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Fuel-Cycle Assessment of Selected Bioethanol Production Pathways in the United States

Energy Systems Division

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by
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NOTATION

The following is a list of the abbreviations, acronyms, and units of measure used in this document. (Some acronyms and abbreviations used only in tables may be defined only in those tables.)

GENERAL ACRONYMS AND ABBREVIATIONS

BC	biochemical
$CaCO_3$	calcium carbonate
CaO	calcium oxide
CBP	consolidated bioprocessing
CCE	Calcium Carbonate Equivalent
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
DDGS	distilled dried grain solubles
DOE	U.S. Department of Energy
E_{assemb}	fabrication and assembly energy
E_{embod}	embodied energy
EERE	Office of Energy Efficiency and Renewable Energy
E_{repair}	repair manufacturing energy
ERS	Economic Research Survey
EtOH	ethyl alcohol, ethanol
FBC	fluidized-bed combustion
FFV	flexible fuel vehicle
gge	gallon gasoline equivalent
GHG	greenhouse gas
GTCC	gas turbine combined cycle
GV	gasoline vehicle
K	potassium
K_2O	potash fertilizer
LDV	light-duty vehicle
N	nitrogen
N_2O	nitrous oxide
NG	natural gas

NO_x	nitrogen oxide
NREL	National Renewable Energy Laboratory
P	phosphorus
P_2O_5	phosphorus fertilizer
PM_{10}	particulate matter with diameters smaller than 10 micrometers
PMgge	mile per gallon gasoline equivalent
PTW	pump-to-wheels
RFG	petroleum reformulated gasoline
SOC	soil organic carbon
SO_x	sulfur oxide
TAR	total accumulated repair
TC	thermochemical
USDA	U.S. Department of Agriculture
VOC	volatile organic compound
WTP	well-to-pump
WTW	well-to-wheels

UNITS OF MEASURE

Btu	British thermal unit
bu	bushel
dt	dry ton
ft	feet
g	gram(s)
gal	gallon(s)
h	hour(s)
HP	horsepower
kcal	kilocalorie(s)
kg	kilogram(s)
kW	kilowatt(s)
kWh	kilowatt hour(s)
lb	pound(s)
mi	mile(s)

FUEL-CYCLE ASSESSMENT OF SELECTED BIOETHANOL PRODUCTION PATHWAYS IN THE UNITED STATES

by

May Wu, Michael Wang, and Hong Huo

ABSTRACT

A large amount of corn stover is available in the U.S. corn belt for the potential production of cellulosic bioethanol when the production technology becomes commercially ready. In fact, because corn stover is already available, it could serve as a starting point for producing cellulosic ethanol as a transportation fuel to help reduce the nation's demand for petroleum oil. Using the data available on the collection and transportation of corn stover and on the production of cellulosic ethanol, we have added the corn stover-to-ethanol pathway in the GREET model, a fuel-cycle model developed at Argonne National Laboratory. We then analyzed the life-cycle energy use and emission impacts of corn stover-derived fuel ethanol for use as E85 in flexible fuel vehicles (FFVs). The analysis included fertilizer manufacturing, corn farming, farming machinery manufacturing, stover collection and transportation, ethanol production, ethanol transportation, and ethanol use in light-duty vehicles (LDVs). Energy consumption of petroleum oil and fossil energy, emissions of greenhouse gases (carbon dioxide [CO_2], nitrous oxide [N_2O], and methane [CH_4]), and emissions of criteria pollutants (carbon monoxide [CO], volatile organic compounds [VOCs], nitrogen oxide [NO_x], sulfur oxide [SO_x], and particulate matter with diameters smaller than 10 micrometers [PM_{10}]) during the fuel cycle were estimated. Scenarios of ethanol from corn grain, corn stover, and other cellulosic feedstocks were then compared with petroleum reformulated gasoline (RFG). Results showed that FFVs fueled with corn stover ethanol blends offer substantial energy savings (94–95%) relative to those fueled with RFG. For each Btu of corn stover ethanol produced and used, 0.09 Btu of fossil fuel is required. The cellulosic ethanol pathway avoids 86–89% of greenhouse gas emissions. Unlike the life cycle of corn grain-based ethanol, in which the ethanol plant consumes most of the fossil fuel, farming consumes most of the fossil fuel in the life cycle of corn stover-based ethanol.

1 INTRODUCTION

The accelerated development and rapid commercialization of environmentally sound renewable fuel technologies is a high national priority and is central to President Bush's Advanced Energy Initiative. The use of alternative energy sources is not only critical to our national security, but it is also key to maintaining environmental quality and America's economic competitiveness, because alternative energy sources offer a tremendous opportunity for farmers, businesses, and rural communities across our nation. A study for the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE) (Perlack et al. 2005) estimated that up to 823 million tons of cellulosic biomass could be sustainably removed from agricultural land within the next 35–40 years. Many existing sources of cellulosic biomass — such as woody biomass and lumber industry waste, forage crops, industrial and municipal waste, animal manure, and crop residue — could be potential candidates for the bioenergy industry. The most abundant sources of biomass currently available for the production of ethanol are crop residues. Crop residues could contribute 446 million dry tons of biomass, accounting for 54% of the total cellulosic biomass sources (Perlack et al. 2005). Of the crop residues, bagasse and rice straw have already being collected and are thus readily available. Yet, their production volumes, while regionally important, are not sufficient enough to have a significant impact on our nation's total fuel needs.

Alternatively, a large amount of corn stover is available in the U.S. corn belt for the potential production of cellulosic ethanol when the production technology becomes commercially ready. The quantity of corn stover produced is significant. On average, one ton of harvested corn grain results in one ton of dry stover. In 2005, a total of 283 million tons of corn stover was produced in the United States (NCGA 2006). With high corn yield over time and changes in land use, it was predicted that 376 million dry tons of corn stover could be produced for ethanol production (Perlack et al. 2005). Of course, pressing technical and logistic issues need to be addressed for the corn stover-to-ethanol pathway to become a reality. Ongoing research and development efforts are mainly aimed at overcoming technical hurdles in the areas of feedstock pretreatment and cellulosic fermentation. Other challenges in the areas of corn stover harvest, collection, transport, and storage are being addressed. With increased research, development, and deployment interest from the agricultural sector, ethanol industry, academia, and government, corn stover ethanol production and utilization will likely accelerate and overcome these barriers. This pathway could serve as a starting point for producing cellulosic liquid transportation fuels to reduce the nation's demand for petroleum oil.

As with other feedstocks for fuel production, the production of corn stover-based cellulosic ethanol has been the subject of many recent analyses. Perlack and Turhollow (2002) provided a thorough cost analysis of collecting, storing, and transporting stover as an energy feedstock. Another study examined issues associated with stover growers, custom operators, and processors in corn stover harvesting on the basis of stover harvesting experiences in 1997 and 1998 (Schechinger and Hettenhaus 2004). Sheehan et al. (2004) presented a life-cycle assessment of the production of corn stover in corn farms in Iowa for use in flexible-fuel vehicles (FFVs) to displace gasoline in U.S. Midwest urban areas. Assuming continuous corn production with "no till" practice, the analysis found that reductions of 95% in petroleum oil, 102% in fossil energy, and 113% in greenhouse gas (GHG) emissions can be achieved. Kim and Dale (2005) analyzed a continuous corn growth system and concluded that the removal of corn stover for ethanol production could lower soil nitrous oxide (N_2O) emissions and allow energy recovery from fermentation residues, while the limitations associated with removal of corn stover include a low rate of soil organic carbon (SOC) accumulation and high fuel use during stover harvesting. A cropping system of corn stover with winter cover crop was recommended. A similar environmental impact analysis was performed to investigate the use of corn stover-based ethanol in automobiles in Ontario, Canada (Spatari, Zhang, and Maclean 2005).

In this analysis, we assessed life-cycle energy and emission impacts of corn stover-derived fuel ethanol to displace gasoline in light-duty vehicles (LDVs) in the United States by using extensive databases in the GREET model. Our analysis includes:

- Fertilizer manufacturing;
- Farming machinery manufacturing;
- Corn farming;
- Applications of fertilizers, lime, and pesticide/herbicide to soil;
- Stover collection and transportation to ethanol plants;
- Ethanol production;
- Ethanol transportation; and
- Ethanol use in LDVs as E85.

Two time frames were assessed: near term (2012) and long term (2030). We estimated the energy consumption of petroleum oil and fossil energy; the emissions of greenhouse gases carbon dioxide (CO_2), N_2O, and methane (CH_4); and the emissions of criteria pollutants carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter with diameters smaller than 10 micrometers (PM_{10}) during the fuel cycle. We then compared scenarios of ethanol produced from corn grain, corn stover, and forest wood residue to gasoline.

Since 1995, with support primarily from DOE's Office of Energy Efficiency and Renewable Energy (EERE), Argonne has been developing the GREET model. 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. The latest version — GREET 1.7 — is capable of analyzing more than 90 transportation fuel pathways and 75 vehicle/fuel systems (Wang, Wu, and Elgowainy 2005). As a licensed software product available free of charge to the public, GREET has more than 3,000 registered users worldwide. They include governmental agencies, automotive companies, energy companies, universities and research institutions, and non-governmental organizations.

For a given vehicle and fuel system, GREET separately calculates:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal), and petroleum;

- Emissions of CO_2-equivalent greenhouse gases — primarily CO_2, CH_4, and N_2O; and

- Emissions of five criteria pollutants: VOCs, CO, NO_x, PM_{10}, and SO_x.

These criteria pollutant emissions are further separated into total and urban emissions. By incorporating available data for the collection and transportation of corn stover and for the production of cellulosic ethanol, we have added the corn stover-to-ethanol pathway in the GREET model.

This study does not include energy or emissions associated with vehicle manufacturing, capital equipment, building structure, and infrastructure in manufacturing facilities. Nonetheless, studies indicated that the contribution of infrastructure-related activities to total life-cycle energy use and emissions is relatively small (Hill et al. 2006). However, since it has been debated that energy embedded in farming machinery could be a significant source to fuel ethanol pathways (Pimentel and Patzak 2005), we included this item in our current analysis.

2 SYSTEM BOUNDARY AND ANALYSIS SCENARIOS

2.1 SYSTEM BOUNDARY

Biofuel pathways simulated in this study are divided into five stages: (1) farming and harvesting; (2) feedstock transportation; (3) fuel production; (4) fuel product transportation, distribution, and storage; and (5) fuel use during vehicle operation. The GREET modeling boundary for this study is depicted in Figure 1. The bioethanol life cycle begins with the manufacture of fertilizer and farming machinery. Farming operations include chemical application, irrigation, tillage, and harvest. For corn stover, harvesting (collecting, baling, and staging) and additional chemical application as a result of stover removal are considered. Harvested cellulosic biomass is transported via trucks to a fuel production facility, where it undergoes biochemical (BC) or thermochemical (TC) processing for fuel production. The demand for heat and power (steam and electricity) from the BC and TC is met by electricity and steam generated by using a biomass fluidized-bed combustion (FBC) boiler, gas turbine combined cycle (GTCC), grid electricity, and/or natural gas (NG). Liquid fuel products are then transported to refueling stations via rails, barges, and trucks. Bioethanol is used as E85 (mixture of 85% ethanol and 15% gasoline by volume) to FFVs. The gasoline life cycle, on the other hand, begins with crude oil recovery in oil fields and ends in gasoline combustion in gasoline vehicles.

2.2 ANALYSIS SCENARIOS

Corn stover-derived ethanol in the near term (2012) is produced from an advanced BC ethanol-production process that co-produces heat and electricity. This technology was analyzed by the National Renewable Energy Laboratory (NREL). In the long term (2030), ethanol will be produced through a biorefinery process that integrates a consolidated bioprocessing (CBP) and GTCC to co-produce heat and power, which was analyzed by Dartmouth College and Princeton University (Greene et al. 2004; Wu, Wu, and Wang 2005).

We took into account advances in the production of gasoline and ethanol that will occur by conducting near-term (2012) and the long-term (2020–2030) analyses. The analyses included gasoline production from conventional crude in 2012 and from the mix of conventional crude and oil sands in 2030. For cellulosic ethanol production, we considered biochemical conversion in the near term and BC/TC or CBP/GTCC in the long term. The yield from the production of corn grain ethanol will improve over the years. A total of seven cases were analyzed, as listed below.

1. Conversion of conventional crude to gasoline in 2012,
2. Conversion of corn to ethanol through conventional bioconversion in 2012,
3. Conversion of corn stover to ethanol through BC conversion in 2012,

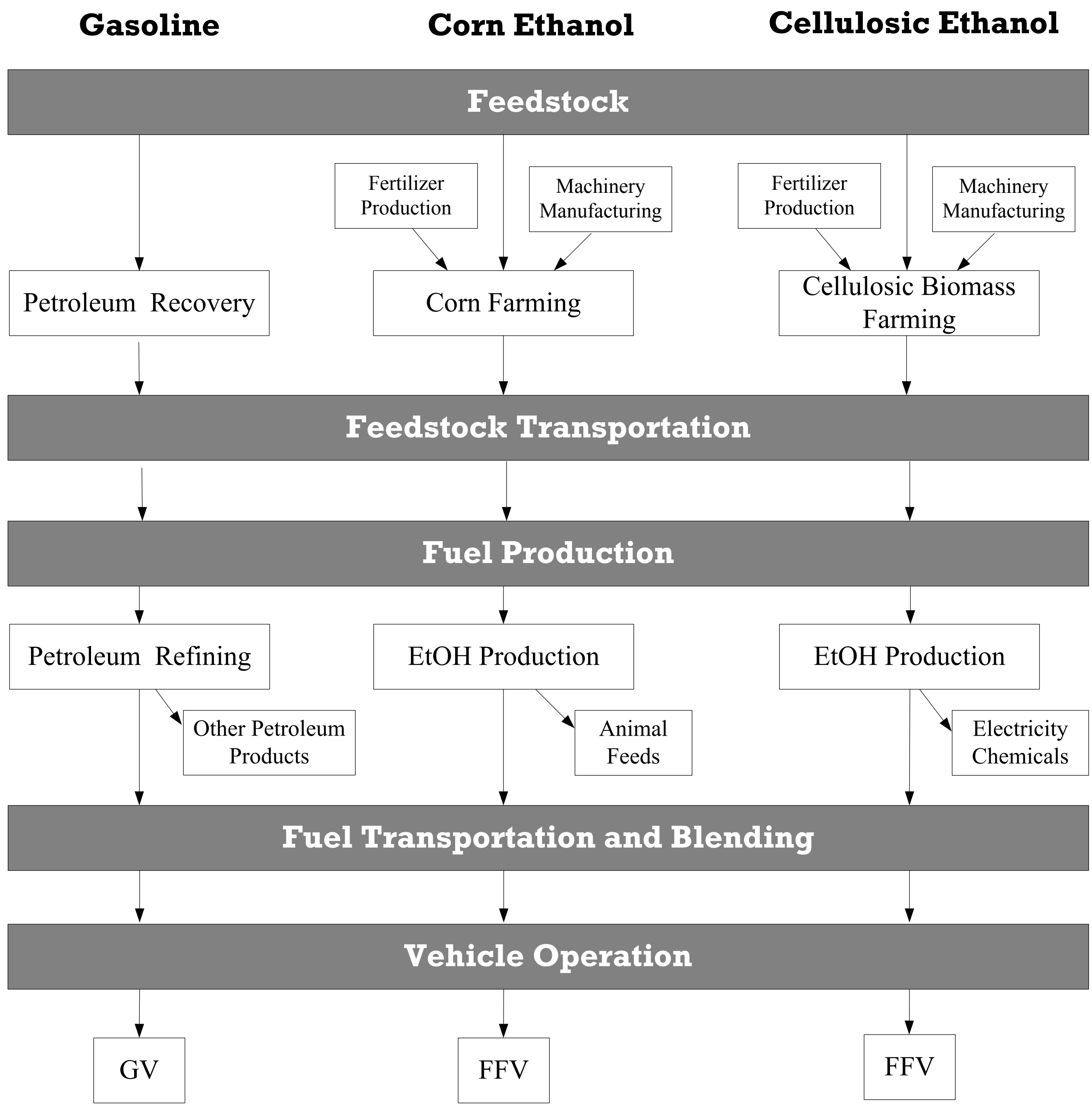


FIGURE 1 Schematic Representation of Well-to-Wheels Analysis System Boundaries for Biofuels and Petroleum Gasoline

4. Conversion of conventional crude and oil sands to gasoline in 2030,

5. Conversion of corn to ethanol through conventional bioconversion in 2030,

6. Conversion of corn stover to ethanol through a biorefinery with consolidated bioprocessing CBP and gasification turbine combined cycle GTCC in 2030, and

7. Conversion of forest residues to mixed alcohols through the BC/TC biorefinery in 2030.

Of the seven cases, the conversion of crude oil to gasoline and the conversion of corn grain to ethanol in 2012 and 2030 (Cases 1, 2, 4, and 5) were based on data collected in GREET (Wang, Wu, and Elgowainy 2005; Brinkman et al. 2005). Cellulosic bio-ethanol cases (Cases 3, 6, and 7) were based on Aspen Plus simulations. Case 3 (corn stover in 2012) was simulated by NREL for a 2,000-dt/d (dry ton per day) advanced BC process ethanol plant (Figure 2) (Jechura 2006). Case 6 used the CBP/GTCC process that was simulated by Dartmouth College and Princeton University for a 5,000-dt/d cellulosic biomass feedstock biorefinery (Figure 3) (Laser and Jin 2004). Forest wood residue with its high lignin content (Table 1) is a choice for thermochemical production of biofuels. As shown in Case 7 (Figure 4), a 2,000-dt/d combined BC/TC biorefinery was designed by NREL (Jechura 2006) for this scenario. Feedstock compositions of corn stover and forest wood residue are listed in Table 1.

