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# Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context

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ABSTRACT

Products other than biofuels are produced in biofuel plants. For example, corn ethanol plants produce distillers' grains and solubles. Soybean crushing plants produce soy meal and soy oil, which is used for biodiesel production. Electricity is generated in sugarcane ethanol plants both for internal consumption and export to the electric grid. Future cellulosic ethanol plants could be designed to co-produce electricity with ethanol. It is important to take co-products into account in the life-cycle analysis of biofuels and several methods are available to do so. Although the International Standard Organization's ISO 14040 advocates the system boundary expansion method (also known as the "displacement method" or the "substitution method") for life-cycle analyses, application of the method has been limited because of the difficulty in identifying and quantifying potential products to be displaced by biofuel co-products. As a result, some LCA studies and policy-making processes have considered alternative methods. In this paper, we examine the available methods to deal with biofuel co-products, explore the strengths and weaknesses of each method, and present biofuel LCA results with different co-product methods within the U.S. context.



## 1. Introduction

Biofuels are being promoted on a global basis because their use may potentially reduce greenhouse gas (GHG) emissions and help achieve energy security by reducing the transportation sector's use of and reliance upon petroleum (RFA, 2007; EC, 2009a, 2009b; BRDi, 2008; CARB, 2009; EPA, 2009). The pursuit of the various biofuel types and production pathways with true GHG and energy benefits requires examination of the energy use and emission burdens of the whole life cycle of biofuels, covering agricultural chemical production, farming of biofuel feedstocks, biofuel production, and biofuel utilization in motor vehicles. A traditional life-cycle analysis (LCA) is conducted by following each biofuel life-cycle step to derive the total energy use and emission burdens for a given amount of biofuels produced and used. Furthermore, biofuel LCA energy use and emission results are usually compared to those of baseline fuels to be displaced with biofuels so that the relative merits of biofuels can be assessed (Wang, 2008).

Several major LCA models are available and studies have been completed with them (see Delucchi, 2003; Brinkman et al., 2005; CONCAWE/EUCAR/JRC, 2007; (S&T)[2] Consultants Inc., 2008). The seemingly straightforward LCA for biofuels is data intensive. Major efforts are continuing to collect the best data to reflect current practice and future trends of biofuel production. Besides, the current debate on the relative energy and environmental benefits of biofuels focuses on indirect changes (such as indirect land use changes) at the global scale as well as direct changes at the local/regional scale that could be caused by large-scale biofuel production (Searchinger et al., 2008). Major regulatory efforts began recently to tackle these complex issues within the LCA context (CARB, 2009; EPA, 2010).

In recent years, LCAs for biofuels have been examined closely for their general approach regarding LCA methodology selection between the so-called attributional LCA and consequential LCA (see Ekvall and Weidema, 2004). Traditionally, LCAs for transportation fuels have followed the attributional LCA approach, through which individual processes of a fuel cycle are identified (especially with technology advancements), and the energy use and emission burdens of a given process are allocated among different products. The approach has been developed from conventional engineering analysis of system designs and performance. It has been advocated and used by many (ISO, 1997; Wang, 1999; Delucchi, 2003; (S&T)[2] Consultants Inc., 2008; CONCAWE/EUCAR/JRC, 2007). On the other hand, the consequential LCA approach takes into account the effects of processes that are directly involved in the generation of a given product and all the indirect effects, such as the secondary and tertiary effects of introducing the product to the marketplace. Historically, consequential LCAs were conducted with economic input–output models within an economy (usually within a country), but they

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have recently been expanded to the global economy, taking all of the direct and indirect effects at the global scale into account. Regulatory development of biofuel policies has applied both LCA approaches. For example, CARB (2009), in its recently adopted low-carbon fuel standards (LCFS), relied on the attributional LCA (except for land use changes that are caused by biofuel production) by using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed at Argonne National Laboratory. On the other hand, the EPA (2010) applied the consequential LCA approach in its regulation for U.S. renewable fuel standards under the 2007 U.S. Energy Independence and Security Act (RFS2, as opposed to renewable fuel standards under the 2005 U.S. Energy Policy Act, RFS1). To do so, EPA used the FASOM model (for Forestry and Agricultural Sector Optimization Model), which was developed at the Texas A&M University for U.S. domestic agriculture and forestry and the FAPRI (Food and Agricultural Policy Research Institute) model, which is being used at Iowa State University to simulate international agriculture effects of U.S. biofuel production. To supplement both models, EPA used the GREET model to develop emissions for processes of fuel production pathways.

At present, direct and indirect land use change issues for biofuels are being vigorously debated. Attributional and consequential LCAs are beginning to be closely examined. Reliable data to reflect technology advancement for agricultural practices and biofuel production are being pursued. One of the remaining issues is the analytic method of dealing with the co-products from the biofuel production pathways. In virtually all current and future biofuel production pathways, products besides biofuels are generated. These products generally have significant commercial value and are part of the viability of biofuels themselves. Biofuel LCAs must take into account these products.

Several methods have been developed and applied to deal with non-biofuel products in biofuel LCAs (see Wang, 2005). Depending on the method selected, biofuel LCA results can vary widely. Even though some attention has been paid to this issue and while there is general consensus on what method should be used in dealing with multiple products in LCAs, no agreement has been reached on which method should be used in biofuel LCAs. For example, while the displacement method is advocated or used by the ISO (1997), Delucchi (2003), Wang (2005), the U.K. Renewable Fuels Association, 2009, CONCAWE/EUCAR/JRC (2007), CARB (2009), and EPA (2009), the energy-based allocation method was adopted in the EC renewable energy directive and fuel quality directive (EC, 2009a and 2009b). The following discussions present several methods that are being used now in biofuel LCAs, conduct biofuel LCAs with these methods by applying the GREET model, and demonstrate the effects of method selection on biofuel LCA results within the U.S. context.

## 2. Co-products of biofuel production

There are several key biofuel production pathways in practice around the world and additional biofuel production pathways are being intensely researched and developed. Table 1 summarizes these key pathways and their products. As the table shows, the main energy products for the pathways are liquid fuels for transportation applications. Other products could be animal feed for their nutrition and caloric values (such as distillers' grains and solubles [DGS]); other energy products (such as electricity); and specialty chemicals (such as acetone and glycerin). The fuel products and other products with very different applications pose a challenge to designing and applying methods to deal with multiple products in biofuel LCAs.

## 3. Potential methods of dealing with multiple products

There are five potential methods to address multiple products of biofuel production pathways (ISO, 1997; Shapouri et al., 2003; Wang et al., 2004; Wang, 2005). Wang et al. (2004) quantitatively evaluated implications of four out of five methods (except for the displacement method) by applying the methods to petroleum refinery products. Each of the five methods is discussed below.

### 3.1. *The mass-based method*

Using this method, the energy use and emission burdens of a given biofuel pathway are allocated among all products according to their mass output shares. This allocation method is based on the presumption that energy use and emissions are somewhat related to the amount of mass processed. This method is widely used in LCAs of consumer products and in some generic LCA models. Sheehan et al. (1998) applied the method to an LCA of soybean-based biodiesel. It is applicable as long as all products are used on a mass basis (e.g., a ton of steel for use). However, this method becomes problematic when products have distinctly different uses. For example, in the sugarcane ethanol and cellulosic ethanol production pathways in which electricity is co-produced, the electricity does not have any mass and thus cannot use the mass allocation method.

