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Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types

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Abstract
Since the United States began a programme to develop ethanol as a transportation fuel, its use has increased from 175 million gallons in 1980 to 4.9 billion gallons in 2006. Virtually all of the ethanol used for transportation has been produced from corn. During the period of fuel ethanol growth, corn farming productivity has increased dramatically, and energy use in ethanol plants has been reduced by almost by half. The majority of corn ethanol plants are powered by natural gas. However, as natural gas prices have skyrocketed over the last several years, efforts have been made to further reduce the energy used in ethanol plants or to switch from natural gas to other fuels, such as coal and wood chips. In this paper, we examine nine corn ethanol plant types—categorized according to the type of process fuels employed, use of combined heat and power, and production of wet distiller grains and solubles. We found that these ethanol plant types can have distinctly different energy and greenhouse gas emission effects on a full fuel-cycle basis. In particular, greenhouse gas emission impacts can vary significantly—from a 3% increase if coal is the process fuel to a 52% reduction if wood chips are used. Our results show that, in order to achieve energy and greenhouse gas emission benefits, researchers need to closely examine and differentiate among the types of plants used to produce corn ethanol so that corn ethanol production would move towards a more sustainable path.

Keywords: corn ethanol, life-cycle analysis, greenhouse gas emissions, ethanol plants

1. Introduction

During the second oil crisis in 1979, the US government decided to promote the use of fuel ethanol to help diversify the national transportation fuel supply. The US fuel ethanol programme began in 1980; about 175 million gallons of ethanol were used that year. To encourage fuel ethanol production, the federal government initially provided an incentive of 54 cents per gallon of fuel ethanol used. This incentive was later reduced to the current level of 51 cents. Besides the federal government incentive, various states provided incentives to encourage the construction of ethanol plants.

The 1990 Clean Air Act Amendments established the oxygenated fuel programme and the reformulated gasoline programme to encourage the use of ethanol as an oxygenate in gasoline to help reduce criterion air pollutant emissions, primarily emissions of carbon monoxide and precursors for ozone formation. These provisions helped increase fuel ethanol use to over 1.7 billion gallons per year by 2001.

In 2001 and 2002, the discovery of underground water contaminated with methyl tertiary butyl ether (MTBE), used as an additive in reformulated gasoline, led several states on the west coast and in the Northeast to ban the use of MTBE in reformulated gasoline. Ethanol became the only oxygenate to meet oxygen content requirements for reformulated gasoline. The switch from MTBE to ethanol in states along both coasts caused a significant increase in fuel ethanol use. By 2004, ethanol use reached 3.4 billion gallons per year.

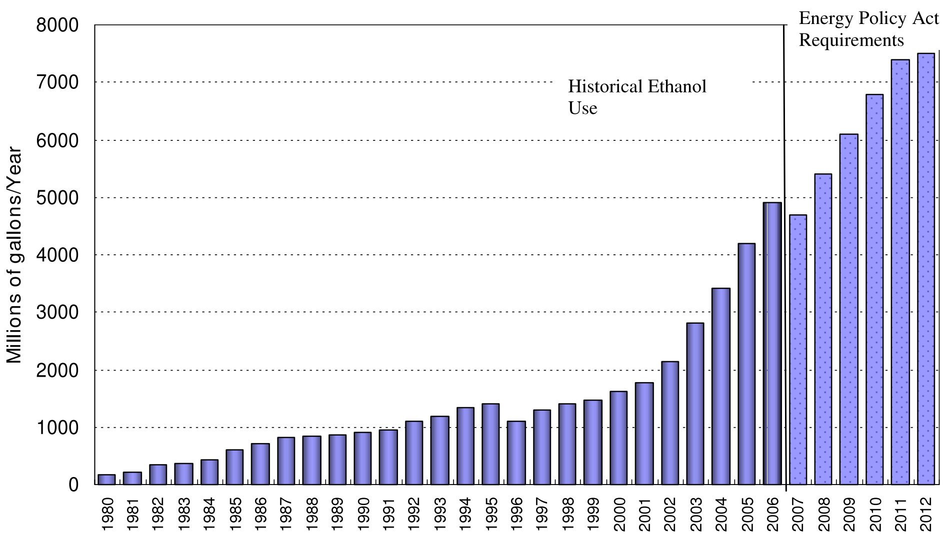

Figure 1. Historical fuel ethanol use and the 2005 Energy Policy Act fuel ethanol use requirements (historical data are from Renewable Fuels Association (2007) and US Congress (2005)).

The 2005 Energy Policy Act established a renewable fuel standard (RFS) that increased the mandated use of renewable fuels—including ethanol and biodiesel—from 4 billion gallons in 2005 to 7.5 billion gallons in 2012. This mandate has spurred the construction of many new ethanol plants and has intensified interest in the research and development (R&D) of technologies to produce ethanol from the cellulose in grass, trees, and other biomass feedstocks. By the end of 2006, fuel ethanol use in the United States had reached 4.9 billion gallons—far exceeding the 4.2 billion gallon mandate in the Energy Policy Act. Figure 1 shows the historical fuel ethanol use in the United States and the Energy Policy Act requirements through 2012. Researchers generally agree that actual fuel ethanol use through 2012 will exceed the volumes required by the Energy Policy Act.

Most corn ethanol plants built in recent years in the United States use natural gas as the process fuel. The average ethanol plant built several years ago had an annual production capacity of about 50 million gallons. By building ethanol plants of this size and installing natural-gas-based boilers, plant owners could obtain state permits on a fast-track basis because such ethanol plants would be classified as minor emission sources. The US corn ethanol industry is undergoing a tremendous expansion. Ethanol plant size has increased significantly; a new ethanol plant could well reach an annual capacity of 100 million gallons. The fuel cost in ethanol plants is the second largest expense after the cost for corn feedstock. Skyrocketing natural gas prices have forced ethanol plant owners to explore ways to reduce plant energy use and find alternatives to using natural gas as a process fuel. The uptrend in ethanol plant sizes makes it feasible for some owners to consider using coal as a process fuel and installing the necessary emission control equipment; unfortunately, this approach would have a detrimental effect on the greenhouse gas (GHG) emission benefits of corn ethanol. Other plant owners have begun to explore other options to reduce energy use in their plants: (1) use of biomass feedstocks or distiller grains and solubles (DGS), (2) production of wet DGS (for animal feedlot use), and (3) use of combined heat and power (CHP) systems. These options can extend the GHG reduction benefits of corn ethanol.