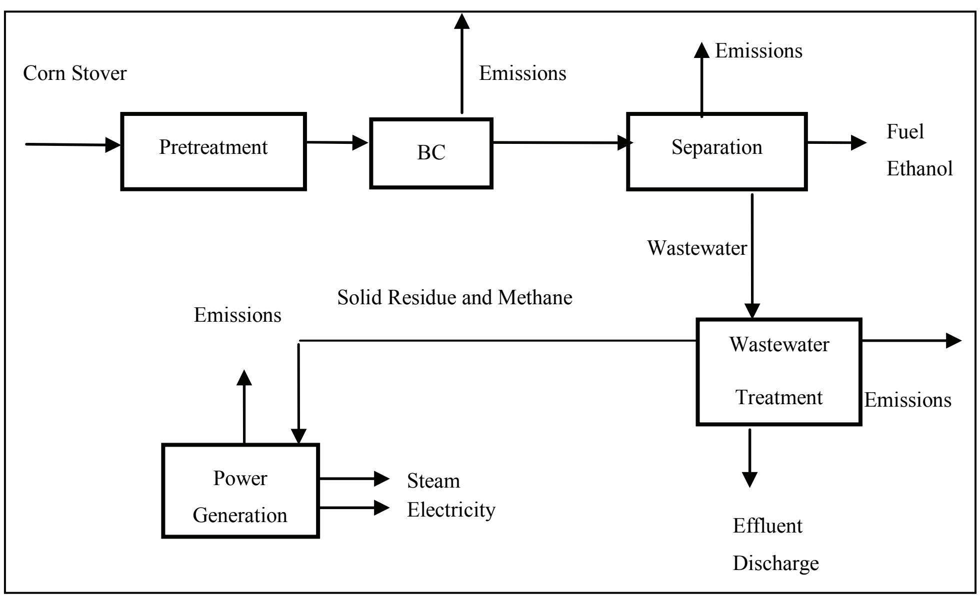


FIGURE 2 Simplified Process Flow Diagram of Biochemical Conversion of Corn Stover to Ethanol with Steam and Electricity Co-Generation, Case 3

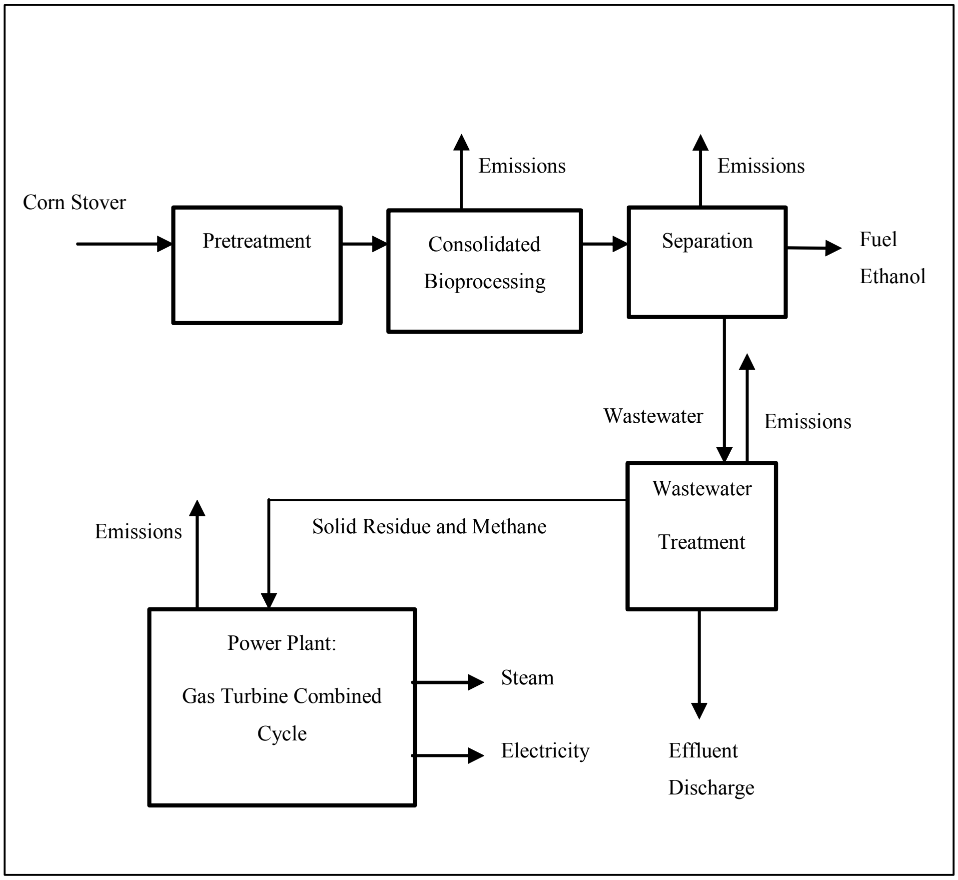


FIGURE 3 Simplified Process Flow Diagram of a Biorefinery That Co-Produces Ethanol, Steam, and Electricity from GTCC, Case 6

TABLE 1 Feedstock Composition

Component	Corn Stover (%)	Forest Wood Residue (%)
Extractives	4.68	0.01
Cellulose	37.40	42.67
Xylan	21.07	19.06
Galactan	1.94	0.24
Arabinan	2.92	0.79
Manna	1.56	3.93
Lignin	17.99	27.69
Ash	5.23	0.97
Acetate	2.93	4.62
Protein	3.10	0.01
Soluble solids	1.12	0.01
Total	99.94	100.00
Moisture content	15	15

Source: J. Jechura (NREL 2006). Feedstock at ethanol plant gate.

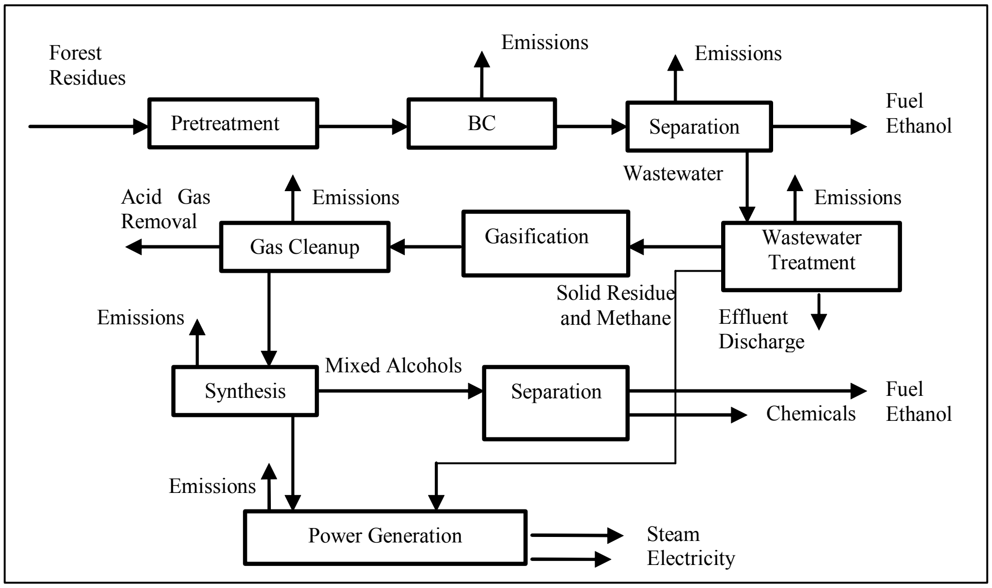


FIGURE 4 Simplified Process Flow Diagram of a Biorefinery That Co-Produces Ethanol, Steam, Electricity, and Other Chemicals from Forest Residues, Case 7

3 DATA SOURCES AND ASSUMPTIONS

Input parameters for GREET modeling are collected from the available literature, published reports, field expertise, and ASPEN simulations. Table 2 lists major processes and operations and the sources for these data.

3.1 ADDITIONAL FERTILIZER REQUIREMENT AND SOIL CARBON CHANGE CAUSED BY CORN STOVER REMOVAL

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 (nitrogen [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 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. The additional fertilizer requirement, soil carbon change, and minimal stover required in the field for erosion control have been studied (Perlack and Turhollow 2002; Sheehan et al. 2004; Powers 2005). In our calculations, we used field data on supplemental nitrogen fertilizer required as a result of the removal of corn stover (Powers 2005) and a dry mass ratio of stover to grain of 1:1. Table 3 details additional fertilizer needs and soil carbon change in this analysis. As is indicated in the table, for each gram of stover collected, the corn field will lose 0.0045 g (0.45%) of nitrogen

TABLE 2 Major Processes and Their Data Sources

Process	Data Sources
Corn stover farming operations (additional fertilizer, harvesting), stover transport	Sheehan et al. (2004), Perlack and Turhollow (2002), Powers (2005), Kim and Dale (2005)
Corn grain-to-ethanol pathway	GREET default values with technology advancement to 2030
Cellulosic biomass to ethanol through BC (2012)	Jechura (2006)
Biorefinery CBP to ethanol with GTCC (2030)	Laser and Jin (2004)
Forest wood residue collection and transportation	Hess and Kelley (2006), Haynes (2003), Hess and Perlack (2006)
Ethanol transportation	GREET default values
Vehicle operation	GREET default values

TABLE 3 Additional Fertilizer Needs and Soil Carbon Change

Items	Assumptions	References
Nitrogen	0.0035 g N/g stover collected	Powers (2005)
Phosphorus	0.0018 g P/g stover collected	Sheehan et al. (2004)
Potash	0.0092 g K/g stover collected	Kim and Dale (2005)
Corn grain-to-stover mass ratio (dry matter basis)	1:1	IPCC (1996)
Nitrogen content in corn stover	0.45% by weight	Sheehan et al. (2004)
Corn stover moisture content	15%	--
Soil carbon change due to land use	Zero	Kim and Dale (2005)

embedded in the stover while receiving 0.0035 g of additional nitrogen fertilizer. In other words, there is an apparent shortage of nitrogen in the soil, unless a corn/soybean rotation system is used to supplement soil nitrogen through nitrogen fixation by means of a legume system, such as that provided by soybeans.

The issue of energy and emission partitioning between corn and corn stover arises when estimating baseline fertilizer use for both grain and stover. In previous corn ethanol life-cycle analyses (Kim and Dale 2005), as well as in this study, baseline fertilizer use is allocated to corn grain. Only the additional fertilizer required as a result of corn stover removal 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 examined when stover is no longer an agricultural residue but a commercial feedstock.

3.2 N_2O EMISSION FROM ADDITIONAL NITROGEN FERTILIZER

Adding nitrogen fertilizer to corn farming results in N_2O emissions directly or indirectly from the soil. N_2O is emitted through following routes: (1) volatilization of nitrogen fertilizer; (2) leaching of fertilizer and its conversion to N_2O through ground water and surface water (river), which then enters estuaries; and (3) direct emission from nitrogen fertilizer in soil. This estimate does not include N_2O from livestock-excreted nitrogen, nitrogen fixation, or nitrogen from the application of sewage sludge. Through previous work, we estimated an emission rate of 2% (weight basis, N_2O-N/N-fertilizer) from the application of nitrogen fertilizer (Wang, Saricks, and Lee 2003).

Crop residue contains nitrogen. When left in the field, a fraction of nitrogen in corn stover is converted through microbial activity to N_2O and then emitted from the soil. This portion of N_2O emissions is avoided where stover is collected. The N_2O emission credit (*N_2Oc*) per unit of stover removed is expressed in equation 1:

$$N_2Oc(\frac{kgN_2O-N}{kgstoverremoved}) = Frac_{NCRo} \times EF_1 \qquad (1)$$

Where:

$Frac_{NCRo}$ = the nitrogen contained in the corn stover on a weight basis (Table 4) and

EF_1 = the Emission Factor, direct soil N_2O emissions (Table 4).

Net N_2O emission due to the removal of stover as a result of farming operations is the difference between the emission from the additional application of nitrogen fertilizer and N_2O avoided (credit) due to the removal of stover. Thus,

$$NetN_2O(\frac{kgN_2O-N}{kgstoverremoved}) = N_{add} \times \frac{N_2O}{Nfert} - Frac_{NCRo} \times EF_1$$

$$= 0.0035 \times 2\% - 0.45\% \times 0.0125 = 0.00001375.$$

For each kilogram of stover harvested, 0.01375 g is emitted as N_2O-N. The emission without a N_2O credit is 0.00007 g (0.0035 × 2%) N_2O-N/g stover. With a N_2O credit, the net emission becomes 20% (0.00001375/0.00007) of what it would be. In another words, the actual net N_2O emission factor becomes 20% of the original emission factor of 2% because of the N_2O credit, or 20% × 2% = 0.4%.

TABLE 4 Parameters and Emission Factors to Estimate N_2O Emission Credit

Parameter	Value	Reference
$Frac_{NCRo}$	0.45% by weight in corn stover	Sheehan et al. (2004)
EF1	0.0125 kg N_2O-N/kg N	IPCC (1996)
$\frac{N_2O}{Nfert}$	2% gN_2O-N/gNfert	GREET 1.7 default

3.3 LIME APPLICATION

Lime is applied to the field 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 soil type and its buffer capacity. Typically, lime is applied every few years. In another words, only a fraction of corn acreage receives lime each year. Thus, net lime application rate per planted acre is expressed as:

$$NLA_i(tone/acre_p/yr) = LAR_i \times \%acre_{p_i} \tag{2}$$

Where:

NLA_i	=	Net lime application rate per all planted acre at year i *(tone/acre$_p$/yr)*
$acre_p$	=	Acreage planted with corn
LAR_i	=	Lime application rate of year i *(tone lime/acre received lime)*
$\%acre_{pi}$	=	Percent of planted acreage that receives lime at year i

Our estimate of lime application rate was based on a USDA Economic Research Survey (ERS) survey (USDA ERS 2003; USDA ERS 2006). The survey provides, on a yearly basis, the average rate of lime application at corn farms in the United States in pounds per acre and percent of acreage applied from 1988 to 2001 (missing value in year 1995) (Table 5). For the percent of acreage that received lime, the responses to the survey showed a sudden increase, primarily as a result of a change in the survey questionnaire beginning in 1996. During the survey years of 1988–1994, about 4–6% of corn acreage was limed, according to responses to the survey question of “did you apply lime last year?” Since 1996, however, the USDA survey questionnaire has been changed to “have you ever applied lime on this field?,” which implies multiple years instead of that specific year of interest. As a result, survey responses from corn farmers since 1996 jumped from 4–6% to 55% of acreage. We believe that such results are no longer representative of a particular year in question; instead, the results show cumulative or historical data and therefore could not be used in yearly calculations. We chose to use an average of 5% acreage that received lime treatment, which was derived from 1988–1994 data. A three-year moving average of the lime application rate from 1990 to 2001 was used to build a time series look-up table in GREET.