**Table 1**
Key Biofuel Production Pathways and Their Products.

| Feedstock | Fuel Product | Co-Products | Co-Product Uses |
|---|---|---|---|
| Corn | Ethanol (EtOH) | Distillers' grains and solubles (DGS) | Animal feed; potentially as process fuel for steam generation in corn ethanol plants |
| Sugarcane | Ethanol | Bagasse | Steam and electricity production in sugarcane ethanol plants |
| Wheat | Ethanol | DGS | Animal feed; potentially as process fuel for steam generation in wheat ethanol plants |
| Sugarbeet | Ethanol | Sugar beet pulp and dried slop | Animal feed; potentially as process fuel for steam generation in sugarbeet ethanol plants |
| Cassava | Ethanol | DGS | Animal feed; potentially as process fuel for steam generation in cassava ethanol plants |
| Soybeans | Biodiesel | Soy meals and glycerin | Soy meals as animal feed; glycerin as specialty chemical |
| Rapeseeds | Biodiesel | Rapeseed meals and glycerin | Rapeseed meals as animal feed; glycerin as specialty chemical |
| Palms | Biodiesel | Residual fertilizer and glycerin | Fertilizer for farming; glycerin as specialty chemical |
| Cellulosic biomass | Ethanol | Lignin | Steam and electricity production in cellulosic ethanol plants |
| Soybeans | Renewable diesel | Fuel gas and heavy oils | Energy sources for plant internal use; or energy products for sale |
| Corn | Butanol | DGS and acetone | DGS as animal feed or potentially as process fuel for steam generation in corn butanol plants; acetone as a chemical feedstock |

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### 3.2. The energy-content-based method

Using this method, the energy use and emission burdens of a given fuel production pathway are allocated among products according to their energy output shares. The energy output of all products is calculated by taking the amount of the product(s) produced and multiplying that total by the product's energy content (i.e., usually the heating content of the products). This method is applicable where most of the products, if not all, are used for their energy content purposes. A good example is provided by petroleum refineries, where most products are indeed energy products (gasoline, diesel, residual oil, etc.; see Wang et al., 2004). In its renewable energy directive and fuel quality directive, the EC (2009a, 2009b) adopted the energy allocation method out of its concern about the uncertainties that the displacement method introduces to regulation development. Nonetheless, the Commission suggested that the displacement method should continue to be used for biofuel policy analysis. However, similar to the mass-based method, the method becomes problematic when products have distinctly different uses. For example, starch-based ethanol plants produce ethanol and animal feeds. Even though animal feeds have energy content, they are used because of their significant nutritional and caloric values, which are on par with conventional animal feeds (such as corn and soybean meal). Even though the energy-content-based method can be applied to biofuel LCAs, the application reflects neither the use of individual products nor the energy use and emissions of producing individual products.

### 3.3. The market-value-based method

This method allocates energy and emission burdens based on economic revenue shares of individual products. The economic revenue of a given product is calculated from the product yield of a given pathway and the price of the product. Economists generally advocate use of this method. In fact, some LCA applications of general equilibrium models adopt this method. While the United Kingdom's Renewable Transport Fuel Obligation has adopted the displacement method as its default method, the market value allocation method was adopted in situations where the displacement method cannot be applied (RFA, 2009). This method assumes that activities and decisions are driven by economics and thus burdens should be disbursed according to economic benefits. One unique advantage of this method is that it normalizes all products to a common basis—their economic values—regardless of the purpose of their use. However, in practice this method is subject to great fluctuation of product prices. Some researchers have applied average prices over a period to limit this problem. Still, for products to be produced in the future, one will have to predict the prices of new products in the future, which are uncertain. In addition, the actual energy use and emissions that accrue during a fuel pathway may not be related to the economic values of individual products.

### 3.4. The process-purpose-based method

This method estimates energy use and emissions of individual processes in a facility. The energy use and emissions of a given process are allocated to a given product if the purpose of that process is solely the production of the given product. An example is the dryer in a corn ethanol plant. The dryer is installed to dry DGS. Thus, energy use and emissions from the dryer operation are allocated to DGS. Shapouri and McAloon (2004) used this method to estimate the net energy balance of corn ethanol in the United States. However, in many cases, individual processes in a facility may produce multiple products (see Wang et al., 2004), which leads to the problem of allocating the energy use and emissions of a given process among all of the products of that process. Furthermore, this method requires energy use and emissions data at the process (but not at the facility) level, which may not be available for many biofuel facilities. Even if the process-purpose-based method is applied to a given facility, the activities upstream of the facility still need to be allocated. For example, this method can be applied to allocate energy use and emissions of corn ethanol plants between ethanol and DGS; however, a determination still needs to be made concerning the allocation of energy use and emissions of corn farming between ethanol and DGS. This decision might be based on the mass-, energy-content-, or market-based methods.

### 3.5. The displacement method

In the displacement method (also called the "system boundary expansion method" or the "substitution method"), the products that are to be displaced by non-fuel products are determined first. The energy use and emissions burdens of producing the otherwise displaced products are then estimated. The estimated energy use and emissions burdens are credits that are subtracted from the total energy use and emission burdens of the biofuel production cycle. Fig. 1 shows a schematic of the displacement method in the LCA context, with DGS from corn ethanol plants as the example.

The displacement method tends to represent the actual effects of generating multiple products from a pathway. The method was adopted as the default method in dealing with biofuel co-products in transportation LCA models (Delucchi, 2003; Wang, 2005; (S&T)[2] Consultants Inc., 2008; and LBST, 2008) and used in biofuel regulations development (see CARB, 2009; EPA, 2010; RFA, 2009). The so-called consequential LCAs are actually an application of the displacement method wherever needed in the life cycle of a pathway (plus many other secondary and tertiary market mitigation effects; see Ekvall and Weidema, 2004). While the displacement method is generally advocated for conducting LCAs, its implementation poses some major challenges. Fig. 1 shows the method requires conducting LCAs for the conventional products to be displaced, which could be time intensive and resource consuming. In some cases, the user must arbitrarily decide

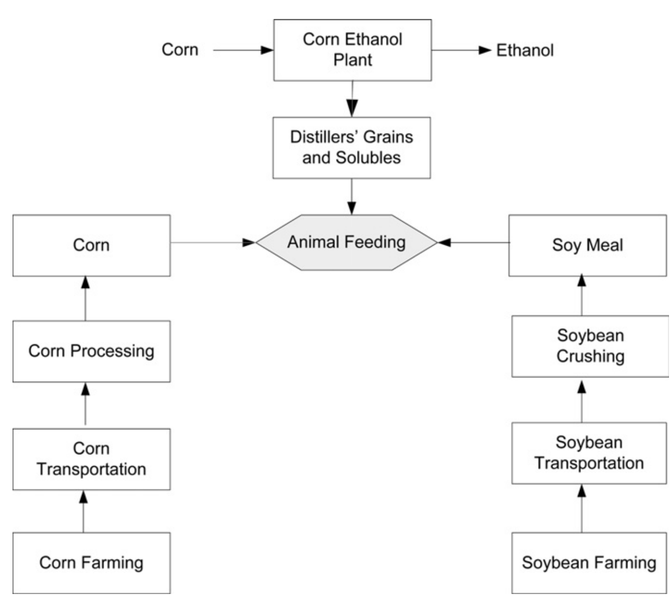


**Fig. 1.** The Displacement Method to Estimate Energy and Emission Credits of DGS from Corn Ethanol Plants.

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whether an LCA needs to be conducted for a conventional product when the displaced amount is below a determined threshold. Furthermore, the displacement effect could be circular. For example, soy meal from the crushing process in a biodiesel plant could displace soy meal from a regular soybean crushing facility. In this case, the energy use and emissions credits of the soy meal from the regular crushing plant may be estimated to be the same as the energy use and emissions burdens of the soybean-to-biodiesel pathway up to the crushing process.

