Energy and Emission Benefits of Alternative Transportation Liquid Fuels Derived from Switchgrass: A Fuel Life Cycle Assessment

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REVIEW

Energy and Emission Benefits of Alternative Transportation Liquid Fuels Derived from Switchgrass: A Fuel Life Cycle Assessment

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We conducted a mobility chains, or well-to-wheels (WTW), analysis to assess the energy and emission benefits of cellulosic biomass for the U.S. transportation sector in the years 2015−2030. We estimated the life-cycle energy consumption and emissions associated with biofuel production and use in light-duty vehicle (LDV) technologies by using the *G*reenhouse gases, *R*egulated *E*missions, and *E*nergy use in *T*ransportation (*GREET*) model. Analysis of biofuel production was based on ASPEN Plus model simulation of 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. Our study revealed that cellulosic biofuels as E85 (mixture of 85% ethanol and 15% gasoline by volume), FTD, and DME offer substantial savings in petroleum (66−93%) and fossil energy (65−88%) consumption on a per-mile basis. Decreased fossil fuel use translates to 82−87% reductions in greenhouse gas emissions across all unblended cellulosic biofuels. In urban areas, our study shows net reductions for almost all criteria pollutants, with the exception of carbon monoxide (unchanged), for each of the biofuel production option examined. Conventional and hybrid electric vehicles, when fueled with E85, could reduce total sulfur oxide (SO_x) emissions to 39−43% of those generated by vehicles fueled with gasoline. By using bio-FTD and bio-DME in place of diesel, SO_x emissions are reduced to 46−58% of those generated by diesel-fueled vehicles. Six different fuel production options were compared. This study strongly suggests that integrated heat and power co-generation by means of gas turbine combined cycle is a crucial factor in the energy savings and emission reductions.

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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 ultimate goals are to reduce the dependence of the U.S. transportation sector on petroleum fuel and limit greenhouse gas (GHG) emissions. 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 primary production option so far in the United States, Brazil, and some other countries. There has also been a significant increase in biodiesel production from soybeans (in the United States) and rapeseed (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, fractionation, and conversion technologies for the ligninocellulose 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. These R&DD advances have emerged into a biorefinery concept that offers multiple products: biofuels, chemicals, protein, steam, and electricity are co-produced to maximize the utility of the feedstocks and improve the energy efficiencies and economics of the bio-products. Such a biorefinery complex could include biological processes, thermochemical processes, and steam and electricity co-generation.

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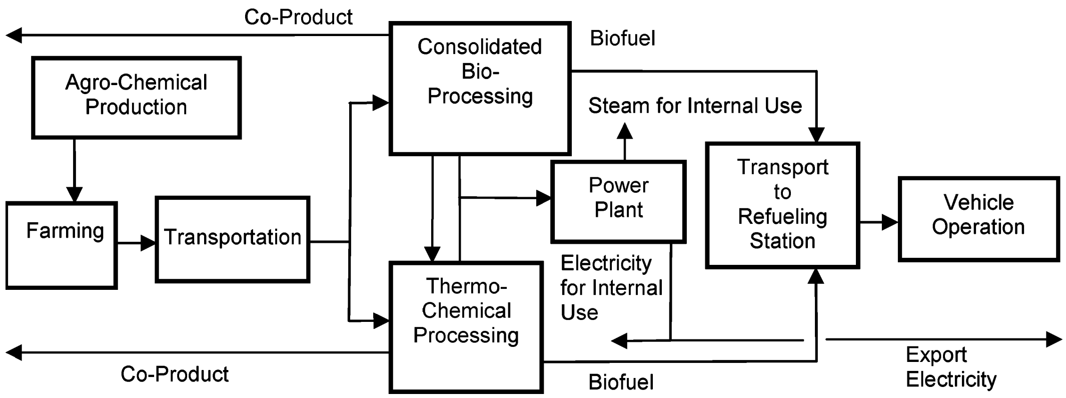

Figure 1. *GREET* modeling boundary for biofuels production from cellulosic biomass.

As members of a research team for The Role of Biomass in America's Energy Future (RBAEF) project, we conducted this study to analyze and assess the potential of biorefinery-produced cellulosic transportation fuels in light-duty vehicles (LDVs). The goal of the RBAEF project is to examine the potential of cellulosic biofuel production and use in the years 2015−2030 by considering technological improvements that could be made with aggressive R&DD efforts. Cellulosic biofuels analyzed in this work are ethanol, FTD, and DME. Use of DME in vehicle systems is currently facing some significant technical hurdles. We believe that there is a much higher potential for the use of bio-FTD to replace conventional diesel. Therefore, our inclusion of bio-DME in this analysis is for comparison purpose only. We selected fuel production and utilization performance parameters on the basis of the most likely estimates by experts to achieve optimal energy efficiencies and conversion yields and to control emissions to meet U.S. Environmental Protection Agency (EPA) requirements. Our study examined an advanced biological process; a thermochemical process; and a combined heat and power plant to co-produce fuel, steam, electricity, and other fuels/products. Fuel production processes were designed and simulated by researchers at Dartmouth College and Princeton University (*1*). Vehicle technologies employing biofuels were provided by the Union of Concerned Scientists (UCS). Argonne National Laboratory (ANL) conducted 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. We are fully aware that the technologies and processes described here are at the early stages of R&DD and that their feasibility remains to be demonstrated. However, the proposed process presents a new concept of bio-refining that has generated increasing interest among industrial, academic, governmental, and nongovernmental organizations (NGOs). As a result of the Energy Policy Act of 2005 that includes Renewable Fuels Standards (RFSs) and the subsequent establishments of RFSs at the state level, the biofuel industry will likely double production over the next several years. This study provides an early benefit analysis for the processes fed by switchgrass feedstocks and for biofuel products, compares these processes and products with those of the existing fuel industry, and provides information to support biofuel product selection and biorefinery development.

In 1995, with support from the U.S. Department of Energy (DOE), the Center for Transportation Research at ANL began to develop the *GREET* model to estimate the full fuel-cycle energy and emissions impacts of alternative transportation fuels and advanced vehicle technologies. *GREET* includes total energy use (all energy sources), petroleum use, and fossil energy use (petroleum, natural gas [NG], and coal). For emissions, the model estimates three major GHGs (carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]) and five criteria pollutants (volatile organic compounds [VOCs], carbon monoxide [CO], nitrogen oxide [NO_x], particulate matter with diameters of 10 μm or less [PM_{10}], and sulfur oxides [SO_x]) from various vehicle systems. Since its first release in 1996 (*2*), the *GREET* model has been expanded, updated, and upgraded. The most recent version of the *GREET* model consists of more than 85 fuel production pathways and 70 vehicle/fuel systems.

Although this work covers the fuel life cycle, from cellulosic feedstocks production, to fuel processing, to vehicle operations, it does not include farm equipment and vehicle manufacturing, capital equipment in manufacturing facilities, and transportation infrastructures. *GREET* estimates include energy use and emissions associated with different fuel production options and light-duty vehicle (LDV) technologies. The results for the six biofuel production options are compared with one another and with vehicle technologies fueled by gasoline and diesel.