Lime is applied on the basis of planted corn acreage. In farming practice, usually not all of the planted acreages are harvested. USDA annual statistics from 1988 to 2005 indicate that, on average, 90% of corn-planted acreage in the United States was harvested (USDA ERS http://www.ers.usda.gov/Data/). The lime application rate of per acre planted was therefore adjusted by the Harvest/Plant (H/P) ratio of 90% to obtain the lime application rate per acre harvested (Equation 3).

$$NLA_i(movingave, lb/acre_h/yr) = \frac{NLA_i(movingave, ton/acre_p/yr)}{\frac{H}{P}} \tag{3}$$

Where:

NLA_i *(movingave, lb/acre$_h$/yr)* = Three-year moving average of net lime application rate NLA_i in pounds of lime per acre harvested per year at year i

$\frac{H}{P}$ = Ratio of harvested corn acreage to planted acreage, $acre_h/acre_p$, 90%

NLA_i *(movingave,ton/acre$_p$/yr)* = Three-year moving average of net lime application rate NLA_i in short ton of lime per acre planted per year at year *i*

The chemical form of the lime was not clearly defined in the USDA survey. There are several chemical forms of lime: calcium oxide (CaO) or burned lime, calcium carbonate ($CaCO_3$) or limestone, and other forms of lime (Dolomite and slaked lime). $CaCO_3$ has a CCE (Calcium Carbonate Equivalent) value of 1.00, while CaO gives the highest CCE of 1.73 among the four chemical forms of lime, which implies higher CO_2 emissions. As a conservative measure, we assume the value from the USDA survey is in the form of CaO with 100% purity. Equation 4 is used to calculate the amount of CaO as equivalent amount of limestone applied:

$$NLA\_CaCO_{3_i} = NLA_i(movingave, ton/acre_h/yr) \times 1.73 \quad (4)$$

Where:

NLA_CaCO_{3i} = Net limestone application rate for corn, $lbCaCO_3/acre_h \bullet yr$ at year *i*

1.73 = CCE of CaO

Table 5a presents the results of limestone application rate from 1988 to 2001. Lime requirements may increase as a result of applications of nitrogen fertilizer because excess amounts of nitrogen fertilizer tend to neutralize and further lower soil buffer capacity. Historical data, especially in the past 10 years, show fluctuation yet little increase in average fertilizer application rate (Table 5b, 5c, 5d). We further projected that corn yield will grow 1% annually as a result of plant genetic technology, independent of fertilizers, and lime use. With these considerations, N-, P-, and K-fertilizer application rates after 2005 and lime after 2001 are assumed to remain constant. Finally, the lime and fertilizer application rate per bushel of corn harvested for 1990–2020 was derived on the basis of USDA corn yield statistics. The results of the application rates for lime and fertilizers shown in Table 5e are used in GREET.

Emissions associated with lime mining, production, and application to cornfields were estimated on the basis of the AP42 documents from the U.S. EPA (EPA 1995). Upstream lime production (mining) energy consumption was assumed to be similar to that of potash fertilizer (K_2O); thus, the operational data in GREET default was used for this analysis. Lime application was not allocated to corn stover removal.

TABLE 5a Rate of Lime Application in Major Corn-Producing States in the United States

	CaO Application Rate				$CaCO_3$ Application Rate
Year	Application Rate for the Acres Received (tons/applied acre)	Application Rate across All Acres Planted (tons/planted acre)	Three-Year Moving Average (tons/planted acre)	Three-Year Moving Average (lb/harvested acre)	Three-Year Moving Average (lb $CaCO_3$/ harvested acre)
1988	1.9	0.095			
1989	1.4	0.07			
1990	**1.6**	**0.080**	**0.08**	**181.11**	**313.32**
1991	1.7	0.085	0.08	173.72	300.53
1992	1.9	0.095	0.09	192.20	332.50
1993	1.7	0.085	0.09	195.89	338.90
1994	1.7	0.085	0.09	195.89	338.90
1995*	**2.0**	**0.100**	**0.09**	**199.59**	**345.29**
1996	2.3	0.115	0.10	221.77	383.66
1997	2.3	0.115	0.11	243.94	422.02
1998	2.1	0.103	0.11	246.00	425.57
1999	2.1	0.106	0.11	239.53	414.38
2000	**2.3**	**0.116**	**0.11**	**239.99**	**415.18**
2001	2.1	0.105	0.11	241.63	418.02

* Lime data for 1995 are not available; they were interpolated from 1994 to 1996.

* Data in bold are used in GREET time series table.

3.4 STOVER HARVESTING AND COLLECTION

Corn stover is left to dry in the field before it is collected. The collection operation 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 bale 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 do exist. We assumed that a farm implement can be developed that will allow for 50% stover collection (Nelson 2002). 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 (Table 6), as suggested in Perlack and Turhollow (2002). A study by Schechinger and Hettenhaus (2004) concluded that custom operators will be preferred for the reliable harvesting of corn stover. For comparison, equipment used for corn grain farming is listed in Table 7.

Harvesting equipment is fueled by diesel. Fuel consumption was estimated on the basis of a stover collection rate regression model in Sheehan et al. (2004). Lubricant oil use during stover collection is less than 1% of diesel use (volumetric basis), according to Sheehan et al. (2004), which is so small and thus ignored in our analysis.

TABLE 5b Rate of Nitrogen Fertilizer Application in Major Corn-Producing States in the United States

	Nitrogen Fertilizer Application Rate				
Year	Application Rate for the Acres Received (lb/applied acre)	Percentage of Corn Acreage Receiving Nitrogen Fertilizer	Application Rate across All Acres Planted (lb/planted acre)	Three-Year Moving Average (lb/planted acre)	Three-Year Moving Average (lb/harvested acre)
1988	137	97	132.89		
1989	131	97	127.07		
1990	**132**	**97**	**128.04**	**129.33**	**143.41**
1991	128	97	124.16	126.42	140.18
1992	127	97	123.19	125.13	138.75
1993	123	97	119.31	122.22	135.52
1994	129	97	125.13	122.54	135.88
1995	**130**	**97**	**126.10**	**123.51**	**136.96**
1996	133	98	130.34	127.19	141.03
1997	130	99	128.70	128.38	142.35
1998	133	98	130.34	129.79	143.92
1999	133	98	130.34	129.79	143.92
2000	**136**	**98**	**133.28**	**131.32**	**145.61**
2001	127	96	122.18	128.60	142.59
2002	137	96	131.52	128.99	143.03
2003	136	96	130.56	128.09	142.03
2004	NA	NA	NA	131.04	145.30
2005	**138**	**96**	**132.48**	**131.52**	**145.83**

* NA – data not available

* Data in bold are used in GREET time series table.

3.5 STOVER TRANSPORT TO ETHANOL PLANT

Corn farms supply corn stover to an ethanol plant with a capacity of 2,000 dry tons of feed per day in the near term and 5,000 dry tons of feed per day in the long term. The plant is surrounded by corn farms (Aden et al. 2002) with 75% acreage use. After harvest, stover bail is loaded on a wagon to 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 × 6 ft (diameter × length). We assume the following moisture content for biomass feedstocks during feedstock transportation: 20% for forest wood residue, 15% for herbaceous biomass, 15% for corn stover, and 25% for short rotation trees (farmed trees). The truck delivers stover with an average one-way distance of 23.6 miles from the edge of field to the ethanol plant gate in 2012 and 35.5 miles in 2030, as determined by Equations 5 and 6. Forest wood residue will be transported by using a 17-short-ton payload heavy truck that travels 75 miles to the ethanol plant. The fuel economy of the heavy-duty truck is estimated by using GREET default.

TABLE 5c Rate of Phosphorus Fertilizer (P_2O_5) Application in Major Corn-Producing States in the United States

	P_2O_5 Fertilizer Application Rate				
Year	Application Rate for the Acres Received (tons/applied acre)	Percentage of Corn Acreage Receiving P_2O_5 Fertilizer	Application Rate across All Acres Planted (lb/planted acre)	Three-Year Moving Average (lb/planted acre)	Three-Year Moving Average (lb/harvested acre)
1988	63	87	54.81		
1989	59	84	49.56		
1990	**60**	**85**	**51**	**51.79**	**57.43**
1991	60	82	49.2	49.92	55.35
1992	57	82	46.74	48.98	54.31
1993	56	82	45.92	47.29	52.43
1994	57	83	47.31	46.66	51.73
1995	**56**	**81**	**45.36**	**46.20**	**51.22**
1996	57	85	48.45	47.04	52.16
1997	57	84	47.88	47.23	52.37
1998	54	83	44.82	47.05	52.17
1999	54	82	44.28	45.66	50.63
2000	**57**	**84**	**47.88**	**45.66**	**50.63**
2001	57	78	44.631	45.60	50.56
2002	60	79	47.4	46.64	51.71
2003	59	79	46.61	46.21	51.24
2004	NA	NA	NA	47.01	52.12
2005	**58**	**81**	**46.98**	**46.80**	**51.89**

* NA – data not available

* Data in bold are use in GREET time series table.

$$A(acre) = \frac{Demand \times 350}{Ystover \times 75\% \times Collection(\%) \times 50\%} \tag{5}$$

Where:

A = Stover harvest area (acre)
Demand = Ethanol plant demand for stover (dry ton/day)
350 = 350 days of operation in a year
Ystover = Corn stover yield (dry ton/acre)
75% = % of acreage available for corn farming
Collection = Stover collection rate, %
50% = Land use for corn in corn and soybean rotation system

TABLE 5d Rate of Potash Fertilizer (K_2O) Application in Major Corn-Producing States in the United States

	K_2O fertilizer application rate				
Year	Application Rate for the Acres Received (tons/applied acre)	Percentage of Corn Acreage Receiving K_2O Fertilizer	Application Rate across All Acres Planted (lb/planted acre)	Three-Year Moving Average (lb/planted acre)	Three-Year Moving Average (lb/harvested acre)
1988	85	78	66.3		
1989	81	75	60.75		
1990	**84**	**77**	**64.68**	**63.91**	**70.87**
1991	81	73	59.13	61.52	68.22
1992	79	72	56.88	60.23	66.78
1993	79	71	56.09	57.37	63.61
1994	80	72	57.6	56.86	63.04
1995	**78**	**70**	**54.6**	**56.10**	**62.20**
1996	79	73	57.67	56.62	62.79
1997	81	72	58.32	56.86	63.05
1998	82	66	54.12	56.70	62.87
1999	81	67	54.27	55.57	61.62
2000	**79**	**66**	**52.14**	**53.51**	**59.33**
2001	83	65	54.29	53.57	59.40
2002	85	68	57.8	54.74	60.70
2003	85	64	54.4	55.50	61.54
2004	NA	NA	NA	56.10	62.21
2005	**84**	**65**	**54.6**	**54.50**	**60.43**

* NA – data not available.
* Data in bold are use in GREET time series table.

$$L = \frac{1}{2} \times \left[\frac{A}{\left(\frac{\pi}{4}\right)} \right]^{\frac{1}{2}} \tag{6}$$

Where:

L = Corn stover transportation distance

3.6 ENERGY USE ASSOCIATED WITH MANUFACTURING FARMING MACHINERY

Machinery used for corn farming and harvesting for grain and stover, as listed in Tables 6 and 7, is analyzed for its life-cycle manufacturing energy use. The average equipment lifetime was assumed to vary from 10 to 15 years. The equipment serves a U.S. average corn farm of

TABLE 5e Rate of Limestone, Nitrogen, Phosphorus, and Potassium Fertilizer Application per Bushel of Corn Harvested Used in this Study*

	Corn Yield					
Year	Bushel/Harvested Acre	Three-Year Moving Average (bu/harvested acre)	$CaCO_3$ Rate (g/bushel)	Nitrogen Rate (g/bushel)	P_2O_5 Rate (g/bushel)	K_2O Rate (g/bushel)
1988	85					
1989	116					
1990	**119**	**106**	**1,336**	**612**	**245**	**302**
1991	109	114	1,192	556	220	271
1992	132	120	1,263	527	206	254
1993	101	114	1,354	542	210	254
1994	139	124	1,245	499	190	232
1995	**114**	**118**	**1,333**	**529**	**198**	**240**
1996	127	126	1,378	507	187	226
1997	127	122	1,565	528	194	234
1998	134	129	1,493	505	183	221
1999	134	132	1,429	496	175	213
2000	**137**	**135**	**1,396**	**490**	**170**	**199**
2001	138	136	1,392	475	168	198
2002	129	135	1,408	482	174	204
2003	142	137	1,390	472	170	205
2004	160	144	1,318	458	164	196
2005	**148**	**150**	**1,264**	**441**	**157**	**183**

* This table serves as GREET default. Bolded values were used in GREET time series look-up table.

TABLE 6 Equipment and Energy Estimate Parameters for Corn Stover Harvesting and Collection

Machinery per Farm[a]	Weight (metric ton)	Assembly Energy[b] (kcal/kg)/(10^6 Btu/ton)	Assembly Energy[c] (kcal/kg)/(10^6 Btu/ton)	TAR[d] (%)
Mower/conditioner	3.1	3,108/11.2	1,022/3.684	92.58
Wheel rake	0.5	1,499/5.4	1,022/3.684	75.98
Baler	3.0	1,499/5.4	1,022/3.684	60.69
Bale wagon	4.3	1,499/5.4	1,022/3.684	75.98
Telescopic handlers	4.5	3,108/11.2	1,022/3.684	60.69
Small tractor	5.4	3,494/12.6	1,022/3.684	89.10
Large tractor	8.9	3,494/12.6	1,022/3.684	89.10

[a] Assumptions for the equipment: JD956 Mover conditioner, 15 ft, 75–112 kW; JD Frontier WR1008 wheel rake, transport width 10 ft; JD568 Round baler with mega tooth pickup. Bale diameter 3–6 ft, requires 75-kW tractor; 2,500 round bale carrier, 14 five-foot bales; JCB 520 Telescopic handlers, 76 HP; Case IH MXM120 tractor (small), 95 HP; Case IH MX230 tractor (large), 190 HP.

[b] Source: Doering (1980)

[c] GREET 2.7 (Burnham 2006)

[d] Total Accumulated Repair cost as percentage of total equipment cost. Source: Doering (1980)

TABLE 7 Parameters for Estimating Energy Demands Associated with Corn Grain Farming Machinery

Machinery per Farm[a]	Weight (metric ton)	Assembly Energy Use[b] (kcal/kg)/ (10^6 Btu/ton)	Assembly Energy[c] (kcal/kg)/ (10^6 Btu/ton)	TAR[d] (%)
Large tractor — 215 HP	9.16	3,494/12.6	1,022/3.684	89.10
Small tractor — 135HP	5.15	3,494/12.6	1,022/3.684	89.10
Field cultivator	2.4	1,995/7.2	1,022/3.684	74.25
Chisel plow/ripper	3.6	2,061/7.4	1,022/3.684	92.58
Planter	3.4	2,061/7.4	1,022/3.684	75.98
Combine	12.45	3,108/11.2	1,022/3.684	75.98
Corn combine head	3.6	2,061/7.4	1,022/3.684	75.98
Gravity box (×4)	6.6	1,499/5.4	1,022/3.684	45.88
Auger	0.8	1,499/5.4	1,022/3.684	45.88
Grain bin (×3)	9.5	1,499/5.4	1,022/3.684	45.88
Irrigation	4.16	1,995/7.2	1,022/3.684	75.98
Sprayer	0.5	1,995/7.2	1,022/3.684	75.98

[a] Source: Hill et al. (2006)

[b] Source: Doering (1980).

[c] GREET 2.7 (Burnham 2006)

[d] When TAR of the particular equipment was not available, an assumption is made on the basis of weight approximation.

546 acres, on the basis of a USDA survey of 12 corn-growing states (Table 8). According to a USDA corn farm irrigation survey in the same 12 states, irrigated corn farm acreage is 13% on average. The weight of irrigation equipment for corn farming, as shown in Table 6, represents our adjusted irrigation rate (13%) from Hill's (2006) estimate of 15%. The energy value of manufacturing forest wood residue machinery was not available at the time of this study. An assumption was made that the energy required for manufacturing forest wood residue machinery is similar to that for manufacturing machinery for harvesting corn stover. The energy value will be updated once such data become available to the public.

The energy to manufacture farming machinery consists of three major parts: energy embedded in the materials, or embodied energy (E_{embod}); fabrication and assembly energy (E_{assemb}); and repair parts manufacturing energy (E_{repair}). Several studies have been conducted to estimate the energy to manufacture farming machinery since the 1970s (Bullard, Penner, and Pilati 1976; Doering 1980). Doering (1980) described a methodology to estimate the embodied energy and assembly energy with a metric of energy factors (kcal/kg) that were derived from statistical data on manufacturing. Studies showed that material-embodied energy for steel

TABLE 8 Corn Farm Acreage and Percent of Acreage Irrigated

State	Acre/Farm[a]	Irrigated Acre[b]	Harvested Acre[b]	Percentage of Acre Irrigated
IL	377	211,167	10,742,787	1.97
IN	254	180,305	5,123,291	3.52
IA	355	86,261	11,761,392	0.73
NB	952	4,505,579	7,344,715	61.34
ND	1,300	54,445	991,390	5.49
SD	1,392	123,229	3,165,190	3.89
WI	201	83,602	2,862,031	2.92
MN	345	178,457	6,556,082	2.72
KS	732	1,346,807	2,494,179	54.00
MI	191	180,261	2,007,021	8.98
MS	287	246,315	2,677,491	9.20
KY	164	8,195	1,043,990	0.78
Average	546	600,385	4,730,797	13

[a] NASS 2005 data (for corn farm acreage), http://www.nass.usda.gov/, accessed Aug. 2006.

