# Energy and Environmental Contributions of Corn-Ethanol

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## Introduction

Rapid development of regulatory mechanisms to mitigate greenhouse gas (GHG) emissions requires that the biofuel industry employ standard methods to evaluate biofuel systems comprising both crop production systems and biorefineries. Biofuel systems associated with a variety of organic feedstocks have a range of performance capabilities, and recent life-cycle assessment studies of these different systems have used inconsistent methods, leading to confusion about biofuel energy efficiency and GHG mitigation (Liska and Cassman, submitted). Hence, there is a critical need for well documented life-cycle metrics for consistent biofuel evaluation that are established and supported by a national or international governing body. Standardization of net energy and GHG metrics is essential for consistent estimates of individual biofuel system performance, meeting the requirements of low-carbon fuel markets (Arons 2007, Brandt 2007), and potential GHG emissions trading markets (Liska 2007a, McElroy 2007, *Economist* 2007). To demonstrate system variability, the life-cycle energy efficiency and GHG mitigation of high performance corn-ethanol biofuel systems were determined by applying data from experimental progressive cropping systems and state-of-the-art biorefinery efficiencies (Liska 2007b). The new BESS model software (www.bess.unl.edu) for evaluating individual corn-ethanol facilities provides a standardized framework that has the flexibility to include all parameters required for determining GHG emissions reductions under a range of conditions and system configurations (Liska 2007c).

## Technological frontiers of corn grain-ethanol performance

Previous analyses of the net energy yield of corn-ethanol systems have estimated a relatively low efficiency of 1.2:1 (energy output:input) and a 13% reduction in GHG emissions (Farrell 2006). These studies were based on aggregate average crop production data and average biorefinery efficiencies to estimate the performance of the standard USA corn grain ethanol production system. In contrast, we analyzed the potential energy efficiency of the most advanced corn-ethanol systems that now represent the majority of the USA ethanol production capacity, which comes from plants built within the past 2-3 years. Net energy yield of corn-ethanol systems were estimated based on the methods of Farrell *et al.* (2006) substituting data from long-term field experiments (rainfed and irrigated) with progressive crop and soil management practices, in conjunction with updated biorefinery energy efficiencies, and theoretical technological improvements in crop nitrogen use-efficiency (+10% grain yield per unit N fertilizer), maize genetics for high-starch (72-75%), biorefinery engineering (closed-loop systems reduce life-cycle energy needs by ~55%), and fermentation efficiency (91-97%). In addition, we evaluated a closed-loop facility in which co-product distiller's grains are not dried (wet distiller's grains) and fed to cattle in a feedlot adjacent to the ethanol plant, where the associated livestock manure and urine is used for anaerobic digestion to produce methane and replace natural gas in the ethanol plant. All of the above improvements were compared side-by-side to determine which factors have the greatest influence on the life-cycle energy yield and efficiency.

Results documented that crop yield has a much larger impact on ethanol yield than improved conversion efficiency at the biorefinery or crop genetics. Biorefinery improvements (state-of-the-art equipment and closed-loop engineering) and co-product handling (non-drying distiller's grains) have the greatest impact on life-cycle energy efficiency. Biorefineries that use feedstock from corn production systems with progressive management practices and higher yields (as obtained in our field studies) had net life-cycle energy ratios of 1.9:1 with biorefineries producing wet distiller's grains, and 2.7:1 for closed-loop systems. Systems with progressive management practices produce more energy per crop area at the same level of efficiency. The combination of all improved technologies gave a 5.7 fold increase in the net energy productivity of maize grain ethanol systems compared to the aggregate analysis of Farrell et al., and these progressive systems decreased GHG emissions by 55-80% compared to conventional gasoline (Liska, 2007b). Our results indicate that previous studies of the energy productivity and efficiency of corn-ethanol systems have substantially underestimated their potential to replace fossil fuel and to mitigate climate change. Moreover, corn-ethanol efficiencies of progressive systems approach the theoretical efficiency of cellulosic ethanol as calculated by Farrell et al. Importantly, the technologies for significant improvement of crop yields and biorefinery energy efficiency are currently available and could be implemented more widely to increase the national average energy efficiency of corn-ethanol systems with adaptive research and extension to implement them. This study indicates that existing food-crop biofuel systems can be more extensively exploited in order to produce greater amounts of fuel while contributing to the mitigation of GHG emissions.

