Greenhouse Gases in the Corn-to-Fuel Ethanol Pathway

98-WP61B.04

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ABSTRACT

Argonne National Laboratory (ANL) has applied its Greenhouse gas, Regulated Emissions and Energy in Transportation (GREET) full-fuel-cycle analysis model to examine greenhouse gas (GHG) emissions of corn-feedstock ethanol, given present and near-future production technology and practice. On the basis of updated information appropriate to corn farming and processing operations in the four principal corn- and ethanol-producing states (Illinois, Iowa, Minnesota, and Nebraska), the model was used to estimate energy requirements and GHG emissions of corn farming; the manufacture, transportation to farms, and field application of fertilizer and pesticide; transportation of harvested corn to ethanol plants; nitrous oxide emissions from cultivated cornfields; ethanol production in current average and future technology wet and dry mills; and operation of cars and light trucks using ethanol fuels. For all cases examined on the basis of mass emissions per travel mile, the corn-to-ethanol fuel cycle for Midwest-produced ethanol used in *both* E85 and E10 blends with gasoline outperforms conventional (current) and reformulated (future) gasoline with respect to energy use and GHG production. Also, GHG reductions (but not energy use) appear surprisingly sensitive to the value chosen for combined soil and leached N-fertilizer conversion to nitrous oxide. Co-product energy-use attribution remains the single key factor in estimating ethanol's relative benefits because this value can range from 0 to 50 %, depending on the attribution method chosen.

INTRODUCTION

Concern about global "greenhouse" warming and its short- and long-term effects on world economies and habitats has led decision makers to recognize that reducing in the rate of atmospheric carbon loading due to combustion may help slow such warming. This concern, in turn, has kindled an interest in transportation fuels that contain lower carbon per unit of energy delivered and/or that are produced from renewable sources so that less or no net carbon is added to the atmosphere from fuel combustion. One such fuel is ethanol (C_2H_5OH), an alcohol currently produced in the United States predominantly by fermentation and distillation associated with wet- and dry-mill processing of feed grain (primarily corn). Thus, there is considerable interest in the potential for ethanol, when used as a gasoline substitute, to help reduce greenhouse gas emissions, especially in light of the recent Kyoto Conference, at which United States negotiators renewed a commitment to controlling indigenous greenhouse gas (GHG) emissions by 2012 to a level below that of 1990. Will the current and near-future ethanol pathway prove compatible with efforts to check the growth of and eventually reduce those emissions?

Although a crop-based fuel such as ethanol has the implicit advantage over petroleum in that it is both (1) renewable and (2) characterized by near-zero net carbon emissions resulting from fuel combustion (carbon dioxide is absorbed from the atmosphere by feedstock plants during photosynthesis), the activities involved in its feedstock cultivation and milling do consume energy, which is provided chiefly by fossil fuels. Analysts do not agree on the absolute magnitudes of difference between petroleum and ethanol fuel for each phase of the production and use cycle. Different assumptions have been applied about the energy intensiveness and fuel inputs of virtually every process, giving rise to a wide range of energy use and GHG emission estimates for each link

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in the chain of extraction (for petroleum, the wellhead; for ethanol, the cornfield), production (refining of petroleum and milling of ethanol), distribution (to point of dispensing into vehicle), and end use. Results from previous full-cycle analyses are summarized in Table 1.

We undertook this study on the dual premises that (a) data and information essential to an informed choice about the corn-to-ethanol cycle need to be updated, thanks to scientific and technological advances in both corn farming and ethanol production, and (b) generalized national estimates of energy intensities and GHG production are of less near-term relevance than estimates based specifically on activities and practices in the upper Midwest, which is the principal domestic corn production and milling region. Corn production is vital to the economies of upper midwestern states. The four largest corn-producing states - Illinois, Iowa, Minnesota, and Nebraska - were included in this analysis. Collectively, they account for about one-half of the total domestic corn harvest in a given year, about 90 % of the U.S. total ethanol production capacity of 1.58 billion gallons, and (in most years) about 95% of total domestic ethanol production. The vast majority of ethanol produced in Illinois and Iowa (and about one-half of that produced in Nebraska and Minnesota) is distilled from wet milling processes that generate multiple co-products that optimally utilize the protein and sugar components of the corn kernel (ethanol is derived from the starch). The remaining production capacity in these states employs the dry milling process, from which there is but one principal co-product: distillers' dried grains and solubles (DDGS). In this study we used updated information appropriate to corn operations in America's heartland to examine the role of corn-feedstock ethanol with respect to GHG emissions, given *present and near-future* production technology and practice. We obtained information about these technologies and practices from a panel of experts consisting of U.S. Department of Agriculture technical staff; faculty of midwestern universities with expertise in corn production; and acknowledged authorities in ethanol plant engineering, design, and operations.

As Table 1 shows, previous studies have estimated GHG emissions of corn-based ethanol to vary from a decrease of 70% to an increase of 80% relative to the gasoline fuel cycle. Uncertainties in corn ethanol GHG emissions are attributable to differences in key assumptions about the energy intensity of corn farming, corn yield, nitrous oxide (N_2O) emissions from nitrogen fertilizer, the energy intensity of ethanol plants, the type of process fuel used in ethanol plants, and the way in which emissions and energy use are allocated between ethanol and co-products. Some of these assumptions remain valid, others require updating, and some may be accurate for ethanol fuel cycle effects on a national scale but less so on a regional scale. These issues will be addressed in this paper.

DATA AND METHODOLOGY

Fundamentals of GREET

For a given transportation fuel, a fuel cycle includes the following chain of processes: primary energy recovery; primary energy transportation and storage; fuel production; fuel transportation, storage, and distribution; and vehicular fuel combustion. Usually, fuel-cycle activities before vehicular fuel combustion are referred to as upstream activities. The full fuel-cycle for corn to ethanol, shown in Figure 1, includes corn farming, ethanol production, ethanol transportation and distribution, and ethanol combustion in motor vehicles. Our study also includes the production of corn farming inputs (i.e., fertilizers, herbicide, pesticide, and fuels) and farming operations.

