencies of 2.9 gal/bu. It was assumed that in the future this value would be the industry average.

Chapter4: Lignocellulosic Ethanol Life-Cycle Assessment

While ethanol is currently produced from sugar and starch, ethanol can also be produced from cellulosic material. Cellulosic-based ethanol is seen as a second generation biofuel, the has the potential to surpass corn grain ethanol in scale. However, currently ethanol produced from cellulosic material is mainly still in the research phase, though pilot test facilities are being built. As ethanol production increases, biomass from agricultural residues as well as dedicated energy crops may be utilized as cellulosic feedstocks. This chapter examines the potential fossil energy consumption, GHG emissions, petroleum displacement, and land use impacts from cellulosic-based ethanol production. This study analyzes the use of corn stover and switchgrass as two potential cellulosic feedstocks. The impacts considered were assessed through a life-cycle assessment model with an integrated Monte Carlo analysis as previously done for corn grain ethanol.

Corn stover is an agricultural residue from corn grain production. It consists of the leaves and stalks of maize plants left on the field after harvest, and has a grain to stover mass ratio of 1:1 [1].

Switchgrass: *(Panicum virgatum)*, an example of a potential energy crop, is a perennial drought-tolerant prairie grass with an extensive natural range in North America [2]. Switchgrass has a variety of cultivars that flourish under different climates. Alamo, Blackwell, Cave-In-Rock, Kanlow, and Trailblazer are just a few cultivar examples [3]. Currently, switchgrass is used as a cover crop on degraded agricultural land.

Lignocellulosic material is a combination of lignin and cellulose that is found in biomass. Biomass is defined as any plant derived organic matter. This includes forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and municipal and industrial wastes. Cellulose is a complex carbohydrate, $(C_6H_{10}O_5)_n$, composed of glucose units, that forms the main constituent of the cell wall in most plants [4]. Cellulose is also important in the manufacturing of numerous products, such as paper, textiles, pharmaceuticals, and explosives. Lignin is a complex polymer, the chief non-carbohydrate constituent of biomass, which binds to cellulose fibers, hardening and strengthening the cell walls of plants [4].

Ethanol produced from cellulosic sources, such as corn stover and switchgrass, undergoes different pretreatment and conversion steps than corn ethanol due to its different molecular structure and mass components. Corn stover and switchgrass have three main components, cellulose, hemicellulose and lignin. Table 4-1 breaks down the average mass fractions of these feedstocks. 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 [4]. In some cases excess heat can be used to produce electricity that can be used on site or sold to the electric grid. In this case, electricity sold to the grid would be considered a coproduct to cellulosic ethanol production.

	Corn Stover	Switchgrass
Cellulose	36.2%	32%
Hemicellulose	23.2%	25.2%
Lignin	18.5%	18.1%
Protein	0%	0%
Oil	0%	0%
Extractives	8.1%	17.5%
Acids	3.2%	1.2%
Ash	10.7%	6%

Table 4- 1 – Corn Stover and Switchgrass Mass Fractions [1, 5, 6]

The availability of large amounts of biomass from agricultural residues and forest waste make biofuels from lignocellulosic material desirable. Additionally, these types of biomass sources along with various bioenergy crops provide an opportunity to decentralize biofuels production from the Corn Belt. The utilization of the lignin as a power source also reduces the life-cycle fossil energy consumption and GHG emissions compared to corn grain ethanol.

For this study, all corn stover results are from an MIT PhD thesis by Jeremy Johnson, *Technology Assessment of Biomass Ethanol: A multi-objective, life-cycle approach under uncertainty* [7]. A full life-cycle assessment of switchgrass is completed in this study and compared to Jeremy Johnson's previously reported corn stover results. Given that the agricultural production of switchgrass and cellulosic ethanol production is still in the research phase, a future scenario was created to assess the potential impact of improvements this system may realize.

History of Bioenergy Feedstock Development Program in the US

The Department of Energy (DOE) begun the Bioenergy Feedstock Development Program (BFDP) at Oak Ridge National Laboratory (ORNL) in 1978 to identify and develop fast growing trees and herbaceous crops as a potential renewable energy source. BFDP also assessed the potential of agricultural residues as a source of biomass feedstock for the nations future energy needs [3, 8]. The major components of BFDP include energy crop selection and breeding, crop management research, environmental assessment, and crop production and supply logistics [9]. The program focused on two types of biomass, short rotation forest trees such as poplar, willow, and cottonwoods, and herbaceous crops such as fast growing high yielding grasses [3, 9]. Crop development centers were created within regions as a strategy, for advancing energy crops. Initially the BFDP focused on identifying the best species and geographic regions. The evaluation was based on species comparisons through field trials to select promising lignocellulosic herbaceous crop species based on biomass yields (Mg/ha) [3].

Projects were started in the Southeast (Auburn University, Virginia Polytechnic Institute and Virginia State University), the Midwest, and Lake states (Cornell University, Geophyta, and Purdue University) [9]. These areas were chosen due to their large amounts of cropland and relatively few environmental restrictions on productivity, such as rain fall, soil conditions, and climate. [9]. Throughout the years additional test sites were started in the Great Plains (Iowa State University and North Dakota State University) as well. Each study compared a number of different species under different crop management practices. The switchgrass inputs and results of these reports are used as system inputs for the switchgrass life-cycle assessment that will be discussed in later sections.

In 1991, switchgrass was identified as a model herbaceous crop with the potential for widespread use throughout the United States. Research efforts were then focused at comparing different cultivars (plant species), improving yield, standardizing crop management practices, breeding, and performing basic studies of biological processes [9]. While switchgrass is the first chosen species for development as a bioenergy crop the BFDP recognizes that alternative species such as short rotation woody crops (hybrid poplars, eucalyptus, and willows) may also be potential candidates [10]. These other species can be grown in geographic regions where switchgrass is not optimal, which can provide alternatives for producers. They also potentially can obtain higher yields in some locations, and have desired chemical characteristics that make them desirable for chemical conversion [9].

Corn Stover as a Biomass Feedstock

While today ethanol is produced from corn grains, the potential next step will be utilizing agricultural residue as a feedstock for cellulosic ethanol production. Agricultural residues, such as corn stover, are seen as the initial feedstock for a cellulosic ethanol industry as they are readily available and located within an existing ethanol production and distribution network. The biomass ratio of corn kernels to corn stover is typically 1:1 on a dry basis [7]. Therefore from this ratio, in 2006 approximately 332 million metric ton of corn stover was produced. In the future as corn production increases due to increased ethanol demand, the production of corn stover will also increase as they are dependent.

Currently, as a combine passes over the field, it uptakes the entire corn plant harvesting the corn kernels and returning the corn stover to the field. Corn stover, left on the ground, provides protection to the soil from wind and water erosion. Additionally, during the decomposition process, stover returns nutrients back into the soil decreasing the amount of fertilizer required the subsequent year. It also adds organic matter back into the soil increasing biological activity which serves as a vital link in the dynamics of soil nutrient storage, release and use by plants [1]. These positive environmental impacts reduce soil quality degradation over time and minimize fertilizer application rates. Therefore, when considering stover as a feedstock, long term research is needed to determine the maximum quantity that can be removed without having negative environmental impacts on the soil. Initial studies have indicated an allowable removal rate of 30%-50% [1, 7, 11]. In our study a removal rate of 30% is is always assumed.

All the fossil energy consumed in growing the corn plant, as defined in Chapter 3, is allocated towards corn grain production, as stover is currently seen as a residue [7]. Therefore, for this analysis the only agricultural fossil energy associated with corn stover is due to its collection, removal, and packaging. The main ethanol conversion steps for converting corn stover into ethanol are described later within this chapter. The main difference in determining the ethanol yield from various cellulosic feedstocks like corn stover and switchgrass is the mass fractions of cellulose and hemicellulose.

Agricultural Production of Switchgrass

Characteristics of Switchgrass

Switchgrass (Panicum virgatum) is a warm season (C_4) perennial that is a rapidly growing North American tall prairie grass [6, 8] Switchgrass has a geographic range that covers most of the US and extends into Canada, with a northern limit of 51°N (Figure 4-1) [6]. Due to milder winters at comparable latitudes, switchgrass may be grown in higher latitudes in Europe. Currently switchgrass, along with other native prairie grasses have become important as forage grasses in the Midwest because of their capacity to grow in the hot summer months with limited water [6, 12].

Figure 4- 1 Switchgrass (www.newfarm.org)

Switchgrass is categorized as lowland or upland ecotypes. Lowland ecotypes are categorized as tall and thick-stemmed plants that can adapt to wet conditions. Upland ecotypes are described as short, rhizomatous, thin-stemmed plants that can adapt well to drier conditions [6, 13]. Examples of lowland varieties are Alamo switchgrass which is typically grown in the Deep South and mid-latitudes, as well as Kanlow which are more tolerant of cold temperatures and is recommended to be grown in mid-latitudes [3, 6]. Upland switchgrass varieties include Cave-In-Rock, Blackwell, and Trailblazer which are recommended to be grown in the central and northern states [6, 13]. Both ecotypes are high yielding drought tolerant grass that have low nutrient demands, can be grown in diverse geographic locations, and can provide important soil and water conservation benefits [3, 6].

Unlike the single planting and cultivation season for corn, switchgrass is planted once and cultivated over a ten-year period [3]. Eliminating an annual planting cycle reduces soil loss and soil degradation. Additionally, switchgrass has an extensive rooting system that can range from 2.6m to 3.7m, with an annual below ground production of two to four times the above ground biomass production [3, 6]. This extensive rooting system helps decrease soil erosion rates through stabilizing soil, capturing nutrients more efficiently, reducing leaching losses, and increasing organic matter through increased biological activity. Significant quantities of organic matter improve soil structure, increase water holding capacity through porosity changes, and improve nutrient conservation [3]. Additionally, the continuous crop cover intercepts rainfall and decreases erosion potential [14]. Currently, a range of varieties of switchgrass are used extensively on acreage set aside by the federal Conservation Reserve Program (CRP) to minimize erosion. Switchgrass is also often planted as streamside buffers, or vegetative filter strips, due to its stiff stems that act like barriers to slow runoff, promote infiltration, and encourage in-field sedimentation [6]. Blanco-Canqui *et al.* (2004) estimated that a switchgrass barrier reduced nitrogen runoff by 4.9 times, reduced phosphorus runoff by 3.7 times, and reduced sediment loss by 1.5 times [6, 15]. Switchgrass also provides an ecological value as a wildlife habitat, especially for birds [6].

Switchgrass can be easily adopted into current farming operations because conventional farming equipment can be used for seeding, crop management, and harvesting [16]. The first year or planting year for switchgrass is dedicated to plant establishment and weed control. During the first year only 30% of the maximum yield is expected. The second year continues with weed management and minimal fertilization with yields increasing to two-thrids the maximum expected yield. Full yields are assumed for years three through ten with fertilizer application [3, 16, 17]. While corn ethanol results represent a single planting year, switchgrass ethanol results are represented over a ten-year average crop yield. This incorporates the varying inputs over the lifetime of the crop.

Crop management practices such as harvesting time, can minimize the environmental impacts of switchgrass production. For example, harvesting switchgrass at optimal time periods can decrease the amount of fertilizer needed in the following year. This is because throughout the growing season nitrogen and other nutrients accumulate in the above-surface mass of the plant [18]. However, in preparation for winter the nutrients relocate from the shoots to the roots [18]. Therefore, harvesting switchgrass after a killing frost (during the Fall) when nutrients are in the roots reduces the amount of nutrient application needed the following year, as nutrients within the roots are retained

[18]. The entire above ground portion of the plant is assumed to be harvested leaving the rooting system in place eliminating the need for yearly plantings.

Switchgrass, being very similar to alfalfa and hay, is harvested and baled using similar practices and equipment. Once baled, switchgrass will need to stored either on the farm, at a storage facility, or at the ethanol facility site [2, 19]. This is one area where continued research is needed to determine the most cost effective option. If left on the field, the bales may need to be covered to prevent them from getting wet and rotting [20]. In a storage facility, issues related to the potential of spontaneous combustion of the biomass will need to be addressed. Additionally, the costs of loading and unloading at an additional facility will need to be considered. Typically ethanol facilities have storage space to accommodate one months worth of feedstock. Therefore, more space would be needed to have switchgrass stored at a facility.

Switchgrass Agricultural System Inputs

This section describes the agricultural system boundary for analyzing the fossil energy consumption and GHG emissions of switchgrass production. There a range of switchgrass cultivars that flourish under certain growing conditions and climates. The Southern Plains of the United States have been reported as having the greatest potential for growing Alamo switchgrass, and specifically Alabama [3]. Therefore, to decrease system variability and determine the systems sensitivity to geographic location Alamo switchgrass production was analyzed in Alabama. This scenario represents our best cellulosic case scenario. Cave-In-Rock switchgrass grown in Iowa was chosen as an alternative cultivar and state for its regional differences and the availability of state specific data.

Switchgrass agricultural data was gathered from a variety of published papers, government and national laboratory reports, and university publications [3, 8, 10, 12, 13, 16, 21-26]. Switchgrass crop management, yearly yield, and growing characteristics were gathered from [3, 8, 10, 13, 16, 17, 24-27]. Databases from the Energy Efficiency and Renewable Energy division of US DOE[37] were used to gather physical properties and cellulose, hemicellulose, and lignin mass fractions for modeling Alamo switchgrass [10, 27-29]. Modeling the mass fractions of switchgrass was needed to determine the ethanol conversion rate at different conversion efficiencies. This model will be discussed in later in the chapter.

The agricultural system boundary for switchgrass ethanol includes:

1. Nitrogen, Phosphate fertilizer production, transport, and application rates
2. Herbicides production, transport, and application rates
3. Farm machinery fossil fuel consumption
4. Switchgrass yield that is year dependent

Table 4-2 lists the inputs and values that were assumed for this analysis. All the input data is state specific and being that the data was complied from research test plots the standard deviations are larger than seen in corn production. Switchgrass is also assumed to be harvested with conventional alfalfa and hay harvesting equipment and stored as bales on the field. All system input distributions were modeled as normal defined by their average and standard deviation.

Switchgrass Ethanol System Inputs

Direct System Input Values		Alabama		Iowa	
	Units	*Average*	*Standard Deviation*	*Average*	*Standard Deviation*
Farm Input Values					
Switchgrass Yield					
Year 1	Mg/ha	4.5	1.5	3.8	0.9
Year 2	Mg/ha	9.9	3.1	8.3	1.9
Year 3 - 10	Mg/ha	14.9	4.6	12.5	2.8
Nitrogen Fertilizer Application Rates					

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[37] 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

Year 1-2	kg/ha	-	-	-	-
Year 3 - 10	kg/ha	84.6	37.9	130.0	24.6
Phosphate Fertilizer Application Rates					
Year 1 - 2	kg/ha	16.8	3.4	16.8	3.4
Year 3 - 10	kg/ha	-	-	-	-
Herbicide Application Rates					
Year 1-2	kg/ha	1.6	0.6	1.6	0.6
Year 3 - 10	kg/ha	-	-	-	-
Fuel Farm Machinery					
Year 1-2	l/ha	44.9	3.7	44.9	3.7
Year 3 - 10	l/ha	16.4	3.3	16.4	3.3
Switchgrass Transport					
Distance (roundtrip)	miles	100	-	100	-
Loaded Engine Fuel Efficiency	km/l	2.1	-	2.1	-
Unloaded Engine Fuel Efficiency	km/l	3.4	-	3.4	-
Trailer Capacity	Mg/trailer	23.5	-	23.5	-
Switchgrass Mass Fractions[38]					
Cellulose	%	33.6	1.3	33.6	1.3
Hemicellulose (Xylan)	%	26.2	0.1	26.2	0.1
Lignin	%	18.7	1.6	18.7	1.6
Ethanol Processing[39,40]					
Xylan to Xylose Yield	%	67.5	-	67.5	-
Cellulose to Glucose Yield	%	63.5	-	63.5	-
Xylose to Ethanol	%	90.2	-	90.2	-
Glucose to Ethanol Yield	%	95.0	-	95.0	-
Ethanol Yield					
Switchgrass Ethanol (Current Day)	l/ha	3,165	500	3,375	500

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[38] Energy Efficiency and Renewable Energy, Alternative Fuels Comparison Chart, Biomass Feedstock Composition and Property Database http://www1.eere.energy.gov/biomass/feedstock_databases.html and from 28. Laser, M., *Switchgrass Composition Method.* 2004.

[39] 11. Aden, A., et al., *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover.* June 2002, Golden, Colorado: National Renewable Energy Laboratory.

[40] 29. Sheehan, J. and A. Aden, *Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol.* Journal of Industrial Ecology. Vol. 7. 2004. 117-146.

Switchgrass Ethanol (Current Day)	l/Mg	238	37	238	37
Switchgrass Ethanol (Current Day)	gal/dry ton	63	10	63	10
Switchgrass Ethanol (Future)	l/ha	7,183	1,200	-	-
Switchgrass Ethanol (Future)	l/Mg	328	10	-	-
Switchgrass Ethanol (Future)	gal/dry ton	87	7	87	7

Table 4- 2 – Switchgrass to Ethanol LCA System Model Inputs.

Since historic trends for switchgrass are not available to estimate future input values, biomass yield and conversion efficiency values were assumed for the year 2025 using published projections. The input values for the switchgrass future scenario are in Table 4-3. As this is an agricultural crop that has not been grown to maximize yield, there is great potential for improvements in the future. Continued research focusing on improved crop management practices such as optimal seeding rate, herbicide and fertilizer application rates all can improve yield over time. Additionally, if this crop begins to be used a bioenergy crop, farmers will gain experience over time and adjust their farming practices to improve the crops yield. Science can also play a role through genetic engineering to improve switchgrass yields, as it has with corn yields. Therefore, a 2% yearly yield increase was assumed resulting in a yield of 24.4 ± 7.5 Mg/ha in the year 2025 [3]. A 2% yearly yield increase has been seen in other crops such as corn grains whose yields initially increased 3-5% per year [3, 30].

2025 Alabama Switchgrass Ethanol System Inputs

Direct System Input Values	*Units*	*Average*	*Standard Deviation*
Farm Input Values			
Year 1	Mg/ha	7.3	2.5
Year 2	Mg/ha	16.3	5.1
Year 3 - 10	Mg/ha	24.4	7.5
Nitrogen Fertilizer Application Rates			
Year 1-2	kg/ha	-	-

Year 3 - 10	kg/ha	76	36.7
Herbicide Application Rates			
Year 1-2	kg/ha	1.6	0.6
Year 3 - 10	kg/ha	-	-
Phosphate Fertilizer Application Rates			
Year 1	kg/ha	16.8	3.4
Fuel Farm Machinery			
Year 1-2	l/ha	44.9	3.7
Year 3 - 10	l/ha	16.4	3.28
Switchgrass Mass Fractions[41]			1.4
Cellulose	%	33.6	1.29
Hemicellulose (Xylan)	%	26.2	0.1
Lignin	%	18.7	1.55
Switchgrass Transport			
Distance (roundtrip)	miles	100	-
Loaded Engine Fuel Efficiency	km/l	3	-
Unloaded Engine Fuel Efficiency	km/l	4.3	-
Trailer Capacity	Mg/trailer	23.5	-
Ethanol Processing[42,43]			
Xylan to Xylose Yield	%	90	-
Cellulose to Glucose Yield	%	90	-
Xylose to Ethanol	%	90	-
Glucose to Ethanol Yield	%	95	-

Table 4- 3 – 2025 Switchgrass to Ethanol LCA Models Inputs

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[41] Energy Efficiency and Renewable Energy, Alternative Fuels Comparison Chart, Biomass Feedstock Composition and Property Database http://www1.eere.energy.gov/biomass/feedstock_databases.html and reference 28. Laser, M., *Switchgrass Composition Method.* 2004.

[42] 11. Aden, A., et al., *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover.* June 2002, Golden, Colorado: National Renewable Energy Laboratory.

[43] 29. Sheehan, J. and A. Aden, *Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol.* Journal of Industrial Ecology. Vol. 7. 2004. 117-146.

Switchgrass Agricultural Energy Consumption & GHG Emission Results

Figure 4-2 and Figure 4-3 display the fossil energy and GHG emission PDFs for the agricultural inputs for Alamo switchgrass grown in Alabama. The variable is represented by a white box symbol with whiskers. The white 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) [31]. The fossil energy consumed is broken down by year, as different agricultural inputs are required. The highest amount of energy per hectare is consumed during year 1, the establishment year, as switchgrass yield is only a third of its potential. The focus during this year is weed management, as large amounts of weeds will result in lower over switchgrass yields the following years. Years 3-10 are the lowest energy intensive years as minimum fertilizer is applied and full yields are realized. When considering all agricultural inputs averaged over a ten year production time, 1,300 MJ/ha of energy is consumed.

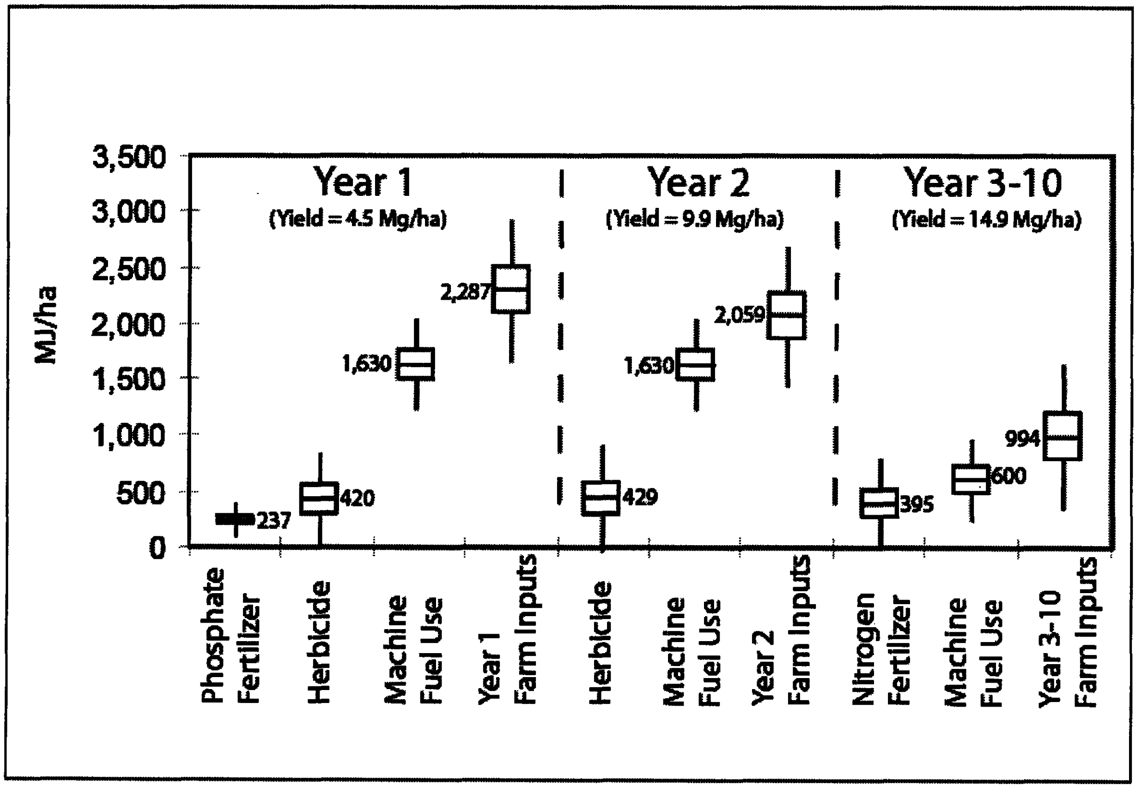


Figure 4- 2 – Alabama Alamo Switchgrass LCA Farm Inputs (MJ/ha)

These agricultural results are based on experimental test plots and USDA growing recommendations [3, 10, 13, 16, 23]. Currently, there is no economic incentive for a farmer to increase switchgrass yields, and thus these results represent that situation. In the future, if switchgrass is cultivated for biofuels production, an economic incentive will lead farmers to improve yields by changing their crop management practices. This may lead to increased fertilizer application rates and irrigation. These increases in agricultural inputs would lead to higher fossil energy consumption though also higher yields. Therefore, while these results show a significant benefit compared to corn grain production, in the future this benefit may be smaller and needs to be considered when making policy choices.