[b] http://www.nass.usda.gov/statistics_by_state

reduced rapidly (Fruehan et al. 2000; de Beer, Worrel, and Blok 1998; WEC 1995; Worrell et al. 1994). Similar work has been performed extensively in the automobile industry (Berry and Fels1972; ANL, PNNL, NREL, 1997; Gaines, Stodolsky, and Cuenca 1998; Wang, Saricks, and Lee 2003). We adopted the methodology that Doering (1980) used in his study with updated material embodied energy and assembly energy in our analysis to reflect these changes.

During an investigation of energy use and emissions associated with vehicle life cycle, Burnham, Wu, and Wang (2006) found that a typical U.S. steel mix consists of 30% virgin steel and 70% recycled steel in the automobile industry. Because of the similarity between the automobile and farming equipment industries in major material use and manufacturing processes, approximating the steel mix for farming equipment is reasonable. However, many previous farming machinery studies did not consider recycled steel — in fact, a majority of recycled steel is used in cold-rolled virgin steel for machinery. The energy required to produce recycled steel is estimated to be 76% that of virgin steel. If a steel mix of 30/70 (virgin/recycle) is elected, the total embedded energy would be lower, or 83% that of virgin steel. For our study, we chose the 30/70 steel mix for estimating the cost of manufacturing farming machinery. To compare our study with other studies, we built two sensitivity cases that involve using 100% virgin steel for farming machinery.

Life-cycle material production energy (embedded) and associated emissions for steel and rubber tire have been estimated (Burnham et al. 2006) on the basis of a U.S. industry average from 1980 to 1995 (ANL, NREL, PNNL 1997). Current embedded energies are 10,800 kcal/kg (38.9×10^6 Btu/ton) for virgin steel and 10,340 kcal/kg (37.3 mmbtu/ton) for rubber. The material use is split by weight into 17.9% of tires and 82.1% of steel body, which is all part of the equipment, excluding tires (Doering 1980). Although updated material split data are not available in the published literature, changing this split is not likely to have a major impact on the energy use of manufacturing machinery over its life cycle, given that the embodied energy between virgin steel (10,800 kcal/kg) and rubber (10,340 kcal/kg) is close. Tires consist of approximately two-thirds rubber material and one-third steel (Burnham 2006). Hence, the machinery contains a total of 88.1% steel and 11.7% rubber materials.

Data on the energy to fabricate and assemble farming machinery are from two sources. The first source was originally obtained from a major manufacturer of farming machinery (Doering 1980). The fabrication and assembly energy was described by a metric of kcal/kg for each type of equipment, ranging from 5.4 to 12.6 × 10^6 Btu/ton (1,499 to 3,497 kcal/kg) of machinery fabricated and assembled (Tables 6 and 7). With advancements in technology, the process energy input per unit of equipment produced may decrease with time, which means up-to-date assembly and fabrication technology would consume less energy. The second source of fabrication and assembly energy is from recent GREET vehicle model development (Burnham et al. 2006). The vehicle cycle analysis estimated that 3.7 × 10^6 Btu/ton (1,022 kcal/kg) was spent on a passenger car for fabrication and assembly on a life-cycle basis, which includes energies required for process fuel production. In GREET, users can select two sets of fabrication and assembly energy inputs. This analysis adopted 3.7 × 10^6 Btu/ton for estimating the energy required for farming machinery. We recognize the limitation of this approach in that the value may not be specific to describing the different farming equipment. Therefore, in the sensitivity case 1, we present an estimate using Doering's machinery assembly energy value and GREET's embodied energy value for 100% virgin steel. The energy for assembling rubber tires was not available at this time, and so we did not include it in our assessment. Table 9 summarizes key assumptions associated with estimating the life-cycle energy costs to manufacture farming machinery. Shares of process fuels in machinery fabrication and assembly were approximated with those of automobiles. Boyd (2005) presented a statistical analysis on the basis of energy use data of 35 U.S. vehicle assembly plants from 1998 to 2000, which provided a process fuel breakdown of an average 67% fossil fuels and 33% electricity. The fossil fuels are further split to 90% NG and 10% coal. Farming machinery embodied energy and its assembly energy are expressed in Equation 7a and 7b:

$$E_{embod} = W \times (E_{embod\_S} \times (82.1\% + 17.9\% \times 1/3) + E_{embod\_R} \times 17.9\% \times 2/3) \quad (7a)$$

$$E_{assemb} = E_{assemb\_S} \times (82.1\% + 17.9\% \times 1/3) \quad (7b)$$

Where:

W = *Total* equipment weight (*ton*)
E_{embod} = Embodied energy (*kcal, or 10^6 Btu*)
E_{assemb} = Life-cycle assembly and fabrication energy use (*kcal, or 10^6 Btu*)
E_{embod_S} = Steel embodied energy (*kcal/kg, or 10^6 Btu/ton*)
E_{embod_R} = Rubber embodied energy (*kcal/kg, or 10^6 Btu/ton*)
E_{assemb_S} = Life-cycle assembly and fabrication energy use (*kcal/kg, or 10^6 Btu/ton*)

TABLE 9 Key Assumptions in Farming Machinery Life Cycle Energy Estimate: Base Case and Sensitivity Cases

Attributes	Base Case for Corn, Stover, and Forest Wood Residue	Sensitivity Case 1: Corn	Sensitivity Case 2: Corn
Steel mix	30% virgin steel; 70% recycled steel	100% virgin steel	100% virgin steel
Steel embodied energy	32.4×10^6 Btu/ton (9,005 kcal/kg)	38.9×10^6 B tu/ton (10,800 kcal/kg)	38.9×10^6 Btu/ton (10,800 kcal/kg)
Rubber embodied energy	37.3×10^6 Btu/ton (10,340 kcal/kg)	37.3×10^6 Btu/ton (10,340 kcal/kg)	37.3×10^6 Btu/ton (10,340 kcal/kg)
Weight percent of tire	17.9	17.9	17.9
Weight percent of the equipment excluding tire	82.1	82.1	82.1
Fraction of steel and rubber in tire (steel:rubber)	1/3:2/3	0:3/3	1/3:2/3
Fabrication and assembly energy	3.7×10^6 Btu/ton (1,022 kcal/kg)	See Tables 6 and 7	3.7×10^6 Btu/ton (1,022 kcal/kg)

Energy use associated with repair parts is calculated on the basis of total accumulated repair (*TAR*) equations. *TAR* represents accumulated repair and maintenance costs as a portion of the original equipment price up to any point in the life of equipment (Doering 1980). Dollar costs were taken as a proxy for energy costs. Only one-third of the *TAR* values was taken to represent total repair costs that excludes labor and other maintenance costs. The embodied and assembly energies for repair parts are represented by Equation 7c. The total energy to manufacture machinery is a sum of material-embodied energy, fabrication and assembly energy, and repair parts energy, as shown in equation 8. The *TAR* costs for each of the equipment are described in Table 6 for corn stover harvesting and Table 7 for corn grain farming.

$$E_{repair} = (E_{embod} + E_{assemb}) \times TAR \times \frac{1}{3} \tag{7c}$$

Where:

E_{repair} = Energy used for production of repair parts (*kcal, or 10^6 Btu*)

$$E_{total} = E_{embod} + E_{assemb} + E_{repair} \tag{8}$$

Where:

E_{total} = Total machinery manufacturing energy (*kcal, or 10^6 Btu*)

3.7 COMPARISON OF ESTIMATES FROM LITERATURE FOR ENERGY ASSOCIATED WITH MANUFACTURING CORN FARMING MACHINERY

Advances in steel and rubber production technologies have improved energy efficiency in the past 30 years, which has led to a drastic reduction in their production energy. With the latest estimates, embodied energy could reach as low as 5,733–8,375 kcal per kg of steel (cold-rolled, virgin steel) (WEC 1995; Fruehan et al. 2000; Worrell et al. 1994) and 10,340 kcal per kg of rubber tire (ANL, NREL, PNNL, 1997; Burnham et al. 2006). Estimates of manufacturing energy from six studies were compared: Doering (1980), Berry and Fels (1972), Pimentel and Patzek (2005), Fruehan et al. (2000), WEC (1995), and Hill et al. (2006). Each of the studies estimated manufacturing energy for a 13,400-lb (6,078-kg) model tractor with two-wheel drive and a 125-hp (PTO) engine. Total manufacturing energy was calculated from embodied energy, assembly energy, and repair parts energy, when provided (Doering 1980; Pimentel and Patzek 2005; Berry and Fels 1972). For those who investigated steel embodied energy only (Hill et al. 2006; Fruehan et al. 2000; and WEC 1995), total energy for the tractor was obtained from (1) their own estimates of steel embodied energy, (2) the assumption of embodied energy in the rubber of 10,340 kcal/kg, and (3) use of Doering's method to account for fabrication and assembly and repair parts energy. This study generates three cases using GREET: a base case and two sensitivity cases (Table 9). Results of this comparison are presented in Table 10.

The total energy to manufacture machinery per equipment weight decreased by approximately 30% since the 1980s and reached 46% since 1970. The energy savings is largely credited to gains in energy efficiency in the steel production process. Most steel mills in the United States have been moving toward a high level of integration for process heat and power. If this trend continues, the embodied energy for steel is likely to decrease further.

Sensitivity analysis shows that updated embodied energies alone decreased the total energy spent on tractor manufacturing by 24% (case 1, Table 10) since the 1970s. Encouraging the use of up to 70% recycled steel could further cut the total energy expense by another 9% (case 2 vs. base case). An additional 11% energy savings could be achieved through improved energy use during assembly (case 2 vs. case 1). On the whole, energy for steel making accounts for over one-half of the energy savings, making it the single most important factor in determining overall energy requirements for manufacturing machinery. Results suggest that the steel mix by their feedstocks (such as virgin steel and recycled steel) could have a significant impact on the total energy to manufacture machinery. Producing recycled steel is not as energy-intensive as producing virgin steel. On average, 29.7×10^6 Btu of energy is required to produce one ton of

TABLE 10 Comparison of Machinery Manufacturing Energy Use from Various Studies

Parameter	Pimentel et al. (1973)[a] Pimentel and Patzek (2005)[a]	Berry and Fels (1972)[a]	Doering (1980)	Fruehan et al. (2000)[b,c]	WEC (1995)[b,c]	Hill (2006)[b,c]	This study, Base case[c,d]	This study, Sensitivity case 1[c,e]	This study, Sensitivity case 2[c,f,g]
Embodied energy (kcal/kg)									
Steel		14,648		8,375	5,733	5,972	9,005	10,800	10,800
Rubber tire				10,340	10,340	10,340	10,340	10,340	10,340
Embodied energy (kcal/kg)									
Tractor	18,800[h]		11,814						
Total energy[f] (kcal/kg)	19,928[i]	19,890	16,396	12,949	10,526	10,745	11,260	15,172	12,906
Reductions from 1973 estimate (%)			17.72	35.02	47.18	46.08	43.5	23.9	35.24

[a] Energy for making rubber was not included.

[b] Assume embodied energy for rubber is 10,340 kcal/kg.

[c] Total energy is calculated by using Doering's method and assembly energy specified in Table 6.

[d] 30% virgin steel and 70% recycled steel; GREET value for embodied energy and assembly energy. Rubber weighs 11.9% of total equipment.

[e] GREET embodied energy value — 100% virgin steel, and rubber weighs 17.9% of total equipment. Tires are consist of 100% rubber.

[f] Total energy is the summary of embodied energy, energy for fabrication and assembly, and energy to manufacture repair parts.

[g] GREET embodied energy value — 100% virgin steel, and rubber weighs 11.9% of total equipment. Use GREET's vehicle assembly energy. Use Doering's method for total energy calculation.

[h] Includes energy for assembly.

[i] Energy for repair parts is included, which was estimated to be 6% of embodied and assembly energy.

recycled steel. This is a quarter less than that required to produce virgin steel (38.9 × 10^6 Btu). Encouraging the use of recycled steel for manufacturing could, therefore, generate more savings in the embodied energy of steel.

3.8 FOREST WOOD RESIDUE HARVEST AND TRANSPORTATION

Although the ethanol production process would be similar among different cellulosic feedstocks, major differences arise in the feedstock farming, harvesting, and transportation steps. Harvesting forest wood residue 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). Assuming a wood mix of 59% pine and 41% hardwood, the operation will need 2.38 gallons of diesel per ton of wood harvested (Table 11). 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. Harvesting and transportation distance data for forest wood residue were estimated from the operation cost data provided by Idaho National Laboratory and North Carolina State University (Hess and Kelley 2006).

3.9 TECHNOLOGY ADVANCEMENT OVER TIME

Over time, advances in bioprocessing technology for biofuel production from corn, stover, and forest residue will have impacts on the life-cycle energy use and associated emissions. We assumed the following in this analysis:

1. Corn yield will continue to increase as a result of improved farming management, genetic engineering, and other factors;

2. The capacity of a plant producing cellulosic ethanol will increase from 2,000 dt feedstock/day to 5,000 dt/day to take advantage of the economy of scale (which, on the other hand, will increase the distance of transporting stover and forest wood to ethanol plants); and

3. Ethanol yield from cellulosic biomass will increase as a result of the R&D efforts on pretreatment and fermentation.

These factors are summarized in Table 11.

3.10 ETHANOL PRODUCTION PROCESS AND TRANSPORTATION

The BC and CBP process produce fuel ethanol, while the TC process generates chemicals of n-propanol, n-butanol, n-pentanol, and methanol in addition to ethanol. The cellulosic ethanol plant (stover and forest wood residue) is self-sufficient through the combustion of lignin residue to generate steam and electricity. Surplus electricity is exported to the grid to displace the U.S. average mix of electricity. The emission credit of the exported electricity is thus estimated on the

TABLE 11 Assumptions about Key Ethanol Fuel-Cycle Parameters for 2012 and 2030

Parameter	Year 2012	Year 2030
Corn yield (bu/acre)	154	180
Stover yield (dry metric tons/acre)	3.67	4.29
Stover collected (dry metric tons/acre)	1.84	2.15
Stover transportation distance, one-way (mi)	24	35
Fuel consumption during forest wood harvesting (gal of diesel/ton of wood)	Not analyzed	2.38
Share of different types of wood harvested	Not analyzed	pine 59%, hard wood 41%
Cellulosic ethanol plant capacity (dry tons of feedstock/day)	2,000	5,000

basis of the U.S. average generation mix. Table 12a–b lists the process output from corn grain, corn stover, and forest wood residue scenarios. Assumptions about heat and power production are presented in Table 13. Ethanol production process data for Cases 3, 6, and 7 were from Aspen Plus simulations and serve as GREET inputs. Criteria pollutant emissions from combustion units were estimated on the basis of EPA AP-42 emission factors and the National Emissions Inventory (EPA 1995; 1999).

3.11 VEHICLE OPERATION

Corn grain- and cellulosic-based fuel ethanol will be blended into E85, which is 85% ethanol and 15% reformulated gasoline (RFG) by volume. E85 is used to fuel flexible-fueled vehicles (FFVs), and RFG is used to fuel gasoline vehicles (GVs). We assumed that E85-powered FFVs could achieve the same fuel economy per gallon gasoline equivalent (gge) as gasoline-powered GVs do (Table 14). WTW results are presented in two base systems: a per-mile-driven-based system and a per-million-Btu-based system. In the per-mile-driven-based system, results of energy or emissions are expressed as Btu or gram per mile the vehicle traveled. This system emphasizes fuel demand and the effect of vehicle technology, assuming abundant fuel supply. Emission of criteria pollutants VOC, CO, PM_{10}, SO_x, and NO_x is a key issue to vehicle operation because of tail pipe emission regulations — therefore, it is expressed in the per-mile-driven-based system. The per-million-Btu-based system, on the other hand, emphasizes fuel supply, which implies fuel demand is not limiting. Energy and emission results are expressed in Btu or grams per million Btu of fuel produced and used. This base is more appropriate from a fuel supply perspective. In our WTW analysis, energy and GHGs results are presented on the basis of per-million Btu. With this unit, the effect of fuel economy is removed. Furthermore, we presented the fuel ethanol results as E100 or 100% fuel ethanol, which means only the attributes from the ethanol portion of E85 is accounted for.