Modeling Methodology and Assumptions

1. 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 during vehicle operation. The *GREET* modeling boundary for this study is depicted in Figure 1. Switchgrass was selected as the biomass feedstock. 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 gas turbine combined cycle (GTCC) or a steam Rankine cycle power plant. Fuel products are then transported to refueling stations via pipelines, rails, barges, and trucks. Bio-EtOH is used as E85 (mixture of 85% ethanol and 15% gasoline by volume) to fuel flexible-fuel vehicles (FFVs) and hybrid electric vehicles (HEVs). Bio-DME and bio-FTD are used to fuel compression-ignition, direct-injection (CIDI) vehicles and HEVs. Model parameters and assumptions were chosen for the year 2015. Under the project assumption that mature technologies will be introduced starting in the year 2015, results will be the same over the simulation period (2015−2030).

1.1. *Feedstock Farming.* Factors considered for the farming process include energy use during farming and biomass transportation, fertilizer and pesticide use, N_2O emissions from farms, and CO_2 emissions/sequestrations that occur at the farms. The key *GREET* input data for switchgrass farming used in this

Table 1. Farming Energy, Fertilizer, and Pesticide Use

	corn (per bushel)	switchgrass (per dry ton)
farming energy (Bti)	22 500	217 230
fertilizer		
nitrogen (g)	460.0	10 635
phosphate (P_2O_5) (g)	165.0	142.0
potash (K_2O) (g)	205.0	226.0
herbicide (g)	8.10	28.00
insecticide (g)	0.68	0.00

study is summarized in Tables 1 and 2. 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 2003 study (*3*) and a U.S. Department of Agriculture (USDA) survey (*4*). Farming and chemical use input data for switchgrass were derived from *GREET* default values (*2*). The energy and emissions values for fertilizer manufacturing and transportation used in this study were obtained from Wang et al. (*3*). Feedstock switchgrass contains (w/w) 47% carbon, 5.3% hydrogen, and 41.4% oxygen with a low heating value (LHV) of 16.7 MJ/kg (dry basis).

No extensive field studies have been conducted to quantify N_2O emissions resulting from switchgrass farming. Sources of N_2O emissions can be direct or indirect. Direct emissions are those released to the air from soil by nitrogen (N)-fertilizer and by microbial nitrification and denitrification in soil; indirect N_2O emissions come from N-fertilizer surface runoff and leaching to groundwater as nitrate and then transforming to N_2O as a result of microbial activities. A recent study assumed total N_2O emissions from corn farming, as a percentage of total N-fertilizer, to be 2.0% (*3*). In the case of switchgrass, the amount of N-fertilizer runoff is less than that of corn, because the long perennial root system of switchgrass is capable of retaining nutrients and preventing runoff of N-fertilizer (*5*). On the basis of these considerations, we assume that switchgrass N_2O emissions during farming are 75% of those associated with corn growing. Thus, a value of 1.5% N-fertilizer application emitted as N_2O was used as our input to *GREET* (Table 2).

Cultivation of switchgrass affects the CO_2 content in the soil. The improvement in soil carbon content is significant when switchgrass is cultivated in cropland (*6*). Together with the amount of carbon contained in the harvested switchgrass and remaining root, these changes lead to a net CO_2 sequestration (*6*−*8*). In a soil carbon study by Andress (*8*), the equilibrium soil carbon sequestration (per unit of biomass) is estimated to be 48,800 g of CO_2 per dry ton (dt) of switchgrass when 39% of switchgrass is cultivated on cropland and the remainder is cultivated on pastureland and other sources. Assume the percent of cropland for switchgrass cultivation is around 38−39%, the CO_2 sequestration value would be 48,500 g CO_2/dt switchgrass (Table 2).

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 (*9*). Thus an average distance of 100 mi (round trip) between farm and the fuel plant was applied for this study (Table 2). Harvested switchgrass feedstocks are transported to biofuel plants by means of Class 8b heavy-duty trucks with a payload of 17 tons and a fuel economy of 5.0 mpg diesel.

1.2. *Biofuel Production Options.* The project aims at a fuel/power co-production, multi-fuel and multi-product biorefinery approach employing both biological and thermochemical processes. We conducted a comparative analysis for six fuel

Table 2. Assumptions of Emissions and Feedstock Transportation

parameter	value
N_2O emissions from farming as % of N in N-fertilizer	
corn	2.0
switchgrass	1.5
CO_2 emissions or sequestrations from land use changes	
corn (g/bushel)[a]	195
switchgrass (g/dry ton)	−48,500
heavy-duty truck cargo payload (tons)	17
fuel economy of the heavy-duty truck (mpg diesel)	5.0
distance from farm to processing facility, round trip (mi)	100

[a] Source: Brinkman et al., 2005 (*10*).

production options, listed in Table 3. 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.

Bio-EtOH is the only fuel derived from consolidated bioprocessing (CBP); fuels produced via thermochemical plant (TCP) processes 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; fermentation is used for ethanol and gasification 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 Fischer-Tropsch naphtha and Fischer-Tropsch gasoline (FTG) are generated. Because of uncertainties about the fuel characteristics, 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* per-mile analysis. Table 4 summarizes *GREET* input parameters for each production option.

1.3. *Biofuel Production Process.* Total feedstocks of 5,000 tons (4,536 metric tonnes) per day (dry basis) are processed in an advanced ethanol plant by means of ammonia fiber explosion (AFEX) pretreatment and CBP, which involves the following steps: hydrolysis, fermentation, cellulase production, and separation to produce fuel ethanol. Wastewater from CBP is discharged into an on-site wastewater treatment plant (WWTP), where it undergoes anaerobic and aerobic digestion. In the 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 2−4. Figure 2 describes 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). Detailed descriptions of the power production processes are presented in Larson, Celik, and Jin (*11*). ASPEN results for the different production options are described in Lynd et al. (*1*) and an ANL report (*12*).

1.4. *Emissions from Production Processes.* Process emissions are estimated on the basis of source combustibility for each production option. Noncombustion 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 WWTP, and small amounts of organics emitted from the distillation step

Table 3. Fuel Production Options from Biological and Thermochemical Process[a]

option	power export	fuel product	co-product fuel	co-product pthers
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

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

during ethanol separation. Combustion emissions are primarily generated as exhaust gas from the heat recovery steam generation (HRSG) unit in the power plant. Sulfur-containing acid gas from the Rectisol unit is attributable to HRSG emissions. This stream is converted to sulfur dioxide (SO_2) in a gas or steam turbine and subsequently emitted from the HRSG unit. Residual sludge from WWTP digesters is another source contributing to HRSG emissions. The sludge is combusted in a gas or steam turbine before entering the HRSG unit. The resultant gas stream therefore contains CO_2, SO_x, VOCs, PM10, and NO_x.

In the power plant design, a GE model 7FB gas turbine, which represents the most advanced gas turbine technology at this production scale, was selected for GTCC. *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. Because N_2O estimates are not available from ASPEN Plus simulations, these estimates for GTCC options were based on a *GREET* default emission value of 1.5 g/mmBtu of gas turbine input energy. Emissions of VOCs, CO, SO_2, and CH_4 from the biological process, thermochemical process, and power plant were summed to obtain total system emissions.