Energy is consumed and emissions are generated during upstream fuel-cycle activities, as well as during vehicular activities. In each upstream activity, fossil energy is burned and emissions are generated. Also, fuel leakage and evaporation that ultimately generate emissions are associated with upstream activities. The Greenhouse gas, Regulated Emissions and Energy in Transportation model (GREET), developed at Argonne National Laboratory, takes into consideration all emissions and energy-consuming sources and includes various fuel-cycle paths, including the corn-to-ethanol path.(1) GREET calculates fuel-cycle grams-per-mile (g/mi) emissions and Btu-per-mile (Btu/mi) energy use for each fuel cycle. It includes emissions of five criteria pollutants (volatile organic compounds [VOCs], carbon monoxide [CO], nitrogen oxide [NO_X], particulate matter with diameter smaller than 10 micrometers [PM_{10}], and sulfur oxides [SO_X]) and three GHGs (methane [CH_4], nitrous oxide [N_2O], and carbon dioxide [CO_2]). The three GHGs are further combined together with their global-warming potentials as CO_2-equivalent GHG emissions. GREET calculates energy consumption for three types of energy: total energy (all energy sources), fossil energy (petroleum, natural gas, and coal), and petroleum only. For a given fuel-cycle stage, energy use (in Btu per million Btu of energy throughput) is calculated. The calculated total energy use for the particular stage is allocated into different process fuels (e.g., natural gas, residual oil, diesel, coal, and electricity). Fuel-specific energy use, together with emission factors of the combustion technology for a specific fuel, is then used to calculate combustion emissions for the stage. GREET has an archive of combustion emission factors for various combustion technologies fueled with different fuels and equipped with different emission-control technologies. Emission factors for VOC, CO, NO_X, PM_{10}, CH_4, and N_2O for combustion technologies are derived primarily from the U.S. Environmental Protection Agency's (EPA's) AP-42 document. SO_X emission factors for most fuels are calculated on the assumption that all sulfur contained in process fuels is converted into sulfur dioxide (SO_2). CO_2 emissions are calculated with a carbon balance approach; that is, the carbon contained in the fuel burned, minus the carbon contained in combustion emissions of VOC, CO, and CH_4, is converted to CO_2. GHG emissions from vehicular fuel combustion are calculated in a similar way.

GREET was revised and upgraded to address corn farming and ethanol production in four Midwestern states. Our analysis assumes that both passenger cars and light trucks use ethanol, which is available in the form of either E85 (85% ethanol and 15% gasoline by volume) or E10 (10% ethanol and 90% gasoline by volume—an oxygenated fuel that is about 3.5% oxygen by weight). E85 is used in flexible-fueled vehicles (FFVs), and E10 is used in any light-duty gasoline vehicles.

Energy and Chemicals Requirements of Corn Farming

Virtually all corn harvested in Illinois and Iowa is grown on land requiring no irrigation. There is a small amount of irrigated cropland in Minnesota, while in Nebraska, at least one-half of the cornfields are irrigated. Thus, while the energy use profiles of corn farming in the former three states are very similar, Nebraska corn farming is somewhat more energy intensive; the net result is that the weighted mean crop-production energy requirement in Btu/bushel is higher than if the computation were performed for Illinois and Iowa alone.

Table 2 shows the individual and weighted energy requirements of corn farming in the four states (exclusive of fertilizer and pesticide production, which is handled separately). The weighting factor is based on the 1994 - 96 share of corn production from the February 1997 edition of *Crop Values* (2), while energy intensities are derived from Tables 2 and 3 of reference 3. By extrapolating recent trends from the National Agricultural Statistics Service (NASS), we conservatively estimated the four-state average corn yield per acre for current (1997) conditions at 130 bushels/yr. The values shown for diesel equipment utilization for the eastern-most three states may underestimate the actual current share of diesel-powered farm equipment in use, but no more recent comparable data have been found. Gasoline use includes that for powering farm trucks used in fields, some tractors, and some spreading equipment. As the population of spark ignition implements continues to decline, the shift to diesel will result in a modest overall improvement in efficiency for equipment use and further reduce the total energy requirement for corn farming.

As shown in Table 2, a weighted energy intensity for corn farming of *19,176 Btu/bushel* is used in the four-state analysis (Note: lower heating values for fuels are used throughout this paper). For the reasons cited above, this value should be considered conservative.

Field corn cultivation generally requires the application of nitrogen, phosphate, and potash fertilizers (and sometimes a lime application to more acidic soils) at the beginning of and/or (sometimes twice) during the growing season. Amounts applied per acre vary by state, generally as a function of soil mineral content and crop rotation practice (i.e., alternating corn with soybeans or other nitrogen-fixing crops every other year tends to help soil retain more nitrogen, reducing the nitrogen fertilizer requirement during field corn years). NASS's *Agricultural Chemical Usage 1996 Field Crops Summary* (4) was used, together with state shares weighted according to planted acreage, to yield a four-state average for fertilizer application, by type, in grams per bushel corn yield. These results are shown in Table 3.

Energy Intensity of Fertilizer Manufacture

The most recent documented analysis of energy use and intensity at nitrogen, phosphate, and potash production plants was conducted in 1992 by the Fertilizer Institute and is incorporated into reference 3. The analysis indicates that plant efficiencies have improved significantly since the early 1980s, with net energy intensity being reduced by up to 40% on average. Again, by using lower heating values for energy inputs and by adding a conservative 2.5 Btu/g for packaging and handling of raw material and product (transportation and application are already accounted for in other sections of this paper), the following average energy intensities (Btu/g of active ingredient, weighted according to share of process fuel used in the production of each) have been used: 46.5 for N, 10.8 for P_2O_5, and 5.0 for K_2O.

N_2O Emissions from N-Fertilizers Applied in Cornfields

The nitrogen fertilizer (N-fertilizer) applied to cornfields is extracted by corn plants as a plant nutrient, absorbed (chemically bound) into soil organic materials, entrapped in soil aggregates (chemically unbound), then (a) transformed to and emitted as N_2O through microbial nitrification and denitrification, (b) volatilized as NH_3, and (c) leached as nitrate from soil to streams and groundwater via surface runoff and the subsurface drainage system. The majority of N-fertilizer left in soil stabilizes in non-mobile organic form (5). Some of the nitrogen in leached nitrate (nitrate-N) eventually re-bonds as N_2O and migrates to the atmosphere. In our estimate, we include both direct N_2O emissions from soil and those from leached nitrate-N. The N_2O emission rate, expressed as the percentage of nitrogen in fertilizer (fertilizer-N) that becomes the nitrogen in N_2O (N_2O-N), is determined by factors that include soil type (especially sand content), soil water content, soil pH, soil temperature, soil organic carbon, soil ammonium or nitrate content, N-fertilizer type, fertilizer application form (e.g., liquid or powder), fertilizer application frequency, time of application, weather, crop type, vegetation, farming practice, and microbial organisms in the soil. In addition, the amount of N-fertilizer leached as nitrate is determined by such factors as soil type (especially sand content), hydrogeology, and depth of water table.