TABLE 12a Process Outputs (Fuel, Chemicals, and Electricity) from Ethanol Plants: Corn Stover and Corn Grain at 2012 and 2030

Case	Ethanol Yield (gal/dt for cellulose; gal/bu for grain)	Electricity export (kWh/dt feed)
2012		
Case 2: Corn grain to ethanol	2.72 (dry mill); 2.62 (wet mill), mix: 85% dry mill and 15% wet mill	
Case 3: Corn stover to ethanol through BC conversion	90	215.5
2030		
Case 5: Corn grain to ethanol through conventional bioconversion[a]	2.85 (dry mill); 2.75 (wet mill); mix: 90% dry mill and 10% wet mill	
Case 6: Corn stover to ethanol through CBP and GTCC power	105	604.3

TABLE 12b Process Outputs (Fuel, Chemicals, and Electricity) from Ethanol Plants: Forest Wood Residue at 2030

Case	Fuel and Chemical Yield (gal/dt, unless specified)					Electricity export (kWh/dt feed)
	Ethanol	n-Propanol	n-Butanol	n-Pentanol	Methanol	
Case 7: Forest residues to mixed alcohols through BC/TC biorefinery	104	1.81	0.70	0.32	0.37	765.6

TABLE 13 Assumptions about Process Fuel Generation in Cellulosic Ethanol Plants

Process	Assumptions
Steam and power generation from corn stover-based BC plants in 2012	Small industrial boiler used for power generation from residue of corn stover; 180 Btu diesel/gal EtOH for equipment operation
Steam and power generation in corn stover-based CBP and GTCC in 2030	The RBAEF (The role of renewable biomass in America energy future) simulation results (Wu, Wu, and Wang 2005); 180 Btu diesel/gal EtOH for equipment operation
Steam and power generation in forest wood residue-based BC/TC refinery in 2030	NG of 3,539 Btu/gal to provide additional heat and power; NG utility industrial boiler (>100 × 10^6 Btu/h) used for syngas and NG power generation for TC plant. 337 Btu diesel/gal EtOH for equipment operation
Criteria pollutant emissions from BC process in 2012	GREET default values from EPA (1995; 1999)
Criteria pollutant emissions from corn stover-based ethanol plants in 2030	The RBAEF simulation results (Wu, Wu, and Wang 2005)
Criteria pollutants emissions from TC process for ethanol and chemical production	Based on NREL (2006) Aspen simulations and GREET default boiler emission factors (which were from AP-42 and NEI data). Emissions from TC process were very small (i.e., 10^{-7}g/gal ethanol) and therefore ignored.

TABLE 14 Gasoline-Equivalent On-Road Fuel Economy of Light-Duty Vehicles (MPgge)*

Year	Flexible Fuel Vehicles with E85	Gasoline Vehicles
2012	24.9	24.9
2030	26.6	26.6

* MPgge – mile per gallon gasoline equivalent

4 CO-PRODUCT CREDIT ALLOCATION

During ethanol production from cellulosic feedstocks, other products are generated for export with ethanol. Such co-products include electricity and chemical co-products (i.e., n-propanol, n-butanol, and n-pentanol). Methanol produced through a TC process from forest wood residue is consumed internally in ethanol plants; therefore, it is not treated as a co-product. The surplus electricity is sold to a grid, and chemicals are exported to the market. These products are credited for their energy and emissions by the energy allocation method.

The allocation method is based on the shares of output product energy. For each fuel production case, total energy and emissions of the bioethanol and co-products were first estimated. Then, their energy shares were determined on the basis of product yields and energy content. Finally, the total energy and emissions from the fuel production process and upstream feedstock activities were allocated to bioethanol and co-products (chemicals and bio-electricity) by multiplying the total energy and emissions by their energy shares. The energy partitioning results serve as GREET inputs.

This energy allocation approach tends to be conservative in determining energy and emission credits for electricity. This approach treats all energy products from the production process as equal, regardless of the form and quality differences among energy products. We recognize the complexity of this issue. Until additional production data of the displaced chemical products (i.e., petroleum-based n-propanol, n-butanol, and n-pentanol) become available and resources allow the consideration of other methods (such as the displacement method), the allocation approach serves as a good approximation. Output energy shares (as percentages) for each production option are shown in Table 15. For a plant producing corn ethanol, the displacement method is used to address energy credits of animal feeds from such plants.

TABLE 15 Energy Allocation for Ethanol, Electricity, and Chemicals

	Output Energy Share (%)		
Case	Ethanol	Electricity	Chemicals
Case 3: Corn stover to ethanol through BC conversion	91.20	8.80	0
Case 6: Corn stover to ethanol through CBP and GTCC	79.6	20.4	0
Case 7: Forest residues to mixed alcohols through BC/TC biorefinery	91.45	5.42	3.13%

5 RESULTS AND DISCUSSION

5.1 PETROLEUM ENERGY USE

Biofuel options offer substantial oil savings. All of the three feedstocks (corn grain, corn stover, and forest wood residue) can avoid more than 90% of petroleum use. On a fuel-life-cycle (or WTW) basis, for each million Btu of ethanol produced and used in light-duty vehicles, corn stover-derived ethanol reduces petroleum use by 94–95%, and corn grain ethanol reduces petroleum use by 92%, relative to gasoline (Figure 5). Petroleum energy used in the ethanol fuel cycle is entirely from upstream fuel production process or the well-to-pump (WTP) stage. Fuel use in the pump-to-wheels (PTW) stage — where fuel combustion during vehicle operation takes place — is 100% petroleum for gasoline, in contrast to that for ethanol, which is zero. Slightly higher oil use by ethanol derived from forest wood residue is primarily the result of high collection energy use, where diesel equipment was used for wood stumpage, harvesting, and transportation.

5.2 FOSSIL ENERGY USE

This study shows, for each Btu of fuel produced and used in light-duty vehicles, 1.22 Btu of fossil energy is required with gasoline, 0.76 Btu with corn ethanol, 0.16 Btu with ethanol from wood residue, and 0.09 Btu with ethanol from corn stover (Figure 8). Despite the across-the-board reductions in fossil energy use relative to gasoline by ethanol from all three feedstocks (Figure 6), differences among the three ethanol options remain large. Corn ethanol achieves a moderate reduction of 38% (2012), while stover ethanol could reduce fossil fuel use by an additional 53% (2012, Figure 6). The gap between the two options is attributable to coal and NG use (Figure 7) in fuel production and corn grain ethanol farming steps (Figure 8b). The conventional corn grain ethanol plant receives its process heat and power from NG and coal. Without taking into consideration a co-product distilled dried grain solubles (DDGS) credit, the fossil fuels used for ethanol production could be 75% of fossil energy use in the life cycle of corn ethanol. A DDGS credit brings net fossil energy use in ethanol plant down to 57% (Figure 8b). In contrast, cellulosic ethanol plant is self-sufficient in heat and power supply in that lignin residue from stover is burned to meet internal energy demands. In another words, bio-heat and bio-power displaces fossil-based process fuels. Moreover, cellulosic ethanol production allows surplus electricity production. As such, the ethanol plant becomes an exporter of net electricity. The average U.S. grid electricity is generated from a mix of coal (49–51%), NG (19–24%), and residue oil (2.7%), or a total of 78% fossil energy. Using bio-power in place of U.S. mixed electricity implies at least 78% of fossil fuel can be avoided for each kilowatt-hour of bio-electricity generated. Fossil energy savings could even be greater if the bio-power is to displace power generated from coal-based power plants.

Nitrogen fertilizer use is another factor that is partially responsible for the fossil energy gap. Nitrogen fertilizer is produced from NG feedstock, which accounts for 18% of total fossil use in the corn ethanol life cycle (Figure 8b). As indicated earlier, the baseline fertilizer use in corn fields is allocated to corn grains in the current study. Corn stover shares the burden of additional nitrogen fertilizers. Likewise, energy use in farming operations is allocated to corn grain ethanol, except that used for corn stover harvest and collection.

Among the bioethanol options, the distribution of fossil energy expenditures varies with feedstock and production processes examined (Figure 8). Corn stover-derived ethanol (Case 6) requires 28.7% fossil energy for farming operation (stover harvesting). Together with machinery (12.3%) and fertilizer production (25.7%), farming activities for corn stover ethanol option make up the majority of fossil energy use (67%). Fertilizer-related fossil energy could rise once the stover is considered a crop rather than an agricultural residue (as we assumed in our analysis). In that case, baseline fertilizer applied to a corn field (0.14 Btu/Btu of ethanol) will be allocated between corn grain and corn stover. Consequently, fossil energy use for stover ethanol would increase and that for corn grain would decrease. As an example, with a 50/50 split of the fossil energy spent on baseline fertilizer production to be allocated between corn and stover, the WTW fossil energy use associated with corn grain ethanol could be reduced by 9% to 0.69 Btu/Btu of ethanol, while the WTW fossil energy use associated with stover ethanol could increase by 78%, to 0.16 Btu/Btu of ethanol (which is still small).

Corn ethanol (Case 5) consumes over one-half of the WTW fossil energy at the ethanol plant (57%), followed by fertilizer use (18%). Efforts are under way by the EPA to expand CHP-based ethanol plants to improve their energy efficiency. Biomass and co-product DDGS combustion to produce heat and power for ethanol plants is also being investigated. Together, these new efforts can lead to the displacement of NG and/or coal as process fuels in corn ethanol plants, resulting in decreases in fossil energy use by the corn ethanol fuel cycle.

In the forest wood residue option (Case 7), process fuel use in an ethanol production plant is the major step in fossil fuel use. For the TC/BC process, 30% of the total life-cycle fossil energy is expended on NG use. Farming (harvesting) ranked second in fossil fuel use (27%). Fuel use in harvesting varies with the wood types. Harvesting soft wood requires less fuel than harvesting hard wood, and so a change in the wood mix could have a strong impact on the life cycle of forest wood residue-based ethanol.

Whether the energy to manufacture farming machinery plays an important role in the life cycle of corn ethanol has been debated. This analysis includes the energy use associated with manufacturing farming machinery in the biofuel life cycle to understand the degree to which this step affects the life cycle of corn ethanol. As indicated in Figure 8b, the fossil energy use (0.01 Btu/Btu of ethanol) associated with farming machinery contributes to 1.5% of total fossil energy use in the life cycle of corn grain ethanol. The benefit of corn ethanol, in comparison with gasoline, changed by 0.8% in fossil energy and by 1% in GHGs (Figure 9) when machinery energy is considered. Therefore, the role of farming machinery is insignificant. However, for a fair comparison, machinery used by fuel production in both biofuel and gasoline refining should be accounted for. The current GREET model does not include machinery used for oil drilling and gasoline refining. Users can elect to include or not include farming machinery into their analysis.

5.3 GHG EMISSIONS

Cellulosic ethanol from corn stover and forest wood residue is able to avoid a significant amount of GHG emissions. Cellulosic ethanol produced from corn stover could avoid GHG emissions by 86–89% (Figure 10), and ethanol produced from forest residues in 2030 could reduce GHG emissions by 85%. Reductions of GHG in corn ethanol cases are moderate (21–24%). Accounting for lime applications and farming machinery in the assessment of the life cycle of corn ethanol causes an increase in GHG emissions of about 4% and 1%, respectively (Figure 9). Lime application increases CO_2 and therefore GHGs emissions because of its $CaCO_3$ chemistry. With one million Btu of fuel, gasoline emits 98 kg of GHGs from wells to wheels, while corn stover-derived ethanol emits only 14 kg of GHGs. GHG emissions here are CO_2-equivalent emissions of CO_2, N_2O, and CH_4, weighted with their global warming potentials (1, 296, and 23, respectively). WTW results for CO_2 emissions are presented in Figure 11. The trend for CO_2 is similar to that for GHGs. One million Btu of corn stover-based ethanol to displace one million Btu of gasoline could avoid 85 kg of CO_2. The CO_2 data are presented here to allow comparison with the results from some other studies, which only estimate CO_2 emissions. Apparently, ignoring N_2O and CH_4 emissions gives fuel ethanol some unwarranted additional benefits.

5.4 CRITERIA POLLUTANT EMISSIONS

The results of criteria pollutant emissions, expressed in grams of emissions per mile driven in FFV fueled with E85, are presented in Figures 12–16. These emissions are separated into total and urban emissions. Total emissions are the sum of the urban and rural emissions. Urban emissions have long been an environmental and health concern because the potential of exposing the human population to emissions in that setting is high.

In comparison with gasoline, ethanol can achieve net reductions in the urban criteria pollutant emissions of VOCs, CO, NO_x, PM_{10}, and SO_x. This phenomenon can be explained by the location of bio-ethanol plants. Corn and cellulosic ethanol plants are most likely to be built near farms to minimize feedstock transportation costs. Criteria pollutants emitted from the farming, feedstock transportation, and ethanol-production steps contribute to rural emissions only. In contrast, a number of petroleum refineries (up to 60%) are currently situated in or near urban areas, which results in a high urban share of emissions from petroleum refining. Most significant reductions occur with SO_x, where 60% of current SO_x emissions due to vehicles fueled with gasoline could be avoided (Figure 16). As a result, there is a shift in the emission of criteria pollutants from urban to rural areas with bio-based ethanol in the near term. While urban emissions of VOCs, CO, NO_x, PM_{10}, and SO_x decrease, total emissions (urban and rural) increase, which means there are increased emissions in the rural area. Because urban-area emissions are more of an environmental and health concern, this shift provides at least a positive step toward the reduction of regulated pollutants. Cellulosic ethanol derived from corn stover could achieve a net reduction of total VOCs, NO_x, PM_{10}, and SO_x emissions in 2030.

In the near-term scenario (2012), corn stover-derived ethanol emits slightly higher VOCs than does corn grain ethanol (Figure 12). This higher emission is caused by VOC emissions from the biomass boiler. In contrast, NG and coal-fired boilers used in corn grain ethanol plants have lower VOC emissions. Total VOC emissions from corn ethanol plants are further decreased by co-product credit. DDGS — a co-product produced in corn grain ethanol plants — claims VOC credit when it displaces soy protein as animal feed. The production of soy protein usually emits a large amount of VOCs. The effect of co-product VOCs from stover-derived ethanol became much smaller in the long-term scenario, in which a biorefinery with integrated GTCC heat and power is used for the production of corn stover ethanol.

From a fuel life cycle perspective, biorefinery production of fuel ethanol, stationary combustion technology, and tailpipe control are the major factors in avoiding NO_x and PM_{10} emissions. From 2012 to 2030, corn stover ethanol could reduce 0.4 g of NO_x — or 60% of total NO_x emissions — when a vehicle fueled by E85 is driven for one mile. Of the reduction, a biorefinery to displace the conventional BC/TC process and GTCC contributes to an improvement of 53%, and emission control contributes to an improvement of 7%. The trend for PM_{10} emissions follows closely that of NO_x emissions.

Corn-based ethanol shows increased emissions of criteria pollutants in both 2012 and 2030 relative to gasoline. The corn ethanol plants analyzed employ a conventional fermentation process that relies on coal and NG-fired combustion systems to supply heat and on grid electricity (U.S. mix) to supply power. Providing adequate heat and power could use more than 80% of the NG and coal demand in the entire corn ethanol fuel cycle. The heat and power supply is responsible for the emissions of major criteria pollutants: NO_x (from NG and coal), PM_{10} (from coal), and SO_x (from coal). Although technologies will be improved over time (as suggested in cellulosic ethanol scenarios), this study did not assume that the technology and process fuel for corn ethanol plants would change from 2012 to 2030. From the result charts for 2030, readers may mistakenly conclude that the results for corn-based ethanol cases are much worse than those for cellulosic ethanol cases. This conclusion could be drawn because different assumptions about production technology and scale were used for cellulosic ethanol for 2012 and 2030. In fact, criteria pollutant emissions associated with corn-based ethanol remain relatively constant between 2012 and 2030, while those of cellulosic ethanol are reduced significantly between 2012 and 2030.