Another major problem with the displacement method is that when non-fuel products are a large share of the total output, the method generates distorted fuel-based results. This problem is demonstrated in the following example, in which we examine the case of a facility that produces one fuel product and one non-fuel product. The outputs are represented as $Output_{fuel}$ and $Output_{nonfuel}$, and the total GHG emissions are represented as $GHG_{total}$. Furthermore, the non-fuel product displaces a conventional product (indicated by the subscript "convproduct") with a displacement ratio of R (i.e., R units of convproduct to be displaced by one unit of the non-fuel product). In addition, the GHG emissions per unit of the convproduct on an LCA basis are represented as $GHG_{convproduct}$. In using the displacement method, the GHG emissions per unit of the fuel product are determined as follows:

$$GHG_{fuel} = (GHG_{total} - GHG_{convproduct} \times R \times Output_{nonfuel})/Output_{fuel} \tag{1}$$

Current regulatory development of low-carbon fuel standards in Europe and North America requires estimation of $GHG_{fuel}$ by using the equation shown above for the displacement method.

As the above equation indicates the total GHG emissions from the facility and the total GHG emission credits from displacement between the non-fuel product and the conventional product are averaged over the total amount of fuel produced from the facility. If $Output_{nonfuel}$ is equal to or greater than $Output_{fuel}$, $GHG_{fuel}$ is mathematically reduced, compared to the case in which $Output_{nonfuel}$ is smaller than $Output_{fuel}$. A practical example is the soybean-based biodiesel pathway. The soybean crushing process produces roughly 82% of mass as soy meal and 18% as soy oil (which is used for biodiesel production, see Table 5 later). If the displacement method is used for this stage of the biodiesel pathway, it normalizes emissions of soybean farming and crushing to a much smaller basis (18% of the actual basis).

Thus, even though the displacement method is generally accepted in dealing with multiple products, this method should not be applied universally without examining the individual situation. We propose here that if non-fuel products are a small share of total output (in terms of mass, energy, or revenue), the non-fuel products should be categorized as the by-products and the fuel product as the main product. If non-fuel products are a significant share of total output but their share is still a lower percentage than the share of the fuel product, then both the non-fuel and fuel products should be categorized as co-products. In this situation, the displacement method may still generate reasonable results for fuel products. However, if non-fuel products are the main product and fuel is a by-product, the displacement method may not be appropriate at all for the LCA of the fuel product and other allocation methods may need to be considered. Of course, the above definitions of by-products, co-products, and main products are qualitative and indicative but not precise. The actual decision about whether to use the displacement method likely will have to be made on a case-by-case basis, which at times could be arbitrary.

In the following sections of this paper, we use the GREET model that we developed at Argonne National Laboratory to examine the five methods for four of the biofuel production pathways (i.e., corn ethanol, cellulosic ethanol, soybean biodiesel, and soybean renewable diesel) within the U.S. context. The objective is to determine quantitatively the implications of these methods on LCA results.

## 4. The GREET model and the fuel pathways examined

We developed the GREET model to examine the potential benefits to energy use and emissions of the use of advanced vehicle technologies and new transportation fuels (the GREET models, reports, and documentation are available at http://www.transportation.anl.gov/modeling_simulation/GREET/index.html). The GREET model is a life-cycle, or well-to-wheels (WTW), analytical tool that researchers and analysts can use to examine the energy and emission effects of different vehicle/fuel options. The most recent version—GREET 1.8c—was released in March 2009. GREET evaluates total energy use, fossil fuel use, natural gas use, coal use, and petroleum use; emissions of carbon-dioxide ($CO_2$)-equivalent GHGs, including $CO_2$, methane ($CH_4$), and Nitrous oxide ($N_2O$), and emissions of six criteria pollutants—volatile organic compounds (VOC), carbon monoxide (CO), nitrogen oxide ($NO_x$), particulate matter with diameters smaller than 10 μm ($PM_{10}$), particulate matter with diameters smaller than 2.5 μm ($PM_{10}$), and sulfur oxide($SO_x$). Criteria pollutant emissions are further separated into total and urban emissions to reflect human exposure to air pollution caused by emissions of the six pollutants.

GREET 1.8c includes many biofuel production pathways, as shown in Table 2. For the purpose of examining different methods of dealing with multiple products in this paper, we selected four biofuel pathways—corn to ethanol, switchgrass to ethanol, soybeans to biodiesel, and soybeans to renewable diesel. Each pathway is described below. Even though GREET generates results for energy use, GHG emissions, and criteria pollutant emissions, we only present energy use and GHG emission within the U.S. context results in this paper to demonstrate the importance of co-product method selection.

### 4.1. Corn to ethanol

The United States is the largest corn-to-ethanol producer in the world. In 2008, it produced 9 billion gallons of corn-based ethanol, which consumed more than 30% of total U.S. corn production that year (Renewable Fuels Association, 2009). The 2007 Energy Independence and Security Act established a goal of producing 15 billion gallons of corn-based ethanol in the United States in 2015. Historically, wet-mill corn ethanol plants, which produce ethanol and several other products (such as corn oil, gluten meal, gluten feed, etc.), have accounted for a significant share of total U.S. corn ethanol production capacity. However, in

**Table 2**
Some of the Biofuel Pathways Included in GREET 1.8c.

| Feedstock | Fuel |
|---|---|
| Corn | Ethanol |
| Switchgrass | Ethanol |
| Fast-growing trees | Ethanol |
| Corn stover | Ethanol |
| Forest residues | Ethanol |
| Sugarcane | Ethanol |
| Corn | Butanol |
| Soybeans | Biodiesel |
| Soybeans | Renewable diesel |
| Soybeans | Renewable gasoline |

recent years all new corn ethanol plants have been dry-mill plants in which ethanol and DGS are co-produced. The near-future expansion of the U.S. corn ethanol industry will likely rely on dry-mill plants. In the current study, we consider such plants to examine different methods for dealing with ethanol and DGS.

Fig. 2 presents the corn-to-ethanol pathway used in the LCA. This life cycle begins with production of fertilizers and other agricultural inputs and ends with ethanol combustion (blended with gasoline) in motor vehicles. DGS is produced from corn ethanol plants. In the case of all of the co-product methods except the displacement method, energy and emission burdens from fertilizer production, corn farming, corn transportation, and ethanol production are allocated between ethanol and DGS. Energy and emission burdens from ethanol transportation and combustion are allocated solely to ethanol.

### 4.2. Switchgrass to ethanol

Major research and development (R&D) efforts are under way to develop and commercialize technologies for producing ethanol from cellulosic biomass. In terms of resource availability and potential benefits of GHG emission reductions, cellulosic ethanol has larger potential than ethanol from corn and other grains. The major challenges with cellulosic ethanol are to (1) reduce the costs of cellulosic technology and (2) develop the production and logistic bases of cellulosic biomass feedstock. Table 2 shows that the GREET model includes four types of cellulosic biomass types—switchgrass, fast-growing trees, corn stover, and forest residues. In this paper, we evaluate only the switchgrass-to-ethanol pathway.

