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Mobility Chains Analysis of Technologies for Passenger Cars and Light-Duty Vehicles Fueled with Biofuels: Application of the GREET Model to the Role of Biomass in America's Energy Future (RBAEF) Project

Energy Systems Division

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Mobility Chains Analysis of Technologies for Passenger Cars and Light-Duty Vehicles Fueled with Biofuels: Application of the GREET Model to the Role of Biomass in America's Energy Future (RBAEF) Project

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NOTATION

ACRONYMS AND ABBREVIATIONS

AFEX	ammonia fiber explosion (a pretreatment process)
ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
C	carbon
CBP	consolidated bioprocessing
CH_4	methane
CIDI	compression-ignition direct-injection
CO	carbon monoxide
CO_2	carbon dioxide
DME	dimethyl ether
DOCEO	Department of Commerce and Economic Opportunity
DOE	U.S. Department of Energy
E100	100% ethanol
E85	mixture of 85% ethanol and 15% gasoline by volume
EPA	U.S. Environmental Protection Agency
EtOH	ethanol
FBC	fluidized bed combustion
FFV	flexible fuel vehicle
FTD	Fischer-Tropsch diesel
FTG	Fischer-Tropsch gasoline and Fischer-Tropsch naphtha upgraded to a gasoline-blending component
GE	General Electric
GHG	greenhouse gas
GREET	*G*reenhouse Gases, *R*egulated *E*missions, and *E*nergy Use in *T*ransportation
GTCC	gas turbine combined cycle
GTI	Gas Technology Institute
H_2	hydrogen
H_2S	hydrogen sulfide
HCHO	formaldehyde
HEV	hybrid electric vehicle
HLDT	heavy light-duty truck
HRSG	heat recovery steam generation

I/M	inspection and maintenance
ICE	internal combustion engine
K_2O	potash fertilizer
LDT	light-duty truck
LLDT	light light-duty truck
LSD	low-sulfur diesel
MeOH	methanol
MON	motor octane number
N	nitrogen
NG	natural gas
N_2O	nitrous oxide
NMOG	non-methane organic gas
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
OBD	on-board diagnostic
ORNL	Oak Ridge National Laboratory
P_2O_5	phosphate fertilizer
PFD	process flow diagram
PM	particulate matter
PM_{10}	particulate matter with diameters of 10 micrometers or less
PTW	pump-to-wheels
RBAEF	Role of Biomass in America's Energy Future
RD&D	research, development, and deployment
RFG	reformulated gasoline
RON	research octane number
SI	spark-ignition
SO_2	sulfur dioxide
SOC	soluble organic carbon
SO_x	sulfur oxides
SUV	sport utility vehicle
syngas	synthetic gas
T&BW	tire and brake wear
TCP	thermochemical plant
UCS	Union of Concerned Scientists
USDA	U.S. Department of Agriculture

VMT	vehicle miles traveled
VOC	volatile organic compound
WTP	well-to-pump
WTW	well-to-wheels
WWT	wastewater treatment

UNITS OF MEASURE

°F	degrees Farenheit
Btu	British thermal unit(s)
cm	centimeter(s)
dt	dry short ton(s)
g	gram(s)
gal	gallon(s)
h	hour(s)
kg	kilogram(s)
kWh	kilowatt hour(s)
mi	mile(s)
MJ	mega joule(s)
mmBtu	million Btu
mpg	mile(s) per gallon
mpgge	mile(s) per gallon gasoline equivalent
yr	year
Hz	hertz

ACKNOWLEDGMENTS

This work was sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. The report was prepared by Argonne National Laboratory to present the results of a study conducted for the Role of Biomass in America's Energy Future (RBAEF), a multi-institution, multi-sponsor research project. We would like to thank the following individuals for providing data and helpful comments for our analysis: Mr. Fuat Celik of Princeton University, Mr. Nathanael Greene of the Natural Resource Defense Council, Dr. Haiming Jin of Dartmouth College, Dr. Eric Larson of Princeton University, Dr. Mark Laser of Dartmouth College, Prof. Lee Lynd of Dartmouth College, Mr. Donald MacKenzie of the Union of Concerned Scientists, Mr. Jason Mark of the Union of Concerned Scientists, and Mr. John Sheehan of the National Renewable Energy Laboratory.

SUMMARY

S.1 INTRODUCTION

The Role of Biomass in America's Energy Future (RBAEF) is a multi-institution, multiple-sponsor research project. The primary focus of the project is to analyze and assess the potential of transportation fuels derived from cellulosic biomass in the years 2015 to 2030. For this project, researchers at Dartmouth College and Princeton University designed and simulated an advanced fermentation process to produce fuel ethanol/protein, a thermochemical process to produce Fischer-Tropsch diesel (FTD) and dimethyl ether (DME), and a combined heat and power plant to co-produce steam and electricity using the ASPEN Plus™ model. With support from the U.S. Department of Energy (DOE), Argonne National Laboratory (ANL) conducted, for the RBAEF project, a mobility chains or well-to-wheels (WTW) analysis using the *G*reenhouse gases, *R*egulated *E*missions, and *E*nergy use in *T*ransportation (GREET) model developed at ANL. The mobility chains analysis was intended to estimate the energy consumption and emissions associated with the use of different production biofuels in light-duty vehicle technologies.

S.2 STUDY METHODOLOGY

ANL conducted GREET modeling of six fuel production options, listed below. Three of the options produce bio-ethanol (bio-EtOH) only (options 1, 2, and 4), one (option 3) produces both bio-EtOH and bio-FTD, and the remaining two (options 5 and 6) produce either bio-DME or bio-FTD.

1. Bio-EtOH with cogeneration of power by means of gas turbine combined-cycle (GTCC) **(bio-EtOH/GTCC)**
2. Bio-EtOH with cogeneration of power by means of steam Rankine cycle **(bio-EtOH/Rankine)**
3. Bio-EtOH and bio-FTD with cogeneration of power by means of GTCC **(bio-EtOH/bio-FTD/GTCC)**
4. Bio-EtOH and protein with cogeneration of power by means of steam Rankine cycle **(bio-EtOH/protein/Rankine)**
5. Bio-DME with cogeneration of power by means of GTCC **(bio-DME/GTCC)**
6. Bio-FTD with cogeneration of power by means of GTCC **(bio-FTD/GTCC)**

ANL obtained energy and mass balance data for these biofuel production options from ASPEN Plus™ simulations conducted by researchers at Dartmouth College and Princeton University. By using the GREET model, ANL analyzed life-cycle energy use and emissions, including total energy use, fossil energy use, and petroleum use; greenhouse gas (GHG) emissions; and emissions of criteria pollutants, for biofuels produced by using the six production options. Conventional fuels — gasoline and diesel — served as the baseline. The mobility chains analysis estimates energy consumption and emissions for various vehicle/fuel combinations for each mile driven. The vehicle technologies and fuel combinations analyzed included spark-ignition (SI) vehicles fueled with reformulated gasoline (RFG) or a mixture of 85% ethanol and 15% gasoline by volume (E85); SI hybrid electric vehicles (HEVs) fueled with RFG or E85; compression-ignition, direct-injection (CIDI) vehicles fueled with low-sulfur diesel (LSD), DME, or FTD; and CIDI HEVs fueled with LSD, DME, or FTD. The fuel economy of these vehicle technologies, applied to passenger cars and light-duty trucks, was simulated by researchers from the Union of Concerned Scientists (UCS) for the RBAEF project. Tailpipe emissions of criteria pollutants resulting from vehicle operations were obtained by ANL from the U.S. Environmental Protection Agency's (EPA's) mobile source emission factor model (MOBILE6.2).

S.3 STUDY RESULTS

Our study revealed that biofuels offer substantial savings in petroleum and fossil energy consumption. By switching to cellulosic bio-EtOH E85, bio-FTD, or bio-DME in our passenger cars and light-duty trucks, drivers can potentially reduce the use of petroleum by 68% (bio-EtOH E85) to 93% (bio-FTD and bio-DME) and reduce the use of fossil energy by 65% (bio-EtOH E85) to 88% (bio-FTD and bio-DME) (on a per-mile basis). Without gasoline blending (i.e., with EtOH in E85), the fossil energy reduction increases to 89% and the petroleum reduction to 93% for ethanol.

For each million Btu of biofuel produced from switchgrass, at the fuel production (or well-to-pump [WTP]) level, bio-EtOH provides the greatest amount of fossil fuel displacement of the three biofuels. Bio-based ethanol, regardless of its feedstock and production process, reduces petroleum use by an equivalent amount for each mile driven or each gallon gasoline equivalent used. Bio-EtOH produced via the bio-EtOH/bio-FTD/GTCC option (option 3) appears to be the most favorable of the bio-EtOH production options. The bio-EtOH and bio-FTD co-produced via this option consume the smallest amount of petroleum and fossil energy and achieve the greatest reductions in GHGs and criteria pollutants when used with both conventional vehicle and HEV technologies, when compared to conventional gasoline and diesel.

From a multiple-production perspective, the results of our study reveal the significant impact of the different biofuel production options on overall energy and emissions displacement in the fuel, power, and chemical sectors. Energy consumption and emissions associated with the six production options were compared on the basis of their relative benefits in terms of displacing fuel, power, and chemicals. A dry ton of biomass feedstock could yield bio-EtOH (in million Btu) at more than twice the amount of bio-DME and more than one and a half times the amount of bio-FTD and bio-Fischer-Tropsch gasoline (bio-FTG) together. On a per-ton biomass input basis, the bio-EtOH/GTCC option (option 1) stands at the top of the production options studied, with solid performance in overall energy and emissions. The bio-EtOH/bio-FTD/GTCC option (option 3) yields the highest total amount of energy products, but offers smaller criteria pollutant reductions.

The major reductions in fossil energy consumption that result from using biofuels made from switchgrass are attributable to the renewable nature of the energy in biofuels. Additional savings come from the fuel production stage. Instead of using coal and natural gas as process fuels, the biological process analyzed in this study relies on biomass residuals and gaseous methane from sludge digestion in an on-site wastewater treatment plant for power and steam production. Decreased fossil fuel use translates directly to lower GHG emissions. Study results indicate that GHG reductions are 82–87% for all unblended cellulosic biofuels (on a per-gallon-gasoline-equivalent basis). Using bio-EtOH as E85, even when it is blended with gasoline, results in a 60–62% reduction in GHG emissions.

The single most significant change in criteria pollutant emissions that results from using fuels derived from cellulosic biomass occurs for sulfur oxides (SO_x). When fueled with bio-EtOH as E85, conventional and hybrid electric vehicles could reduce total SO_x emissions to 39–43% of those generated by vehicles fueled with gasoline (on a per-mile basis). For each unit of EtOH used in E85, the SO_x reduction is 53–59%. By using bio-FTD and bio-DME in place of diesel, total SO_x emissions are reduced to 46-58% of those generated by diesel-fueled vehicles (on a per-mile basis). These benefits likely result from (1) a change of feedstock, and (2) a switch to biomass-based power and heat generation (from the average U.S. electricity mix) to fuel the production process.

This study strongly suggests that GTCC is a crucial factor in the energy and emission benefits associated with biofuel production. Results from this study show that the NO_x emissions from bio-EtOH production could be much less than expected. The advanced GTCC minimizes NO_x emissions by 9- to 34-fold through its excellent low-NO_x/low-PM_{10} gas turbine combustion technology. Additional NO_x reductions are also possible through decreased use of nitrogen fertilizer in growing switchgrass relative to growing corn. Bio-EtOH produced via the bio-EtOH/GTCC and bio-EtOH/bio-FTD/GTCC options (options 1 and 3) lead to a total NO_x increase of 36% (bio-EtOH/GTCC) and 27% (bio-EtOH/bio-FTD/GTCC) relative to gasoline (as E85, on a per-mile basis). This is a significant improvement when compared to the 107% increase in NO_x emissions that results from the bio-EtOH/Rankine option (option 2). Similarly, the two bio-EtOH production options that employ advanced GTCC reduce total PM_{10} emissions by 26–37% compared with gasoline (on a per-mile basis).

The limitation of the proposed options is an increase in total volatile organic compound (VOC) emissions for almost all options (per-mile, per-gallon-gasoline-equivalent, and per-ton results). One exception is the bio-EtOH/protein/Rankine option (option 4). In this case, organic carbon is extracted as a protein product instead of being burned to produce power and generate VOC emissions. The study results also reveal no improvement in total carbon monoxide (CO) emissions compared with gasoline or diesel on either a per-mile or a per-gallon-gasoline-equivalent basis, and even result in a net increase per ton of biomass feed.

1 INTRODUCTION

Research, development, and deployment (R&DD) efforts are being made to produce transportation fuels from cellulosic biomass feedstocks such as grass and fast-growing trees. The goals are to reduce the dependence of the U.S. transportation sector on petroleum fuel and to limit emissions of greenhouse gases (GHGs) and criteria pollutants from motor vehicles. Transportation fuels that could potentially be produced from various biomass feedstocks include ethanol (EtOH), Fischer-Tropsch diesel (FTD), dimethyl ether (DME), methanol (MeOH), and hydrogen (H_2). Ethanol produced from corn and sugarcanes through fermentation processes has been the main production option so far in the United States, Brazil, and some other countries. In addition, there has been a significant increase in biodiesel production from soybeans (in the United States) and rapeseeds (in Europe) in recent years (although the absolute production level of biodiesel is far less than that of ethanol). For cellulosic-biomass-based biofuel production, there is a heightened interest in advanced bioprocessing, resulting in exploration and application of new pretreatment and conversion technologies for the fermentation process. Thermochemical processes have also attracted increasing attention with their potentially high thermal efficiency and the flexibility they offer in producing different transportation fuels, such as DME, FTD, H_2, and MeOH. Another concept that has emerged recently is production of multiple fuels and other products through a biorefinery approach. This approach involves co-production of multiple products — biofuels, chemicals, proteins, steam, and electricity — to maximize the utility of the feedstock and improve the energy efficiencies and economics of the bio-products. A biorefinery complex could include biological processes, thermochemical processes, and steam and electricity generation.

The Role of Biomass in America's Energy Future (RBAEF) project is a multi- institution, multi-sponsor research project to analyze and assess the potential of transportation fuels derived from cellulosic biomass in the years 2015 to 2030. Participating institutions include Dartmouth College, Princeton University, Michigan State University, the National Renewable Energy Laboratory (NREL), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and the Union of Concerned Scientists (UCS).

The goal of the RBAEF was to examine the potential of biofuel production and use by considering technological improvements that could be made with aggressive R&DD efforts. The project examined an advanced fuel ethanol process; a thermochemical process; and a combined heat and power plant to co-produce fuel, steam, electricity, and other fuels/products. The designs and simulations for the fuel production processes were completed by researchers at Dartmouth College and Princeton University. Researchers at both universities simulated the processes by using ASPEN Plus™ software. Vehicle technologies employing biofuels were analyzed by UCS researchers for the RBAEF project. ANL conducted a mobility chains (or well-to-wheels [WTW]) analysis — from feedstock production to vehicle operations — using the *G*reenhouse Gases, *R*egulated *E*missions, and *E*nergy Use in *T*ransportation (GREET) model, which was developed at ANL to estimate energy consumption and emissions associated with different fuel production options and light-duty vehicle technologies. Prior to this project, GREET contained energy and emissions data for bio-EtOH made from cellulosic biomass and corn. Through the RBAEF project, however, GREET was expanded to include bio-DME and bio-FTD made from cellulosic biomass. For the mobility chains analysis, ANL used energy and mass balance data for the fuel production options that were developed by Dartmouth and Princeton researchers. We also used future projections of vehicle fuel economy made by the UCS researchers for the RBAEF project.

By using GREET, ANL obtained WTW results in terms of total energy use, fossil energy use, petroleum use, GHG emissions, and emissions of criteria pollutants (including volatile organic compounds [VOCs], carbon monoxide [CO], oxides of nitrogen [NO_x], particulate matter with diameters of 10 micrometers or less [PM_{10}], and sulfur oxides [SO_x]) per mile driven by a given fuel/vehicle system. The study compared per-mile results for six biofuel technologies options with one another and with vehicle technologies fueled by gasoline and diesel. This report documents the methodologies, data, and results of ANL's mobility chains analysis for the RBAEF project.

2 GREET MODELING TIME FRAME, MODELING BOUNDARY, AND FUEL PRODUCTION OPTIONS

ANL conducted GREET modeling of six fuel production options, listed below. Three of the options (options 1, 2, and 4) produce bio-EtOH only; one (option 3) produces both bio-EtOH and bio-FTD; and the remaining two (options 5 and 6) produce either DME or FTD.

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4. Bio-EtOH and protein with cogeneration of power by means of steam Rankine cycle **(bio-EtOH/protein/Rankine)**
5. Bio-DME with cogeneration of power by means of GTCC **(bio-DME/GTCC)**
6. Bio-FTD with cogeneration of power by means of GTCC **(bio-FTD/GTCC)**

2.1 MODELING TIME FRAME

The production process design by Dartmouth and Princeton targets the period from 2015 to 2030. Technologies selected in the design by the two universities assume that R&DD hurdles will be overcome, allowing the technologies to reach maturation. Performance parameters were chosen, based on the most likely estimates by experts, to achieve optimal energy efficiencies and conversion yields and to control all emissions to meet U.S. Environmental Protection Agency (EPA) requirements.

2.2 MODELING BOUNDARY

Fuel pathways simulated in this study are divided into five stages: biomass farming; biomass feedstock transportation; fuel production; fuel product transportation, distribution, and storage; and fuel use in vehicles. Switchgrass was selected as the biomass feedstock for this study. Biomass is transported via trucks to the fuel production facility, where it undergoes biological or thermochemical processing for fuel production. The demand for heat and power (steam and electricity) from the biological and thermochemical plant is met with an integrated GTCC or a steam Rankine cycle power plant. Fuel products are then transported to refueling stations via pipelines, rails, barges, and trucks. Bio-DME and bio-FTD are used to fuel compression-ignition, direct-injection (CIDI) vehicles and hybrid electric vehicles (HEVs). Bio-EtOH is used as E85 (mixture of 85% ethanol and 15% gasoline by volume) to fuel flexible-fuel vehicles (FFVs) and HEVs. GREET modeling of fuel production from cellulosic biomass is based on ASPEN Plus™ process simulation results obtained by researchers at Dartmouth and Princeton. The GREET modeling boundary is depicted in Figure 1.

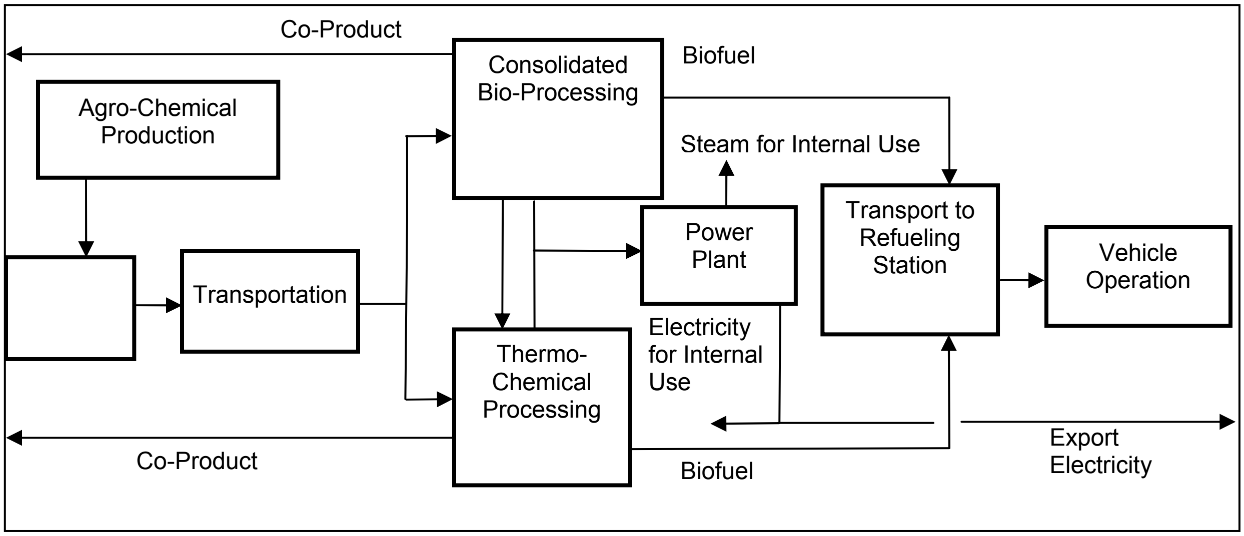

FIGURE 1 GREET Modeling Boundary for Biofuels Production from Cellulosic Biomass

2.3 FEEDSTOCK FARMING

Switchgrass is the herbaceous biomass feedstock employed for biofuel production in this study. Factors considered for the farming process include energy use during farming and biomass transportation, fertilizer and pesticide use (energy and emissions embedded in them), nitrous oxide (N_2O) emissions from farms, and carbon dioxide (CO_2) emissions/sequestrations that occur at the farms. The key GREET input data for switchgrass farming used in this study are summarized in Tables 1 through 4. Besides cellulosic ethanol, this study includes corn-based ethanol for comparison purposes. Farming energy and chemical use for growing corn (Table 1) were based on an ANL study (Wang et al. 2003) and a U.S. Department of Agriculture (USDA) survey (Shapouri et al. 2002). Farming and chemical use input data for switchgrass were derived

TABLE 1 Farming Energy, Fertilizer, and Pesticide Use

Category	Corn	Switchgrass
Farming energy use	Btu/bushel	Btu/dry ton
	22,500	217,230
Fertilizer use	g/bushel	g/dry ton
Nitrogen	460.0	10,635
Phosphate (P_2O_5)	165.0	142.0
Potash (K_2O)	205.0	226.0
Herbicide use	g/bushel	g/dry ton
	8.10	28.00
Insecticide use	g/bushel	g/dry ton
	0.68	0.00

from GREET default values (Wang 1999); these values were originally provided by M. Walsh of ORNL. The energy and emissions values for fertilizer manufacturing and transportation used in this study were obtained from Wang et al. (2003).