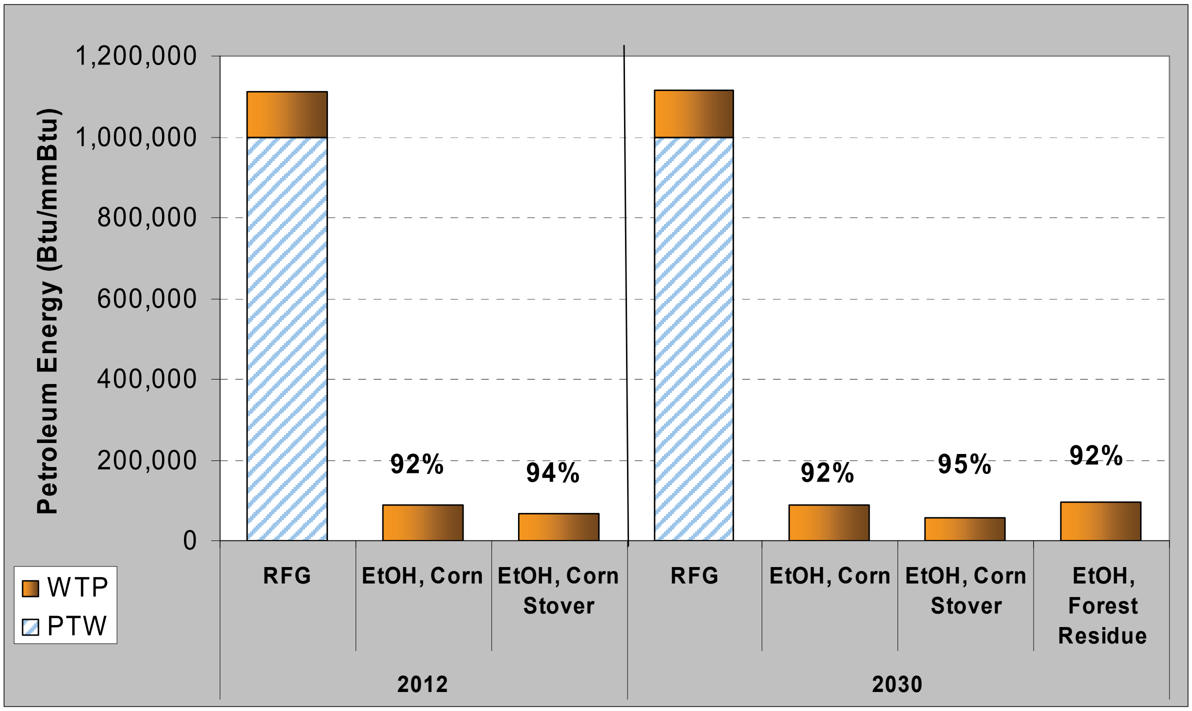


FIGURE 5 WTW Petroleum Energy Use by Different Bio-Ethanol Cases as E100, Compared with Gasoline in 2012 and 2030

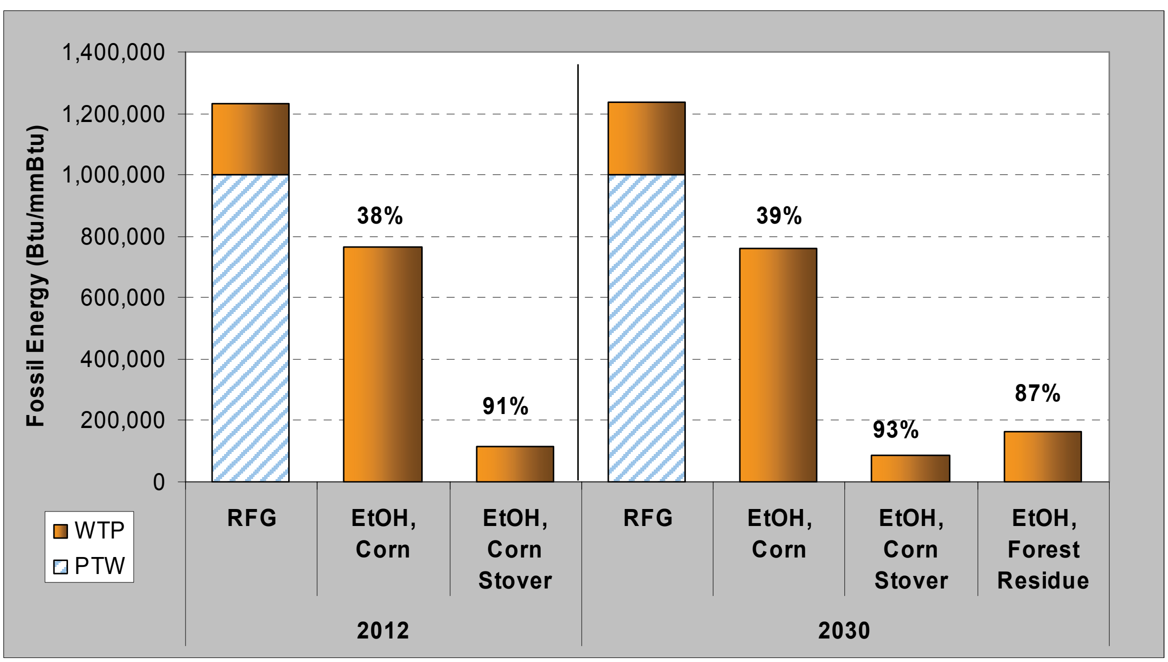


FIGURE 6 WTW Fossil Energy Use by Different Feedstocks and Well-to-Wheel (WTW) Fossil Reductions, Compared with Gasoline in 2012 and 2030

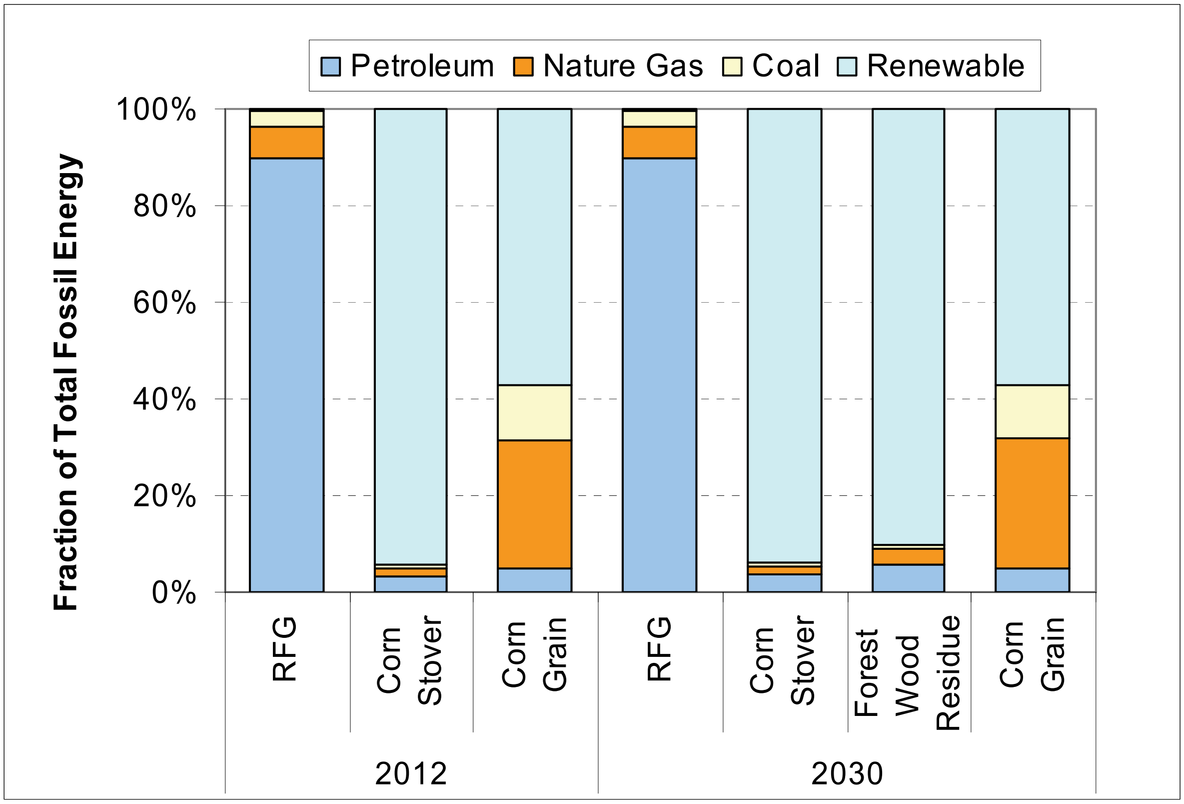
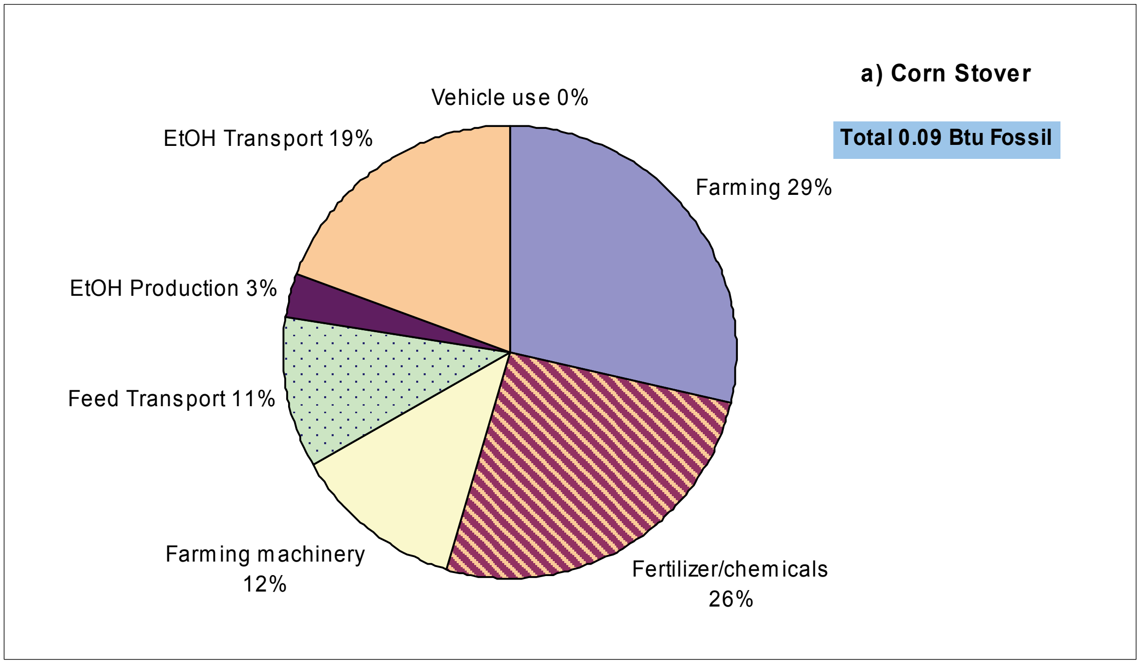


FIGURE 7 Types of Fossil Energy Used in Fuel Production and Utilization in WTW Cycle



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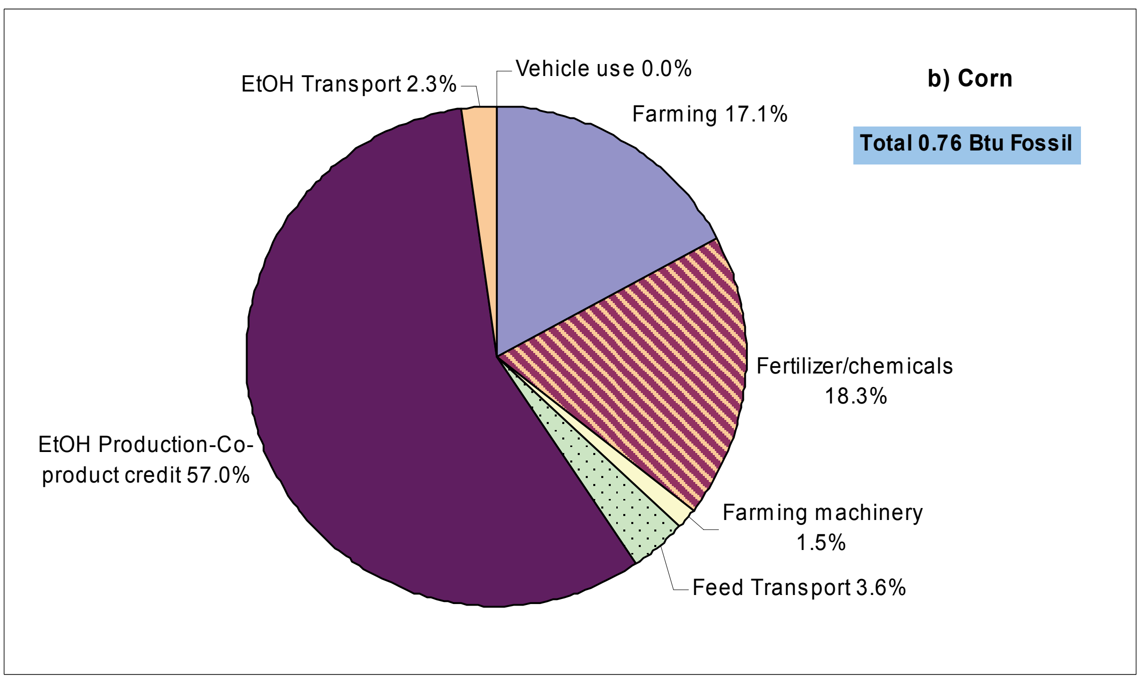

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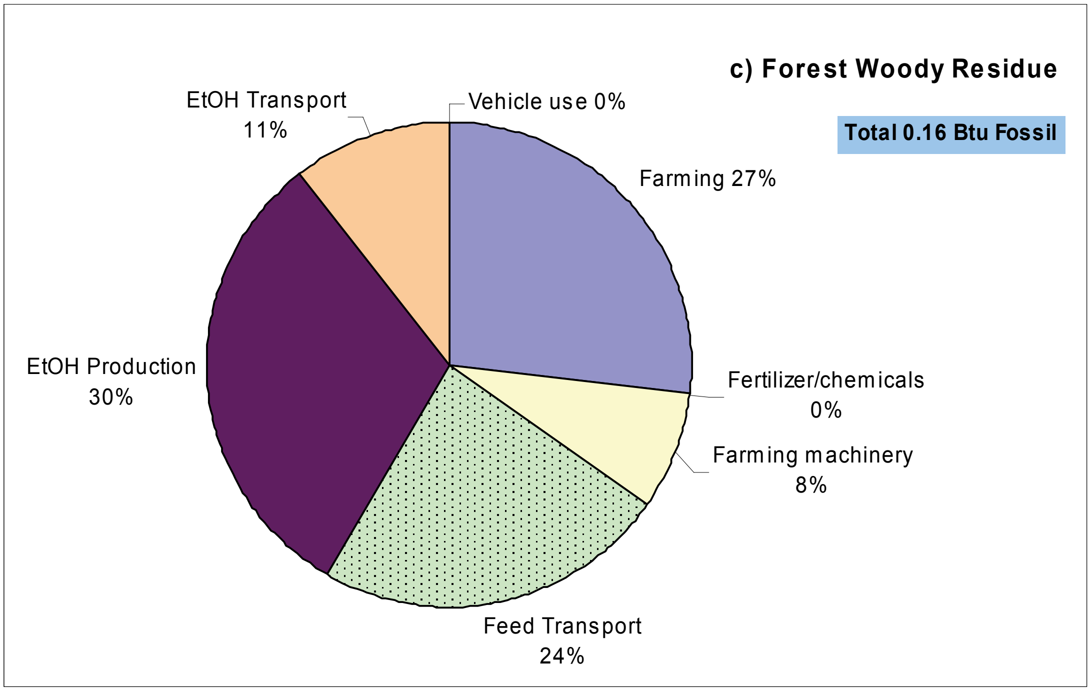
FIGURE 8 Breakdown of Fossil Energy Use in Various Stages of Fuel Life Cycle (2030) for (a) Corn Stover Ethanol, Case 6; (b) Corn Grain Ethanol, Case 5; (c) Wood Residue Ethanol, Case 7; (d) RFG, Case 4.



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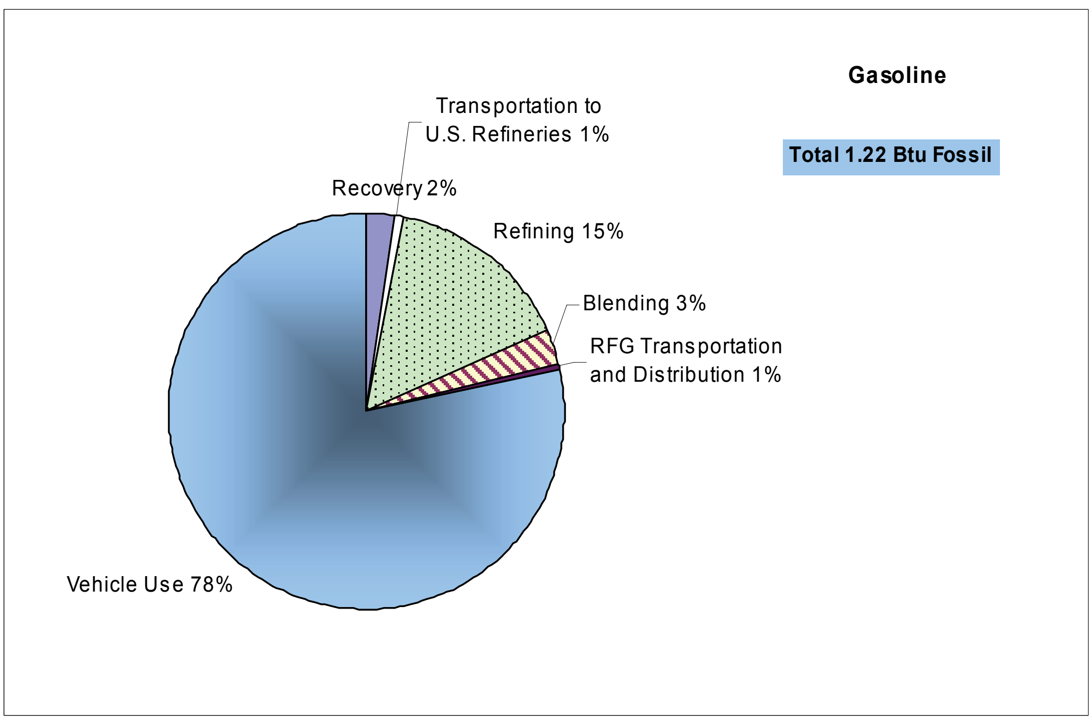

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FIGURE 8 (Cont.)

