

Supporting Online Material for:

Ethanol Can Contribute To Energy and Environmental Goals

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Contents

Methods.....	2
The ERG Biofuels Analysis Meta-Model (EBAMM)	2
Net energy value	3
Appropriate Metrics	5
Agricultural energy	6
Net Yield	7
Biorefinery energy	8
Coproducts.....	8
Fossil Fuel Use.....	10
Greenhouse Gas Emissions	11
Supporting Text.....	13
Sensitivity Analysis.....	15
EBAMM cases.....	16
Errors, Omissions, and Inconsistencies.....	17
Explanatory notes for Table S2.....	17
References	22

Tables and Figures

Table S1. Coproduct energy credit	9
Figure S1: Trend in corn yield and assumed values (29).....	14
Figure S2: Variability in corn yield by county in Iowa (29).....	15
Table S2. Errors, Omissions, and Inconsistencies	17
Table S3. EBAMM Results.....	21

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Methods

The ERG Biofuels Analysis Meta-Model (EBAMM)

To understand the effects of biofuel use, the entire lifecycle must be considered, including the manufacture of inputs (e.g. fertilizer), crop production, transportation of feedstock from farm to production facilities, and then biofuel production, distribution, and use. These processes are each complex and may be expected to change in the future, making any evaluation challenging. The literature on biofuels contains conflicting studies, and in addition, published studies often employ differing units and system boundaries, making comparisons across studies difficult. To address these problems, we developed the ERG Biofuel Analysis Meta-Model (EBAMM), which is structured to provide a relatively simple, transparent tool that can be used to compare biofuel production processes. However, EBAMM ignores end use technologies and does not fully address all aspects of biofuel production, and should be supplemented by more sophisticated analyses when additional detail is desired (*1*). (Readers should send comments, questions, and corrections of the spreadsheet to rael@berkeley.edu.)

In this study, EBAMM release 1.0 is used to compare six published articles that illustrate the range of assumptions and data found for one biofuel, corn-based ethanol (2-7). Although the six articles have rather divergent results, the fundamental structure of their analyses are virtually identical. In this study, EBAMM is used to identify which differences in structure and data lead to divergent results, and to examine the sensitivity of results to specific parameters. In addition, three possible scenarios for the production of ethanol are considered, illustrating how cellulosic-based production will almost certainly be necessary if ethanol is to contribute significantly to reducing greenhouse gas (GHG) emissions.

The structure of EBAMM is discussed below. The EBAMM release 1.0 model is implemented as an Excel spreadsheet, available at <http://socrates.berkeley.edu/~rael/EBAMM/>. The model consists of a set of worksheets sharing an identical layout and computational structure, referred to herein as “study sheets”. Each study sheet is parameterized to either (a) the original data provided in one of the six studies, (b) an “adjusted” version of one of the six studies, normalized to consistent system boundaries, or (c) an EBAMM case: *Ethanol Today*, *CO₂ Intensive*, or *Cellulosic* (*8*) Because the original studies focused on net energy (defined below), EBAMM is structured around this calculation. Where the studies have provided values in the units chosen for use in EBAMM, they are entered directly, and the original sources used in each study are shown, if reported. Where unit conversions are needed, this is accomplished directly in the individual study sheet. EBAMM replicates the results of the six studies to within one half of one percent (*9*).

While the six studies compared here are very similar, each uses slightly different system boundaries. To make the results commensurate, we adjusted all the studies so that they conformed to a consistent system boundary. Two parameters, caloric intake of farm workers and farm worker transportation, were deemed outside the system boundaries and were thus set to zero in the adjusted versions. (These factors are very small and the qualitative results would not change if they were included.) Six parameters were added if not reported: embodied energy in farm machinery, inputs packaging, embodied energy in capital equipment, process water, effluent restoration, and coproduct credit. Typical coproducts include distillers dried grains with

solubles, corn gluten feed, and corn oil, which add value to ethanol production equivalent to \$0.10-\$0.40 per liter of corn ethanol. For each study, if a value for any of the six parameters was reported it was used; if not, the most well-supported of the reported values was added. Both the original and adjusted values are summarized in a worksheet labeled “NetEnergy” where the adjusted parameter values are shown in pink highlighted cells.