Switchgrass is a native grass in the United States in the Midwest region. Fig. 3 shows the switchgrass-to-ethanol pathway. Similar to the corn-to-ethanol pathway, this pathway begins with fertilizer production and ends with ethanol combustion in vehicles. The intensity of fertilizer use for switchgrass farming is much lower than that of corn farming. As the figure shows, cellulosic ethanol plants in general—and switchgrass ethanol plants in particular—produce electricity besides ethanol. Lignin, the unfermentable portion of cellulosic biomass, is burned in cellulosic ethanol plants to provide steam and electricity for plant operation. The amount of electricity generated from the available amount of lignin far exceeds the electricity need in cellulosic ethanol plants, resulting in a significant amount of electricity that can be exported to the electric grid. At present, there are no commercial cellulosic ethanol plants and thus they provide no practical examples of electricity export. However, sugarcane ethanol plants in Brazil currently produce a large amount of electricity from the burning of bagasse for export to the electric grid. That is, the co-production of fuels and electricity in biofuel plants is already being carried out commercially.

### 4.3. Soybeans to biodiesel

Biodiesel, which consists of short chains of alkyl esters, is produced from transesterification of vegetable oil or animal fat. Soybean oil to biodiesel is the major production pathway in the United States, whereas in Europe it is rapeseed oil to biodiesel and in Southeast Asia it is palm oil to biodiesel. Animal fat and waste cooking oil also are feedstock supplies for biodiesel production. This paper examines the soybeans-to-biodiesel pathway (Fig. 4). Biodiesel is blended with petroleum diesel for combustion in diesel vehicles. The pathway shows two co-products with biodiesel—soy meal from the soybean crushing process and glycerin from the soy-oil transesterification process. While soy meal is an animal feed, glycerin is a specialty chemical. In this case, the energy use and emissions burdens of the activities from fertilizer production to the soybean crushing process are allocated between soy oil and soy meal. In addition, both the above-mentioned energy use and emissions burdens allocated to soy oil and the energy use and emissions burdens in the soy-oil transesterification process are allocated between biodiesel and glycerin.

### 4.4. Soybeans to renewable diesel

Renewable diesel can be produced from vegetable oil or animal fat via hydrocracking to break big molecules into smaller ones by using hydrogen directly or hydrogenation to add hydrogen. Several renewable diesel plants are either in operation or under construction in various countries. At present, the production scale of

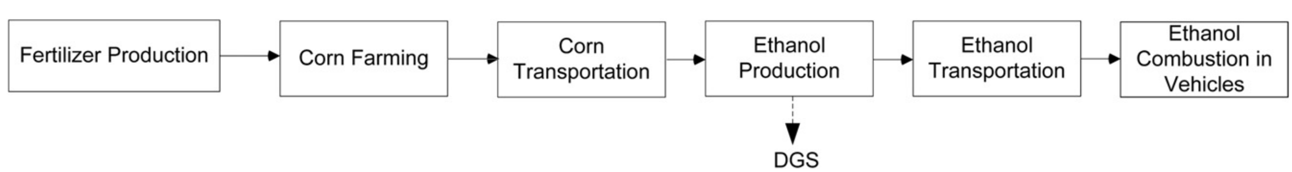


**Fig. 2.** Corn-to-Ethanol Life Cycle.

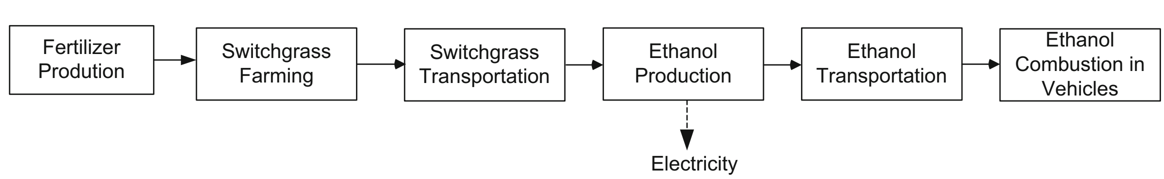


**Fig. 3.** Switchgrass-to-Ethanol Life Cycle.

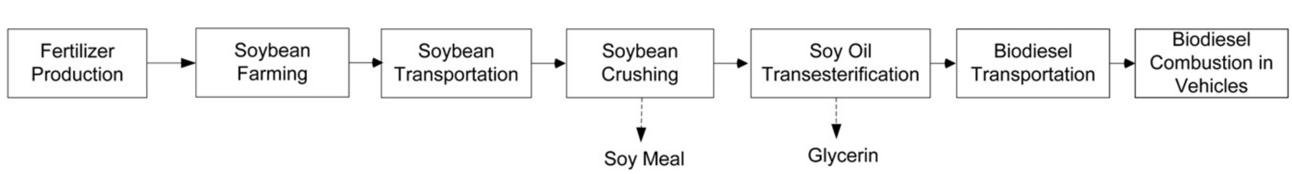


**Fig. 4.** Soybeans-to-Biodiesel Life Cycle.

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renewable diesel is much smaller than that of biodiesel. In this paper, we examine the soybeans-to-renewable diesel pathway (Fig. 5). The renewable diesel pathway is similar to the biodiesel pathway except that the former produces fuel gas and heavy oils—two energy products—in place of the specialty chemical, glycerin produced in the latter pathway. Because multiple co-products are produced from multiple stages in the renewable pathway, the allocation for this pathway is the same as that for the biodiesel pathway.

Table 2 also shows a pathway of producing ethanol from corn stover. At present, corn stover is left in cornfields after corn grain is harvested. The value of corn stover left in cornfields is that nutrients are released from its decomposition, which supports crop growth in the next season and helps prevent soil erosion. In the evaluation of corn grain-based ethanol production with the GREET model, we treat corn stover as a waste with the exception that the nutrient value primarily affects fertilizer inputs for corn farming. In the case of the corn stover-to-ethanol pathway, stover is removed from cornfields (at an environmentally sustainable level) for cellulosic ethanol production. In the case of harvesting of both corn grain and stover, the GREET tool treats stover with the displacement method. In particular, when stover is removed from cornfields for ethanol production, the additional fertilizers that are needed to supplement the nutrients that are removed from cornfields (i.e., when the stover is removed) are estimated and accounted for in the corn stover-to-ethanol pathway (Wu et al., 2006). In addition, the activities of collecting and transporting the stover from cornfields to cellulosic ethanol plants are taken into account for the corn stover-to-ethanol pathway. If the practice of harvesting corn stover for ethanol production becomes widespread, it could be argued that both corn grain and stover play an important role in corn farming decisions. The farming energy and emission burdens could arguably be allocated between corn grain and corn stover based on mass-, energy-, or market revenue-based allocation method.

## 5. Key parameters and issues for well-to-wheels analysis of the selected biofuel pathways with different co-product methods

This section presents the key parameters for the five co-product methods evaluated in this study. Table 3 presents density and lower heating values of the products from the biofuel production pathways. These values are needed for determining the shares of mass and energy content of individual products from a given production pathway.