From an extensive database of results from about 30 studies conducted during 1978 - 97, we have estimated an averaged cornfield N_2O soil direct emission rate (expressed as percentage of fertilizer-N converted to N_2O-N) of 1.22%, with all data falling in a range from 0% to 3.2% (and most data falling within 1.0% - 1.8%).

N-fertilizer lost through leaching is in the form of NO_3^-, which is the mobile form of nitrogen; this nitrate in water is converted to N_2O, primarily through microbial denitrification, and up to 1% of initial nitrate nitrogen undergoes denitrification and emission as N_2O-N (6). Thus, to estimate N_2O-N emissions from N-fertilizer-derived NO_3^- leached into the drainage system, runoff streams, and groundwater, we have used 1% as the conversion factor for transformation of nitrate nitrogen to N_2O-N.

We examined some 30 studies covering N_2O emissions from cornfields, of which nine used available data for Midwest cornfields. Applying information from those nine studies, we have derived an average rate of 24% for total fertilizer-N converting to nitrate nitrogen (NO_3^--N) through leaching into surface runoff, the subsurface drainage system, and groundwater. With our assumed conversion factor of 1% from nitrate to N_2O emissions, we estimate a rate of 0.24% of N_2O emissions due to leaching. Summing soil-direct emissions and leaching thus produces a total N_2O emission rate of 1.5%, the value we use in our study.

Pesticide Requirements and Energy Intensity of Pesticide Manufacture

Corn cultivation generally requires application of both herbicide and insecticide to planted acreage during and after sowing. Genetic modification and hybridization to produce hardier, insect-resistant strains of field corn have proven successful in recent years; therefore, the rate of insecticide application, with a few exceptions where rootworm remains a problem, appears to be headed consistently downward in the upper Midwest. That is not the case with herbicide: favorable growing conditions and nutrient-rich soils that help increase corn yields also favor volunteer vegetation, which often must be controlled by herbicide applications, both at the beginning of and during the growing season. Also, increasingly common non-tilling practices in modern farming tend to require additional herbicide applications.

In addition to fertilizer use, the USDA (through NASS and its Economic Research Service - ERS) has tracked pesticide application trends in a number of publications, notably *Pesticide and Fertilizer Use and Trends in US Agriculture* (7) and, as with fertilizer, *Agricultural Chemical Usage: 1996 Field Crops Summary* (4). These publications indicate stable popularity in the study states of the three herbicide agents most commonly applied in corn cultivation (atrazine, metolachlor, and cyanazine) but, since the early 1990s, a supplanting of the fourth most popular agent, alachlor, by acetochlor. Active ingredient applied ranges from one to three pounds per planted acre, with cyanazine and metolachlor applied at the higher rates in this range. Application rates during the 1960s and 1970s averaged one pound per acre in the study states, clearly showing that the quantity of active ingredient applied has increased in recent years.

State-specific and mean weighted (over *all* types of agent applied) herbicide application rates, based on 1996 data, are shown in Table 4 for the top four corn herbicides in the study states, together with the total energy requirement (Btu/g) for the manufacture and packaging of each. The 1996 harvest has been selected as the basis for computation because it was generally good but not spectacular across the Midwest - a reasonable midpoint in the range of yields of the past decade that is also indicative of the effect of recent developments in cultivation practices and technology applied to corn farming. Manufacturing energy intensity values are derived from results published in 1987 (8). It is possible that the energy intensity of farm chemicals manufacturing has declined in the last ten years, but we were unable to obtain more recent data on this variable. Furthermore, information was not found for acetochlor, so values for alachlor (very similar to those for metolachlor) were substituted. Also shown in Table 4 are state-specific and mean weighted (by summed quantity) insecticide application rates, again based on 1996 data, for the four study states, as well as mean energy intensity, again from reference 8. Except for the application rates in Nebraska, rates for active ingredient are quite low, as is the weighted average, which is used in the GREET computation.

Transportation of Chemicals from Farm Chemical Plants to Farms and Corn from Farms to Ethanol Plants

Chemicals Transportation

Farm chemicals (fertilizers, herbicide, and pesticide) are transported from manufacturing plants to application sites in three steps: from manufacturing plants to bulk distribution centers, from distribution centers to mixers, and from mixers to farms. Table 5 presents our assumptions regarding travel distance, transportation mode, and transportation energy intensity for each step. In steps two and three, empty backhaul (i.e., round trip distance) is included in the energy calculation, while for step one, the backhaul is assumed to be an unrelated revenue movement. The high energy intensity for transportation from plants to bulk centers is attributable to long distance travel, while that for mixers to farms is due to the relatively small payload for class 6 trucks. For transportation between manufacturing plants and bulk distribution centers, both barge and rail modes are used. The four-state average share of chemical tonnage hauled is calculated using planted acreage as the weighting factor. New Orleans is the assumed origin for barge travel because a large volume of chemicals is trucked to the Port of New Orleans from the primary locations of high-volume farm-chemical production in Texas, Louisiana, Oklahoma, and Florida for shipment up the Mississippi. Rail travel origin is assumed to be (a) Oklahoma City for Illinois, Iowa, and Nebraska, and (b) Manitoba, Canada, for Minnesota; Oklahoma is a high-volume farm chemical source for rail shipments to the core Midwestern states, while Canadian production plants serve much of Minnesota. The respective (nominal) rail and barge destinations for each state are St. Louis, Dubuque, Omaha, and Minneapolis.

Energy use by barge is estimated as 374 Btu/ton-mi, which is the national average for 1995. AP-42 emission factors for barges fueled with residual oil or bunker fuel are 27, 100, 50, and 280 lb per 10^3 gal. of fuel for SO_x, CO, HC, and NO_x, respectively. Energy use by rail is estimated as 372 Btu/ton-mile, which is again the national average in 1995. Assuming diesel-power for locomotives, respective AP-42-derived emission factors for PM, CO, HC, and NO are 25, 130, 94, and 370 lb per 10^3 gal.

Thus, assuming a 50/50 tonnage split between barge and rail hauls, average energy use per ton of chemicals transported between plants and bulk centers is estimated to be 294,940 Btu per ton ([1060 x 374 + 520 x 372)]/2). Emissions are calculated with the energy use rate and the emission factors in grams per mmBtu of fuel used.

