The Lifecycle Carbon Footprint of Biofuels

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Well-to-Wheels Energy and Greenhouse Gas Emission Results and Issues of Fuel Ethanol

Michael Q. Wang[1]

Introduction

The use of fuel ethanol in the United States has increased from fewer than 200 million gallons (gal) at the beginning of the US fuel ethanol program in 1980 to 6.5 billion gal in 2007. The recent federally adopted *Energy Independence and Security Act of 2007* established the goal of 36 billion gal of biofuel use in the United States by 2022, of which 15 billion gal will be corn-based ethanol. In addition, the promotion of low-carbon fuel standards (LCFS) by California and several other states could help increased use of ethanol, especially cellulosic ethanol.

In the United States, corn ethanol is produced through the fermentation of corn in dry and wet milling plants, most of which are located in the Midwest. In 2006, about 82% of the total US fuel ethanol was produced from dry milling plants, and the remaining 18% from wet milling plants (Renewable Fuels Association, 2007). Ethanol can be produced from cellulosic biomass through fermentation of cellulose and semicellulose. The US Department of Energy (DOE) has been undertaking extensive research and development (R&D) efforts for cellulosic ethanol technologies.

Since 1997, Argonne National Laboratory has been evaluating the energy and emission effects of fuel ethanol relative to those of petroleum gasoline. In 1997, Argonne National Laboratory published its findings from an ethanol analysis conducted for the State of Illinois (Wang *et al.*, 1997). With DOE support, Argonne National Laboratory has continued its efforts to analyze the effects of fuel ethanol (Wang *et al.*, 1999a,b; Wang *et al.*, 2003; Wu *et al.*, 2005; and Wu *et al.*, 2006).

As fuel ethanol production and usage in the United States have rapidly expanded in the past several years, corn ethanol plant technologies have been evolving. In addition, while corn yield per acre continues to increase, concerns have been raised that increased corn farming could result in switches in crop farming in the United States and potential land use changes in other countries. These factors together could cause different energy and greenhouse gas (GHG) emission results for corn ethanol. This chapter presents Argonne National Laboratory's updated energy and GHG emission results for fuel ethanol.

Well-to-Wheels Analysis Approach

Since 1995, with support primarily from the DOE Office of Energy Efficiency and Renewable Energy (EERE), Argonne National Laboratory has been developing the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. Argonne National Laboratory released the first version of the model – GREET 1.0 – in June 1996. GREET is a Microsoft® Excel™-based multidimensional spreadsheet model that addresses the well-to-wheels (WTW) analytical issues associated with transportation fuels (including ethanol) and vehicle technologies. For a given vehicle and fuel system, GREET separately calculates the following.

- Consumption of total energy (energy in nonrenewable and renewable sources); fossil fuels (total of petroleum, natural gas, and coal); natural gas; coal; and petroleum.
- Emissions of GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).
- Emissions of six criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter measuring less than 10 microns in diameter (PM_{10}), particulate matter measuring less than 2.5 microns in diameter ($PM_{2.5}$), and sulfur oxides (SO_X). These criteria pollutant emissions are further separated into total and urban emissions.

Figure 1 shows the coverage of the GREET model for WTW analyses. As the figure shows, the WTW (or fuel-cycle) analysis in GREET covers energy feedstock recovery (*e.g.*, crude oil recovery), energy feedstock transportation (*e.g.*, crude transportation), fuel production (*e.g.*, petroleum refining to gasoline and diesel), fuel transportation, and fuel use in vehicles.

The current GREET version – GREET1.8 – contains more than 100 fuel production pathways. These pathways include energy feedstocks such as petroleum, natural gas, coal, and biomass feedstocks; and fuel products such as gasoline, diesel, hydrogen, electricity, ethanol, and many other liquid

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fuels. Figure 2 shows groups of fuel production pathways from feedstocks to fuels that are included in GREET.

A variety of biofuel production pathways are under the research and development (R&D) efforts. For example, ethanol could be produced from sugar crops, starch crops, and cellulose and semi-cellulose in biomass. Biodiesel and renewable diesel could be produced from oils in oil crops, waste cooking oil, and animal fat. Cellulosic biomass could be gasified, and fuels could then be produced from synthesis gas. Recently, interest has been raised regarding butanol production from corn or sugar beets. Finally, hydrogen and liquid fuels could be produced by algae. Figure 3 summarizes these potential biofuel production pathways.

The GREET model contains only a subset of these potential biofuel production pathways. In particular, GREET includes ethanol from sugarcane, corn, cellulosic biomass types such as crop residues, forest residues, and energy crops; butanol from corn; biodiesel and renewable diesel from soybeans; and Fitscher-Tropsch diesel, hydrogen, and methanol from cellulosic biomass via gasification. However, this chapter covers only ethanol from corn and cellulosic biomass. Figure 4 presents the ethanol pathways reviewed in this chapter and the stages included in WTW analysis of these pathways.

The Corn Ethanol Pathway and Key Factors Determining Its WTW Results

Of the activities that comprise the corn ethanol production pathway, key factors that determine corn ethanol WTW results include nitrogen (N) fertilizer production, fertilizer conversion in soil, corn farming energy use, the amount and type of fossil energy use in corn ethanol plants, energy and emission credits of distillers' grains and soluables (DGS), and potential land use changes from corn ethanol production.

Nitrogen Fertilizer Production

Corn farming requires intensive use of N fertilizer. N fertilizers are produced primarily from natural gas, although some significant amounts of nitrogen fertilizers are produced from coal in China. Because of the dramatic increase in natural gas prices in North America in recent years, many North American N fertilizer plants were shut down. Consequently, the United States has increased imports of N fertilizers from other countries. N fertilizer plants recently built outside of North America have relatively lower energy intensities than the old North American plants.

A study by Wang *et al.* (2003) concluded the following energy use for N fertilizer production: 27.5 million British

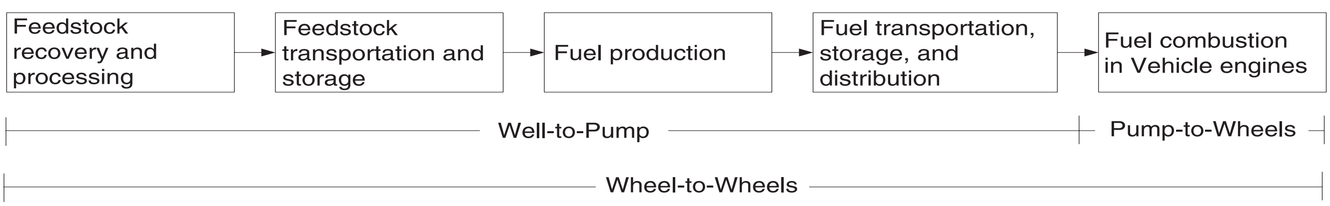

Figure 1: Coverage of Well-To-Wheels Analysis with the GREET Model.

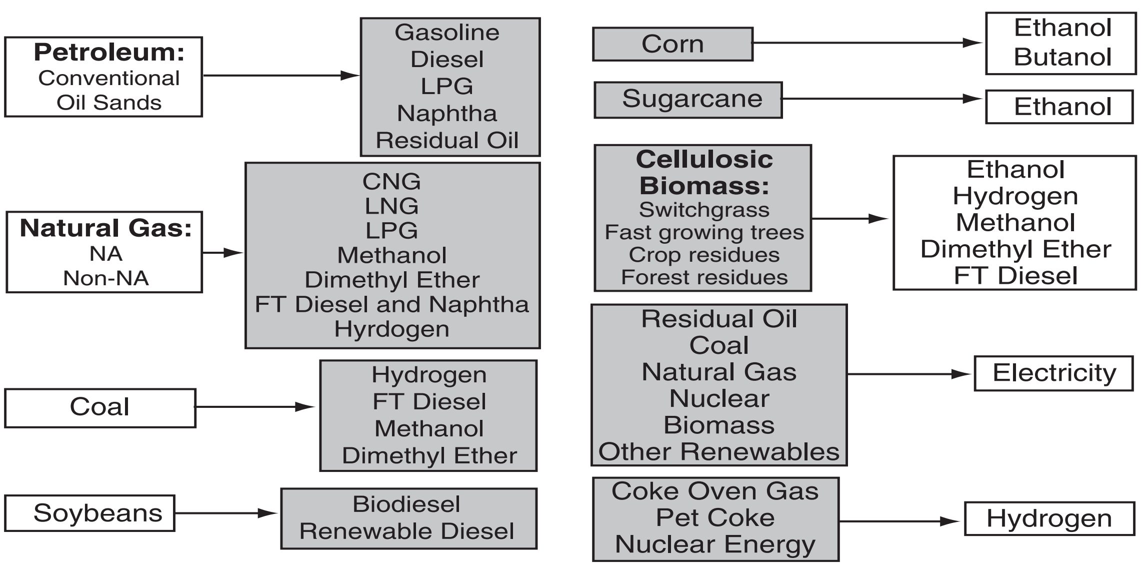

Figure 2: Fuel Production Pathway Groups Contained in the GREET Model.