The market-value-based method requires having the price of each product. Table 4 shows prices for biofuels and their co-products for the last 11 years. Table 5 presents product yields for the biofuel production pathways examined in this paper. These values are needed to develop each of the methods applied in this study.

By using the key parameters presented in the above section, we configured the GREET model to conduct well-to-wheels simulations of the biofuel pathways selected in this study with different co-product methods. Table 6 lists the fuel production pathways and co-product methods that we simulated in this study. All together, we examined 17 combinations of pathways and co-product methods.

The displacement method requires identification of the conventional products that are to be displaced by biofuel co-products. Table 7 lists the displaced products used in our simulations. These are based on actual market activities and the similar properties and functions between biofuel co-products and conventional products. Simulations of energy use and emissions of these conventional products, which are required for the displacement method, are built into the GREET model.

In addition, we included the pathways of petroleum to gasoline and diesel so that biofuel results can be compared to those of the two petroleum pathways. Petroleum refineries produce multiple products. We earlier examined energy and GHG results for gasoline and diesel with different co-product methods (Wang et al., 2004). We found that different co-product methods had small effects on WTW results for gasoline and diesel. We used the energy allocation methods with adjustment of refining intensities required for different products as the GREET default method.

It is important to note that all five co-product methods are not listed for a given biofuel pathway. For example, the mass- and process-purpose-based methods were not used for the switch-grass-to-ethanol pathway. Since electricity does not have weight, the mass-based method is not applicable. It is believed that future cellulosic ethanol plants will be equipped with co-generation units that produce both steam and electricity. Thus, the process-purpose-based approach is invalid. For the pathways of soybeans to biodiesel and renewable diesel, we also did not include the process-purpose-based method. These pathways have two steps to produce multiple co-products (see Figs. 4 and 5). Both soybean crushing and production of biodiesel or renewable diesel and their energy use are required for the process-purpose-based method; such process energy data are not available to implement the method.

We added a hybrid allocation method for the soybeans-to-renewable diesel pathway. This method combines the displacement method to estimate energy and emission credits for soy meal from soybean crushing units and the energy-content-based method

**Table 3**
Density and Lower Heating Value of Key Products.

| Product | Density (lb/gal) | Lower Heating Content (Btu/lb) |
|---|---|---|
| Ethanol | 6.59 | 11,587 |
| Biodiesel | 7.41 | 16,134 |
| Renewable Diesel[a] | 6.53 | 18,729 |
| DGS | Not needed | 8,703 |
| Soy Oil | 7.68 | 16,000 |
| Soy Meal | Not needed | 6,981 |
| Glycerin | 10.52 | 7,979 |
| Fuel Gas | 0.064[b] | 27,999 |
| Heavy oils[c] | 7.56 | 20,617 |

[a] Renewable diesel is assumed to have a molecular formula of $C_{18}H_{38}$.
[b] Fuel gas density is expressed as lb/ft$^3$.
[c] Heavy oils assumed to have a carbon:hydrogen (C:H) ratio of 80:20 on the mass basis with mix of $C_{26}H_{34}$ and naphtha.

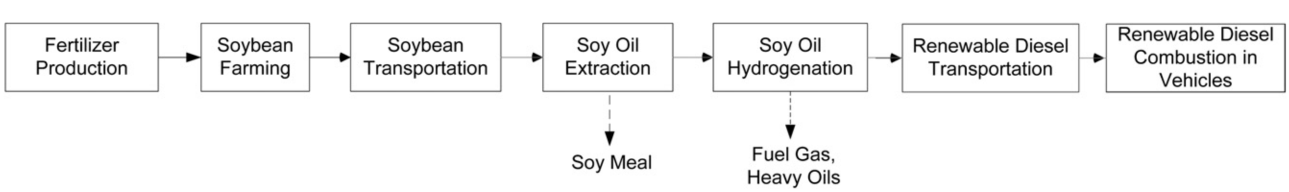


**Fig. 5.** Soybeans-to-Renewable Diesel Life Cycle.

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**Table 4**
U.S. Historical Prices of Biofuels and Their Co-Products (in U.S. 2007$[a]).

| Year | Ethanol ($/gal)[b] | Biodiesel ($/gal)[c] | Renewable Diesel ($/gal)[d] | Fuel Gas ($/mmBtu)[e] | Heavy Oils ($/gal)[f] | Electricity (cents/ kWh)[g] | DGS ($/ ton)[h] | Soy Meal ($/ton)[i] | Soy Oil ($/ton)[j] | Glycerin ($/ton)[k] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1997 | 0.82 | | | | | 5.68 | 168.3 | 232.4 | 647.1 | |
| 1998 | 0.72 | | | | | 5.56 | 113.1 | 171.8 | 493.7 | |
| 1999 | 0.66 | | | | | 5.42 | 108.2 | 205.0 | 381.5 | |
| 2000 | 1.09 | | | | | 5.55 | 89.5 | 207.8 | 338.6 | |
| 2001 | 1.02 | | | | | 5.90 | 101.3 | 196.0 | 384.7 | |
| 2002 | 0.71 | | | | | 5.60 | 93.7 | 208.6 | 506.3 | |
| 2003 | 0.88 | | | | | 5.75 | 103.1 | 288.0 | 674.1 | |
| 2004 | 1.20 | | | | | 5.74 | 117.6 | 199.9 | 503.1 | |
| 2005 | 1.28 | 3.60 | 3.52 | 9.22 | 1.23 | 6.07 | 80.2 | 184.4 | 495.8 | 105.9 |
| 2006 | 2.10 | 3.52 | 3.45 | 8.21 | 1.39 | 6.32 | 91.4 | 210.9 | 636.8 | 41.1 |
| 2007 | 1.51 | 3.32 | 3.25 | 7.71 | 1.53 | 6.36 | 117.2 | 335.0 | 1045.0 | 160.0 |
| Minimum | 0.66 | 3.32 | 3.25 | 7.71 | 1.23 | 5.42 | 80.2 | 171.8 | 338.6 | 41.1 |
| Mean | 1.09 | 3.48 | 3.41 | 8.38 | 1.38 | 5.81 | 107.6 | 221.8 | 555.2 | 102.3 |
| Maximum | 2.10 | 3.60 | 3.52 | 9.22 | 1.53 | 6.36 | 168.3 | 335.0 | 1045.0 | 160.0 |

[a] Historical nominal prices have been converted to real prices (in U.S. 2007$) by using implicit price deflator, reported by EIA/DOE (2007).
[b] Ethanol price data are from *Hart Oxyfuel News* and Oil Price Information Service, and price data refer to the U.S. Midwest ethanol spot price after deducting subsidy and are for denatured ethanol.
[c] Biodiesel price data refer to average retail fuel price obtained from EERE/DOE (2008).
[d] Price of renewable diesel is assumed to be the same as biodiesel on a per-Btu basis.
[e] Price of fuel gas is assumed to be the same as natural gas on a per-Btu basis, and natural gas price refers to industrial price obtained from the EIA/DOE (2008a).
[f] Price of heavy oils is assumed to be the same as residual oil on a per-Btu basis, and residual oil price is sales-to-end-users price obtained from EIA/DOE (2008b).
[g] Electricity price is for industrial sector and obtained from EIA/DOE (2008c).
[h] DGS price refers to wholesale price, obtained from ERS/USDA (2008a).
[i] Soy meal prices obtained from ERS/USDA (2008b).
[j] Soy oil prices obtained from ERS/USDA (2008c).
[k] Crude glycerin price data obtained from Nilles (2006) and Kotrba (2007).