Switchgrass Transport & Handling

Once switchgrass is baled it will need to be transported to a storage facility and/or a cellulosic ethanol facility. The transport of switchgrass was modeled after the transport of other forage crops such as alfalfa and hay which can be transported by trailer. Figure 4-3 and 4-4 present an example of baled and transported switchgrass.

Figure 4-3 – Baled Switchgrass (www.agweb.com)

Figure 4-4 – Transporting Switchgrass [2]

The switchgrass transport sector assumptions include:

1. Switchgrass bales and transport capacity information was modeled with respect to hay cultivation and transport [20].
2. Diesel fuel consumption assuming a 100-mile roundtrip from the farm location to the ethanol processing plant [32]
3. Semi-trailer truck capacity 23.5 ton/truck [20]
4. Semi-trailer truck loaded engine efficiency (5 miles/gal) and unloaded engine efficiency (8miles/gal) [33]

The costs associated with switchgrass handling and transport can be large. Being a low density material switchgrass is more costly to transport than corn grains for the same mass. Research has been conducted to examine the cost impact of preprocessing the biomass on the farm to improve transport costs. Transport and handling costs, without preprocessing, have been estimated from \$5/dry ton-mile to \$10/dry ton-mile, for within a 50 mile radius [32, 34-36]. Transport costs directly affect the biomass transport distance and thus the potential geographic regions that can supply a large scale cellulosic facility.

Switchgrass Transport Energy Consumption and GHG Emissions

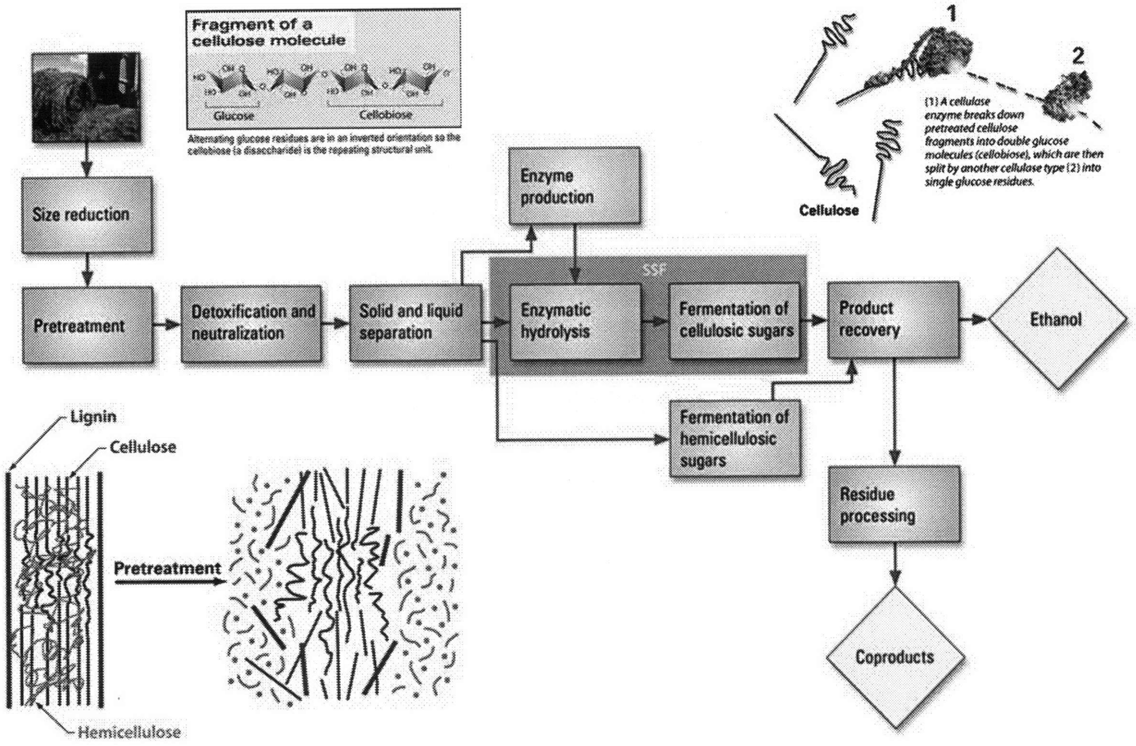
Switchgrass is assumed to be transported by trailer at a capacity of 23.5 ton/truck [20]. For an assumed 100 mile roundtrip shipping distance, 94 MJ per Mg of switchgrass (0.36 MJ/L-Ethanol) is consumed emitting 8,370 gCO2-equivalents per Mg of transported switchgrass. In the future, preprocessing techniques to increase the transportation capacity could further decrease the energy consumption and GHG emissions associated to this sector

Lignocellulosic Ethanol Production

Overview of Lignocellulosic Ethanol Production

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. Ethanol processing information and conversion efficiencies were obtained from published reports [11, 29, 37-40].

The biochemical conversion of cellulosic biomass to ethanol currently involves three primary steps which will be discussed in detail (Figure 4-5) [2]. Step 1 is the size reduction and thermo chemical pretreatment of raw cellulosic biomass to make cellulose polymers more accessible to enzymatic breakdown and free up hemicellulosic sugars (Figure 4-6 and 4-7) [2]. Step 2 is the production and application of special enzyme preparations (cellulases) that hydrolyze plant cell-wall polysaccharides, producing a mixture of simple sugars (Figure 4-8) [2]. Step 3 is the fermentation, mediated by bacteria or yeast, to convert these sugars to ethanol and other coproducts.



Alternating glucose residues are in an inverted orientation so the cellobiose (a disaccharide) is the repeating structural unit.

(1) A cellulase enzyme breaks down pretreated cellulose fragments into double glucose molecules (cellobiose), which are then split by another cellulase type (2) into single glucose residues.

Figure 4- 5 – Traditional Cellulosic Ethanol Conversion, with Pretreatment & Hydrolysis [2]

Step 1: Biomass size reduction and pretreatment process

Figure 4-6 contains a pictorial representation of a plants cell wall, which shows the cellulose, hemicellulose, and lignin intertwined. For the enzymes to be affective in breaking down the cellulose and hemicellulose to simple sugars, they first need to be exposed [2, 11]. This pretreatment process is needed to increase the accessibility of cellulose to enzymes that will later be converted to sugar [2, 11]. Pretreatment happens with heat, enzymes, and/or acids that destroys the matrix of polymers so that the cellulose is accessible during hydrolysis (Figure 4-7) [2, 11]. Pretreatment is an additional step from the starch to ethanol conversion process and is one of the most expensive processing steps due to large equipment cost and the high costs of enzymes [2, 11]. Two companies that are advancing research to decrease the cost of enzymes are Genencor and Novozymes Biotech. Currently enzymes costs between $0.8-$0.26/L ($0.3-$1.0/gal) and are needed to decrease to $0.03/L ($0.1/gal) to be cost competitive with corn grain ethanol. The efficiency of the pretreatment process impacts the ethanol yield of lignocellulosic materials [2, 11]. Improving this process has been a major obstacle to making lignocellulosic ethanol high yielding and cost competitive.

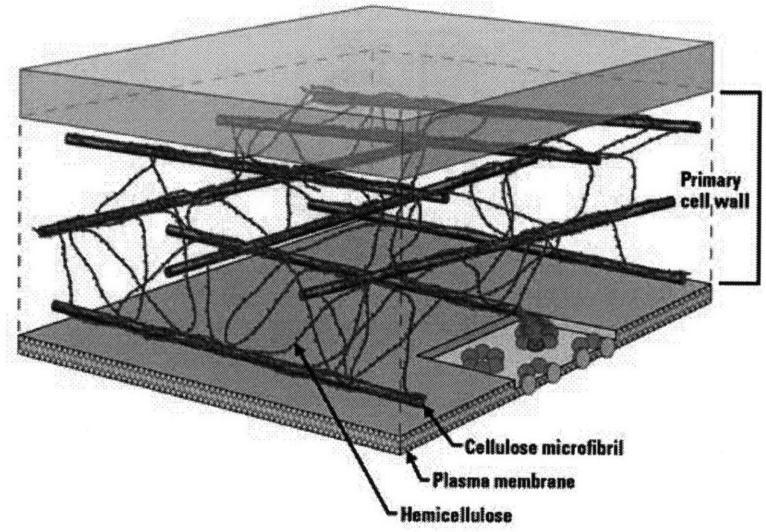


Figure 4- 6- Simplified Model of a Primary Plant Cell Wall. The cellulose core is surrounded by hemicellulose, a five carbon (pentose) and six carbon (hexose) sugars [2]

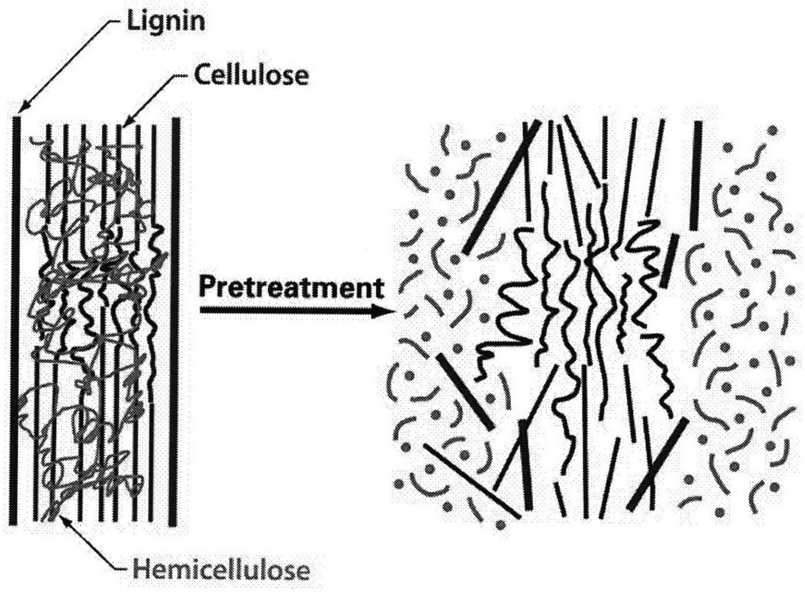
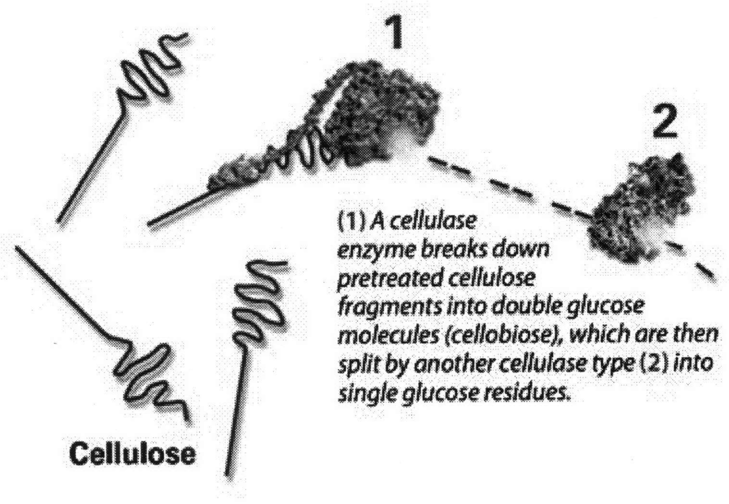


Figure 4- 7 – Cellulosic Ethanol Biomass Pretreatment Process. The goal is to make cellulose assessable to enzymatic breakdown (hydrolysis) and solubilize hemicellulose [2]

Step 2: Enzyme application and hydrolysis

Once the cellulose and hemicellulose is exposed, enzymes are then used to break them down to sugars that can then be fermented. This process is called hydrolysis [2, 11, 29]. Cellulose is a six carbon carbohydrate, similar to starch and therefore enzymes to break down this type of molecule are already developed at high conversion rates. Enzymes such as cellulases are synthesized by fungi and bacteria to work together to degrade cellulose and other structural polysaccharides in biomass [2, 11]. However, hemicellulose is a five carbon molecule and therefore enzymes to break down this type of molecule are currently being developed to increase the cellulosic yield from biomass feedstocks [2, 11, 29]. Current hemicellulose to sugar conversion rates have been demonstrated at 67.5% in laboratory tests at NREL [11].



(1) A cellulase enzyme breaks down pretreated cellulose fragments into double glucose molecules (cellobiose), which are then split by another cellulase type (2) into single glucose residues.

Figure 4- 8 – Hydrolysis of Cellulose to Sugars. Enzymes are synthesized by fungi and bacteria work together to break down cellulose into fermentable sugars [2].

Step 3: Fermentation

Once cellulose and hemicellulose are broken down to simpler sugars, the next step of fermentation can begin. Fermentation is the biological process in which yeast convert sugars to ethanol and carbon dioxide under anaerobic conditions [2]. While there is no commercial scale lignocellulosic ethanol facility, research test have shown a current ethanol yield rate of 238±6.4 liter/Mg at a 67.5% conversion efficiency [2, 11, 29]. This conversion rate again depends on the mass fraction of the biomass, the efficiency of pretreatment process, the hydrolysis efficiency, and fermentation [2]. Therefore, as research continues to improve the efficiencies of these processes the ethanol yield from cellulosic sources will increase. At a 90% conversion efficiency 328±9.1 liter/Mg of ethanol would be produced from switchgrass [11, 29]. Switchgrass has a theoretical maximum ethanol yield of 432±12 liter/Mg.

The following equations represent the main chemical conversion steps in converting cellulose and hemicellulose to ethanol. The cellulosic ethanol conversion efficiency was modeled based on published switchgrass mass fractions and demonstrated ethanol conversion yields [5, 11, 29].

Cellulose To Ethanol [11, 29]

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

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6 \qquad \text{Equation 4- 1}$$

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

$$C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2 \qquad \text{Equation 4- 2}$$

Hemicellulose to Ethanol [11, 29]

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

$$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5 \qquad \text{Equation 4- 3}$$

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

$$3C_5H_{10}O_5 \rightarrow 5C_2H_6O + 5CO_2 \qquad \text{Equation 4- 4}$$

Through the process of distillation ethanol is then separated out of the "beer" as a 190 proof or a 96% ethanol mixture [11]. This mixture then undergoes a dehydration step where the remaining water is removed by a molecular sieve resulting in 200 proof ethanol called anhydrous ethanol. The 200 proof ethanol is then denatured by adding 5% gasoline to prevent human consumption [11].

The remaining residue contains mainly lignin and some of the cellulose and hemicellulose from the feedstock that remains unconverted through the hydrolysis process [2]. Anaerobic digestion (AD) is used to convert this remaining waste water, which is high in soluble solids, to a biogas high in methane and small amounts of waste biomass called sludge [2, 11]. AD is the biological degradation of organic matter in the absence of air. The methane and sludge produced from AD can then be burned to generate steam and electricity. The use of these two waste streams enable the facility to be self sufficient in energy, reduces soil waste disposal costs, and generates an additional revenue stream through selling excess electricity to the grid as a coproduct [2, 11]. Utilizing the remaining biomasses chemical energy, mainly from lignin, eliminates the need for additional fossil fuel consumption which in a corn grain ethanol facility accounts of 60-70% of the total life-cycle fossil energy use and GHG emissions. This is one of the main reasons lignocellulosic ethanol has a high NEV and low life-cycle GHG emissions when compared to corn grain ethanol and gasoline.

Lignocellulosic Ethanol Model and Assumptions

Lignocellulosic ethanol from switchgrass was modeled based on the assumptions and equations defined earlier in the chapter. All corn stover results are based on [7]. While the corn grain ethanol industry provides the ethanol conversion efficiency data needed for a life-cycle assessment, the ethanol conversion rate from switchgrass is not as widely known or accepted as the process is still in the research phase. Therefore, for this analysis the ethanol yield from switchgrass was determined based on the mass fractions of cellulose and hemicellulose in switchgrass and equations 4-1 through 4-4. Probability distributions were created to represent the mass fractions of cellulose, hemicellulose, and lignin to account for this variability in the composition of switchgrass. Databases from the Energy Efficiency and Renewable Energy division of US DOE[44] were used to gather physical properties and cellulose, hemicellulose, and lignin mass fractions for modeling

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[44] 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

Alamo switchgrass [10, 27-29]. This was then used to determine the ethanol conversion rates at different conversion efficiencies.

While Table 4-2 and equations 4-1 through 4-4 provide the ethanol conversion efficiencies assumed as a present value, in the future this ethanol conversion rate is assumed to increase from the current demonstrated levels of approximately 65% to the projected future level of 90% [11, 29]. The 2025 future switchgrass scenario inputs are defined in Table 4-3.

The ethanol processing sector assumptions:

1. All process steam and electricity is obtained through the burning of lignin [2, 11, 29]
2. Additional electricity may be produced from excess process energy that can then be sold to the gird. This is considered a coproduct of this process. For this analysis coproduct credits are <u>not included</u> as the amount of electricity sold to the grid depends on the facility's design [2, 11].
3. Ethanol yield is calculated from the mass fractions of cellulose and hemicellulose in switchgrass (Equations 4-1 to 4-4).
4. Enzyme, chemical, and yeast production energy are excluded
5. Embodied facility structural energy is not included

Lignocellulosic Ethanol Energy Consumption and GHG Emission Results

The section presents and discusses the fossil energy consumption and GHG emissions associated with cellulosic ethanol production from corn stover and switchgrass. Figure 4-9 and Figure 4-10 displays the NEV and GHG emissions for five different scenarios. All cellulosic ethanol scenarios have high NEV's as it is assumed that the unprocessed lignin will provide the cellulosic ethanol facilities energy for steam and electricity. Corn stover ethanol production energy consumption is made up of the energy needed to collect, preprocess, handle, and transport the stover from the field to a processing facility. The majority of the energy consumed in this scenario is during the collection and preprocessing. Switchgrass ethanol's NEV is only slightly higher than ethanol produced from corn stover due to its lower agricultural inputs. Switchgrass grown in Iowa resulted in negligible NEV and GHG emission difference, showing that geographic variation has little impact, at least between these two states. Geographic variation can still be a factor in other states where switchgrass was originally not native.

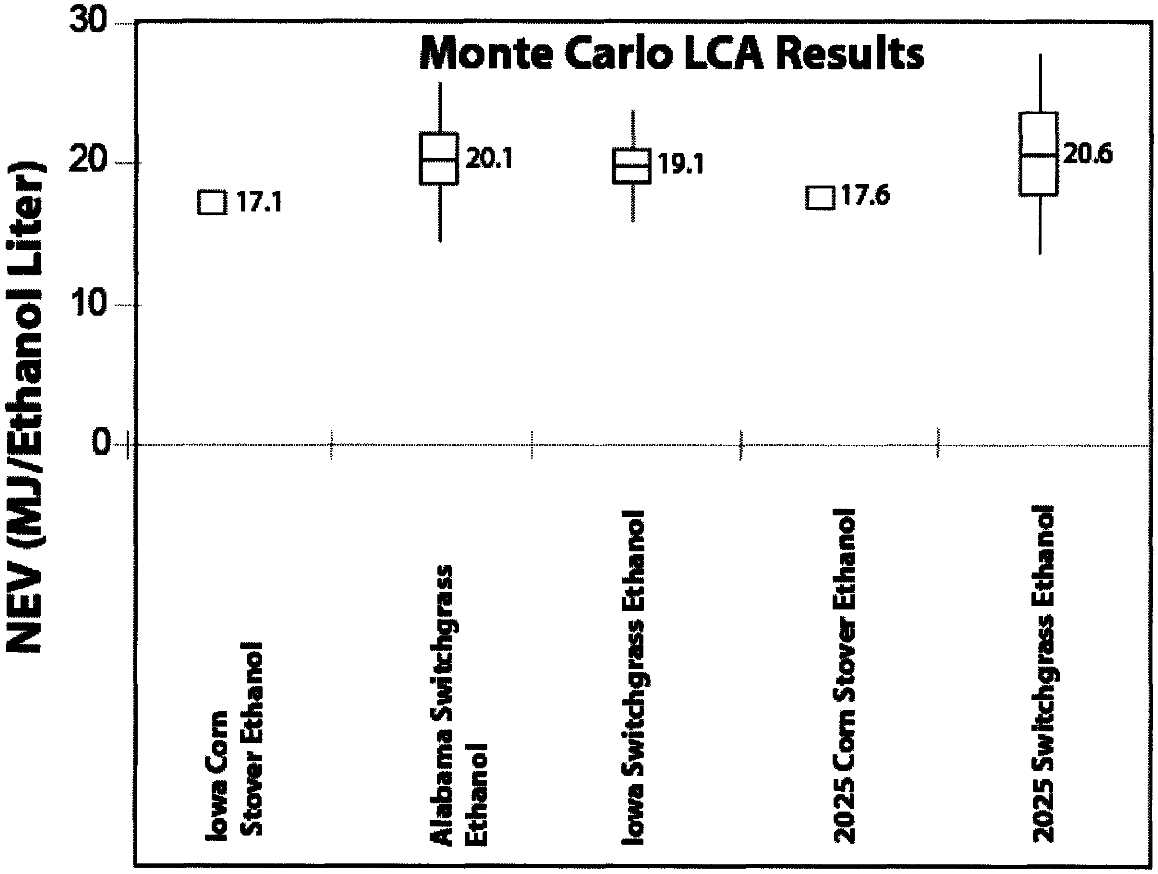

Figure 4- 9 – Cellulosic Ethanol LCA Net Energy Values – (MJ of fossil energy consumed per liter of ethanol produced). Based on the LHV

In the future, even with improved crop management practices, increased biomass yield, and increased cellulosic ethanol conversion yields, there is almost no change in the average value for the NEV and GHG emissions, though the standard deviation is larger. Compared to gasoline, cellulosic ethanol from corn stover and switchgrass reduces GHG emissions by 70% and 95% respectively.

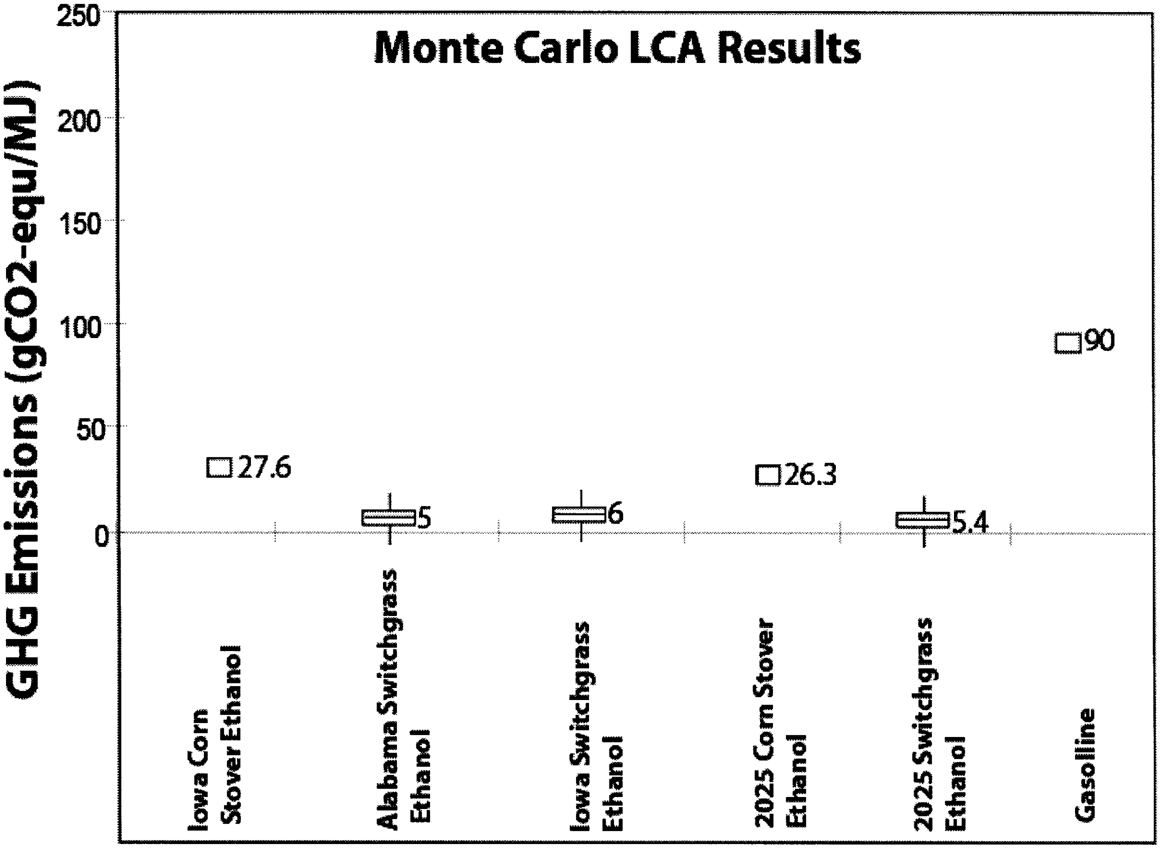

Figure 4- 10 – Cellulosic Ethanol LCA Greenhouse Gas Emissions – (gCO_2 equivalent per MJ of fuel). Results for gasoline represent today's average value including upstream and downstream emissions. For gasoline consumption, the 18 gCO_2-equivalent represents the upstream emissions, and 72 gCO_2-equivalent represent its combustion.