1.5. *Vehicle Fuel Economy.* Fuel economy and vehicle miles traveled (VMT) for conventional and hybrid vehicles were provided by UCS. It is predicted that baseline vehicle VMT will increase annually for each vehicle/fuel system under a business-as-usual scenario. Changes in fleet average fuel economy for the vehicle/fuel system of interest are negligible for the 2015−2030 time periods (*12*). In this study, bio-FTD and bio-DME are compression-ignition (CI) engine fuels that are assumed to displace conventional diesel. In the United States, CI engines are used mainly in heavy-duty trucks (HDTs). Thus, a WTW analysis should include both HDTs and LDTs (light-duty trucks). However, available resources did not allow us to address vehicle fuel economy and VMT projections for HDTs. Thus, the WTW analysis is limited to LDVs (cars and LDTs). At present, the LDV market encompasses predominantly spark-ignition (SI) engines. To evaluate bio-FTD and bio-DME as CI engine fuels in LDVs, we assumed that CI engines penetrate the U.S. LDV market. Use of petroleum diesel to power CI engines in LDVs is followed by a fuel switch from petroleum diesel to bio-FTD or bio-DME. Finally, the effects of fuel switching are assessed. Fuel economies of cars and LDTs were combined according to the VMT shares of gasoline vehicles, because all technologies are assumed to penetrate the gasoline LDV market. Combined baseline fuel economies (by vehicle/fuel system) for the *GREET* WTW simulations are presented in Table 5.

1.6. *Vehicle Tailpipe Emissions.* Tier 2 standards for passenger cars and LDTs were adopted by EPA in 2001 and will be fully in effect in 2009. We assume all passenger cars and LDTs meet the Tier 2 standards. EPA's mobile source emission factor model, MOBILE6.2, was used to simulate emission factors for different vehicle technologies by vehicle class. Table 6 presents the emission standards that were assumed for passenger cars and LDTs for the various vehicle technologies assuming calendar year 2016, the lifetime mileage midpoint of 2010-model-year passenger cars and LDTs. Emission factors for 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 emission factors simulated by MOBILE6.2 for Tier 2 diesel vehicles are less reliable. 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. 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 included. 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 6). Other assumptions for the MOBILE6.2 model are an on-board diagnostic system, inspection and maintenance 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 from the July and January scenarios were averaged. Finally, emission factors for passenger cars and LDTs were combined by VMT share for the year 2030 for each fuel (gasoline, E85, and diesel). Table 7 lists the combined emission factors for vehicle operation by various vehicle/fuel systems.

2. Co-Product Credit Partition. We have compared four available methods to address credit partitioning of electricity and other co-products: displacement, market value, process energy input, and allocation (*13*). Each of them emphasizes a different point of view and offers advantages and disadvantages. The displacement method displaces electricity purchased from the grid, which is generated from different sources (i.e., the U.S. generation mix), with bio-electricity. In this case, the fuel production process that produces the most electricity shows huge emission benefits. Energy allocation is based on output product energy share. For each fuel production option, we first estimate total energy and emissions of the biofuels and co-products from the fuel production plant. Then we determine their energy shares based on product energy content. Finally, the total energy and emissions are allocated to each of the products and co-products by multiplying the total energy and emissions by their energy share. The energy allocation approach tends to be conservative in energy and emission credit of electricity. However, this approach treats all energy products from the production process as equal, regardless of form and quality differences. We recognize the complexity of this issue and acknowledge that, for a given fuel/process, there will be a range of emission credits by electricity production depending on the credit partitioning method used.

Our main focus for this analysis was to assess the environment and energy impacts of liquid biofuel production instead of bio-power production. The six production processes analyzed are very different, ranging from biological fermentation to thermochemical gasification. As indicated in Table 8, besides liquid biofuel, another major product is electricity that is produced with residual biomass and syngas through GTCC or the steam Rankine cycle. After satisfying the process demand, extra power

Table 4. Biofuel Production Process ASPEN Outputs Used To Determine *GREET* Inputs[a]

options	fuel yield (gal/h)				protein (kg/h)	power export (MW)
	Bio-EtOH	Bio-FTD	Bio-DME	Bio-FTG		
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

[a] Biomass feedstock input is 5,000 dt/day. For detail, see ANL report (*12*).

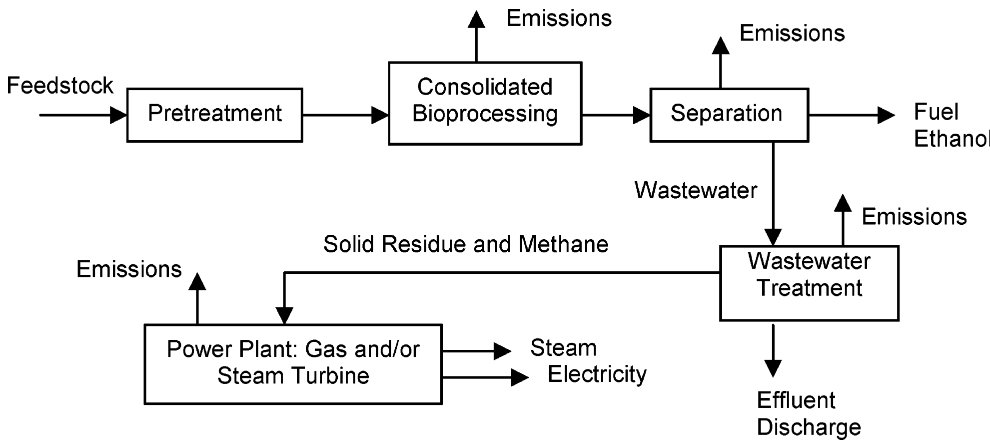

Figure 2. Simplified process flow diagram of ethanol production through biological process with heat and electricity co-generation.

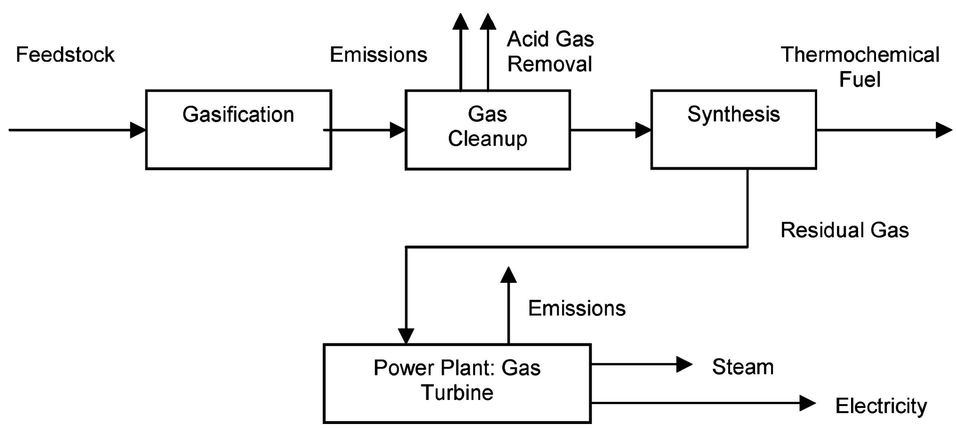

Figure 3. Simplified process flow diagram for thermochemical production of FTD and DME with heat and electricity co-generation.

is exported to the grid. There is no steam export. In particular, the two thermochemical fuel production options (bio-DME and bio-FTD) generated large amounts of electricity with an energy share almost identical to that of the fuel product (Table 8). On the contrary, the biological options (1−4) produce much less electricity for export. As we mentioned earlier, the electricity exported to displace grid electricity (with the displacement method) usually results in a large fossil and GHG emission credit, which makes comparison of liquid fuel production impacts difficult. Therefore, a co-product credit partitioning method (such as energy allocation) that minimizes the electricity effect would allow better comparison of the proposed liquid fuel production technology with existing conventional technologies. Therefore, until other, more precise methods are developed, we believe the allocation approach is most appropriate for this study (Table 8).