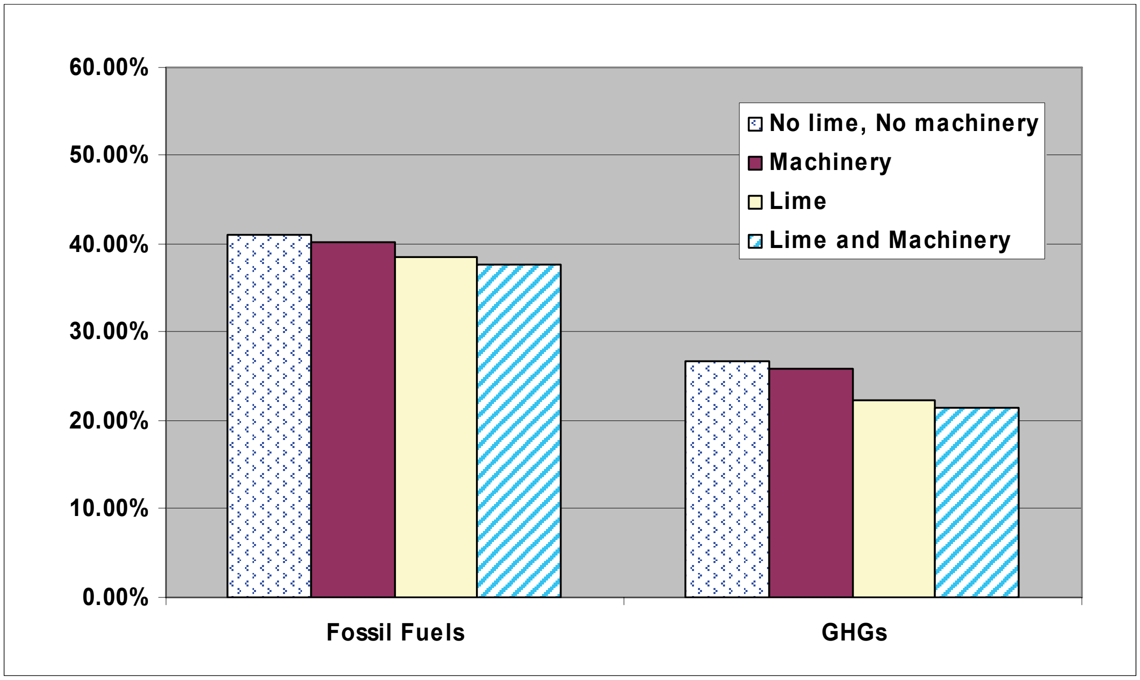


FIGURE 9 Contribution of Farming Machinery and Lime Application Steps to WTW Corn Ethanol Fossil Energy Use and GHG Emissions

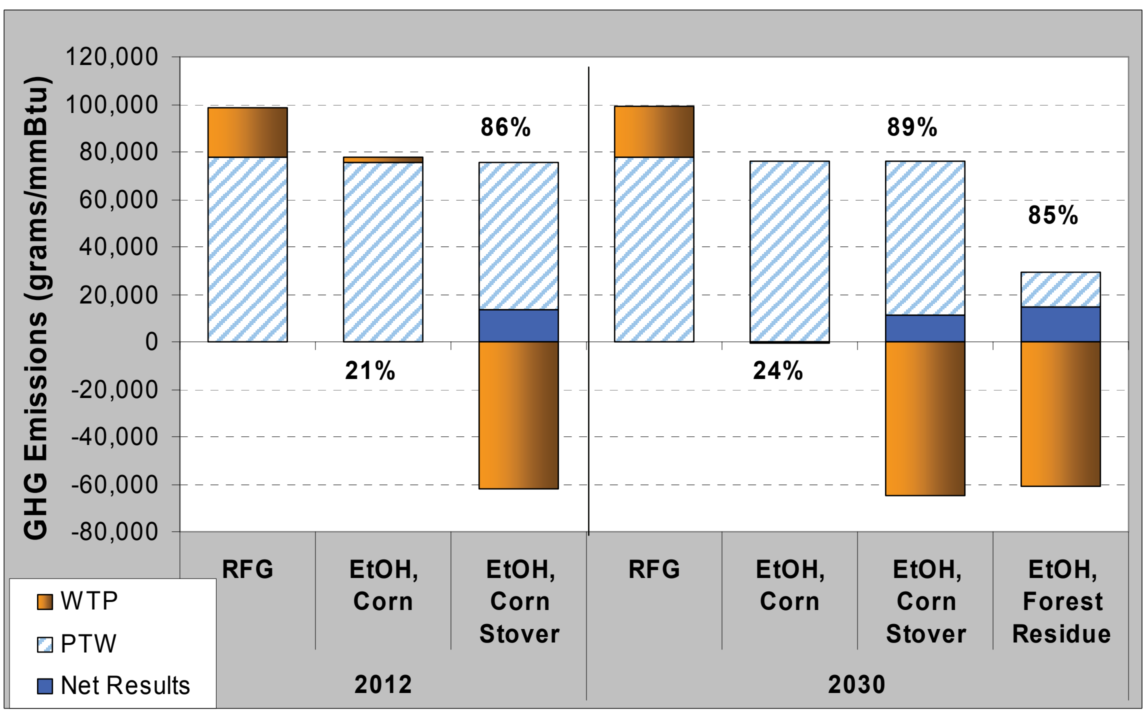


FIGURE 10 WTW GHG Emissions by Different Bio-Ethanol Cases as E100, Compared with Gasoline in 2012 and 2030. Net results here are the sum of WTP and PTW emissions. A positive value means net emissions, while a negative value means a net uptake.

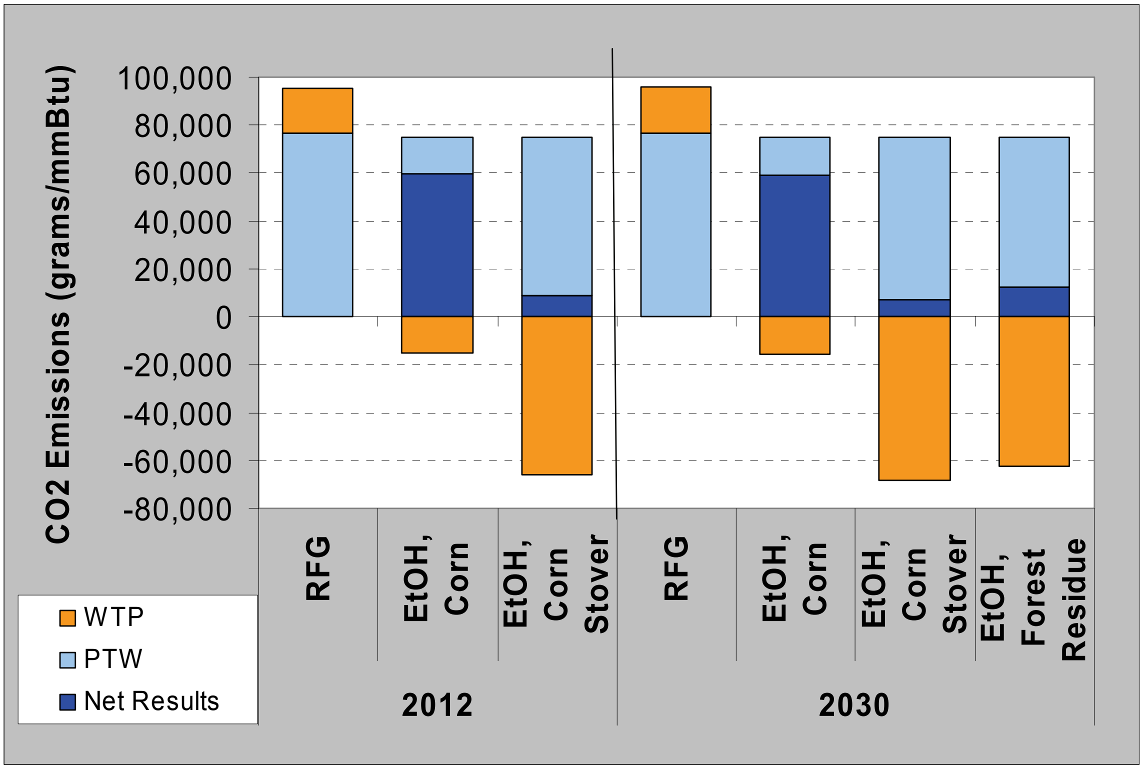


FIGURE 11 WTW CO_2 Emissions by Different Bio-Ethanol Cases as E100, Compared with Gasoline in 2012 and 2030. Net results denote the sum of WTP and PTW emissions. A positive value means net emissions, while a negative value means a net uptake.

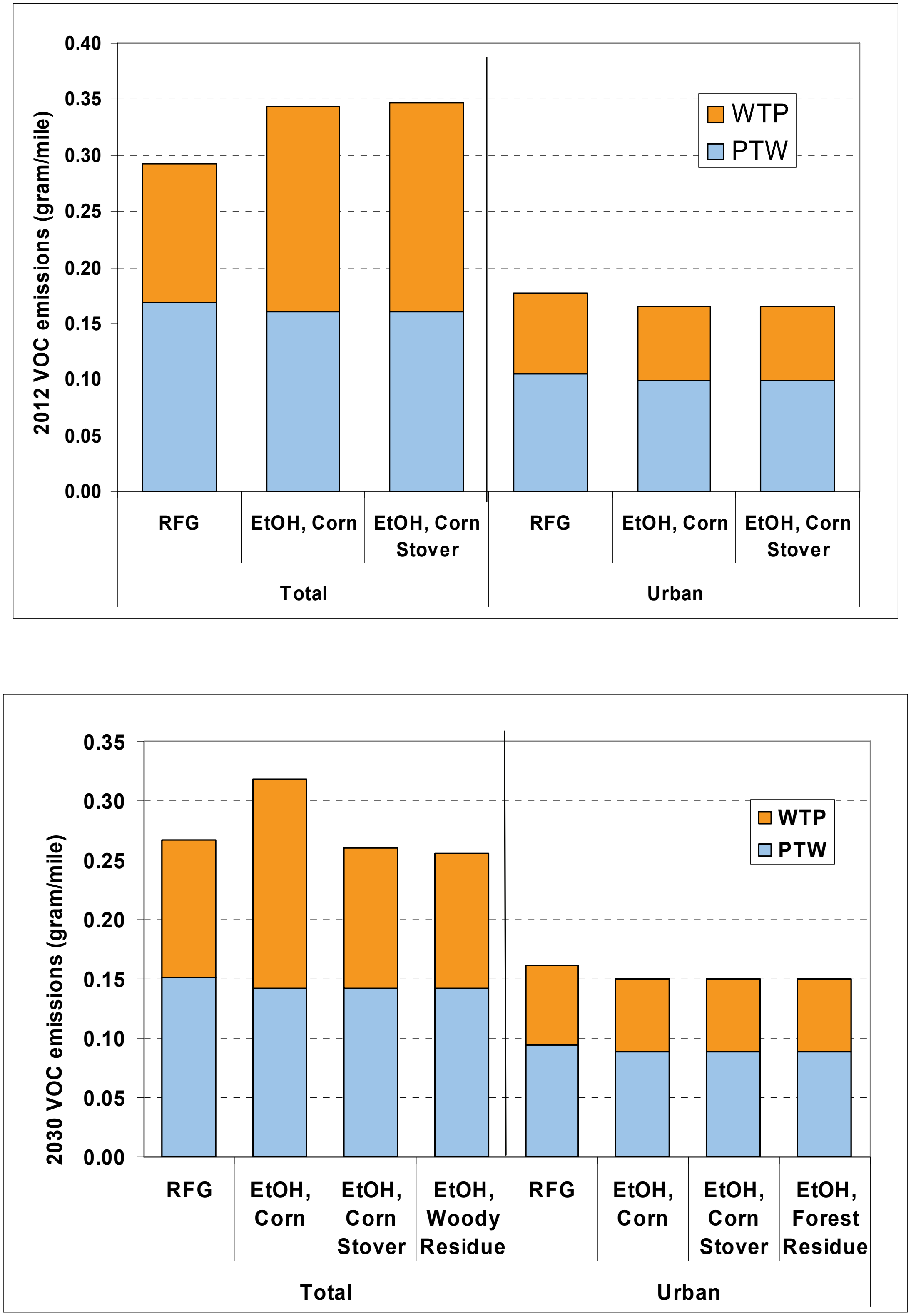
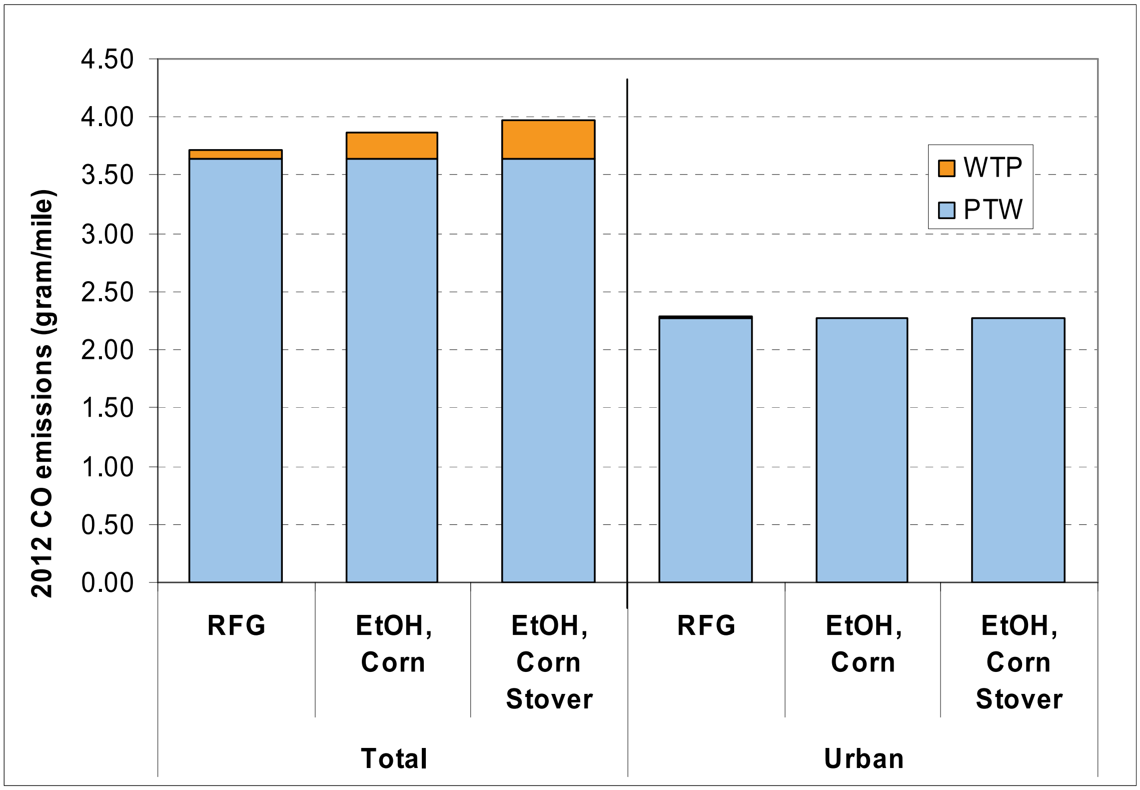


FIGURE 12 WTW Total and Urban VOC Emissions by Different Bio-Ethanol Cases as E85, Compared with Gasoline in 2012 and 2030