The main reason for this is the utilization of lignin by the ethanol processing facility for its power needs. Though to realize these GHG benefits many challenges will still need to be overcome. With corn stover as a feedstock, research is still needed to determine a maximum removal rate that minimizes additional environmental impacts. Additionally, new techniques and possible machinery will need to be developed to minimize damage to the top soil. With switchgrass as a feedstock, the large scale agricultural process will need to be developed. Major challenges will include improving biomass yields, and developing storage options. Additionally, unlike corn stover which is an agricultural residue, switchgrass as a bioenergy crop would need an existing cellulosic market and/or government incentives to provide the economic security needed to move acres into production. Chapter 5 will summarize and discuss the LCA results thus far for corn grain, corn stover, and switchgrass based ethanol production.

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Chapter 5: LCA Comparison of Bioethanol Production Pathway's

Thus far this study has modeled and assessed the fossil energy, GHG emissions, and petroleum displacement of ethanol production from corn grains, corn stover, and switchgrass. Each of these scenarios has been discussed in chapters 3 and 4, independently of the others. The goal of this chapter is to compare the different bioethanol production pathways and highlight where differences between options arise. This chapter will also evaluate and discuss the land use efficiency for these different feedstocks. This is needed as the scale of production ultimately depends on the most optimal use of land.

The main starch and cellulosic ethanol production pathways modeled and evaluated are *Corn Grain Ethanol, Corn Stover Ethanol,* and *Switchgrass Ethanol.* Within each pathway there are additional scenarios that were analyzed to evaluate how different aspects of the system affect the results. For example, scenarios that represent different geographic regions or alternative uses of coproduct credits are considered as well. These three main scenarios are then projected into the future some 20 years to evaluate how improving aspects of the system can impact future fossil energy consumption and GHG emission results. Their detailed descriptions and analysis assumptions are given in Chapters 3 and 4. Below is simply a summary of the scenarios considered under each feedstock option:

Life-Cycle Assessment Scenario Summaries

Corn Grain Ethanol (Chapter 3)

- **Iowa Corn Grain Ethanol** – This scenario looks at corn grain ethanol production in Iowa. Agriculture characteristics of Iowa are used to represent a corn grain ethanol scenario from a high corn yield state from the Corn Belt. This scenario is intended to represent the most efficient option as Iowa is the state with the highest average corn yield [1]. No coproducts are assumed for this scenario.

- **Georgia Corn Grain Ethanol** – Corn grown in Georgia was analyzed to illustrate the affect of growing corn for ethanol production in a traditionally low corn producing state outside the Corn Belt. This scenario was chosen to demonstrate the affects of using different geographic regions for corn production. Understanding this will become increasingly important as the entire ethanol system expands and new lands are utilized for corn production. In this scenario it is also assumed that the corn produced would be shipped to an ethanol conversion facility in the Corn Belt initially. In the future, if enough of the feedstock was locally available, a facility could be built closer to the feedstock. No coproducts are assumed for this scenario.

- **Iowa Corn Grain Ethanol Plus A <u>20%</u> Coproduct Credit** – This scenario adds onto the *Iowa Corn Grain Ethanol* scenario by incorporating the assumption that a "credit" should be given for the sale of dried distillers grains with solubles. A 20% to 40% coproduct credit range has been used in the literature [2]. This means that 20%-40% of the process energy and thus GHG emissions are not counted for in the final result. This scenario assumes a 20% coproduct credit to show how this assumption affects the energy and GHG emission results.

- **Iowa Corn Grain Ethanol Plus DDGS** – This scenario looks at corn grain ethanol production in Iowa and considers the use of DDGS as a facility fuel source rather than selling it as an animal feed. Burning the DDGS can be used as a fuel source to offset an ethanol facilities natural gas and electricity consumption [3]. Currently, DDGS is sold within the animal feed market resulting in a second economic source for the ethanol facility. A variety of changes to the system may make the use of this product as a fuel source more economical. For example, under high natural gas prices or a low DDGS market price, DDGS could be burned to offset facility fuel costs [3]. DDGS may also be used a fuel source, if facility sites expand to regions where there either is no animal feed market or the transport costs are too high to ship DDGS to market. In this scenario, burning DDGS would offset the total corn grain ethanol fossil energy use and GHG emissions [3].

- **Iowa Coal Powered Corn Grain Ethanol** – Facing high natural gas prices, some ethanol conversion facilities are being approved that utilize coal as their fuel source. This scenario considers corn grain ethanol produced in Iowa by a coal powered, rather than natural gas powered, ethanol conversion facility. This scenario was developed to look at the fossil energy and GHG impact of producing corn grain ethanol when the conversion facility utilizes coal instead of natural gas for its energy needs. No coproducts are assumed for this scenario.

- **2025 Iowa Corn Grain Ethanol** – This scenario projects the Iowa Corn Grain Ethanol scenario to the year 2025 to evaluate the potential future system NEV and GHG emissions. This scenario is used to identify which aspects of the system, if improved could reduce the overall fossil energy consumption and GHG emissions the greatest. Iowa historic agricultural data is used to project each input into the future some 20 years. No coproducts are assumed for this scenario.

Corn Stover Ethanol (Chapter 5)

- **Corn Stover Ethanol** – This scenario looks at ethanol produced from corn stover. The location of the stover is assumed to be within a 50 mile radius of an ethanol conversion facility. The agricultural inputs to produce the corn are traditionally allocated to the grains and not the stover, as stover is a residue of corn production [4]. A laboratory demonstrated cellulosic ethanol conversion rate of 67% (238L/dry ton) is assumed [5]. In practice initially this value would be lower. Corn stover LCA results from a MIT PhD thesis by Jeremy Johnson will be used [4]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design.

- **2025 Corn Stover Ethanol** – This scenario projects corn stover ethanol production into the future some 20 years. The main assumption that changes in this scenario is the cellulosic feedstock to ethanol conversion efficiency rate, which improves from

67% to 90% (328L/dry ton) [5]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [5].

Switchgrass Ethanol (Chapter 5)

- **Alabama Switchgrass Ethanol** – This scenario examines the use of Alamo switchgrass as a bioenergy crop. This scenario considers switchgrass that would be grown in Alabama, as an example of a high biomass yield state. Through previous experimental field testing, Alabama has been shown to have the potential of producing high switchgrass yields [6]. As in the corn stover scenarios, the location of switchgrass is assumed to be within a 50 mile radius of a conversion facility. Currently, demonstrated cellulosic ethanol conversion yields of 67% (238L/dry ton) are assumed [5]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [5].

- **Iowa Switchgrass Ethanol** – This scenario represents Cave-In-Rock switchgrass produced in Iowa. This state was chosen to evaluate whether geographic variation affects the systems fossil energy consumption and GHG emissions. The location of switchgrass is assumed to be within a 50 mile radius of a conversion facility due to economic constraints. Currently, demonstrated cellulosic ethanol conversion yields of 67% (238L/dry ton) are assumed [5]. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [5].

- **2025 Alabama Switchgrass Ethanol** – This scenario projects Alabama switchgrass grown in Alabama into the future some 20 years. The location of switchgrass is assumed to be within a 50 mile radius of a conversion facility. This scenario examines the systems fossil energy consumption and GHG emission impacts of improved system inputs such as biomass yield and ethanol conversion efficiency. It is also assumed that lignin, a part of the plant not converted to ethanol, will be used to provide the facility's energy requirements. A coproduct credit was not assumed for any electricity that could be sold to the grid during the ethanol conversion process, as that depends on the facility design [5].

Biomass to Ethanol LCA Results and Discussion

Figure 5-1 and 5-2 display the total system NEV and GHG emission results for all previously published studies as presented by Farrell, and the Monte Carlo LCA results for corn grain, corn stover, and switchgrass ethanol scenarios[45]. As discussed in Chapter 3, all previously published corn grain ethanol NEV results are within one standard deviation of the Monte Carlo *Iowa Corn Grain Ethanol* scenario expect for the study by Pimentel. The reason is that, while most studies have different input values, they are still from data sources that represent the system currently. Pimentel's data is often outdated to a point where the likelihood of them occurring today is very low.

A 20% coproduct credit is often assumed in US government studies such as the one by Shapouri and Wang [7, 8]. In this study the scenario, *Iowa Corn Grain Ethanol With 20% Coproduct Credits* represents a case when a coproduct credit is incorporated. When coproduct credits are assumed, the studies that assume a coproduct credit are within one standard deviation. Pimentel does not assume any credit. Currently, policy is being written assuming this coproduct credit, which raises the NEV and decreases the overall GHG emissions attributed to corn grain ethanol. Additional research is needed to truly determine if the sale of DDGS is actually displacing animal feed production, which is

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[45] Net Energy Value (NEV) = Ethanol LHV – Fossil Energy Consumed During the LCA. Discussed in more detail in chapter 2.

what this credit assumes. This is difficult to accurately assess, and therefore unwise to create policy based on an assumption that may or may not be true. With high natural gas prices and new facilities located beyond animal feed markets, facilities are considering an alternative use of DDGS, as a fuel source. This scenario is represented by *Iowa Corn Grain Ethanol Plus DDGS*. If DDGS is utilized as a fuel source for a conversion facility, the NEV increases 4 fold and GHG emissions decrease almost 3 fold compared to today's current practice. This is because the facility fossil energy consumption represents approximately 70% of the total corn grain ethanol system fossil energy consumption. The use of DDGS either as a coproduct or as a fuel source ultimately depends on the economics of the system. Though in the future, potential GHG policy may improve the economics of burning DDGS.

The same increase in the NEV is seen from all cellulosic sources. This is again due to the utilization of lignin in biomass, which is burned to produce the facility's steam and electricity needs. For example, if an agricultural residue, such as corn stover is utilized as a feedstock, the NEV increases 3.5 fold from today's current corn ethanol values. Ethanol produced from corn stover also has a higher NEV and lower GHG emissions because none of the associated inputs for corn production are attributed to it. Only the harvesting and transporting fossil energy use and associated GHG emissions are considered.

Ethanol produced from switchgrass also results in high NEV and low GHG emissions. When compared to corn grain ethanol, switchgrass additionally has 92% lower agricultural fossil energy consumption. The fossil energy consumed during the agricultural process of growing corn grains in Iowa is 5.1 MJ/L, while for switchgrass produced in Alabama the energy consumed is 0.4 MJ/L. This is mainly due to the factors listed below:

1. Nitrogen fertilizer is the most energy consuming and GHG emitting agricultural input for both feedstocks. The nitrogen fertilizer application rate is 47% lower for switchgrass than for corn production. This is due to the deep

rooting system of switchgrass and its efficiency at utilizing the nitrogen in the soil.

2. The farm machine fuel use is 83% lower for switchgrass than corn stover. This is because switchgrass requires fewer inputs per year, and therefore less farm machinery use.

3. Switchgrass crop management practices (i.e. cutting which leaves the roots in the soil) minimize the need for additional agricultural inputs the following year.

4. Switchgrass is a drought tolerant species and therefore irrigation is not needed. Though in the future, if yield is an economic driver for farmers, irrigation may be used.

5. The average biomass yield of corn grain is 9,116 kg/ha, while for switchgrass it is 21,880 kg/ha.

Corn grain ethanol fossil energy consumption and GHG emissions are more sensitive to geographic location than switchgrass production. This can be seen when comparing state specific results for each of the feedstocks. For corn grain ethanol, there is a factor of 3 difference between Iowa and Georgia's NEV. For switchgrass ethanol in Alabama and Iowa, the results are approximately the same. This is partially explained by the fact that switchgrass use to be a native species to much of the middle and eastern part of the country. It is also considered a very hardy species, and suited for a variety of climates and growing conditions. Unlike switchgrass, high yield corn production is more geographically specific to the Corn Belt. Therefore, the geographic location of corn production is much more limited than for switchgrass production.

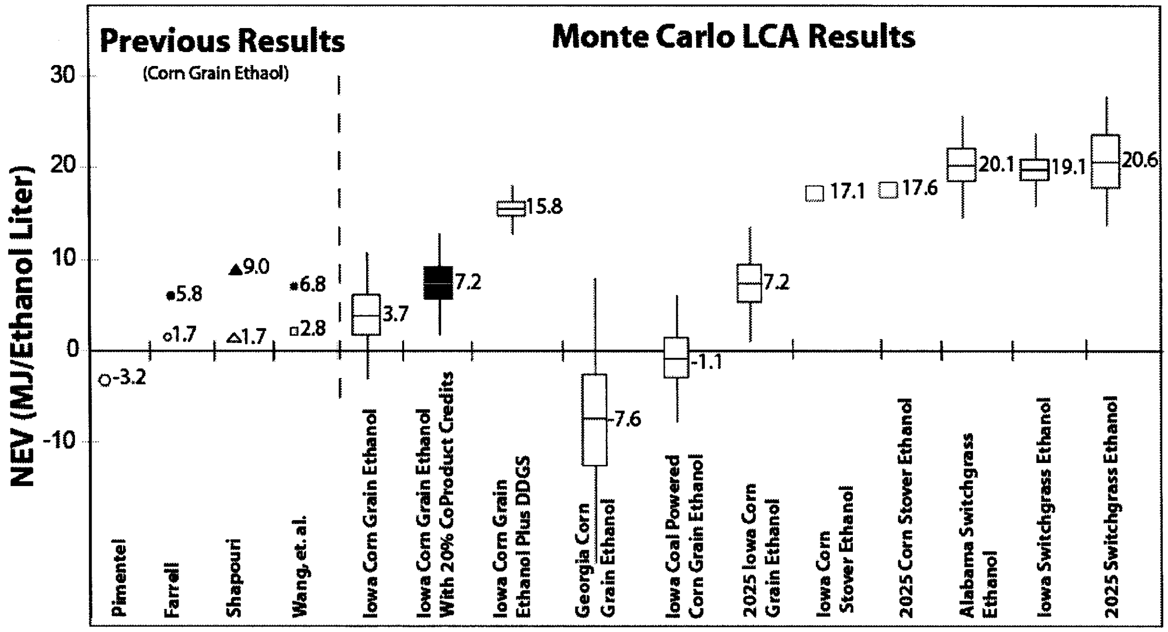

Figure 5- 1 – Net energy value (NEV) for various bioethanol production pathways. Based on the LHV

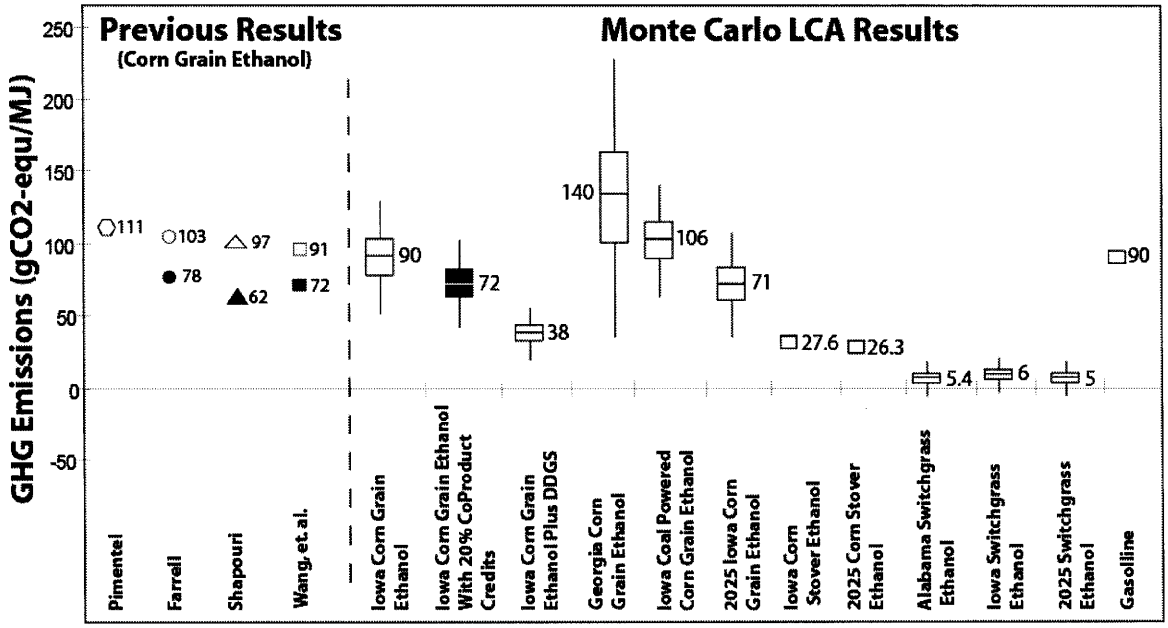

Figure 5- 2 – GHG emissions for various bioethanol production pathways

In the future, biomass from geographic locations that have varying land use efficiencies will be utilized to support a growing biofuels industry. Ultimately, large-scale biofuels production, and thus petroleum displacement will depend on land availability and its productivity. Defining a land use efficiency is one metric that can be applied to determine which crops will yield the largest amount of biofuels. Land use efficiency is defined here as the amount of biofuels, in this case ethanol, that can be produced on a given area of land. Figure 5-3 depicts current (2006) and future (2025) land use efficiencies for the various ethanol production pathways. 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 used. For example, land used to produce corn grain ethanol in Georgia is 29% less efficient than ethanol production from corn grains produced in Iowa (Figure 5-3). This impact can be seen in the decreased NEV and increased GHG emissions (Figure 5-1 and 5-2). Future Iowa corn kernel ethanol scenarios project a 50% increase in land use efficiency due to projected higher corn and ethanol yields in 2025.

Corn stover is expected to be one of the first feedstocks for cellulosic ethanol production because of its collocation with the existing ethanol industry. In the future, ethanol could be produced from corn and corn stover from the same land area. When both these feedstocks are used to produce ethanol, the land use efficiency increases 11% compared to when only the corn grain is used to produce ethanol.

Currently, land required per unit of switchgrass ethanol is comparable to land required for corn ethanol. In the future however, land that is dedicated for switchgrass production is expected to out perform future corn ethanol hectares by 45%. This is due to the expectation that switchgrass yields, as well as cellulosic ethanol conversion rates will improve.

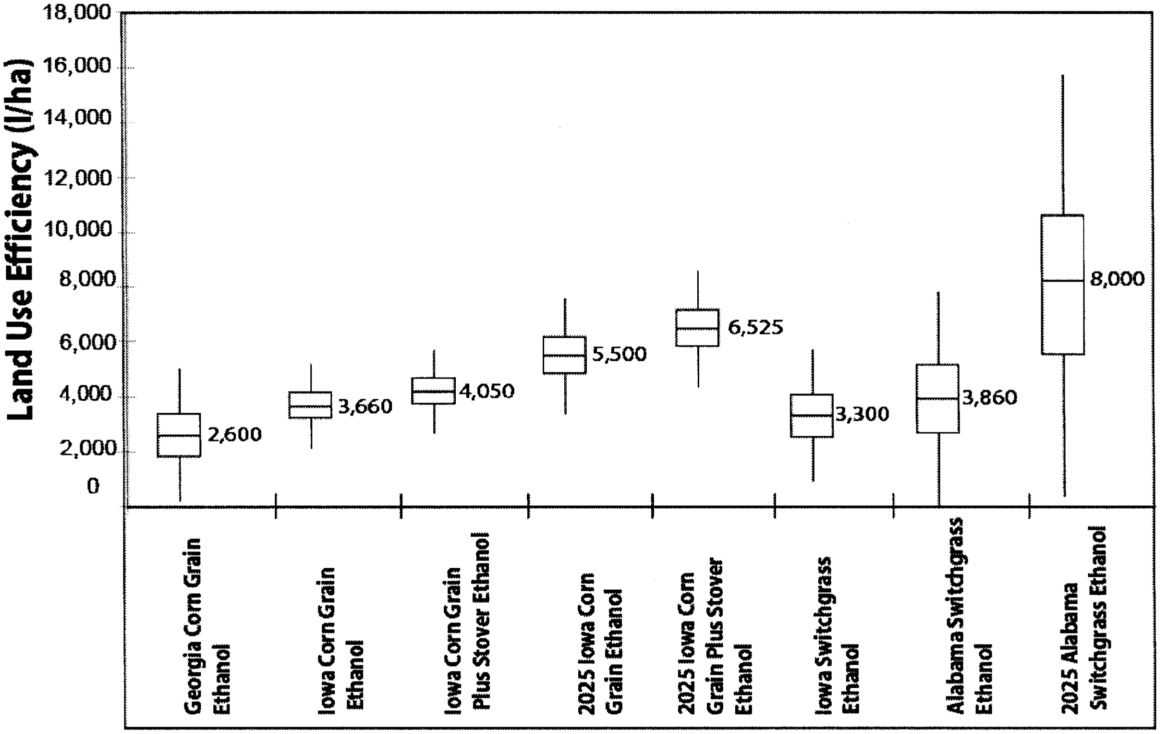

Figure 5- 3 – Land Use Efficiency for Various Bioethanol Production Pathways (liters of ethanol produced per hectare of land used)

Biomass productivity and availability needs to be optimized for ethanol production to increase to levels where significant quantities of petroleum could be displaced. This will depend on land availability and incentives to land owners that encourage them to sell biomass residue, which could shift land use from its current practice towards a bioenergy crop. In Chapter 6, this study assesses the potential scale that biomass from current crops, agricultural residues, and bioenergy crops may have. It considers future production levels of current corn grain production, as well as the potential transition of agricultural cropland to bioenergy feedstocks, such as switchgrass. Finally in Chapter 6, the potential scale of ethanol production from these feedstocks is concluded. Life-cycle assessment results from this chapter are then applied to determine the impact of ethanol production from these various biomass sources at their potential maximum scale.

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Chapter 6: United States Scale of Ethanol Production

Within the transportation sector, society is often looking for a "sliver bullet" when it comes to replacing petroleum as our nation's primary motor fuel. Though there is a variety of vehicle technologies and alternative fuels, none to date are seen as a complete petroleum replacement. Instead, each has a role to play at reducing our dependence on oil. The magnitude of their impact depends on a wide range of factors such as technology adaptability, economic competitiveness, versatility, and its ability to integrate within existing infrastructure. Biofuels, and specifically ethanol, have a unique advantage, because its initial industry and technical knowledge was already developed. It is also easily integrated into gasoline at low blends without consumer knowledge or consumer behavioral change. Currently ethanol displaces 2.5% of US gasoline consumption, making its role more of a fuel additive than a gasoline displacement or alternative. Currently, 50% of gasoline is blended with some fraction of ethanol. Most ethanol now produced is blended at rates below 10% and able to be used in flex-fuel vehicles which can operated up to gasoline blends of 85% ethanol (E85). For ethanol to be considered a motor fuel alternative to gasoline, the scale of ethanol production will have to increase significantly. While corn grain ethanol production is expected to increase in the next 10 years, alternative cellulosic feedstock sources are seen as necessary for ethanol production to displace a significant portion of the transportation petroleum-based fuel market.