In addition, each study sheet calculates the coal, natural gas and petroleum energy consumed at each stage of production. This permits us to estimate the total primary energy required to produce ethanol. Similar calculations are performed in the study worksheets for net GHG emissions. These results are summarized in worksheets labeled “Petroleum” and “GHGs,” respectively.

The major results are plotted in two figures shown in a worksheet labeled “Scatterplot.”

Additional worksheets include: two that evaluate cellulosic (switchgrass) ethanol production, which were considered while developing the EBAMM Cellulosic case; three that contain conversion factors and calculations; and one that contains a simple analysis of the energy embodied in farm machinery (discussed below).

One of the studies (7) evaluated here uses Higher Heating Value (HHV) while rest use Lower Heating Value (LHV), resulting in slightly different totals. We have converted HHV values to LHV to make all six studies commensurate (10). In some cases, we use GREET 1.6, a widely used, relatively disaggregated model developed by Argonne National Laboratory to provide data that other studies do not include (6).

For simplicity, we consider the production of neat (100%) ethanol, and we avoid discussing blends such as E10 and E85. The effects of neat ethanol are compared to those of “conventional gasoline” (CG), which thus serves as our baseline. Comparing neat ethanol and CG simplifies and clarifies the analysis. We use CG because the bulk of gasoline displacement by increased ethanol use will be conventional gasoline, and, in the absence of an oxygenate requirement, the future composition of reformulated gasoline is subject to uncertainty. Data for CG is taken from (6), using near-term technology assumptions.

Net energy value

The six studies examined here, as well as much of the public debate, focuses on the *net energy* of ethanol. Typically, the net energy value (NEV, or energy balance) and/or the net energy ratio is calculated. However net energy is poorly defined and used in variety of ways in different studies, adding to the difficulty in comparing across studies. For instance, in (4) net energy is defined as the “energy content of ethanol minus fossil energy used to produce ethanol,” while (5) uses “the energy in ethanol and coproducts less the energy in the inputs.” Thus, treatment of coproducts may be different across just these two definitions.

These definitions also fail to specify how nuclear and renewable energy (inputs to the electricity used in the biorefinery) are treated. Thus, all net energy calculations ignore important differences in energy quality, greatly diminishing the usefulness of this metric (11). Nonetheless, because the

objective of this study is to compare some of the existing literature on ethanol and these articles focus on NEV, we are forced to calculate it.

Further complications arise for NER because, as a ratio of output energy to input energy, it is extraordinarily sensitive to assumptions that are typically hidden, such as how coproducts are treated. The best analysis of how to define NER is Appendix A of (12), however even this study ignores the role of coproducts. The key question is whether the energy credit associated with coproducts should be subtracted from the input energy or added to the output energy. While neither of these choices is *a priori* conceptually superior, the value of the NER is sensitive to this choice, particularly when coproduct credits are large in comparison to input and output energies.

As an illustration, consider the adjusted values for the *Ethanol Today* case: non-renewable input energy is 20.7 MJ/L, output energy is 21.2 MJ/L, and the coproduct credit is 4.1 MJ/L. Treating coproducts as a subtraction from input energy yields $NER = (21.2)/(20.5-4.1) = 1.3$, while treating coproducts as an addition to output energy yields $NER = (21.2+4.1)/(20.5) = 1.2$. Compare this small difference to what happens in the *Cellulosic* case; non-renewable input energy is 3.1 MJ/L and the coproduct credit is 4.8 MJ/L, based on the primary energy displaced by export of electricity from the cellulosic biorefinery to the grid. Treating coproducts as a subtraction from input energy yields $NER = (21.2)/(3.1-4.8) = -12.5$, while treating coproducts as an addition to output energy yields $NER = (21.2+4.8)/(3.1) = 8.3$. Further, these calculations ignore burning the byproduct lignin to produce electricity for use in the biorefinery, a standard technology common in the pulp and paper industry today and in designs for cellulosic biorefineries. This is considered “Recycled Biomass Energy” in the spreadsheet. Including this value (26 MJ/L) as both coproduct and input, yields an NER of 1.8.