**Table 5**
Product Yields of Different Biofuel Production Pathways[a].

| Product | Yield |
|---|---|
| Corn to ethanol: per bushel of corn input | |
| Ethanol: undenatured gallons | 2.72 |
| DGS: lb (dry matter) | 14.51 |
| Switchgrass to ethanol: per dry ton of switchgrass input | |
| Ethanol: undenatured gallons | 95.0 |
| Electricity credit: kWh | 54.34 |
| Soybean crushing: per bushel of soybean input | |
| Soy oil: lb | 10.5 |
| Soy meal: lb (dry matter) | 47.16 |
| Soy oil to biodiesel: per lb of soy oil input | |
| Biodiesel: lb | 0.962 |
| Glycerin: lb | 0.205 |
| Soy oil to renewable diesel: per lb of soy oil input | |
| Renewable diesel: lb | 0.662 |
| Fuel gas: lb | 0.168 |
| Heavy oils: lb | 0.116 |

[a] Source: All yield data from GREET 1.8c (Argonne National Laboratory, 2009).

**Table 6**
Biofuel production pathways and co-product methods included in this Study.

| Biofuel Pathway | Method of Dealing with Multiple Products | Case Number |
|---|---|---|
| Corn to ethanol | Displacement | C-E1 |
| | Mass | C-E2 |
| | Energy content | C-E3 |
| | Market value | C-E4 |
| | Process purpose | C-E5 |
| Switchgrass to ethanol | Displacement | G-E1 |
| | Energy content | G-E2 |
| | Market value | G-E3 |
| Soybeans to biodiesel | Displacement | S-BD1 |
| | Mass | S-BD2 |
| | Energy content | S-BD3 |
| | Market value | S-BD4 |
| Soybeans to renewable diesel | Displacement | S-RD1 |
| | Mass | S-RD2 |
| | Energy content | S-RD3 |
| | Market value | S-RD4 |
| | Hybrid allocation | S-RD5 |

to allocate energy products from the renewable diesel plants. We implemented this method because the amount of co-produced energy products in renewable diesel plants is significant and we intend to compare this hybrid approach with the first case for the renewable diesel pathway where displacement method is applied to both soybean crushing and renewable diesel production.

For the corn-to-ethanol pathway, the process-purpose-based method was used to allocate energy and emissions of corn ethanol plants. The energy use and emissions of activities occurred prior to ethanol production need to be allocated between ethanol and DGS with other methods. In this study, we used the market-value-based method to allocate energy use and emissions for those prior activities.

## 6. Well-to-wheels energy and greenhouse gas results with different co-product methods

### 6.1. Energy results

Figs. 6–8 present WTW results for total energy use, fossil energy use, and petroleum energy use for the 19 cases examined in this study. In these charts, we present well-to-pump (WTP) and pump-to-wheels (PTW) results (sum of the two is WTW results). Results are in per million Btu of fuel produced and used in motor vehicles. Fig. 6 shows that all biofuels consume more total energy than the two petroleum fuels. This difference arises because of the energy loss during conversions from biomass feedstocks to biofuels, besides fossil energy use for the conversions. On the other hand, fossil energy use for biofuel pathways is less than that of the petroleum pathways (Fig. 7). This difference occurs because, while gasoline and diesel contain fossil energy, biofuels do not. Fossil energy here includes energy in petroleum, natural gas, and coal. Petroleum use for the biofuel pathways is much lower than that of the petroleum pathways (Fig. 8).

**Table 7**
Conventional products to be displaced by biofuel co-products for the displacement method.

| Biofuel pathway | Co-products | Displaced products |
|---|---|---|
| Corn to ethanol | DGS | Corn, soybean meal, N-Urea |
| Switchgrass to ethanol | Electricity | U.S. average electricity |
| Soybeans to biodiesel | Soybean meal<br>Glycerin | Soybeans<br>Petroleum glycerin |
| Soybeans to renewable diesel | Soybean meal<br>Fuel gas<br>Heavy oil | Soybeans<br>Natural gas<br>Residual oil |

Of the co-product methods examined in this study, the method selection has a much greater effect on the results for biodiesel and renewable diesel than corn and cellulosic ethanol (i.e., larger variations among methods for biodiesel and renewable diesel than for corn ethanol and cellulosic ethanol). As discussed above, this difference primarily occurs because the pathways for biodiesel and renewable diesel produce more co-products in terms of mass, energy, or market revenue.

### 6.2. Greenhouse gas emission results

Fig. 9 presents WTW GHG emission results for the 19 cases. The GHG emissions here are $CO_2$-equivalent ($CO_2e$) emissions of $CO_2$, $CH_4$, and $N_2O$ combined with their global warming potentials