Ethanol's scale of production depends on feedstock and a wide range of factors. This study assesses the potential scale of ethanol production from three different feedstocks; corn grain, corn stover; and switchgrass. Within each feedstock option six factors were defined that affect its potential to scale; land availability, technological feasibility, economic viability, development and synergy of industries, policy, and environmental impact. Each of these factors is discussed in detail to identify system barriers in all sectors that will need to be overcome to increase biomass and ethanol production. Below is a brief description of each of these six factors:

- **Land Availability** – Land availability to either harvest agricultural residue or grow bioenergy crops will limit the scale at which domestic ethanol production can grow. Current agricultural land and land within the USDA's Conservation Reserve Program (CRP) is considered for potential agricultural residue removal and bioenergy crop production. CRP land is degraded agricultural land that has been taken out of production for environmental reasons or due to its low productivity [1].

- **Technological Feasibility** – This relates to the technological challenges that need to be overcome in the agricultural, biomass collection and transport, and ethanol conversion arenas. It includes issues relating to improving biomass yields, collection techniques, to biomass storage practices, and ethanol conversion efficiencies.

- **Economic Viability** – This address the economic competitiveness of bioethanol relative to gasoline. This depends on oil and ethanol prices, feedstock and transport costs, cellulosic ethanol facility costs, and ethanol distribution costs.

- **Development & Synergy of Industries** – This addresses the need for initial and further development of the key industries to both further scale-up corn ethanol production and to create an industry for cellulosic ethanol production. Industries that need to be either further developed or created include: farmers, biomass transport infrastructure, biomass storage facilities, cellulosic ethanol facilities, and ethanol distribution infrastructure. In the corn grain ethanol industry, development mainly relates to ethanol distribution bottlenecks as the feedstock and conversion facilities are already developed. In cellulosic ethanol it relates to all aspects of developing a new industry such as, feedstock availability and certainty of a cellulosic market, biomass transport, storage, facility development, and ect.

- **Policy** – This relates to the role that national and state governments play and policies they use, in initiating and motivating the increase in bioethanol production.

- **Environmental Impact** – This assesses the fossil energy consumption and GHG emissions as the scale of ethanol production increases from each of the three biomass sources. It also considers the most effective use of land for biofuels production by examining the land use efficiency, defined as the liters of ethanol produced for hectare of land.

The remaining sections explain how these six 6 factors affect the potential scale of ethanol production for each feedstock.

Scale of Production of Corn Grain Ethanol

Currently in the United States ethanol is produced from corn grains. Corn production in the United States is centered within the Corn Belt where approximately 83% of 2007 corn grain production was produced from 10 states (Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, South Dakota, Wisconsin, Missouri, and Minnesota) [2, 3]. Ethanol facilities are also centered within the Corn Belt to keep grain and DDGS transport costs low. Chapter 3 has a detailed description of historic corn yields and agricultural inputs. In the past few years acreage dedicated to corn production has increased due to increased demand from the ethanol industry. From 2006 to 2007, harvested corn acreage increased 20%, coming mainly from soybean, wheat, and cotton acreage [4]. As the corn grain ethanol industry continues to increase, this study examines the question: *How much ethanol can be produced from corn grains, while still meeting other corn market demands?* This section explores this question and looks at the factors that may limit and/or bound this industry's growth. The fossil energy and GHG displacement at this production capacity is also evaluated and discussed.

Factors That Affect Corn Grain Ethanol Scale of Production

The six factors that were defined that affect the corn grain ethanol scale of production are discussed below:

Land Availability – Corn production is an established agricultural practice that is centered in the Corn Belt. Corn planted acreage expanded by 20% from 2006 to 2007 in response to increased ethanol demand [4]. In the future, corn acreage is expected to continue to increase, though total cropland is likely to remain constant. The majority of this increasing corn acreage will come from the shifting of other agricultural crops to corn production. While ethanol production is concentrated within the Corn Belt, there are a few facilities being built in Arizona, Oregon, and New York. When producing ethanol outside of the Corn Belt, local corn grain supplies and animal feed markets are often utilized. Areas outside the Corn Belt may be able to sustain a small number of corn grain ethanol facilities but the majority of production is expected to stay within the Corn Belt for economic and feedstock availability reasons.

Technological Feasibility – This factor includes the potential technological advances in both corn grain yields and corn grain ethanol conversion rates. Corn grain production is an agricultural practice that has been around at large scale since the early 1900s. Since then there have been substantial increases in corn yields through advancements in crop management practices, the development of fertilizers, and genetic engineering (Figure 3-3, 3-4, 3-5). In the future, yields are expected to continue to increase due to continued incremental advances within these arenas. Corn grain ethanol production is also an established industry based on a mature technology. Currently new facilities have conversion rates of 11 l/bu (2.9 gal/bu), where the theoretical maximum is 13 l/bu (3.4 gal/bu). Incremental improvements to the system can further increase the starch-to-ethanol conversion efficiency, though the major advancements have already been realized. In the end, while incremental improvements to this system will continue, major advances are unlikely.

Economic Viability – Corn grain ethanol production is sensitive to both oil prices and production costs. The main ethanol facility production costs are the cost of corn and fossil fuels to power the facility. Since 2006 the market price of corn has surged from $1.86 per bushel to around $4 per bushel. Though corn costs could continue to increase, there is a limit to which ethanol facilities will continue to pay. That limit depends on oil prices and the market price for ethanol. In 2006 the market price of ethanol surged to \$1.04/L (\$3.95/gal) and averaged \$0.58-\$0.61/L (\$2.20-\$2.30/gal). In October 2007 the price dropped to \$0.42/L (\$1.60/gal) due to a surplus in ethanol production. This surplus is partly due to the saturation of local markets and the bottleneck in infrastructure to transport the fuel to further away coastal markets. Some see this as a short-term problem while others are looking for a longer-term solution such as retrofitted existing pipelines to transport gasoline ethanol blends or creating a new ethanol pipeline infrastructure. At 2006 average corn prices, the average corn grain ethanol cost of production was \$3.20 per bushel of corn, or \$0.32/L (\$1.23 per gallon) of ethanol produced [5].

Development & Synergy of Industries – When ethanol demand increased, the industry mainly had to scale up as players within the corn grain ethanol industry had already existed. This can be seen from the 3 fold increase in corn grain ethanol production since the year 2000 [2]. Additionally, by the year 2009 facility expansion and the construction of new facilities will have increased the industries capacity to beyond 28 billion liters (7.5 billion gallons) [6]. One of the main obstacles in the road for this industry is the ethanol distribution network. The infrastructure to transport ethanol to coastal markets has seen bottlenecks due to the limited availability of rail cars and trailers. Some see this as a short-term temporary problem while others are looking for a longer term solution such as retrofitting existing pipelines or creating a new pipeline infrastructure.

Policy – Increased ethanol production resulted from two major events: the first being the phasing out of methyl tertiary-butyl ether (MTBE) and the second being the adoption of the Renewable Fuels, Consumer Protection, and Energy Efficiency Act of 2007, the new RFS. MBTE was used as a gasoline oxygenate additive to raise the fuels octane number. A high octane number is need to prevent engine knock an abnormal and potentially destructive combustion process [7]. Due to widespread contamination of groundwater by MBTE leaking from gasoline fuel storage tanks, various states have been banning its use. Ethanol, also a fuel oxygenate, was then discussed and promoted as an alternative to MTBE. By 2006, the use of MBTE in gasoline had mostly been phased out, with the expectation that ethanol would be used instead.

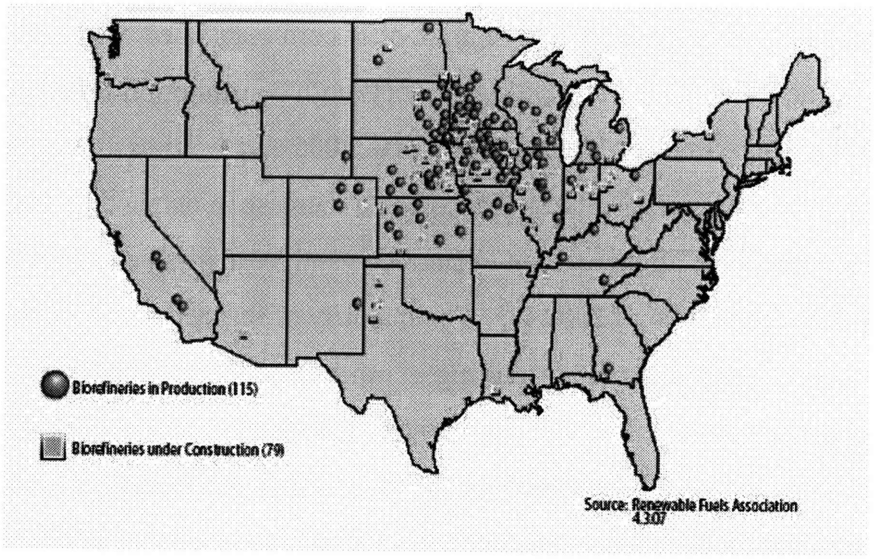
The second factor promoting the growth of the ethanol industry was when it became supported by both national and state governments. It was seen as a way to improve national energy security through displacing oil and through supporting a domestic industry. The new RFS was the first government mandate that boosted the production of ethanol, by requiring 28 billion liters of renewable fuel to be blended with gasoline by 2012. That target is expected to be met by 2009. The US government's blenders tax credit of $0.13/L ($0.51/gal) made producing ethanol economically feasible. State government polices also boosted demand for ethanol. State legislation that requires minimum ethanol blends have been enacted in Minnesota, Hawaii, and Montana. While Washington, Colorado, Illinois, Iowa, Kansas, Missouri, and New Mexico all have proposed minimum blending requirements.

In December of 2007, a new RFS was passed that increased the renewable fuels mandate from 28 billion liters to 136 billion liters (36 billion gallons) of renewable fuels by 2022 [8]. This bill allows corn-based ethanol to contribute 57 billion liters (15 billion gallons) and cellulosic ethanol to make up the difference and starting to be available at large-scale by 2009 [8].

Environmental Impact – Corn ethanol production has a range of environmental impacts associated with its agricultural and facility practices. Corn production is one of the most energy intensive and environmentally damaging crops. Corn production requires large amounts of fertilizers that are known to contaminate ground water, lakes, and be the main cause of the hypoxia in the northern region of the Gulf of Mexico. This past year, the hypoxia in the Gulf of Mexico has increased, and researchers are pointing at the increased corn crop acreage as the cause. Corn grain ethanol processing also consumes 4-7 gallons of water per gallon of ethanol produced [9]. Depending on the source for this water, this can have a large affect on ground water levels and reservoirs.

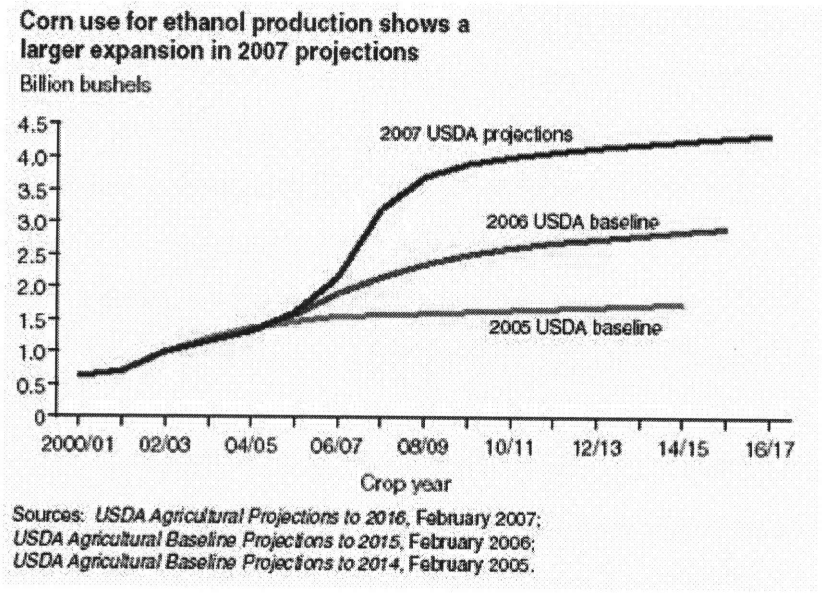
Determining Corn Grain Ethanol Scale of Production

Ethanol production increased substantially in the past 3 years due to the banning of MTBE and the enactment of the Renewable Fuels Standard (RFS) in 2007. The banning of MBTE, lead to ethanol being a direct substitute for this gasoline additive. The 2007 RFS mandated the blending of 28 billion liters of renewable fuels, providing an increased demand for biofuels. Ethanol, being an established industry, was able to quickly expand to meet this requirement. Since 2000, ethanol production has increased 3 fold [6]. Currently, ethanol production is centered in the Corn Belt with 131 facilities having the capacity to produce 26 billion liters (6.9 billion gallons) of ethanol per year [6]. Over the next 2-3 years an additional 23 billion liters (6.5 billion gallons) of capacity is being added from current facilities expanding their capacity and the addition of 73 new facilities [6]. Therefore by 2009, the corn grain ethanol industry in the United States will be a 50 billion liter (13 billion gallon) industry [6]. It is expected that corn grain ethanol production will continue to increase over the next decade, especially as second generation biofuels in the near-term are still not economical or scalable.



Source: Renewable Fuels Association 4.3.07

Figure 6- 1 –Current and Future Corn Grain Ethanol Conversion Facility's [6]

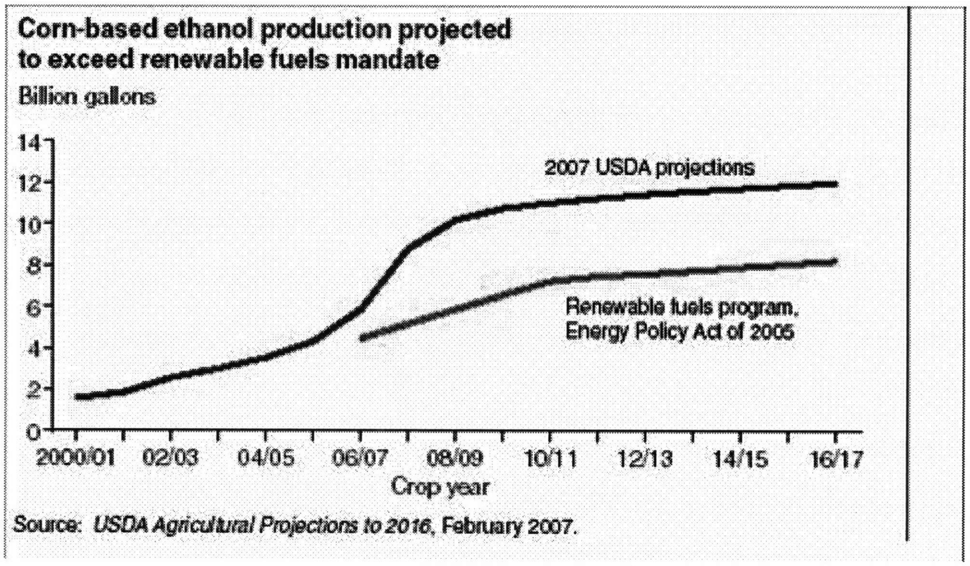


Sources: *USDA Agricultural Projections to 2016*, February 2007; *USDA Agricultural Baseline Projections to 2015*, February 2006; *USDA Agricultural Baseline Projections to 2014*, February 2005.

Figure 6- 2 Corn Use for Ethanol Production Till 2016 [4]

Every year the USDA reports on the expected next 10 year production levels of the major crops within the agricultural industry [4]. This report, called the *USDA Agricultural Projections to 2016*, is used to estimate future corn production levels [4]. Figure 6-2 represents the USDA's projections for the amount of corn consumed by the ethanol industry for the next ten years. The USDA projects corn consumption for ethanol production to be approximately 3 times higher than 2005 and 1.5 times the 2006 projections [4]. This increase is due to the expected increase in demand by the ethanol industry. In a response to an increase in ethanol demand, corn production has already expanded by 20% from 2006 to 2007 [4]. The majority of this acreage is not in the expansion of total cropland but in the shifting of other agricultural crops, such as cotton and soybeans to corn production [4]. Additionally corn is expected to be shifted from the export sector to the ethanol industry [4]. In the past, US world corn exports represented 60-70% of the US corn market; with an expanding ethanol industry that share is expected to drop to 50-60% [4]. At this corn production rate, the USDA is projecting that the corn grain ethanol industry will level out at a production capacity of 57 billion liters (15 billion gallons) by 2016 (Figure 6-3) [4]. This level of ethanol production is expected to consume 30% of the US corn grain production by 2010. Since 2006, the market price of corn has surged from \$1.86 per bushel to around \$4 per bushel [10].

Long-term projections show average corn prices reaching \$3.75/bu in 2009/10 and then declining to \$3.30/bu by 2016 [4].



Source: *USDA Agricultural Projections to 2016*, February 2007.

Figure 6- 3 Corn-based Ethanol Production Compared to 2005 RFS [4]

Currently, both state and national policies are both expected to provide incentives to further the expansion of the corn grain ethanol industry. States, particularly in the Midwest, who have saturated their E10 market, are trying to mandate the use of higher blended ethanol fuels like E15 and E20. The EPA is currently testing higher ethanol blended fuels with the goal of defining additional blends as motor fuels. The new RFS also increases the renewable fuels target to 136 billion liters (36 billion gallons) [11]. Increasing the RFS mandate will further solidify a market place for ethanol facilities. As ethanol production increases in the future it is expected that advances in improving corn grain yield and ethanol conversion rates can additionally further the expansion of corn grain based ethanol. The scale of ethanol produced from corn grain as defined by the new RFS will level out at 57 billion liters, by the year 202 [4, 8]. This is based on the projections by the USDA and the expected industry wide efficiency gains [4]. At this level of production, the US is expected to still represent 50% of the corn grain export market, and meet its other animal feed and food product demands [4]. At this scale and with the assumed system and efficiency gains in the 2022, corn grain ethanol would displace 6.5% of petroleum consumption and 1% of vehicle transportation GHG emissions (Figure 6-9). These results are based on the LCA of corn grain ethanol discussed in Chapter 3. Second generation cellulosic biofuels from feedstocks from agricultural residues, such as corn stover, and bioenergy crops, such as switchgrass, are expected to increase biofuel production levels even further in the future, but the time frame and to what production scale is uncertain.

Corn Stover Production from Agricultural Land

Corn stover is the agricultural residue left on the field once the corn grain is harvested. Stover includes the entire green part of the corn plant besides the corn grain, and has a mass ration of 1:1 with corn grains [12]. Currently, stover provides protection from soil erosion caused by wind and rainfall [12]. It also promotes improved soil quality by replenishing the soil with nutrients as it biodegrades. Corn stover is seen as potential cellulosic feedstock for ethanol production as it is collocated within the Corn Belt and near the current ethanol industry. The productivity of corn stover is based on corn grain production, and can be estimated by future corn grain projections discussed in the previous section. The amount of stover that may be collected from the field without environmental impacts is estimated at 30%-50%, though it is field specific and further long-term research is needed [12]. This study assumes an average 30% removal rate.

Factors That Affect Corn Stover Scale of Production

The six factors that were defined that affect the corn stover ethanol scale of production are discussed below:

Land Availability – Corn stover is an agricultural residue from corn grain production. Therefore, as corn production expands as described in the previous section so will corn stover production. The availability of corn stover is therefore limited by the growth potential of corn grain production. In 2006, there is approximately 330 million tons of corn stover. At a 30% removal rate, 100 million tons of corn stover would be available for cellulosic ethanol conversion. By 2016 corn grain production is projected to reach 14.3 billion bushels, or 363 million tons [4]. This scale of corn grain production would result in 109 million tons of available corn stover at a 30% removal rate.

Technological Feasibility – Ethanol produced from corn stover has many uncertainties and challenges to overcome in the arenas of, estimating the removal rate to minimize environmental impacts, collection, storage, and the yield and economics of cellulosic ethanol conversion. Currently research indicates a stover removal rate of 30%-50% without adverse environmental impacts. Further research is being conducted to clearly understand the longer-term dynamics between corn stover and soil quality. This could lead to potential soil testing techniques that indicate a maximum acceptable stover removal rate and thus an industry average removal rate.

In terms of collection, stover is currently not usually collected. During corn grain harvesting, a combine is used to collect the entire plant, keeping the corn kernels and releasing the stover back onto the field. A farmer minimizes the number of passes the machinery makes on the field, to preserve the fields topsoil. The topsoil is the top 2-6 inches of soil, which has the highest organic mater and concentration of microorganisms [12]. Plants generally establish the bulk of their roots in the topsoil and obtain most of their nutrients from this layer [12]. For stover to be collected, another piece of machinery would have to go onto the field and collect the stover. While collecting the stover, the topsoil would be further disrupted. An alternative to this is the development of machinery that could co-collect corn grains and a portion of the stover. Once collected, stover can be baled into round or square bales that can be stored and transported. Stover can either be stored at the field or at a storage facility located at the ethanol facility. The cost and logistics of multiple options for baling, handling, transport, and storage are aspects of the system that have yet to be determined.

On the ethanol conversion side, advances in improving the yield of ethanol from cellulosic sources needs to occur. The main areas where improvements need to be made are increasing the efficiency and cost-effectiveness of the pretreatment process, hydrolysis, and yeast conversion rates. The efficiency of the pretreatment process depends on the amount of cellulose and hemicellulose that was successfully separated from the biomass and therefore available for chemical and biological treatment. There are numerous pretreatment options; these often depend on the feedstock being converted. Enzymatic hydrolysis is the application of enzymes to break down the cellulose and hemicellulose into simpler fermentable sugars [13, 14]. Currently, hydrolysis and fermentation are two different steps, though research is trying to combine these two processes into one known as simultaneous saccharification and fermentation (SSF) [13, 14]. In SSF the microbes are placed in one vessel making this a one step process of sugar production and fermentation [13, 14]. NREL has developed a microorganism that more effectively converts cellulosic material to biomass by being able to simultaneously convert both five and six carbon sugars to ethanol [15]. The disadvantage of SSF is that both these steps are operating at the same non-optimal conditions, which lowers the overall ethanol yield [14]. To improve cellulosic ethanol yields research is needed to improve the efficiency of yeast and reduce the time scales of converting both five and six carbon sugars to ethanol.

Economic Viability – The economic viability of cellulosic ethanol depends on both the feedstock costs and ethanol conversion facility economics. Currently corn stover is not sold as a coproduct of corn grain production. If collected and sold, corn stover would provide an additional source of income to the farmer. The minimum feedstock price is determined by the farmer while the maximum price is determined by the cellulosic ethanol facilities economics. Studies preformed by NREL and ORNL have estimate a stover delivered cost between $35-$50/dry ton [16]. POET, formally known as Broin, is currently building a cellulosic ethanol facility based on corn stock at a delivered price in the range of $50/dry ton [17].

Technological advances in the cellulosic ethanol conversion technology also need to be made, to make this process more cost-effective. Economically, the pretreatment process and equipment, and enzymes to breakdown the plant matter are cost prohibiting. Currently, it is estimated that cellulosic ethanol would cost $0.58/L ($2.20/gal), at a conversion rate of 238 L/dry ton (65gal/dry ton) and feedstock price of 53$/dry ton (Figure 6-4) [16]. Government funding and research efforts are currently being focused in all of these areas, to lower the production costs to $0.29/L ($1.10/gal) in 2012, to be cost competitive with corn grain ethanol [16].