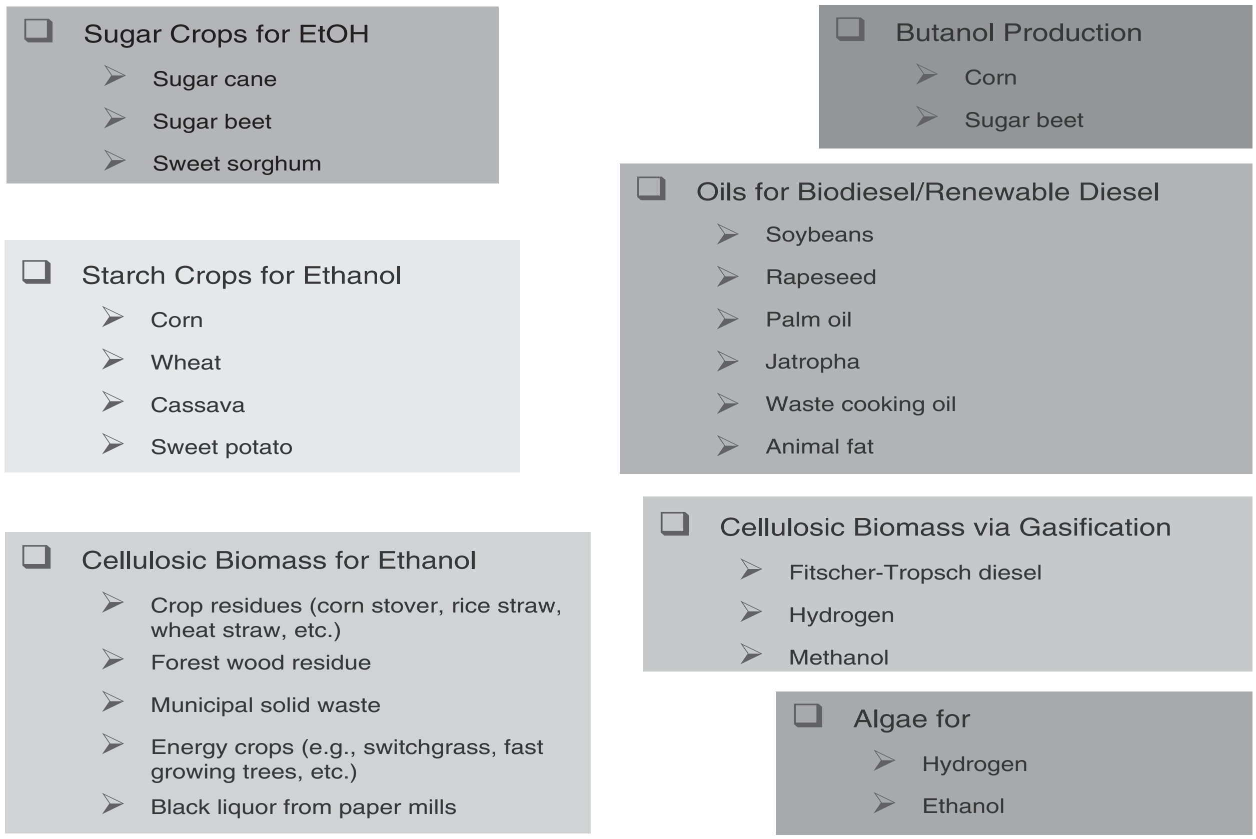

Figure 3: Biofuel Production Pathways with Current Research and Development Efforts.

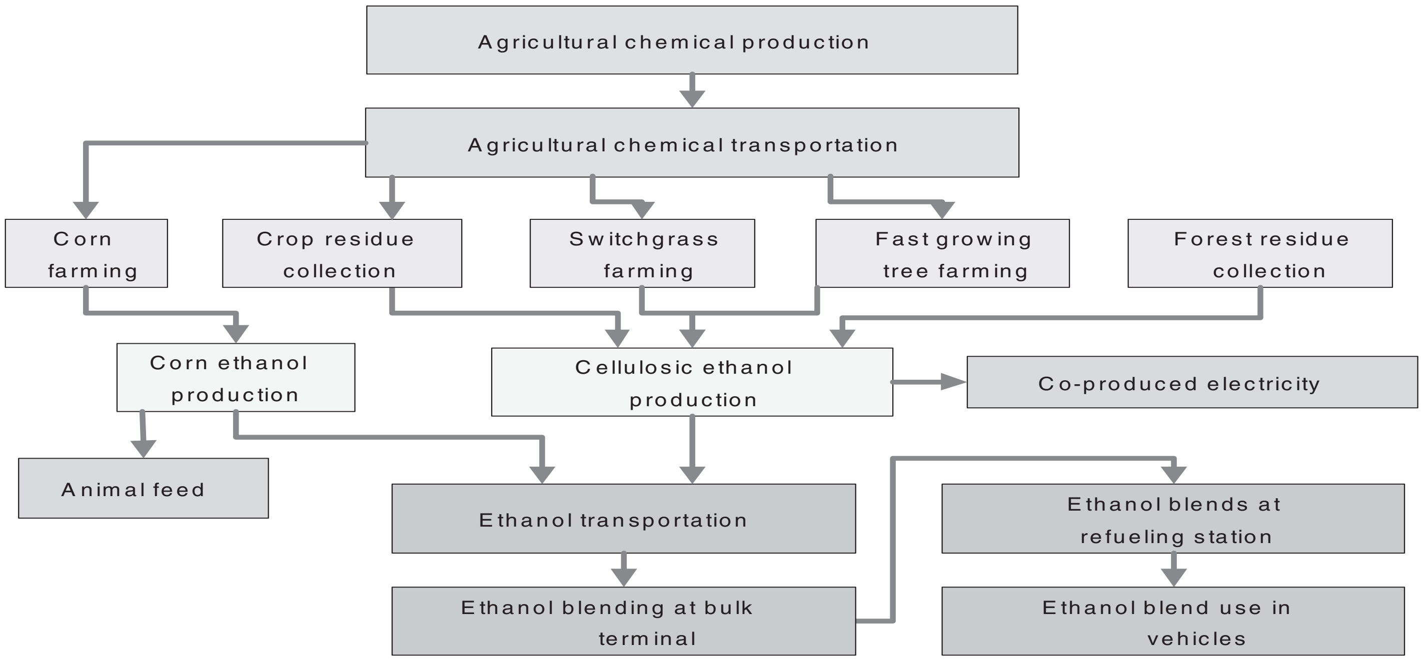

Figure 4: Ethanol Pathways and Related Activities Included in this Chapter.

Table 1: Historical Corn Yield and Chemical Use of US Corn Farms (Three-Year Moving Averages on a Per-Harvested-Acre Basis).

Year	Corn Yield (bu/acre)	Nitrogen (N) Fertilizer (lb/acre)	Phosphorous (P_2O_5) Fertilizer (lb/acre)	Potash (K_2O) Fertilizer (lb/acre)	Lime ($CaCO_3$) (lb/acre)
1970	79	118.2	68.8	66.5	Not Available
1971	82	119.8	67.7	65.6	
1972	86	122.6	69.0	67.1	
1973	92	122.8	65.5	65.3	
1974	87	122.5	65.9	69.2	
1975	83	117.8	62.1	67.4	
1976	82	125.3	64.6	71.2	
1977	88	135.1	66.6	73.5	
1978	93	142.1	69.7	76.8	
1979	100	142.1	68.9	76.7	
1980	101	141.8	67.5	77.1	
1981	103	146.5	67.7	79.7	
1982	104	147.0	66.2	81.0	
1983	101	150.4	66.1	81.8	
1984	100	150.4	64.5	81.2	
1985	102	151.4	62.1	78.7	
1986	115	146.6	59.2	73.7	
1987	119	143.6	56.8	70.7	
1988	108	144.9	59.0	71.9	
1989	107	145.8	58.5	71.9	
1990	106	146.1	58.5	72.2	365.6
1991	114	140.2	55.4	68.2	299.3
1992	120	138.1	54.1	66.5	305.7
1993	114	137.1	53.1	64.4	274.3
1994	124	136.9	52.1	63.5	294.4
1995	118	137.8	51.6	62.6	324.4
1996	126	138.9	51.4	61.8	377.8
1997	122	140.4	51.7	62.2	416.2
1998	129	142.3	51.6	62.2	420.7
1999	132	142.6	50.2	61.1	410.6
2000	135	144.5	50.2	58.9	411.9
2001	136	141.3	50.1	58.9	414.3
2002	135	143.5	51.9	60.9	NA
2003	137	142.9	51.6	61.9	NA
2004	144	142.9	51.6	61.9	NA
2005	150	144.5	51.5	60.0	NA

Source: Economic Research Service, 2007.

thermal unit (Btu) (lower heating value based) per ton of ammonia, which could be directly applied to corn fields or be the main ingredient for production of urea, nitric acid, and ammonium nitrate (which is produced from ammonia and nitric acid; the latter is, in turn, produced from ammonia).