The subject of N_2O emissions that result from corn farming has been revisited since 1997 (Wang et al. 1997). Based on the results of a recent study, total N_2O emissions from corn farming, as a percentage of total nitrogen (N)-fertilizer, was assumed to be 2.0% for the GREET model (Wang et al. 2003). No extensive field studies have been conducted to quantify N_2O emissions resulting from switchgrass farming. Sources of N_2O emissions can be classified as direct and indirect. Direct emissions are those released to the air from soil by N-fertilizer and by microbial nitrification and denitrification in soil; indirect N_2O emissions come from N-fertilizer leaching as nitrate, then transforming to N_2O as a result of microbial nitrification and denitrification activities. For switchgrass, the amount of N-fertilizer runoff is lower than that for corn because of the long perennial root systems of switchgrass. On the basis of these considerations, we assume that switchgrass N_2O emissions during farming are 75% of those associated with corn growing. Thus, we used a value of 1.5% N-fertilizer application emitted as N_2O as our input to GREET (Table 2).

TABLE 2 N_2O Emissions as Percent of Nitrogen in Nitrogen Fertilizer

Corn	Switchgrass
2.0%	1.5%

TABLE 3 CO_2 Emissions or Sequestration from Land Use Changes

Corn (g/bushel)	Switchgrass (g/dt)
195	-48,500

Note: The positive value for corn represents CO_2 emissions from soil. The negative value for switchgrass means that carbon is sequestered in the soil during switchgrass growth.

TABLE 4 Switchgrass Transportation by Heavy-Duty Truck

Parameter	Value
Cargo payload (tons)	17
Fuel economy (mi/gal diesel)	5.0
Distance from farm to processing facility, round trip (mi)	100

The cultivation of switchgrass affects the CO_2 content in the soil. The improvement in soil carbon (C) content is significant when switchgrass is cultivated in cropland (McLaughlin et al. 2002). Ocumpaugh et al. (2002) reported that 5- and 10-year studies show that soil organic carbon increases at a rate of 30,000 and 22,000 kg per hectare per year (30 cm), respectively, under switchgrass cultivation. The same study also indicates significant improvement in active soluble organic carbon (SOC), which is used as an indicator of changes in soil quality. Together with the amount of carbon contained in the harvested switchgrass and remaining root, these changes lead to a net CO_2 sequestration (Ocumpaugh et al. 2002; McLaughlin et al. 2002; Andress 2002). In a study conducted by Andress in 2002, soil carbon changes resulting from switchgrass cultivation were estimated by using ORNL's Switchgrass Model V.1.1. Assuming that 39% of switchgrass is cultivated on cropland and the remainder is cultivated on pastureland and other sources, we estimated equilibrium soil carbon sequestration (per unit of biomass) at 48,800 grams (g) of CO_2 per dry ton (dt) of switchgrass. We used a value of 48,500 g CO_2/dt switchgrass as GREET input for this study (Table 3).

For the transportation distance from farm field to fuel processing plant, we assumed that the fuel processing plant would be located in an area surrounded by switchgrass farms. For a 5,000-dt/day biofuel plant (as assumed in the RBAEF project), we assumed that switchgrass covers 7% of the land area within a 50-mi radius when the yield is 5 dt/acre/yr (Greene et al. 2004a). Thus an average transportation distance of 100 mi (round trip) was used as GREET input (Table 4). The biomass harvested was assumed to be transported from farms to fuel production plants by means of Class 8b heavy-duty trucks with a payload of 17 tons and a fuel economy of 5.0 miles per gallon (mpg) diesel.

Table 5 lists the chemical and physical properties of the switchgrass used in this study. The characteristics of switchgrass feedstocks were provided by researchers at Dartmouth College and Princeton University.

TABLE 5 Chemical and Physical Properties of Switchgrass in this Study[a]

Proximate Analysis[b]	
Fixed carbon (wt%)	17.1
Volatile matter (wt%)	58.4
Ash (wt%)	4.6
Moisture content (wt%)	20.0
Lower heating value (MJ/kg)	13.5
Ultimate Analysis[c] (dry basis)	
Carbon (wt%)	47.0
Hydrogen (wt%)	5.3
Oxygen (wt%)	41.4
Nitrogen (wt%)	0.5
Sulfur (wt%)	0.1
Ash (wt%)	5.7
Lower heating value (MJ/kg)	16.9

[a] From Larson, Celik, and Jin (2004).
[b] Proximate analysis = composition determination of moisture, volatile matter, fixed carbon, and ash, expressed as weight percent, by prescribed laboratory methods given in the *Annual Book of ASTM Standards*, part 26 (1977).
[c] Ultimate analysis = composition determination of the ash, carbon, hydrogen, nitrogen, oxygen, and sulfur, expressed as weight percent, by prescribed laboratory methods given in the *Annual Book of ASTM Standards*, part 26 (1977).

2.4 FUEL PRODUCTION PROCESS

One of the basic assumptions used in the RBAEF project is a fuel production plant with switchgrass input of 5,000 tons (4,536 metric tonnes) per day (dry basis). This assumption was determined by the RBAEF project team. The feedstock is processed in an advanced ethanol plant by means of ammonia fiber explosion (AFEX) pretreatment and consolidated bioprocessing (CBP), involving hydrolysis, fermentation, cellulase production, and separation to produce fuel ethanol. Wastewater from CBP is discharged into an on-site wastewater treatment (WWT) plant, where it undergoes anaerobic and aerobic fermentation. In the thermochemical plant (TCP), biomass feedstock undergoes gasification; syngas cleaning; fuel synthesis; and separation with a Gas Technology Institute (GTI) oxygen-blown gasifier, conventional gas cleaning and fuel synthesis technologies, and pressure swing adsorption.

Simplified process flow diagrams (PFDs) illustrating CBP and the TCP are provided in Figures 2, 3 and 4. Figure 2 shows CBP for production options 1, 2, and 4: bio-EtOH/GTCC, bio-EtOH/Rankine, and bio-EtOH/protein/Rankine. In Figure 3, the TCP is shown for production options 5 and 6: bio-DME/GTCC and bio-FTD/GTCC. Figure 4 provides the PFD associated with the multi-fuel production process (option 3): bio-EtOH/bio-FTD/GTCC.

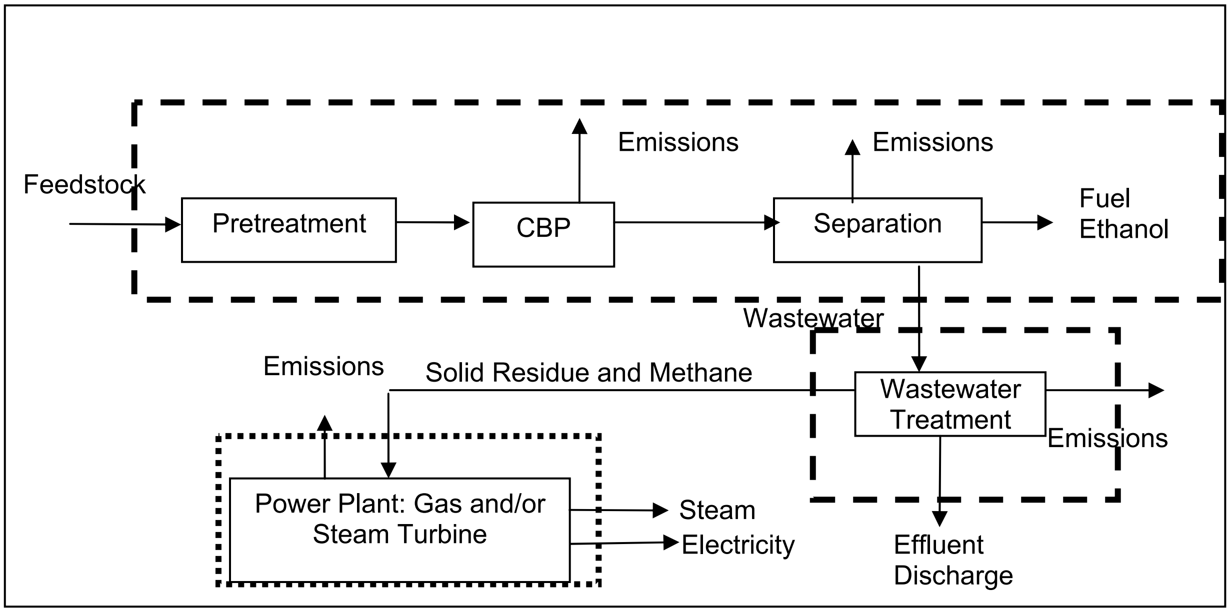

FIGURE 2 Simplified Process Flow Diagram of Ethanol Production through Biological Process with Heat and Electricity Cogeneration (dashed line — ethanol plant; dotted line — power plant)

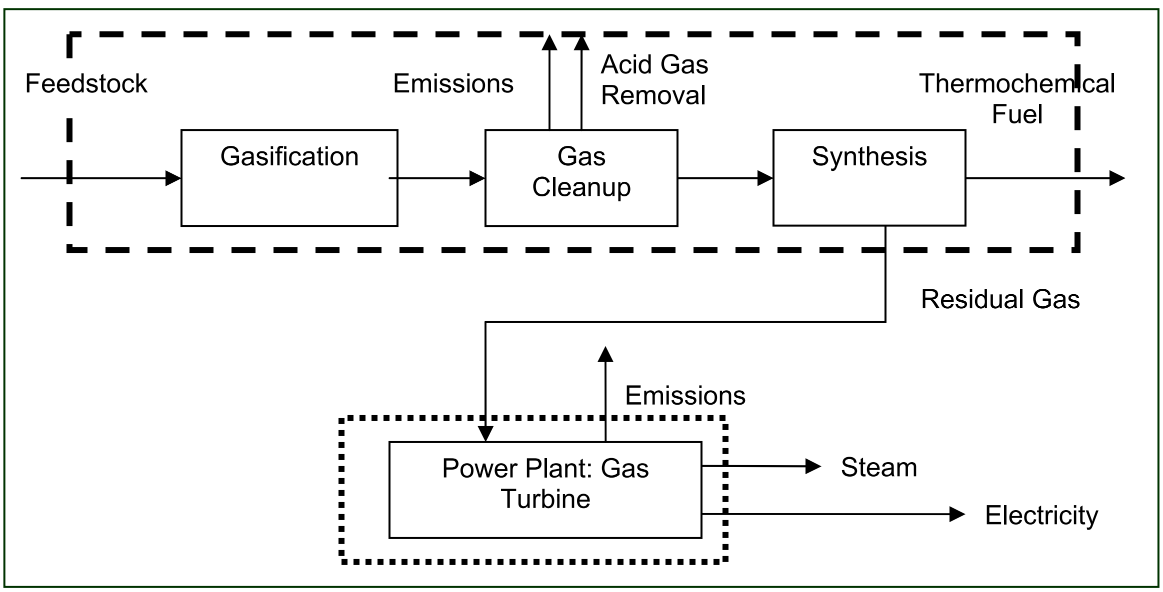

FIGURE 3 Simplified Process Flow Diagram for Thermochemical Production of FTD and DME with Heat and Electricity Cogeneration (dashed line — thermochemical plant; dotted line — power plant)

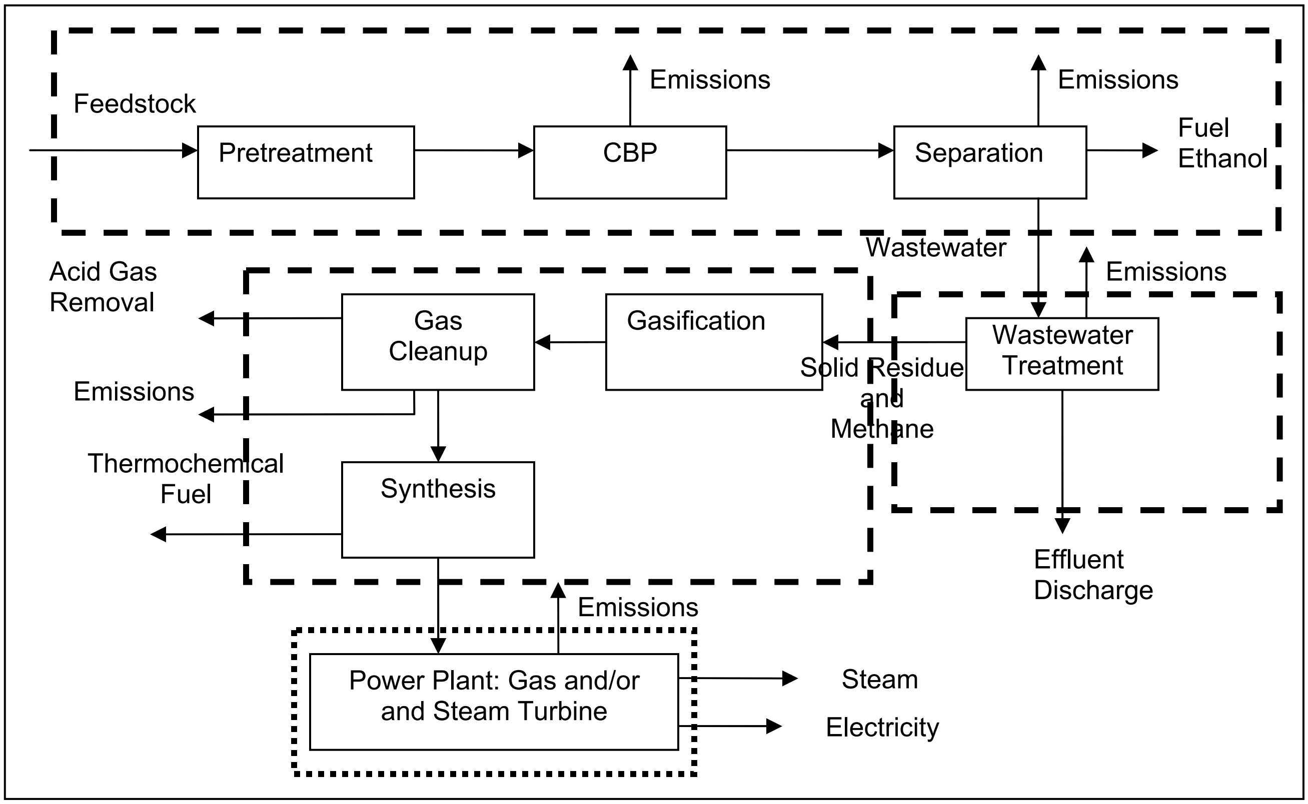

FIGURE 4 Simplified Process Flow Diagram of Multi-Fuel Production Option Bio-EtOH/Bio-FTD/GTCC (dashed line — ethanol and thermochemical plant; dotted line — power plant)

2.5 TEAM AND ELECTRICITY COGENERATION IN FUEL PLANTS

Demands for internal electricity and steam are met through cogeneration of steam and electricity at the power plant. For the ethanol production options, waste sludge is treated with high-rate anaerobic digestion followed by aerobic digestion. Methane gas resulting from waste treatment either proceeds to the TCP plant for additional fuel production or goes directly into the power plant. Waste solid residuals (sludge) from anaerobic digestion contain a large portion of lignin that is resistant to the biological hydrolysis and fermentation. These high carbon- and energy-containing residuals are processed in the power plant — providing fuel to the CBP and TCP and producing electricity for export. The power generation plant also receives tailgas from thermochemical fuel synthesis. Steam and electricity are provided by GTCC or a steam Rankine cycle. In GTCC, syngas is fed to a gas turbine to generate electricity. Exhaust gas from the turbine goes to a heat recovery steam generation (HRSG) unit to provide additional electricity and superheated steam for the gasifier. In the steam Rankine cycle, the sludge and syngas are fed to the boiler to generate electricity and steam. Extra electricity is sold to the grid. Electricity export is included in all ethanol production/co-production options. Detailed descriptions of the power production processes are presented in Larson, Celik, and Jin (2004).

2.6 ENERGY EFFICIENCY

Energy consumption during the thermochemical and biological processes for each fuel production option was calculated on the basis of mass and energy balance from ASPEN Plus™ simulations. The integrated GTCC used a new model of gas turbine (General Electric [GE] 7FB, 60 Hz) that represents the most advanced gas turbine technology at this production scale. We incorporated the gas turbine with 40% efficiency for this study.

2.7 EMISSIONS FROM PRODUCTION PROCESSES

Process emissions from combustion and non-combustion sources are estimated for each production option. Non-combustion emissions are generated primarily from biological process steps, including CBP, ethanol separation, wastewater treatment, and residual drying. There are three point sources of emissions in these steps: CO_2 released from the CO_2 scrubber after fermentation at the CBP; a gas mixture emitted to air from aerobic digestion at the WWT facility; and small amounts of organics emitted from the distillation step during ethanol separation.

The TCP and GTCC power plant generate combustion emissions. The emission sources are sulfur-containing acid gas from the Retisol unit that removes hydrogen sulfide (H_2S) from the fuel gas product and exhaust gas from HRSG. The gaseous H_2S is sent to the gas or steam turbine in the power plant, where it is converted to sulfur dioxide (SO_2).

Another source of combustion emissions is residual sludge processing in the power plant. During bio-EtOH production, sulfur-containing residual sludge from WWT is fed to the gas or steam turbine in the power plant. The resultant gas in the HRSG residual stream from the power plant contains CO_2, SO_2, and small amounts of other criteria pollutants.

The plant design assumes that nearly 100% of the carbon is converted to syngas by means of an oxygen-blown gasifier. The gas turbine selected for GTCC is GE model 7FB. GREET input for NO_x and PM_{10} emissions from GTCC were calculated from gas turbine manufacturer-specified information. For the Rankine cycle, we used NO_x and PM_{10} emissions data for the fluid-bed boilers from the GREET emissions database.

To determine total system emissions from fuel production, we added non-combustion and combustion emissions together. Emissions of VOCs, CO, SO_2, and methane (CH_4) from the biological process, thermochemical process, and power plant were summed to obtain total system emissions. Because N_2O is not available from ASPEN Plus™ simulations, its estimates for GTCC options were based on a GREET default emission value of 1.5 g/mmBtu of gas turbine input energy.

2.8 BIOFUEL PRODUCTION OPTIONS

The project aims at a fuel/power co-production, multi-fuel and multi-product biorefinery approach using both biological and thermochemical processes. Multiple fuels or chemicals are produced from the highly integrated processes. Bio-EtOH is the only fuel derived from CBP; fuels produced via TCP are bio-FTD and bio-DME. All fuel production pathways are integrated with heat and power co-production through GTCC or steam Rankine cycle. In the multi-fuel production option (option 3), bio-EtOH is co-produced with bio-FTD, with fermentation used for ethanol and gasification used for bio-FTD production. In the multi-product option (option 4), bio-EtOH is produced along with protein.

During bio-FTD production, significant amounts of FT naphtha and FT gasoline are generated. The ASPEN Plus™ program included a catalytic naphtha reforming unit that upgrades the low-octane naphtha into an octane-adequate gasoline blending component. As a result, the mixture of FT naphtha and FT gasoline, denoted as bio-FTG in all tables in this report, was assumed to have a research octane number (RON) (measure of the anti-knock quality of a gasoline, as determined by the American Society for Testing and Materials [ASTM] D 2699 method) of 95 and a motor octane number (MON) (measure of the anti-knock quality of a fuel as measured by the ASTM D 2700 method) of 85. The performance and cost for the reforming unit of the plant are based on an ASPEN Plus™ process simulation model of a biomass-based gasification, FT liquefaction, and combined-cycle power plant (Bechtel 1998). Table 6 lists the fuel production options simulated by ASPEN Plus™. Bio-FTG, produced from the bio-EtOH/bio-FTD/GTCC and bio-FTD/GTCC options (options 3 and 6), was not included in the GREET WTW per-mile, per-million Btu and per-gallon gasoline equivalent analysis because of uncertainties about the other fuel characteristics. Table 7 summarizes GREET input parameters for each production option. The biomass input, biofuel yield, electricity generation, and internal power consumption values are from ASPEN Plus™ simulations provided by Dartmouth College and Princeton University (see appendices).

TABLE 6 Fuel Production Options from Biological and Thermochemical Processes

Option	Power Export	Fuel Product	Co-Product (fuel)	Co-Product (others)
1. Bio-EtOH/GTCC	Yes	Ethanol	None	None
2. Bio-EtOH/Rankine	Yes	Ethanol	None	None
3. Bio-EtOH/bio-FTD/GTCC	Yes	Ethanol	FTD/FTG	None
4. Bio-EtOH/protein/Rankine	Yes	Ethanol	None	Protein
5. Bio-FTD/GTCC	Yes	FTD	FTG	None
6. Bio-DME/GTCC	Yes	DME	None	None

Notes:

- Although FTG may be upgraded to a gasoline blending component, it is not included in the WTW analysis.
- FT naphtha, which was produced from the FTD process, cannot be used as a transportation fuel at present.