In this study, we expand the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model developed at Argonne National Laboratory to examine new designs for corn ethanol plants and their associated energy and GHG emission effects. This paper presents our results for differentiated ethanol plant types; we are hopeful that the information provided here will help the corn ethanol industry select the most energy- and GHG-emission-friendly path forward.

2. Life-cycle analysis methodology

Since 1995, with support primarily from the US Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE), we have been developing the GREET model at Argonne National Laboratory. Argonne 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 challenges associated with transportation fuels (including ethanol) and vehicle technologies. By using the latest version of the model—GREET 1.7—users can analyse more than 90 transportation fuel pathways and 75 vehicle/fuel systems (Wang *et al* 2007). As a licensed software product available free of charge to the public, GREET has more than 3500 registered users worldwide. They include governmental agencies, automotive companies, energy companies, universities and research institutions, and non-governmental organizations. GREET and its documents are available at Argonne's transportation web site at http://www.transportation.anl.gov/software/GREET/index.html.

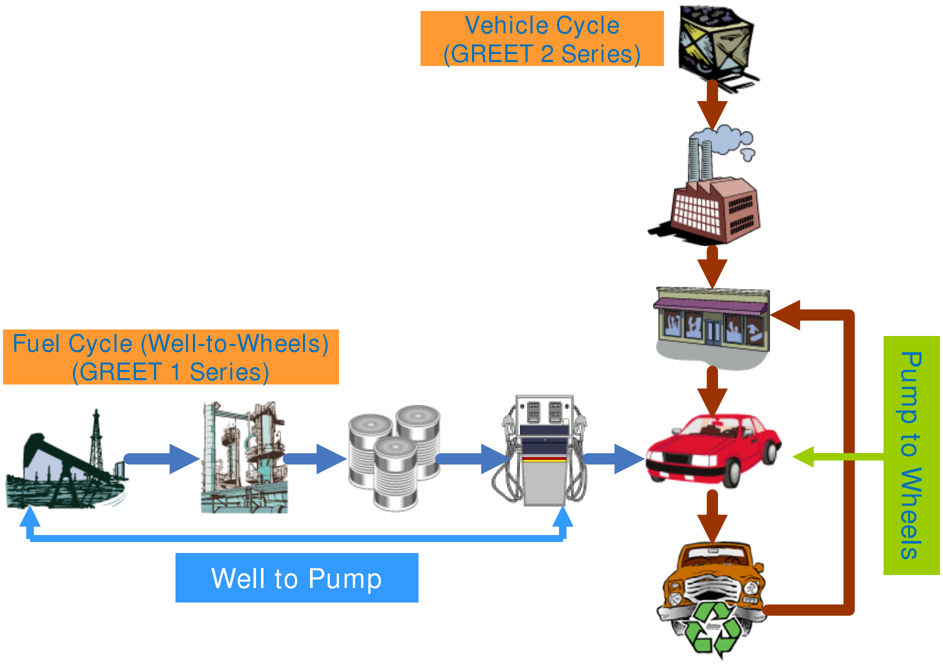

Figure 2. Life-cycle analysis of vehicle/fuel systems with the GREET model.

For a given vehicle and fuel system, GREET separately calculates the following.

- Consumption of total energy (energy in non-renewable 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 criterion pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter measuring less than 10 μm in diameter (PM_{10}), particulate matter measuring less than 2.5 μm in diameter ($PM_{2.5}$), and sulfur oxides (SO_x). These criterion pollutant emissions are further separated into total and urban emissions.

Figure 2 shows the coverage of the GREET model for life-cycle analysis. As the figure shows, the fuel-cycle (or WTW) analysis is conducted by using the GREET 1 series, which 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 figure also shows the vehicle-cycle analysis, conducted by using the GREET 2 series, which includes raw material recovery (e.g. iron ore mining), material production (e.g. steel production), vehicle part fabrication (e.g. engine production), vehicle assembly, and vehicle disposal and material recycling.

In this study, we used the GREET 1 series model (version 1.7) to examine the life-cycle effects of different corn ethanol production options. For fuel ethanol analysis, GREET begins with production of agricultural chemicals (such as fertilizers and pesticides) and extends to vehicles using ethanol—either in low-level gasoline blends (such as E10 (10% ethanol and 90% gasoline by volume)) or in high-level gasoline blends (such as E85 (85% ethanol and 15% gasoline by volume)). Figure 3 shows the fuel ethanol production pathways that are already included in GREET 1.7. Besides corn ethanol, GREET 1.7 includes cellulosic ethanol with cellulosic biomass feedstocks comprising crop residues (e.g. corn stover and wheat straws), switch-grass, fast-growing trees (e.g. hybrid popular and willow trees), and forest residues. We have recently finished an evaluation of sugar-cane-to-ethanol production in Brazil using the GREET model; this new pathway is not yet included in the public version of GREET.

The focus of this study is corn ethanol produced in plants of varying designs. The GREET 1.7 version differentiates corn ethanol into that produced in wet milling versus dry milling plants. Because all ethanol plants built in recent years and those that will be built in the near future are based on dry milling designs, we examine only the different designs of dry milling corn ethanol plants.

Although GREET can be used to estimate emissions of criterion pollutants, as well as energy use and GHG emissions, criterion pollutant emissions are subject to greater uncertainties. For this reason, we have not included emissions of criterion pollutants in this study.

Of all the activities presented in figure 3 for corn ethanol production, the two that have the most significant effects on energy and emissions are corn farming and ethanol production. We address these two activities in detail in the following two sections.

3. Corn farming

Corn farming requires a significant number of chemical inputs, such as nitrogen fertilizer, phosphate fertilizer, potash