Allocation of protein credit for the EtOH/protein/Rankine option was based on protein calorific content to be consistent with other options. Although we recognize protein's value as a nutrient rather than an energy product, this study focused on liquid fuel products from biomass as a first step. The protein issue can be addressed later by using the displacement method, in which energy and emissions generated during soybean protein production replace those from biomass protein production. Furthermore, the energy share of protein based on calorific value in the EtOH/protein/Rankine option is about 13%, which is small in comparison with the 40% of energy share from electricity production in the thermochemical fuel production options (bio-DME and bio-FTD). In that regard, we chose to put more consideration in bio-electricity instead of protein in selecting co-product partitioning methods.

The energy partitioning results serve as *GREET* inputs. Table 8 lists the output energy shares (as percentages) for each production option; the energy shares were calculated from ASPEN Plus results (Table 4). We obtained four sets of energy and emission results: per mile, per mmBtu, and per gallon gasoline equivalent.

3. Comparisons of Cellulosic Fuel Production Options. In addition to the WTW analysis, we compared the six fuel production options. To address the needs and concerns of biomass producers, biofuel producers, the agriculture sector, and other industries, impacts were expressed on the basis of feed

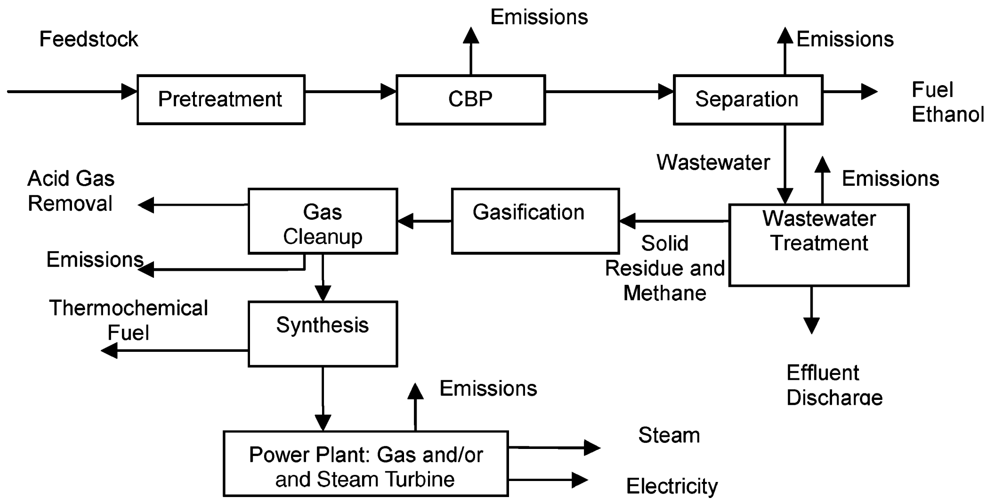

Figure 4. Simplified process flow diagram of multi-fuel production option Bio-EtOH/Bio-FTD/GTCC.

Table 5. Combined Baseline Fuel Economy by In-Use Fleet Vehicle/ Fuel System for 2030 (mpgge)[a]

	RFG[b]	Bio-E85	LSD[c]	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 light-duty vehicles; data for passenger cars and LDTs were combined according to the VMT shares of gasoline vehicle types. [b] RFG = reformulated gasoline. [c] LSD = low-sulfur diesel.

Table 6. 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

Table 7. Combined Emission Factors for Vehicle Operation by Vehicle/Fuel System

pollutant (g/mi)	RFG	E85	diesel	FTD	DME
Light-Duty Vehicles (ICE and FFV)					
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
Light-Duty Vehicles (HEV)					
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

Table 8. Energy Allocation for Product Fuel, Co-Product Fuel, Co-Product, and Electricity

option	fuel product/co-product (fuel)/co-product/electricity[a]	output energy share (%)
EtOH/GTCC	EtOH/NA/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 and 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.

(mass). By using this approach, we estimated energy consumption and emissions generated from a unit of feed biomass for each product derived from each option (Table 4). The methodology used in the comparison was energy allocation in fuel production plants followed by a conversion to a mass-basis; estimate of energy and emissions associated with the products from upstream farming process; and finally, determination of fuel, power, and protein displacement benefits. The results from this analysis are expressed as Btu of energy or grams of emissions per short ton of biomass feedstock.

For export bio-electricity, energy and emissions associated with the electricity production in the fuel plant were first credited by energy share (Table 8). Electricity yield, on a mass basis (in kWh/dt of biomass), was determined. Next, the energy and emissions from biomass farming and transportation that were attributable to this amount of bio-electricity generation were calculated. Results from the farming and fuel production stages were summed as the life-cycle energy and emissions for the bio-electricity generation.

Similarly, energy and emissions for protein production in the EtOH/protein/Rankine option (option 4) were estimated, the protein yield was expressed as kg protein/dt biomass, and energy and emissions associated with biomass farming and transportation attributable to the production of the protein were determined. By adding the farming and transportation to biofuel production stage data, we obtained total life-cycle energy and

Table 9. Average U.S. Electricity Generation Mix Used in This Study[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-laboratory study (Inter-Laboratory Working Group on Energy-Efficient and Clean-Energy Technologies, 2000) (*14*).

Table 10. Assumptions of Product Displacement for Mass-Based Analysis

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

[a] Assumes comparative protein value between soy protein and switchgrass protein (*9*).

emissions results for biomass protein. Other products (bio-EtOH, bio-DME, bio-FTD, etc.) were analyzed by using the same method.

These results were further analyzed to estimate how much petroleum fuel, soy-based protein, and U.S. generation mix electricity could be displaced by products from cellulosic biomass from each of the biofuel production options. Finally the conventional fuel, protein, and electricity displaced by biofuels, biomass protein, and bio-electricity were compared among the six options. Table 9 lists the average U.S. electricity mix used for the displacement simulations. Table 10 presents the assumptions for the displacement of fuel, electricity, and protein.

Results and Discussion

Results from this work are presented in terms of total energy use, fossil energy use, petroleum use, GHG emissions, and emissions of criteria pollutants (including VOCs, CO, NO_x, PM_{10}, and SO_x) by a given fuel/vehicle system. *GREET* 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. Cellulosic biofuels WTW analysis for the fuels produced via the bio-EtOH/GTCC, bio-EtOH/Rankine, bio-EtOH/bio-FTD/GTCC, bio-FTD/GTCC, and bio-DME/GTCC options and used in LDVs were compared with petroleum-based conventional fuels. Figures 5 and 6 illustrate changes relative to gasoline for bio-EtOH; changes relative to diesel for bio-DME and bio-FTD are shown in Figures 7 and 8.