Class 8b trucks (>33,000 lb GVW) are assumed to ship the chemicals from bulk distribution centers to mixers. A typical class 8b tractor/trailer combination with full payload has a gross vehicle weight of 80,000 lb. The tractor weighs 12,000-15,000 lb, and the trailer weighs around 10,000 lb. Thus, the maximum payload is 55,000-58,000 lb, and a typical payload is 40,000-50,000 lb. We assume a payload of 45,000 lb. In calculating energy use and emissions per ton of chemicals transported, a round-trip travel distance of 100 mi is used (see Table 5); no payload is assumed for the trip from mixers to bulk centers. Fuel economy of 4.9 miles per gasoline-equivalent gallon yields transport energy intensity of 105,624 Btu/ton.

Class 6 trucks (19,500-26,000 lb. GVW) are assumed to transport the chemicals from mixers to farms. A typical class 6 truck has a truck (tare) weight of 8,500-10,000 lb. Thus, the maximum payload is 11,000-16,000 lb. We assume a payload of 10,000 lb. Per-ton energy use and emissions are calculated on the basis of a round-trip distance of 60 miles (Table 5), and no payload is assumed for the trip from farms to mixers. At a fuel economy of 6 miles per gallon (gasoline equivalent), transportation energy intensity is estimated as 220,000 Btu/ton.

Corn Crop Transportation

Corn moves to ethanol plants in a two-step process: first in class 6 trucks from farms to collection stacks (a 20-mi round trip, on average), and then in class 8a trucks from stacks to the ethanol plants (an 80-mi round trip). A payload of 15,000 lb is assumed for the class 6 haul and 30,000 lb for the class 8a haul. No goods are assumed to be hauled back from ethanol plants to stacks or from stacks to farms. We apply values of 6 mpg for class 6 truck and 5.1 mpg (gasoline equivalent, see above) for class 8a truck to compute haul energy, and a weight of 56 lb per dry bushel of corn to compute payload volume. Under these assumptions, fully-allocated energy use is 4,081 Btu per bushel transported.

Energy Use and GHG Emissions of Ethanol Production

Ethanol plants represent the largest fossil-energy-consuming process for the entire corn-to-ethanol fuel cycle. Ethanol production R&D efforts in the last two decades have concentrated on increasing ethanol yield and reducing plant energy use to reduce spending on process fuels in ethanol plants (fuel cost is the second largest cost of ethanol plant operation, next to feedstock corn cost). Advanced ethanol-plant designs employ such energy conservation technologies as molecular sieve dehydration and cogeneration of steam and electricity. As a result, newly built ethanol plants are generally more energy efficient than plants that have been operating for many years. However, energy use in existing ethanol plants has also been reduced through process integration. As part of our study, we collected information regarding recent trends in energy use from ethanol plant designers and operators. Using the information collected, we estimated total energy use and the split of energy use between ethanol production and co-product production.

In our analysis, we have included both dry and wet milling ethanol plants. We estimate fuel-cycle energy use and emissions for the two types separately. In reality, there are variations in production processes among the individual plants, but we endeavor to specify a representative plant for which ethanol production is a principal (if not the main) purpose.

In general, few plants employ yeast recycling or CO_2 collecting. Dry milling plants produce ethanol and DDGS. Wet mills produce starch, corn germ, corn gluten feed and meal, high-fructose corn syrup, and/or glucose as co-products. We assume that all the starch derived from corn in wet milling plants is targeted for ethanol conversion. Production of high-fructose corn syrup, a high-value end product derived from corn kernel sugars, takes place in a different process stream and is therefore not included as an ethanol co-product. Our research shows that most plants include molecular sieve dehydration or a comparable process and that about one-half of ethanol plants employ cogeneration systems.

Table 6 presents a summary of total energy input and energy allocation between corn farming products and ethanol production and co-product production in wet and dry milling plants, respectively. The farming allocation is based on relative market value of ethanol and non-ethanol product, while the milling energy allocation is based on process energy share. The table shows that *total* energy use per gallon of ethanol, on a current capacity-weighted basis, is similar for dry and wet milling plants (i.e., the 34,000 Btu/gal energy consumption value is state of the art for wet milling plants and representative of 70% of total wet mill capacity in the four states). As for energy allocation, Table 6 shows that 66-69% of the total energy use in ethanol plants is attributable to ethanol production, and the remainder is assigned to co-product production. Energy use share for co-products in dry milling plants is about 3% more than in wet milling plants. This share is higher because a large amount of energy is consumed by the co-product drying process in dry mills.

Our review of 13 studies of energy use for ethanol production revealed that total energy use per gallon of ethanol produced varies from 36,900 to 53,260 Btu/gal and from 34,000 to 54,980 Btu/gal for dry and wet milling plants, respectively. Most estimates are within 36,000-46,000 Btu/gal for dry milling plants and 46,000-53,000 Btu/gal for wet milling plants.

Established wet milling plants are fueled primarily with coal but are often supplemented by natural gas, as described below. If cogeneration systems are employed, plants can usually generate enough electricity for their own consumption. Otherwise, ethanol plants obtain electricity from the supply grid. Even if coal is burned to generate steam and electricity, natural gas is often used in wet milling plants for the direct drying of products because of (a) the high heat demand and (b) superior economics of natural gas for this purpose. On the basis of our contacts with industry, we have assumed that, for wet milling plants, 80% of total thermal energy is supplied by coal, and the remaining 20% is supplied by natural gas. Because dry milling plants are much smaller, on average, than wet milling plants, their cost savings from switching from natural gas to coal should be small: we expect that most dry milling plants are fueled with natural gas. However, we conservatively assume that 50% of the total thermal energy required in dry milling plants is supplied by natural gas, and the remaining 50% is supplied by coal.

Restrictive environmental regulations precluding new coal-burning permits in many areas have led to new ethanol-plant designs that primarily incorporate natural gas firing as the process fuel. Use of natural gas in ethanol plants results in less total CO_2 emissions from ethanol plants. Electricity use in ethanol plants accounts for 9 - 15% of their total energy consumption. (9, 10) Most established wet mills, which are usually large, are equipped with cogeneration systems to produce both steam and electricity. In contrast, many dry mills purchase electricity from the power grid. Use of cogeneration systems can help reduce plant energy use by as much as 30%. (11) In general, energy use can be reduced by 10% by using cogeneration systems. (12) In our base case analysis, we assume that 50% of dry milling and 100% of wet milling plants employ cogeneration systems, but that, for future cases, cogeneration use will be 100% in all mills.