Although significant amounts of phosphate and potash fertilizers, as well as lime, are used on US corn farms, the energy use needed to produce them is small. Nonetheless, GREET does take into account the energy use involved in producing these fertilizers.

Corn Farming

Table 1 shows corn yields and chemical inputs of corn farming in the United States between 1970 and 2005. During those years, corn yield per acre increased by 90%, while N fertilizer application increased by only 22%; phosphorous fertilizer application was actually reduced by 25%; potash fertilizer application was reduced by 6%; and lime application was increased by 13% between 1990 and 2001, when statistics for lime became available. Corn productivity, defined as bushels (bu)/pound (lb) of three fertilizer types combined, increased by 88% – from 0.312 bu/lb of three fertilizers in 1970 to 0.586 bu/lb in 2005. This was a result of better seed variety, better farming practices, and other agricultural measures.

N_2O Emissions from Nitrogen Fertilizers. N_2O, a potent GHG, is produced from N in the soil through nitrification and denitrification processes (direct N_2O emissions). N_2O can also be produced through volatilization of nitrate from the soil to the air and through leaching and runoff of nitrate into water streams (indirect N_2O emissions).

Estimation of direct and indirect N_2O emissions from crop farming requires two important parameters: (1) the amount of N inputs to soil, and (2) conversion rates of N into N_2O.

There are two major sources of N inputs to soil for crop farming: N from fertilizer application and N in the aboveground biomass left in the field after harvest and in the belowground biomass (*i.e.*, roots). GREET 1.8 takes into account nitrogen in N fertilizers and N in aboveground and belowground biomasses in estimating N_2O emissions from crop farming.

For corn, the Intergovernmental Panel on Climate Change (2006) estimates that the aboveground biomass is 87% of corn yield (on a dry-matter basis). The aboveground biomass has a N content of 0.6%. The belowground biomass is about 22% of the aboveground biomass, with a N content of 0.7%. The total amount of N in the corn biomass that remains in the corn fields per bushel of corn harvested is calculated as shown:

56 lb/bu (corn density) × 85% (dry matter content of corn) × (87% × 0.6% + 87% × 22% × 0.7%) = 0.312 lb N/bu = 141.6 grams (g)/bu.

To estimate N_2O emissions from corn farming, the estimated 141.6 g of N are added to N fertilizer inputs for corn farming (which are about 420 g of N per bu for US corn farming).

The conversion rates from N in soil and water streams to N_2O emissions to the air are subject to great uncertainties (Wang *et al.*, 2003; Intergovernmental Panel on Climate Change , 2006; and Crutzen *et al.*, 2008). The Intergovernmental Panel on Climate Change (2006) presents a conversion rate of 1% for direct N_2O emissions from soil (compared with 1.25% in Intergovernmental Panel on Climate Change (1996)), with a range of 0.3% to 3%.

Indirect N_2O emissions include those from volatilization of nitrate from the soil to the air and leaching and runoff of nitrate into water streams where N_2O emissions occur. The Intergovernmental Panel on Climate Change (2006) estimates a volatilization rate for soil N of 10%, with a range of 3% to 30%. The conversion rate of volatilized N to N in N_2O emissions is assumed to be 1%, with a range of 0.2% to 5%. The leaching and runoff rate of soil N is estimated to be 30%, with a range of 10% to 80%. The conversion rate of leached and runoff nitrogen to N in N_2O emissions is assumed to be 0.75%, with a range of 0.05% to 2.5%.

Thus, the conversion rate for direct and indirect N_2O emissions is 1.325% (1% + 10% × 1% + 30% × 0.75%). This conversion rate was applied to N inputs from N fertilizers and from corn plant biomass in GREET 1.8. In contrast, Crutzen *et al.* (2008) estimated a conversion rate of 3% to 5% from N in N fertilizer to N in N_2O based on global N_2O balance (in comparison, the N_2O conversion rate in GREET equivalent to Crutzen's conversion rate is 1.77% [1.325% × {141.6 + 420} ÷ 420]). While the top-down approach adopted in Crutzen *et al.* is a sound approach, especially for checking and verifying results with the bottom-up approach used by the Intergovernmental Panel on Climate Change and others, data for the top-down approach need to be closely examined in order to generate reliable N_2O conversion factors. In particular, Crutzen *et al.* adopted a global N_2O emission balance from a 2001 study, but N inputs from a separate 2004 study, for deriving N_2O conversion factors. Furthermore, Crutzen *et al.* did not get into agricultural subsystems (such as crop farming, animal waste management, and crop residual burning), which are required for generating N_2O conversion rates for the N inputs into crop farming. The allocation of aggregate N_2O emissions (after subtracting N_2O emissions from industrial sources) to the aggregate agricultural system may result in an overestimation of N_2O conversion rates from N inputs into crop farming systems. Nonetheless, N_2O conversion rates, which are subject to great uncertainties, need to be reconciled between the bottom-up and the top-down approaches.

CO_2 Emissions from Lime. Agricultural lime with the key ingredient calcium carbonate ($CaCO_3$) is applied to fields to increase the pH of acidic soils in order to maintain the 6.5 to 7.0 soil pH necessary for corn growth. Typically, lime is applied every few years. In soil, calcium carbonate in lime is converted into calcium oxide (CaO, the so-called burnt lime) and CO_2. On balance, 44% of the calcium carbonate mass is released to the air as CO_2. With data in Table 1 and the corn yields, GREET 1.8 assumes a lime application of 1,200 g/bu of corn with a CO_2 rate of 528 g/bu. This CO_2 emission source is taken into account in GREET, which accounts for roughly 4% of total GHG emissions of corn-based ethanol.

Energy Use for Corn Farming. Based on a farm survey done by USDA in 2001, we estimated direct fuel use of 15,690 Btu/bu of corn harvested on corn farms. The direct fuel use estimate includes diesel and gasoline for powering farming equipment, liquefied petroleum gas (LPG) and natural gas for drying corn and for other farming operations, and electricity for irrigation. In particular, of the total amount of farming energy use, diesel fuels account for 45%, natural gas 15%, LPG 17%, gasoline 18%, and electricity 5%.

Some have argued that the energy used to produce farming equipment could represent a large energy penalty for the corn ethanol pathway. We have completed a thorough examination of this issue by taking into account the type and lifetime of farming equipment, size of farms to be served by the equipment, material composition of the equipment, and energy intensity of material production and equipment assembly (Wu *et al.*, 2006). Our examination revealed that farming equipment manufacture contributes 2% of energy use and 1% of GHG emissions of the corn ethanol pathway (on a WTW basis); these percentages are well within the uncertainty range for the corn ethanol results.

Energy Use in Ethanol Plants

Corn ethanol plants are usually classified into two types: wet milling and dry milling. In wet milling plants, corn kernels are soaked in water containing sulfur dioxide (SO_2), which softens the kernels and loosens the hulls. Kernels are then degermed, and oil is extracted from the separated germs. The remaining kernels are ground, and the starch and gluten are separated. The starch is used for ethanol production.

In dry milling plants, the whole dry kernels are milled (with no attempt to remove fractions such as germs). The milled kernels are sent to fermenters, and the starch portion is fermented into ethanol. The remaining, unfermentable portions are produced as DGS and used for animal feed. Historically, wet milling plants have been much larger than dry milling plants. For example, several wet milling ethanol plants in the United States have an annual production capacity of about 150 million gal; the annual capacity of dry milling plants has been about 50 million gal. However, some new dry milling plants are beginning to approach the size of wet milling plants. In particular, their capacity is around 100 million gal/year.