## Life-cycle energy and GHG emissions analysis of corn-ethanol biofuel production systems using the BESS model (*B*iofuel *E*nergy *S*ystems *S*imulator)

The goal of reducing net GHG emissions for the transportation fuel industry requires a change in practices that lead to a measurable reduction in life-cycle emissions below the prevailing base-line (the emissions level of dominant petroleum fuels). Reductions from this baseline must account for all direct and indirect GHG emissions generated across the life-cycle of production of a biofuel. In producing corn-ethanol, for example, 50-80% of life-cycle biofuel emissions come from the biorefinery and co-product processing, with the other 20-50% of emissions produced in the crop production phase (Table 1). Hence, a life-cycle assessment of corn-ethanol must include emissions from both the biorefinery and crop production. While life-cycle analysis provides a means to quantify these potential benefits and impacts, inconsistencies in calculations, conversion efficiencies, energy intensity of inputs, spatial and temporal scales of analysis, and system boundaries limit direct comparison of different studies and individual biofuel systems (Liska and Cassman, submitted). Furthermore, variations in crop productivity characteristics for feedstock production and biorefinery performance (fossil fuel intensity and sources of energy) result in a range of GHG-intensities for different individual corn-ethanol systems.

The BESS model was developed to overcome these inconsistencies and present a standardized framework for biofuel systems analysis. The BESS software tool calculates the energy efficiency, GHG emissions, and natural resource requirements of individual corn grain–to-ethanol biofuel production systems (Liska 2007c, www.bess.unl.edu). The model provides a "cradle-to-grave" analysis of the production life-cycle from the creation of material inputs to finished products. The model parameters can be set by the user to achieve the highest accuracy for evaluating an individual corn grain-ethanol biorefinery and its feedstock crop production zone. All input and internal parameters are modifiable as appropriate for a specific system with regard to: (a) crop yields, management, production inputs, (b) biorefinery energy sources and co-product processing, (c) feeding of co-products and cattle performance, and an option for linkage with a closed-loop cattle feedlot and anaerobic digestion system (developed with PRIME Biosolutions, Omaha, NE, www.primebiosolutions.com). The model has a user-friendly graphic interface, fixed internal equations, summary reports, and full documentation in the User's Guide, which describes the default values for parameters and the equations employed (Figure 1). The BESS model equations were developed from the analysis of Farrell et al. (Science 2006), which represents the starting point for an industry standard for life-cycle analysis of corn-ethanol. The BESS model includes more parameters than Farrell's initial assessment, such as tillage options and drying/non-drying of distiller's grains at the biorefinery and other advanced options to increase accuracy in individual system evaluation, including a more realistic co-product credit scheme developed in collaboration with a team of animal scientists (Liska 2007a).

Initial default values for the model are from the USDA databases, industry reports, and scientific literature (e.g., USDA-NASS, Energy and Environmental Analysis, Inc. 2006, Penam et al. 2006; see BESS User's Guide at www.bess.unl.edu). Preliminary results from the BESS model estimate that corn-ethanol systems reduce net GHG emissions compared to gasoline by 26-87% for different biorefinery designs in Nebraska and Iowa depending on crop yields, irrigation, biorefinery energy sources (natural gas, coal, or closed-loop integration), and co-product processing methods (wet or dry distillers grains) (Liska 2007a). The BESS model is currently being expanded to include cellulosic ethanol from corn stover and switchgrass, for consistent evaluation of established and emerging "second-generation" biofuel systems. The BESS model can be used by academia, the public, and the ethanol industry; the model is already being used in classes at the University of Nebraska, and downloaded by professionals from industry and government agencies.