Our energy use values reflect the amount of energy consumed for producing both ethanol and co-products. Co-products include distillers' dried grains and solubles (DDGS) in dry milling plants and corn oil, germ, gluten meal, and gluten feed in wet milling plants. In most previous studies, emissions and energy use during both corn farming and ethanol production were allocated between ethanol and co-products, with a co-product credit that is estimated by using one of four methods: product replacement, market value, energy content, or weight. In this study, we have attempted to separate energy use in ethanol plants into two values: one for ethanol production and the other for co-product production. The separation is based on energy use for a specific process in ethanol plants and whether the specific process is for ethanol or co-product production. A large portion of the total energy used in ethanol plants is for process heating during corn milling. To be conservative, we allocate all the energy for the corn milling process to ethanol production, but inside the plant gate, the energy used within the ethanol processing group and the co-product processing group is assigned to ethanol and co-products, respectively.

In dry milling plants, the most energy-intensive processes are cooking of corn, distillation and dehydration of ethanol, and evaporation and dewatering of DDGS. Thermal energy use in wet mills is more complex. Major energy-consuming processes include liquefaction and distillation for ethanol; steep water evaporation; and germ, fiber, and gluten (co-product) drying.

Table 7 gives the energy use allocation between ethanol and co-products with other allocation approaches from previous studies. As the table shows, the process-based energy allocation in ethanol plants, as calculated in our study, is close to the *market value-based* allocation for wet milling plants and to *energy content-based* allocation for dry milling plants.

Note that although we allocate energy use and emissions *within ethanol plants* on the basis of estimated energy use split between ethanol production and co-product production, we use the market value-based co-product credit for allocating energy use and emissions during *corn farming*. The result is 30% of energy and emissions assigned to co-products in the wet milling process and 24% in the dry milling process.

End-use Vehicle Types and Fuel Economy

We include both passenger cars and light trucks (pickups and minivans) in this study. Although percentage changes in per-mile GHG emissions for both types will be similar, the absolute amount of emissions in grams per mile will be different. We estimate grams-per-mile GHG emissions for light trucks with our base-case scenario to show expected differences. At present, Ford is selling an FFV (flexible-fueled vehicle) Taurus (3.0-L engine), and Chrysler is selling its FFV minivan (3.3-L engine). Ford will produce an FFV Ranger pickup (3.0-L engine) beginning in model-year 1999 and an FFV Windstar minivan (3.0-L engine) in model year 2000. In our comparison between E85 FFVs and gasoline cars, we select Taurus-like mid-size cars, and between E85 FFVs and gasoline light trucks, we select light trucks similar to the Chrysler minivan, the Ford Ranger pickup, and the Ford Windstar. Table 8 presents the gasoline fuel economy of baseline comparison vehicles. E85 use is restricted to new FFVs, but E10 can be used in existing gasoline vehicles without any vehicle modifications. Thus, while the fuel economy shown for E85 FFVs is based on comparison with the few vehicle models listed above, the fuel economy of vehicles using E10 is based on *all* new cars and all new light trucks.

Gasoline-equivalent fuel economy of E85 FFVs is assumed to be 5% higher than that of baseline gasoline vehicles; this assumption is conservative in light of the recent fuel economy performance of production E85 Tauruses. Btu-equivalent fuel economy is assumed to be the same for E10 and gasoline (although in-use experience indicates that E10 has a slight fuel economy penalty *per unit volume*). Furthermore, 1997 MY baseline gasoline vehicles are assumed to be fueled with conventional gasoline, and 2005 MY baseline gasoline vehicles are assumed to be fueled with reformulated gasoline.

RESULTS AND CONCLUSIONS

Using the values for key input parameters discussed in preceding sections, we present the results of fuel-cycle energy use and GHG emissions of using E85 and E10 relative to using CG (under the current case) and RFG (under the 2005 case). We have also performed sensitivity analyses on some key variables, but those results are beyond this paper's scope. We estimate energy use and emissions for a present situation that includes technologies in-place and for a future situation in which various technologies, especially ethanol production technologies, will improve. The future case is applied in 2005. Under the two cases, energy use and emissions are calculated for cars and light-duty trucks using E85 and E10. Baseline gasoline vehicles are fueled with CG under the current case and RFG under the future case. Per-mile energy and GHG emissions results for these cases are presented in Tables 9 - 12, with comparisons are shown in Table 13. The tables show that both wet milling and dry milling of ethanol account for substantial reductions, relative to conventional gasoline over the complete fuel production cycle, in both fossil energy use and GHG when the ethanol is used in a high-ethanol blend such as E85. For both cars and light trucks, the reduction in fossil energy use under current corn cultivation and ethanol production practices exceeds 40% and, in greenhouse gas emissions, 30% for E85 compared to conventional gasoline. These differences are expected to grow to over 45% and 35%, respectively, in the future when compared to reformulated gasoline. Even though it accounts for only about 7 percent of the energy content of E10, the ethanol component displacing gasoline in that blend yields a small total fuel cycle net saving in both fossil energy and GHG.

Thus, for the representative conditions that we have examined in this study, the corn-to-ethanol fuel cycle for ethanol burned as E85 and E10 outperforms both that of conventional (current) and that of reformulated (future) gasoline on the basis of mass emissions per travel mile. While GHG reductions appear sensitive to such factors as varying the value chosen for combined soil and leached N-fertilizer conversion to nitrous oxide, co-product energy use attribution remains the single key factor in estimating ethanol's relative benefits because this value can range from 0 to 50%, depending on the attribution method chosen. However, even for zero co-product attribution, some net savings are realized. We conclude that the use of corn-based ethanol achieves net energy savings and greenhouse gas emissions reductions relative to the gasoline fuel cycle, at least for current and near-term crop and ethanol production conditions in the four states that we examined. If domestic use of corn-based fuel ethanol is increased drastically (e.g., to 10 times current national usage level), corn farming practice and acreage under cultivation for meeting such an increase in demand could be quite different from current conditions. Our results do not apply to such a scenario.

ACKNOWLEDGMENTS

This analysis was funded by Illinois Department of Commerce and Community Affairs (DCCA). The authors thank DCCA project manager David Loos for his input and support, as well as the following individuals for providing data and comments: D. Adler of U.S. Environmental Protection Agency, J. Baker of Iowa State University, A. Blackmer of Iowa State University, M. Buckland of Delta-T Corporation, J. Duffield of U.S. Department of Agriculture, M. Graboski of Colorado School of Mines, E. Harjehausen of Archer Daniels Midland Company, R. Hoeft of University of Illinois at Urbana-Champaign, W. Liegois of Stanley Consultants, P. Madson of Raphael Katzen Assoc. International, T. Merediz of Process Systems, Inc., C. Reeder of ADM Corn Processing, P. Shane of Illinois Corn Growers Association, H. Shapouri of U.S. Department of Agriculture, B. Shroff of Raphael Katzen Associates International, Inc., G. Welch of Pekin Energy Company, and P. Wood of Process Systems, Inc. The authors assume full responsibility for the paper's contents.