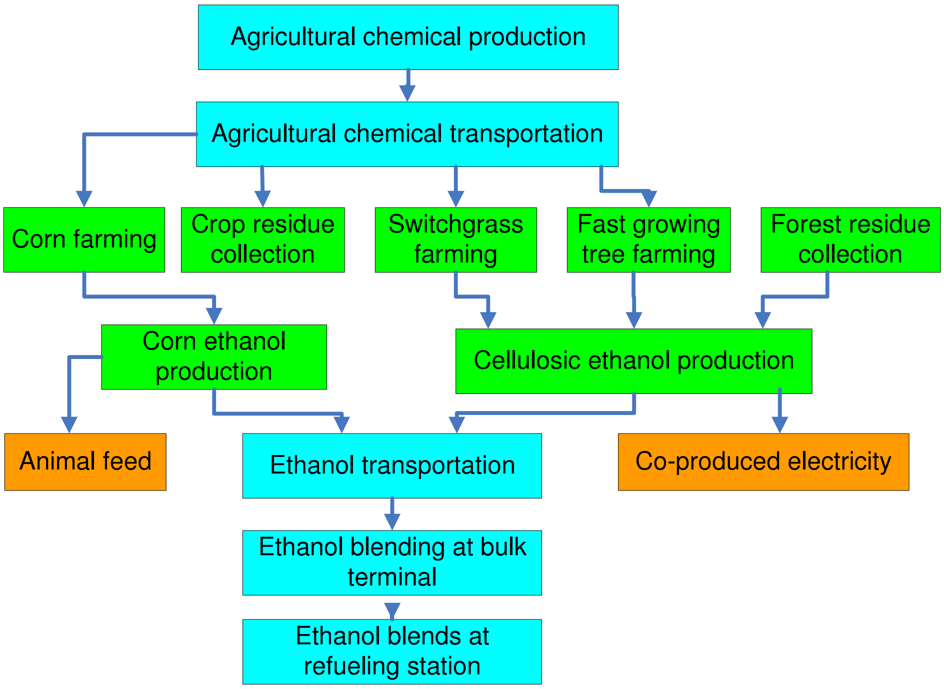

Figure 3. Fuel ethanol production options in GREET 1.7.

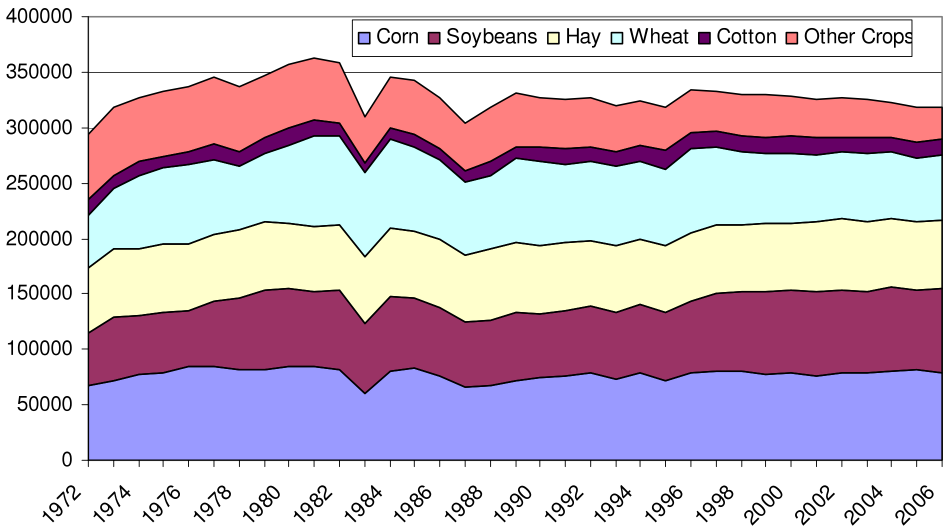

Figure 4. Planted acreage of major crops in the United States (from annual reports of the National Agricultural Statistics Service (US Department of Agriculture, various years); the acreage for hay is harvested acreage).

fertilizer, and lime (for soil conditioning to maintain proper soil acidity). In addition, fossil energy is used to operate farming machinery, to pump water for irrigation, and to dry corn kernels.

The United States has about 80 million acres of corn farms that produce more than 11 billion bushels of corn per year. Figure 4 shows the planted acreage of major crops in the United States. As the figure shows, 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, thanks to 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 almost 30-fold between 1980 and 2006, the number of corn farming acres held steady—at around 80 million acres (figure 4). 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 eightfold (Perlack *et al* 2005). However, the increase in per-acre corn yields before

Table 1. Historical corn yield and chemical use for US corn farms (three-year moving averages on a per-harvested-acre basis, US Department of Agriculture (2007)).

Year	Corn yield (bushels/acre)	Nitrogen (N) fertilizer (lb/acre)	Phosphorus (P_2O_5) fertilizer (lb of/acre)	Potash (K_2O) fertilizer (lb/acre)	Limestone ($CaCO_3$) (lb/acre)
1970	79	118.2	68.8	66.5	
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	NA
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

the 1970s resulted from increased application of chemicals, especially nitrogen 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.

However, since the 1970s, the increase in the corn yield per acre has been achieved as the result of an increase in corn productivity through better seed variety, better farming practices, and other agricultural measures. Table 1 shows that between 1970 and 2005 corn yield increased by 90%, while nitrogen fertilizer application increased by only 22%, phosphorus fertilizer application was reduced by 25%, and potash fertilizer application was reduced by 6% (and limestone application was increased by 13% between 1990 and 2001, when statistics for limestone were available). Corn productivity, defined as bushels/lb of three fertilizer types together, has increased by 88%—from 0.312 bushels/lb of three fertilizers to 0.586 bushels/lb between 1970 and 2005.

Nitrogen fertilizer goes through nitrification and denitrification; during this process, a portion of the nitrogen in fertilizer is converted into nitrogen in nitrous oxide (N_2O), a potent greenhouse gas. GREET assumes a conversion rate of 2% from nitrogen in fertilizer to nitrogen in N_2O.

Limestone is applied to the fields to adjust soil pH and to maintain a certain level of buffer necessary for corn and soybean growth. Corn/soybean rotation farms require a soil pH of 6.5–7.0, depending on the soil type and its buffer capacity. Typically, limestone is applied every few years. In soil, limestone is converted into lime (CaO), and 44% of the limestone mass is released to the air as CO_2. We took this CO_2 emission source into account.

Researchers and policymakers have been engaged in a discussion about possible sources of the additional corn that will be needed to meet the demand if the United States significantly increases its corn ethanol production. 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 bushels/acre, which will be reached in a few years. More optimistic estimates predict a yield of 180 bushels/acre by 2015. Thus, additional corn production from existing corn farms could be 800 to 1600 million bushels of corn per year—providing enough corn for 2.24 to 4.48 billion gallons 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. For example, the USDA recently maintained that an additional 10 million acres could be available for corn farming by 2010, increasing the total corn farming acreage to 90 million acres by 2010 (Associated Press 2007) and providing at least 1.4 billion bushels of corn production.

In the late 1990s, the USDA conducted a detailed simulation of land use changes to accommodate corn ethanol production of 4 billion gallons per year. The simulation included some crop switches and use of CRP lands. Based on the results from that simulation, we estimated soil CO_2 emissions of 195 g/bushel of corn, and incorporated this estimate into the GREET model. Nevertheless, 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.

We estimated direct fuel use of 22 500 Btu/bushel of corn harvested on corn farms. The direct fuel use estimate includes diesel for powering farming equipment, liquefied petroleum gas (LPG) and natural gas for drying corn and for other farming operations, and electricity for irrigation (Wang *et al* 2003).