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 their passenger cars and LDTs, drivers can reduce petroleum use by 68−93% and fossil energy use by 65−88% (Figures 5 and 7) on a per-mile-driven basis. The greatest energy benefits apparently come from cellulosic DME and FTD, which offer up to 93% reductions in petroleum use and 88% reductions in fossil energy use (Figure 7). The roughly 25% difference in energy savings between bio-EtOH (68%) and bio-FTD/bio-DME (93%) 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 (EtOH in E85, Figure 5).

Energy consumption values are similar among the three cellulosic bio-EtOH production options: 755−855 Btu/mi in fossil energy and 443−497 Btu/mi in petroleum (both are EtOH in E85 and with FFVs). This is also the case for each type of vehicle technology, conventional and HEVs. The data reveal similar reductions in petroleum consumption between cellulosic and corn ethanol. There is a moderate change in fossil energy use from corn ethanol. Because biofuel consumes zero fossil and petroleum energy at the vehicle operation stage, the difference must be attributable to feedstock farming, transportation, and fuel production processes. As indicated in Table 11, the difference in fossil energy consumption between cellulosic and corn ethanol results from the fuel production stage. In the cellulosic fuel production plant, the source for power and steam has changed. Instead of using coal or NG to fuel the ethanol plant, as in the corn ethanol production process, the CBP process in this study relies on biomass residuals and methane gas from an on-site WWTP to generate heat and power, which decreases fossil energy consumption.

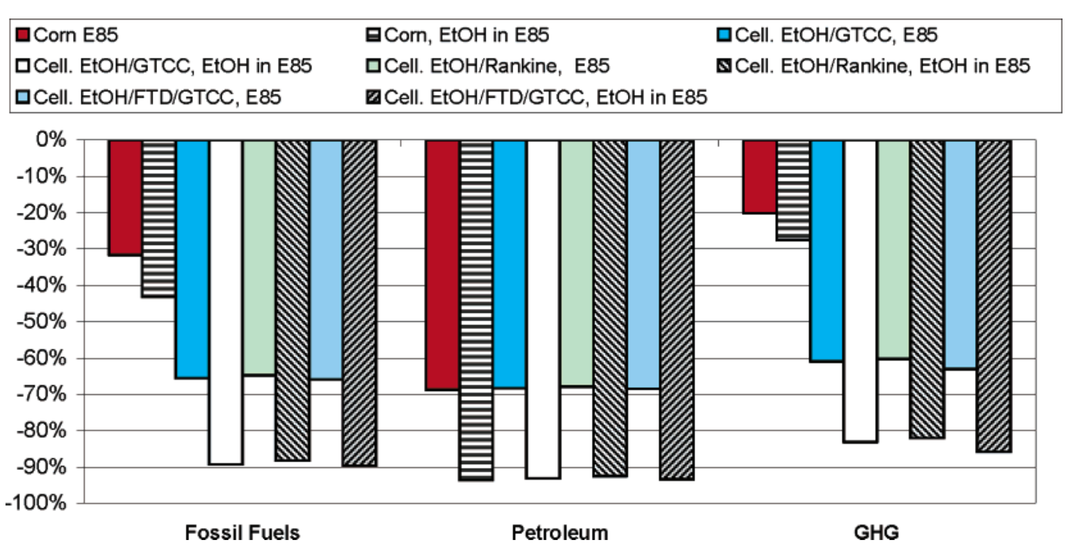

Figure 5. Percent change in energy use and GHG emissions from Bio-EtOH production options relative to gasoline in ICE SI vehicles per mile driven (negative value means reduction).

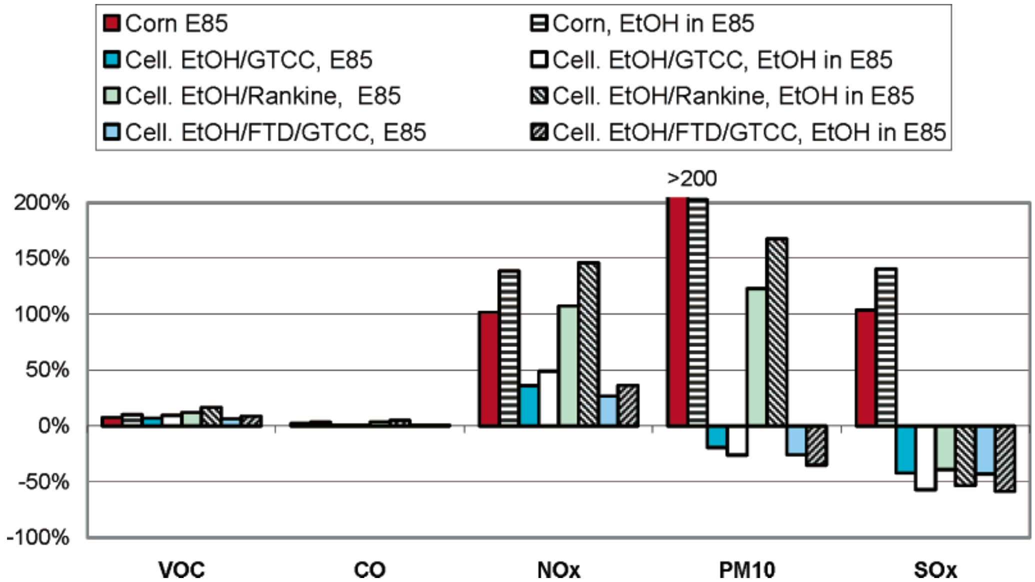

Figure 6. Percent change in total criteria pollutant emissions from Bio-EtOH production options relative to gasoline in ICE SI vehicles per mile driven (negative value means reduction).

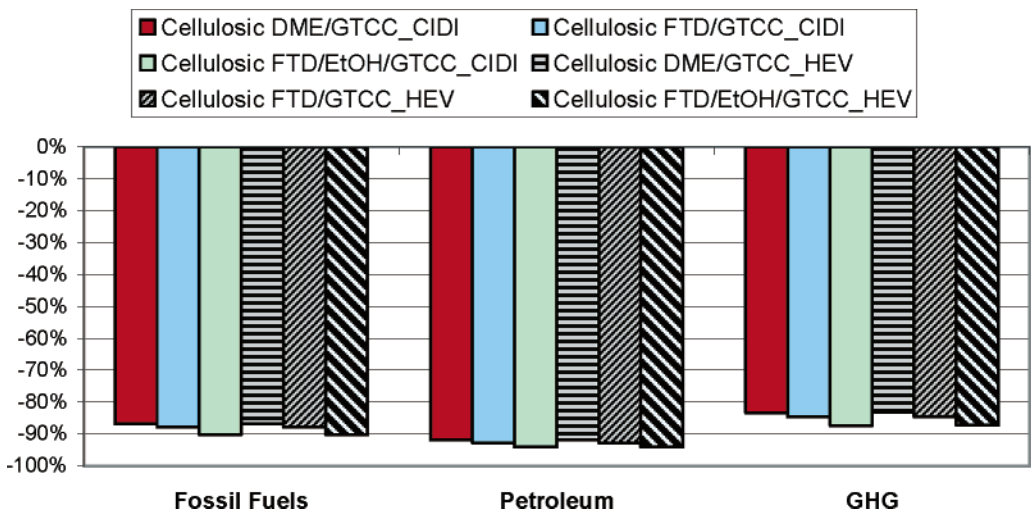

Figure 7. Percent change in energy use and GHG emissions of Bio-FTD and Bio-DME produced from Bio-FTD/GTCC, Bio-DME/GTCC, and Bio-EtOH/Bio-FTD/GTCC options relative to diesel in conventional CIDIs and HEVs per mile driven (negative value means reduction).