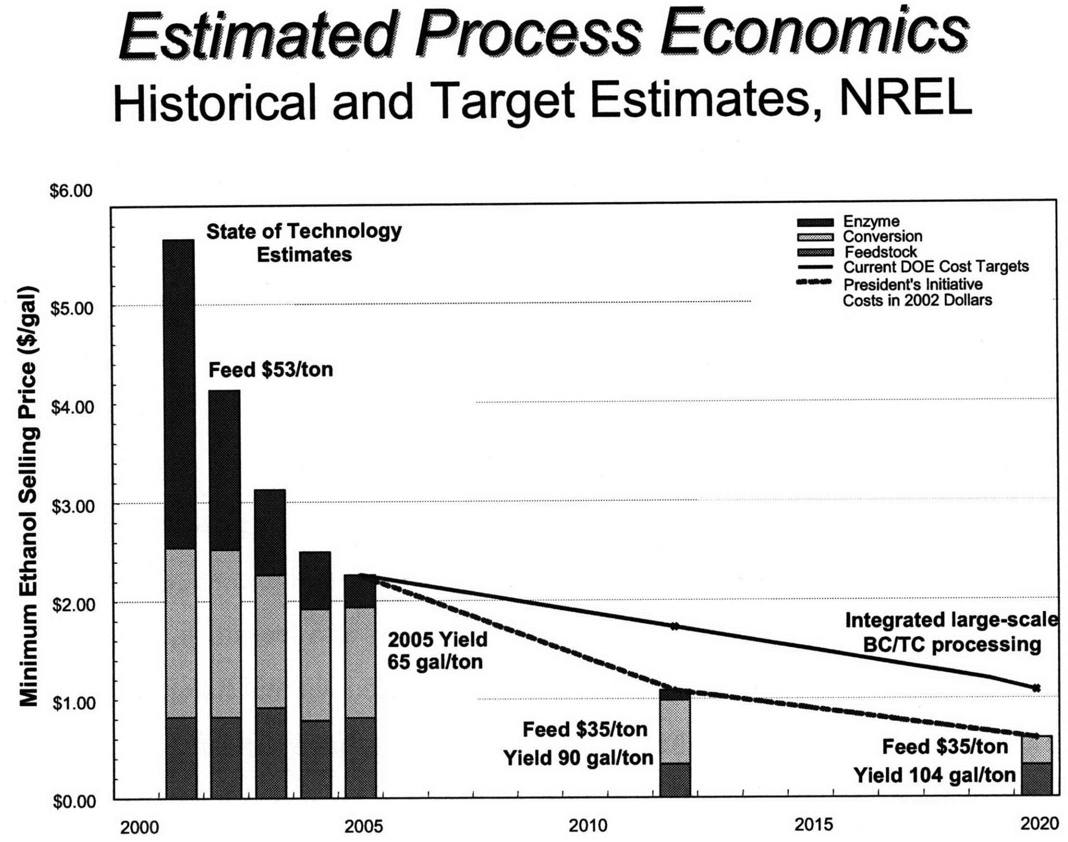


Figure 6- 4 Future Estimated Cellulosic Ethanol Cost of Production [16]

Development & Synergy of Industries – Corn stover has the advantage of being collocated within the Corn Belt near an existing ethanol industry. Therefore, within the region the technical expertise, ethanol facilities, and ethanol distribution networks are already in place. The aspects of the system that will need to be coordinated are the securing of farmers to provide the feedstock within a given radius to the facility and the development of the collection, handling, storage, and feedstock transport sectors. This type of development is characterized by a "local" development, as the main sectors of the industries already exist though they need to be synchronized with new pieces specialized for corn stover within the region.

Policy – The policies that were described within the corn grain ethanol section are applicable to ethanol produced by corn stover. Within in the new RFS, it is expected that 80 billion liters (21 billion gallons) of advanced biofuels will be produced by 2022.

"Advanced biofuels" are defined as any biomass-based fuel other than corn grain ethanol. Additionally, the new RFS expects of that 80 billion liters, 21 billion liters (5.5 billion gallons) of cellulosic ethanol, will be produced by 2022. It is expected that by 2010, 0.4 billion liters (0.1 billion gallons) of cellulosic ethanol will start to be produced.

Environmental Impact – Corn stover provides protection to the soil from wind and water erosion. Stover also returns nutrients back into the soil during the decomposition process decreasing the amount of fertilizer required the subsequent year. This additional organic matter also increases soil biological activity which serves as a vital link in the dynamics of soil nutrient storage, release and use by plants [12]. These positive environmental impacts reduce soil quality degradation over time and minimize fertilizer application rates. Therefore, when considering utilizing stover as a feedstock, research is needed to determine the maximum quantity that can be removed without having negative long-term environmental impacts on the system. Initial studies have indicated an allowable removal rate of 30%-50% though further research is needed [12, 18, 19]. In this study the removal rate is always assumed to be 30%.

Determining Corn Stover Ethanol Scale of Production

Corn stover, being an agricultural residue of corn grain production, is directly dependent on corn grain yields and planted crop acreage. Corn stover and corn grain have an average mass ratio of 1:1 [12]. In 2007 there was approximately 330 million tons of corn stover. At a 30% removal rate, 100 million tons of corn stover would be available for cellulosic ethanol conversion. By 2016 corn grain production is projected to reach 14.3 billion bushels, or 363 million tons [4]. This scale of corn grain production would result in 109 million tons of corn stover at a 30% removal rate. Table 6-1 provides the impacts of utilizing corn stover for ethanol production. Corn stover available today and in the future is analyzed at both today and future cellulosic ethanol conversion rates. At today's ethanol conversion rates of 238L/dry ton, 24 billion liters of ethanol would be produced. Applying the LCA corn stover results in Figure 5-1 and 5-2, results in a 3% and 2% displacement of today's gasoline consumption and light duty vehicle GHG emission, respectively. In the future, 109 million tons of stover could produce 26-36 billion liters depending on the cellulosic ethanol conversion rate. This rate of corn stover ethanol could displace 3%-4% and 2%-3% of gasoline consumption and GHG emissions.

Corn Stover Ethanol	Units	2007 Available Corn Stover (100 million tons)	Future Available Corn Stover (109 million tons)
Today's Demonstrated Ethanol Conversion Rate		*238 +/- 6.4 L/ton*	
Ethanol Produced	*billion liters*	24	26
Corn Stover Ethanol GHG Emissions	*billion gCO_2-equ/L*	13,925	14,440
% Change in GHG Emissions	*%*	2.1	1.8
Gasoline Displacement	*billion liters*	16	18
% Gasoline Displaced	*%*	3	2.5
Future Ethanol Conversion Rate		*328.5 +/- 9.1 L/ton*	
Ethanol Produced	*billion liters*	33	36
Corn Stover Ethanol GHG Emissions	*billion gCO_2-equ/L*	19,188	19,885
% Change in GHG Emissions	*%*	2.9	2.5
Gasoline Displacement	*billion liters*	22	24
% Gasoline Displaced	*%*	4.2	3.5

Table 6- 1 – 2007 numbers are based on 2007 corn production and 2007 US gasoline consumption of 531 billion liters. The future numbers are based on 2016 corn production, which is assumed to remain constant into the future, and the EIA projected 2025 US gasoline consumption of 700 billion liters [20].

Both of these estimates assume that 30% of corn stover will be removed from all corn grain producing fields. It also assumes that all the stover will be utilized by a cellulosic ethanol industry, regardless of economic viability. These assumptions were made to provide an estimated maximum production scale for ethanol produce from corn stover.

In reality, other factors such as collection costs, feedstock transport distance, and cellulosic facility costs, could reduce the actual amount of stover utilized for ethanol production. Other agricultural residues, such as wheat straw, can provide an opportunity to increase this level of cellulosic ethanol production though alternative feedstocks also come with their own economic and technological challenges. Bioenergy crops are also considered as sources for cellulosic biomass. This study considers switchgrass as an example of a cellulosic bioenergy crop that can be utilized for ethanol production. Switchgrass was analyzed as it was considered an optimal bioenergy crop by the Bioenergy Feedstock Development Program [21, 22].

Switchgrass Production from Agricultural Land

Switchgrass has the potential to be the first bioenergy crop grown specifically for biofuels production. Switchgrass was chosen by the Bioenergy Feedstock Development Program as an optimal bioenergy herbaceous crop with potential for widespread use throughout the United States [14, 22]. As corn grain ethanol production is known to be limited in scale, additional feedstocks, such as switchgrass, are being considered. Bioenergy crops also provide additional feedstocks that can be grown outside the Corn Belt decentralizing the current industry. This could help lower the cost of biofuel distribution and minimize the need to develop ethanol specific distribution infrastructure.

This study examines the potential scale of ethanol production from switchgrass in the US. The scale of switchgrass production depends on the type of land considered and the system assumptions. Agricultural land and CRP land are two land categories that are analyzed for switchgrass production. When produced on agricultural land, it is assumed that switchgrass will be competing with the major agricultural crops for land. As there is currently not a market for switchgrass, a model called POLYSYS was used to assess switchgrass production from agricultural land based on the net returns to the farmer and feedstock farm gate prices. POLYSYS is an agricultural policy simulation model developed by the USDA, ORNL, and the University of Tennessee [23, 24]. POLYSYS includes the eight major crops (corn, grain, sorghum, oats, barley, wheat, soybeans, cotton, and rice), and a livestock sector (beef, pork, lamb and mutton, broilers, turkeys, eggs, and milk) [23, 24]. The model was modified to also include hay and pasture land.

POLYSYS runs on a ten year time frame and is based on the *USDA Agricultural Projections to 2016 Baseline [4].* The potential of switchgrass production on CRP land is also considered later in the chapter.

Within POLYSYS the United States is divided into 305 agricultural districts that do not cross state lines (Figure 6-5) [23]. Switchgrass growing characteristics, yields, and costs were added to the model to determine how a bioenergy crop could shift agricultural crop land at various switchgrass farm gate prices [23, 24]. Switchgrass yield is defined on a per county level by a database called ORECCL (Figure 6-6) [25]. Switchgrass is not defined to be grown throughout the United States, which is a current limitation of this program. Switchgrass is assumed to be grown from the central part of the country and east. The county based yield is then related to the agricultural districts used in POLYSYS.

The model starts by introducing switchgrass as an option to farmers with a user defined farm gate price. The farmer's decision to change from their current cropping practice to switchgrass production is based on the net returns to the farmer, which depend on farm gate price, costs of production, and a discount rate of 6.5% [23, 24]. When switchgrass is brought into production, regardless of year, the model assumes that within the first year a 30% yield is realized, within the second year a two-thirds yield is realized, and that full yields are reach starting year three. In the model, once land is converted to switchgrass it stays in production till the end of the ten year time frame that the program runs for. Switchgrass is also assumed to only be grown on land where irrigation is not needed. To prevent large land shifts that would not be realistic, POLYSYS has embedded constraints so that food and projected export demands as defined by the USDA baseline are still met [23, 24].

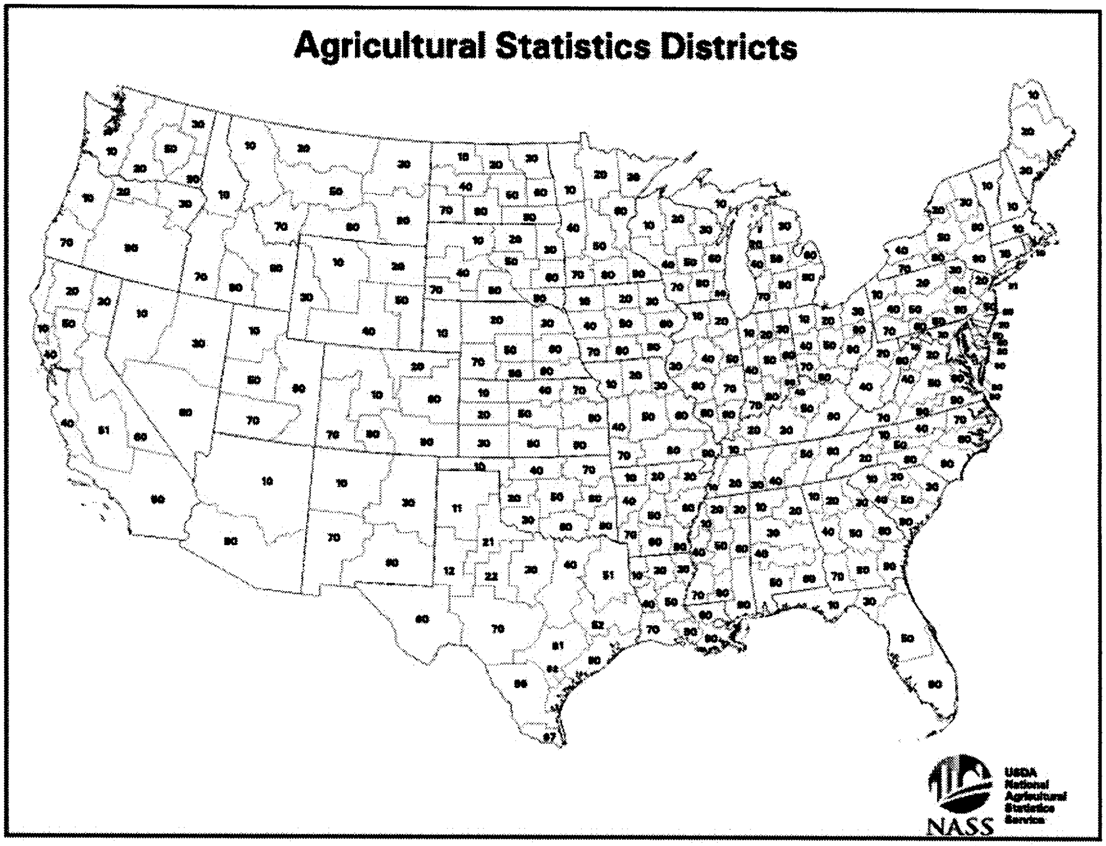


Figure 6- 5 – Agriculture Statistics Districts, by NASS and USDA

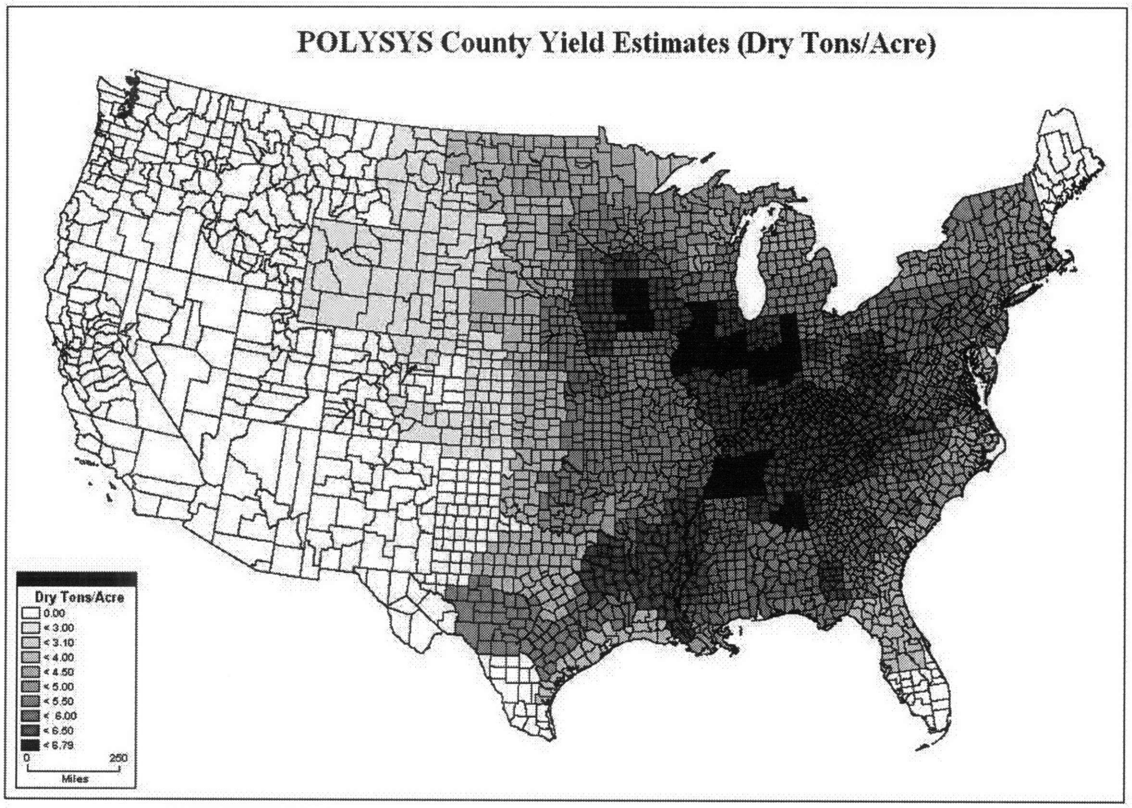


Figure 6- 6 ORECCL – A data base used in POLYSYS that defines switchgrass yields by county (dry tons/acre) [25]

For a given farm gate price, POLYSYS delivers yearly district specific data on the amount of land in production for each of the crops, their productivity, and how their market price changes over ten years. The overall amount of switchgrass produced is then be used to determine the amount of ethanol that could be produced. The amount of biomass and thus ethanol production ultimately depends on the farm gate price. As the farm gate price increases so does land shifting from current agricultural practices to switchgrass production. The maximum farm gate price is limited by the economics of a cellulosic ethanol facility. Therefore, the minimum and maximum expected farm gate price is also discussed in this chapter. Given switchgrass production by districts enables this study to also examine where geographically traditional agricultural land is likely to shift from.

Biomass transport distance is a cost prohibiting process that often determines the maximum radius a facility can collect feedstock from. Therefore, even if switchgrass is produced it may not be utilized if it is not in dense enough amounts. To assess this, the biomass production within a given district is analyzed based on facilities requiring 750 dry tons/day to 5,000 dry tons/day, which is dependent on facility size [16, 19, 26]. This determines which districts have a high enough biomass density to sustain at least one 750 dry ton per day facility. This type of analysis provides some practical usability of the biomass produced in a cellulosic ethanol facility.

Factors That Affect Switchgrass Scale of Production

The six factors that were defined that affect the switchgrass-based ethanol scale of production are discussed below:

Land Availability – The one of the main differences between an agricultural residue and a bioenergy crop is land availability. Agricultural residues already have predefined land that their associated crop is growing on. A bioenergy crop, such as switchgrass, does not have a preexisting industry to draw or expand from. For a bioenergy crop to establish itself as an option, land will have to shift from its current use to land dedicated for biomass production. Land would also have to shift in dense amounts as cellulosic ethanol facilities would require anywhere from 750 dry tons/day to 5,000 dry tons/day depending on the facility size [16, 19, 26]. Economic constraints related to biomass transport costs limit the transport distance, and therefore a dense amount of biomass needs to be available within a maximum radius, which is often sited as 50 miles [16].

This study considers switchgrass being grown both on current agricultural land and on CRP land. The potential of switchgrass on agricultural land is determined by a program called POLYSYS which has already been discussed. The potential for switchgrass to be grown in CPR land is outlined and discussed later in the chapter.

Technological Feasibility – Ethanol produced from switchgrass has hurdles all along the production chain as it is a system that currently does not exist. Within the agricultural sector, large amounts of switchgrass seed would have to be produced to sustain this growing industry. That scale of production would have a time lag that could initially keep the price of switchgrass seed high. Though switchgrass is currently grown, cropping practices are not optimized for maximum yield. Therefore, over time crop management practices will need to be developed over varying geographic regions. In terms of collection, switchgrass is currently not collected. When grown as a top cover it is often burned to maintain the roots organic matter in the soil. During harvesting, switchgrass would have fewer challenges than corn stover as current hay cultivation techniques can be applied. Storage is a major challenge as a current system is not developed. Options for storage include at the field either covered by a tarp or wrapped in plastic to keep it dry, or at the ethanol facility [26, 27]. The cost and logistics of multiple options for storage and handling are aspects of the system that still need to be determined.

On the ethanol conversion side, advances in improving the yield of ethanol from cellulosic sources needs to occur. The main areas where improvements need to be made are increasing the efficiency and cost-effectiveness of the pretreatment process, hydrolysis, and yeast conversion rates. The efficiency of the pretreatment process depends on the amount of cellulose and hemicellulose that was successfully separated from the biomass and therefore available for chemical and biological treatment. There are numerous pretreatment options; these often depend on the feedstock being converted. Enzymatic hydrolysis is the application of enzymes to break down the cellulose and hemicellulose into simpler fermentable sugars [13, 14]. Currently, hydrolysis and fermentation are two different steps, though research is trying to combine these two processes into one known as simultaneous saccharification and fermentation (SSF) [13, 14]. In SSF the microbes are placed in one vessel making this a one step process of sugar production and fermentation [13, 14]. NREL has developed a microorganism that more effectively converts cellulosic material to biomass by being able to simultaneously convert both five and six carbon sugars to ethanol [15]. The disadvantage of SSF is that both these steps are operating at the same non-optimal conditions, which lowers the overall ethanol yield [14]. To improve cellulosic ethanol yields research is needed to improve the efficiency of yeast and reduce the time scales of converting both five and six carbon sugars to ethanol.

Economic Viability – The economic viability of cellulosic ethanol depends on both the delivered feedstock costs and ethanol conversion facility economics. The minimum feedstock price is determined by the net returns to the farmer while the maximum price is determined by the cellulosic ethanol facilities economics. The difference between switchgrass and corn stover is that income earned from switchgrass production would be farmer's sole income while income from selling corn stover is an additional economic stream. Therefore, the net return to the farmer depends on the agricultural cost of production and the farm gate price. If the net returns to the farmer are greater growing switchgrass than their current crop, the farmer will switch production. The details of the actual minimum and maximum farm gate prices for switchgrass are discussed later in the chapter. Estimates for the cost of a cellulosic ethanol conversion facility are in Figure 6-4 and were outlined earlier in this chapter.

Development and Synergy of Industries – Ethanol produced form switchgrass would need an entire industry to be developed and optimized, if not collocated within the Corn Belt. As corn grains are a high priced commodity crop, it is unlikely that switchgrass production at reasonable farm gate prices would displace corn acreage. Therefore, bioenergy acreage will be elsewhere in the United States where ethanol conversion and distribution networks will need to be established. This creates a greater challenge as there are a variety of stakeholders with varying risks and production timelines. A "chicken or the egg" scenario may develop as farmers won't produce switchgrass without a guaranteed market, and a cellulosic ethanol facility will not break ground unless a guaranteed feedstock will be available for a long length of time. This is where the role of policy may be needed to provide a safety net to the players involved.

Policy – The policies that were described within the corn grain and corn stover section are applicable to ethanol produced by switchgrass. Additional policies in the future may be needed to promote incentives to farmers to transition from traditional agricultural crops to bioenergy crops. Incentives may also be needed for cellulosic ethanol producers to build facilities in geographic areas that are traditionally not ethanol producing regions and/or where there is limited feedstock availability.

Environmental Impact – Switchgrass has numerous environmental benefits that were described in detail in Chapter 4. Currently, switchgrass is planted on degraded agricultural land, know as CRP land, to revitalize the soil and minimize soil erosion. Introducing switchgrass as an agricultural crop means that land changes within the agricultural sector will occur. Crops dedicated for example to pasture, hay, cotton, wheat, corn all have the potential to shift into switchgrass production. For traditional agricultural crops, shifting land into switchgrass production is expected to have a positive impact as current switchgrass farming practices are less damaging. Moving hay into switchgrass production would cause minimal environmental changes as farming practices for both those crops are similar. As switchgrass yield becomes an economic driver, farmer's crop management practices will most likely change to optimize biomass production. These practices may include increased fertilizer application rates and irrigation each of which increase the overall systems energy consumption and GHG emissions. These changes in crop practices could potentially also increase nitrification and further affect ground water levels. Policy may be needed to minimize these impacts.

Scale of Switchgrass-Based Ethanol from Agricultural Land

POLYSYS was the modeled used to determine the scale of production of switchgrass at different farm gate prices. Multiple scenarios and assumptions were assessed to determine which parameters increased the overall production of ethanol. A range of farm gate prices was first used to establish the amount of ethanol that could be produced. Afterwards, farmer and facility costs were used to estimate a likely farm gate range. This narrowed the potential range of ethanol production. The general scenarios considered are:

Current Switchgrass Yields at Varying Farm Gate Prices – This scenario represents POLYSYS being run with no time lag in switchgrass introduction. Meaning in year 1 if the net returns to the farmer are positive, switchgrass seed is available and the planting of switchgrass starts. Once planted, the model assumes full yields will be reached in year 3. Switchgrass production is reported as the farm gate price increases in varying increments from $20/dry ton to $100/dry ton. POLYSYS also provides results for which cropland has shifted and from what regions. The amount of ethanol produced is determined by both today's demonstrated cellulosic ethanol conversion rates (238L/dry ton) and future conversion estimates (328L/dry ton).