TABLE 7 Biofuel Production Process ASPEN Plus™ Outputs Used to Determine GREET Inputs

	Fuel Yield (gal/h)					
Options	Bio-EtOH	Bio-FTD	Bio-DME	Bio-FTG	Protein (kg/h)	Power Export (MW)
1. Bio-EtOH/GTCC	21,952					125.9
2. Bio-EtOH/Rankine	21,952					66.0
3. Bio-EtOH/bio-FTD/GTCC	21,952	2,395		1,610		11.4
4. Bio-EtOH/protein/Rankine	21,952				15,111	3.5
5. Bio-FTD/GTCC		5,222		3,513		206.6
6. Bio-DME/GTCC			10,766			269.6

Notes:
- Biomass feedstock input is 5,000 dt/day.
- Data are from Dartmouth College and Princeton University (see appendices)

3 METHODOLOGY FOR GREET MODELING

3.1 CO-PRODUCT/BY-PRODUCT CREDIT PARTITION

The ANL analysis employed two methods for co-product and by-product credit partition: displacement and allocation. We conducted our analysis on the basis of these two methods and obtained four sets of energy and emission results: per-mile, per-mmBtu, and per-gallon-gasoline-equivalent for the allocation method and per-ton of biomass feed for the displacement method. The major product (besides fuel) in most production options is electricity generated during fuel production and subsequently exported. Electricity is produced with residual biomass and syngas through GTCC or steam Rankine cycle. After satisfying the process demand, extra power is exported to the grid. There is no steam export.

In previous studies, the small amount of electricity exported was treated as a by-product and was assumed to displace electricity purchased from the grid, which is generated from different sources (i.e., the U.S. generation mix). In this study, a thermochemical process is used to produce bio-FTD and bio-DME, while a biological process is used for bio-EtOH production. Syngas residue from the thermochemical process is used to produce power. As a result, a large amount of electricity is generated, the energy value of which is almost identical to that of the fuel product. In another words, electricity is no longer a by-product, but a major energy co-product. Thermochemical fuel production options co-produce both fuel and electricity. For fuel production evaluation purposes, we elected to consider electricity export as a major co-product and treated it by using the energy allocation method in our per-mile, per-million Btu, and per gallon-gasoline-equivalent analysis. In this method, the energy contents of the energy products and their shares were first determined for exported electricity and fuels, including bio-EtOH, bio-FTD, bio-DME, and bio-FTG. Total energy and emissions were then allocated to each of these according to their output energy share. The energy partitioning results serve as GREET inputs. To calculate the displacement benefit of each ton of biomass feed, we analyzed and compared the six production options using the displacement method (see Section 3.3). Table 8 lists the output energy shares (as percentages) for each production option; the energy shares were calculated from ASPEN Plus™ simulations (Table 7). A comparison of WTW results using the allocation versus the displacement method for bio-EtOH/GTCC and bio-EtOH/Rankine is provided in the appendices.

3.2 VEHICLE FUEL ECONOMY AND TAILPIPE EMISSIONS

Fuel economy and vehicle miles traveled (VMT) data for conventional and hybrid vehicles were provided by the UCS. Tables 9 and 10 show baseline on-road fleet average fuel economy and baseline new vehicle fuel economy, respectively, by vehicle/fuel system during the period from 2000–2050. UCS predicted negligible changes in fleet average fuel economy for each vehicle/fuel system because no improvements in the fuel economy of new vehicles were assumed.

TABLE 8 Energy Allocation for Product Fuel, Co-Product Fuel, Co-Product, and Electricity

Option	Fuel Product/Co-Product (Fuel)/ Co-Product/Electricity	Output Energy Share (%)
EtOH/GTCC	EtOH/NA[a]/NA/electricity	79.6/0/0/20.4
EtOH/Rankine	EtOH/NA/NA/electricity	88.2/0/0/11.9
EtOH/protein/Rankine	EtOH/NA/protein/electricity	83.2/0/13.3/3.5
EtOH/FTD/GTCC	EtOH/FTD&FTG/NA/electricity	76.5/13.4 & 8.3/0/1.8
FTD/GTCC	FTD/FTG/NA/electricity	36.8/22.9/0/40.4
DME/GTCC	DME/NA/NA/electricity	44.7/0/0/55.3

[a] NA = not available

Table 11 shows UCS predictions of baseline on-road fleet VMT by vehicle/fuel system during the period from 2000–2050. For baseline vehicle VMT, UCS predicted a stable increase annually for each vehicle/fuel system under a business-as-usual scenario. Total VMT for conventional light-duty internal combustion engine (ICE) gasoline trucks increased much faster than that for conventional ICE gasoline cars. In 2050, total VMT by light-duty ICE gasoline trucks reached 2,200 billion miles, very close to the total VMT by ICE gasoline cars (2,400 billion miles). Although VMT by hybrid vehicles and EtOH-fueled vehicles increased every year in this scenario, the total VMT is still small; all of them together (except the conventional gasoline cars and trucks) will contribute 21% of total VMT in 2050. Table 12 presents baseline per-vehicle annual VMT data by vehicle/fuel system; these data were derived from UCS baseline predictions of total VMT and vehicle stocks.

In this study, ASPEN Plus™ simulations produced bio-FTD and bio-DME to displace conventional petroleum-based transportation fuels. A complete analysis should include use of bio-FTD and bio-DME. Both fuels are compression-ignition (CI) engine fuels. In the United States, CI engines are used mainly in heavy-duty trucks. Thus, a WTW analysis should include both heavy-duty trucks and light-duty vehicles (LDVs). However, available resources did not allow the RBAEF team to address vehicle fuel economy and VMT projections for heavy-duty trucks. Thus, the WTW analysis is limited to LDVs. We assume that the bio-FTD and bio-DME are used as CI engine fuels in LDVs. At present, the LDV market encompasses predominantly SI engines. To evaluate bio-FTD and bio-DME, we assumed first that CI engines would penetrate the U.S. LDV market. On the basis of this assumption, we evaluated the use of petroleum diesel to power CI engines in LDVs. Then we assumed a fuel switch from petroleum diesel to bio-FTD or bio-DME in LDV CI engines to evaluate the effects of fuel switching. In our study, the fuel economies of cars and light-duty trucks (LDTs) were combined according to the VMT shares of gasoline vehicles, because all technologies are supposed to penetrate the gasoline LDV market. Table 13 presents the combined baseline fuel economies (by vehicle/fuel system) for the year 2030 that were used for GREET WTW simulations.

TABLE 9 Baseline On-Road Fleet Average Vehicle Fuel Economy (mpg gasoline equivalent [mpgge])

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Cars\hybrid\diesel	33.4	33.7	34.0	34.4	34.7	34.7	34.7	34.7	34.7	34.7	34.7
Cars\hybrid\gasoline	30.5	30.4	30.7	31.1	31.4	31.4	31.4	31.4	31.4	31.4	31.4
Cars\ICE\diesel	27.9	29.4	29.6	29.8	30.1	30.1	30.1	30.1	30.1	30.1	30.1
Cars\ICE\EtOH flex fuel	21.8	21.7	21.8	21.9	22.0	21.9	21.9	21.8	21.8	21.8	21.8
Cars\ICE\gasoline	21.8	21.9	22.0	22.0	22.0	21.9	21.9	21.8	21.8	21.8	21.8
LDTs\hybrid\diesel	27.0	26.1	25.9	25.8	25.6	25.6	25.6	25.6	25.6	25.6	25.6
LDTs\hybrid\gasoline	24.6	24.4	24.3	24.2	24.1	24.1	24.1	24.1	24.1	24.1	24.1
LDTs\ICE\diesel	21.6	21.3	21.2	21.1	21.0	21.0	21.0	21.0	21.0	21.0	21.0
LDTs\ICE\EtOH flex fuel	16.5	16.3	16.7	17.0	17.1	17.1	17.1	17.1	17.1	17.1	17.0
LDTs\ICE\gasoline	16.6	16.4	16.6	16.9	17.0	17.1	17.1	17.1	17.1	17.1	17.0

TABLE 10 Baseline New Vehicle Fuel Economy (mpgge)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Cars\hybrid\diesel	43.4	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3	43.3
Cars\hybrid\gasoline	39.7	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.2
Cars\ICE\diesel	37.9	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5
Cars\ICE\EtOH flex fuel	28.1	27.8	27.6	27.4	27.2	27.2	27.2	27.2	27.2	27.2	27.2
Cars\ICE\gasoline	28.4	27.8	27.6	27.4	27.2	27.2	27.2	27.2	27.2	27.2	27.2
CLDTs\ICE\gasoline	17.2	17.2	17.1	17.9	18.5	19.1	19.4	19.7	19.9	20.0	20.1
LDTs\hybrid\diesel	33.6	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4	32.4
LDTs\hybrid\gasoline	30.6	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5	30.5
LDTs\ICE\diesel	26.8	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5
LDTs\ICE\EtOH flex fuel	20.6	20.2	21.8	21.7	21.6	21.6	21.6	21.6	21.5	21.5	21.5
LDTs\ICE\gasoline	20.6	20.2	21.8	21.7	21.6	21.6	21.6	21.6	21.5	21.5	21.5

TABLE 11 Baseline On-Road Fleet Average Total VMT Predictions (billion miles)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Cars\hybrid\diesel	0.0	0.5	2.0	5.5	10.3	15.0	19.2	22.1	24.0	25.2	26.1
Cars\hybrid\gasoline	0.6	13.7	53.3	109.7	164.8	206.9	243.6	271.5	291.0	305.1	315.7
Cars\ICE\diesel	5.2	3.1	3.1	3.6	4.2	5.1	6.6	8.6	10.8	13.5	16.7
Cars\ICE\EtOH flex fuel	11.3	36.0	63.4	85.6	101.2	111.2	123.3	134.5	143.3	150.0	155.2
Cars\ICE\gasoline	1508.5	1542.7	1544.8	1586.3	1658.0	1747.8	1911.7	2075.9	2208.5	2309.2	2386.1
LDTs\hybrid\diesel	0.0	0.3	0.8	2.0	3.7	5.5	7.1	8.3	9.2	9.8	10.2
LDTs\hybrid\gasoline	0.3	8.2	30.7	61.9	92.3	116.3	138.6	156.5	169.8	179.9	187.4
LDTs\ICE\diesel	16.1	48.3	82.4	108.2	129.2	148.9	175.8	203.7	229.5	253.5	275.8
LDTs\ICE\EtOH flex fuel	12.2	41.0	76.6	108.3	132.6	150.3	170.1	187.8	201.6	212.4	220.4
LDTs\ICE\gasoline	735.6	959.3	1136.1	1300.8	1453.4	1599.2	1782.2	1946.6	2072.4	2166.8	2232.5

TABLE 12 Baseline Per-Vehicle Annual VMT Predictions (miles)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Cars\hybrid\diesel	N/A	N/A	20,300	13,750	14,729	15,030	15,967	15,800	14,994	14,841	14,522
Cars\hybrid\gasoline	N/A	15,200	15,226	15,025	14,713	14,781	15,129	15,337	15,316	15,027	14,614
Cars\ICE\diesel	8,667	10,233	15,550	12,000	14,033	12,775	16,550	17,120	15,486	15,000	15,164
Cars\ICE\EtOH flex fuel	14,175	14,400	14,091	13,798	13,669	14,255	14,859	15,283	15,244	15,000	14,640
Cars\ICE\gasoline	11,944	12,005	12,300	12,772	13,318	13,982	14,796	15,197	15,241	15,024	14,594
LDTs\hybrid\diesel	N/A	N/A	8,200	19,700	18,400	13,650	14,200	13,883	13,100	12,238	12,800
LDTs\hybrid\gasoline	N/A	16,360	14,600	14,395	14,205	14,188	14,284	13,849	13,475	12,941	12,250
LDTs\ICE\diesel	12,415	13,791	13,513	13,199	13,182	13,540	13,955	13,859	13,499	13,066	12,424
LDTs\ICE\EtOH flex fuel	13,556	14,134	13,686	13,539	13,389	13,536	13,828	13,707	13,354	12,874	12,246
LDTs\ICE\gasoline	12,000	12,221	12,348	12,604	12,908	13,282	13,657	13,584	13,293	12,859	12,233

TABLE 13 Combined Baseline Fuel Economies by In-Use Fleet Vehicle/Fuel System for 2030 (mpgge)[a]

	RFG	Bio-E85	LSD	Bio-FTD	Bio-DME
Conventional	19.6	19.6	25.7	25.7	25.7
Hybrid	27.9	27.9	30.3	30.3	30.3

[a] Data presented in this table are fleet-averaged fuel economies of LDVs; data for passenger cars and LDTs were combined according to the VMT shares of gasoline vehicle types. See Section 3.2.

Tier 2 standards for passenger cars and LDTs were adopted by EPA in 2001 and will be fully in effect in 2009. The Tier 2 standards established a number of "bins" with separate full-useful-life emission standards, as shown in Table 14. The overall Tier 2 requirement is implemented from model years 2004 through 2009. Ultimately, all passenger cars and LDVs will be required to meet, on average, a full-useful-life NO_x standard of 0.07 g/mi by 2009, which coincides with the "Bin 5" NO_x emission standard.

In this study, EPA's mobile source emission factor model, MOBILE6.2, was used to simulate emission factors for different vehicle technologies by vehicle class. MOBILE6.2 allows the user to input Tier 2 bin phase-in fractions. The heavier light-duty trucks and sport utility vehicles (SUVs) could be certified to the higher emission bins, while lighter passenger cars could be certified to lower emission bins. Some propulsion systems have inherently lower emissions relative to the baseline conventional system (for example, gasoline HEV vs. gasoline ICE); however, this advantage will be smaller or even offset as conventional vehicles meet the more stringent emission standards. So, in our study, all hybrid cars were assumed to meet the same standards as their conventional counterparts, and all hybrid trucks were assumed to be two bins lower than their conventional counterparts. Diesel vehicles generally have no problem meeting the same bin requirements for CO and VOCs as same-class gasoline vehicles (e.g., gasoline ICE cars vs. diesel CIDI cars), while higher emission bins for NO_x can be compared with gasoline vehicles in the same class. In this study, emission factors for gaseous emissions (CO, VOCs, and NO_x) at each bin, derived from MOBILE6.2 for gasoline vehicles, were directly applied to diesel vehicles at the same class because of the less-reliable emission factors simulated by MOBILE6.2 for Tier 2 diesel vehicles. Table 15 presents the emission standards that were assumed for passenger cars and LDTs for the various vehicle technologies in this study. For evaporative VOC emission factor simulations, we assumed Tier 2 evaporative standards for both gasoline and E85 vehicles and zero evaporative emissions for diesel, FTD, and DME vehicles (see Table 15).

The MOBILE6.2 emission factor simulations were run assuming calendar year 2016 for each bin shown in Table 15, with the lifetime mileage midpoint of a 2010-model-year passenger car and LDT. In 2016, the model indicates that 2010-model-year passenger cars and LDTs will

TABLE 14 Tier 2 Vehicle Emission Standards for Passenger Cars and Light-Duty Trucks (g/mi, for full useful lifetime of 120,000 mi)

	Emission Type				
Bin	NO_x[a]	NMOG[b]	CO	HCHO[c]	PM[d]
10[e,f]	0.60	0.156/0.230	4.2/6.4	0.018/0.027	0.08
9[e,f]	0.30	0.090/0.180	4.2	0.018	0.06
8[e]	0.20	0.125/0.156	4.2	0.018	0.02
7	0.15	0.090	4.2	0.018	0.02
6	0.10	0.090	4.2	0.018	0.01
5	0.07	0.090	4.2	0.018	0.01
4	0.04	0.070	2.1	0.011	0.01
3	0.03	0.055	2.1	0.011	0.01
2	0.02	0.010	2.1	0.004	0.01
1	0.00	0.000	0.0	0.000	0.00

[a] The corporate average NO_x standard will be 0.07 g/mi and will be fully in place by 2009.
[b] NMOG = non-methane organic gas.
[c] HCHO = formaldehyde.
[d] PM = particulate matter.
[e] The high values apply to heavy light-duty trucks (HLDTs), and the low values apply to passenger cars and light light-duty trucks (LLDTs).
[f] Bins 10 and 9 will be eliminated at the end of the 2006 model year for cars and LLDTs and at the end of the 2008 model year for HLDTs.

have accumulated approximately 80,000 mi and 100,000 mi, respectively. The simulation of exhaust PM_{10} in the model includes total carbon PM and sulfate PM. Besides exhaust PM_{10}, tire and brake wear (T&BW) PM_{10} was also evaluated by using MOBILE6.2. For other key parameters in the model, we assumed an on-board diagnostic (OBD) system, inspection and maintenance (I/M) program, RFG, LSD (for PM simulations only), an average speed of 28 mi/h, a fuel Reid vapor pressure of 6.8 for summer (July) and 11.0 for winter (January), and a diurnal temperature of 72–92°F for summer (July) and 25–38°F for winter (January). Emission factors were averaged by modeling the July and January scenarios.

In this study, emission factors for passenger cars and LDTs were combined by VMT share (from UCS) for the year 2030 for each fuel (gasoline, E85, and diesel). Table 16 lists the combined emission factors for vehicle operation by various vehicle/fuel systems. Fuel economy and VMT projections for heavy-duty vehicles were not available at the time of this study, so they were not included in the WTW analysis.

TABLE 15 Emission Standards Assumed for Passenger Cars and Light-Duty Trucks

	Tier 2 Exhaust Emission Bin			Evaporative
Vehicle Technology	VOC&CO	NO_x	PM	VOC
Passenger Cars				
Gasoline ICE	Bin 2	Bin 2	Bin 2	Tier 2 Evap.
Gasoline HEV	Bin 2	Bin 2	Bin 2	Tier 2 Evap.
E85 ICE FFV	Bin 2	Bin 2	Bin 2	Tier 2 Evap.
E85 FFV HEV	Bin 2	Bin 2	Bin 2	Tier 2 Evap.
Diesel CIDI	Bin 2	Bin 3	Bin 2	Zero
Diesel HEV	Bin 2	Bin 3	Bin 2	Zero
FTD CIDI	Bin 2	Bin 3	Bin 2	Zero
FTD HEV	Bin 2	Bin 3	Bin 2	Zero
DME CIDI	Bin 2	Bin 3	Bin 2	Zero
DME HEV	Bin 2	Bin 3	Bin 2	Zero
Light-Duty Trucks				
Gasoline ICE	Bin 5	Bin 5	Bin 5	Tier 2 Evap.
Gasoline HEV	Bin 3	Bin 3	Bin 3	Tier 2 Evap.
E85 ICE FFV	Bin 5	Bin 5	Bin 5	Tier 2 Evap.
E85 FFV HEV	Bin 3	Bin 3	Bin 3	Tier 2 Evap.
Diesel CIDI	Bin 5	Bin 6	Bin 5	Zero
Diesel HEV	Bin 3	Bin 4	Bin 3	Zero
FTD CIDI	Bin 5	Bin 6	Bin 5	Zero
FTD HEV	Bin 3	Bin 4	Bin 3	Zero
DME CIDI	Bin 5	Bin 6	Bin 5	Zero
DME HEV	Bin 3	Bin 4	Bin 3	Zero

3.3 COMPARISONS OF CELLULOSIC FUEL PRODUCTION OPTIONS

This study examines single-fuel, multi-fuel, and multi-product production options that employ biological and thermochemical processes. In order to compare the fuel production options, GREET simulation was performed separately for products and co-product(s) derived from each fuel production option, on the basis of one unit of biomass feed. There are a total of six products and co-products: bio-EtOH, bio-FTD, bio-FTG, bio-DME, electricity (for export), and protein. The biofuel analysis method was discussed in Section 3.1. For electricity generated from each option, energy and emissions associated with electricity in the fuel plant were first credited by energy share (Table 8). Electricity yield, on a mass basis (in kWh/dry ton of biomass) was determined, and the contributions of energy and emissions from the upstream biomass farming stage to electricity were calculated. Finally, the results from the farming and fuel production stages were summarized as the life-cycle energy and emissions for electricity

TABLE 16 Combined Emission Factors for Vehicle Operation by Vehicle/Fuel System

Pollutant	Light-Duty Vehicles (ICE and FFV)				
(g/mi)	RFG	E85	Diesel	FTD	DME
NO_x	0.124	0.124	0.151	0.151	0.151
VOCs					
Exhaust	0.164	0.164	0.164	0.164	0.164
Evaporative	0.069	0.069	0.000	0.000	0.000
CO	6.529	6.529	6.529	6.529	6.529
PM_{10}					
Exhaust	0.004	0.004	0.009	0.009	0.009
T&BW	0.021	0.021	0.021	0.021	0.021

Pollutant	Light-Duty Vehicles (HEV)				
(g/mi)	RFG	E85	Diesel	FTD	DME
NO_x	0.103	0.103	0.114	0.114	0.114
VOCs					
Exhaust	0.144	0.144	0.144	0.144	0.144
Evaporative	0.067	0.067	0.000	0.000	0.000
CO	6.180	6.180	6.180	6.180	6.180
PM_{10}					
Exhaust	0.004	0.004	0.009	0.009	0.009
T&BW	0.021	0.021	0.021	0.021	0.021

generated. The impact of co-product protein in biofuel production was evaluated by using the same method as that with electricity. Energy and emissions for the protein production process in the EtOH/protein/Rankine option (option 4) were determined by output energy share, as presented in Table 8, and the yield was expressed as kg protein/dry ton biomass. By adding the farming stage data, we obtained total energy and emissions results. The results from this analysis are expressed as Btu of energy or grams of emissions per short ton of biomass feedstock.

These results were further analyzed to estimate how much petroleum fuel, soy-based protein, and electricity (U.S. generation mix) could be displaced by each biofuel production option and resultant energy and emission benefits. Table 17 lists the average U.S. electricity mix used for the displacement simulations. Table 18 presents the assumptions for the displacement of fuel, electricity, and protein.

TABLE 17 Average U.S. Electricity Generation Mix Used in this Study — Year 2030[a]

Residual oil	0.3%
Natural gas	33.1%
Coal	30.8%
Nuclear power	17.4%
Others	18.4%

[a] Based on results of a five-lab study (Inter-Laboratory Working Group on Energy-Efficient and Clean-Energy Technologies 2000).