Thus, NER is not a robust metric. We conclude that it is preferable to use the simpler NEV calculation, which produces consistent results regardless of whether coproducts are subtracted from input term or added to output term. Similar conclusions have been reached when treating negative willingness-to-pay in the context of benefit-cost ratios versus net benefit values (13 p. 31). NEV calculations are also insensitive to the choice between the two most sensible treatments of lignin-produced electricity: ignoring it (as a closed loop) or including it as both a coproduct and an input (that is, adding it at one place in the equation and subtracting it at another). If NER must be defined, it seems to us that the best approach is to treat coproducts as an addition to the output energy and to ignore recycled biomass energy, an approach taken by none of the studies examined here. For completeness, the current EBAMM implementation calculates NER using this formulation.

We calculate NEV as shown in Equation S-1, below:

$$NEV(MJ / L_{Fuel}) = Output\ Energy(MJ_{Fuel} / L_{Fuel}) - Input\ Energy(MJ_{Input} / L_{Fuel}) \quad (S-1)$$

Output Energy is the energy contained in the fuel plus energy contained in the co-products, as shown in Equation S-2 below. We use the volumetric energy content (LHV) of neat ethanol, 21MJ/L, for *Fuel Energy*.

$$\begin{aligned}
 & \text{Output Energy (MJ / } L_{\text{fuel}} \text{)} \\
 & = \text{Fuel Energy (MJ / } L_{\text{fuel}} \text{)} \\
 & + \text{Coproduct Energy (MJ / } L_{\text{fuel}} \text{)}
 \end{aligned} \tag{S-2}$$

Input Energy is the sum of all energy required in all phases of biofuel production, including energy used to produce material inputs, sometimes called ‘embodied energy’. The portion of the input energy allocated to the coproducts (discussed below) is subtracted from the sum of agricultural, transport and conversion energies to produce *Input Energy*, as shown in Equation S-3.

$$\begin{aligned}
 & \text{Input Energy (MJ}_{\text{input}} \text{ / } L_{\text{fuel}} \text{)} \\
 & = \frac{\text{Agricultural Energy (MJ}_{\text{input}} \text{ / ha)}}{\text{Net Yield (} L_{\text{fuel}} \text{ / ha)}} \\
 & + \text{Biorefinery Energy (MJ}_{\text{input}} \text{ / } L_{\text{fuel}} \text{)}
 \end{aligned} \tag{S-3}$$

Appropriate Metrics

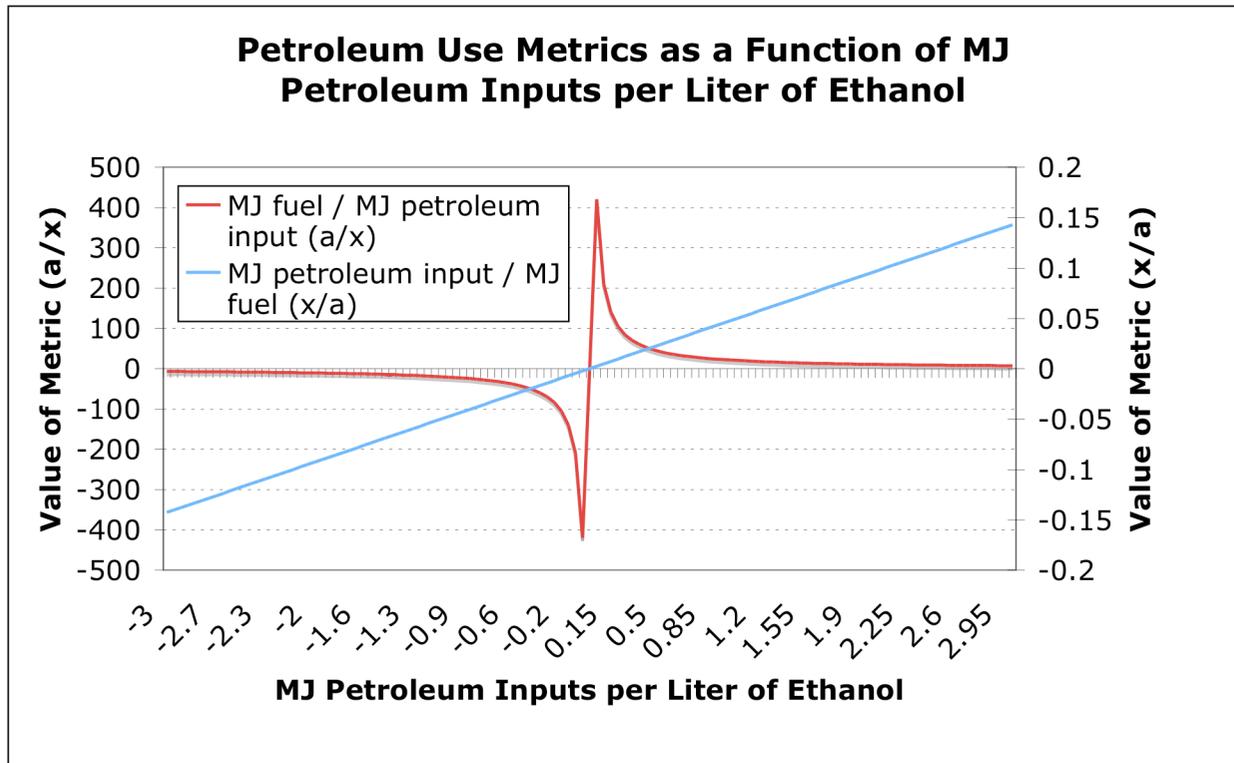
For the reasons outlined above and in the paper, NEV and NER are inadequate metrics for evaluating the environmental and social implications of expanded ethanol production. A more appropriate set of metrics would a) be closely correlated with key policy outcomes, b) have algebraic properties that are intuitive, c) be calculable over the full range of potential input parameters, and d) permit comparisons across technologies as well as across different studies.