Doubling Switchgrass Yields at Varying Farm Gate Prices – If switchgrass was utilized as an energy crop, there would be an economic incentive to increase crop yield. This scenario assesses the potential for switchgrass production if the biomass yields were double from what they were initially defined as in ORECCL. By doubling the biomass yields you also increase the net returns to the farmer, causing more land to shift into production. The yields currently assumed within the model are yields that have been seen on test plots and in some cases extrapolated to other regions. To date, research based on test plots has attempted to maximize crop yield by focusing on crop management practices and location. In the future, genetic engineering, as it did in other crops such as corn, will play a much larger role in increasing switchgrass yields.

Facility Capacity Constraints – This is an assumption applied to the two switchgrass scenarios described above. PLOYSYS gives the total amount of switchgrass produced for each of the 305 agricultural districts. Initially, it is assumed that all of this biomass will be utilized for ethanol production. In reality, only the biomass produced in high densities can be utilized due to high biomass transport costs. Therefore, biomass requirements of a 750 dry tons/day to 5,000 dry tons/day facility, were assumed to determine which geographic locations produced enough biomass to support a facility. The biomass produced in each district was evaluated to determine what size a facility a district could support, assuming biomass did not cross district lines. Ethanol production at today's and future conversion rates were then applied to that new reduced amount of biomass. A limitation of this portion of the analysis is that biomass could be transported from adjacent districts to cellulosic facilities, though for this analysis that was not able to be incorporated. Additionally, a district could be larger than 50 miles which could still be cost prohibiting depending on the location of the biomass within the district [16].

Scenario 1: Current Switchgrass Yields at Varying Farm Gate Prices

Table 6-2 describes the amount of land that would be shifted into switchgrass production, the average switchgrass yield, and the total amount of switchgrass produced in the year 2016 at varying farm gate prices. Added to this analysis is the biomass loss due to harvesting, storage, and drying. During the harvesting and storage process there is an estimated 5% loss in biomass [28]. There is another 5% loss in biomass as switchgrass dries from when it's harvested till its use [28]. The "actual available switchgrass" values included both of these biomass losses. It is these values that are then used to estimate the amount of potential ethanol production.

Farm Gate Price	*$/dry ton*	20	30	35	40	45	50	60	100
Land Use	*million acres*	0	9.1	11.6	12.7	16.2	20.4	25.5	40.4
Average Yield	*dry tons/acre*	0	4.5	4.25	4.2	4	3.8	3.7	3.7
Switchgrass Production	*million dry tons*	0	41	49.33	53	65	77	94	149
Actual Available Switchgrass	*million dry tons*	0	37	44.5	48	59	70	85	134

Table6- 2 Switchgrass land use, average yield, and total production at various farm gate prices in the year 2016. This only considers switchgrass grown on current agricultural land

From the given amount of switchgrass that is produced and available at difference farm gate prices, one can determine the amount of ethanol produced from the shifting of agricultural land. As cellulosic ethanol is not produced on a commercial scale two conversion rates are applied 1) a laboratory demonstrated conversion rate of 65% (238L/dry ton), and 2) a future projected conversion rate of 90% (328.5L/dry ton) [19]. Results from the Monte Carlo life-cycle assessment of cellulosic ethanol from switchgrass described in Chapter 4 were then applied to determine the petroleum displacement and GHG abatement potential at this level of switchgrass ethanol production (Table 6-3).

Farm Gate Price	$/dry ton	20	30	35	40	45	50	60	100
Ethanol Conversion Rate (65%)		*238 +/- 6.4 L/ton*							
Ethanol Production	*billion liters*	0	9	11	11	14	17	20	32
GHG Emissions	*total billion gCO2*	0	933	1,123	1,207	1,480	1,753	2,140	3,392
% GHG Reduction	*%*	0.0%	-0.8%	-1.0%	-1.0%	-1.3%	-1.5%	-1.9%	-2.9%
Gasoline Displacement	*billion liters*	0	6	7	8	9	11	14	22
% Gasoline Displacement	*%*	0.0%	0.9%	1.0%	1.1%	1.4%	1.6%	2.0%	3.1%

Farm Gate Price	$/dry ton	20	30	35	40	45	50	60	100
Ethanol Conversion Rate (90%)		*328.5 +/- 9.1 L/ton*							
Ethanol Production	*billion liters*	0	12	15	16	19	23	28	44
GHG Emissions	*total billion gCO2*	0	1,288	1,550	1,666	2,043	2,420	2,954	4,682
% GHG Reduction	*%*	0.0%	-1.1%	-1.3%	-1.4%	-1.8%	-2.1%	-2.6%	-4.1%
Gasoline Displacement	*billion liters*	0	8	10	11	13	16	19	30
% Gasoline Displacement	*%*	0.0%	1.2%	1.4%	1.5%	1.9%	2.2%	2.7%	4.3%

Current Corn Ethanol = 18 Billion Liters

Estimate Max Corn Ethanol = 65-75 Billion Liters

Table 6- 3 Switchgrass Ethanol Production, GHG Emissions, and Petroleum Displacement at Various Farm Gate Prices in the Year 2016. Gasoline and GHG reductions are based on 2025 EIA projected US gasoline consumption rate of 700 billion liters per year [29]

At demonstrated ethanol conversion rates a range of 9-17 billion liters of cellulosic ethanol can be produced. This would have the potential of displacing 0.9%-2% of gasoline consumption and vehicle GHG emissions. In the future, if ethanol conversion rates increased, ethanol produced from switchgrass could increase to 12-23 billion liters. At this production level, 1.2%-2.7% of gasoline and GHG emissions could be displaced. To narrow the range that the scale of production of ethanol from switchgrass can attain, a minimum and maximum farm gate price is estimated based on the farmer's and ethanol facilities costs of production.

To create an incentive for farmers to switch from growing their current agricultural crop to a bioenergy crop such as switchgrass a minimum farm gate price is needed. This minimum farm gate price is dependent on the net returns to the farmer. Net returns depend on the variable costs of production and an assumed discount rate. The variable cost of production for switchgrass is defined for each state ($/acre), and is also defined by agricultural district when switchgrass yield is incorporated ($/ton). The <u>average</u> variable cost of production for switchgrass as defined by POLYSYS is $93/acre or $19/dry ton [16]. The variable cost of production does not include land rents ($75/acre for cropland and $50/acre for grasslands) [30]. The costs include: seed, lime, nitrogen, phosphorus, potassium, herbicide, insecticide, repairs, operating interest, fuel, lube, depreciation, interest, insurance, taxes, housing, labor, and harvesting [23, 24].

From Table 6-3 at a farm gate price of $20/dry ton, no agricultural land is shifted, which should be expected as switchgrass is defined in POLYSYS to have a variable cost averaging $19/dry ton. As the farm gate price increases above $30/dry ton, the net returns for switchgrass increase and land begins to shift into switchgrass production. As farm gate prices increase further, greater quantities of land begin to shift. This trend continues even up to $100/dry as there is no limiting price assumption. Meaning, if the system was only based on net returns to the farmer, more farmers would shift as farm gate prices increase. What caps a feedstocks farm gate price is the price a purchaser is willing to pay. Therefore, in this case the expected maximum farm gate price is determined by the cost of production of a cellulose ethanol facility and the ethanol market price. A cellulosic ethanol facilities profits are defined as:

$$\begin{aligned}\Pr ofit &= \operatorname{Re} venue - Cost \\ &= (Market \Pr ice\, of\ Ethanol)(Ethanol\ Conversion\ Rate) \\ &\quad - (Facility\ Costs + Biomass\ Costs + Biomass\ Transport\ \&\ Handling\ Costs)\end{aligned}$$

Equation 6- 1

Therefore, to determine the maximum farm gate price of switchgrass this study considers today's expected values for the estimated cost of production and ethanol conversion rates [16].

Current Cellulosic Ethanol Facility Costs of Production

During 2006 ethanol's market price was \$0.58-\$0.61/L (\$2.20-\$2.30/gallon). In October of 2007, the price of ethanol begun to drop due to increased production creating an imbalance of supply and demand in the market. This surplus is partly due to the saturation of local markets and the bottleneck in infrastructure to transport the fuel to further coastal markets. Some see this as a short-term problem while others are looking for a longer-term solution such as retrofitted existing pipelines or creating a new ethanol pipeline infrastructure. Currently, ethanol's market price is averaging \$0.42/L (\$1.6/gal). For this analysis a market price of \$0.61/L (\$2.3/gal) was assumed. For cellulosic ethanol to be cost competitive it needs to be economical within a wide range of ethanol market prices as they can be volatile at times. Additionally, the feedstock price has a large impact on the facilities long-term financial success, as does the cellulosic conversion efficiency. At the laboratory scale NREL has demonstrated a cellulosic conversion rate of 65% or 238 L/dry ton (63 gallon/dry ton) [19]. While at larger scales this efficiency would initially decrease, for this analysis, the current conversion rate for a large scale cellulosic facility is assumed to be 238L/dry ton (63gal/dry ton) [19]. Estimated current cost of production for a cellulosic facility **before feedstock purchase and transport/handling** is \$0.42/L (\$1.60/gal) or \$100/dry ton (Figure 6-4) [16]. Using these inputs equation 6-1 becomes:

Profit = ($0.61/liter)*(238L/dry ton) – ($100/dry ton + Biomass Costs + Biomass Transport & Handling)

= $145/dry ton - ($100/dry ton + Biomass Costs + Biomass Transport & Handling)

= $45/dry ton – (Biomass Costs + Biomass Transport & Handling)

Therefore, to break even a facility can not afford to pay more than approximately $45-$50/dry ton as a delivered biomass cost (Biomass Costs + Biomass Transport & Handling). Transport and handling costs have been estimated at 8 cents per dry ton mile and $4/dry ton, respectively [26, 31]. Therefore for an assumed 50 mile radius, transport and handling costs are $8/dry ton [16, 26, 31, 32]. This results in a maximum feedstock price of $42/dry ton, using today's economic estimates. If a conversion rate of 90% or 328.5 L/dry ton (87 gallon/dry ton) is assumed, this would result in a maximum farm gate price of $100/dry ton. At today's lower ethanol market costs of $0.42/L the facility wouldn't be profitable at any farm gate price.

At a farm gate price between $35-$45/dry tons, 50-65 million tons of switchgrass is produced, though 45-70 million tons is actually available after harvesting, storage, and drying losses (Table 6-3). At this level of switchgrass production 9-14 billion liters of ethanol could be produced, displacing 1%-1.5% of gasoline consumption today (Table 6-3). At this level of production, 11-16 million acres of agricultural cropland would have shifted to switchgrass production (Table 6-2). The question than becomes, which crops shift out of production? Given the information by POLYSYS, this study was able to determine which agricultural crops shifted into switchgrass production. This shift is limited by the following constraints:

1. Land is shifted based on net returns to the farmer ($/acre)
2. Once land is shifted to switchgrass production, it stays in biomass production
3. POLYSYS is based on the *USDA Agricultural Projections to 2016 Baseline*
4. Hay demands as reported by the USDA baseline must be met.
5. Pasture land is available per district to replace hay land that may shift out of production to keep the hay demands met

6. Additional pasture land can also be brought into production for any crop including switchgrass
7. Switchgrass can only be grown on lands where irrigation is not needed

Figure 6-7 is a map showing where switchgrass production at a farm gate price of \$45/dry ton would be and in what amounts. Switchgrass production is generally located in the southern part of the Untied States. The Corn Belt region is mainly not accessible to switchgrass at these farm gate prices as corn has higher net returns, being a high commodity crop.

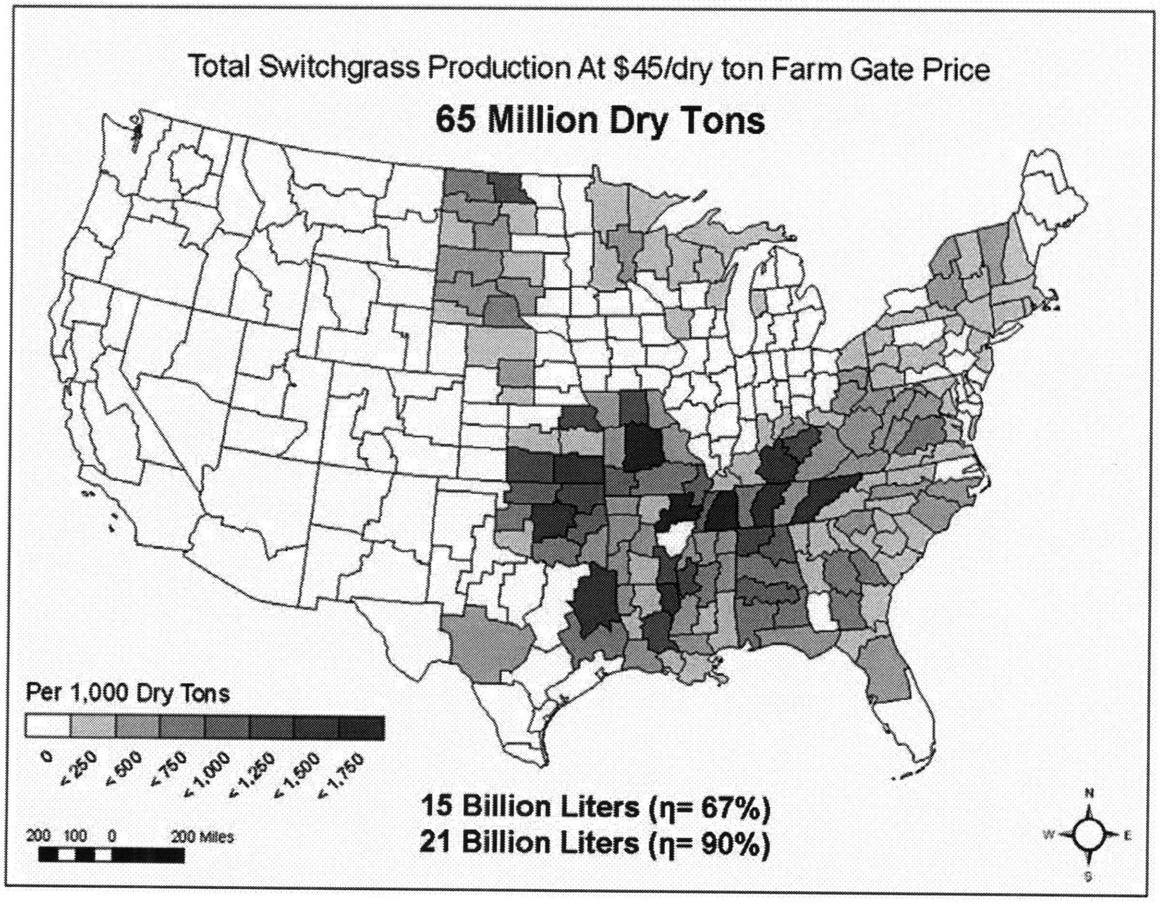


Figure 6- 7 – Total Switchgrass Production at a Farm Gate Price of \$45/dry ton

Evaluating which agricultural land shifted to switchgrass production was analyzed for the top switchgrass producing districts and states. 70% of switchgrass production mainly comes from 9 states (Tennessee, Missouri, Oklahoma, Alabama, Arkansas, Louisiana, Mississippi, Kentucky, and Texas). Table 6-4 displays the shift in acreage for each agricultural crop from the baseline defined in 2007 to 2012 and to 2016 levels. Table 6-5 presents the same information but as a percent change from the 2007 baseline. Initially, land dedicated to the production of hay first shifts into switchgrass production. This is because hay has similar production costs and net returns. Pasture land is then brought into hay production to meet the USDA 2016 baseline projections for required hay production. In some cases pasture land is also brought into production for additional switchgrass production.

		$35/dry ton			$45/dry ton	
Crop	2007 Baseline	2012	2016		2012	2016
			million acres			
Corn	86	90.02	90.03		90.02	90.03
Grain Sorghum	6	5.79	5.54		5.77	5.5
Oats	4.1	4.14	4.14		4.13	4.11
Barley	3.5	3.51	3.48		3.51	3.47
Wheat	60	58.72	58.87		58.39	57.62
Soybeans	71	69.7	69.74		69.46	68.72
Cotton	13.7	13.31	12.59		13.21	12.39
Rice	3.1	2.89	3.18		2.89	3.05
Hay	60.6	71.58	72.95		72.17	73.37
Pasture	56.2	39.5	31.3		38	28.9
Switchgrass	0	4.64	11.6		6.18	16.24
Total land Area	364.2	363.8	363.42		363.73	363.4

Table 6- 4 Total crop, pasture, and switchgrass acreage at farm gate prices of $35/dry ton and $45/dry ton

	$35/dry ton			$45/dry ton	
Crop	2012	2016		2012	2016
	% Change From Baseline				
Corn	0.02%	0.03%		0.02%	0.03%
Grain Sorghum	1.58%	0.73%		1.23%	0.00%
Oats	0.98%	0.98%		0.73%	0.24%
Barley	0.29%	-0.57%		0.29%	-0.86%
Wheat	0.38%	0.63%		-0.19%	-1.50%
Soybeans	1.01%	1.37%		0.67%	-0.12%
Cotton	-2.85%	-8.77%		-3.58%	-10.22%
Rice	-5.86%	2.91%		-5.86%	-1.29%
Hay	17.34%	20.78%		18.31%	21.47%
Pasture	-29.72%	-44.31%		-32.38%	-48.58%
Total land Area	-0.27%	-0.13%		-0.29%	-0.13%

Table 6- 5 Percent of land use changes from the baseline for 2012, and 2016 with switchgrass at a farm gate price of $35/dry ton and $45/dry ton

Land dedicated to cotton, is the first agricultural crop whose acreage decreases. The cotton industry is centered in the South on land that has been sited to have the potential of growing highly productive grasses such as switchgrass. By 2016 cotton acreage has decreased between 8-10% depending on switchgrass farm gate price. In some districts land is also shifted from wheat and soybean production. At this price level, corn acreage would not shift into switchgrass production.

Thus far, it has been assumed that all the switchgrass produced can be utilized for ethanol production, providing a theoretical maximum. In practice though, the location and biomass density of a region as well as the biorefinery size limit the actual amount of produced biomass that can be utilized for ethanol production. Reports evaluating the technological and economic feasibility of cellulosic ethanol facilities have assumed a range of potential facility capacities. In a majority of studies, a facility capacity of 2,000 dry tons/day and 1,000 dry tons/day are often assumed [16, 26]. A facility capacity of 750 dry tons/day is also considered, as this rate is the current capacity of the new pilot scale cellulosic facility that POET is building to convert barn and corn cobs into ethanol [17]. The biomass produced in each district was evaluated to determine what size a facility a district could support; assuming biomass did not cross district lines. A limitation of this portion of the analysis is that biomass could be transported between adjacent districts to nearby cellulosic facilities, though for this analysis that was not incorporated.

Table 6-6 describes the amount of utilized switchgrass and ethanol produced for different biorefinery capacity sizes at two different farm gate prices, $35/dry ton and $45/dry ton. The number of districts that produce enough switchgrass to support at least one biorefinery ranges from 20 to 79 districts depending on farm gate price and facility capacity. For both farm gate prices, and a facility capacity of 750 dry tons/day, there was a maximum facility density of 5 facilities in a given agricultural district.

Farm Gate Price	**Facility Capacity**	**Number of Facilities**	**Number of Districts**	**% of Utilized SWG Production**	**Ethanol Production**	
$/dry ton	*dry tons/day*			%	*Billion Liters in 2016*	
					238 liters/dry ton	*328 liters/dry ton*
35	2,000	21	20	44%	5	7
35	1,000	81	53	76%	9	12
35	750	120	66	84%	10	14
45	2,000	31	28	50%	8	11
45	1,000	108	63	76%	12	16
45	750	162	79	83%	13	18

Table 6- 6 Cellulosic ethanol facility density, utilized switchgrass production, and expected ethanol production

From Table 6-6, the amount of ethanol produced at $35/dry ton and $45/dry drops from 12 and 15 billion liters, to a maximum of 9.8 and 12.9 billion liters respectively at today's ethanol conversion rates. In the future it decreases from 16 and 21 billion liters to 13.5 and 17.7 billion liters.

While the smallest facility of 750 dry tons/day maximizes ethanol production, economies of scale still prove that larger ethanol facilities are more profitable. It is also possible to have a combination of facility capacity depending on biomass availability and project economics. These estimates are solely based on feedstock availability and density within a district to provide an approximation for the amount of biomass that is actually utilized for ethanol production. The actual number of facilities and their location will still depend on a wide range of logistical and economic factors.

Figure 6-8 graphically displays which districts would and would not produce enough switchgrass to support at a minimum a 750 dry ton/day facility. The yellow districts are the districts whose switchgrass production is below this capacity and therefore not utilized. The majority of these districts are in the Northern Central states, as minimal amounts of land shifted into switchgrass production at a farm gate price of $45/dry ton. Assuming a minimum biomass requirement, decreases the amount of available switchgrass to 54 million tons, or by 17%.

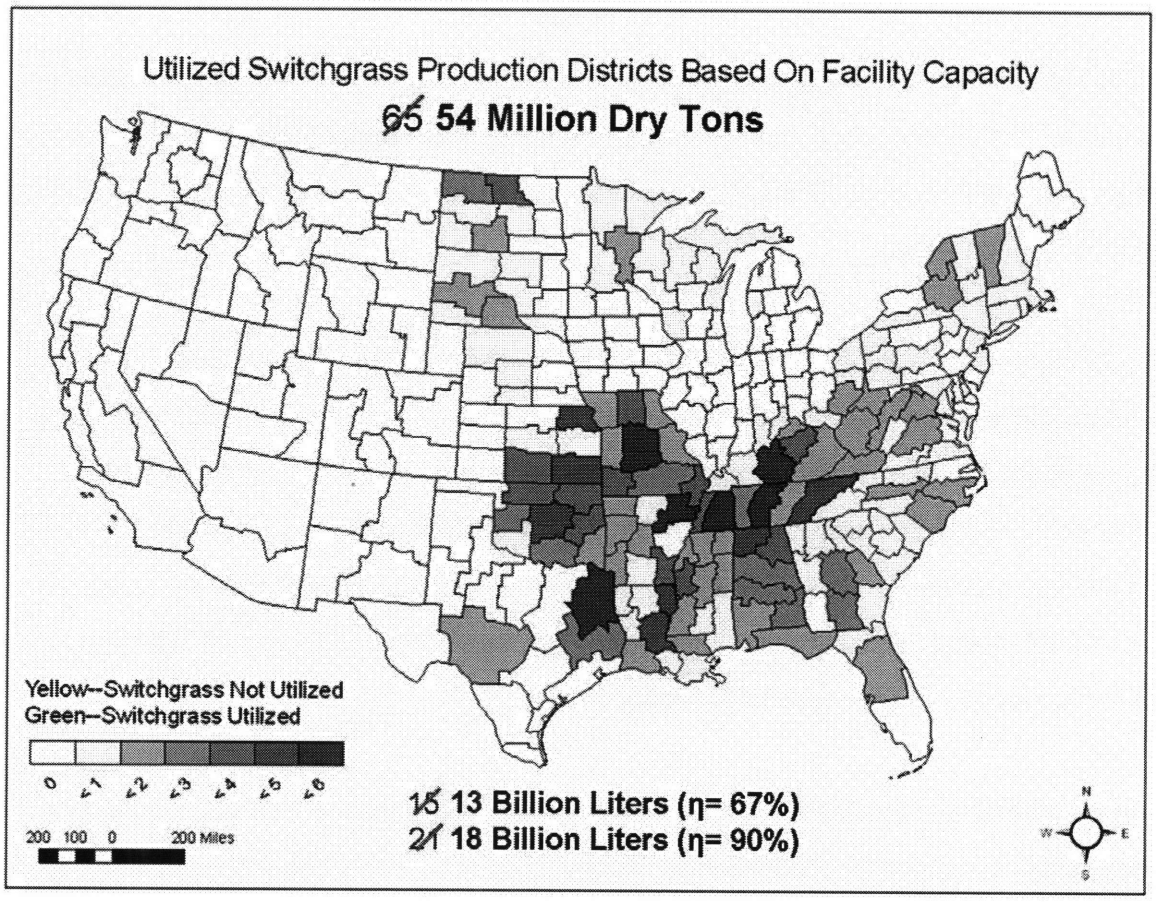


Figure 6- 8 – Utilized switchgrass production based on cellulosic ethanol facility capacity

Scenario 2: Doubling Switchgrass Yield at Varying Farm Gate Prices

Currently, switchgrass is planted on degraded land to re-stabilize soil nutrients and prevent wind and water erosion. It is often planted on CRP land, pasture land, and along rivers to prevent nitrification. The use of switchgrass has generally had an environmental focus, and therefore maximizing the yield has not been a main driver. That could change if switchgrass was utilized as an energy crop, as there would be an economic incentive to increase crop yield. To date, research maximizing crop yield has focused on crop management practices and location. In the future, genetic engineering, as it did in other crops such as corn, will play a much larger role. This scenario analyses the affects that doubling current switchgrass yields on biomass and ethanol production.