All corn ethanol plants that have come online in the past several years, and those that will come online within the next few years, are dry milling plants (Renewable Fuels Association, 2007). Dry milling plants are fueled primarily with natural gas. Process fuel costs are the second largest expense in ethanol plants (after corn feedstock). Because natural gas prices have skyrocketed in recent years, new plant designs are being developed that will reduce process fuel requirements or allow the use of process fuels other than natural gas. Wang *et al.* (2007) evaluate the energy use of different ethanol plant types and the consequent WTW energy and GHG emission results of those corn ethanol plant types. The results of ethanol plant energy use from that study are summarized below.

Industry Average. For the current industry average ethanol production, we assumed that 82% of US total ethanol production is from dry milling plants and 18% from wet milling plants. On average, for a gallon of ethanol produced, the corn ethanol industry uses 26,420 Btu of natural gas, 8,900 Btu of coal, and 0.88 kilowatt-hour (kWh) of electricity.

New Ethanol Plant Types. There are more than 100 corn ethanol plants which are either under construction or in the planning phase. Because of the increased price of natural gas, these plants could significantly differ from existing ethanol plants in terms of the amount and type of energy use. For example, a large number of new ethanol plants will still be based on natural gas, with lower natural gas consumption than older natural-gas-fueled ethanol plants. Some existing ethanol plants are selling wet DGS to nearby animal farms, and additional new corn ethanol plants will do so as well. It is estimated that about one-third of the thermal energy used in ethanol plants is consumed by dryers used to dry DGS to about 10% moisture content for long-distance transportation and long shelf life.

Skyrocketing natural gas prices in recent years has also encouraged the use of coal as a process fuel in several ethanol plants under construction or in the planning phase.

Two corn ethanol plants in Minnesota are adding wood chip gasifiers to produce synthesis gas (syngas) from wood chips. Steam generated from the syngas will then be used to operate the ethanol plants. As such, wood chips are replacing natural gas as the process fuel in these plants.

Lastly, as the corn ethanol industry rapidly grows, there is a concern that the animal feed market could be oversupplied with DGS from corn ethanol plants. While R&D efforts

Table 2: Energy Use in New Ethanol Plant Types (per Gallon of Ethanol Produced).

Ethanol Plant Type	Natural Gas (Btu)	Coal (Btu)	Renewable Process Fuel (Btu)	Electricity (kWh)
1. Plant with natural gas (NG)	33,330	None	None	0.75
2. Plant with NG and wet DGS	21,830	None	None	0.75
3. Plant with coal	None	40,260	None	0.90
4. Plant with coal and wet DGS	None	26,060	None	0.90
5. Plant with wood chips	None	None	40,260	0.90
6. Plant with DGS as fuel	None	None	40,260	0.75

Note: See Wang *et al.* (2007) for details.

Table 3: Shares of Total Energy Burdens of Corn Ethanol Cycle Allocated to Co-Products.

Method	Dry Milling Plant (%)	Wet Milling Plant (%)
Weight-based	51	52
Energy-content-based	39	43
Market-value-based	24	30
Energy use of individual processes	41	36
Displacement	20	16

in the animal feed field are under way to expand the use of DGS as animal nutrients, an alternative is to use DGS as the process fuel for ethanol plant operation. On a dry-matter basis, one ton of DGS has a lower heating value (LHV) of about 18 million Btu. In dry milling ethanol plants, for each gallon of ethanol produced, about 6 lb of dry DGS are produced (Renewable Fuels Association, 2007), which have an LHV of about 53,760 Btu. For comparison, a coal-fired ethanol plant requires 40,260 Btu of coal/gallon of ethanol produced. Thus, the amount of energy contained in the DGS is more than the amount of energy that an ethanol plant needs.

Table 2 presents energy use in ethanol plants for the six new ethanol plant types.

Energy and Emission Credits of Co-Products from Ethanol Plants

Of the total mass of corn kernels in a typical dry milling ethanol plant, one-third ends up in ethanol, one-third in DGS, and one-third in CO_2. Although CO_2 is collected in some ethanol plants as a commercial product for use, GREET simulations do not consider CO_2 as a co-product in ethanol plants. On the other hand, DGS from ethanol plants is commonly sold in the animal feed market. In fact, the economics of many ethanol plants depend partly on the sale of DGS. In 2006, a total of 12 million tons of dry DGS (DDGS) were produced from corn ethanol plants. Figure 5, which shows DDGS usage shares in North America, reveals that dairy and beef farms are the two major DDGS markets.

In evaluating the energy and emission effects of ethanol, animal feed co-products must be taken into account. Table 3 shows five potential methods to address the co-products of ethanol plants. The weight-based method splits the total energy and emission burdens of corn farming and ethanol production between ethanol and animal feeds according to their weight output shares in ethanol plants. Similarly, the energy-content-based method splits total energy and emission burdens according to the energy output shares, and the market-value-based method according to the market value shares of the products.

The process-energy-based method analyzes the energy use of individual processes in ethanol plants. The energy use of any process that is in place for ethanol production is allocated to ethanol production; the energy use of any process (such as animal feed drying) that is in place for animal feed production is allocated to animal feed production.

With the displacement method (also called the system boundary expansion method in the lifecycle analysis field), the product that is to be displaced by DGS is determined first. The energy and emissions burdens associated with producing the otherwise displaced product are then estimated. The estimated energy and emission burdens are subtracted from the total energy and emission burdens of the ethanol production cycle.

Table 3 lists the percentages of energy that are allocated to animal feeds according to the five methods. Argonne National Laboratory uses the displacement method because it is the most defensible and robust in dealing with co-products when co-products have very different values and purposes (*e.g.*, energy value for ethanol versus nutrition value for animal feed). It is also the most conservative method for estimating the energy and emission benefits of corn ethanol.

With the displacement method, it is necessary to determine the amount of co-products that is produced from corn

Table 4: Co-Product Yields in Ethanol Plants.

Co-Product	Yield (Bone-Dry lb/bu of Corn)
Dry Milling Plants	
DDGS	15.8
Wet Milling Plants	
Corn gluten meal	2.6
Corn gluten feed	11.2
Corn oil	2.08

Note: See Wang *et al*. (1999b).

Table 5: Co-Product Displacement Ratios.

Product	Displacement Ratios (lb of Displaced Product per lb of Ethanol Co-product)
DDGS	
Corn	1.077
Soybean meal	0.823
Corn Gluten Meal	
Corn	1.529
N in urea	0.023
Corn Gluten Feed	
Corn	1.000
N in urea	0.025
Corn Oil	
Soybean oil	1.000

Note: See Wang *et al*. (1999b).

ethanol plants and the products that the ethanol co-products displace. Table 4 shows co-product yields in ethanol plants, and Table 5 shows the products to be displaced by ethanol's co-products.

It is arguable that as corn ethanol production in the United States expands rapidly, the displacement ratios between ethanol co-products and displaced products will differ from those determined in Wang *et al.* (1999b). This issue needs to be reexamined to reflect current practices in the animal feed market. There are some concerns that DGS may oversupply the animal feed market to a level at which the DGS market value would quickly diminish. If this would occur, ethanol plants could use DGS as a process fuel – one of the options presented in Table 2.

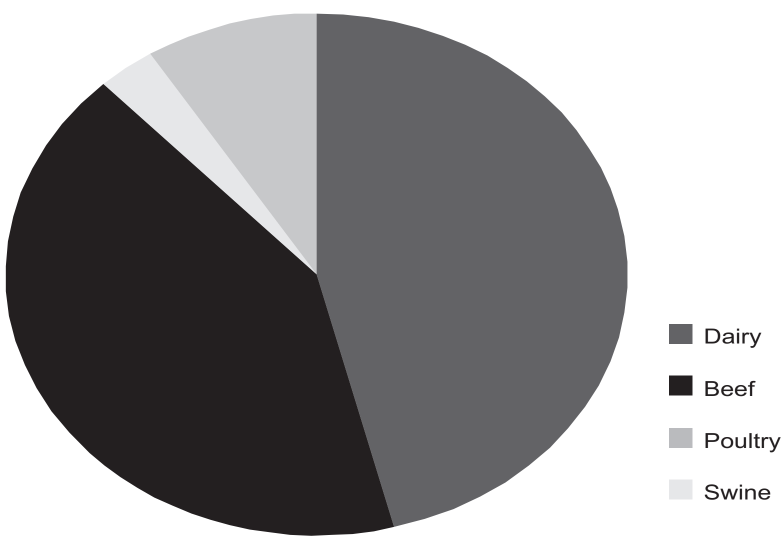

Figure 5: North American Dry Distillers' Grains and Soluables Usage Shares (2006).
Source: Renewable Fuels Association, 2007.