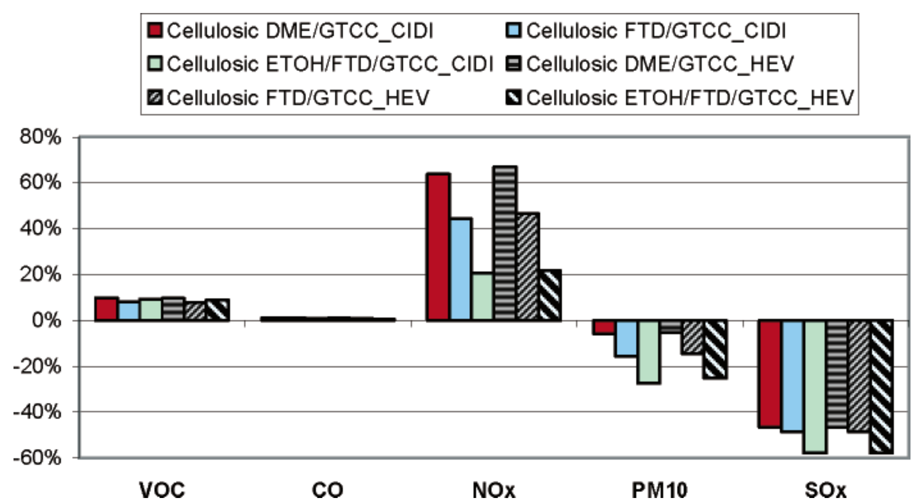

Figure 8. Percent change in total criteria pollutants emissions of Bio-FTD and Bio-DME produced from Bio-FTD/GTCC, Bio-DME/GTCC, and Bio-EtOH/Bio-FTD/GTCC options relative to diesel in conventional CIDIs and HEVs per mile driven (negative value means reduction).

To understand the attributes of different biofuels in the fuel production chain, the *GREET* results were expressed as per gallon gasoline equivalent (gge). By using this unit of measure, we excluded vehicle type and fuel economy effects. The per-gallon results agree well with the per-mile data on oil and fossil reduction benefits. Bio-based ethanol, regardless of its feedstock

Table 11. 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

	fossil fuels			petroleum		
	feedstock	fuel production	vehicle operation	feedstock	fuel production	vehicle operation
gasoline ICE	232	1126	5923	73	577	5923
corn E85 FFV	678	3460	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] Value in this table is derived from ethanol in E85.

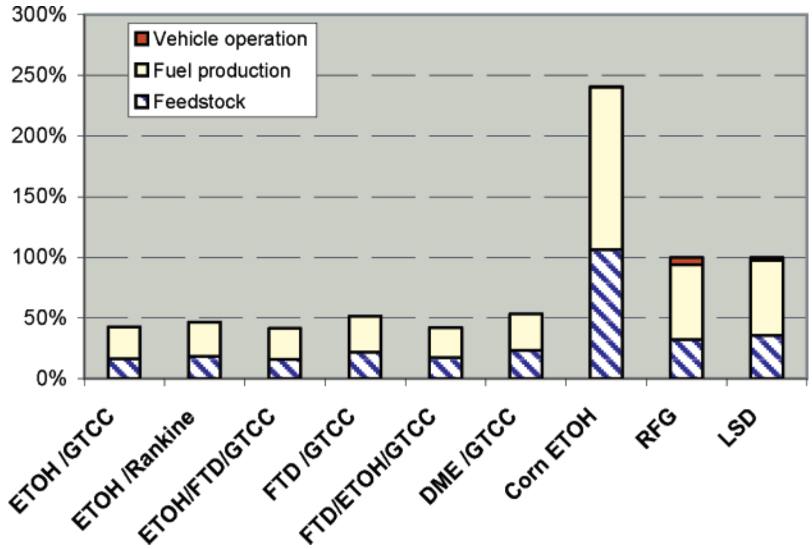

Figure 9. SO_x emissions from each stage of biofuel production and utilization cycle as percentage of total SO_x emissions of conventional fuel, Bio-EtOH relative to RFG, Bio-FTD and Bio-DME relative to LSD (conventional vehicles, EtOH in E85 [as unblended], per mile).

and production process, provides an equivalent amount of petroleum fuel reduction (91−93%) for each gallon of bio-EtOH used (as gge, unblended). Bio-FTD and bio-DME produced by means of TCP reduce petroleum energy use by up to 94% and fossil energy use by up to 90%.

Major reductions in fossil energy use by switchgrass-derived biofuels result from the renewable nature of the biofuel energy. Because fossil fuel is primarily responsible for GHG emissions, decreased fossil fuel use translates directly to 82−87% reductions in GHG emissions across all unblended cellulosic biofuels, on a per-gge basis. A significant reduction of CO_2 (up to 94−96%) compared with petroleum-based conventional fuel is achieved with the use of cellulosic biofuels. When the biofuel is blended with gasoline as E85, the GHG reductions are 60−62% and the CO_2 reduction is 70%.

2. Criteria Pollutant Emissions from Biofuels.

2.1. *SO_x*. The most significant change in criteria pollutant emissions occurs for SO_x (Figures 6 and 8). 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% (Figure 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) (Figure 8). These benefits likely result from changes in the feedstock and fuel production stages (Figure 9). GTCC gasifies biomass residue and uses methane from digestion to produce steam and electricity for the plant. The surplus electricity is exported to the grid, which further reduces the demand for coal-based electricity. Coal is the single largest source of SO_x emissions, and coal-based power accounts for 30% of the average U.S. electricity mix (Table 9); therefore, biofuel options that include GTCC showed large reductions in SO_x. 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 SO_x emissions come from the production of phosphorus fertilizer. Switchgrass requires much lower amounts of P_2O_5 fertilizer because its root system has excellent capabilities in retaining nutrients (*5*), which translates to fewer SO_x emissions.

2.2. *NO_x*. Most studies conducted so far have concluded that producing biofuels may double total NO_x emissions compared with conventional petroleum-based fuels. This study indicates, however, that through reduced N-fertilizer use and GTCC power co-production, total NO_x emissions from biofuel production could be much less than expected (Figures 6 and 8). Production of bio-EtOH as E85 via the bio-EtOH/GTCC and bio-EtOH/bio-FTD/GTCC options (options 1 and 3) leads to a total NO_x increase of 36% (bio-EtOH/GTCC) and 27% (bio-EtOH/bio-FTD/GTCC) relative to gasoline (Figure 6). This is a significant improvement when compared with the 107% increase in NO_x emissions that results from the bio-EtOH/Rankine option (option 2).