We calculate a simple set of alternative policy metrics related to greenhouse gas emissions and the use of different types of primary energy. Each of these metrics is of the form $y=x/a$, where x is the variable of interest (e.g. greenhouse gas emissions per liter of ethanol) and a is a constant related to the specific fuel (e.g. MJ energy per liter of ethanol). The constant a , serves to normalize the results for comparison across different fuels, yielding a metric expressed in terms of policy impact per MJ of liquid transportation fuel. These metrics are:

- Greenhouse Gas Emissions / MJ fuel
- Petroleum Inputs / MJ fuel
- Coal Inputs / MJ fuel
- Natural Gas Inputs / MJ fuel
- Other Energy Inputs / MJ fuel

These metrics are linear as a function of x , the actual variable of interest that varies among studies or among ethanol production processes. Thus, if policy incentives were tied to the value of this metric, the marginal incentive to improve would be constant at all values of the metric. Furthermore, these metrics yield easily interpreted and well-defined values, even if the value of x is less than or equal to zero. It is entirely possible for life-cycle greenhouse gas emissions or primary energy use to assume zero or negative values given the displacement of coproducts discussed below.

We have specifically chosen not to calculate metrics of the form $y=a/x$, where a and x are defined as above (e.g. MJ fuel per MJ petroleum inputs). Such a function, like NER, produces non-intuitive and poorly defined values for values of x less than or equal to zero. Furthermore, as a non-linear transformation of the variable of interest, the marginal incentive to improve varies for different value of the metric. Specifically, for higher values of x , there is little marginal incentive to improve, whereas for small positive values of x , the marginal incentive is quite large since the function $y=a/x$ has an asymptote at $x=0$. The following figure illustrates the difference between a metric of the form $y=x/a$ and $y=a/x$ for the case of petroleum inputs.



Agricultural energy

The energy consumed in growing the biomass feedstock is called *Agricultural Energy* in EBAMM, although inputs include both pre-farm and on-farm energy inputs. Energy inputs are placed into seven categories: the energy embodied in farm inputs, energy to package the inputs, energy to transport inputs to the farm, energy used directly on the farm, energy used by farm labor, energy used to transport labor to the farm, and the energy embodied in farm machinery (sometimes called capital energy). Specific farm inputs considered are fertilizers containing nitrogen (as elemental N), phosphorus (as P_2O_5), and potassium (as K_2O); agricultural lime (crushed limestone, $CaCO_3$); herbicides; insecticides; and seeds. Direct energy used on farms can be disaggregated to gasoline, diesel, liquefied petroleum gas (LPG), and electricity, which can be further disaggregated into primary energy inputs. Energy inputs are shown in Equation S-4, and the categories of farm inputs in Equation S-5. The application rate of each input is multiplied by the energy consumed in its production to yield a per hectare energy value for each input.