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 thorough examination revealed that farming equipment manufacture contributes a 2% increase in energy use and a 1% increase in GHG emissions to the corn ethanol pathway (on a full fuel-cycle basis); these percentages are well within the uncertainty range for the corn ethanol results.

4. Ethanol production

Historically, corn ethanol plants are 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. In general, wet milling plants are 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 gallons; the annual capacity of dry milling plants has been about 50 million gallons until very recently.

All corn ethanol plants that have come online in the past several years, and those that will come online in the next few years, are dry milling plants (Renewable Fuels Association 2007). The capacity of some of the new dry milling plants is 100 million gallons per year. Dry milling plants have been fuelled 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. We established a current average and a 2010 average ethanol case to represent ethanol production of the whole industry now and in the future, evaluated nine dry milling ethanol plant types, and examined the aggregate ethanol production from all ethanol plants. Each of the cases and plant types is discussed below.

4.1. Current average and 2010 average ethanol cases

For the current average ethanol case, we used the following assumption: of the 4.9 billion gallons of corn ethanol produced and used in the United States in 2006, 80% was from dry milling plants and 20% from wet milling plants.

We analysed the 2010 average ethanol case so that results for new ethanol plant types could be compared directly with future average ethanol production. In developing the 2010 average ethanol case, we assume that all the new ethanol plants to be built from now until 2010 will be dry milling plants. We also assume that by 2010, total ethanol production in the United States will reach 8 billion gallons. On the basis of these assumptions, we concluded that by 2010 87.5% of ethanol will be produced from dry milling plants and 12.5% from wet milling plants.

4.2. New ethanol plant types

New ethanol plants fuelled with natural gas. A large number of new ethanol plants are still fuelled with natural gas. Natural gas boilers are less expensive than other boiler types, and plants with natural gas boilers are classified as minor emission sources, which helps expedite the process of obtaining emission permits from individual states. These new natural-gas-fuelled ethanol plants have lower natural gas consumption compared with some older natural-gas-fuelled ethanol plants.

New ethanol plants fuelled with natural gas and producing wet DGS. 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. Some new ethanol plants are sited near animal feedlots so that wet DGS can be moved directly to the feedlots, eliminating the need to dry the DGS and resulting in large energy savings for the ethanol plants.

New ethanol plants fuelled with natural gas and CHP systems. A CHP system produces both steam and electricity for plant operation. Adding CHP systems to ethanol plants can help eliminate or substantially reduce the amount of electricity that must be purchased by ethanol plants, thus decreasing overall plant energy use. The US environmental protection agency (EPA) has been working with several ethanol plants to install CHP systems.

New ethanol plants fuelled with coal. Skyrocketing natural gas prices in recent years have encouraged the use of coal as a process fuel in several ethanol plants under construction or in planning. Because the size of ethanol plants has increased, a large coal-fired boiler—even one equipped with the necessary emission controls—may still be economical relative to a gas-fired boiler. One hurdle to construction of coal-fuelled ethanol plants is that these plants may be classified as major emission sources under the current EPA classification system, requiring plant owners to go through a longer process to obtain emission permits. Ongoing discussions among the ethanol industry, individual states, and the EPA are aimed at encouraging regulators to consider increasing the emission cap—from the current 100 tons of VOCs and NO_x a year to a higher level of emissions (between minor and major emission sources).

New ethanol plants fuelled with coal and producing wet DGS. Similar to the gas-fuelled ethanol plants, this ethanol plant design includes transport of wet DGS to nearby animal feedlots to avoid the need for drying DGS.

New ethanol plants fuelled with coal and CHP systems. Adding CHP systems to coal-fuelled ethanol plants will help reduce overall energy use.

New ethanol plants fuelled with wood chips. Two corn ethanol plants in Minnesota are adding wood chip gasifiers to produce synthesis gas (syngas) from wood chips and then steam from the syngas for ethanol plant operation. So wood chips are replacing natural gas as the process fuel in these two plants. In the long run, crop residues, such as corn stover, could be used as the process fuel in corn ethanol plants located in the US corn belt. This option could well serve as a bridge from production of corn ethanol to production of cellulosic ethanol, because it will help identify and solve the logistical issues associated with the use and transportation of cellulosic biomass such as forest residues or crop residues.

New ethanol plants fuelled with natural gas and producing syrup. Corn syrup (or dewatered distiller solubles) left over from the ethanol distillation process can be burned (instead of being used as DGS) to provide a portion of the steam needed in ethanol plants. The remaining steam requirement can be met by burning natural gas. This technology has already been installed in the Corn Plus ethanol plant located in Winnebago, MN. In that plant, the use of corn syrup as a process fuel accounts for 19% of the total dry mass of DGS (Coil 2006).

New ethanol plants fuelled with DGS. As the corn ethanol industry rapidly grows, there is a concern that the animal feed market could be flooded with DGS from corn ethanol plants. While R&D efforts in the animal feed field are underway 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 17 920 000 Btu. In dry milling ethanol plants, for each gallon of ethanol produced, about 6 lb of dry DGS is produced (Renewable Fuels Association 2007), which has an LHV of about 53 760 Btu. For comparison, a coal-fired ethanol plant requires 40 260 Btu of coal per gallon of ethanol produced. Thus, the amount of energy (in Btu) contained in the DGS is more than the amount of energy that an ethanol plant needs.

We designed this ethanol plant option so that all of the steam needed in a corn ethanol plant is provided through combustion of DGS. There are two advantages to this approach. First, use of DGS as a plant process fuel eliminates the need for drying of DGS as an animal feed. Second, use of the DGS displaces use of fossil fuels (such as natural gas or coal) in ethanol plants, thus helping corn ethanol achieve larger energy and GHG emission reduction benefits.

Table 2 presents energy use in ethanol plants for the nine ethanol plant types, plus the current average ethanol and the 2010 average ethanol cases.

5. Results

On the basis of the assumptions listed in table 2 and on other GREET default assumptions, we simulated energy use and GHG emissions (on a WTW basis) for the nine corn ethanol plant types and the current and 2010 average ethanol cases. To put the results into perspective, we included *current* gasoline production and use and 2010 gasoline production and use. We also included cellulosic ethanol production from switch-grass in the future. GREET default assumptions for current and future gasoline and future cellulosic ethanol were used to simulate these three pathways.