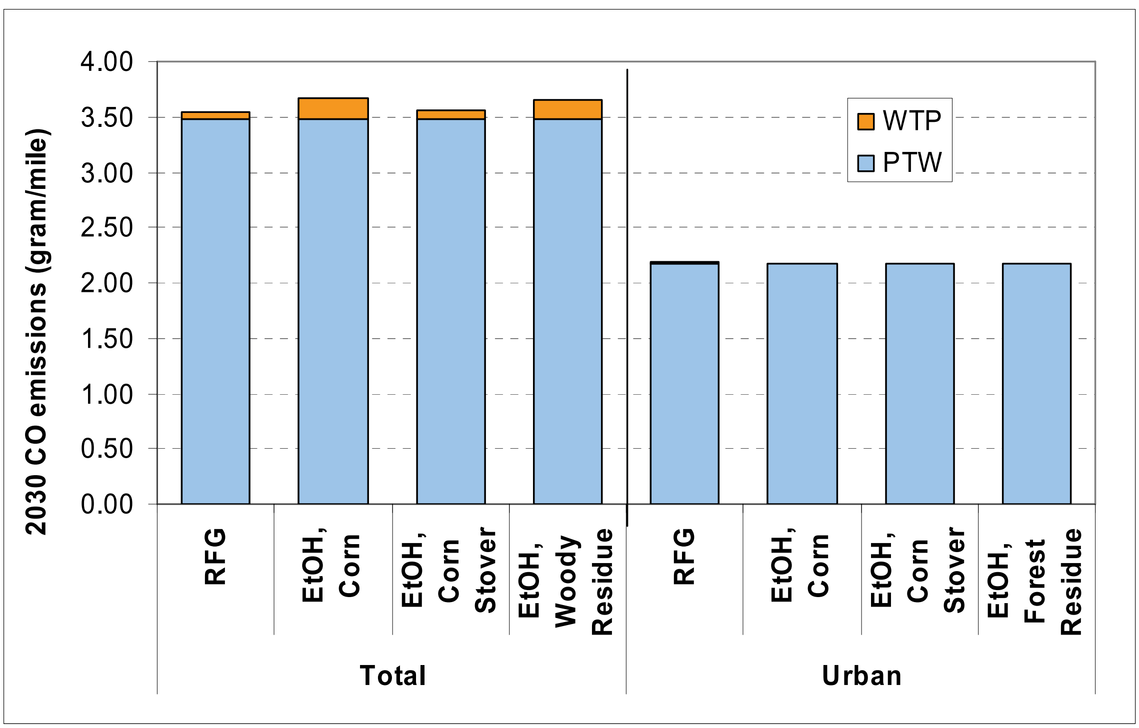
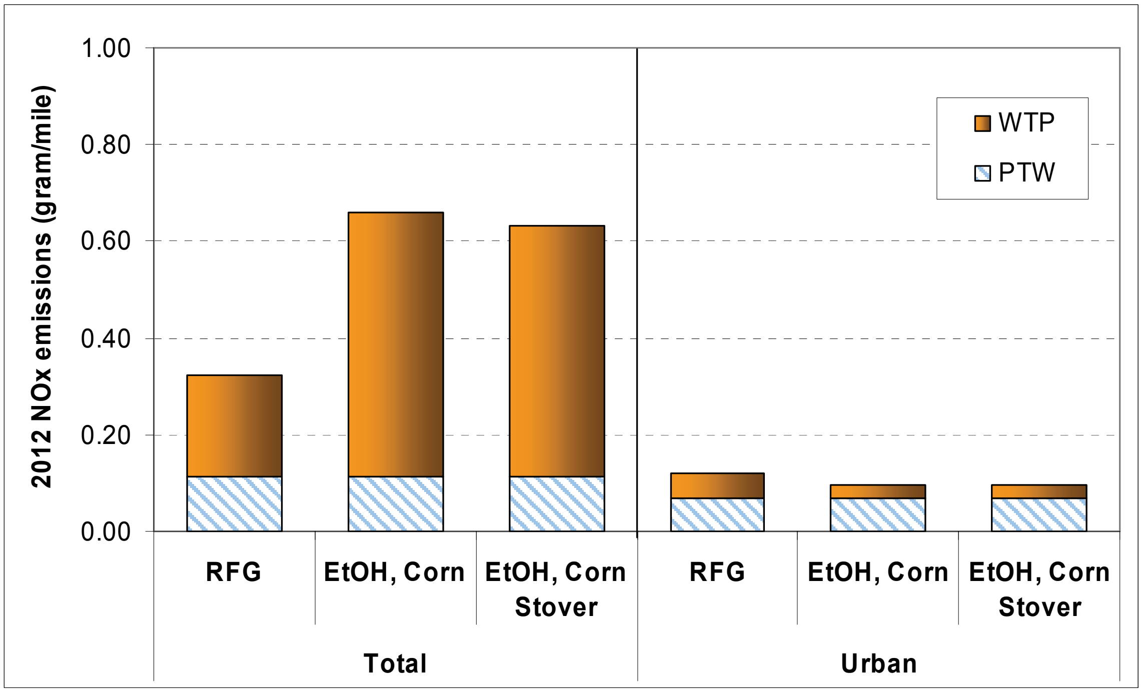


FIGURE 13 WTW Total and Urban CO Emissions by Different Bio-Ethanol Cases as E85, Compared with Gasoline in 2012 and 2030



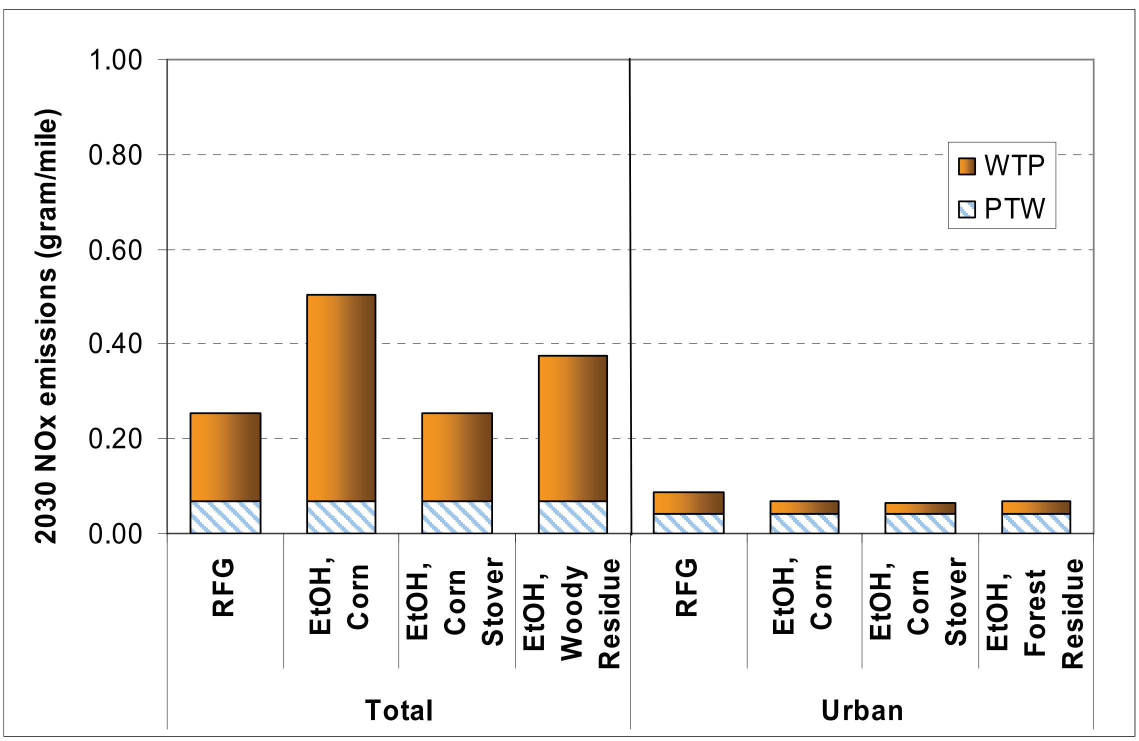


FIGURE 14 WTW Total and Urban NO_x Emissions by Different Bio-Ethanol Cases as E85, Compared with Gasoline in 2012 and 2030

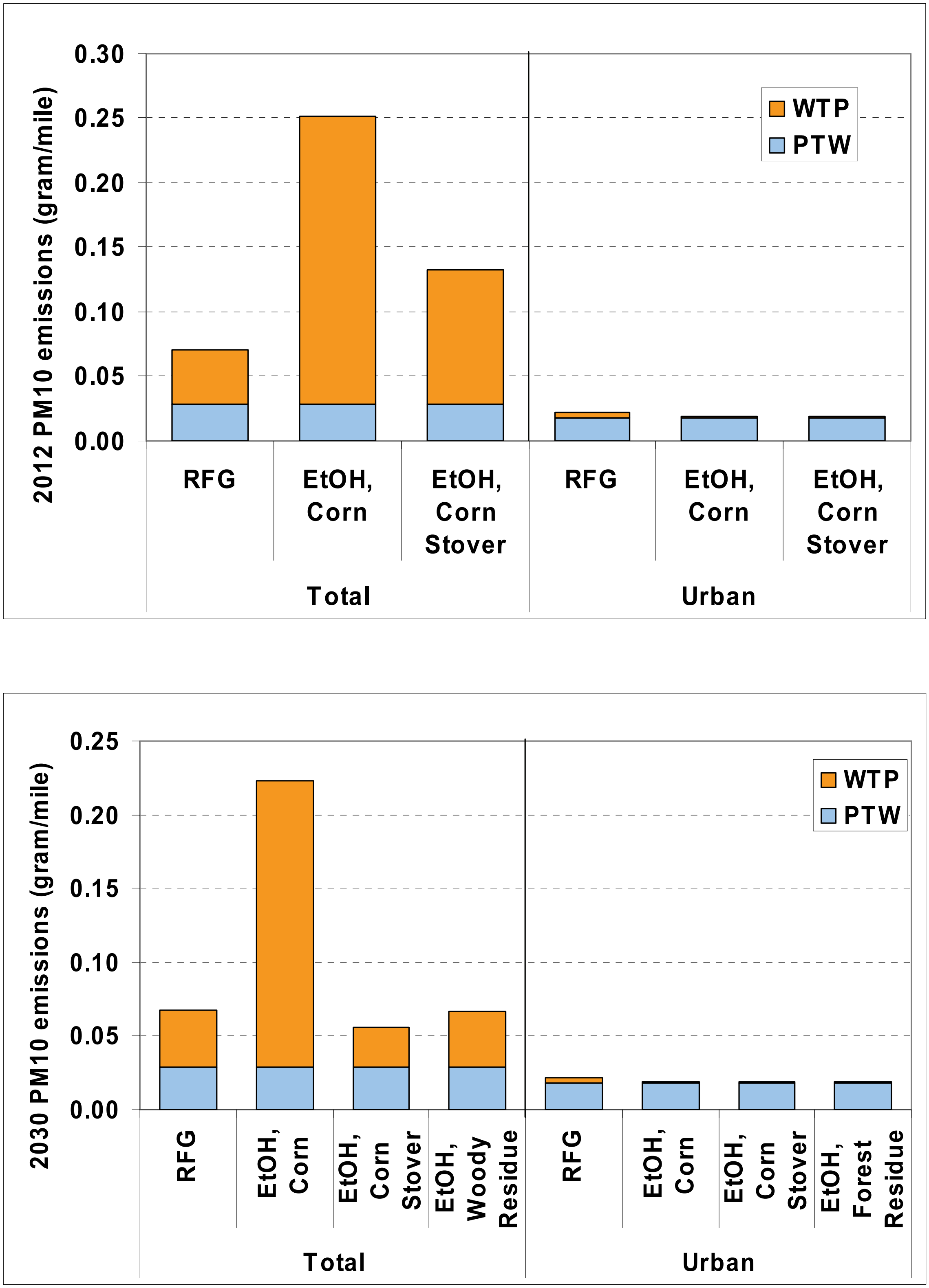
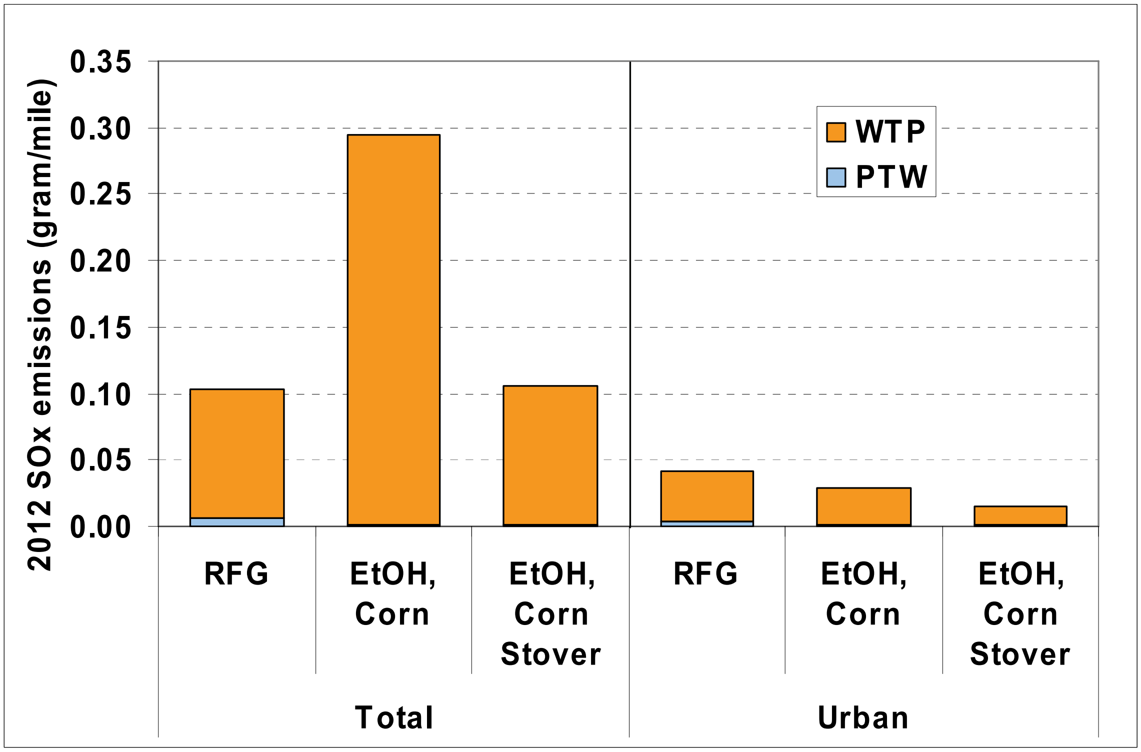


FIGURE 15 WTW Total and Urban PM_{10} Emissions by Different Bio-Ethanol Cases as E85, Compared with Gasoline in 2012 and 2030



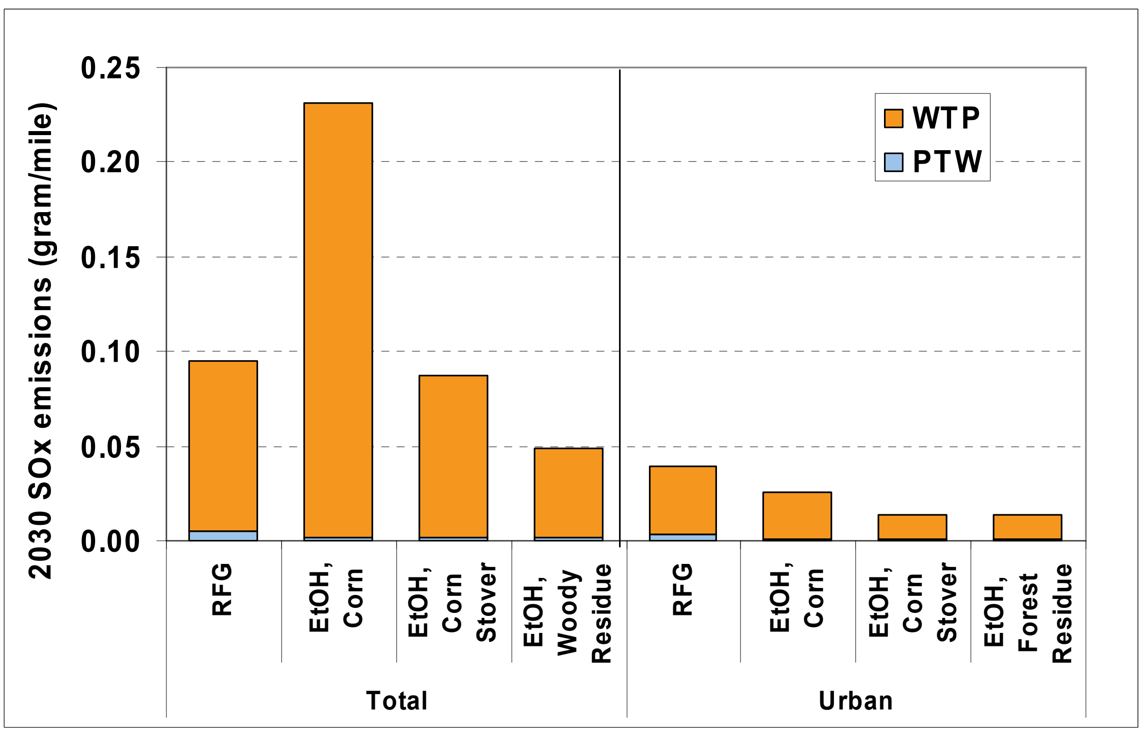


FIGURE 16 WTW Total and Urban SO_x Emissions by Different Bio-Ethanol Cases as E85, Compared with Gasoline in 2012 and 2030

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