Agricultural Energy (MJ/ha)

$$\begin{aligned}
&= \sum_{i \in \text{FarmInputs}} (\text{Embodied Energy}_i \text{ (MJ/kg)} \times \text{Application Rate}_i \text{ (kg/ha)}) \\
&+ \sum_{i \in \text{FarmInputs}} (\text{Transport Energy (MJ/kg)} \times \text{Application Rate}_i \text{ (kg/ha)}) \\
&+ \text{Farm Direct Energy (MJ/ha)} \\
&+ \text{Farm Labor Energy (MJ/ha)} \\
&+ \text{Farm Labor Transport Energy (MJ/ha)} \\
&+ \text{Farm Machinery Energy (MJ/ha)} \\
&+ \text{Inputs Packaging Energy (MJ/ha)}
\end{aligned} \tag{S-4}$$

where,

Farm Inputs

$$= N \text{ fertilizer, } P \text{ fertilizer, } K \text{ Fertilizer, } \text{Lime, } \text{Herbicides, } \text{Insecticides, } \text{Seed} \tag{S-5}$$

There has been considerable controversy in the literature over how much energy is embodied in farm machinery. Three of the studies considered here report a value for this parameter, but only one thoroughly documents the data and methodology used in its calculation (5). The value reported in (5), 320 MJ/ha, is only 0.4% of the input energy. The other two studies that include energy embodied in farm machinery report values that are an order of magnitude greater; in one case 6,050 MJ/ha and in the other 4,259 MJ/ha (2, 3). Upon close examination, these higher estimates were found to rely on 35-year-old data (although the vintage of the data is not presented clearly) that could not be verified. (See Table S-2 below.)

In order to cross-check these two very different estimates – 320 MJ/ha versus 4,000 to 6,000 MJ/ha – we used the Economic Input-Output Life Cycle Analysis (EIOLCA) model available online at www.eoilca.net in conjunction with recent USDA dollar estimates of farm equipment used per acre in corn farming (14)(15). The EIOLCA result (127 MJ/ha) is of the same order of magnitude as the lower, better documented estimate (5). This lower value (320 MJ/ha) is applied to the “adjusted” version of studies that do not report a value for this parameter in order to make them commensurate with the others. (See the “NetEnergy” and “Farm Equipment” worksheets of the EBAMM spreadsheet for details.)

Net Yield

In order to enable comparison across all parameters, we specify agricultural energy data in units of energy input per cropped area (MJ/ha), total them, and divide by the *Net Yield* (L/ha) (16). *Net Yield* is simply *Crop Yield* (kg/ha) multiplied by the *Conversion Yield* (L/kg), as shown in Equation S-6 below. Here, *Crop Yield* refers to the portion of the plant harvested for ethanol production and *Conversion Yield* is the amount of ethanol produced at the biorefinery for a unit of corn input. For convenience, the net yield value is also calculated in terms of MJ per hectare.

$$\begin{aligned}
 & \text{Net Yield (L / ha)} \\
 & = \text{Crop Yield (kg / ha)} \times \text{Ethanol Production Yield (L / kg)}
 \end{aligned}
 \tag{S-6}$$

Biorefinery energy

The energy consumed in producing ethanol from feedstock is called *Biorefinery Energy* in EBAMM is computed as shown in Equation S-7. Note that the parameter *Biomass Energy Inputs* is used only in the cellulosic ethanol cases, in which the lignin fraction provides fuel for the production of electricity and process heat.

$$\begin{aligned}
 & \text{Biorefinery Energy (MJ}_{input} / L_{fuel}) \\
 & = \text{Feedstock Transport Energy (MJ / L)} \\
 & + \text{Electricity Inputs (MJ / L)} \\
 & + \text{Coal Inputs (MJ / L)} \\
 & + \text{Natural Gas Inputs (MJ / L)} \\
 & + \text{Diesel Inputs (MJ / L)} \\
 & + \text{Biomass Energy Inputs (MJ / L)} \\
 & + \text{Process Water Inputs (MJ / L)} \\
 & + \text{Effluent Water Energy (MJ / L)} \\
 & + \text{Embodied Energy (MJ / L)}
 \end{aligned}
 \tag{S-7}$$