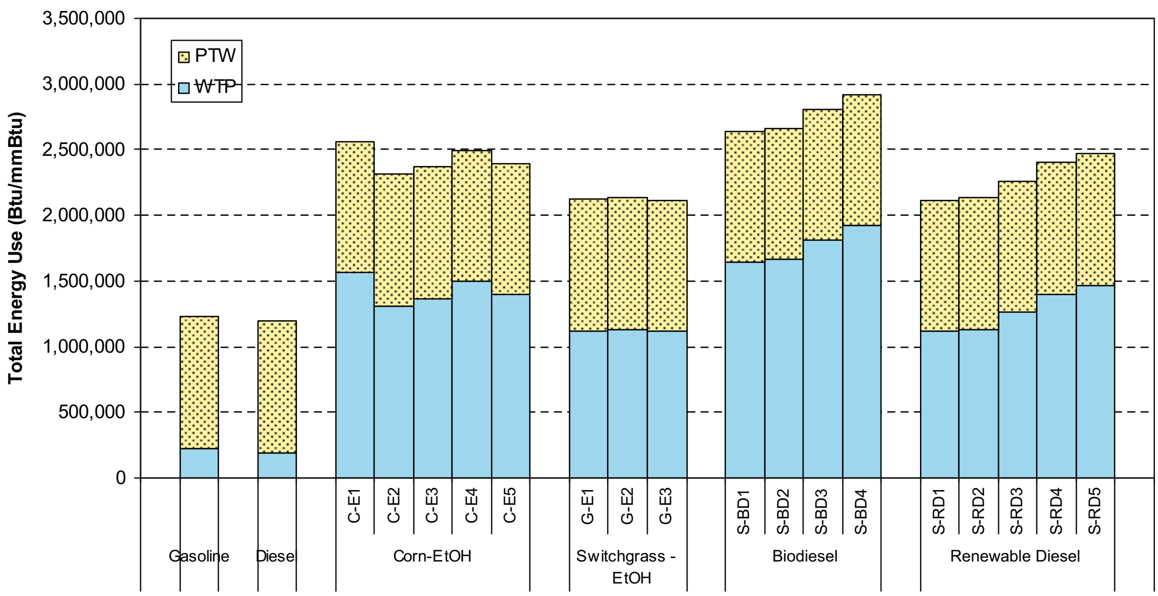


**Fig. 6.** WTW Total Energy Use of Petroleum Fuels and Biofuels (Btu/million Btu).

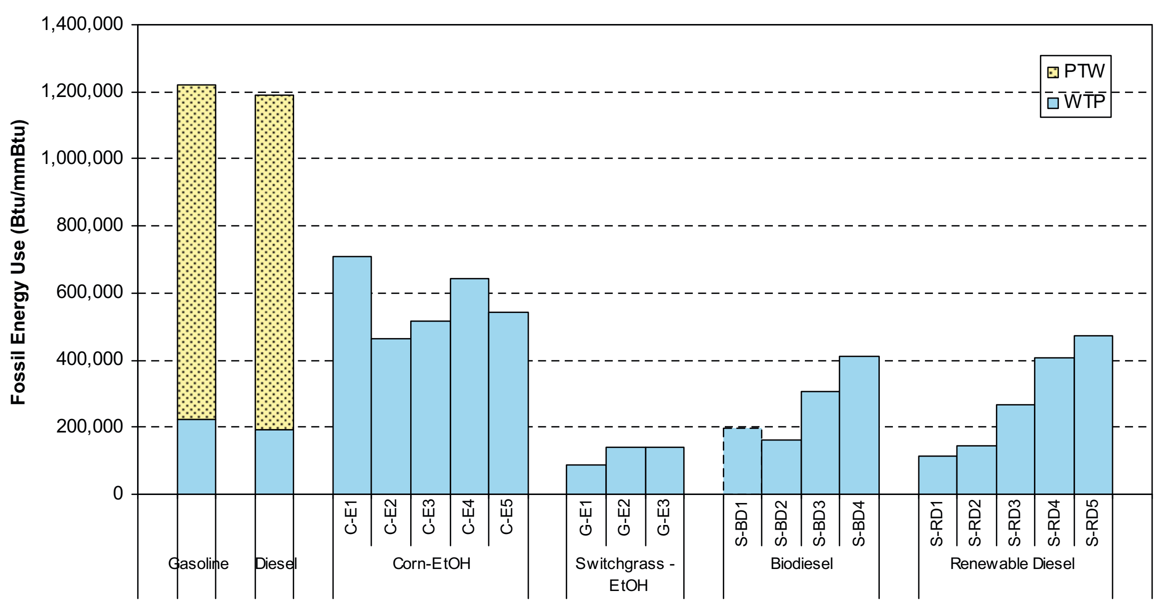


**Fig. 7.** WTW Fossil Energy Use of Petroleum Fuels and Biofuels (Btu/million Btu).

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as developed by the Intergovernmental Panel on Climate Change. The current GREET version includes GHG emissions resulting from direct but not indirect changes in land use. Even though both direct and indirect land use changes are being debated now, large uncertainties remain in addressing both issues and the potential resultant GHG emissions (see Wang, 2008). Nonetheless, we, as well as many other organizations, are at present addressing the issues regarding land use change.

Fig. 9 presents GHG emissions for the WTP stage and the PTW stage separately. For the 17 biofuel cases, the WTP stage has negative GHG emissions because of the carbon uptake from air by plants in fields during the growing season. The carbon in biofuels is released to the air during biofuel combustion, resulting in positive GHG emissions during the PTW stage. The dark bars inside the bars representing the biofuel cases depict the net GHG emissions on the WTW basis.

All biofuel cases show lower GHG emissions as compared to the two petroleum cases; of the 17 biofuels cases, cellulosic ethanol, biodiesel, and renewable diesel show considerably lower GHG emissions. The co-product methods have significant effects on the biofuel WTW GHG results. This finding is especially true for corn ethanol, biodiesel, and renewable diesel. Fig. 10 shows WTW GHG emission reductions for biofuels relative to petroleum fuels. The reductions for corn and cellulosic ethanol are relative to petroleum gasoline, and those for biodiesel and renewable diesel are relative to petroleum diesel. Results using the displacement method for biodiesel and renewable diesel indicate huge GHG reductions. In fact, using this method shows that renewable diesel reduces GHGs by 130%. The results for biodiesel and renewable diesel demonstrate the distortion by the displacement method when outputs of co-products are so large (as discussed above).

Table 8 presents the allocation of WTW fossil energy use and GHG emissions for the four biofuel production pathways with individual co-product methods. The table reiterates the significant effects that the choice of which co-product method to use has on WTW results for