Potential Land Use Changes

Before 2007, the United States had about 80 million acres of corn that produced more than 11 billion bu of corn per year. Figure 4 depicts the historical planted acreage of major crops in the United States. As shown in the figure, the total US crop acreage peaked at 360 million acres in 1981. Since then, the number of acres planted for crops has gradually declined to 319 million acres in 2006 – the result of the Conservation Reserve Program (CRP) and other US Department of Agriculture (USDA) environmental protection programs.

It is worth noting that while corn ethanol production increased by almost 30 times between 1980 and 2006, the number of corn farming acres held steady – at around 80 million acres (Figure 6). One major reason is that the corn yield per acre has steadily increased. Over the past 100 years, the US corn yield per acre has increased nearly eight times (Perlack *et al.*, 2005). However, the increase in per acre corn yields before the 1970s resulted from increased application of chemicals, especially N fertilizer, to corn farms. While the high chemical inputs during that period helped increase per-acre corn production, they did not help corn yield per unit of fertilizer input, which is directly related to corn ethanol's energy and emission effects.

Researchers and policymakers have been engaged in discussions about possible sources of the additional corn that will be needed to meet the demand as the United States significantly increases its corn ethanol production to 15 billion gal in the next ten years. There are several alternatives. First, the existing 80 million acres of corn farms will continue to increase their per acre yields. One conservative estimate of corn yield is about 160 bu/acre will be reached in a few years. More optimistic estimates predict a yield of 180 bu/acre by 2015. Thus, additional corn production from existing corn farms could be 800 to 1,600 million bu of corn per year – providing enough corn for roughly 2.24 to 4.48 billion gal of ethanol production. Switching from other crops to corn and using some other lands (such as CRP lands) are other alternatives to further increase corn production. In fact, in 2007, an additional 12 million acres originally intended for soybean farming were switched to corn farming, which partly drove up soybean prices in 2007. It remains to be seen if this switch from soybean farming to corn farming will be permanent or temporary and what are the consequences of N application rates from the switch. In addition, about 2 million acres might have been converted from marginal land to corn farming acres in 2007.

It has been debated recently whether potential land use changes to be induced by large-scale biofuel production could result in significant changes in soil carbon and, therefore, could affect WTW GHG emission results of biofuels (Delucchi, 2007). This issue is especially relevant to GHG results of corn ethanol, sugarcane ethanol, soybean biodiesel, rapeseed biodiesel, and palm oil biodiesel, as their production is rapidly expanded.

Land use changes induced by biofuel production can be separated into direct and indirect components. Direct land use changes concern displacement of original land use directly by farming of feedstocks for biofuel production. Indirect land use changes concern secondary effects on land use changes by biofuel production. For example, as corn ethanol production may be increased significantly in the United States, additional

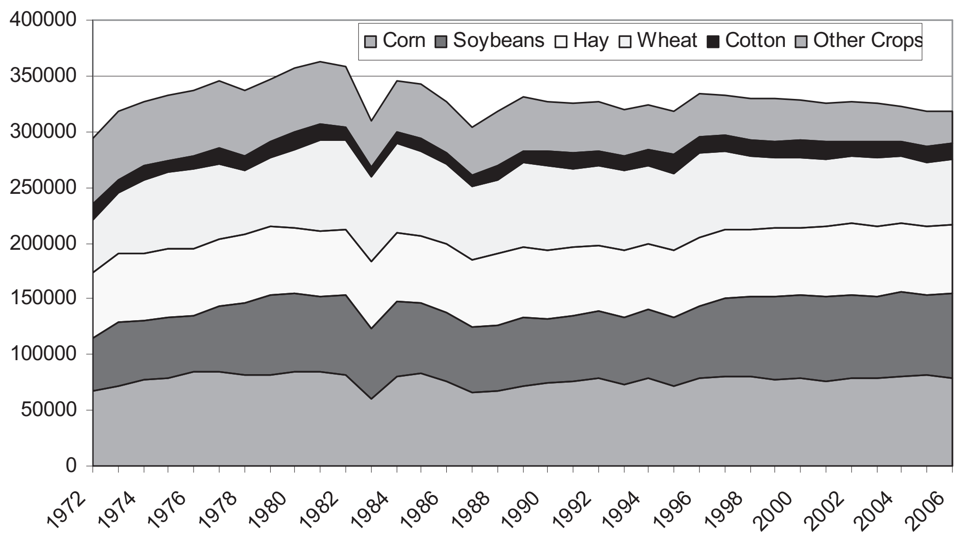

Figure 6: Planted Acreage of Major Crops in the United States (the Acreage for Hay is Harvested Acreage).
Source: National Agricultural Statistics Service, various.

corn will be farmed on the land that is currently used for soybean farming and other crops (the direct land use change). In addition, corn use for ethanol production in the United States will result in reductions in US corn export and in use of corn as a direct animal feed and for other purposes. The reductions in US corn export, in the US soybean production (as a switch of some soybean farms to corn farms), and in the animal feed supply could result in an increase in the production of corn and other agricultural commodities in some other parts of the world.

Limited efforts have been made to address direct land use changes from production of corn ethanol and cellulosic ethanol in the United States. In the late 1990s, the USDA conducted a detailed simulation of land use changes to accommodate corn ethanol production of 4 billion gal/year. The simulation concluded some crop switches and use of CRP lands. Based on the results from that simulation, we estimated soil CO_2 emissions of 195 g/bu of corn, and incorporated this estimate into the GREET model.

However, as corn ethanol production in the United States is to increase dramatically, those past results no longer reflect what will happen in the future regarding the direct land use changes to be caused by corn ethanol production. Land use changes need to be simulated for a much greater expansion of corn ethanol production to reflect future corn ethanol production in the United States.

Indirect land use changes are much more difficult to model. To do so requires the use of general equilibrium models to take into account supply and demand of agricultural commodities, land use patterns, and land availability (all at the global scale), among many other factors. Efforts began only very recently to address both direct and indirect land use changes with general equilibrium models or partial equilibrium models (see Birur *et al.*, 2007; Searchinger *et al.*, 2008). It will be awhile before definitive results can be obtained. Nonetheless, land use changes could be the most significant factor to determine the GHG emission effects of certain biofuel types.

Even after land use changes are simulated for biofuel production, two key remaining issues will still need to be addressed. First, stabilized carbon profiles of different land use types are needed to generate carbon differences of changes from one land use to another. Second, the lifetime of a biofuel program will need to be assumed in order to amortize the total amount of carbon changes over the total amount of biofuel produced during the lifetime of the biofuel program. These factors, together with land use changes, will affect the final results of GHG emissions attributable to biofuel production.

Cellulosic Ethanol Production Pathways

Figure 7 presents a simplified schematic of cellulosic ethanol production. Cellulosic biomass is pretreated in ethanol plants and then undergoes fermentation to produce ethanol from cellulose and semi-cellulose. The unfermentable portion of biomass is used to generate the steam and electricity that are needed for ethanol plant operation. In fact, this plant design generates more electricity than is needed for plant operation – resulting in a net export of co-generated electricity to the electric grid. This plant design is currently under intensive R&D efforts by governments and industries.

Four cellulosic ethanol pathways are analyzed in this chapter. The key parameters of these four pathways are discussed below.

Corn Stover Collection

Corn stover is typically retained in the field to provide nutrients to the soil and to minimize soil erosion. Harvesting corn stover – an agriculture residue – for biofuel production thus implies that an additional fertilizer (N, phosphorus [P], and potassium [K]) is required to supplement its nutrient value to the soil. Fertilizer is a major source of the energy use and emissions associated with corn farming operations. The

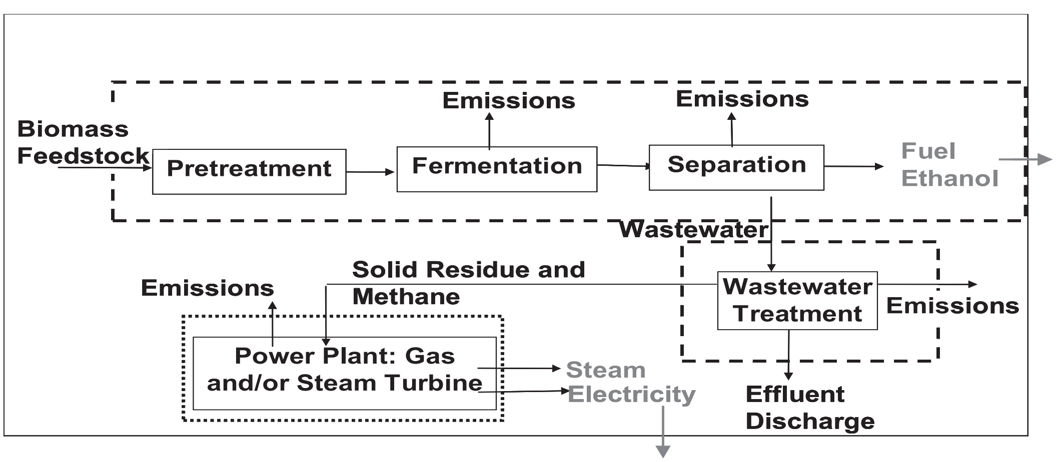

Figure 7: Schematic of Cellulosic Ethanol Plant Design under Intensive Research and Development Efforts.