TABLE 18 Assumptions of Product Displacement for Biomass Mass-Based Analysis

1. 1 Btu of EtOH displaces 1 Btu of RFG
2. 1 Btu of FTG displaces 1 Btu of RFG
3. 1 Btu of FTD displaces 1 Btu of LSD
4. 1 Btu of DME displaces 1 Btu of LSD
5. 1 Btu of GTCC/Rankine kWh displaces 1 Btu of U.S. mix kWh
6. 1 kg switchgrass-protein displaces 1 kg soy-protein[a]

[a] Assumes comparative protein value between soy-protein and switchgrass-protein (Greene et al. 2004b).

4 RESULTS AND DISCUSSION

Tables 19–21 present the GREET energy use and emissions results for cellulosic biofuel life cycles with fuels produced via the bio-EtOH/GTCC, bio-EtOH/Rankine, bio-EtOH/bio-FTD/GTCC, bio-FTD/GTCC, and bio-DME/GTCC options in light-duty vehicles. Energy use and emissions are expressed as per-mile driven — in other words, the amount of energy that would be used or emissions that would be generated by driving conventional and/or hybrid electric vehicles fueled with biofuels for 1 mi. Petroleum and fossil energy use, GHG emissions, and criteria pollutant emissions in the year 2030 were simulated. Under the assumption of this study that mature technologies will be introduced starting in the year 2015, the per-mile results will be the same over the simulation period (2015–2030). Bio-based fuels are compared with petroleum-based conventional fuels by calculating percentage changes relative to gasoline for bio-EtOH and relative to diesel for bio-DME and bio-FTD (Figures 5–7).

4.1 PETROLEUM AND FOSSIL ENERGY SAVINGS FOR EACH BIOFUEL

Biofuels provide significant reductions in oil and fossil energy use. By switching from petroleum gasoline and diesel to cellulosic bio-EtOH (E85), bio-FTD, and bio-DME in our passenger cars and light-duty trucks, drivers can reduce petroleum use by 68–93% and fossil energy use by 65–88% (Figures 5–7) on a per-mile basis. The greatest energy benefits apparently come from cellulosic DME and FTD, which offer up to 93% reductions in petroleum and 88% reductions in fossil energy consumption (Figure 7). The roughly 25% difference in energy savings between bio-EtOH and bio-FTD/bio-DME is attributable to the fact that E85 contains 15% (by volume) gasoline, while bio-DME and FTD are 100% pure. The relatively lower energy savings from bio-EtOH E85 reflects the effect of gasoline blending. We further considered the ethanol portion of E85 (i.e., fossil and petroleum energy use for ethanol without taking into account the gasoline portion), which resulted in an 89% fossil energy reduction and a 93% petroleum reduction (Tables 19 and 20).

Energy consumption values are similar among the three bio-EtOH production options — 755–855 Btu/mi (EtOH in E85) in fossil energy and 443–497 Btu/mi (EtOH in E85) in petroleum (both with FFVs). The data reveal similar reductions in petroleum between cellulosic and corn ethanol. There is a moderate change in fossil energy use from corn ethanol (4,138 Btu/mi [EtOH in E85]). Because biofuel consumes zero fossil and petroleum energy during the vehicle operation stage, the difference in fossil energy use must be attributable to feedstock farming, transportation, and the fuel production process. Table 22 indicates that the major reductions in fossil energy consumption offered by switchgrass bio-EtOH result from the fuel production stage. The key is the source of the power and steam for the production process. Instead of using coal or natural gas to fuel the ethanol plant, as in the corn ethanol production process, the advanced cellulosic bio-EtOH process in this study relies on biomass residuals and methane gas from sludge digestion in the on-site WWT plant for power and steam production, which decreases fossil energy consumption.

TABLE 19 WTW Energy Use and Emissions of Bio-EtOH with Different Production Options for Each Mile Driven with ICE SI Vehicles (in Btu for fossil and petroleum fuels and grams for emissions) (fuel economy: 19.6 mpgge)

	Fuel Production Option								
		Corn EtOH		Cellulosic EtOH/GTCC		Cellulosic EtOH/Rankine		Cellulosic EtOH/FTD/GTCC	
Item	RFG	E85	EtOH in E85[a]	E85	EtOH in E85	E85	EtOH in E85	E85	EtOH in E85
Fossil fuels	7,280	4,974	4,138	2,511	781	2,564	855	2,491	755
Petroleum	6,573	2,056	418	2,085	457	2,114	497	2,074	443
GHG	586	468	425	229	99	233	105	217	83
VOC: total[b]	0.374	0.402	0.412	0.400	0.410	0.419	0.436	0.398	0.406
CO: total	6.608	6.768	6.826	6.651	6.666	6.851	6.939	6.652	6.668
NO_x: total	0.377	0.760	0.899	0.513	0.562	0.781	0.928	0.478	0.514
PM_{10}: total	0.071	0.239	0.300	0.057	0.053	0.158	0.190	0.053	0.046
SO_x: total	0.148	0.301	0.355	0.086	0.063	0.090	0.069	0.084	0.061
VOCs: urban	0.226	0.215	0.211	0.217	0.214	0.217	0.214	0.217	0.214
CO: urban	4.082	4.068	4.063	4.071	4.067	4.071	4.068	4.071	4.067
NO_x: urban	0.145	0.103	0.087	0.112	0.100	0.113	0.101	0.112	0.100
PM_{10}: urban	0.021	0.017	0.016	0.017	0.016	0.017	0.016	0.017	0.016
SO_x: urban	0.054	0.026	0.015	0.018	0.006	0.019	0.006	0.018	0.005

[a] Value is derived from ethanol in E85; that is, fossil and petroleum energy use at each stage for ethanol only, without taking into account the gasoline portion of E85.

[b] Total = total emissions from urban and rural areas; urban = emissions from urban area.

TABLE 20 WTW Energy Use and Emissions of Bio-EtOH with Different Production Options for Each Mile Driven with HEVs (in Btu for fossil and petroleum fuels and grams for emissions) (fuel economy: 27.9 mpgge)

		Fuel Production Option							
		Corn EtOH		Cellulosic EtOH/GTCC		Cellulosic EtOH/Rankine		Cellulosic EtOH/FTD/GTCC	
Item	RFG	E85	EtOH in E85	E85	EtOH in E85	E85	EtOH in E85	E85	EtOH in E85
Fossil fuels	5,115	3,494	2,907	1,764	549	1,802	600	1,750	530
Petroleum	4,618	1,444	294	1,465	321	1,485	349	1,457	311
GHG	414	332	302	164	73	167	77	156	62
VOC: total	0.312	0.332	0.339	0.330	0.337	0.344	0.355	0.329	0.335
CO: total	6.233	6.346	6.386	6.263	6.274	6.404	6.466	6.264	6.275
NO_x: total	0.281	0.550	0.648	0.376	0.411	0.565	0.668	0.351	0.377
PM_{10}: total	0.057	0.175	0.218	0.048	0.044	0.118	0.141	0.044	0.040
SO_x: total	0.104	0.212	0.250	0.060	0.044	0.063	0.048	0.059	0.043
VOCs: urban	0.189	0.182	0.179	0.183	0.181	0.183	0.181	0.183	0.181
CO: urban	3.857	3.848	3.844	3.850	3.847	3.850	3.847	3.850	3.847
NO_x: urban	0.112	0.082	0.071	0.089	0.081	0.089	0.081	0.089	0.080
PM_{10}: urban	0.019	0.017	0.016	0.017	0.016	0.017	0.016	0.017	0.016
SO_x: urban	0.038	0.018	0.010	0.013	0.004	0.013	0.004	0.013	0.004

TABLE 21 WTW Energy Use and Emissions of Bio-FTD and Bio-DME Produced from Different Production Options for Each Mile Driven with Conventional Vehicles and HEVs (Btu for fossil and petroleum fuels and grams for emissions) (fuel economies: 25.7 mpgge for CIDI and 30.3 mpgge for HEV)

	Fuel Production Option							
	CIDI				HEV			
Item	LSD	Cellulosic DME/GTCC	Cellulosic FTD/GTCC	Cellulosic EtOH/FTD /GTCC	LSD	Cellulosic DME/GTCC	Cellulosic FTD/GTCC	Cellulosic EtOH/FTD /GTCC
Fossil fuels	5,451	717	661	534	4,624	608	561	453
Petroleum	4,961	401	360	292	4,208	340	305	248
GHG	447	75	68	56	380	64	59	49
VOC: total	0.201	0.220	0.216	0.219	0.175	0.192	0.188	0.190
CO: total	6.587	6.659	6.649	6.629	6.227	6.288	6.280	6.262
NO_x: total	0.335	0.548	0.483	0.404	0.270	0.451	0.396	0.329
PM_{10}: total	0.062	0.058	0.052	0.045	0.057	0.054	0.049	0.042
SO_x: total	0.102	0.055	0.053	0.043	0.087	0.046	0.045	0.037
VOC: urban	0.116	0.107	0.107	0.107	0.102	0.094	0.094	0.094
CO: urban	4.076	4.067	4.066	4.065	3.855	3.848	3.847	3.846
NO_x: urban	0.141	0.112	0.108	0.106	0.111	0.086	0.083	0.081
PM_{10}: urban	0.022	0.019	0.019	0.019	0.021	0.019	0.019	0.019
SO_x: urban	0.036	0.004	0.004	0.003	0.030	0.004	0.004	0.003

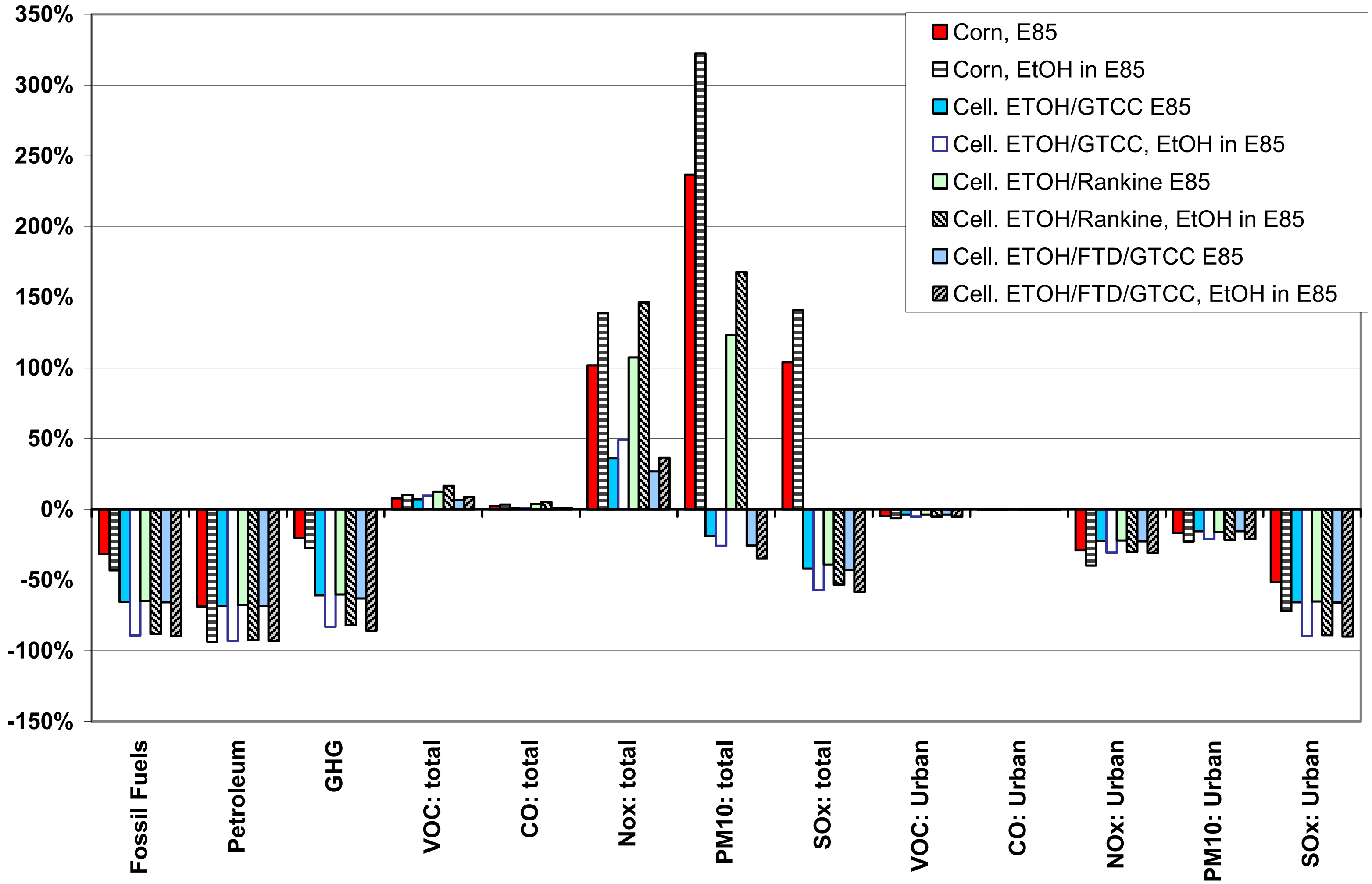

FIGURE 5 Percent Change in Energy Use and Emissions from Bio-EtOH Production Options Relative to Gasoline in ICE SI Vehicles (per mile driven) (Note: negative value means reduction)

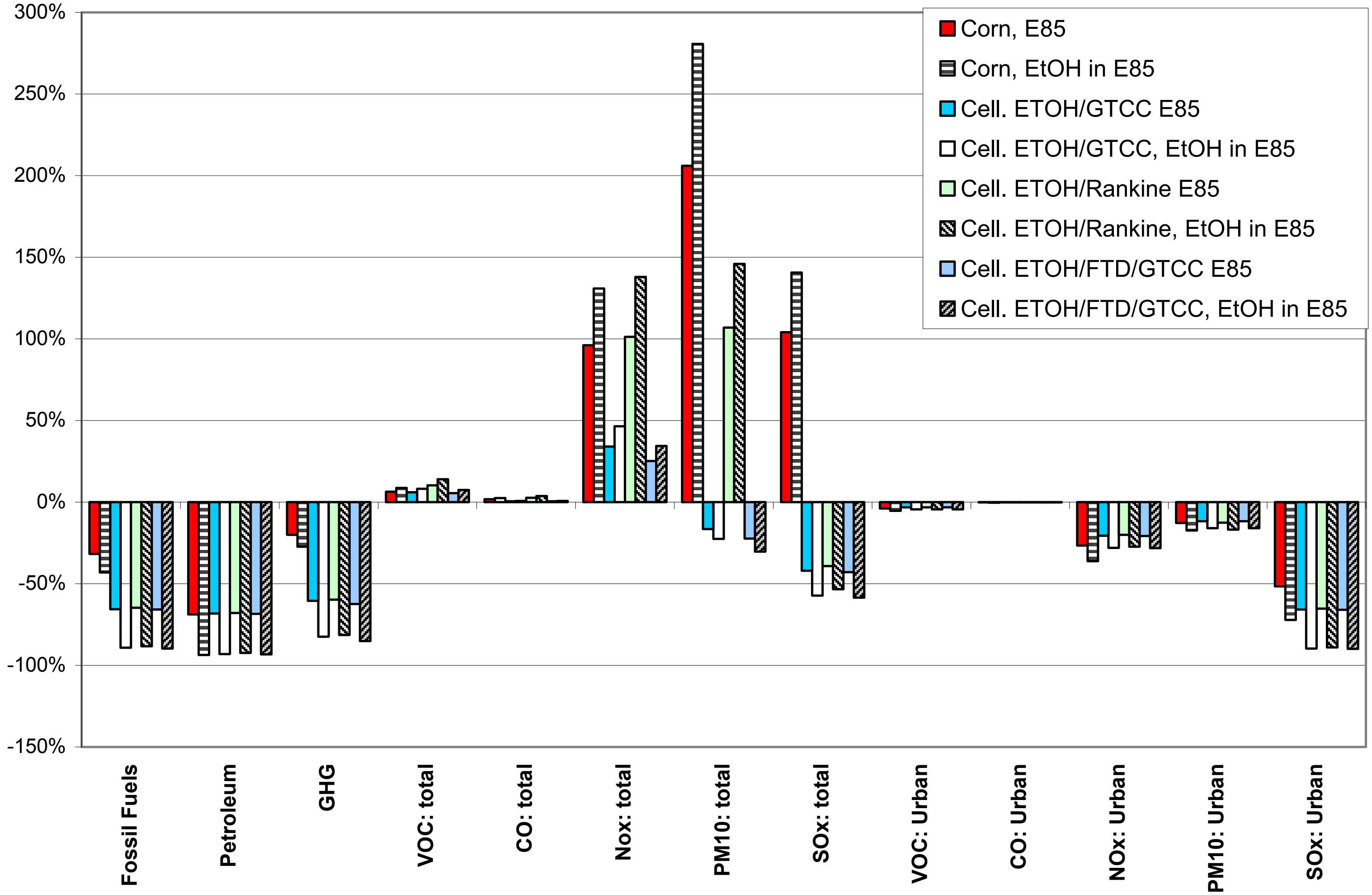

FIGURE 6 Percent Change in Energy Use and Emissions from Bio-EtOH Production Options Relative to Gasoline in HEVs (per mile driven) (Note: negative value means reduction)

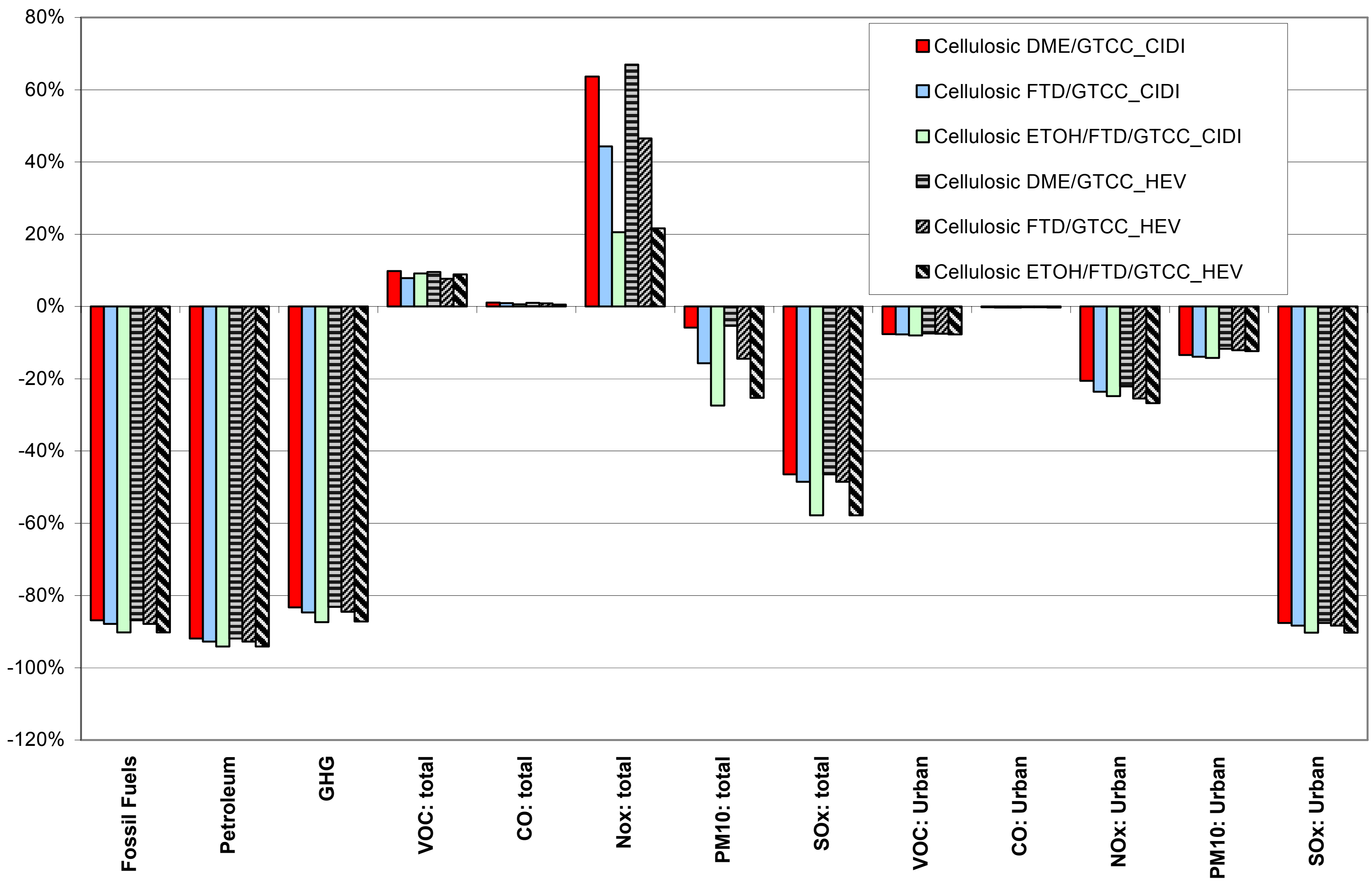

FIGURE 7 Percent Change in Energy Use and Emissions of Bio-FTD and Bio-DME Produced from Bio-FTD/GTCC, Bio-DME/GTCC, and Bio-EtOH/Bio-FTD/GTCC Options Relative to Diesel in Conventional CIDIs and HEVs (per mile driven) (Note: negative value means reduction)

TABLE 22 Fossil Fuel and Petroleum Energy Consumption at Each Stage of Fuel Life Cycle for Ethanol in Bio-EtOH E85[a] (in Btu per mile driven)

Item	Fossil Fuels: Feedstock	Fossil Fuels: Fuel Production	Fossil Fuels: Vehicle Operation	Petroleum: Feedstock	Petroleum: Fuel Production	Petroleum: Vehicle Operation
Corn E85 FFV	678	3,460	0	300	119	0
Cellulosic E85 FFV: EtOH/GTCC	679	102	0	363	95	0
Cellulosic E85 FFV: EtOH/Rankine	753	102	0	402	95	0
Cellulosic E85 FFV: EtOH/FTD/GTCC	653	102	0	348	95	0

[a] Values in this table are derived from ethanol in E85.