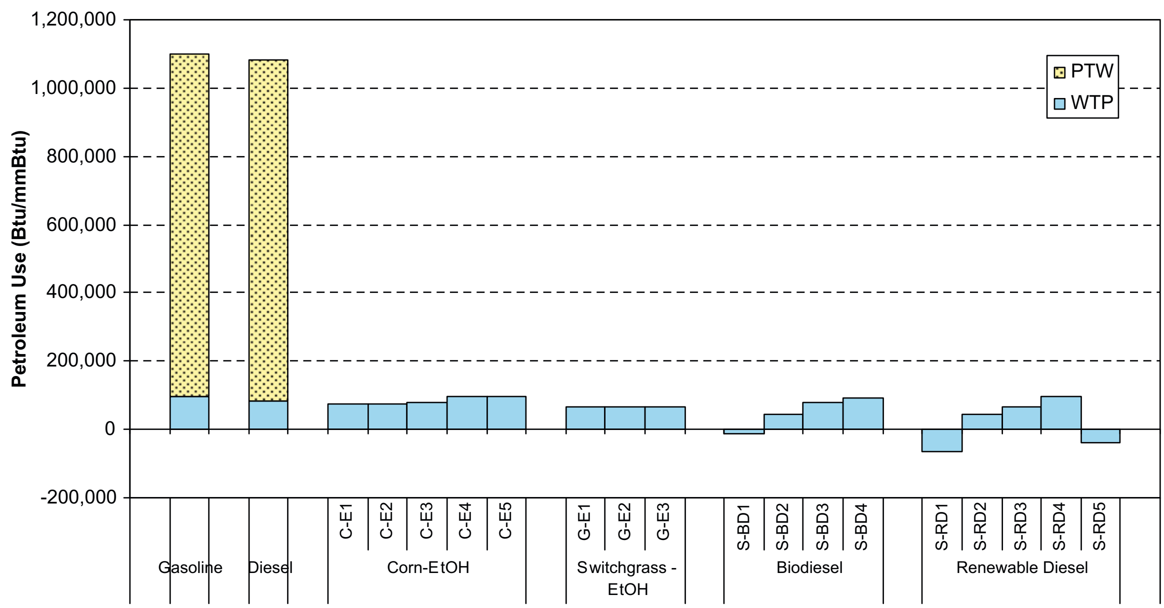


**Fig. 8.** WTW Petroleum Use of Petroleum Fuels and Biofuels (Btu/million Btu).

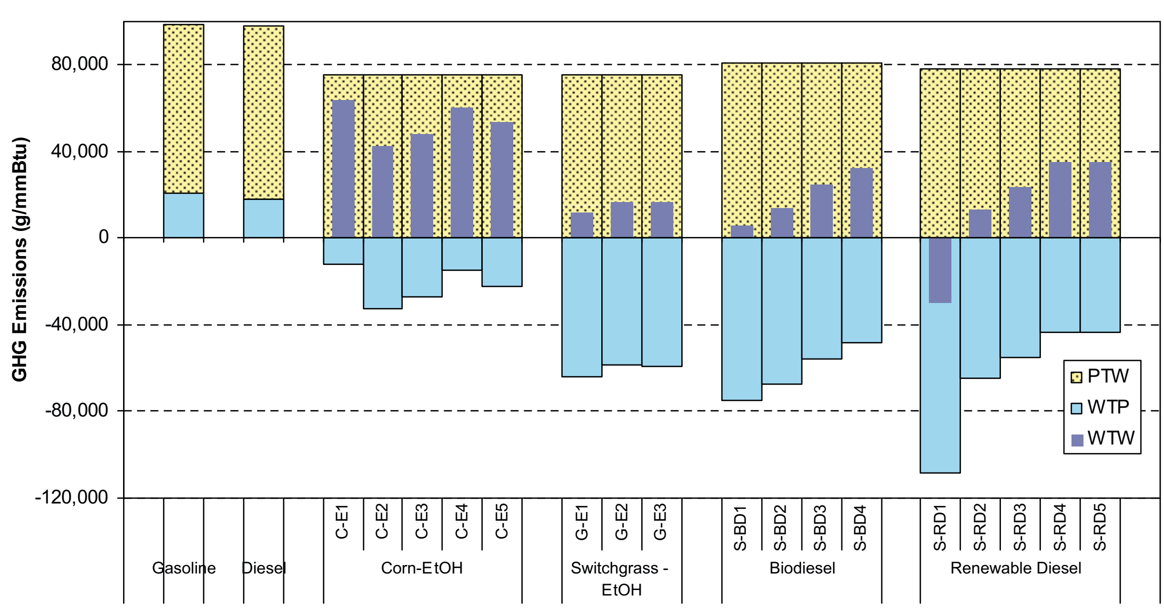


**Fig. 9.** WTW Greenhouse Gas Emissions of Petroleum Fuels and Biofuels (grams of $CO_2e$/ million Btu).

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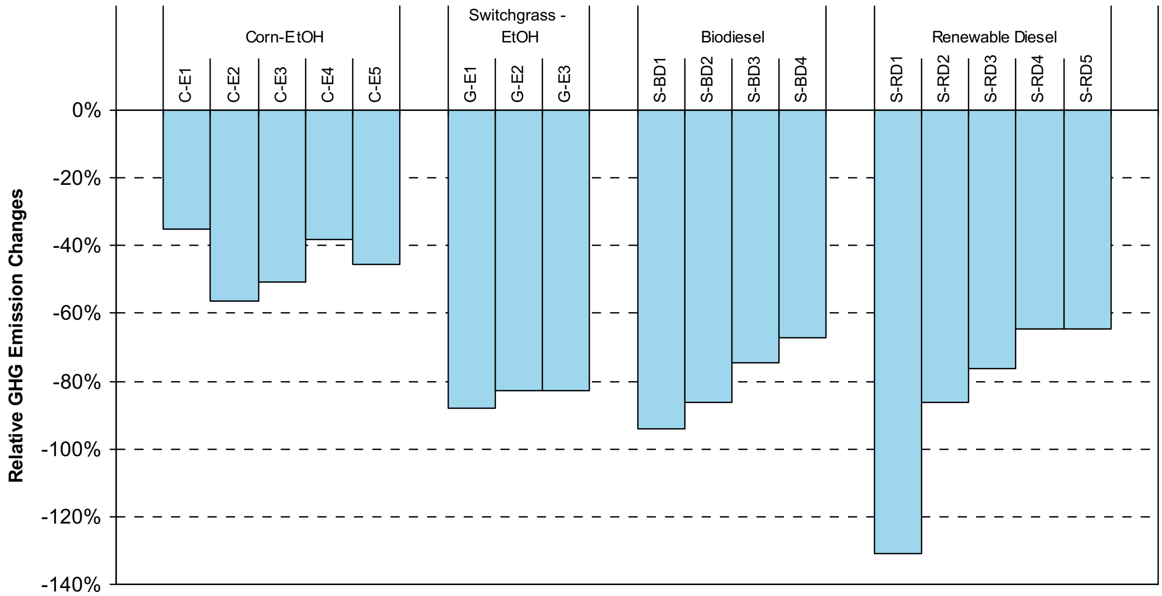


**Fig. 10.** WTW Greenhouse Gas Emission Reductions for Biofuels (ethanol vs. petroleum gasoline and biodiesel/renewable diesel vs. petroleum diesel).

**Table 8**
Shares of WTW fossil energy use and greenhouse gas emissions of biofuel pathways.

| | WTW Fossil Energy Use | | WTW GHG Emissions | |
|---|---|---|---|---|
| **Corn to Ethanol** | Ethanol (%) | DGS (%) | Ethanol (%) | DGS (%) |
| Displacement | 86 | 14 | 81 | 19 |
| Mass | 56 | 44 | 54 | 46 |
| Energy Content | 63 | 37 | 62 | 38 |
| Market Value | 78 | 22 | 77 | 23 |
| Process Purpose | 66 | 34 | 68 | 32 |
| **Switchgrass to Ethanol** | Ethanol (%) | Electricity (%) | Ethanol (%) | Electricity (%) |
| Displacement | 62 | 38 | 69 | 31 |
| Energy Content | 98 | 2 | 98 | 2 |
| Market Value | 97 | 3 | 97 | 3 |
| **Soybeans to Biodiesel** | Biodiesel (%) | Co-Products (%) | Biodiesel (%) | Co-Products (%) |
| Displacement | 21 | 79 | 8 | 92 |
| Mass | 17 | 83 | 18 | 82 |
| Energy Content | 32 | 68 | 33 | 67 |
| Market Value | 44 | 56 | 43 | 57 |
| **Soybeans to Renewable Diesel** | R. Diesel (%) | Co-Products (%) | R. Diesel (%) | Co-Products (%) |
| Displacement | 10 | 90 | −31 | 131 |
| Mass | 13 | 87 | 14 | 86 |
| Energy Content | 24 | 76 | 24 | 76 |
| Market Value | 37 | 63 | 36 | 64 |
| Hybrid Allocation | 42 | 58 | 36 | 64 |

biofuels. Using the GHG emission results as the example, the table shows that 19% to 46% of WTW GHG emissions for the corn-to-ethanol pathway could be allocated to DGS, depending on the method selected. For cellulosic ethanol, 2% to 31% could be allocated to co-generated electricity (because of the extremely low GHG emissions of this pathway, the actual effects [as shown in Figs. 9 and 10] are smaller than the range of the percentages). For the soybean-to-biodiesel pathway, 57% to 92% of WTW GHG emissions could be allocated to co-products (soy meal and glycerin). For the soybean-to-renewable diesel pathway, 64% to 131% could be allocated to co-products (soy meal, fuel gas, and heavy oils).

## 7. Conclusions

It is important to take into account co-products in life-cycle evaluation of the energy use and environmental effects of biofuels. Most LCA studies do so. However, this study shows that

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the choice of co-product method can significantly influence the WTW results of biofuels. Of the five methods examined in this study, ISO 14040 advocates use of the displacement method. As we discussed in principle and simulated in practice, the displacement method can generate distorted LCA results if the co-products are actually main products (for the cases of biodiesel and renewable diesel from soybeans). It is far from settled whether use of a given method should be uniformly and automatically recommended for LCA studies. We suggest that a generally agreed-upon method should be applied for a given fuel production pathway. Consistency in choice of co-product method may not serve the purpose of providing reliable LCA results. On this note, the transparency of LCA method(s) selected is important in given LCA studies and sensitive cases with multiple co-product methods may be warranted in LCA studies where co-products can significantly impact study outcomes.

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