Sources of NO_x emissions at the well-to-pump (WTP) stage are biomass farming (N-fertilizer production, N-fertilizer field application to switchgrass, biomass transportation) and fuel production. NO_x emissions associated with the biofuel production process are sensitive to heat and power production technologies for the fuel production plant. Integrated GTCC heat and power co-generation appears to be superior in reducing NO_x emissions (Figure 10). The advanced gas turbine (e.g., GE

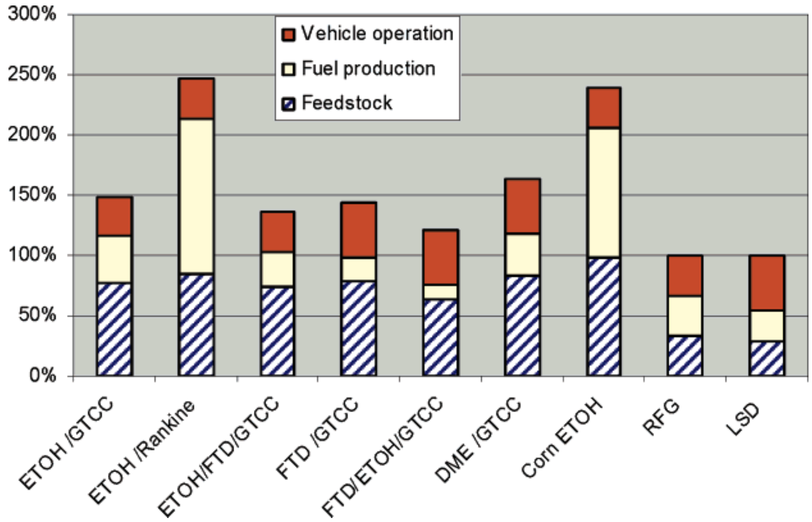

Figure 10. NO_x emissions from each stage of biofuel life cycle as percentage of total NO_x emissions of conventional fuel, Bio-EtOH relative to RFG, Bio-FTD, and Bio-DME relative to LSD (conventional vehicles, EtOH in E85 [unblended], per mile).

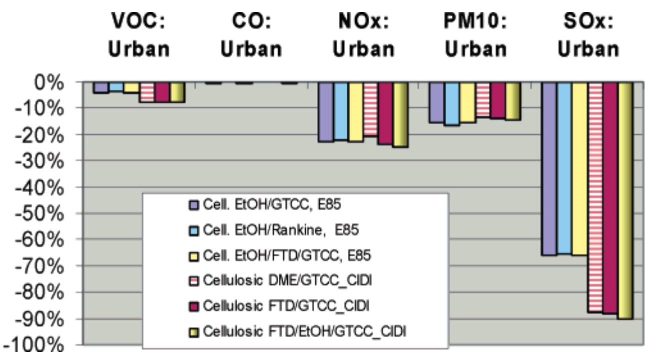

Figure 11. Percent change in urban area criteria pollutants emissions of cellulosic biofuels relative to gasoline and diesel in conventional vehicles per mile driven (negative value means reduction).

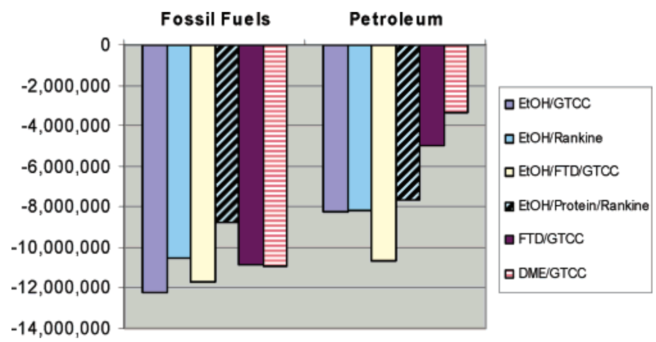

Figure 12. WTW fossil fuel energy and petroleum displaced by cellulosic multi-products in Btu per dry short ton of biomass feed (negative value means net displacement).

Model 7FB) produces 4.5 g of NO_x per mmBtu of biomass-derived syngas input to the gas turbine. In contrast, a fluidized-bed combustion (FBC) boiler emits up to 110 g 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 from steam production with coal and NG-fired industrial boilers. Coal-fired industrial boilers could emit as much as 155 g of NO_x, and NG-fired industrial boilers could emit 40−58 g of NO_x per mmBtu input; these values are 9−34 times higher than NO_x emissions from the advanced gas turbine in this study. Among the thermochemical fuels, bio-FTD produces less NO_x emissions during the fuel production stage than does bio-DME (Figure 10).

2.3. *PM_{10}*. Similarly, with the advanced GTCC co-generation system, total PM_{10} emissions associated with EtOH produced from the bio-EtOH/GTCC and bio-EtOH/bio-FTD/GTCC options (options 1 and 3) could be reduced by 20−25% compared with gasoline (Figure 6). If the power was produced by means of a steam Rankine cycle instead, total PM_{10} emissions would increase up to 123% of those emitted by gasoline. Biofuels produced by means of the thermochemical process achieved net reductions in PM_{10}. These data strongly suggest that GTCC is a crucial factor in the energy and emission benefits of biofuel production. Advanced gas turbine combustion technology enables the elimination of a significant portion of NO_x and further realizes a net reduction in total PM_{10} (Figures 6 and 8).

2.4. *Urban Emissions.* The *GREET* model was used to further assess criteria pollutant emissions in urban areas in order to provide an approximation of potential urban population exposure risk caused by biofuel production and utilization. Our results show net urban emission reductions for almost all criteria pollutants, with the exception of CO (unchanged), for nearly every biofuel production option. The biggest reduction occurs for SO_x, which decreased an average of 90% with pure biofuels and 65% with E85 (Figure 11).

The limitation of the proposed options is an increase in total VOC emissions (Figures 6 and 8) with the exception of the bio-EtOH/protein/Rankine option (option 4). Results also reveal no improvement in total CO emissions for the fuel production options studied compared with gasoline on either a per-mile or a per-gallon basis.

3. Comparison of Biofuel Production Options.

3.1. *Analysis of per-Mile- and per-gge-Based Results.* The production options analyzed are multi-fuel and multi-production in nature. Bio-EtOH and bio-FTD produced from the multi-fuel production option (bio-EtOH/bio-FTD/GTCC, option 3), appears most promising in terms of energy benefits for use in both conventional and HEV technologies (Figures 5−8). This fuel production option is unique in that it offers two fuels, bio-EtOH and bio-FTD, to displace conventional gasoline and diesel and offers a potential for upgrading bio-FTG as a gasoline blending component. 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 (Figures 5 and 6). Bio-FTD produced from this option also outperformed the bio-DME/GTCC and bio-FTD/GTCC options (Figures 7 and 8).

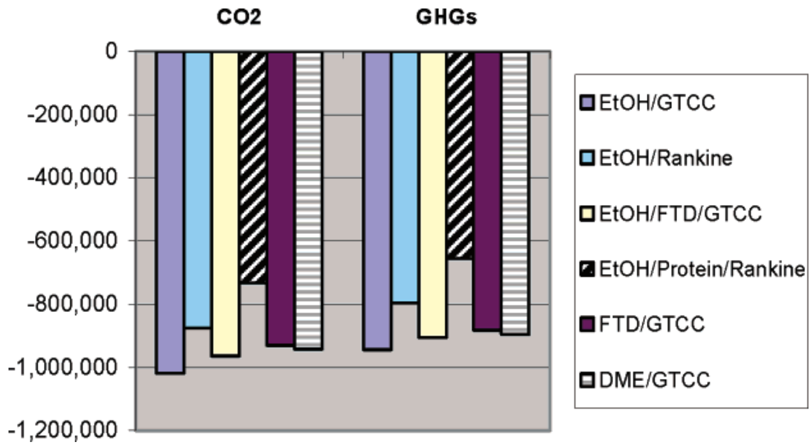

Figure 13. WTW CO_2 and GHG emissions displaced by cellulosic multi-products in gram per dry short ton of biomass feed (negative value means net displacement).