To understand the attributes of different biofuels, the GREET results are expressed as per-gallon-gasoline-equivalent (gge), as seen in Tables 23 and 24. By using this unit of measure, we excluded vehicle type and fuel economy effects. Data for the fuel ethanol portion of E85 are presented along with data for pure bio-FTD and bio-DME. Figure 8 shows that bio-based ethanol, regardless of the feedstock and production process used, provides an equivalent amount of petroleum fuel reduction for each gallon (as gge) of bio-EtOH used. This is also the case for each type of vehicle technology (Figures 5 and 6). For every mile driven by conventional or hybrid electric vehicles, the per-gallon results (Figure 8) agree with the per-mile data (Figures 5 and 6) — biomass- and corn-based fuel ethanol offers similar oil reduction benefits. The fossil energy savings that results from using biomass is doubled. Bio-FTD and bio-DME produced via the thermochemical process reduce petroleum energy consumption up to 95% and fossil energy consumption up to 90% (Figure 9); these results are similar to the per-mile results.

An attempt was made to estimate, for each million Btu biofuel produced, the amount of fossil energy and emissions from biomass farming, transportation, and fuel processing up to the refueling pump. We used the ethanol portion of E85 to compare with 100% FTD and DME to allow a consistent comparison among biofuels and avoid interference from petroleum blending with ethanol. Each of these biofuels is produced via a production option that employs advanced GTCC technology for power generation (bio-EtOH/GTCC, bio-FTD/GTCC, and bio-DME/GTCC). Table 25 shows that, during the fuel production cycle (i.e., from well-to-pump), for each million Btu of biofuel produced from switchgrass, bio-EtOH provides the greatest amount of fossil fuel displacement of the three biofuels. Net fossil fuel displacement by cellulosic biofuels can be ranked, then, as bio-EtOH > bio-FTD > bio-DME.

From a fuel productivity point of view, bio-EtOH yield (in energy units of 105 gal/dt of biomass or 8.04 mmBtu/dt) is much higher than that of bio-DME (52 gal/dt or 3.56 mmBtu/dt), bio-FTD (25 gal/dt or 3.08 mmBtu/dt), and bio-FTG (19 gal/dt or 0.88–1.92 mmBtu/dt). Put in a different way, a dry ton of biomass feedstock could yield bio-EtOH, in million Btu, at more than twice the amount of bio-DME and more than one and a half times the amount of bio-FTD and bio-FTG together. On the other hand, the thermochemical process used to produce bio-FTD and bio-DME generates electricity for export at an energy value (40–55% total output energy) almost

TABLE 23 WTW Energy Use and Emissions of Bio-EtOH in E85 Produced from Various Options (in gallons gasoline equivalent [Btu or g])

Item	RFG	Corn, EtOH in E85	Cellulosic EtOH in E85 EtOH/GTCC	Cellulosic EtOH in E85 EtOH/ Rankine	Cellulosic EtOH in E85 EtOH/ FTD/GTCC
Fossil fuels	142,695	81,104	15,312	16,750	14,790
Petroleum	128,838	8,200	8,967	9,734	8,688
GHGs	11,484	8,327	1,948	2,061	1,633
VOC: total	7.325	8.082	8.030	8.542	7.967
CO: total	129.507	133.782	130.657	136.001	130.685
NO_x: total	7.382	17.626	11.013	18.181	10.077
PM_{10}: total	1.390	5.870	1.029	3.722	0.905
SO_x: total	2.893	6.963	1.239	1.351	1.200
VOC: urban	4.422	4.137	4.187	4.190	4.186
CO: urban	80.002	79.630	79.719	79.725	79.716
NO_x: urban	2.841	1.712	1.970	1.988	1.963
PM_{10}: urban	0.402	0.310	0.318	0.315	0.317
SO_x: urban	1.050	0.292	0.108	0.116	0.105

TABLE 24 WTW Energy Use and Emissions of Bio-FTD and Bio-DME Produced from Bio-FTD/GTCC, Bio-DME/GTCC, and Bio-EtOH/Bio-FTD/GTCC Options (in gallons gasoline equivalent [Btu or g])

Item	LSD	Cellulosic DME: DME/GTCC	Cellulosic FTD: FTD/GTCC	Cellulosic FTD: EtOH/FTD/GTCC
Fossil fuels	140,096	18,418	16,989	13,719
Petroleum	127,507	10,308	9,244	7,501
GHGs	11,479	1,916	1,759	1,450
VOC: total	5.155	5.660	5.561	5.627
CO: total	169.282	171.142	170.873	170.356
NO_x: total	8.603	14.082	12.413	10.375
PM_{10}: total	1.583	1.491	1.334	1.149
SO_x: total	2.623	1.405	1.351	1.106
VOC: urban	2.990	2.760	2.758	2.752
CO: urban	104.748	104.515	104.484	104.470
NO_x: urban	3.621	2.877	2.765	2.723
PM_{10}: urban	0.565	0.489	0.486	0.485
SO_x: urban	0.915	0.113	0.106	0.089

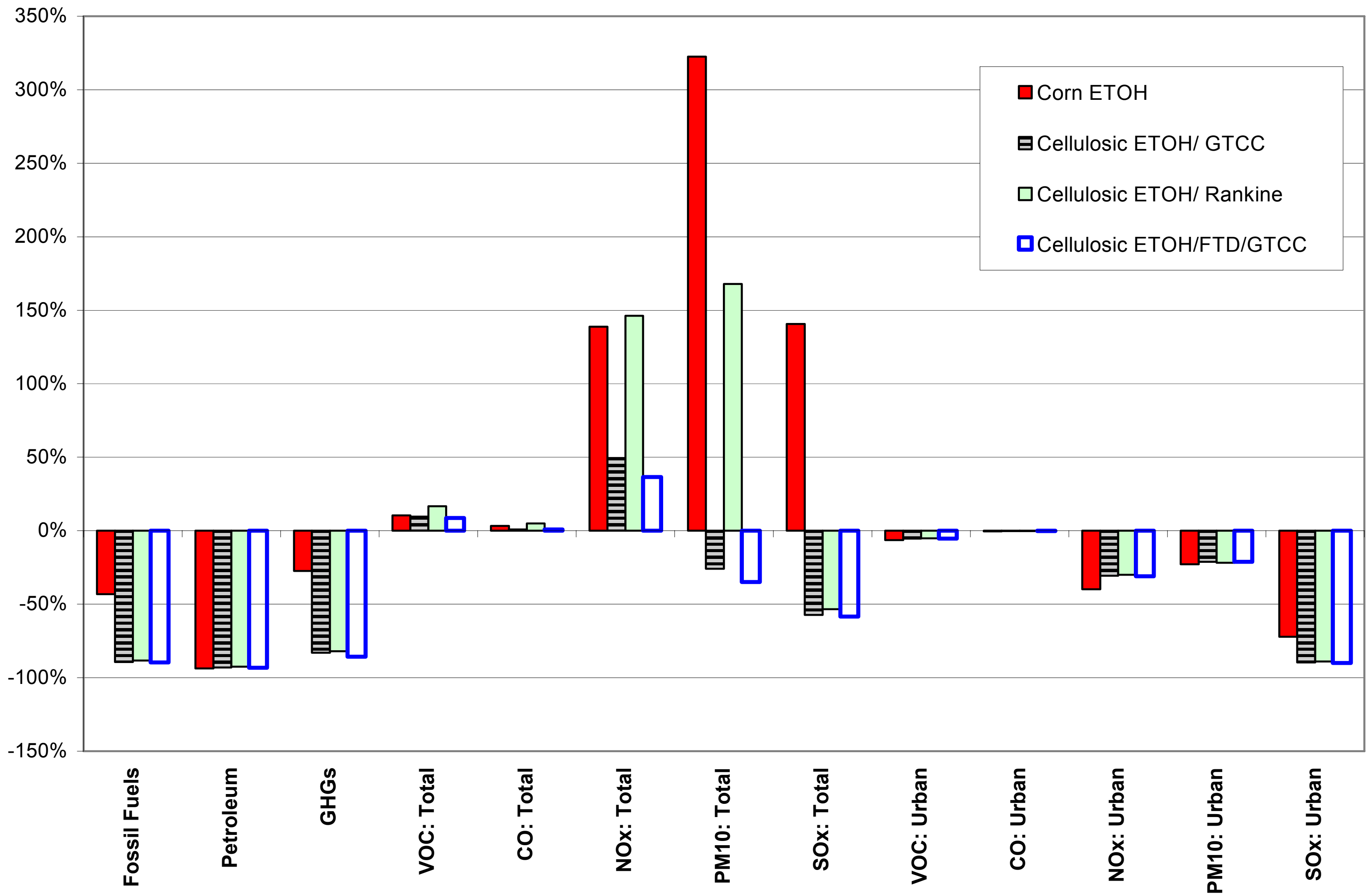

FIGURE 8 Percent Change in Energy and Emissions of Biofuel EtOH (without Blending) Relative to Gasoline (per gallon gasoline equivalent) (Note: negative value means reduction)

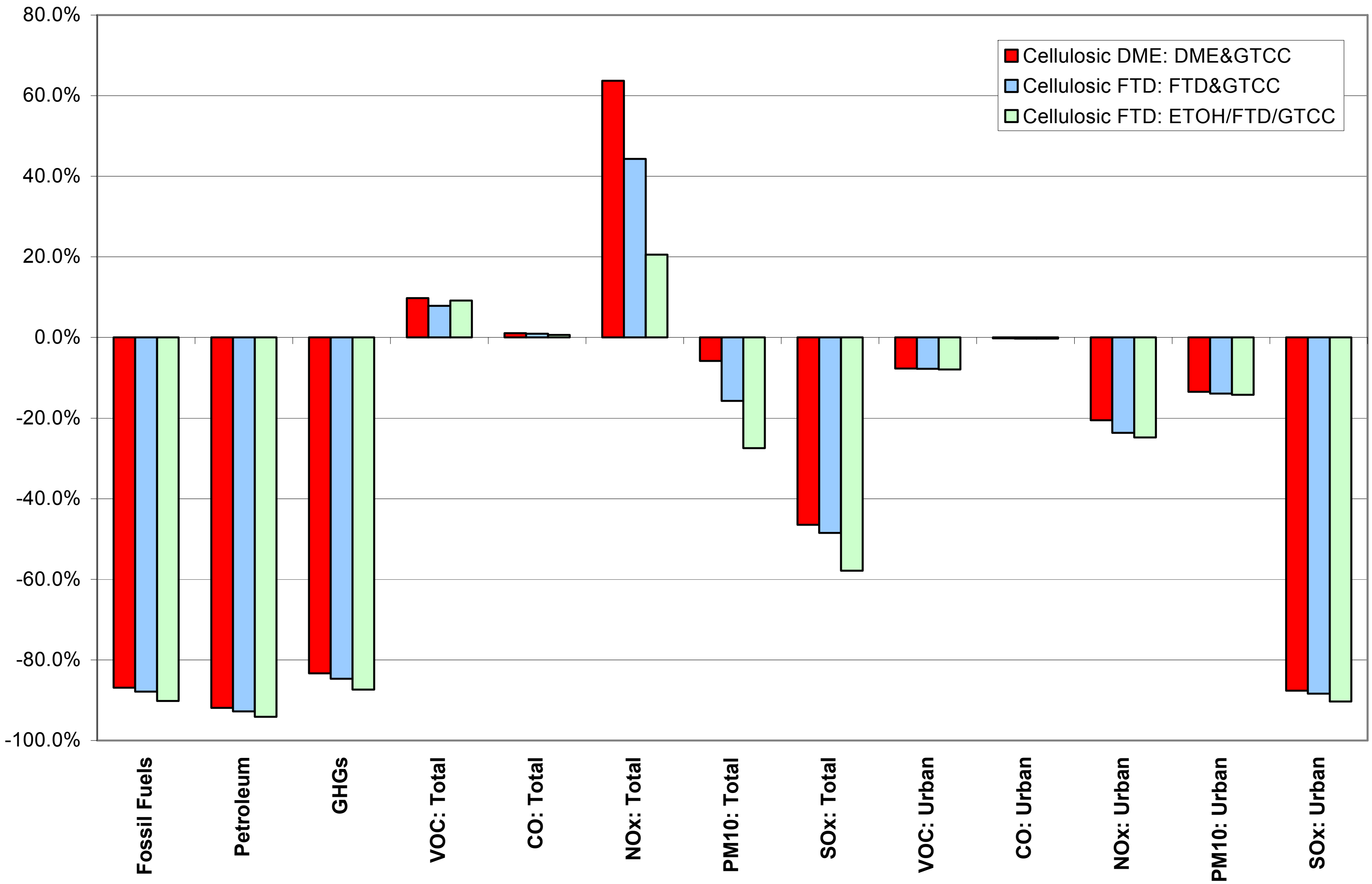

FIGURE 9 Percent Change in Energy and Emissions of Bio-FTD and Bio-DME Relative to Diesel (per gallon gasoline equivalent) (Note: negative value means reduction)

TABLE 25 Btu of Fossil Fuel Energy Displaced for Each mmBtu of Biofuels Produced during Fuel Production Cycle (WTP — from farming to pump)

Btu Fossil Fuel Consumption (per mmBtu fuel produced)					Btu Fossil Fuel Displaced[a] (per mmBtu fuel produced)		
Gasoline (RFG)	Bio-EtOH[b]	Diesel (LSD)	Bio-FTD[c]	Bio-DME[c]	Gasoline – Bio-EtOH	Diesel – Bio-FTD	Diesel – Bio-DME
1,229,175	131,900	1,206,791	146,346	158,650	1,097,275	1,060,445	1,048,141

[a] EtOH to displace gasoline; FTD and DME to displace diesel.

[b] EtOH in E85 is produced from the bio-EtOH/GTCC fuel production option.

[c] FTD is produced from the bio-FTD/GTCC production option; DME is produced from the bio-DME/GTCC production option.

equal to the amount of fuel, as seen in Table 8. Compared with bio-EtOH (EtOH/GTCC: 79.6%), an additional 35–42% of the energy output from these two production options are in the form of export electricity instead of fuel. In other words, the electricity generated from the thermochemical process contributes to energy and emission reductions in the power sector. This issue is discussed in more detail in Section 4.3.

The major reductions in fossil fuel energy consumption by using biofuels made from switchgrass result from the renewable nature of the energy in biofuels. Because fossil fuel use is primarily responsible for GHG emissions, decreased fossil fuel use translates directly to lower GHG emissions. Table 26 clearly indicates that GHG emissions reductions are 82–87% and CO_2 reductions are 94–96% across all unblended cellulosic biofuels. Using bio-EtOH as E85, even when it is blended with gasoline, results in a 60–62% reduction in GHGs and 70% reductions in CO_2. Table 26 demonstrates that the reductions in GHG and CO_2 emissions occur at the well-to-pump stage, as a result of lower consumption of fossil fuels (Table 22).

4.2 CRITERIA POLLUTANT EMISSIONS FROM BIOFUELS

The most significant change in criteria pollutant emissions occurs for SO_x (Tables 19–21). When fueled with bio-EtOH as E85, conventional and hybrid electric vehicles could reduce total SO_x emissions to 39–43% of those generated by vehicles fueled with gasoline (on a per-mile basis). For each unit of EtOH used in E85, the SO_x reduction would be 53–59% (Tables 19–20; Figures 5 and 6). By using bio-FTD and bio-DME in place of diesel, total SO_x reductions would reach 46–58% of those generated by diesel-fueled vehicles (on a per-mile basis) (Table 21; Figure 7). These benefits likely result from the change in feedstock and fuel production stages (Table 27 and Figure 10). Table 27 further shows that, for cellulosic biofuels without blending, SO_x emissions decreased by roughly half at the feedstock stage, by 24–56% at the fuel production stage, and by 100% during vehicle operation. In addition, bio-EtOH emits much less SO_x (0.023–0.027 g/mi) than does EtOH produced from corn (0.157 g/mi) at the farming stage. The difference in SO_x emissions between cellulosic EtOH and corn EtOH can be explained by a change in phosphorus fertilizer use. At the corn farming stage, the majority of

TABLE 26 CO_2 and GHG Emissions Reductions at Different Stages of Fuel Life Cycle for Biofuel Production Options (for each gallon of gasoline-equivalent biofuel used)

Fuel Production Options	CO_2 Emissions (g/gge)			GHG Emissions (g/gge)			Relative Reductions (WTW, %)	
	WTP	PTW	WTW	WTP	PTW	WTW	CO_2	GHGs
Diesel	1,882	9,179	11,061	2,172	9,307	11,479		
Cellulosic DME: DME/GTCC	-7,551	8,115	564	-6,334	8,250	1,916	94.9	83.3
Cellulosic FTD: FTD/GTCC	-8,416	8,905	489	-7,274	9,033	1,759	95.6	84.7
Cellulosic FTD: EtOH/FTD/GTCC	-8,508	8,905	397	-7,584	9,033	1,450	96.4	87.4
RFG	2,079	8,917	10,996	2,376	9,108	11,484		
Corn E85	-1,422	8,752	7,330	212	8,958	9,171	33.3	20.1
Corn E100	-2692	8,693	6,001	-572	8,899	8,327	45.4	27.5
Cellulosic E85: EtOH/GTCC	-5,450	8,752	3,302	-4,469	8,958	4,489	70.9	60.9
Cellulosic E100: EtOH/GTCC	-8,180	8,693	513	-6,951	8,899	1,948	95.3	83.0
Cellulosic E85: EtOH/Rankine	-5,416	8,752	3,336	-4,386	8,958	4,572	69.7	60.2
Cellulosic E100: EtOH/Rankine	-8,133	8,693	560	-6,838	8,899	2,061	94.9	82.1
Cellulosic E85: EtOH/FTD/GTCC	-5,460	8,752	3,292	-4,701	8,958	4,257	70.1	62.9
Cellulosic E100: EtOH/FTD/GTCC	-8,194	8,693	499	-7,267	8,899	1,633	95.5	85.8

Notes:

- Negative emission value indicates sequestration.
- Petroleum-based fuel — includes petroleum recovery and transportation; petroleum refining; and petroleum production, transportation, distribution, and combustion.
- For biobased fuel — includes farming, production, transportation, and combustion; assumes a net zero balance on carbon uptake during growth vs. emissions from combustion.
- GREET results analyzed are for light-duty vehicles (combined cars and trucks).
- WTP — well-to-pump stage includes feedstock, production, and transportation to refueling station.
- PTW — pump-to-wheel stage includes vehicle use (combustion).

SO_x emissions come from the production of phosphorus fertilizer. Switchgrass requires much lower P_2O_5 intensity because its root system has excellent capabilities in retaining nutrients (Ranney and Mann 1994), which translates to lower SO_x emissions. In the biofuel production stage, cellulosic bio-EtOH results in greater SO_x reductions compared to corn EtOH because of a switch to biomass-based power (from coal-based process fuel) to fuel the production process, as discussed earlier.

Most studies conducted so far have concluded that producing biofuel will double total NO_x emission compared to conventional petroleum-based fuels. This study indicates, however, that through GTCC power co-production and reduced N-fertilizer use, the total NO_x emission

TABLE 27 SO_x Emissions at Different Stages of Fuel Life Cycle (feedstock, fuel production, and vehicle operation) for Biofuels (conventional cars and LDTs, combined, in g/mi)

Fuel	Bio-EtOH	Bio-EtOH	Bio-EtOH	Bio-FTD	Bio-FTD	Bio-DME	Corn EtOH	RFG	LSD
Production scenario	EtOH/ GTCC	EtOH/ Rankine	EtOH/FTD/ GTCC	FTD/ GTCC	FTD/EtOH/ GTCC	DME/ GTCC			
Feedstock	0.025	0.027	0.024	0.023	0.018	0.024	0.157	0.048	0.036
Fuel production	0.039	0.042	0.038	0.030	0.025	0.031	0.198	0.091	0.063
Vehicle operation	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.009	0.002

Notes:

- Fuel EtOH (as unblended).
- Fuel economies: EtOH and RFG: 19.6 mpgge; LSD, DME, and FTD: 25.7 mpgge.