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TABLES

Table 1. Summary of major corn-ethanol studies.

Source	Fuel	GHG changes (%) [a]	Remarks
Ref. 13	E100 E85	[22] - [21] [6] - [5]	CO_2 only; co-product credits based on displaced products
Ref. 14	E100	15 - 36	The range reflects assumptions about ethanol production technologies
Ref. 15	E100	[40] - [20]	Co-product credits are based on both market values and displaced products
Ref. 16	E100	[65] - 80 [70] - 0	Coal as the process fuel in ethanol Natural gas as the process fuel
Ref. 17	Ethanol as oxygenate RFG	[35] - 0 [40] - [10] [60] - [40]	Coal as the process fuel in ethanol Natural gas as the process fuel Corn stover (waste) as the process fuel
Ref. 18	E95	20.6	Result cited here is for full fuel cycle
Ref. 1	E100 E85	[31.7] [25.4]	Co-product credits based on energy Coal as the process fuel; co-product credits based on *energy content*
Ref. 19	E85	[18.2]	Coal as the process fuel; co-product credits based on *market values*
	E85	[30.5]	Natural gas as the process fuel; co-product credits based on *market values*

[a]from baseline gasoline; values in brackets are negative (i.e., reductions)

Table 2. Corn farming input energy requirements (Btu/bushel).

ITEM	STATE IL	IA	MN	NE	WEIGHTED TOTAL[a]
Weighting Factor (based on bushels harvested[b], 1996)	0.280	0.330	0.165	0.225	
Seed corn—diesel fuel	159	132	138	253	168
Diesel equipment	3,954	3,954	4,942	17,792	7,231
Gasoline equipment	3,554	2,665	2,665	3,554	3,114
LPG equipment	1,292	3,230	2,585	2,585	2,436
Electricity	97	40	226	783	254
Natural gas	437	0	0	11,716	2,759
Custom work—diesel	1,297	1,129	992	969	1,118
Drying--natural gas	821	1,332	1,202	1,049	1,104
Input haul - same base dist. to farm	992	992	992	992	992
TOTAL	12,603	13,474	13,742	39,693	19,176

[a] weighted total = (Btu/bushel) x weighting factor

[b] The logic for this allocation method is that only corn actually harvested should be included for purposes of ethanol production attribution

Table 3. Field fertilizer requirements in corn growing years (g/bushel).

ITEM	STATE				WEIGHTED TOTAL[a]
	IL	IA	MN	NE	
Weighting Factor (based on planted acreage[b])	0.277	0.320	0.189	0.214	1.0
Nitrogen (granular, N)	578	448	365	482	476
Phosphate (P_2O_5)	234	172	175	93	173
Potash (K_2O)	335	216	196	31	206

[a] weighted total = (Btu/bushel) x weighting factor

[b] The logic for this allocation method is that fields devoted to corn farming will be seeded and fertilized at least once, even if the crop is abandoned; thus, energy will still be expended and N-emissions will occur.

Table 4. Application rates (g/bushel) by state, four-state averages for *all* agents applied, and manufacturing energy intensity (Btu/g of agent applied) of principal corn herbicides and all pesticides.

Item	Herbicides					All Pesticides
	Atrazine	Cyanazine	Metolachlor	Acetochlor	Overall [a]	
Share: (1) among top 4	0.312	0.171	0.281	0.236	1.000	
(2) of total	0.249	0.137	0.225	0.189	0.800	
Application rate by state:						
IL	4.1	10.4	7.3	6.8	10.9	0.68
IA	3.2	8.4	8.0	6.9	9.9	0.49
MN	2.1	5.7	8.9	6.2	8.3	0.29
NE	3.5	6.4	5.2	5.8	8.1	1.26
Four-State Wtd. Av.	3.3	8.1	7.3	6.5	9.5	0.68
Energy use (Btu/g)	180	191	262	264	225	230

[a] The overall application rate for herbicides, other than the principal four, is higher than the four-agent average.

Table 5. Key assumptions and energy use results of chemical transportation.

Item	Step One: Plant to Center	Step Two: Center to Mixer	Step Three: Mixer to Farm
Travel distance, mi, one-way	1060 (barge)	50	30
by mode	520 (rail)	Class 8b truck	Class 6 truck
Energy use (Btu/ton)	294,940	105,620	220,000

Table 6. Summary of ethanol plant energy use (Btu/gal), and ethanol/co-product energy allocation by (1) mill product market value for corn farming and (2) process energy demand for milling.

Item	Dry milling	Wet milling
Total energy use before allocation		
Current (1997)	41,400	40,300
Near future (2005)	36,900	34,000
Process fuel share: current		
Natural gas	47%	20%
Coal	47%	80%
Electricity	6%	0%
Process fuel share: near future		
Natural gas	50%	20%
Coal	50%	80%
Electricity	0%	0%
Energy use allocation: corn farming		
Ethanol market value	76%	70%
Co-product market value	24%	30%
Energy use allocation: ethanol production		
Fuel ethanol	67%	69%
Co-products	33%	31%

Table 7. Comparison of energy use and emissions allocation between ethanol and co-product in corn ethanol plants.

Energy and Emissions Allocation (%)		Basis	Remarks	Source
Ethanol	Co-Products			
57	43	Market value	Wet milling	Ref. 20
70	30	Market value	Wet milling	Ref. 21
76	24	Market value	Dry milling	do.
57	43	Energy content	Wet milling	do.
61	39	Energy content	Dry milling	do.
48	52	Output weight basis	Wet milling	do.
49	51	Output weight basis	Dry milling	do.
81	19	Replacement value	Wet milling	do.
82	18	Replacement value	Dry milling	do.
81	19	Replacement value	Dry milling	Ref. 16
69	31	Process energy basis	Wet milling	This study
66	34	Process energy basis	Dry milling	This study

Table 8. Baseline gasoline vehicle fuel economy (on-road adjusted, combined urban/highway cycle).