In all the corn ethanol cases simulated in this study, electricity is needed for ethanol plant operation (see table 2). The needed electricity is assumed to be purchased from the electric grid. In GREET simulations, we used the US average electricity generation mix for ethanol plant electricity need. That is, 52% of electricity is generated from coal, 16% from natural gas, 20% from nuclear power, 3% from residual oil, 1% from biomass, and 8% from hydro-power.

In our WTW simulations, we assumed the same fuel economy (on a gasoline-equivalent basis) for all vehicles using ethanol blends and gasoline. Thus, the energy use and emission differences between ethanol and gasoline result from the differences in production of the two fuels. Results are presented for each million Btu of fuel used.

The GREET 1.7 version is capable of estimating energy use by total energy, fossil energy, petroleum, natural gas, and coal separately. The results for each separate energy item are presented. We also present CO_2-equivalent GHG emissions of CO_2, CH_4, and N_2O weighted with their global warming potentials (1 for CO_2, 23 for CH_4, and 296 for N_2O).

Table 2. Energy use in each of the ethanol plant types (per gallon of ethanol produced).

Ethanol plant type	Natural gas (Btu)	Coal (Btu)	Renewable process fuel (Btu)	Electricity (kW h)
Current average production case[a]	26 420	8900	None	0.88
2010 average production case[b]	26 050	7950	None	0.95
1. Plant with NG[c]	33 330	None	None	0.75
2. Plant with NG and wet DGS[d]	21 830	None	None	0.75
3. Plant with NG and CHP[e]	34 600	None	None	0.17
4. Plant with coal[f]	None	40 260	None	0.90
5. Plant with coal and wet DGS[g]	None	26 060	None	0.90
6. Plant with coal and CHP[h]	None	44 310	None	0.06
7. Plant with wood chips[i]	None	None	40 260	0.90
8. Plant with NG and syrup[j]	21 000	None	14 000	0.75
9. Plant with DGS combustion[k]	None	None	40 260	0.75

[a] The values here are based on 80% corn ethanol production from dry milling plants and 20% from wet milling plants. Dry milling plants consume 36 400 Btu of fuel per gallon of ethanol produced, and wet milling plants consume 45 990 Btu. Furthermore, 80% of the process fuel used in dry milling plants is natural gas, and 20% is coal, while 60% of the process fuel used in wet milling plants is natural gas, and 40% is coal.

[b] The values here are for 2010 average ethanol production and are based on corn ethanol production of 87.5% from dry milling plants and 12.5% from wet milling plants. All dry milling plants will consume 36 000 Btu of fuel per gallon of ethanol produced, and all wet milling plants 45 950 Btu. Furthermore, 80% of the process fuel used in dry milling plants is natural gas and 20% is coal, while 60% of the process fuel used in wet milling plants is natural gas and 40% is coal.

[c] Based on Mueller and Cuttica (2006). The natural gas consumption value in Mueller and Cuttica is 32 330 Btu per gallon of ethanol. We increased their value by 1000 Btu to account for the uptrend uncertainty in energy use associated with drying of DGS.

[d] Based on Mueller and Cuttica (2006) with the adjustment in footnote c. The difference between total energy need and energy use for drying of DGS is the result here.

[e] From Mueller and Cuttica (2006) and Energy and Environmental Analysis, Inc. (2006).

[f] From Mueller and Cuttica (2006).

[g] From Mueller and Cuttica (2006). The difference between the total energy use need and energy use for drying DGS is the result here.

[h] From Mueller and Cuttica (2006) and Energy and Environmental Analysis, Inc. (2006).

[i] Energy use for coal-fired ethanol plants is assumed here. Carbon neutrality for wood chip combustion is assumed here. Thus, the energy use value here does not affect the carbon emission estimate for wood chip combustion.

[j] Based on Coil (2006) for the Corn Plus ethanol plant in Winnebago, MN. That plant uses about 19% DGS (on a dry-matter basis) to reduce the plant's natural gas usage from 35 000 Btu to 21 000 Btu per gallon of ethanol produced.

[k] The energy use for coal-fired ethanol plants is assumed here. This value does not affect the carbon emission estimate for DGS combustion because the carbon in DGS is ultimately from the air.

5.1. Total energy use

Figure 5 shows WTW total energy use for each million Btu of ethanol (EtOH) and gasoline produced and used. Total energy use includes all energy sources, including fossil energy and renewable energy (i.e. energy embedded in corn kernels and biomass). The chart reveals that ethanol produced from all plant types and cases has higher total energy use than gasoline because of the large amount of total energy use in the WTP stage (the pump-to-wheels (PTW) stage consumes 1 million Btu in all cases because the basis of the chart is 'each million Btu of fuel consumed'). The large increases in the WTP total energy use by all ethanol types are attributable to the fact that a large amount of process energy is consumed in ethanol plants and that a significant energy efficiency loss occurs during the conversion of corn or cellulosic biomass to ethanol.

5.2. Fossil energy use

Figure 6 presents the WTW fossil energy use of 14 fuel production options. Fossil energy use includes petroleum, natural gas, and coal—a subset of the total energy use in figure 5. While the two gasoline options still have 1 million Btu in fossil energy use during the PTW stage, the 12 ethanol options do not have any fossil energy use in the PTW stage because the Btu in ethanol is non-fossil Btu. It should be noted that for the WTP stage, corn-based ethanol options consume much greater amounts of fossil fuel energy than gasoline. The fossil energy consumption for corn ethanol options occurs during fertilizer manufacture, corn farming, and ethanol plant operation. For cellulosic ethanol, the fossil energy use is much lower because switch-grass farming is not chemical and energy intensive and because cellulosic ethanol plants use lignin, instead of fossil fuel, to generate the needed steam.

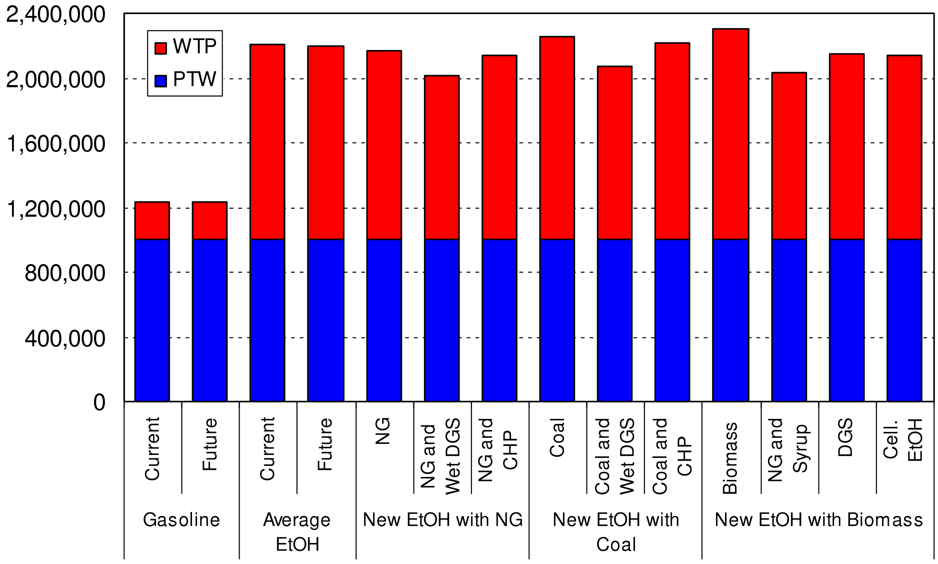

Figure 5. Well-to-wheels total energy use of ethanol and gasoline (Btu per million Btu of fuel produced and used).