There are a number of areas where a better understanding of corn-ethanol system performance is needed to ensure accurate assessment and obtaining full value for GHG mitigation potential: (1) California proposes to begin enforcement of its Low-Carbon Fuel Standard by December 2008 (www.energy.ca.gov/low_carbon_fuel_standard), which would provide a premium market for ethanol producers when ethanol prices are low (*New York Times* 2007a). (2) GHG emissions trading could provide the industry with additional income if the model, or a similar calculation scheme, would be adopted for evaluation of biofuel system performance; for example, BESS simulations show that at emissions prices of $4-20 per metric ton of $CO_2$ equivalents results in additional income of 1.5-7.5 cents per gallon based on average industry performance (natural gas biorefinery, with dry distillers grains), in comparison to the current federal tax credit of 51 cents per gallon. (3) Federal subsidies for corn-ethanol may eventually be contingent on certification of a GHG reduction relative to gasoline. (4) The Securities and Exchange Commission (SEC) may require disclosure of GHG performance to assess risk to investors and stock value if a carbon tax is enacted (see related story on disclosure of GHG emissions, *New York Times*, Sept 2007b). (5) Disclosure of GHG mitigation by ethanol producers to investors would build public support for the biofuel industry.

Through the Low-Carbon Fuel Standard, California will attempt to reduce the GHG emissions intensity of its transport fuel by 10% by 2020 (Arons, 2007), and there are indications that the

European Union will follow with similar policies (*Economist* 2007, Lewandowski 2006). To meet these regulations, standardized methods will need to be established to demonstrate that biofuel systems contribute to GHG reductions relative to gasoline. California's current GHG intensity of fuel is 87.9 gCO2eq $MJ^{-1}$ of fuel, with the 2020 target at an average of 79.1 gCO2eq $MJ^{-1}$. Current average corn-ethanol GHG-intensity is estimated at 76 gCO2eq $MJ^{-1}$, while 58 gCO2eq $MJ^{-1}$ is considered a "Mid-Global-Warming-Impact Biofuel" (Arons, 2007). Simulations using the BESS model estimate that ethanol produced by natural gas-powered ethanol plants in Nebraska, Iowa, and Indiana that produced wet and dry distillers grains have a GHG-intensity in the range of 32-44 gCO2eq $MJ^{-1}$ (**Table 1**), which exceeds this standard by a large margin. And, as more costly petroleum reserves (e.g., tar sands) are developed, the emissions intensity of conventional gasoline will increase substantially compared to currently used petroleum, which is largely obtained from "near-surface" land and coastal oil fields (Bordetsky 2007). Therefore, the magnitude of GHG mitigation potential of biofuel systems will increase over time.

## BESS model in GHG emissions trading markets

Rising concentrations of GHGs and the associated threats of climate change have prompted policy discussions concerning U.S. regulation of GHG emissions, possibly via a cap-and-trade scheme (U.S. Congressional Budget Office, 2007). Restrictions on industrial GHG emissions already exist in an international context through the Kyoto Protocol for participating countries, and a market for GHG emissions trading was established in 2005 via the European Union's Emissions Trading Scheme (Ellerman, 2007). The U.S. Supreme Court has set the foundation for GHG emissions regulation and trading in its April 2, 2007 decision that classifies GHGs as pollutants and gives specific regulatory authority to the Environmental Protection Agency. The EPA has already developed schemes for emissions trading of sulfur dioxide and nitrogen oxide (Schakenbach 2006, Freeman 2007), and will likely oversee any GHG emissions trading schemes that influence the ethanol industry. A US regional cap-and-trade system for GHG reduction will be implemented in seven Northeastern states (under the Regional Greenhouse Gas Initiative; www.rggi.org) and for the 5-state Western Regional Climate Action Initiative, with a national program looming (U.S. Congressional Budget Office, 2007). Such a scheme provides an opportunity for biofuel producers to monetize GHG reductions relative to gasoline, and thereby generate large additional revenue (McElroy, 2007, U.S. Congressional Budget Office, 2007), but only if appropriate GHG accounting and certification methods are developed.

An emissions trading scheme for biofuel producers could increase industry profitability and expansion, reduce the need for subsidies, reduce industry emissions by encouraging adoption of more efficient crop production practices and ethanol plant design, and contribute to agricultural investment and rural revitalization. The BESS model estimates a rough industry average of 50% GHG reduction compared to gasoline (**Table 1**). An average ethanol plant at 35 million gallons annual capacity would mitigate 123,000 Mg of CO2eq in GHG emissions annually. At current carbon prices (~$4 per ton of CO2eq; www.chicagoclimatex.com), such a biorefinery would receive an annual credit of $490,000 (1.51 cents per gallon). The trading potential of the entire Nebraska ethanol industry at the current 1 billion gallon capacity is estimated to be $14 million annually at current prices. At $20 dollars per ton CO2eq. price, which is a conceivable price under a future national GHG trading program, the annual estimate reaches $70.7 million dollars. With a future near-term capacity of 15 billion gallons, the annual credit for the U.S. corn-ethanol will reach between $212 million at current prices and $1.1 billion if C-credit prices rise to $20 per metric ton.