	E85		E10	
	1997 MY	2005 MY	1997 MY	2005 MY
Passenger cars	23[a]	25[c]	28[d]	30[c]
Light trucks	19[b]	21[c]	21[d]	22[c]

[a] Fuel economy of 1997 MY Taurus is 23 mpg. (22)

[b] Fuel economy is 20.3, 17.6, and 19.9 mpg for 1997 MY Chrysler minivan, Ford Ranger pickup, and Ford Windstar minivan, respectively. (22)

[c] Projections for 2005 MY vehicle fuel economy for a given vehicle type based on fuel economy of the 1997 vehicle and new vehicle fuel economy improvement between 1997 and 2005 predicted by Energy Information Administration. (23)

[d] Fuel economy averaged over all new cars and all new light trucks. (23)

Table 9. Fuel-cycle energy use (Btu/mi) and GHG emissions (CO_2-equivalent g/mi): passenger cars and light trucks using **E85** for the **current** technology case (cars/*light trucks*)

	Total Energy Use and GHG Emissions by Category			
Type of emissions by fuel	Feedstock	Fuel	Vehicle Combustion	Total[a]
Baseline gasoline:				
Fossil energy	146/*177*	1,009/*1,222*	5,022/*6,079*	6,177/*7,477*
GHGs	25.4/*30.8*	77.6/*94.0*	366.0/*446.1*	469.1/*570.9*
CO_2	16.2/*19.6*	76.3/*92.4*	362.8/*442.9*	455.4/*555.0*
CH_4	8.8/*10.6*	0.1/*0.1*	1.6/*1.6*	10.5/*12.3*
N_2O	0.5/*0.5*	1.2/*1.5*	1.6/*1.6*	3.2/*3.6*
Ethanol - wet mills:				
Fossil energy	795/*962*	1,669/*2,020*	1,011/*1,224*	3,475/*4,207*
GHGs	110.2/*133.4*	145.3/*175.9*	68.8/*84.9*	324.3/*394.3*
CO_2	58.5/*70.8*	143.7/*173.5*	66.2/*82.4*	268.1/*326.7*
CH_4	1.9/*2.3*	0.9/*1.1*	1.0/*1.0*	3.8/*4.4*
N_2O	49.8/*60.3*	1.1/*1.3*	1.6/*1.6*	52.5/*63.2*
Ethanol - dry mills:				
Fossil energy	828/*1,003*	1,742/*2,108*	1,011/*1,224*	3,581/*4,335*
GHGs	114.8/*139.0*	141.1/*170.8*	68.8/*84.9*	324.7/*394.7*
CO_2	60.9/*73.7*	137.2/*166.0*	66.2/*82.4*	264.3/*322.1*
CH_4	1.9/*2.3*	1.3/*1.6*	1.0/*1.0*	4.2/*4.9*
N_2O	52.0/*63.0*	2.6/*3.2*	1.6/*1.6*	56.2/*67.7*

[a]May not sum precisely due to rounding error

Table 10. Fuel-cycle energy use (Btu/mi) and GHG emissions (CO_2-equivalent g/mi): passenger cars and light trucks using **E85** for the **future** technology case (cars/*light trucks)*

Type of emissions by fuel	Feedstock	Fuel	Vehicle Combustion	Total[a]
	Total Energy Use and GHG Emissions by Category			
Baseline gasoline:				
Fossil energy	131/*156*	1,077/*1,282*	4,520/*5,381*	5,728/*6,819*
GHGs	22.9/*27.3*	81.8/*97.4*	322.6/*386.4*	427.3/*511.0*
CO_2	14.6/*17.4*	80.3/*95.6*	319.5/*383.2*	414.4/*496.2*
CH_4	7.9/*9.4*	0.1/*0.1*	1.6/*1.6*	9.6/*11.1*
N_2O	0.4/*0.3*	1.4/*1.1*	1.6/*1.6*	3.3/*2.5*
Ethanol--wet mills:				
Fossil energy	755/*899*	1,344/*1,600*	895/*1,065*	2,994/*3,564*
GHGs	102.5/*122.1*	116.1/*138.2*	58.4/*71.1*	277.0/*331.3*
CO_2	55.8/*66.4*	114.5/*136.3*	55.8/*68.5*	226.1/*271.1*
CH_4	1.7/*2.0*	0.7/*0.8*	1.0/*1.0*	3.4/*3.8*
N_2O	45.1/*53.7*	0.9/*1.1*	1.6/*1.6*	47.5/*56.3*
Ethanol--dry mills:				
Fossil energy	747/*889*	1,400/*1,667*	895/*1,065*	3,042/*3,621*
GHGs	103.6/*123.3*	109.6/*130.4*	58.4/*71.1*	271.6/*324.8*
CO_2	54.9/*65.3*	107.6/*128.1*	55.8/*68.5*	218.3/*261.9*
CH_4	1.7/*2.0*	1.1/*1.3*	1.0/*1.0*	3.8/*4.4*
N_2O	47.1/*56.0*	0.9/*1.0*	1.6/*1.6*	49.4/*58.6*

[a]May not sum precisely due to rounding error

Table 11. Fuel-cycle energy use (Btu/mi.) and GHG emissions (CO2-equivalent gm/mi.): passenger cars and light trucks using **E10** for the **current** technology case (cars/*light trucks)*

Type of emissions by fuel	Feedstock	Fuel	Vehicle Combustion	Total[a]
	Total Energy Use and GHG Emissions by Category			
Baseline gasoline:				
Fossil energy	120/*160*	829/*1,105*	4,125/*5,500*	5,074/*6,765*
GHGs	20.9/*27.9*	63.8/*85.0*	298.0/*402.2*	382.7/*515.1*
CO_2	13.3/*17.8*	62.7/*83.6*	294.9/*399.1*	370.9/*500.4*
CH_4	7.2/*9.6*	0.1/*0.1*	1.6/*1.6*	8.9/*11.3*
N_2O	0.4/*0.5*	1.0/*1.3*	1.6/*1.6*	2.9/*3.4*
Ethanol--wet mills:				
Fossil energy	168/*224*	881/*1,174*	3,849/*5,132*	4,897/*6,530*
GHGs	27.2/*36.3*	69.0/*92.0*	277.4/*374.5*	373.6/*502.8*
CO_2	16.5/*22.0*	67.9/*90.5*	274.2/*371.4*	358.6/*483.9*
CH_4	6.7/*9.0*	0.1/*0.2*	1.6/*1.6*	8.4/*10.7*
N_2O	4.0/*5.3*	1.0/*1.3*	1.6/*1.6*	6.5/*8.2*
Ethanol--dry mills:				
Fossil energy	170/*227*	886/*1,181*	3,849/*5,132*	4,905/*6,540*
GHGs	27.5/*36.7*	68.7/*91.6*	277.4/*374.5*	373.6/*502.8*
CO_2	16.6/*22.2*	67.4/*89.9*	274.2/*371.4*	358.3/*483.5*
CH_4	6.7/*9.0*	0.2/*0.2*	1.6/*1.6*	8.5/*10.8*
N_2O	4.2/*5.5*	1.1/*1.5*	1.6/*1.6*	6.8/*8.6*