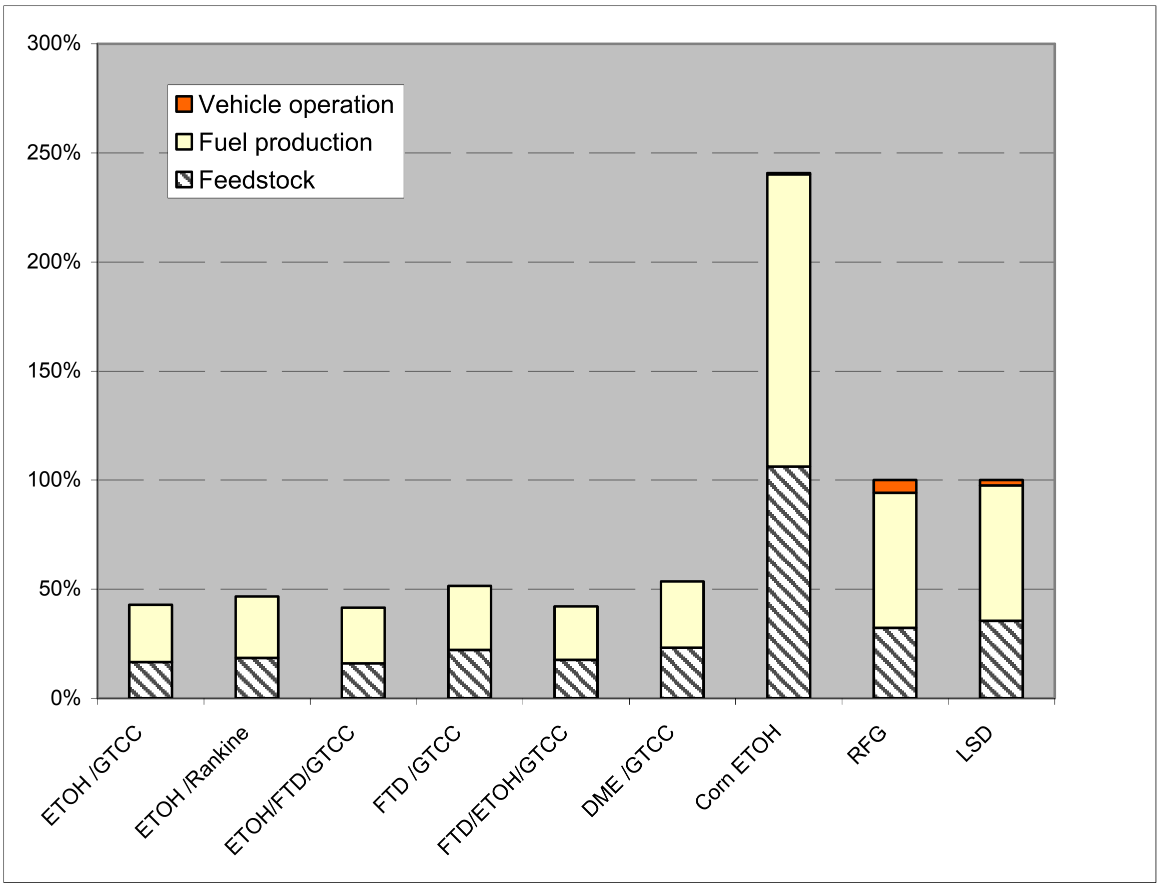

FIGURE 10 SO_x Emissions from Each Stage of Biofuel Life Cycle as Percentage of Total SO_x Emissions of Conventional Fuel, Bio-EtOH Relative to RFG, Bio-FTD and Bio-DME Relative to LSD (conventional vehicles, EtOH in E85 [as unblended], per-mile results)

increase from biofuel production could be much less than expected (Tables 19, 21, and 28; Figure 11). Bio-EtOH as E85, produced via the bio-EtOH/GTCC and bio-EtOH/bio-FTD/GTCC options (options 1 and 3) lead to a total NO_x increase of 36% (bio-EtOH/GTCC) and 27% (bio-EtOH/bio-FTD/GTCC) relative to gasoline (on a per-mile basis; Table 19). This is a significant improvement when compared to the 107% increase in NO_x emissions that results from the bio-EtOH/Rankine option (option 2) (Table 19).

Sources of NO_x emissions at the WTP stage are biomass farming, N-fertilizer production, N-fertilizer field application to switchgrass (direct and indirect emissions from soil and groundwater), biomass transportation, fuel production, and fuel transportation. We observed 14–26% decreases of NO_x at the biomass farming stage compared to corn EtOH (Table 28 and Figure 11). The differences are largely attributable to a 60% decrease in N-fertilizer use for switchgrass (Ranney and Mann 1994). As a result, the emissions from fertilizer field application and those associated with N-fertilizer production are reduced.

Changes in NO_x emissions associated with the fuel production process are more complex. Unlike the results for petroleum and fossil energy, the selection of power production technologies affects criteria pollutant emissions. GTCC power coproduction appears to be superior to steam Rankine cycle in reducing NO_x emissions, as indicated in Table 28 and Figure 11. Advanced GTCC minimizes NO_x emissions by means of its excellent low-NO_x/PM_{10} gas turbine (e.g., GE Model 7FB) combustion technology. The gas turbine produces 4.5 grams of NO_x per mmBtu of biomass-derived syngas input to the gas turbine. In contrast, emissions from a fluidized-bed combustion (FBC) boiler are up to 110 grams of NO_x per mmBtu of biomass input to the boiler. The majority of NO_x emissions in the corn EtOH fuel production process are generated during the ethanol production step. Coal and natural gas (NG)-fired industrial boilers were assumed to produce steam for use in corn ethanol plants. Coal-fired industrial boilers could emit as much as 155 grams of NO_x, and NG-fired industrial boilers could emit 40-58 grams of NO_x per mmBtu input; these values are 9–34 times higher than NO_x emissions from the advanced gas turbine unit. Total NO_x analysis again demonstrates the key role of power cogeneration by advanced GTCC technology in energy consumption and emissions.

TABLE 28 NO_x Emissions at Different Stages of Fuel Life Cycle for Biofuels (conventional cars and LDTs, combined, in g/mi)

Fuel	Bio-EtOH	Bio-EtOH	Bio-EtOH	Bio-FTD	Bio-FTD	Bio-DME	Corn EtOH	RFG	LSD
Fuel production option	EtOH/GTCC	EtOH/Rankine	EtOH/FTD/GTCC	FTD/GTCC	FTD/EtOH/GTCC	DME/GTCC			
Feedstock	0.289	0.321	0.278	0.266	0.212	0.280	0.374	0.123	0.094
Fuel production	0.148	0.482	0.111	0.066	0.041	0.117	0.401	0.129	0.090
Vehicle operation	0.125	0.125	0.125	0.151	0.151	0.151	0.125	0.125	0.151

Notes:
- Fuel EtOH (as unblended).
- Fuel economies: EtOH and RFG: 19.6 mpgge; LSD, DME, and FTD: 25.7 mpgge.

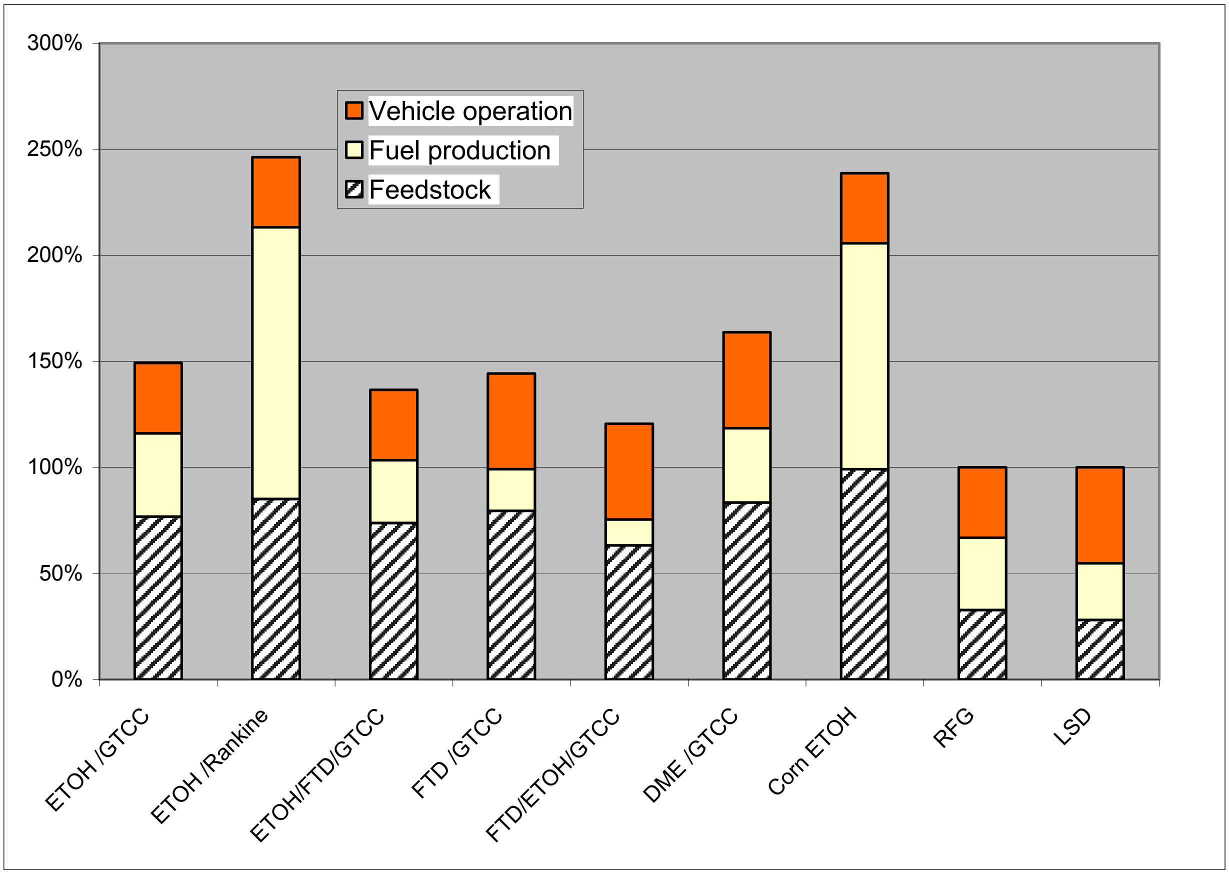

FIGURE 11 NO_x Emissions from Each Stage of Biofuel Life Cycle as Percentage of Total NO_x Emissions of Conventional Fuel, Bio-EtOH Relative to RFG, Bio-FTD and Bio-DME Relative to LSD (conventional vehicles, EtOH in E85 [as unblended], per-mile results)

Similarly, with the advanced GTCC cogeneration system, total PM_{10} emissions associated with EtOH produced from the bio-EtOH/GTCC and bio-EtOH/bio-FTD/GTCC options could be reduced by 20–25% compared with gasoline (as E85, ICE; Table 19 and Figure 5). If the power was produced by means of steam Rankine cycle instead, total PM_{10} emissions could increase up to 123% of those emitted by gasoline. These data strongly suggest that GTCC is a crucial factor in the energy and emission benefits of biofuel production. With advanced GTCC for power coproduction, biofuel ethanol plants could eliminate a significant portion of major criteria pollutants (NO_x and PM_{10}) and realize a net reduction in total PM_{10} (Figure 5).

Among the thermochemical fuels, bio-FTD has lower emissions than bio-DME for almost all criteria pollutants (Figure 7). Reduced NO_x and PM_{10} emissions result from the fuel production stage. Bio-DME emits 0.117 grams of NO_x — double the amount from bio-FTD (0.066 g) when driving a conventional CIDI vehicle for 1 mi (Table 28). The same trend occurs with PM_{10} — bio-DME produces 0.012 grams of PM_{10} (per mile), which decreases by half with bio-FTD production.

The limitation of the proposed options is an increase in total VOC emissions for almost all options (Tables 19–21). One exception is the bio-EtOH/protein/Rankine option (option 4), which is discussed in Section 4.3. The study results also reveal no improvement in total CO emissions compared with gasoline on either a per-mile or a per-gallon basis.

In urban areas, this study shows that net reductions could be achieved for almost all criteria pollutants with the exception of CO (unchanged), for nearly every biofuel production option (Figures 5–7). The biggest reductions were in urban SO_x, which decreased an average of 90% with pure biofuels and 65% with E85.

4.3 COMPARISON OF BIOFUEL PRODUCTION OPTIONS

Bio-FTD produced from the multi-fuel production option (bio-EtOH/ bio-FTD/GTCC), when analyzed by fuel alone, on per-mile, per-gge and per-mmBtu basis, appears promising for use in both conventional and HEV technologies (Figures 5–7). This fuel production option is unique in that it offers two fuels — bio-EtOH and bio-FTD — with a potential for upgrading bio-FTG to displace gasoline. Fuel products from this option can displace conventional gasoline and diesel. For each gallon of biofuel produced, bio-EtOH from this option consumed the least amount of petroleum and fossil energy and generated the lowest GHG and criteria pollutant emissions (Figure 8). Bio-FTD produced from this option also outperformed the bio-DME/GTCC and bio-FTD/GTCC options (Figure 9).

The production options analyzed are multi-fuel and multi-production in nature. Considering variations in output product(s) and their relative energy share (Table 8), especially given the large portion of electric power generated as a co-product in some cases, we recognize that an energy and emission comparison would not be complete if fuels are the only products examined. Comparison of all the output products (fuel, electricity, and chemicals) for each option would provide more insight into the benefits of biomass. GREET results were thus further analyzed for each production option on a per-ton-of-biomass-feed basis. Energy consumption and emissions associated with production of conventional fuels, electric power (U.S. mix), and chemical (soy protein) were assumed to be displaced by biofuels, bio-power export, and protein from switchgrass (Table 18). All six biofuel options provide net petroleum and fossil fuel displacements (Figure 12) and reductions in GHGs, CO_2, and SO_x (Figures 13 and 14). Table 29 shows that the four bio-EtOH options (1, 2, 3 and 4) demonstrate excellent displacement of petroleum because of the high ethanol yield. With the same amount of biomass feed, the bio-EtOH/bio-FTD/GTCC option yields the highest number of fuel and electricity energy products; bio-EtOH/GTCC follows closely. Results suggest the strong impact of different biofuel production options on energy and GHG emissions displacement. The gap in petroleum energy displaced among the six options can be as large as 7 mmBtu/dt of feed (between bio-EtOH/bio-FTD/GTCC and bio-DME/GTCC; Figure 12). For fossil fuel displacement, bio-EtOH/GTCC is clearly a winner, with about 3.5 mmBtu savings over bio-EtOH/protein/Rankine (Figure 12). Similarly, the same option can offer CO_2 and GHG benefits of 280 kg more than bio-EtOH/protein/Rankine per ton of switchgrass (Figure 13).

TABLE 29 Total Energy and Chemical Products Yields from Six Production Options (in mmBtu or kg per dry ton of biomass feed)

Production Option	1	2	3	4	5	6
	Bio-EtOH/ GTCC	Bio-EtOH/ Rankine	Bio-EtOH/bio-FTD/GTCC	Bio-EtOH/ protein/ Rankine	Bio-FTD/ GTCC	Bio-DME/ GTCC
Bio-EtOH	8.04	8.04	8.04	7.43		
Bio-FTD			1.41		3.08	
Bio-FTG			0.88		1.92	
Bio-DME						3.56
Electricity	1.90	0.99	0.17	0.29	3.11	4.06
Protein				72.53		

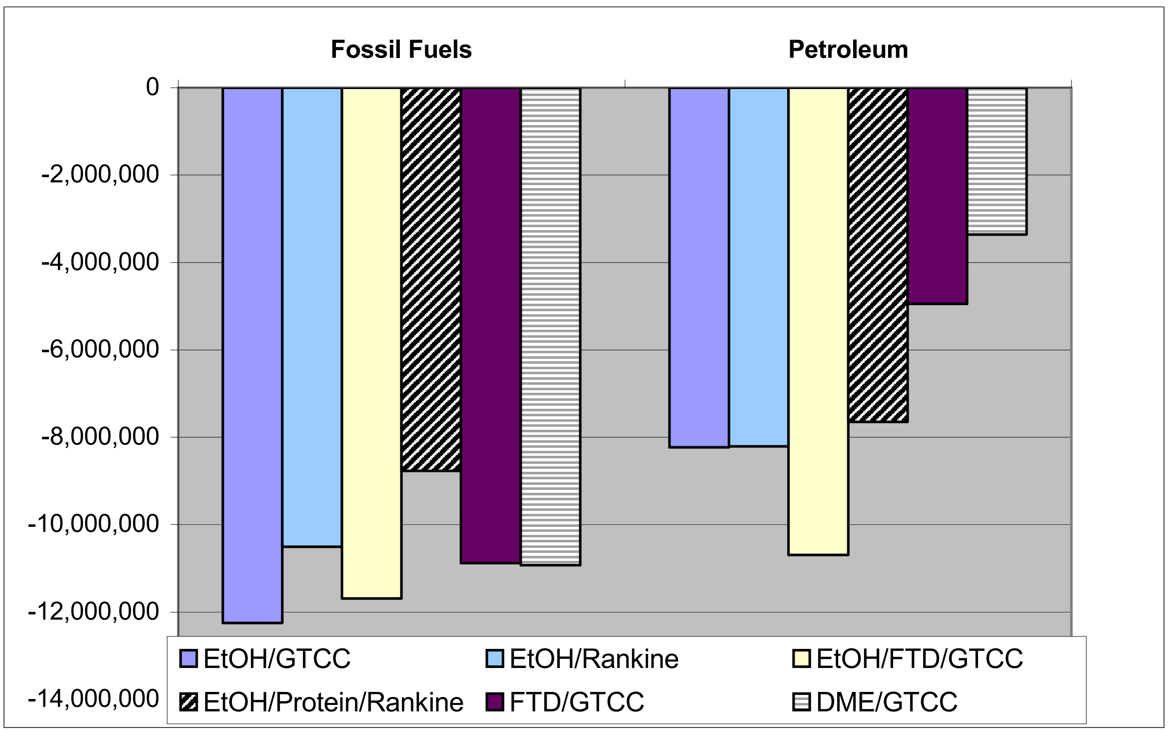

FIGURE 12 WTW Fossil Fuel Energy and Petroleum Displaced by Cellulosic Multi-Products (in Btu per dry short ton of biomass feed) (Note: negative value means net displacement)

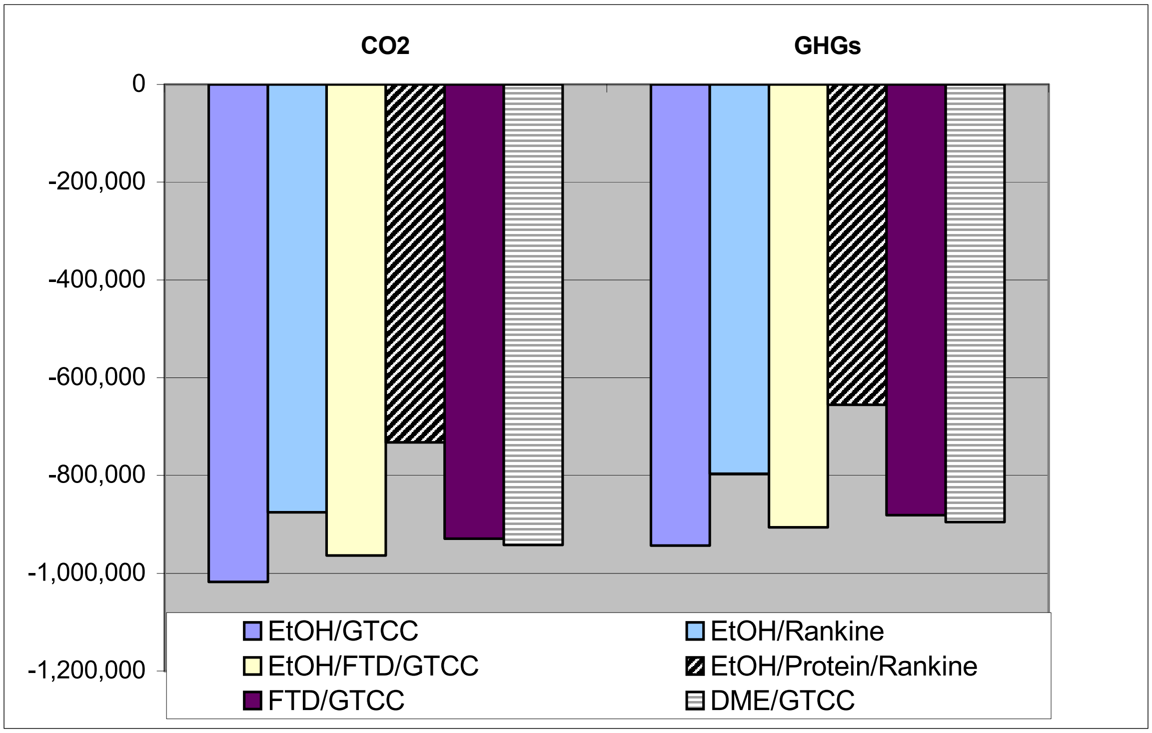

FIGURE 13 WTW CO_2 and GHG Emissions Displaced by Cellulosic Multi-Products (in grams per dry short ton of biomass feed) (Note: negative value means net displacement)

Thermochemical options (bio-FTD/GTCC and bio-DME/GTCC) lead in terms of total NO_x, PM_{10}, and SO_x reductions (Figure 15). Most biofuel/GTCC options show a net benefit in total NO_x and PM_{10} emissions. The gap between maximum displacement (negative value) and net increase (positive value) is 800 grams of PM_{10} to 1,200 grams of NO_x (Figure 15). The total SO_x emissions reduction per ton of biomass reflects a reduction in SO_x from fuel production and power generation. Bio-power displaces the U.S. electricity generation mix, which uses about 30% coal (Table 17); therefore, less SO_x is emitted from the biomass production options. The limitation of the proposed options is a net increase in total CO and VOC emissions (Figure 15) per ton of biomass feed for most of them.

The bio-EtOH/protein/Rankine production option offers a high-economic-value protein product, in addition to cellulosic fuel ethanol and power export. Readers should be cautious in judging the energy and environmental benefits based on product energy value because protein is not valued as an energy product but a biochemical (Table 29). The results shown in Figure 15 indicate that biomass-based fuels increase total VOC emissions in general, with the exception of the bio-EtOH/protein/Rankine option. In this case, organic carbon is extracted as protein product instead of being burned to produce power and VOC emissions. Unfortunately, this option shows weak performance in the rest of the parameters. In particular, the Rankine cycle is responsible for increased criteria pollutant emissions.