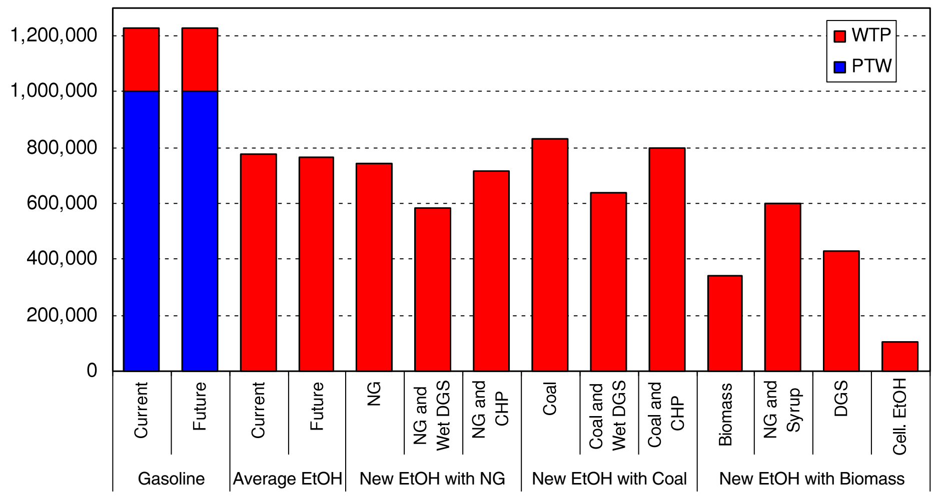

Figure 6. Well-to-wheels fossil energy use of ethanol and gasoline (Btu per million Btu of fuel produced and used).

All ethanol options reduce WTW fossil energy use relative to gasoline. The reductions result from the fact that ethanol itself is a non-fossil fuel. When biomass—such as wood chips, corn syrup, or DGS—is used in corn ethanol plants or when DGS is not dried, corn ethanol can achieve substantial reductions in fossil energy use.

The fossil energy balance of corn ethanol—defined as energy in a fuel minus fossil energy used to produce the fuel and fossil energy embedded in the fuel—is often debated. Figure 7 presents the energy balance of the 12 ethanol options and the two gasoline options, which are derived from the results in figure 6. As the figure shows, gasoline has a negative energy balance because it begins with 1 million Btu of petroleum already embedded in it. On the other hand, all corn ethanol options have positive fossil energy balances. The fossil energy balance values for corn ethanol vary from 170 000 to 660 000 Btu per million Btu of ethanol, depending on the type of process fuels used and ethanol plant designs. Cellulosic ethanol based on switch-grass has an even higher positive energy balance: 900 000 Btu per million Btu of ethanol.

5.3. Petroleum use

Figure 8 shows WTW petroleum use for the 14 fuel options. The WTP stage consumes some petroleum in all 14 options. For the ethanol options, petroleum energy is primarily in the form of diesel fuel for farming equipment and for the trucks and locomotives needed to transport ethanol from plants to bulk terminals and then to refuelling stations.

The significant reductions in petroleum use by all ethanol types relative to gasoline options, as shown in figure 8, result from the fact that gasoline is a petroleum-based product and ethanol is not.

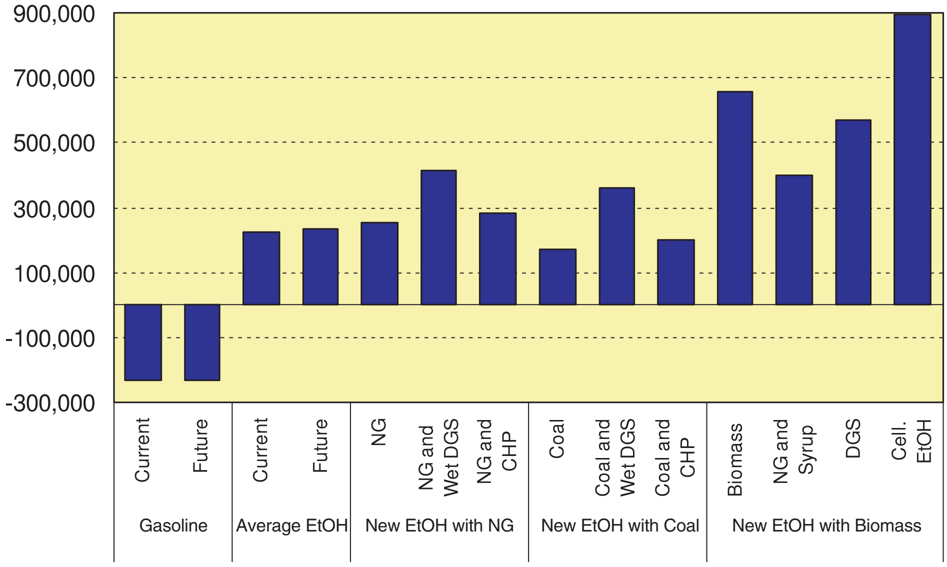

Figure 7. Fossil energy balance per million Btu of ethanol and gasoline (1 million Btu in fuel minus fossil Btu used to produce the fuel and the fossil Btu embedded in the fuel).