[a]May not sum precisely due to rounding error

Table 12. Fuel-cycle energy use (Btu/mi.) and GHG emissions (CO2-equivalent gm/mi.): passenger cars and light trucks using **E10** for the **future** technology case (cars/*light trucks)*

Type of emissions by fuel	Total Energy Use and GHG Emissions by Category: Feedstock	Fuel	Vehicle Combustion	Total[a]
Baseline gasoline:				
Fossil energy	109/*149*	897/*1,224*	3,767/*5,136*	4,774/*6,509*
GHGs	19.1/*26.0*	68.2/*92.9*	266.9/*368.3*	354.1/*487.2*
CO_2	12.2/*16.6*	66.9/*91.3*	263.7/*365.1*	342.8/*473.0*
CH_4	6.6/*9.0*	0.1/*0.1*	1.6/*1.6*	8.3/*10.7*
N_2O	0.3/*0.5*	1.2/*1.6*	1.6/*1.6*	3.0/*3.6*
Ethanol--wet mills:				
Fossil energy	153/*209*	921/*1,256*	3,514/*4,792*	4,589/*6,257*
GHGs	24.8/*33.9*	71.0/*96.8*	248.2/*342.8*	344.0/*473.4*
CO_2	15.0/*20.5*	69.7/*95.1*	245.0/*339.6*	329.8/*455.2*
CH_4	6.2/*8.4*	0.1/*0.2*	1.6/*1.6*	7.9/*10.1*
N_2O	3.6/*5.0*	1.1/*1.5*	1.6/*1.6*	6.3/*8.1*
Ethanol--dry mills:				
Fossil energy	155/*212*	925/*1,262*	3,514/*4,792*	4,595/*6,266*
GHGs	25.1/*34.3*	70.5/*96.1*	248.2/*342.8*	343.8/*473.2*
CO_2	15.2/*20.7*	69.2/*94.4*	245.0/*339.6*	329.5/*454.8*
CH_4	6.2/*8.4*	0.1/*0.2*	1.6/*1.6*	7.9/*10.2*
N_2O	3.8/*5.2*	1.1/*1.5*	1.6/*1.6*	6.5/*8.2*

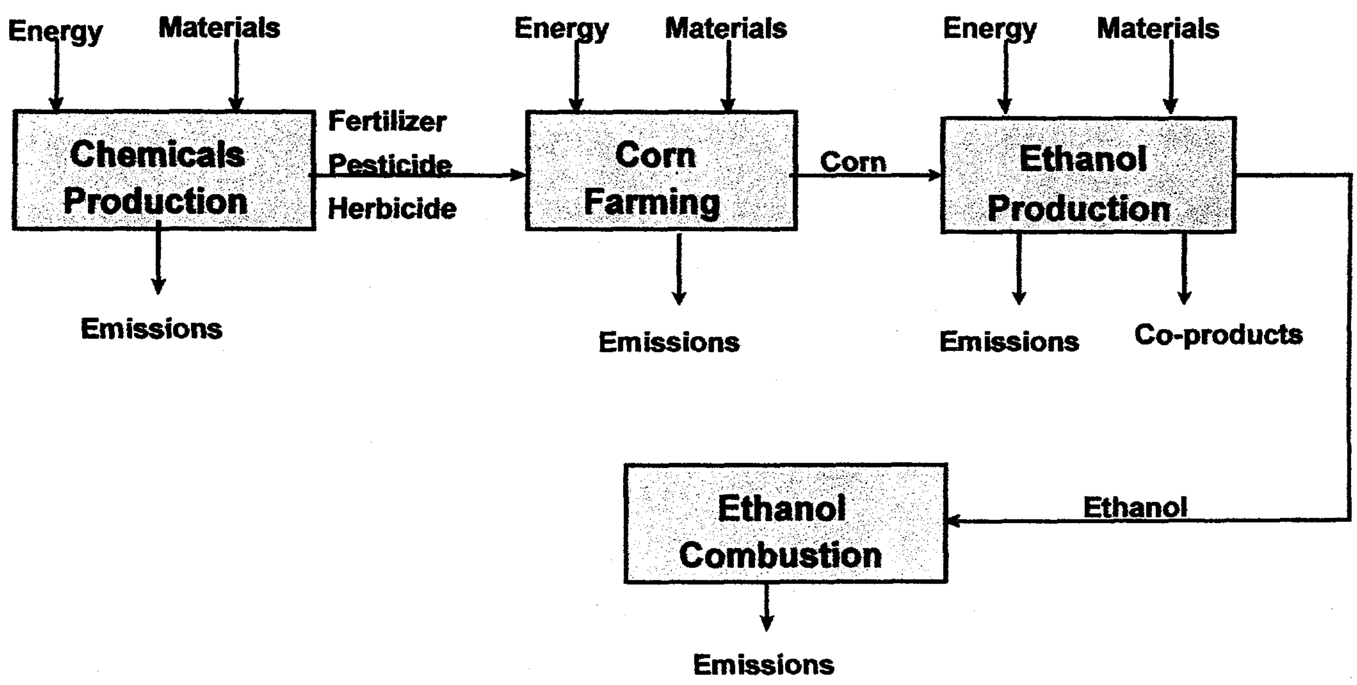
[a]May not sum precisely due to rounding error

Table 13. Per-Mile energy use and emissions reductions by E85 and E10 blend (relative to CG for current and to RFG for future conditions)

Fuel Type	Energy & Emissions	Current Conditions		Future Conditions	
		Wet Milling	Dry Milling	Wet Milling	Dry Milling
E85 Blend:					
Cars	Fossil energy	43.7%	42.0%	47.7%	46.9%
	GHGs	30.9%	30.8%	35.2%	36.4%
Light trucks	Fossil energy	43.7%	42.0%	47.7%	46.9%
	GHGs	30.9%	30.9%	35.2%	36.4%
E10 Blend:					
Cars	Fossil energy	3.5%	3.3%	3.9%	3.7%
	GHGs	2.4%	2.4%	2.9%	2.9%
Light trucks	Fossil energy	3.5%	3.3%	3.9%	3.7%
	GHGs	2.4%	2.4%	2.8%	2.9%

FIGURE

Figure 1. Flow chart of the corn-to-ethanol fuel cycle



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