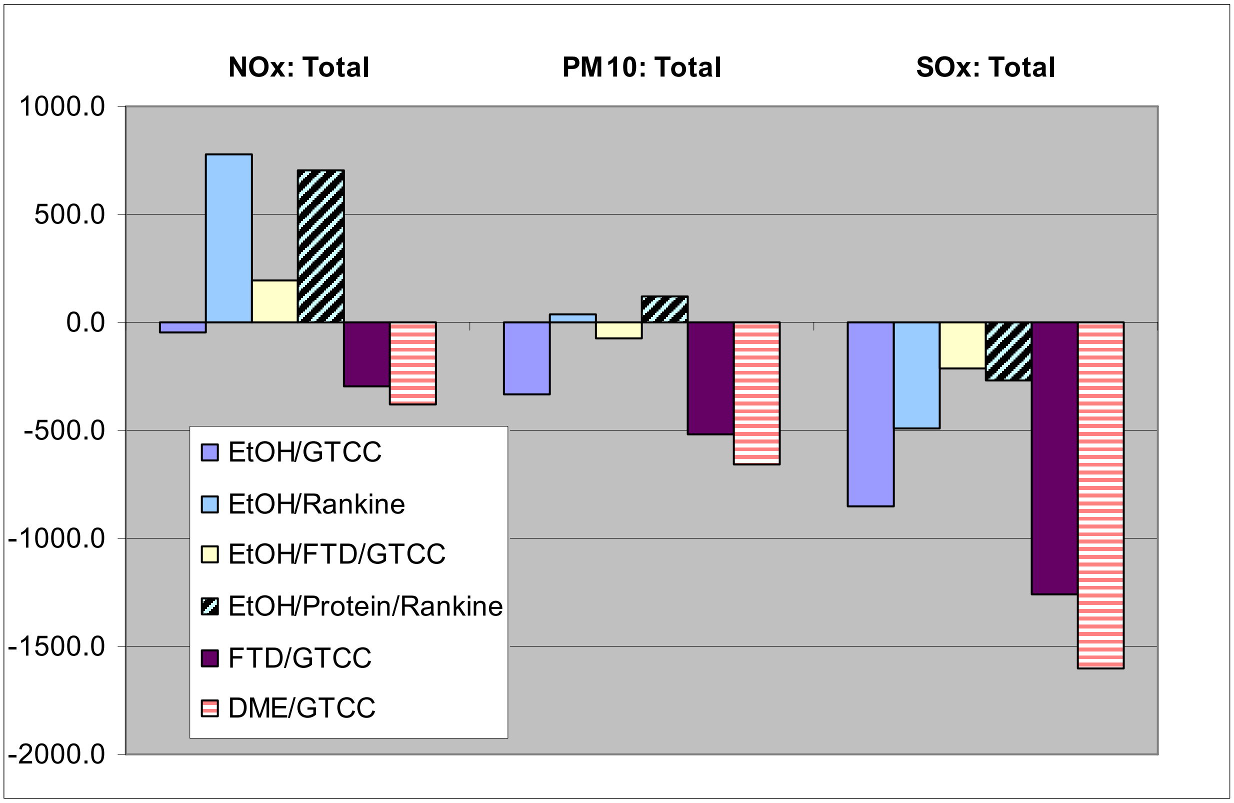

FIGURE 14 WTW Total NO_x, PM_{10}, and SO_x Emissions Displaced by Cellulosic Multi-Products (in grams per dry short ton of biomass feed) (Notes: negative value means net displacement; positive value indicates an increase)

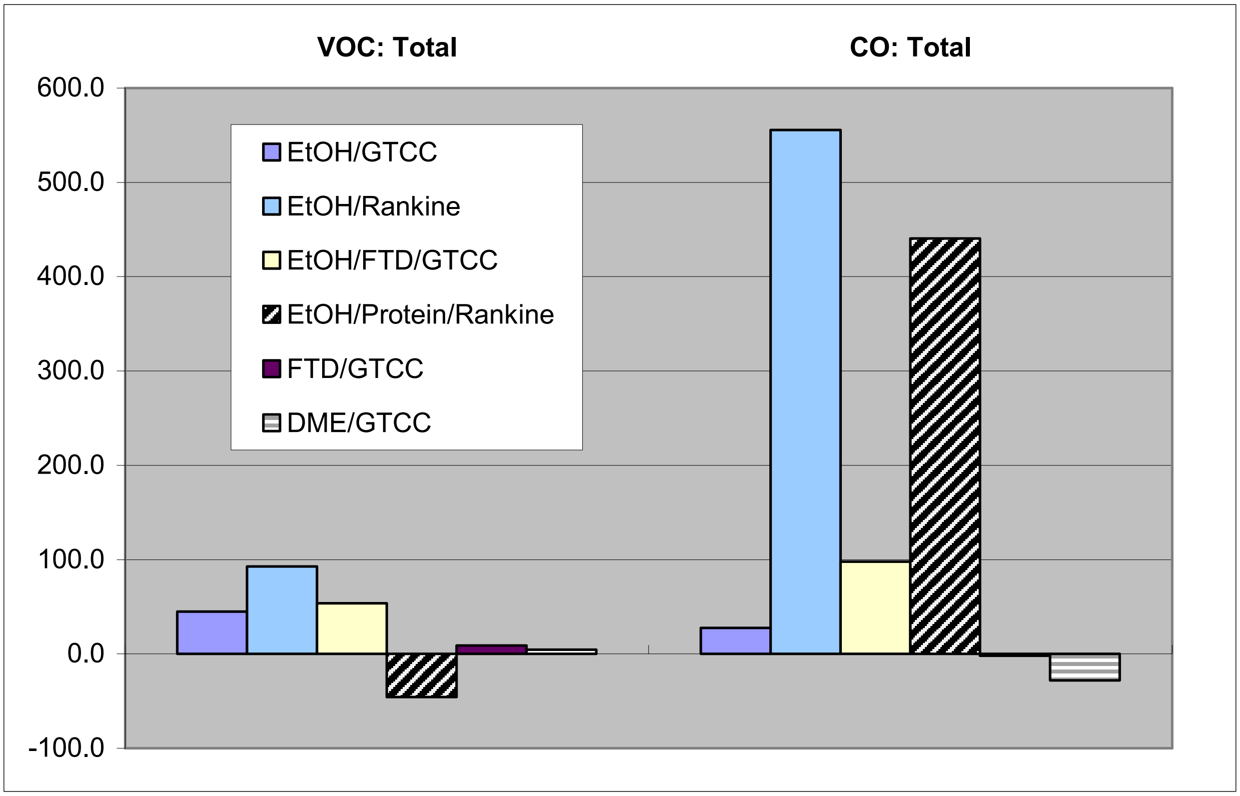

FIGURE 15 WTW Total VOC and CO Emissions Displaced by Cellulosic Multi-Products (in grams per dry short ton of biomass feed) (Notes: negative value means net displacement; positive value indicates an increase)

5 CONCLUSIONS

On the basis of our WTW results, we present the following conclusions:

- Advanced GTCC with low-NO_x gas turbine combustion technology (such as GE Model 7FB) plays a key role in providing significant reductions in criteria pollutants (NO_x and PM_{10}) during biofuel production. GTCC power co-production is superior to the steam Rankine cycle in reducing criteria pollutant emissions.

- Bio-EtOH and bio-FTD co-produced through biological and thermochemical processes with power cogeneration by GTCC (bio-EtOH/bio-FTD/GTCC) is the most effective option in that it consumes the least petroleum and fossil energy and achieves the greatest reductions in GHGs and all criteria pollutants with both conventional and HEV technologies, when compared with conventional gasoline and diesel.

- From a multiple-production perspective, for each unit of biomass, the bio-EtOH/GTCC option that co-produces cellulosic ethanol from a consolidated biological process and power from advanced GTCC is the most promising option in that it displaces the greatest amount of fossil fuel and ranks at the top in overall energy and emission benefits among the six production options.

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APPENDICES

Appendix A. ASPEN Plus™ Results of the Six Biofuel Production Options

1. Bio-EtOH with cogeneration of power by means of gas turbine combined-cycle (GTCC) power **(bio-EtOH/GTCC)**
2. Bio-EtOH with cogeneration of power by means of steam Rankine cycle power **(bio-EtOH/Rankine)**
3. Bio-EtOH and bio-FTD with cogeneration of power by means of GTCC **(bio-EtOH/bio-FTD/GTCC)**
4. Bio-EtOH and protein with cogeneration of power by means of steam Rankine cycle **(bio-EtOH/protein/Rankine)**
5. Bio-DME with cogeneration of power by means of GTCC **(bio-DME/GTCC)**
6. Bio-FTD with cogeneration of power by means of GTCC **(bio-FTD/GTCC)**

A-1. Product Options 1 and 2: Bio-EtOH/GTCC and bio-EtOH/Rankine

TABLE A-1 Bioethanol/Rankine Energy Balance

Adv. Ethanol/Rankine Cycle Simulation Results

	Mass Flow		Heating Values, MW LHV	HHV	Efficiency LHV	HHV
Input Biomass	5000.00	Tons/day	887.25	981.23		
Bioethanol	18.18	Kg/Sec	487.29	540.23	54.92%	55.06%
Power		MW	66.01	66.01	7.44%	6.73%
Total Efficiency					**62.36%**	**61.78%**

Exported Electricity Calculation	
ST Power, KW	104521
GT Power, KW	0
Onsite Use for Thermochemical/Power (-), KW	5633
Power Use for Bioethanol process (-), KW	32881
	0
Net Power Output, KW	66008

TABLE A-2 Mass Balance for the Power Island of the Bioethanol/Rankine Scenario

	Air to Boiler	Stream to Stack
Temperature C	25	90
Pressure bar	1.01	1.01
Mole Flow kmol/hr	39984.649	44834.014
Mass Flow kg/hr	1157941.690	1274506.350
Mass Flow kg/hr		
CO		0.001
H2		
CO2		146845.449
H2O		101132.546
O2	268049.351	135265.384
N2	875035.892	876399.779
AR	14855.081	14855.081
SO2		9.383
Mass Frac		
CO	0	1.01E-09
H2	0	1.05E-10
CO2	0	0.1152175
H2O	0	0.0793503
O2	0.2314879	0.1061316
N2	0.7556833	0.6876377
AR	0.0128288	0.0116555
CH4	0	1.94E-35
H2S	0	4.27E-25
SO2	0	7.36E-06
NH3	0	7.37E-18
Mole Frac		
CO		1 PPB
H2		1 PPB
CO2		0.074
H2O		0.125
O2	0.209	0.094
N2	0.781	0.698
AR	0.009	0.008
CH4		trace
H2S		trace
SO2		3 PPM

TABLE A-3 Bioethanol/GTCC Energy Balance

Adv. Ethanol/GTCC Simulation Results

	Mass Flow		Heating Values, MW		Efficiency	
			LHV	HHV	LHV	HHV
Input Biomass	5000.00	Tons/day	887.25	981.23		
Bioethanol	18.18	Kg/Sec	487.29	540.23	54.92%	55.06%
Power		MW	125.88	125.88	14.19%	12.83%
Total Efficiency					**69.11%**	**67.88%**

Exported Electricity Calculation	
ST Power, KW	60185
GT Power, KW	113330
Onsite Use for Thermochemical/Power (-), KW	14781
Power Use for Bioethanol process (-), KW	32856
Net Power Output, KW	125878

TABLE A-4 Mass Balance for the Power Island of the Bioethanol/GTCC Scenario

	Syngas to GT	Air to GT	GT Exhaust to HRSG	HRSG Exhaust to Stack
Temperature C	316.1	25	648	90
Pressure bar	26.83	1.01	1.07	1.01
Vapor Frac	1	1	1	1
Mole Flow kmol/hr	6127.433	33714.065	35531.676	35531.676
Mass Flow kg/hr	152082.974	976339.039	1018542.242	1018542.242
Volume Flow cum/hr	11188.286	824364.992	2555795.141	1057882.385
Mass Flow kg/hr				
H2O	32123.087		81714.455	81714.455
CO2	77619.360		146865.610	146865.610
CO	15038.148		2.691	2.691
CH4	15593.864			
H2	1501.417		0.083	0.083
N2	7367.105	737802.319	685483.158	685483.158
O2		226010.620	92239.036	92239.036
C2H4	211.038			
C2H6	225.903			
NH3	3.409			
SO2	0.001		9.383	9.383
H2S	4.991			
TAR	522.605			
AR	1872.047	12525.328	12226.895	12226.895
Mass Frac				
H2O	0.211		0.080	0.080
CO2	0.510		0.144	0.144
CO	0.099		3 PPM	3 PPM
CH4	0.103			
H2	0.010		82 PPB	82 PPB
N2	0.048	0.756	0.673	0.673
O2	trace	0.231	0.091	0.091
C2H4	0.001			
C2H6	0.001			
NH3	22 PPM		trace	trace
SO2	3 PPB		9 PPM	9 PPM
H2S	33 PPM		trace	trace
TAR	0.003			
AR	0.012	0.013	0.012	0.012
Mole Flow kmol/hr				
H2O	1783.102		4535.841	4535.841
CO2	1763.684		3337.112	3337.112
CO	536.877		0.096	0.096
CH4	972.019			
H2	744.795		0.041	0.041
N2	262.984	26337.428	24469.791	24469.791
O2		7063.097	2882.578	2882.578
C2H4	7.523			
C2H6	7.513			
NH3	0.200			
SO2			0.146	0.146
H2S	0.146			
TAR	1.728			
AR	46.862	313.541	306.070	306.070
Mole Frac				
H2O	0.291		0.128	0.128
CO2	0.288		0.094	0.094
CO	0.088		3 PPM	3 PPM
CH4	0.159			
H2	0.122		1 PPM	1 PPM
N2	0.043	0.781	0.689	0.689
O2	trace	0.209	0.081	0.081
C2H4	0.001			
C2H6	0.001			
NH3	33 PPM		trace	trace
SO2	1 PPB		4 PPM	4 PPM
H2S	24 PPM		trace	trace
AR	0.008	0.009	0.009	0.009
HHV kJ/kg	8886.153			
LHV kJ/kg	7573.909			
HHV, btu/hr	1.281E+10			
LHV, btu/hr	1.092E+10			

TABLE A-5 Emissions of the Bioethanol/GTCC Scenario

NOx	ppmvd @ 15% O2	9.000
NOx AS NO2	kg/MW-hr	0.155
NOx	mg/Nm^3, dry, 15% O2	18.300
CO	ppmvd	9.000
CO	kg/MW-hr	0.024
CO	mg/Nm^3, dry	11.300
UHC	ppmvw	undetectable
UHC	kg/MW-hr	undetectable
Particulates (PM10 Front-half Filterable Only)	kg/MW-hr	0.025

SITE CONDITIONS

Elevation	meter	0.0
Site Pressure	bar	1.0135
Inlet Loss	mm H2O	76.2
Exhaust Loss	mm H2O	139.7 @ ISO Conditions
Relative Humidity	%	60
Application		Hydrogen-Cooled Generator
Power Factor (lag)		0.8
Combustion System		9/42 DLN Combustor

A-2. Production Option 3: Bio-ETOH/bio-FTD/GTCC

TABLE A-6 Bioethanol/FT Once-Through/GTCC Energy/Mass Balance

Energy Balance				
Energy Input	**MW**	**MW**	**TCF Power Consumption**	**MW**
	HHV	LHV	ASU power	-6.43
Biomass	983.22	886.80	O2 compressor power	5.00
			N2 Expander & Compressor	8.38
Efficiency	HHV	LHV	Biomass handling	0.66
Electric efficiency	1.2%	1.3%	Lock Hopper	0.52
Fuels, F-T diesel	9.4%	9.7%	Rectisol 1 power	1.02
Fuels, F-T gasoline	6.0%	6.0%	Recovery compressor	0.04
Fuels, bioEtOH	54.9%	54.9%	Syngas compressor	0.00
Electricity + fuels	71.4%	72.0%	CO2 compressor	5.79
			CO2 boost compressor	0.02
			H2 Expander	-0.06
Electricity	1.2%	1.3%	H2-feed compressor	0.09
Fuels, total	70.3%	70.7%	H2 tail gas compressor	0.03
Electricity + fuels	71.4%	72.0%	Fuel gas compressor	2.58
			Refinery	0.09
			Refrigeration duty, total	0.98
			Water cycle pumps, total	0.00
			Steam cycle pumps, total	0.82
			Sat Water recovery	-0.01
			CH4 Compressor	3.71
			Plant electricity consumption	23.24
			Bioethanol Power Consumption	**MW**
			EtOH process	32.86
			Power Output	**MW**
			Gas turbine output	31.26
			Steam turbine gross output	36.23
			Total gross output	67.49
			Net Power	**MW**
			Total gross output	67.49
			Plant electricity consumption	56.09
			Net electric output	11.40

TABLE A-7. Mass and Energy Balance of TCP, CBP, and Power Plant

Biomass	
wet tonne/hr	209.9965
dry tonne/hr	188.9968
wet kg/s	58.33235
dry kg/s	52.49911
wet tonne/day	5039.915
dry tonne/day	4535.924

Fuel Products	F-T diesel		F-T gasoline		Bioethanol	
Flowrate, kmol/s						
Flowrate, kg/s	2.007		1.261		18.177	
purity, mol %						
purity, mass %						
Recovery, %						
	HHV	LHV	HHV	LHV	HHV	LHV
Fuel, MW	92.13	86.31	58.91	53.61	539.86	487.29

TABLE A-8. Mass Balance for the Power Island of the Bioethanol/FT Once-Through/GTCC Scenario

Streams	Syngas to GT	Air to GT	CO2 to GT	ASU N2 to GT	GT Exhaust	HRSG Exhaust to Stack
Temperature C	168.1	25	136.4	465.4	663.1	90
Pressure bar	26.83	1.01	26.83	20	1.06	1.01
Vapor Frac	1	1	1	1	1	1
Mole Flow kmol/sec	0.2786	4.3299	0.4989	1.0991	3.6935	3.6935
Mass Flow kg/sec	5.4406	125.3885	21.9611	30.8937	112.3440	112.3440
Volume Flow cum/sec	0.3818	105.8711	0.6016	3.3978	270.0337	109.9696
Enthalpy MMBtu/hr	-54.0776	-0.1207	-663.5607	49.2662	-905.4208	-1152.9208
Mass Flow kg/sec						
CO	1.2465	0.0000	0.0000	0.0000	0.0014	0.0014
H2	0.1872	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.7018	0.0000	21.9597	0.0000	30.4531	30.4531
H2O	0.0008	0.0000	0.0000	0.0000	5.4415	5.4415
CH4	1.1201	0.0000	0.0000	0.0000	0.0000	0.0000
C4H10-1	0.3860	0.0000	0.0000	0.0000	0.0000	0.0000
C4H8-1	0.5066	0.0000	0.0000	0.0000	0.0000	0.0000
MEOH	0.0028	0.0000	0.0000	0.0000	0.0000	0.0000
O2	0.0000	29.0260	0.0000	0.3876	3.1137	3.1137
N2	0.6825	94.7540	0.0000	30.3316	71.8573	71.8573
AR	0.6066	1.6085	0.0000	0.1748	1.4749	1.4749
H2S	0.0000	0.0000	0.0014	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0025	0.0025
Mass Frac						
CO	0.2290	0.0000	0.0000	0.0000	0.0000	0.0000
H2	0.0340	0.0000	0.0000	0.0000	0.0000	0.0000
CO2	0.1290	0.0000	1.0000	0.0000	0.2710	0.2710
H2O	0.0000	0.0000	0.0000	0.0000	0.0480	0.0480
CH4	0.2060	0.0000	0.0000	0.0000	0.0000	0.0000
C4H10-1	0.0710	0.0000	0.0000	0.0000	0.0000	0.0000
C4H8-1	0.0930	0.0000	0.0000	0.0000	0.0000	0.0000
MEOH	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000
O2	0.0000	0.2310	0.0000	0.0130	0.0280	0.0280
N2	0.1250	0.7560	0.0000	0.9820	0.6400	0.6400
AR	0.1110	0.0130	0.0000	0.0060	0.0130	0.0130
H2S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE A-9. Emissions of the Bioethanol/FT Once-Through/GTCC Scenario

NOx	ppmvd @ 15% O2	9.000
NOx AS NO2	kg/MW-hr	0.157
NOx	mg/Nm^3, dry, 15% O2	18.500
CO	ppmvd	9.000
CO	kg/MW-hr	0.159
CO	mg/Nm^3, dry	11.300
UHC	ppmvw	undetectable
UHC	kg/MW-hr	undetectable
Particulates (PM10 Front-half Filterable Only)	kg/MW-hr	0.025

SITE CONDITIONS

Elevation	meter	0.0
Site Pressure	bar	1.0135
Inlet Loss	mm H2O	76.2
Exhaust Loss	mm H2O	139.7 @ ISO Conditions
Relative Humidity	%	60
Application		Hydrogen-Cooled Generator
Power Factor (lag)		0.8
Combustion System		9/42 DLN Combustor

A-3. Production Option 4: Bio-ETOH/Protein/Rankine

TABLE A-10. Overall Material Balance for Advanced Ethanol + Protein Production

Stream	Description	Mass Flow (kg/h)	
Inputs			
101	Biomass feed	209,961	
F712	Ammonia column steam	137,849	
F200W	Make-up water to protein extraction	373,089	
F701	Make-up NH3	2,024	
219	PT slurry dilution	522,826	
311	DAP to fermentor	393	
311A	NH3 to fermentor	0	
592	Distillation steam	82,763	
596	Molecular sieve steam	2,606	
524	CO2 scrubber water	115,292	
557	pneumapress air	13,426	
944	Cooling tower blowdown	36,791	
960	Thermochemical process blowdown	4,458	
630	WWT nutrients	1,257	
631	Coagulant polymer	1	
626	Air to aerobic reactor	4,000	
F245A	Steam to protein dryer 1	15,888	
F255	Steam to protein dryer 2	8,288	
F290	Air to protein pneumapress	55,611	
TOTAL		1,586,523	
Outputs			
550	CO2 from scrubber	59,227	Vented to atmosphere
560	Air from compressor	13,691	Vented to atmosphere
597	Mol. Sieve steam outlet	2,606	Returned to steam cycle
515	Ethanol product	61,000	Stored in tank
615	CH4 out	23,614	Input to Rankine process
620	CO2 out	4,426	Vented to atmosphere
624	Treated water out	1,175,680	Retuned to process
803	Wet residue out	84,158	Input to Rankine process
624B	Treated water bleed stream	63,323	Discharged to environment
F247	Protein product 1	12,134	Stored in warehouse
F254	Protein product 2	5,241	Stored in warehouse
F245B	Steam from protein dryer 1	15,888	Returned to Rankine process
F256	Steam from protein dryer 2	8,288	Returned to Rankine process
F233EX	Air from protein pneumapress	57,265	Vented to atmosphere
TOTAL		1,586,542	
Balance (Out – In)		19	

Ethanol yield: 97.4 gallons/dry ton biomass

Protein yield: 0.08 kg/kg dry biomass

TABLE A-11. Mass Balance for the Power Island of the Bioethanol/Protein/Rankine Scenario

	Air to Boiler	Stream to Stack
Temperature C	25	90
Pressure bar	1.01	1.01
Mole Flow kmol/hr	39984.649	44834.014
Mass Flow kg/hr	1157941.690	1274506.350
Mass Flow kg/hr		
CO		0.001
H2		
CO2		146845.449
H2O		101132.546
O2	268049.351	135265.384
N2	875035.892	876399.779
AR	14855.081	14855.081
SO2		9.383
Mass Frac		
CO	0	1.01E-09
H2	0	1.05E-10
CO2	0	0.1152175
H2O	0	0.0793503
O2	0.2314879	0.1061316
N2	0.7556833	0.6876377
AR	0.0128288	0.0116555
CH4	0	1.94E-35
H2S	0	4.27E-25
SO2	0	7.36E-06
NH3	0	7.37E-18
Mole Frac		
CO		1 PPB
H2		1 PPB
CO2		0.074
H2O		0.125
O2	0.209	0.094
N2	0.781	0.698
AR	0.009	0.008
CH4		trace
H2S		trace
SO2		3 PPM

Five streams are discharged to the environment:

- 550—CO2 from scrubber
- 560—Air from distillation bottoms pneumapress
- 620—CO2 from wastewater treatment
- 624B—Treated water bleed stream
- F233EX—Air from protein extraction pneumapress

Mass flow rates and compositions of these streams are listed in Table 2.