Originally, switchgrass yields were defined by ORECCL on a per county basis and range from 0-6 tons per acre [23]. For this scenario, it was assumed that the average yield per county would double to 6-12 tons per acre. Table 6-7 represents the amount of switchgrass acreage and production at varying farm gate prices in the year 2016 for this double yield scenario. The "actual utilized switchgrass" again represents the total amount of available switchgrass once the harvesting, storage, and drying loss are included.

Farm Gate Price	*$/dry ton*	20	30	35	40	45	50	60
Land Use	*million acres*	26	39	41	42	43	44	46
Average Yield	*dry tons/acre*	11.0	11.1	11.1	11.3	11.2	11.0	10.6
Switchgrass Production	*million dry tons*	281	427	458	473	478	484	493
Actual Utilized Switchgrass	*million dry tons*	254	385	413	427	431	437	445

Table 6- 7 Double switchgrass yield scenario: land use, average, yield, and production at various farm gate prices in the year 2016.

The biomass produced at $35 and $45 per dry ton increased, 10 and 5 fold respectively. The biomass produced does not just double since crop acreage shifting to switchgrass production depends on the net returns to the farmer and additional land constraints on the system that were already defined. In this scenario, at a farm gate price of $20 per dry ton, 26 million acres of cropland were shifted to switchgrass production. This produces 281 million dry tons of switchgrass rather than zero in the original switchgrass scenario as presented in Table 6-2. Crop land shifts at a lower farm gate price because the cost per dry ton to the farmer is lower if the yield increases while farming variable costs remain constant. Assuming an average yield of 7.5 dry tons per acre results in a farmer variable cost of $12.4/dry ton, lowering the minimum switchgrass production farm gate price by 35%. This is possible, through improved crop management practices and as improvements in switchgrass seed through genetic engineering become available. The farming variable cost may initially be higher as switchgrass seed availability may be limited due to a production time lag as switchgrass seed is not currently produced on this scale. Though over time, as the production increases seed prices would be expected to decrease lowering the farming variable production cost.

As biomass production from switchgrass increases as does ethanol production and gasoline and GHG displacement. Table 6-8 displays the amount of ethanol produced at current and future ethanol conversion rates. For demonstrated conversion rates, ethanol produced at $35 and $45 per dry ton increases 9 fold, with the potential to displace 40-70 billion liters of petroleum, or 9% of petroleum consumption. At this scale, ethanol can also displace 9% of vehicle transportation GHG emissions.

Farm Gate Price	*$/dry ton*	**20**	**30**	**35**	**40**	**45**	**50**	**60**
Ethanol Conversion Rate (65%)		*238 +/- 6.4 L/ton*						
Ethanol Production	*billion liters*	60	92	98	102	103	104	106
GHG Emissions	*total billion gCO2*	6,398	9,722	10,428	10,769	10,883	11,020	11,225
% GHG Reduction	*%*	-5.5%	-8.4%	-9.0%	-9.3%	-9.4%	-9.6%	-9.7%
Gasoline Displacement	*billion liters*	41	62	67	69	70	71	72
% Gasoline Displacement	*%*	5.9%	8.9%	9.6%	9.9%	10.0%	10.1%	10.3%
Farm Gate Price	*$/dry ton*	**20**	**30**	**35**	**40**	**45**	**50**	**60**
Ethanol Conversion Rate (90%)		*328.5 +/- 9.1 L/ton*						
Ethanol Production	*billion liters*	83	127	136	140	142	143	146
GHG Emissions	*total billion gCO2*	8,831	13,419	14,393	14,864	15,022	15,210	15,493
% GHG Reduction	*%*	-7.7%	-11.6%	-12.5%	-12.9%	-13.0%	-13.2%	-13.4%
Gasoline Displacement	*billion liters*	57	86	92	95	96	98	99
% Gasoline Displacement	*%*	8.1%	12.3%	13.2%	13.6%	13.8%	13.9%	14.2%
Current Corn Ethanol = 18 Billion Liters **Estimate Max Corn Ethanol = 65-75 Billion Liters**								

Table 6- 8 Double switchgrass yield scenario: ethanol production, GHG emissions, and petroleum displacement at various farm gate prices in the year 2016. Gasoline and GHG reductions are based on 2025 EIA projected US gasoline consumption rate of 700 billion liters per year [29]

In the future along with switchgrass yields increasing, the conversion of bioethanol can potentially increase as well. In this future scenario, 83-145 billion liters of ethanol can be produced, potentially displacing 14% of gasoline consumption and 13% of vehicle GHG emissions.

The majority of land is shifting out of pasture and into crop production. Meeting hay demands is a constraint of POLYSYS, and therefore pasture land is utilized to meet this requirement as hay producing land is shifted to switchgrass and other crops. Pasture, hay, and cotton acreage are where the major land shifts to switchgrass production are occurring (Table 6-9 and Table 6-10).

	$35/dry ton				$45/dry ton		
Crop	2007	2012	2016		2007	2012	2016
	million acres						
Corn	86	89.35	85.54		86	89.32	84.53
Grain Sorghum	6	5.58	5.07		6	5.57	4.99
Oats	4.1	4.03	3.85		4.1	4.03	3.84
Barley	3.5	3.44	3.27		3.5	3.44	3.26
Wheat	60	56.62	51.13		60	56.47	50.79
Soybeans	71	65.8	60.94		71	65.84	60.9
Cotton	13.7	12.75	11.26		13.7	12.75	11.26
Rice	3.1	2.8	3		3.1	2.8	2.91
Hay	60.6	72.75	73.54		60.6	72.75	73.98
Pasture	56.2	36.2	24.6		56.2	36.2	24
Switchgrass	0	14.44	41.05		0	14.6	42.83
Total land Area	364.2	363.76	363.25		364.2	363.77	363.29

Table 6- 9 – Double switchgrass yield scenario: total crop, pasture, and switchgrass acreage at farm gate prices of $35/dry ton and $45/dry ton for double switchgrass yield scenario

	$35/dry ton			$45/dry ton	
Crop	2012	2016		2012	2016
	% Change From Baseline				
Corn	-0.7%	-5.0%		-0.8%	-6.1%
Grain Sorghum	-2.1%	-7.8%		-2.3%	-9.3%
Oats	-1.7%	-6.1%		-1.7%	-6.3%
Barley	-1.7%	-6.6%		-1.7%	-6.9%
Wheat	-3.2%	-12.6%		-3.5%	-13.2%
Soybeans	-4.6%	-11.4%		-4.6%	-11.5%
Cotton	-6.9%	-18.4%		-6.9%	-18.4%
Rice	-8.8%	-2.9%		-8.8%	-5.8%
Hay	19.3%	21.8%		19.3%	22.5%
Pasture	-35.6%	-56.2%		-35.6%	-57.3%
Total land Area	-0.3%	-0.2%		-0.3%	-0.2%

Table 6- 10 Double Yield Scenario - Percent of Land use changes from the baseline for 2012, and 2016 with switchgrass at a farm gate price of $35/dry ton and $45/dry ton

The facility capacities analyzed for this scenario are 5,000, 2,000, and 1,000 dry tons per day at a farm gate price of $35 and $45 per dry ton. For this scenario 74%-98% of the biomass produced can be utilized for ethanol production (Table 6-11). Currently there are 122 corn ethanol plants and an additional 74 under construction [6]. Iowa has the largest number of ethanol facilities with 27 corn ethanol plants and 30 under construction and planning [6]. At $35/dry ton Illinois would have fifteen 5,000 capacity facilities, the greatest number per state. Missouri and Kansas each would have 13 and 10 facilities at the same size. These estimates are solely based on feedstock availability and density. The actual number of facilities and their location still depend on a wide range of logistical and economic factors.

Farm Gate Price	Facility Capacity	Number of Facilities	Number of Districts	% of Utilized SWG	Ethanol Production	
$/dry ton	dry tons/day	Number	Number	%	billion liters in 2016	
					238 liters/dry ton	328 liters/dry ton
35	5,000	140	103	74%	80.40	110.80
35	2,000	513	181	95%	103.26	142.31
35	1,000	1,134	210	98%	107.18	147.71
45	5,000	145	105	74%	84.36	116.26
45	2,000	540	189	95%	108.97	150.18
45	1,000	1,193	215	98%	112.33	154.81

Table 6- 11 - Cellulosic Ethanol facility Density, Utilized Switchgrass Production, and Expected Ethanol Production when Switchgrass Yield is doubled

Potential of Conservation Reserve Program (CRP) Land for Switchgrass Production

Studies often site the potential of growing switchgrass on degraded agricultural land within the Conservation Reserve Program (CRP). CRP land has the advantage of not directly competing with current agricultural land and thus food production. Currently, there is 36 million acres enrolled in CRP [1]. Land is enrolled within 3 potential areas within CRP; general sign-up, continuous sign-up, and farmable wetlands [1]. Table 6-12 shows the break down of CRP land by each of these areas.

Land Within the Conservation Reserve Program	
Sign-Up Type	**Acres**
General	32,449,279
Continuous	3,400,233
Farmable Wetlands	153,788
Total	36,003,300

Table 6- 12 – CRP Land by Sign-up Category [1]

Definition of CRP Sign-up Categories [1]
General – Landowners and operators apply for acceptance based on an environmental benefits index (EBI) during specific enrollment periods.

Continuous – Landowners and operators may enroll certain high priority conservation practices and/or to address specific environmental objectives.

Farmable Wetlands – Landowners and operators can apply to enroll small non-flood plain wetlands

This analysis does not consider utilizing land enrolled in the continuous and farmable wetland sign-up category for switchgrass production as the environmental reasons for CRP enrollment are too grave. This analysis considers three different scenarios for utilizing general sign-up CRP land for switchgrass production.

- **Switchgrass Production Based on General Sign-Up** – This considers growing switchgrass on all of the land within the general sign up category. Ethanol production is calculated based on switchgrass biomass yields representing current potential yields of 3 dry tons/acre and future potential yields of 6 dry tons per acre.

- **Switchgrass Production Based On Erodibility Index (EI)** – Often land is enrolled within CRP for erosion control purposes. Switchgrass, due to its large rooting system, is a crop that is often used to decrease erosion. Therefore, this scenario considers switchgrass production on land enrolled within general sign-ups with an EI between 1 and 8, and a EI between 1 and 15 [1]. Land that is enrolled with an EI greater than 15 should not be used for crop production due to the environmental damage that can be caused. For an EI between one and eight, 2.7 million acres are available for switchgrass production. For an EI between eight and fifteen, 361,102 acres are potentially available for switchgrass production.

- **Switchgrass Production Based On Conservation Practice** – Land is enrolled within in CRP based on 33 conservation practice categories. This scenario determines the approximate amount of CRP land that can be utilized for switchgrass production based on these conservation practice categories within the general sign-ups. Conservation categories considered applicable to switching to switchgrass production are labeled as "grasses". Land that is categorized as trees, wetlands, buffers, and erosion control are not included. This results in 25 million acres that could potentially be used for switchgrass production [1].

Table 6-13 and Figure 6-9 describe the amount of the land available for switchgrass production, the amount of switchgrass that could be produced at 3 and 6 dry tons per acre, and the amount of ethanol that could be produced at 238 and 328 liters per dry ton.

Switchgrass Production Based One General Sign-up			
General Sign-Up	Acres	32,449,279	
		Today	Future
Average Switchgrass Yield	dry ton/acre	3	6
Switchgrass Production		97,347,837	194,695,674
Ethanol Conversion Efficiency	liter/dry ton	238	328
Ethanol Produced	billion liters	23	64
Switchgrass Production Based On Erodibility Index (EI)			
1<EI<8			
General Sign-Up	Acres	2,765,575	
		Today	Future
Average Switchgrass Yield	dry ton/acre	3	6
Switchgrass Production	dry tons	8,296,725	16,593,450
Ethanol Conversion Efficiency	liter/dry ton	238	328
Ethanol Produced	billion liters	2	5
8<EI<15			
General Sign-Up	Acres	361,102	

		Today	Future
Average Switchgrass Yield	dry ton/acre	3	6
Switchgrass Production	dry tons	1,083,306	2,166,612
Ethanol Conversion Efficiency	liter/dry ton	238	328
Ethanol Produced	billion liters	0.25	0.70
Switchgrass Production Based On Conservation Practice			
General Sign-Up	Acres	25,187,585	
		Today	Future
Average Switchgrass Yield	dry ton/acre	3	6
Switchgrass Production	dry tons	75,562,755	151,125,510
Ethanol Conversion Efficiency	liter/dry ton	238	328
Ethanol Produced	billion liters	18	50

Table 6-13 – Summary of switchgrass and ethanol production for each of the three CRP scenarios

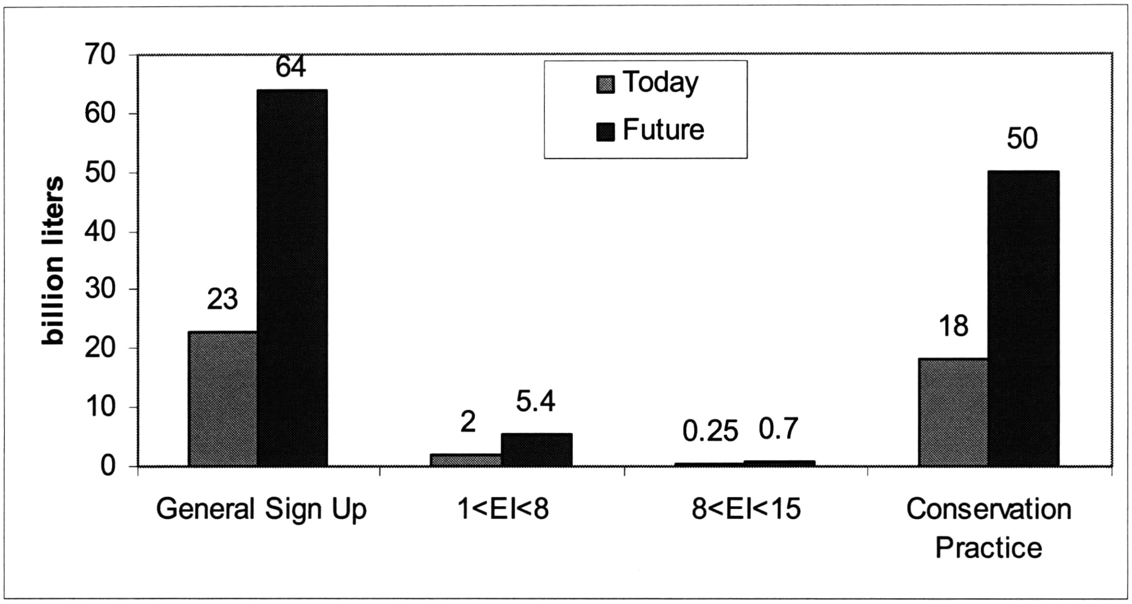


Figure 6- 9 – Switchgrass-based ethanol production from switchgrass grown in CRP land for three different scenarios

Though switchgrass on CRP land has the potential to produce up to 64 billion liters of ethanol, there are still hurdles. For example, CRP land is spread out throughout the United States (Figure 6-10). This could present a challenge switchgrass grown on CRP land, as a dense amount of switchgrass would be needed within a given radius to a cellulosic ethanol facility. Additionally, the environmental reasons for land being enrolled in CRP may lower the productivity of switchgrass production and potentially increase its cost of production. Therefore, while CRP land has the potential for producing switchgrass, there are still many challenges that need to be addressed.

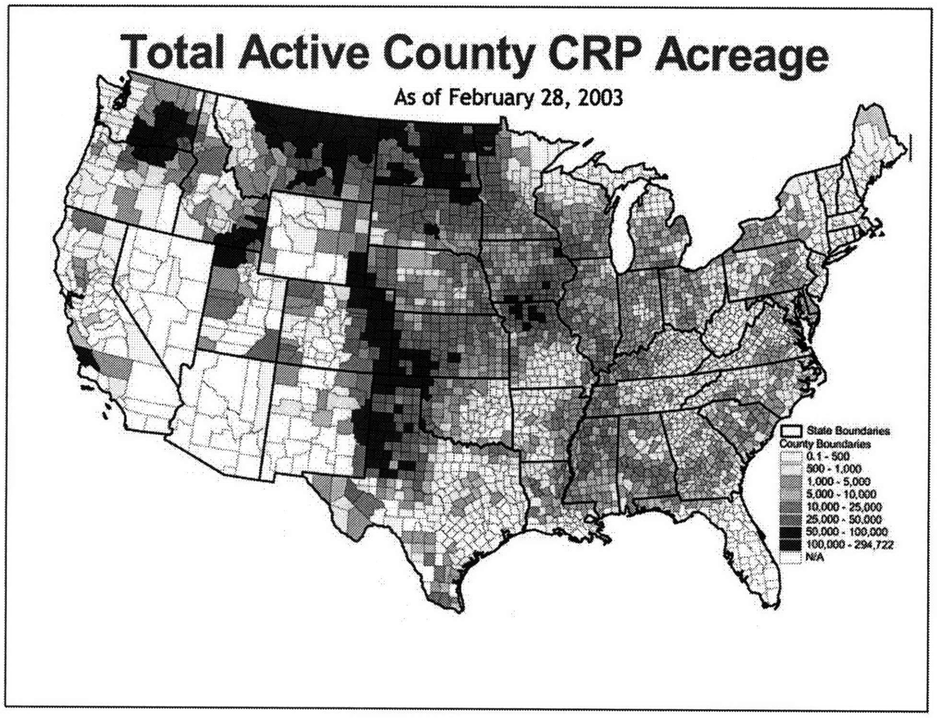


Figure 6- 10 – Total US CRP Acreage

Biomass-Based Ethanol Scale Comparison

This analysis was performed to discuss the potential scale of production of ethanol. Table 6-14 and Figure 6-11 summarizes the production scale of ethanol from corn grains, corn stover, and switchgrass. Future corn grain ethanol production is expected to consume 30% of the corn grain market and plateau between 57 and 68 billion liters. The potential for this industry to expand beyond this level is low as corn grains are utilized throughout the food industry and are a large part of the export market. As corn stover is dependent on corn grain production, its scale is inherently limited as well. The potential scale of production of corn stover ethanol is between 24-36 billion liters. This amount depends on the stover removal rate, which for this study is assumed to be 30%. Ethanol production could grow if the average rate of corn stover removal increased, though is may have other environmental impacts. Switchgrass produced on agricultural land has the potential of producing 9-20 billion liters of ethanol depending on conversion rate and farm gate price (Figure 6-11). In the future, it is assumed that switchgrass yields could double, resulting in the production of 60-145 billion liters of ethanol depending on the cellulosic ethanol conversion rate and farm gate price (Figure 6-11).

Ethanol Scale of Production From Various Biomass Sources					
		Today (2006)		**Future (2025)**	
Corn Grain	*billion liters*	18		57 to 68	
Cellulosic Ethanol Conversion Rate		*238L/dry ton*	*328L/dry ton*	*238L/dry ton*	*328L/dry ton*
Corn Stover	*billion liters*	24	33	26	36
Switchgrass (agriculture)	*billion liters*	9 to 14	12 to 20	60 to 100	85 to 145
Switchgrass (CRP)	*billion liters*	0.25 to 23	0.35 to 32	0.5 to 36	0.7 to 64

Table 6- 14 – Summary of ethanol production from corn grains, corn stover, and switchgrass grown on agricultural and CRP land

Figure 6-11 gives the percent of petroleum displacement and GHG abatement of each of these ethanol production scenarios at their respective scale. The size of the symbol represents the range at a particular value can have. Compared to corn grain ethanol, or ethanol produced from switchgrass has a wide range of values as the uncertainty of the system is large. Corn grain ethanol has the potential to displace 2.5%-6.5% of petroleum and 0.9%-1% of GHG emissions. This is assuming the best case scenario results of *Iowa Corn Grain Ethanol* as described in Chapter 3. In actuality, corn grains from less efficient lands will be used at this scale resulting in less GHG benefits. The petroleum displacement benefits will be the same as petroleum is minimally used during corn grain ethanol's production life-cycle. Corn stover has the potential of displacing 3%-3.5% of gasoline and 2%-2.5% of GHG emissions. The impacts of corn stover if produced today were determined by the *Corn Stover Ethanol* scenario defined in Chapter 4. The future stover impacts were determined by the *2025 Corn Stover Ethanol* scenario. If switchgrass is used as a bioenergy crop it has the potential of displacing 1%-14% of petroleum consumption and GHG emissions depending biomass switchgrass yields. These results are based on the *Alabama Switchgrass Ethanol* and *2025 Alabama Switchgrass Ethanol* scenarios defined in Chapter 4.

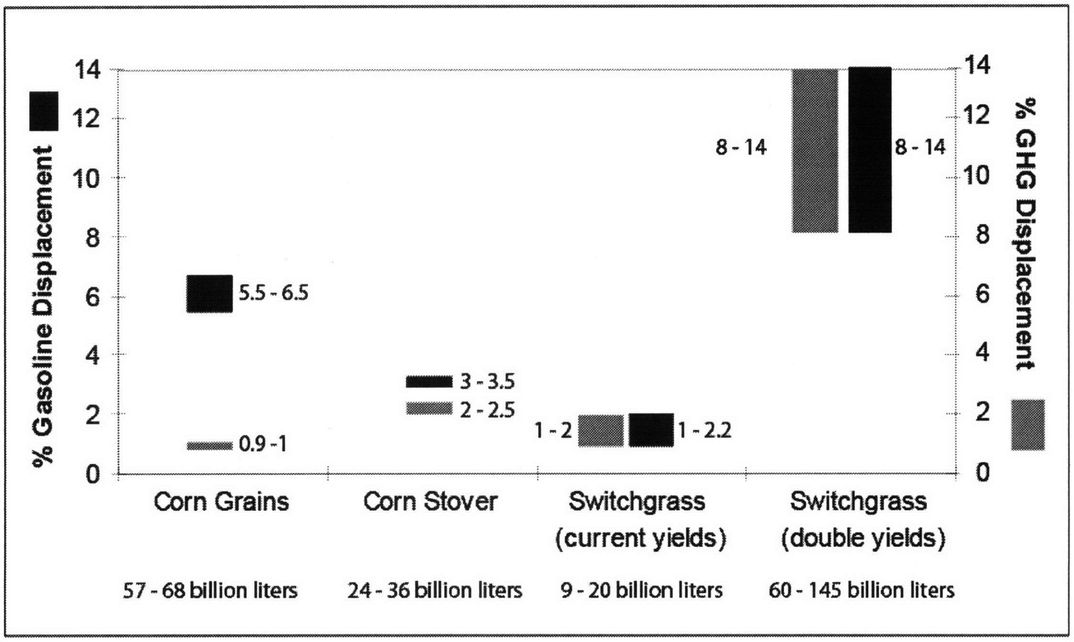


Figure 6- 11 – Summary of ethanol production, gasoline displacement, and GHG displacement, from corn grains, corn stover, and switchgrass grown on agricultural land. The scenario labeled as Switchgrass (double yields) is a "what if" scenario to help show how sensitive ethanol production is to biomass yields

While current efforts are almost entirely placed on improving the cellulosic ethanol conversion yield, for economic reasons, scalability ultimately depends on biomass availability. From Table 6-14 and Figure 6-11, the impact of improving the biomass yield of switchgrass has a much greater affect an increasing ethanol production levels than the increase in cellulosic conversion efficiency. Therefore, to improve the potential scale of cellulosic ethanol production, efforts should be placed on improving its productivity as land availability is ultimately an overall constraint. In addition, to land availability, and productivity, the scalability of cellulosic ethanol also depends on the agricultural and cellulosic conversion facility economics, technological advances, synergy of industries, and policy.