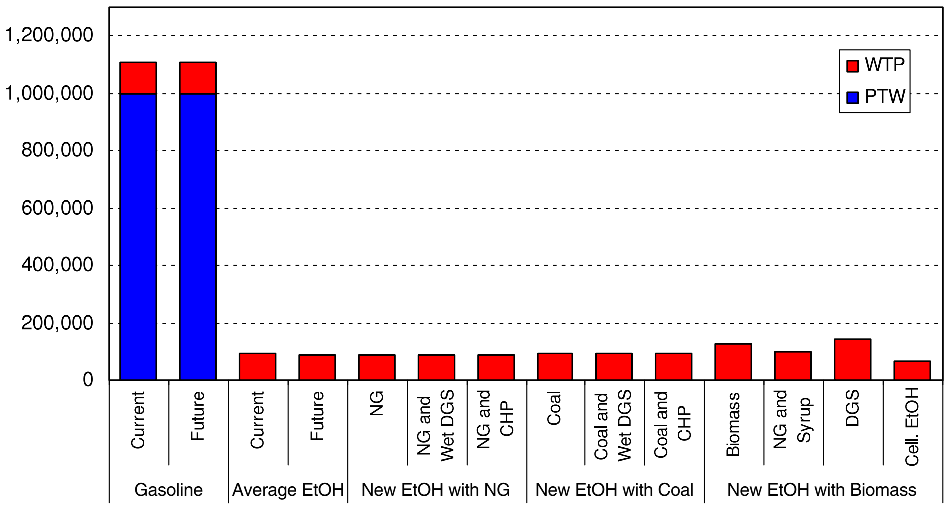

Figure 8. Well-to-wheels petroleum use of ethanol and gasoline (Btu per million Btu of fuel produced and used).

5.4. Natural gas use

Figure 9 presents WTW natural gas use for all of the fuel options. The small amount of natural gas for the two gasoline options is natural gas used in petroleum refineries. For the two average ethanol options (current and 2010), the three natural-gas-powered ethanol options, and the ethanol option with syrup combustion and natural gas supplement, the amount of natural gas is increased significantly because these corn ethanol options rely primarily on natural gas as process fuels in the ethanol plants (see table 2). In the coal-based ethanol options and the cellulosic ethanol option, natural gas is mainly used in production of nitrogen fertilizer.

Figure 9 reveals that the production and use of corn ethanol increases natural gas use compared with the production and use of gasoline. One could argue that this fact shows that ethanol serves as a means to convert gaseous energy into liquid energy for automotive applications. Others could argue that, because the United States will increasingly rely on imported natural gas to meet demand, the increased use of natural gas may offset the energy security benefits achieved through the reductions in petroleum use offered by the ethanol options (see figure 8). It is useful to note that the increase in natural gas use by the ethanol options (up to 600 000 Btu) is considerably smaller than the reduction in petroleum use (about 1 million Btu) achieved by the ethanol options.

5.5. Coal use

Figure 10 presents WTW coal use results. The three coal-based ethanol options significantly increase the use of coal compared with the gasoline options and other ethanol options.

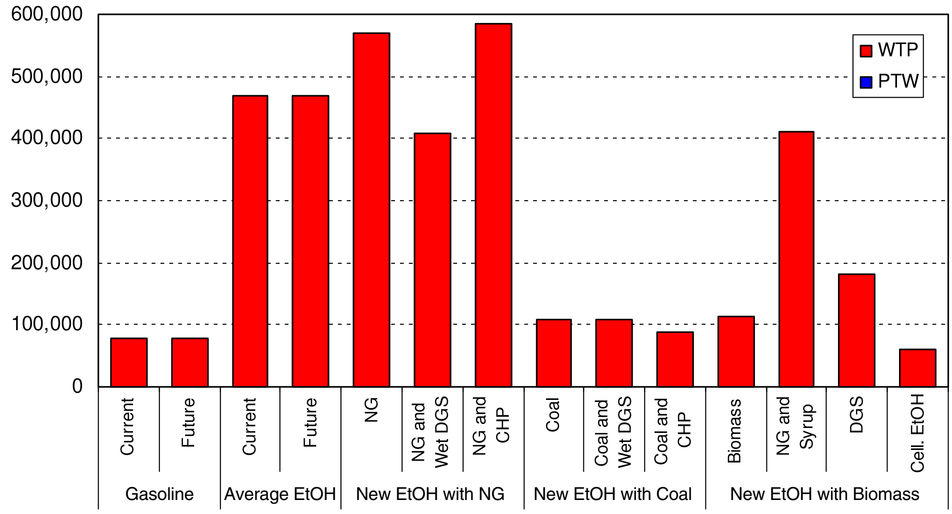

Figure 9. Well-to-wheels natural gas use of ethanol and gasoline (Btu per million Btu of fuel produced and used).

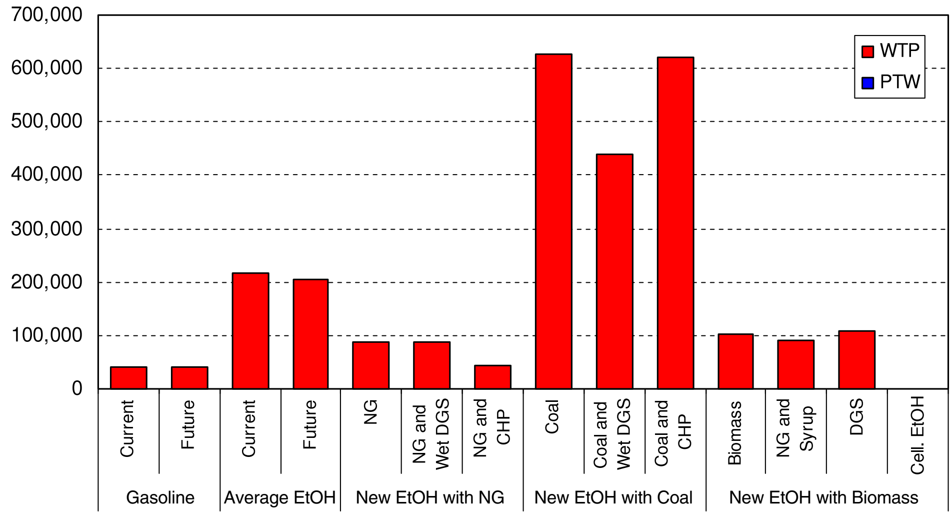

Figure 10. Well-to-wheels coal use of ethanol and gasoline (Btu per million Btu of fuel produced and used).

The two average ethanol cases (current and 2010) consume coal because some ethanol plants are fuelled with coal (see table 2). Coal use for the other fuel options in figure 10 results primarily from electricity use in these options; more than 50% of US electricity is generated from coal.

Some may argue that using coal for ethanol production offers an energy benefit because the United States has a large coal reserve. But burning coal to produce ethanol will certainly reduce the GHG emission benefits offered by corn ethanol (see the following section).