TABLE A-12. Mass Flow Rates and Compositions of Process Effluents to Environment

	Stream				
Component	550	560	620	624B	F233EX
Soluble Solids	0.0000	0.0000	0.0000	0.3027	0.0000
Soluble Lignin	0.0000	0.0000	0.0000	1.0723	0.0000
Xylan Oligomers	0.0000	0.0000	0.0000	0.0884	0.0000
Mannan Oligomers	0.0000	0.0000	0.0000	0.0012	0.0000
Galactan Oligomers	0.0000	0.0000	0.0000	0.0040	0.0000
Arabinan Oligomers	0.0000	0.0000	0.0000	0.0479	0.0000
Xylitol	0.0000	0.0000	0.0000	0.0389	0.0000
Protein	0.0000	0.0000	0.0000	0.2516	0.0000
Ethanol	4.2922	2.1819	0.0014	0.0546	0.0000
H2O	966.3775	265.3946	83.4968	63242.5700	1008.6050
N2	0.0000	10604.9600	3146.7480	0.8828	42658.2800
CO2	57833.8000	0.0000	848.5476	12.3087	0.0000
O2	422.5623	2818.7290	333.1495	0.1819	12952.7500
CH4	0.0000	0.0000	13.6898	0.0082	0.0000
NO2	0.0000	0.0000	0.0362	0.7217	0.0000
NH3	0.0008	0.0000	0.0000	0.0004	645.2460
Lactic Acid	0.0000	0.0001	0.0000	0.0550	0.0000
Acetic Acid	0.0000	0.2204	0.0001	0.1176	0.0000
Ammonium Acetate	0.0000	0.0000	0.0000	0.0084	0.0000
Glycerol	0.0000	0.0000	0.0000	0.0505	0.0000
Succinic Acid	0.0000	0.0000	0.0000	0.0912	0.0000
Diammonium Phosphate	0.0000	0.0000	0.0000	0.4001	0.0000
WW treatment nutrients	0.0000	0.0000	0.0000	64.0806	0.0000
SO2	0.0000	0.0000	0.0019	0.0117	0.0000
TOTAL	59,227	13,691	4,426	63,323	57,265

TABLE A-13 Ethanol Plant Overall Water Balance

Stream	Description	Mass Flow (kg/h)
Inputs		
219	Pretreated slurry dilution	522,826
524	CO2 scrubber water	115,292
944	Cooling water blowdown	36,791
F200W	Make-up water to protein extraction	373,089
960	Thermochemical process blowdown	4,458
101	Water in biomass feed	20,996
F712	Ammonia column steam	137,849
592	Make-up distillation steam	82,763
F701	NH3 Feed	10
F245A	Steam to protein dryer 1	15,888
F255	Steam to protein dryer 2	8,288
TOTAL		1,318,250
Outputs		
Stream	Description	
624	Treated water	1,174,180
803	Water in wet residue	39,355
703	Water in ethanol outlet	305
560	Water in pneumapress air outlet	265
550	Water in CO2 scrubber overhead	966
615	Water in CH4 from anaerobic digestor	901
620	Water in CO2 from aerobic digester	83
F247	Protein product 1	1,211
F254	Protein product 2	521
F245B	Steam from protein dryer 1	15,888
F256	Steam from protein dryer 2	8,288
F233EX	Protein pneumapress air outlet	1,009
624B	Treated water bleed stream	63,243
TOTAL		1,306,217
Water consumed by hydrolysis		12,670
Water released by cell growth		612
Balance (Out – In + Consumed – Released)		25

TABLE A-14 Cooling Tower Water Balance

Streams	Description	Mass Flow (kg/h)
Inputs		
941	Make-up to cooling tower	404,698
947	Cooling tower return	23,772,800
TOTAL		24,177,498
Outputs		
942	Windage Losses	23,773
946	Total cooling water out	23,772,800
949	Evaporative Losses	344,134
944	Blowdown	36,791
TOTAL		24,177,498
Balance (Out – In)		0

TABLE A-15 Plant Make-Up Water Demand

Stream	Description	Mass Flow (kg/h)
F702	Water to NH3 quench	373,089
219	Pretreated slurry dilution	522,826
524	CO2 scrubber water	115,292
941	Cooling water make-up	404,698
906	Clean-in-place water	143
905B	Make-up to thermochemical process	199,844
624	Treated wastewater	1,174,180
943	Total plant make-up water	441,712

TABLE A-16 Energy Inputs and Outputs for Biological Processing

Energy Inputs	% Feedstock LHV	% Feedstock HHV
Feedstock	100.00%	100.00%
Make-up NH3	0.84%	1.00%
WWT chemicals	0.56%	0.57%
Steam	16.56%	15.25%
Electricity	6.08%	5.59%
TOTAL	124.04%	122.41%
Energy Outputs		
Ethanol	50.95%	51.93%
CH4	13.15%	13.44%
Protein	8.18%	8.27%
Residue	23.29%	23.46%
CO2	0.03%	0.03%
Cooling duty	28.43%	26.18%
TOTAL	124.02%	123.29%
Energy Out - Energy In	-0.01%	0.88%

TABLE A-17a Overall Energy Efficiency for Ethanol/Protein/Rankine Process

		Heating Values (MW)			
	Mass Flow	LHV	HHV	LHV	HHV
Input Biomass	5,000 dry tons/day	884.36	960.46		
Bioethanol	20,288 gal/h	485.02	537.70	50.95%	51.93%
Exported Power	19,121 kW	19.12	19.12	2.16%	1.99%
Protein	15,111 kg/h	72.37	79.45	8.18%	8.27%
Total Efficiency				61.29%	62.19%

TABLE A-17b Exported Electricity Calculation

Power Source/Sink	**Electricity** (kW)
Gross Steam Turbine Power Production	66,230
Onsite Use for Thermochemical/Power Side Only	4,777
Power Use for Bioethanol process	42,332
Net Power Output	**19,121**

A-4. Production Options 5 and 6: Bio-FTD/GTCC and bio-DME/GTCC

TABLE A-18. DME/GTCC Energy Balance

Energy Balance				
Energy Input	**MW**	**MW**	**Power Consumption**	**MW**
	HHV	LHV	ASU power	-8.48
Biomass	983.22	886.80	O2 compressor power	5.44
			Nitrogen expander	-2.57
Efficiency	HHV	LHV	Biomass handling	0.66
Electric efficiency	27.4%	30.4%	Lock Hopper	0.52
Fuels, DME	24.3%	24.5%	Rectisol 1 power	2.19
Fuels, MeOH	0.0%	0.0%	Recovery compressor	0.09
Fuels, H2	0.0%	0.0%	Syngas compressor	11.65
Electricity + fuels	51.7%	54.9%	CO2 compressor	11.61
			CO2 boost compressor	0.07
			Syngas expander	-1.68
			Syngas compressor	0.02
			Methanol pump	0.01
			Refrigeration duty, total	3.01
			Water cycle pumps, total	0.06
			Steam cycle pumps, total	2.81
			Plant electricity consumption	25.41
			Power Output	**MW**
			Gas turbine output	150.74
			Steam turbine gross output	144.22
			Total gross output	294.96
			Net Power	**MW**
			Total gross output	294.96
	HHV	LHV	Plant electricity consumption	25.41
Net Output	508.28	486.70	Net electric output	269.55

Fuel Products	DME		MeOH		H2	
Flowrate, kmol/s	0.163		0.000		0.000	
Flowrate, kg/s	7.530		0.000		0.000	
purity, mol %	99.9%		0.0%		0.0%	
purity, mass %	99.9%		0.0%		0.0%	
Recovery, %	96.2%		0.0%		0.0%	
	HHV	LHV	HHV	LHV	HHV	LHV
Fuel, MW	238.72	217.15	0.00	0.00	0.00	0.00

TABLE A-19 Mass Balance for the Power Island of the DME/GTCC Scenario

	Air to GT	Syngas to GT	GT Exhaust	HRSG Exhaust
Temperature C	25	147.1	653.4	90
Pressure bar	1.01	26.83	1.06	1.01
Vapor Frac	1	1	1	1
Mole Flow kmol/sec	14.603	2.049	14.315	14.315
Mass Flow kg/sec	422.899	31.859	419.678	419.678
Volume Flow cum/sec	357.072	2.654	1035.799	426.214
Enthalpy MMBtu/hr	-0.407	-712.482	-2654.983	-3575.247
Mass Flow kg/sec				
MEOH	0	0	0	0
DME	0	0.293	0	0
CO	0	11.027	0.001	0.001
H2	0	1.783	0	0
CO2	0	8.119	76.009	76.009
H2O	0	6.327	29.515	29.515
O2	97.896	0	46.773	46.773
N2	319.578	0.595	262.182	262.182
AR	5.425	0.651	5.092	5.092
CH4	0	3.063	0	0
H2S	0	0	0	0
COS	0	0	0	0
C	0	0	0	0
SO2	0	0	0.105	0.105

TABLE A-20 Emissions of the DME/GTCC Scenario

NOx	ppmvd @ 15% O2	9.000
NOx AS NO2	kg/MW-hr	0.157
NOx	mg/Nm^3, dry, 15% O2	18.500
CO	ppmvd	9.000
CO	kg/MW-hr	0.029
CO	mg/Nm^3, dry	11.300
UHC	ppmvw	undetectable
UHC	kg/MW-hr	undetectable
Particulates (PM10 Front-half Filterable Only)	kg/MW-hr	0.025

SITE CONDITIONS

Elevation	meter	0.0
Site Pressure	bar	1.0135
Inlet Loss	mm H2O	76.2
Exhaust Loss	mm H2O	139.7 @ ISO Conditions
Relative Humidity	%	60
Application		Hydrogen-Cooled Generator
Power Factor (lag)		0.8
Combustion System		9/42 DLN Combustor

TABLE A-21 FT/GTCC Energy Balance

Energy Balance				
Energy Input	**MW**	**MW**	**Power Consumption**	**MW**
	HHV	LHV	ASU power	-8.48
Biomass	983.22	886.80	O2 compressor power	5.44
			Nitrogen expander	-2.57
Efficiency	HHV	LHV	Biomass handling	0.66
Electric efficiency	21.0%	23.3%	Lock Hopper	0.52
Fuels, F-T diesel	20.4%	21.2%	Rectisol 1 power	2.18
Fuels, F-T gasoline	13.1%	13.2%	Recovery compressor	0.09
	0.0%	0.0%	Syngas compressor	0.00
Electricity + fuels	54.5%	57.7%	CO2 compressor	12.44
			CO2 boost compressor	0.07
			H2 Expander	-0.17
Electricity	21.0%	23.3%	H2-feed compressor	0.19
Fuels, total	33.5%	34.4%	H2 tail gas compressor	0.08
Electricity + fuels	54.5%	57.7%	Fuel gas compressor	5.74
			Refinery	0.20
			Refrigeration duty, total	2.41
			Water cycle pumps, total	0.00
			Steam cycle pumps, total	2.20
			Plant electricity consumption	21.00
			Power Output	**MW**
			Gas turbine output	86.69
			Steam turbine gross output	140.91
			Total gross output	227.60
			Net Power	**MW**
			Total gross output	227.60
	HHV	LHV	Plant electricity consumption	21.00
Net Output	535.91	511.67	Net electric output	206.60

Fuel Products	F-T diesel		F-T gasoline		
Flowrate, kmol/s					
Flowrate, kg/s	4.376		2.751		
purity, mol %					
purity, mass %					
Recovery, %					
	HHV	LHV	HHV	LHV	
Fuel, MW	200.84	188.15	128.47	116.92	

TABLE A-22 Mass Balance for the Power Island of the FT/GTCC Scenario

	Air to GT	Syngas to GT	GT Exhaust	HRSG Exhaust
Temperature C	25	164.3	658.6	90
Pressure bar	1.01	26.83	1.06	1.01
Vapor Frac	1	1	1	1
Mole Flow kmol/sec	10.56	0.621	9.442	9.442
Mass Flow kg/sec	305.81	12.715	286.785	286.785
Volume Flow cum/sec	258.208	0.841	686.983	281.143
Enthalpy MMBtu/hr	-0.294	-162.4	-1972.842	-2594.305
Mass Flow kg/sec				
CO	0	3.952	0.001	0.001
H2	0	0.33	0	0
CO2	0	2.081	67.898	67.898
H2O	0	0.002	12.789	12.789
CH4	0	3.15	0	0
C4H10-1	0	0.842	0	0
C9H20-1	0	0	0	0
C15H32	0	0	0	0
C21H44	0	0	0	0
C4H8-1	0	1.106	0	0
C9H18-1	0	0	0	0
C15H30	0	0	0	0
C21OL	0	0	0	0
MEOH	0	0.006	0	0
DME	0	0	0	0
O2	70.791	0	28.701	28.701
N2	231.095	0.595	173.7	173.7
AR	3.923	0.652	3.591	3.591
H2S	0	0	0	0
COS	0	0	0	0
C	0	0	0	0
SO2	0	0	0.105	0.105

TABLE A-23 Emissions of the DME/GTCC Scenario

NOx	ppmvd @ 15% O2	9.000
NOx AS NO2	kg/MW-hr	0.157
NOx	mg/Nm^3, dry, 15% O2	18.500
CO	ppmvd	9.000
CO	kg/MW-hr	0.048
CO	mg/Nm^3, dry	11.300
UHC	ppmvw	undetectable
UHC	kg/MW-hr	undetectable
Particulates (PM10 Front-half Filterable Only)	kg/MW-hr	0.025

SITE CONDITIONS

Elevation	meter	0.0
Site Pressure	bar	1.0135
Inlet Loss	mm H2O	76.2
Exhaust Loss	mm H2O	139.7 @ ISO Conditions
Relative Humidity	%	60
Application		Hydrogen-Cooled Generator
Power Factor (lag)		0.8
Combustion System		9/42 DLN Combustor

APPENDIX B GREET Results of Power Credit Displacement and Allocation Method for Biofuel Production Options of Bio-EtOH/GTCC and Bio-EtOH/Rankine

TABLE B-1 WTW Results of Bio-EtOH/GTCC and Bio-EtOH/Rankine Using Displacement Method in Btu or Grams per Mile Driven with FFV and HEV

	EtOH/GTCC						EtOH/Rankine					
	FFV			HEV			FFV			HEV		
	WTP	PTW	Total	WTP	PTW	Total	WTP	PTW	Total	WTP	PTW	Total
Total Energy	422,771	1,000,000	1,422,771	422,771	1,000,000	1,422,771	682,414	1,000,000	1,682,414	682,414	1,000,000	1,682,414
Fossil Fuels	-293,340	0	-293,340	-293,340	0	-293,340	-77,531	0	-77,531	-77,531	0	-77,531
Petroleum	86,648	0	86,648	86,648	0	86,648	89,625	0	89,625	89,625	0	89,625
CO2	-106,667	74,880	-31,787	-106,667	74,861	-31,806	-89,025	74,880	-14,145	-89,025	74,861	-14,165
CH4	-43.566	16.461	-27.105	-43.566	23.432	-20.134	-10.108	16.461	6.354	-10.108	23.432	13.325
N2O	42.667	4.727	47.394	42.667	6.729	49.396	40.506	4.727	45.233	40.506	6.729	47.235
GHGs	-95,039	76,658	-18,382	-95,039	77,391	-17,648	-77,268	76,658	-610	-77,268	77,391	123
VOC: Total	29.143	39.423	68.566	29.143	51.263	80.406	34.433	39.423	73.855	34.433	51.263	85.695
CO: Total	16.453	1102.489	1118.943	16.453	1484.956	1501.409	71.775	1102.489	1174.264	71.775	1484.956	1556.731
NOx: Total	36.985	21.054	58.038	36.985	24.898	61.883	124.455	21.054	145.508	124.455	24.898	149.353
PM10: Total	-33.649	4.204	-29.445	-33.649	5.984	-27.665	10.840	4.153	14.993	10.840	5.912	16.752
SOx: Total	-80.457	0.000	-80.457	-80.457	0.000	-80.457	-36.136	0.000	-36.136	-36.136	0.000	-36.136
VOC: Urban	11.309	24.521	35.830	11.309	31.885	43.194	11.451	24.521	35.972	11.451	31.885	43.336
CO: Urban	-1.912	685.748	683.837	-1.912	923.643	921.731	-0.496	685.748	685.252	-0.496	923.643	923.146
NOx: Urban	-5.611	13.095	7.485	-5.611	15.487	9.876	-0.928	13.095	12.167	-0.928	15.487	14.558
PM10: Urban	-0.310	2.615	2.305	-0.310	3.722	3.412	-0.098	2.583	2.485	-0.098	3.677	3.579
SOx: Urban	-13.617	0.000	-13.617	-13.617	0.000	-13.617	-6.636	0.000	-6.636	-6.636	0.000	-6.636

TABLE B-2 WTW Results of Bio-EtOH/GTCC and Bio-EtOH/Rankine Using Allocation Method in Btu or Grams per Mile Driven with FFV and HEV

	EtOH/GTCC						EtOH/Rankine					
	FFV			HEV			FFV			HEV		
	WTP	PTW	Total	WTP	PTW	Total	WTP	PTW	Total	WTP	PTW	Total
Total Energy	788,811	1,000,000	1,788,811	788,811	1,000,000	1,788,811	771,446	1,000,000	1,771,446	771,446	1,000,000	1,771,446
Fossil Fuels	134,681	0	134,681	134,681	0	134,681	147,065	0	147,065	147,065	0	147,065
Petroleum	79,798	0	79,798	79,798	0	79,798	86,405	0	86,405	86,405	0	86,405
CO2	-70,246	74,880	4,634	-70,246	74,861	4,615	-69,840	74,880	5,040	-69,840	74,861	5,021
CH4	17.451	16.461	33.913	17.451	23.432	40.884	21.652	16.461	38.114	21.652	23.432	45.084
N2O	34.409	4.727	39.136	34.409	6.729	41.138	36.161	4.727	40.889	36.161	6.729	42.891
GHGs	-59,660	76,658	16,998	-59,660	77,391	17,732	-58,638	76,658	18,020	-58,638	77,391	18,754
VOC: Total	29.748	39.423	69.171	29.748	51.263	81.010	34.286	39.423	73.709	34.286	51.263	85.549
CO: Total	22.987	1102.489	1125.476	22.987	1484.956	1507.943	70.190	1102.489	1172.680	70.190	1484.956	1555.146
NOx: Total	73.810	21.054	94.864	73.810	24.898	98.708	137.545	21.054	158.598	137.545	24.898	162.443
PM10: Total	4.661	4.204	8.865	4.661	5.984	10.645	28.152	4.153	32.305	28.152	5.912	34.064
SOx: Total	10.670	0.391	11.062	10.670	0.391	11.062	11.642	0.391	12.033	11.642	0.391	12.033
VOC: Urban	11.557	24.521	36.078	11.557	31.885	43.442	11.582	24.521	36.103	11.582	31.885	43.467
CO: Urban	0.955	685.748	686.703	0.955	923.643	924.597	1.006	685.748	686.755	1.006	923.643	924.649
NOx: Urban	3.893	13.095	16.989	3.893	15.487	19.380	4.054	13.095	17.149	4.054	15.487	19.541
PM10: Urban	0.122	2.615	2.737	0.122	3.722	3.844	0.129	2.583	2.712	0.129	3.677	3.806
SOx: Urban	0.947	0.243	1.190	0.947	0.243	1.190	1.014	0.243	1.257	1.014	0.243	1.257

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