Table 6: Additional Fertilizer Needs.

Items	Assumptions
N	0.0035 g N/g stover collected
P	0.0018 g P/g stover collected
K	0.0092 g K/g stover collected
Corn grain-to-stover mass ratio (dry matter basis)	1:1
N content in corn stover	0.45% by weight
Corn stover moisture content	15%

Table 7: Farming Inputs for Switchgrass and Fast Growing Trees (per Dry Ton of Biomass).

	Switchgrass	Fast Growing Trees
Farming energy: Btu	217,230	234,770
N fertilizer: grams	10,635	709
P fertilizer: grams	142	189
K fertilizer: grams	226	331

Note: See Wang *et al*. (1999b).

additional demand for fertilizers is accounted for in the corn-stover-based pathways. Removal of corn stover also removes carbon contained in the corn stover, which would remain in the soil. Based on literature, we determined key input parameters for corn farming after corn stover is removed for ethanol production (Table 6; see Wu *et al.*, 2006). As is indicated in the table, for each gram of stover collected, the corn field will lose 0.0045 g (0.45%) of N embedded in the stover, while receiving 0.0035 g of additional N fertilizer.

The issue of energy and emission partitioning between corn and corn stover arises when estimating baseline fertilizer use for both grain and stover. In our study, baseline fertilizer use is allocated to corn grain. Only the additional fertilizer required as a result of corn stover removal (Table 6) is allocated to stover. Some portion of the baseline fertilizer use could be partitioned to corn stover in the future, if corn stover becomes a vital feedstock for ethanol production. Consequently, the energy and emission benefits of corn stover to ethanol should be reexamined when stover is no longer an agricultural residue but a commercial feedstock.

The collection operation for corn stover includes harvesting, bailing, and moving the stover to the edge of field and stacking. Stover would be collected in large round bales. Wagons would typically be used for transporting bales to the edge of the field. Specialized equipment for harvesting and collecting corn stover has not been designed and commercialized to date. However, farming machinery with similar functions does exist. We assumed that farm equipment can be developed that will allow for 50% stover collection. Major equipment required for the operation includes a forage mower/conditioner, a wheel rake, a round baler, a bale wagon, a telescopic handler, and two tractors dedicated to stover operation. Harvesting equipment is fueled by diesel.

After harvest, the stover bail is loaded on a wagon at the edge of the field and then moved to the plant by a heavy-duty diesel truck with a payload of 24 short tons and a 48 ft flatbed trailer. The trailer is able to load 30 round bales at 5 ft x 6 ft (diameter x length). The truck delivers stover with an average one-way distance of 25 miles from the edge of field to the ethanol plant gate.

Forest Waste Collection

Harvesting forest wood residues includes stumpage and harvesting, which requires a large amount of diesel fuel. Fuel consumption during harvesting varies, depending on the type of wood (*i.e.*, softwood [pine] or hardwood). We estimated that the operation will need 2.38 gal of diesel per ton of wood harvested. The wood residue is transported from the collection site to an ethanol plant by using heavy-duty trucks with a payload of 17 tons traveling 75 miles one way.

Growth and Transportation of Switchgrass and Fast Growing Trees

Switchgrass (*Panicum virgatum*), a native prairie grass in the US Midwest, can be farmed for cellulosic ethanol production. Similarly, fast growing trees, such willow trees and poplars, can be grown for cellulosic ethanol production. Based on simulations at Oak Ridge National Laboratory, Wang *et al.* (1999b) assessed farming inputs for switchgrass and fast growing trees (Table 7).

For transportation from farms to cellulosic ethanol plants, GREET assumes a one-way distance of 40 miles for both switchgrass and trees, with a truck payload of 24 tons for baled switchgrass and 17 tons for trees.

The cultivation of switchgrass and trees affects the CO_2 content in the soil. The improvement in soil carbon content is significant when switchgrass and trees are cultivated on cropland. Assuming that 39% of switchgrass is cultivated on cropland and the remainder is cultivated on pastureland and other sources, in a previous study, we estimated equilibrium soil carbon sequestration (per unit of biomass) at 48,800 g of CO_2 per dry ton of switchgrass (Wu *et al.*, 2005). We assumed that fast growing trees would double that amount of CO_2 sequestration in the soil.

Cellulosic Ethanol Production

For the four cellulosic ethanol cases, we used ethanol yields and exported electricity credits, as shown in Table 8.

Well-to-Wheels Energy and GHG Emission Results of Fuel Ethanol

In this section, we present the GREET-simulated energy and GHG emission impacts of fuel ethanol relative to those of petroleum gasoline to show the relative energy and emission merits of fuel ethanol. Detailed technical assumptions regarding petroleum gasoline simulations are presented elsewhere (Brinkman *et al.*, 2005).

Figures 8-10 show energy use per million Btu of fuel produced and used for gasoline, seven types of corn ethanol, and four types of cellulosic ethanol.

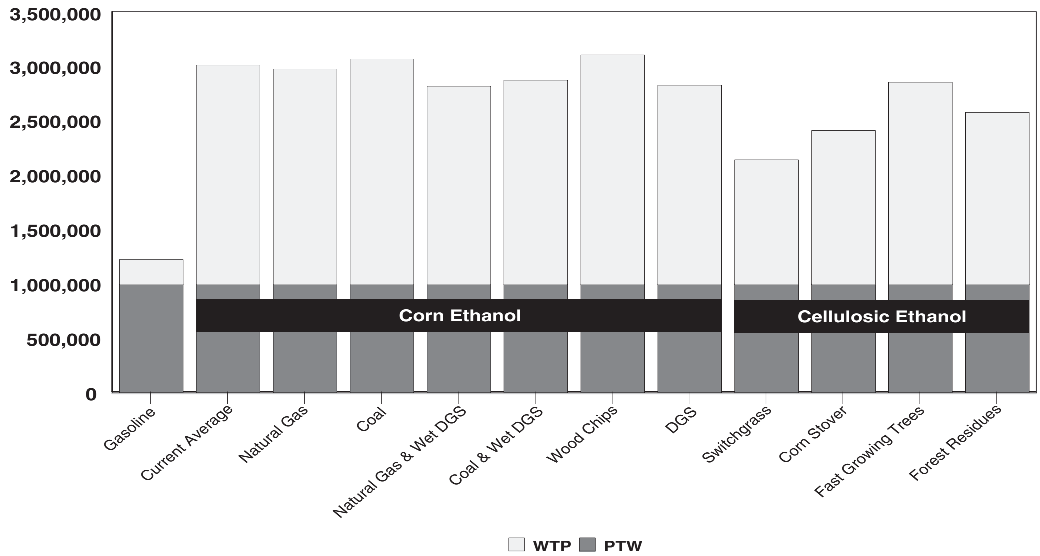

Figure 8: Well-to-Wheels Total Energy Use of Gasoline and Ethanol (Btu per Million Btu of Fuel Produced and used).