5.6. Greenhouse gas emissions

Figure 11 presents CO_2-equivalent grams of GHGs (CO_2, CH_4, and N_2O) for the 14 fuel options. While GHG emissions for the two gasoline options are dominated by CO_2, N_2O emissions from nitrification and denitrification of nitrogen fertilizer in corn fields are a significant GHG emission source for the corn ethanol options.

To clearly show the effects of different ethanol production options on GHG emissions, figure 12 presents the changes in GHG emissions for the 12 ethanol options relative to the results for future gasoline. The 12 fuel ethanol options are arranged from the worst to the best in terms of GHG emissions. If coal is used as the process fuel in corn ethanol plants, the GHG emission reduction benefits of corn ethanol vanish. If wet DGS is produced in coal-fuelled corn ethanol plants, corn ethanol still offers a GHG reduction of 18%. On average, corn ethanol reduces GHG emissions by 19% now and by 21% in 2010.

For corn ethanol produced in plants fuelled with natural gas, GHG emission reductions vary from 28% to 39%, so natural-gas-fuelled corn ethanol offers distinct GHG emission reduction benefits. Furthermore, if DGS or biomass (such as wood chips) is used as a process fuel, corn ethanol could

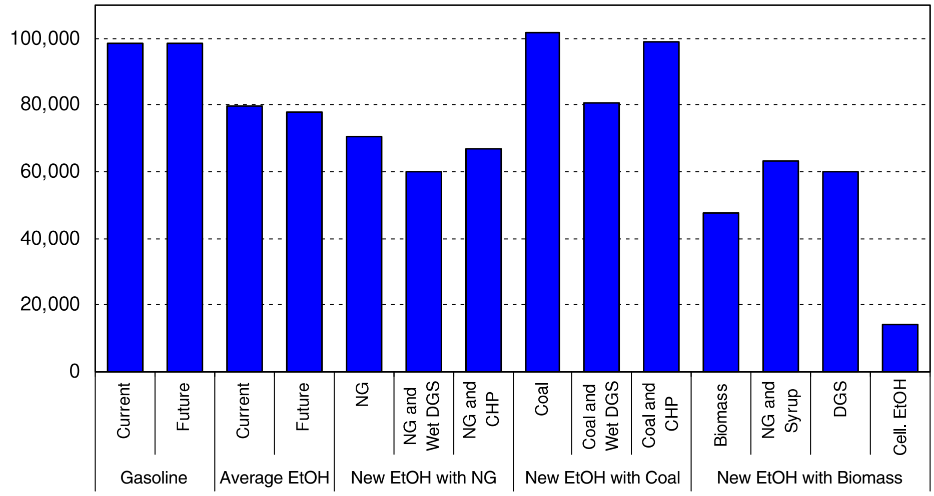

Figure 11. Well-to-wheels GHG emissions of ethanol and gasoline (CO_2-equivalent grams per million Btu of fuel produced and used).

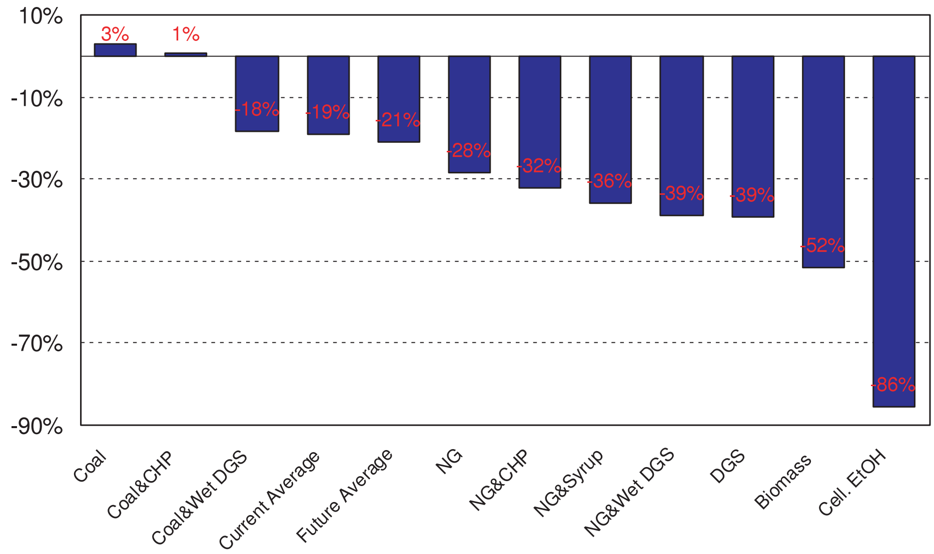

Figure 12. Well-to-wheels GHG emission changes by fuel ethanol relative to gasoline.

achieve 39–52% reductions in GHG emissions. However, cellulosic ethanol is—by far—the best option to reduce GHG emissions. When resource supply (corn versus cellulosic biomass) is taken into account, cellulosic ethanol is certainly the ultimate ethanol option, offering GHG reductions of 86%.

6. Conclusions

Of the corn ethanol production options (nine ethanol plant types plus the current average and 2010 average cases) evaluated in this study, all achieve positive fossil energy balances. A close examination of the energy use associated with each of these ethanol production options shows that all of the options reduce petroleum use relative to gasoline, but at the expense of increasing natural gas use (when natural gas is the process fuel) or coal use (when coal is the process fuel). One may argue that the conversion of gaseous or solid fuel to liquid fuel (i.e. corn ethanol) for automotive applications is indeed an intended benefit.

We found that the ethanol plant types that we examined can have distinctly different energy and GHG emission effects when evaluated on a full fuel-cycle basis. Switching from natural gas to coal as a process fuel in corn ethanol plants may eliminate the GHG reduction benefits of corn ethanol. On the other hand, switching from fossil fuels to biomass-based process fuels (such as wood chips and DGS) significantly increases corn ethanol's energy and GHG benefits. Eliminating the need for drying of DGS in corn ethanol plants can also have a significant positive effect on corn ethanol's energy and GHG emission benefits because the dryers are very energy intensive. Installing CHP systems in ethanol plants offers smaller energy and GHG emission reduction benefits because the amount of electricity used in corn ethanol plants is small.

Our study shows that the GHG emission impacts of corn ethanol could vary from a 3% increase (if coal is used as the process fuel) to a 52% reduction (if wood chips are used). These results suggest that we need to closely examine corn ethanol plant types to identify and promote those that offer the greatest energy and GHG benefits. On the other hand, because cellulosic ethanol produced from switch-grass clearly offers the greatest energy and GHG benefits (by far), this option may represent a long-term, sustainable ethanol production pathway.

Acknowledgments

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