Table 12. Total Energy and Chemical Products Yields from Six Production Options[a]

	production options					
products	BioEtOH/GTCC	BioEtOH/Rankine	BioEtOH/BioFTD/GTCC	BioEtOH/Protein/Rankine	BioFTD/GTCC	BioDME/GTCC
BioEtOH	8.04	8.04	8.04	7.43		
BioFTD			1.41		3.08	
BioFTG			0.88		1.92	
BioDME						3.56
electricity	1.90	0.99	0.17	0.29	3.11	4.06
protein (kg)				72.53		

[a] In mmBtu or kg per dry ton of biomass feed.

3.2. *Production Options Comparison Based on a Ton of Biomass Feed.* 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, bio-FTD and bio-DME production options (options 5 and 6) generate electricity for export (40−55% total output energy share) at an energy value almost equal to the amount of fuel, as seen in Table 8. Compared with bio-EtOH produced from EtOH/GTCC (Option 1, 20.4% electricity share), an additional 20−35% of the energy output from these two production options is in the form of export electricity instead of fuel. In other words, the electricity generated from the TCP contributes to energy and emission reductions in the power sector.

Given the large portion of electric power generated as a co-product in these 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 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. generation mix), and chemical (soy protein) were assumed to be displaced by biofuels, exported bio-power, and protein from switchgrass (Table 10).

With a ton of cellulosic biomass, all six biofuel options provide net petroleum and fossil fuel displacements (Figure 12), net reductions in GHGs and CO_2 (Figure 13) and in SO_x. Production option 3 (bio-EtOH/bio-FTD/GTCC) achieves the highest oil displacement (Figure 12). For reductions in fossil fuel and GHGs emissions, the bio-EtOH/GTCC option (option 1) is a clear winner (Figures 12 and 13). Thermo-chemical options (bio-FTD/GTCC and bio-DME/GTCC, options 5 and 6) take the lead in terms of total NO_x, PM_{10}, and SO_x reductions.

Results suggest a strong impact of different biofuel production options on overall energy and GHG emissions. Four bio-EtOH options (1−4) demonstrated excellent oil displacement because of the high ethanol yield (Figure 12). The gap in petroleum energy displaced among the six options can be as large as 7 mmBtu/dt of feed, between the bio-EtOH/bio-FTD/GTCC (option 3) and the bio-DME/GTCC option (option 6, Figure 12). With the same amount of biomass feed, the bio-EtOH/bio-FTD/GTCC option (option 3) yielded the highest amount of energy products (fuel and power); bio-EtOH/GTCC (option 1) followed closely (Table 12).On the basis of one ton of cellulosic biomass input, through the bio-EtOH/bio-FTD/GTCC option (option 3), we can potentially displace 10.5 million Btu of petroleum fuels and 11.5 million Btu of fossil energy and reduce 900 kg of CO_2-equivalent GHG emissions.

One should be reminded that biofuel production options are not limited to the six presented above. There are many possible fuel production options with the same feedstock or mixed feedstocks. Furthermore, a change in the ratio of electricity output to fuel output (electricity/fuel, or E/F) for each production option may bring significant changes in energy consumption, oil displacement, and emissions. Increase in E/F ratio could result in an increased production of bio-power to displace fossil-based power generation. The end result is a reduction of GHG in the power sector. On the other side, this could also lead to less liquid bio-fuel production and thus less petroleum oil displacement. In case of option 1, bio-EtOH/GTCC, an increase in E/F ratio means more bio-power generation and fossil energy savings although less petroleum oil displacement.

3.3. *Bio-EtOH with Co-Production of Protein and Power.* The bio-EtOH/protein/Rankine production option offers a high-economic-value protein product, in addition to cellulosic fuel ethanol and power export. Caution should be taken in judging the energy and environmental benefits based on product energy value because protein is not valued as an energy product but a biochemical or nutrient (Table 12). This production option offers the benefit of a net reduction in total VOCs, unlike the increase in total VOC emissions associated with biomass-based fuels production in general. In this case, organic carbon is extracted as a protein product instead of being burned to produce power and VOC emissions. Unfortunately, this option shows weak performance in the rest of the emission factors. In particular, the Rankine cycle is responsible for increased criteria pollutant emissions.

Conclusions

On the basis of the WTW results, we conclude that production of cellulosic biofuels (bio-EtOH, bio-FTD, and bio-DME) and use of these biofuels in LDV technologies offer substantial petroleum and fossil energy savings. The displacement of fossil energy with biofuels results in significant GHG reductions compared with petroleum-based conventional fuels. All three biofuels reduce overall SO_x and PM_{10} emissions. In urban areas, net reductions in NO_x, SO_x, VOCs, and PM_{10} could be achieved for nearly every biofuel production option studied. This work strongly suggests that integrated heat and power co-generation by advanced GTCC technology plays a key role in reduction of criteria pollutant emissions. The multi-fuel production option shows promise in terms of oil displacement. Co-production of bio-EtOH and bio-FTD by means of biological and thermochemical processes with power cogeneration by GTCC (bio-EtOH/bio-FTD/GTCC, option 3) is very effective because it consumes the least petroleum and fossil energy and achieves the greatest reductions in GHGs and all criteria pollutants when used with both conventional and HEV technologies compared with conventional gasoline and diesel. The limitation of the cellulosic biofuel production options studied is an increase in total VOC emissions and an increase in NO_x emissions in most cases.

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Notation

Acronyms

ANL	Argonne National Laboratory
AFEX	ammonia fiber explosion
CBP	consolidated bioprocessing
CI	compression ignition
CIDI	compression-ignition direct-injection
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
DME	dimethyl ether
DOE	U.S. Department of Energy
E/F	electricity output to fuel output
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
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
HDT	heavy-duty truck
HEV	hybrid electric vehicle
HRSG	heat recovery steam generation
ICE	internal combustion engine
K_2O	potash fertilizer
LDT	light-duty truck
LDV	light-duty vehicle
LHV	low heating value
LSD	low-sulfur diesel
MeOH	methanol
N	nitrogen
NG	natural gas
NGO	non-governmental organization
N_2O	nitrous oxide
NO_x	nitrogen oxides
P_2O_5	phosphate fertilizer
PFD	process flow diagram
PM_{10}	particulate matter with diameters of 10 micrometers or less
PTW	pump-to-wheels
RFG	reformulated gasoline
RFS	Renewable Fuels Standards
SI	spark-ignition
SO_2	sulfur dioxide
SO_x	sulfur oxides
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
WWTP	wastewater treatment plant

Units of Measure

Btu	British thermal unit(s)
dt	dry short ton(s)
g	gram(s)
gal	gallon(s)
gge	per gallon gasoline equivalent
h	hour(s)
kg	kilogram(s)
mi	mile(s)
MJ	megajoule(s)
mpg	mile(s) per gallon
mpgge	mile(s) per gallon gasoline equivalent
MW	megawatt(s)
yr	year(s)

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