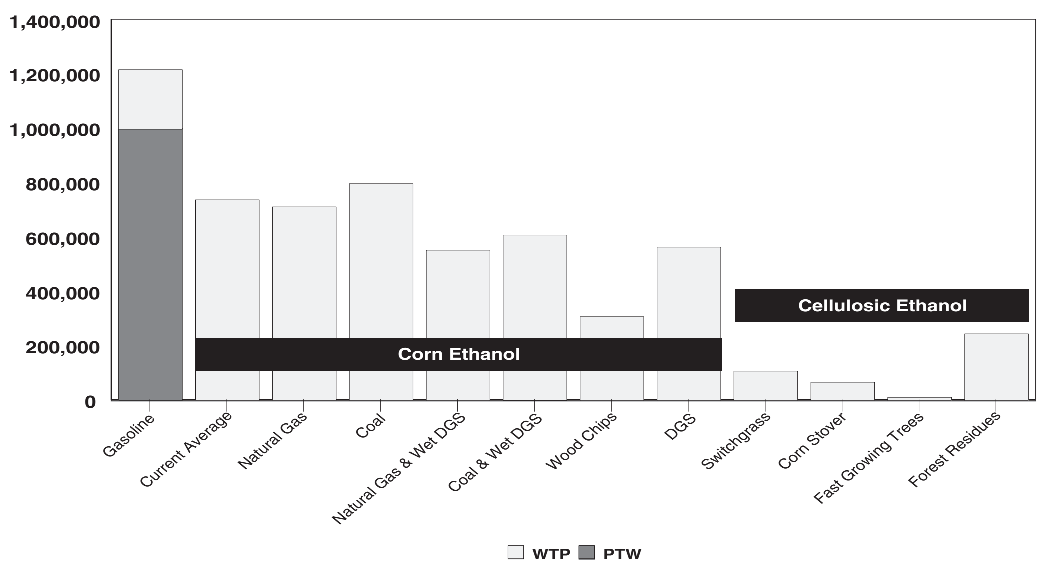

Figure 9: Well-to-Wheels Fossil Energy Use of Gasoline and Ethanol (Btu per Million Btu of Fuel Produced and Used).

Table 8: Cellulosic Ethanol Yields and Exported Electricity Credits.

Cellulosic Feedstock	Ethanol Yield: Gallons/Dry Ton	Exported Electricity Credit: kWh/Gallon of EtOH
Switchgrass	95	0.572
Corn stover	95	0.572
Fast growing trees	90	1.145
Forest residues	90	1.145

Figures 8-10 present the energy effects for three energy types: total energy use, fossil energy use, and petroleum use. Total energy use includes both renewable Btus and fossil Btus. Fossil Btus include those in coal, natural gas, and petroleum. Figure 8 shows that both corn ethanol and cellulosic ethanol consume more total energy sources than gasoline. This is caused by the large total energy use during the well-to-pump (WTP) stage for the 11 ethanol cases. That is, a significant amount of energy in feedstock is lost during the conversion of feedstocks into ethanol, besides a significant amount of fossil fuels consumed for corn ethanol production.

Figure 9 depicts fossil energy use by gasoline and ethanol. While the use of gasoline consumes 1 million Btu of fossil Btu embedded in gasoline, all 11 ethanol cases do not have fossil Btu embedded in ethanol. On the other hand, fossil energy use in the WTP stage for the seven corn ethanol cases is significantly higher than that for the gasoline case. But the four cellulosic ethanol cases have WTP fossil energy use smaller than that of petroleum gasoline and corn ethanol. This is because the lignin portion of cellulosic biomass, instead of fossil fuels, is assumed to generate steam and electricity for cellulosic ethanol plant operations.

Figure 10 shows petroleum energy use by gasoline and ethanol. All 11 ethanol cases have significantly lower petroleum energy use than gasoline. As shown in the figure, this is caused by the 1 million Btu embedded in the gasoline.

In Figures 8-10, the separation of energy use in these three energy types is intended to show that, depending on the type of energy under evaluation, the results between ethanol and gasoline could be very different. For example, if one focuses on total energy results, all ethanol types are worse than gasoline, and cellulosic ethanol has the highest total energy use. When one focuses on fossil energy results, corn ethanol offers a moderate fossil energy reduction relative to gasoline, and cellulosic ethanol offers a huge reduction. Furthermore, if one looks at petroleum use, both corn and cellulosic ethanol offer huge reductions relative to gasoline. These three charts demonstrate the importance of considering the type, as well as the amount, of energy used when comparing ethanol to gasoline.

Use of fuel ethanol may result in GHG emission reductions mainly because the carbon in fuel ethanol is taken up from the air during biological plant growth via photosynthesis (Figure 11). Of course, ethanol production activities require fossil fuel use and generate GHG emissions. Thus, use of ethanol to displace gasoline does not result in a 100% reduction in GHG emissions.

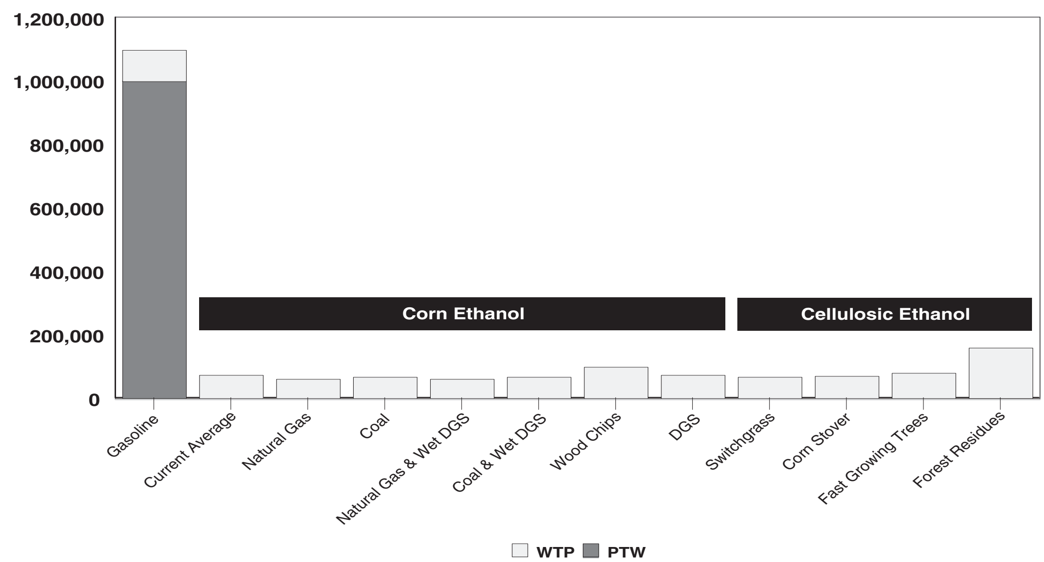

Figure 10: Well-to-Wheels Petroleum Energy Use of Gasoline and Ethanol (Btu per Million Btu of Fuel Produced and Used).

Figure 12 shows the GHG emissions of producing and using one million Btu of gasoline and ethanol. The GHG emission results are CO_2-equivalent emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O). Note that a large amount of N_2O emissions are associated with corn ethanol production; these emissions, which are caused by nitrification and denitrification of N fertilizer in cornfields, are included in GREET simulations. The figure shows that corn ethanol in general has moderately lower GHG emissions, but cellulosic ethanol has much lower GHG emissions than gasoline. The elimination of drying DGS in corn ethanol plants results in lowered GHG emissions. Use of renewable process fuels, such as wood chips and DGS, significantly lowers GHG emissions of corn ethanol. However, corn ethanol plants based on coal may have GHG emissions similar to those of gasoline.

The four cellulosic ethanol cases have much lower GHG emissions than gasoline and corn ethanol. The negative GHG emissions for cellulosic ethanol from fast growing trees are the result of the carbon content increase in the soil where the trees are grown and the GHG credits of electricity exported from cellulosic ethanol plants to displace conventional grid electricity. (It is assumed in GREET simulations that cellulosic ethanol plants would displace grid electricity with the US average generation mix.)