This potential represents an unprecedented opportunity for the ethanol industry to capitalize on these measured GHG reductions, as well as build public support for this rapidly expanding industry.

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Table 1. Percent of life-cycle GHG emissions by category for BESS Default Scenario #3 (natural gas-powered biorefinery, w/ dry distillers grains) and Scenario #4 (natural gas-powered biorefinery, w/ wet distillers grains) for Nebraska, Iowa, and Indiana average crop production practices.

| Component | GHG emission category | (#3, NE) % of LC | (#4, NE) % of LC | (#3, IA) % of LC | (#3, IN) % of LC |
|---|---|---|---|---|---|
| CROP Production | | | | | |
| | Nitrogen fertilizer, N* | 7.5 | 8.6 | 7.5 | 8.5 |
| | Phosphorus fertilizer, P* | 1.1 | 1.2 | 1.7 | 2.5 |
| | Potassium fertilizer, K* | 0.1 | 0.1 | 1.0 | 1.7 |
| | Lime* | 1.3 | 1.5 | 5.0 | 6.2 |
| | Herbicides* | 3.2 | 3.7 | 2.7 | 2.3 |
| | Insecticides* | 0.3 | 0.3 | 0.0 | 0.2 |
| | Seed* | 0.3 | 0.3 | 0.3 | 0.3 |
| | Gasoline** | 1.1 | 1.3 | 0.6 | 1.1 |
| | Diesel** | 8.1 | 9.4 | 3.1 | 3.1 |
| | LPG** | 1.2 | 1.4 | 2.2 | 1.0 |
| | Natural gas** | 2.7 | 3.1 | 0.0 | 0.4 |
| | Electricity** | 4.6 | 5.3 | 0.5 | 0.9 |
| | Depreciable capital | 0.5 | 0.5 | 0.5 | 0.5 |
| | N Fertilizer emissions (N2O) | 13.5 | 15.6 | 13.6 | 15.4 |
| | TOTAL | 45.4 | 52.4 | 38.7 | 44.0 |
| BIOREFINERY | Biorefinery model component | | | | |
| | Natural Gas Input*** | 27.4 | 31.6 | 30.7 | 28.1 |
| | NG Input: drying DG*** | 13.4 | 0.0 | 15.0 | 13.7 |
| | Electricity input*** | 9.4 | 10.8 | 10.5 | 9.6 |
| | Depreciable capital | 0.7 | 0.9 | 0.8 | 0.8 |
| | Grain transportation | 3.7 | 4.3 | 4.2 | 3.8 |
| | TOTAL | 54.6 | 47.6 | 61.3 | 56.0 |
| CO-PRODUCT CREDIT | Cattle model component**** | | | | |
| | Diesel | -0.0 | -0.0 | -0.0 | -0.0 |
| | Urea production | -8.4 | -10.1 | -9.5 | -8.6 |
| | Corn production | -19.1 | -24.7 | -16.3 | -18.5 |
| | Enteric fermentation (CH4) | -4.4 | -10.0 | -5.0 | -4.6 |
| | TOTAL | -32.0 | -42.2 | -30.8 | -31.8 |
| | *Default co-product credit* | *(-40.2)* | *(-46.4)* | *(-45.1)* | *(-41.2)* |
| GHG reduction relative to gasoline, % | Life-cycle GHG emissions | 50.4 | 63.1 | 54.9 | 51.4 |
| GHG-intensity, g CO2eq $MJ^{-1}$ of Ethanol | Life-cycle GHG emissions | 44 | 32 | 40 | 43 |

*USDA-ERS 2005
**USDA-ERS 2001
***Energy and Environment Analysis, Inc. 2006
****Co-product distiller's grains displace corn and urea in the cattle diet (thus substituting for energy-intensive inputs); diesel and enteric fermentation emissions are saved because cattle with co-product in the diet (~20-40% dry matter inclusion) have a higher rate of gain and are on feed less days (see BESS *User's Guide* for more details at www.bess.unl.edu).

**Figure 1.** BESS model output page for crop production