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Chapter 7: Is The New US Renewable Fuels Target of 36 Billion Gallons Feasible?[46]

In recent years, concerns surrounding the US petroleum supply, national security, and impact on the environment have increased. One of the first political responses to this concern was the implementation of the Renewable Fuels Standard (RFS) in 2007 which mandated 7.5 billion gallons of biofuels – mainly ethanol- by 2012 [1]. Ethanol was selected as the renewable fuel of choice because it was a mature technology, readily available, and easily initially scalable due to its existing infrastructure. Over the past 5 years, ethanol producers have stepped up to this challenge and have even surpassed it. Currently, ethanol production has reached 4.8 billion gallons, a three fold increase from 2000 [2]. Based on current facility expansions, it is expected that by 2009, ethanol production capacity will reach 11 billion gallons, 3.5 billion gallons above the original RFS [1, 2].

In response to surpassing current targets, policy makers have passed a new RFS, *The Energy Independence and Security Act of 2007*, that increases the renewable fuels target from 7.5 billion gallons per year to 36 billion gallons [3]. Ethanol produced from corn grains is capped at 15 billion gallons, with the remaining 21 billion gallons coming from advanced biofuels. The bill defines advanced biofuels, as any renewable fuel expect corn starch-based ethanol [3]. It also stated that cellulosic ethanol will represent 5.5 billion gallons of this industry by 2022 [3]. This bill is seen as a way to promote the additional development of biofuels, and specifically second generation cellulosic-based biofuels, as a way to further decrease our nation's petroleum consumption and greenhouse gas emissions.

Given the new RFS, the goal of this chapter is to assess the feasibility of achieving 36 billion gallons of renewable fuel, both in terms of production scale and in terms of timeline. The first questioned addresses, is there enough feedstocks available, from corn

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[46] This chapter will be in English units to stay consistent with what was written in the Senate and House energy bills

grains, corn stover, and switchgrass, to produced 36 billion gallons of ethanol? The second question asks, can the ethanol industry grow to a capacity of 36 billion gallons by 2022, based mainly on cellulosic ethanol?

The feedstocks considered to achieve these goals are corn grains, corn stover, and switchgrass. The potential scale of production of ethanol from these feedstocks was assessed in Chapter 6. The fossil energy use, petroleum and GHG displacement results from these 3 feedstocks as discussed in Chapter 5, will be applied to assess the potential impact 36 billion gallons of ethanol may have.

The new RFS bill defined milestones for renewable fuels production from both corn grain and second generation cellulosic feedstocks, such as corn stover, wheat straw, and switchgrass. The bill defines a renewable fuel as a motor fuel produced from renewable sources [3]. The new RFS outlined the following timeline expected for renewable fuel production [3]:

- 36 billion gallons of renewable fuels by 2022
- 9 billion gallons of renewable fuels by the year 2008
- 15 billion gallons of corn grain ethanol
- 3 billion gallons of cellulosic biofuels by 2015
- 7.25 billion gallons of advanced biofuels by 2016
- 21 billion gallons of advanced biofuels by 2022,

This renewable fuels package expects that 3 billion gallons of advanced biofuels from cellulose will start to be produced in 2015 [3]. Therefore, for the next almost 10 years it is expected that corn grain will remain the dominant feedstock for ethanol production in the United States.

To assess the potential for achieving 36 billion gallons of bioethanol the availability of feedstocks needs to be discussed. Table 7-1 displays the amount of biomass available for ethanol production, as assessed in Chapter 6. Five to six billion bushels of corn grains is assumed to represent the maximum amount feedstock that could be used for corn grain ethanol production while still meeting the US food and export demands as outlined by the USDA Agricultural Baseline [4]. At this level 15 to 18 billion gallons of corn grain ethanol could be produced, consuming over 30% of future corn grain production [4]. The amount of corn stover available directly relates to the amount of corn grain produced as it's an agricultural residue of corn. As a result 100 million dry tons of stover would be available today, and 109 million dry tons of stover would be available in the future, for cellulosic ethanol production (Table 7-1), at a 30% stover removal rate. If switchgrass was introduced as a bioenergy crop competing on agricultural land, 45-60 million dry tons would be available at current assumed yields between a farm gate price of $35-$45/dry ton (details discussed in Chapter 6).

Figure 7-1 displays the amount of ethanol that can be produced from each of these sources today and in 2025. The 2025 future cellulosic scenarios assume an increased conversion efficiency of 87 gal/dry ton. Corn grain ethanol, though today produces 4.8 billion gallons, has the potential of production 15-18 billion gallons of ethanol by 2012 (Chapter 6). This is based on current facility capacity expansions and the construction of new corn grain ethanol facilities. Ethanol produced from corn stover has the potential of producing 24-36 billion gallons depending on availability of feedstock and cellulosic conversion efficiency. For switchgrass introduced as a bioenergy crop, there would be a potential of producing 2-38 billion gallons of ethanol depending on switchgrass yield, farm gate price, and conversion efficiency (Chapter 6).

Ethanol Scale and Impact of Production From Various Biomass Sources					
Corn Grain		**Today[47]**		**2025 Future Scenario[48]**	
	billion bushels	2.15		5 to 6	
	billion gallons	4.8		15 to 18	
	% Gasoline Displaced	2.5%		5.5% to 6.6%	
	% GHG Emissions Displaced	0%		0.9% to 1%	
Corn Stover (Cellulosic Ethanol)		**Today[49]**		**2025 Future Scenario[50]**	
		63 gal/dry ton	87 gal/dry ton	63 gal/dry ton	87 gal/dry ton
Corn Stover	*million dry tons*	100		109	
	billion gallons	6.3	8.7	6.9	9.5
	% Gasoline Displaced	3%	4.2%	2.5%	3.5%
	% GHG Emissions Displaced	2.1%	3%	1.8%	2.5%
Switchgrass[51] (Cellulosic Ethanol)		**Today[52]**		**2025 Future Scenario[53]**	
		63 gal/dry ton	87 gal/dry ton	63 gal/dry ton	87 gal/dry ton
Switchgrass	*million dry tons*	45 to 60[54]		400 to 430[55]	
	billion gallons	2.4 to 3.7	3.2 to 5.3	15.9 to 26.4	22.5 to 38.2

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[47] Petroleum & GHG results are based on *Iowa Corn Grain Ethanol* LCA scenario results in Chapter 3

[48] Petroleum & GHG results are based on *2025 Iowa Corn Grain Ethanol* LCA scenario results in Chapter 3

[49] Petroleum & GHG results are based on *Iowa Corn Stover Ethanol* LCA scenario results in Chapter 4

[50] Petroleum & GHG results are based on 2025 *Corn Stover Ethanol* LCA scenario results in Chapter 4

[51] Switchgrass results are based on POLYSYS results and not CRP results.

[52] Petroleum & GHG results are based on *Alabama Switchgrass Ethanol* LCA scenario results in Chapter 4

[53] Petroleum & GHG results are based on *2025 Switchgrass Ethanol* LCA scenario results in Chapter 4

[54] This is based on current assumed switchgrass yields of 0-6 dry tons per acre

[55] This assumes the "Switchgrass (double yield)" scenario which is why the amount of switchgrass and ethanol produced is so high. This is a "what if" scenario to show the impact of improved biomass yields

	% Gasoline Displaced	1% to 2%	1.4% to 2.2%	8% to 10%	12% to 14%
	% GHG Emissions Displaced	1% to 2%	1.3% to 2%	8% to 9.5%	11% to 13%
Total Production	*billion gallons*	14	18	43	58

Table 7- 1 - Ethanol Scale and Impact of Production from Various Biomass Sources. The RFS target is 36 billion gallons

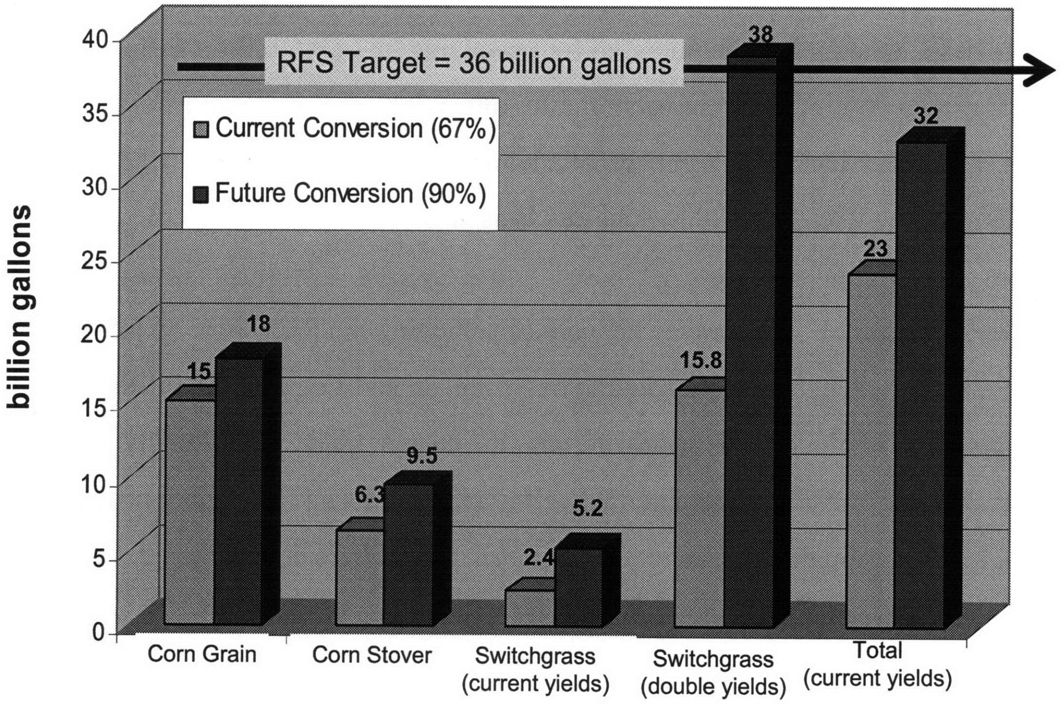

Figure 7- 1 – Summary of ethanol production by various biomass sources. The scenario labeled as *Switchgrass (double yields)* is a "what if" scenario to help show how sensitive ethanol production is to biomass yields. Ethanol produced is given for current and future expected ethanol conversion rates as defined in Chapter 4

Is the scale of 36 billion gallons of ethanol achievable?

When comparing these production scales to the RFS goal of 36 billion gallons, it is clear that first corn grain ethanol production will account for approximately 15 billion gallons of this target, which is achievable. This leaves 21 billion gallons of advanced biofuels that will need to be produced mainly from cellulosic sources. It is expected that an agricultural residue, like corn stover, will be utilized as an initial cellulosic feedstock. This is because stover is already centrally located within the Corn Belt, near current existing ethanol production and distribution infrastructure. Utilizing an agriculture residue also lowers the risk for cellulosic ethanol producers, as it is a feedstock that is guaranteed to be available in dense amounts. Adversely with a bioenergy crop like switchgrass, farmers initially would need to decide to shift their lands from current practices to bioenergy crops in large enough quantities to produce enough feedstock within a given area. This could lead to a longer timeline for biofuels production based on a bioenergy crops such as switchgrass.

Corn stover-based ethanol has the potential for producing up to 9.5 billion gallons of ethanol assuming a 90% ethanol conversion rates and a 30% removal rate from every field. This still leaves 11.5 billion gallons of advanced biofuels that would need to be produced to meet the RFS goal. If switchgrass is assumed to become available in the future, it has the potential at current estimated biomass yields to produce between 2-5 billion gallons of ethanol. This leaves the goal of achieving the RFS short by 6.5-9.5 billion gallons. If switchgrass yields double overtime, an additional 16-38 billion gallons of ethanol could be produced, this would surpass the current goal. Additionally, other agricultural and forest residues are potential cellulosic feedstocks for ethanol production. Ultimately, there is enough biomass to convert reach the RFS goal, another question is, can it be collected, transported, and converted into ethanol economically?

Can 36 billion gallons of renewable fuels be produced by 2022?

The second question addresses was how realistic is the RFS timeline of creating a billion gallon cellulosic ethanol industry by 2013 and a 5.5 billion gallon cellulosic industry by 2022? Currently, commercial scale production of cellulosic ethanol is still not economical. To expedite the matter, the DOE has recently approved the investment of up to $385 million dollars over the next four years in 6 pilot scale cellulosic ethanol facilities. These facilities expect to utilize agricultural residues such as corn stover and wheat straw to produce up to 136 million gallons of cellulosic ethanol. It is expected that these facilities will be operational by 2010. These are the first cellulosic ethanol facilities that will test laboratory technology with the goal of narrowing down the field of options that second generation cellulosic facilities will adopt. Some of the key challenges that remain are; improving cellulosic ethanol conversion rates through superior enzymes and yeast, improving economic constraints, and synergizing the various players within this industry to enable the scale-up of production. Given these constraints, as well as the timeline for conclusions to be made from these 6 pilot facilities, is the expectation that cellulosic ethanol production will be in the billions of gallons by 2013, realistic or just challenging? For this to occur, a pilot scale industry producing 150 million gallons will need to be expanded to a few billion gallon scale within 6 years. While it's not unfeasible, it does appear to be very challenging given the progress that needs to be made, the potential bumps in the road that can occur, the adoption time of new technology, and the long timelines for projects to be developed and built.

Additional constraints can also affect ethanol's potential scale such as, E10 market saturation and infrastructure development constraints. Currently, only E10, a blend of 10% ethanol and 90% gasoline, is approved for use in standard gasoline engines. The market for E10 would be saturated at approximately 15 billion gallons of ethanol which could be produced from corn grain ethanol in the next 5 years [2]. For ethanol production to increase further, additional markets for increased levels of ethanol would need to be created. In the future, this may come from flex-fuel vehicles or dedicated ethanol vehicles.

In the end, the RFS goal of producing 36 billion gallons of renewable energy by 2022 will be challenging both in production scale and within the given timeline. While corn grain ethanol is expected it achieve the 15 billion gallon target, advanced biofuels, and specifically cellulosic biofuels, have many more challenges ahead that need to be overcome to achieve 21 billion gallons. When determining what affects the scale the most, it is clear that improved biomass yields result in a much larger impact on increasing scale than increased conversion rates (Figure 7-1). Currently, most research efforts are placed in improving cellulosic ethanol conversion rates for economic reasons. While improving ethanol conversion rates are needed, improving biomass yields are essential as land availability and land productivity are ultimately the systems production constraint.

Chapter 7 References:

1. *Renewable Fuels, Consumer Protection, and Energy Efficiency Act of 2007*, in *S.1419*. 2007.
2. Association, R.F., *Annual Industry Outlook*. 2006.
3. *Energy Independence and Security Act of 2007,* 2007-2008.
4. USDA, *USDA Agricultural Baseline Projections to 2016*, ed. USDA. 2006, Washington DC: USDA.

Chapter 8: Summary and Conclusions

There were two main objectives of this research; first to evaluate the potential production level of ethanol from three different biomass sources; corn grains, corn stover, and switchgrass, and second to assess the environmental impacts of producing ethanol at these levels from these three biomass sources. The environmental impacts analyzed were the total life-cycle fossil energy consumption, greenhouse gas emissions, and petroleum displacement, and land use efficiency. It was shown that the fossil energy consumption and GHG emissions of bioethanol production largely depended on the system configuration and boundary assumptions, input values, and system variability (Figure 5-2).

For corn grain ethanol, the GHG emissions could be greater than or less than current gasoline emissions. This is dependent on the geographic location of crop production, assumed coproduct credits, and the ethanol facilities fuel source. When looking at current best practices, without a coproduct credit, corn grain ethanol on average has about the same GHG impact as gasoline. When coproduct credits are assumed, corn grain ethanol's GHG emissions are lower compared to gasoline. Additionally, if an ethanol facility utilizes biomass as their main fuel source, the life-cycle GHG emissions for corn grain ethanol would decrease substantially below current-day gasoline emissions.

Cellulosic-based ethanol, either from corn stover or switchgrass both significantly decrease life-cycle GHG emissions compared to gasoline (Figure 5-2). The main reason for this is the use of lignin, a part of the plant not converted to ethanol, as a fuel source within the ethanol conversion facility. The corn grain ethanol results were more sensitive to the geographic variation for crop production than the switchgrass based results. This was because, switchgrass has a variety of cultivars that can be grown under a range of climate conditions, while high corn productivity is centered within the Corn Belt.

To achieve the second goal of this research, the life-cycle assessment results were applied to determine the impact of increased bioethanol production from these three feedstocks.

It was estimated that corn grain ethanol would level off at approximately 57-68 billion liters per year. At this ethanol production level in the year 2025, 30% of current US corn grain production would be consumed, 5-7% of gasoline would be displaced, and approximately 1% of GHG emissions would be displaced (Table 7-1).

It was also estimated that 24-36 billion liters per year of ethanol could be produced from corn stover, based on a 30% stover removal rate. At this level of production in 2025, stover could displace 2.5-3.5% of gasoline and 1.8-2.5% of GHG emissions (Table 7-1). While corn stover is a likely fist candidate for cellulosic ethanol due to its location near existing infrastructure in the Corn Belt, there are still many challenges that need to be overcome. These challenges are collection technique, biomass storage, and advances in cellulosic ethanol conversion rates, and improved economics.

The potential for a bioenergy crop, such as switchgrass as an agricultural crop competing for agricultural land was also considered. A model called POLYSYS was used to determine the amount of agricultural land that would shift into switchgrass production as a function of farm gate price and the net returns to the farmer. At current assumed yields between 0-6 dry tons/acre and a farm gate price of $35-$45/dry ton, 9-14 billion liters per year could be produced at a cellulosic conversion rate of 238 l/dry ton. At this rate of ethanol production, 1-1.5% of gasoline and GHG emissions could be displaced. In the future, if projected cellulosic conversion rates of 328 l/dry ton are achieved, 12-20 billion liters per year of ethanol could be produced, displacing 1.5-2.5% of gasoline and GHG emissions.

The affect of increased biomass yield was also assessed by considering a scenario where the yield of switchgrass doubles over time, to 6-12 dry tons/acre. Under this assumption, and at a farm gate price of $35-$45/dry ton, 60-100 billion liters per year of ethanol could be produced at today's conversion rates, and 85-145 billion liters per year at future projected conversion rates. At these levels of ethanol production, 8-14% of gasoline and GHG emissions would be displaced. Improving the yield of switchgrass would require a significant amount of genetic engineering research and development in the future.

At switchgrass farm gate prices between \$35-\$45/dry ton, switchgrass does not displace corn producing land but instead displaces hay and cotton land, centered within the south and southeastern part of the United States. Thus, the introduction of switchgrass as a bioenergy crop does not displace ethanol produced form corn but rather complements it. When considering ethanol produced from these three biomass sources, there is a potential to produce 124-249 billion liters per year, and displace 12-25% and 6-17% of 2025 gasoline and GHG emissions respectively[56].

While there is the potential to displace such amounts of gasoline and GHG emissions, there are significant hurdles in the way. One of the major hurdles is: where will 124-249 billion liters of ethanol go in the market place? Ten percent of ethanol can be blended with gasoline and used in current non flex-fuel vehicles without modification. The E10 market will be saturated within the US, with 57 billion liters of ethanol, a level of production that could be met by future projected corn grain ethanol production. Flex-fuel vehicles make up slightly over 2% of the light-duty vehicle fleet. Thus an important question is: what market will demand/consume an increase in ethanol production beyond what corn can supply? Is there really a market demand in the near-term for ethanol that would require it to be produced from cellulosic sources? These are short and long-term issues given that a billion liter cellulosic ethanol industry is still at least a decade away? Questions like these still need to be addressed if ethanol production is to continue to increase in the future.

While demand for ethanol is one side of the equation, what hurdles remain on the supply side? First, the ethanol distribution infrastructure needs to be developed so it can more efficiently supply U.S. east and west coast markets. Whether that should be in the form of a dedicated ethanol pipeline, as done in Brazil, or increased rail and truck use is still to be determined. Secondly, where would increasing amounts of ethanol be used? Ethanol

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[56] Producing 248 billion liters, displacing 25% of petroleum, and displacing 17% of GHG emissions, assumes a scenario where switchgrass yields doubled to 6-12 dry tons/acre. The lower numbers in each of these ranges assume current switchgrass yields of 0-6 dry tons/acre and more accurately represent current day and the near term.

could be used in standard light-duty vehicles without engine modifications up to an ethanol blend of 10%. Ethanol produced beyond 10% of the transportation fuel market could then be used in flex-fuel vehicles or more efficiently in vehicles solely dedicated to ethanol. Flex-fuel vehicles can operate on gasoline and ethanol blends up to E85, though higher engine efficiencies are experienced when running gasoline. Dedicated ethanol vehicles, running on E85, can be designed to increase engine efficiency at higher ethanol blends. Currently, flex-fuel vehicles are approximately 2% of the light-duty vehicle market place, and therefore increased sales are needed to create an additional market place for higher ethanol blended fuels. Increased flex-fuels or dedicated ethanol vehicles could then provide an incentive to fueling stations to increase the number of pumps that sell higher ethanol fuel blends. While this may happen in the future, there is still a significant time delay of over 10 to 15 years until flex-fuel vehicles create significant ethanol demand within the vehicle fleet. A third supply hurdle is that cellulosic ethanol needs to become economically competitive within the transportation fuel market. The majority of government research is being focused on the cellulosic conversion arena. This includes research on lowering enzyme costs, lower facility equipment costs, and increasing cellulosic biomass to ethanol conversion yields. Research is also needed to increase biomass yields, as land is ultimately the main constraint to scale.

Given the results presented in this chapter and in the subsequent ones, a question that is often asked is, should biofuels, and specifically ethanol, be the path that the US should be on? The answer to this question often depends on what ones objective is? For example, if the intent is improving national security through displacing petroleum: then, yes, ethanol does displace petroleum and thus increase national security. Even with a 30% lower energy density, ethanol displaces 68% of petroleum as little oil is consumed during its production. However, if the objective is to displace GHG emissions, then the answer is less clear. Corn grain ethanol, without a coproduct assumption, is equivalent or worse relative to GHG emissions emitted by gasoline production and combustion. However, cellulosic ethanol significantly decreases GHG emissions when compared to gasoline. Many people feel that corn grain ethanol is a stepping stone to cellulosic ethanol, and therefore that the end result will be lower GHG emissions from the transportation sector.

Another potential objective of bioethanol production is to boost the agricultural industry. This has had both a positive and negative economic affect locally and abroad. It has boosted certain agricultural sectors, such as corn production, while also increasing the cost of production in other industries, such as animal feed. Whether these economic impacts are short-term or long-term issues remains to be seen.

The long-term future scale and impact of biofuels in the US is not yet clear, though current policy is driving the industry's expansion. While biofuels may contribute to the primary government objective of increasing national security through displacing petroleum, there are other technologies and renewable sources that could be adapted. Increased petroleum-fueled vehicle fuel economy, hybrid and electric vehicles are technological examples that can reduce and also displace petroleum. In an electric vehicle scenario, biomass could be used, along with low carbon releasing electricity generation, to displace petroleum. Biodiesel also could play a role within the freight transport sector by displacing some diesel fuel consumption. In the near term, there is no one silver bullet that can displace a major fraction of our petroleum consumption and reduce our GHG emissions. Biofuels is one of many changes that will be needed. Only when many effective actions are combined will we be able to displace a portion of our transportation petroleum consumption and GHG emissions.