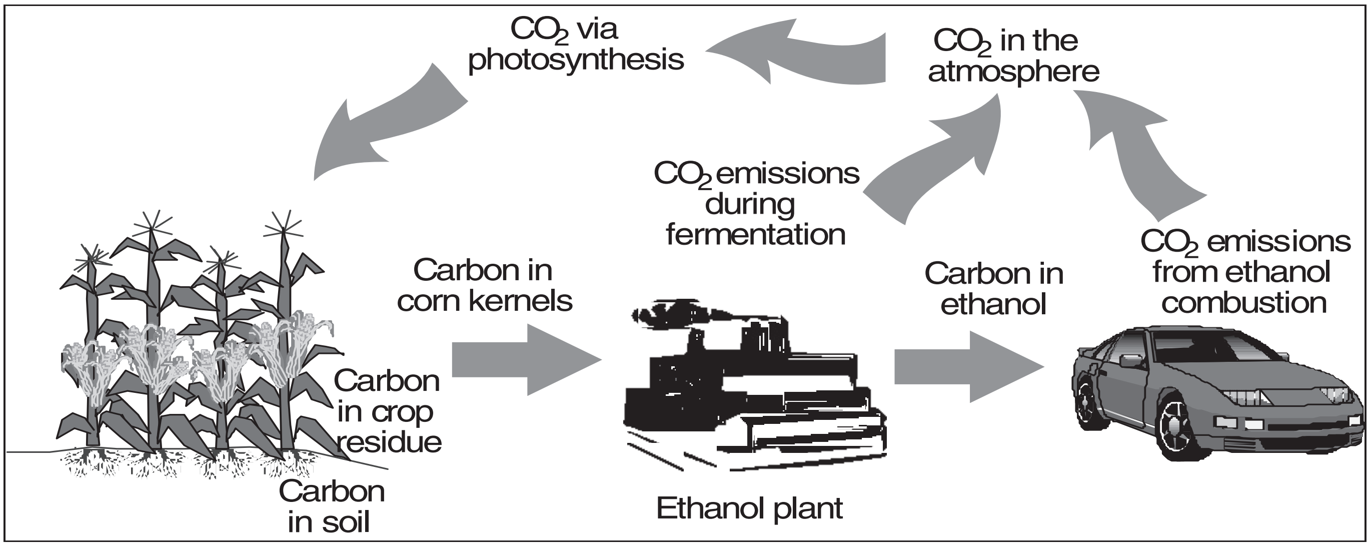

Figure 11: Recycling of Carbon in Fuel Ethanol Production and Use.

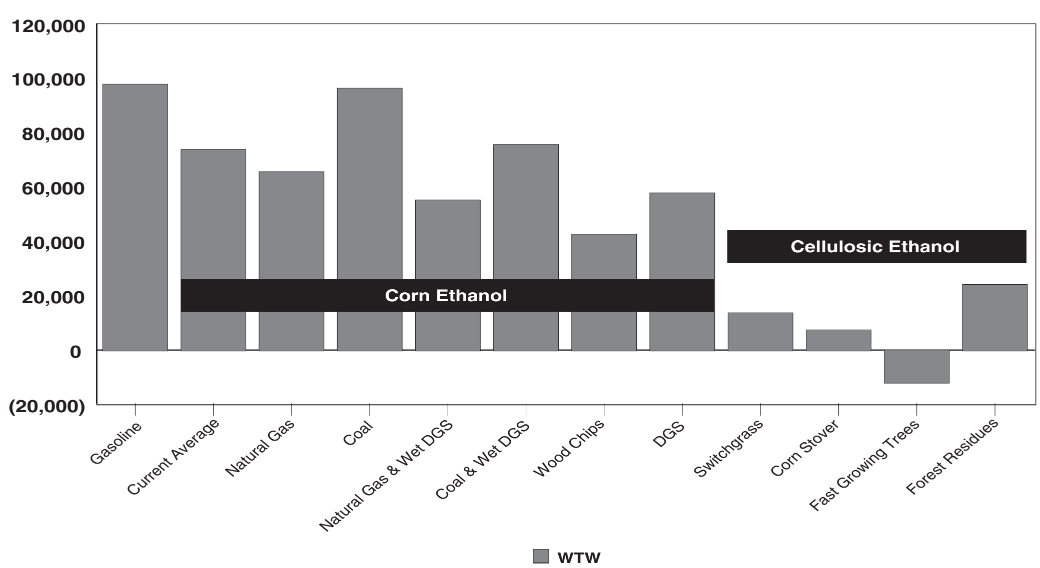

Figure 12: Well-to-Wheels GHG Emissions of Gasoline and Ethanol (Grams of CO_2-e per Million Btu of Fuel Produced and Used).

Figure 13 shows GHG emission reductions by the 11 ethanol cases relative to gasoline. The results are derived from those in Figure 12.

Figures 14 present breakdowns of corn ethanol GHG emissions. The stages that contribute to corn ethanol GHG emissions are ranked from large to small in this order: ethanol production, N_2O emissions from corm farming, N fertilizer production, corn farming, and production and use of other chemicals such as phosphate and potash fertilizer, lime, and pesticides and herbicides. In general, transportation activities have small contributions to total GHG emissions.

Summary

So far, corn-based ethanol in the United States seems to result in moderate GHG emission reductions. As US corn ethanol production is expected to expand rapidly in the next 10 years, it remains to be seen if and how much GHG reductions will result from corn ethanol. The unclear future of the GHG results for corn ethanol stems from the potential land use changes that may be caused by the demand for corn by ethanol production in the near future, as well as by the intensity of fertilizer use in new corn farms, among many other factors. On the other hand, cellulosic ethanol could substantially reduce GHG emissions, and the level of GHG reductions by

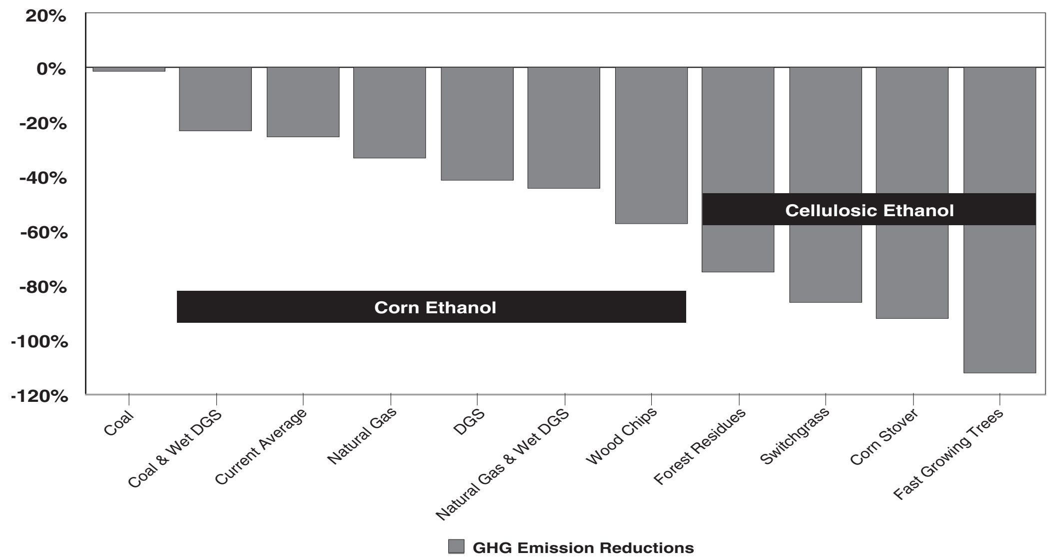

Figure 13: GHG Emission Reductions of Ethanol Relative to Gasoline (One Million Btu of Ethanol to Displace One million Btu of Gasoline).

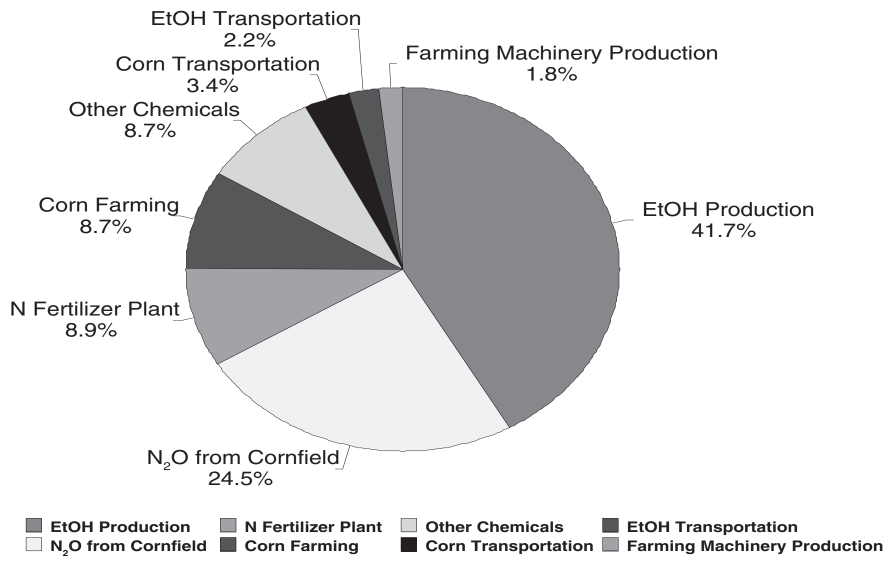

Figure 14: Shares of GHG Emission Sources for Corn Ethanol.

cellulosic ethanol seems to overwhelm the uncertainties of potential GHG emissions from land use changes by cellulosic biomass growth.

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