Coproducts

Biofuel production yields various coproducts, depending on the feedstocks and processes employed. For example, ethanol production from corn co-produces corn oil, distiller's dried grains with solubles (DDGS), corn gluten feed (CGF) and/or corn gluten meal (CGM), depending on whether dry- or wet-milling is utilized. When these coproducts have a positive economic value, they will displace competing products that also require energy to make (1, 17). Coproducts produced from both current and anticipated increases in corn ethanol production are expected to be valuable feed products that will displace whole corn and soybean meal in animal feed (18).

Several approaches to estimating this displacement effect have been suggested, including: *process*, *market-based*, and *displacement* methods (17). The process method typically uses a process simulation model (e.g. ASPEN) to model the actual mass and energy flows through a production sequence, allocating coproduct energy according to estimated process requirements (4). The market-based method allocates total input energy to the various products according to the relative market value of each. Kim and Dale argue persuasively for the displacement (or 'system expansion') method, which brings into the analysis the production of the commodities that the ethanol coproducts displace (17). This approach thus evaluates the total change in energy occurring with the production of biofuels. The displacement method credits the coproduct with the energy required to produce a functionally-equivalent quantity of the nearest substitute, e.g. distillers dried grains with solubles (DDGS, a coproduct of dry-mill corn ethanol production) is

considered a substitute for soybean protein. This method requires a life cycle energy analysis of the substitute good to determine the displaced energy.

While the most accurate method for estimating coproduct energy allocation is still a matter of some debate in the literature, our analysis leads us to agree with Delucchi, who concludes that the most comprehensive method would be a displacement approach that utilizes a general equilibrium model to estimate price and quantity effects in each substitute and input market and then calculates net energy impacts from the ethanol coproduct production (1). However, approximations based on simpler displacement (or system expansion) approaches should yield reasonable results, especially for the modest changes in fuel and agricultural production contemplated here (6, 18).

Sensitivity analysis with EBAMM, as well similar analyses reported in other studies (e.g. 4) have shown that the model assumption with the greatest individual influence on all results is coproduct allocation. Table S1 summarizes the coproduct credits used in the six studies and three cases, and the methods used to determine these allocations.

Table S1. Coproduct energy credit.

Study	Value (MJ/L)	Allocation method
Patzek (2)	0	None
Pimentel & Patzek (3) - Corn	0	None
- Switchgrass	0	
Dias de Oliveira (7)	0	None
Shapouri <i>et al.</i> (4)	-7.3	Corn production and transport: mass basis Ethanol production: process simulation
Graboski (5)	-4.1	Displacement
Wang (3) - Corn	-4.0	Displacement
- Switchgrass	-4.8	Displacement
EBAMM <i>Today</i>	-4.1	Displacement
EBAMM <i>CO₂ Intensive</i>	-4.1	Displacement
EBAMM <i>Cellulosic</i>	-4.8	Displacement

The two studies that show a negative NEV for corn ethanol assume that ethanol coproducts should not be credited with any of the input energy. Various reasons are given for excluding coproducts, for instance, “all of the ethanol processing leftovers should be returned to the field to replenish soil humus and microelements” (2). However, this study provides no quantitative analysis to support this claim and does not consider the efficacy of dumping marketable coproducts on the soil relative to other methods of replenishing soil humus and micronutrients. The normative argument does not substitute for a positive analysis.

Pimentel and Patzek argue that “[t]he energy and dollar costs of producing ethanol can be offset partially by the by-products produced... these energy credits are contrived because no one would actually produce livestock feed from ethanol at great costs in fossil energy and soil depletion” (3). However, this logic reverses the causal chain. Current ethanol plants sell by-products and

current designs for cellulosic biorefineries include the use of the combustible fraction of lignin for electricity generation (including offsite sales) and waste heat recovery, much as the pulp and paper industry does today (19).

Dias de Oliveira *et al.* ignore coproduct energy because no satisfactory estimate was available (20).

Shapouri *et al.* employ a hybrid of process methods to allocate input energy between ethanol and its coproducts (4). Energy inputs for corn production and transportation to the ethanol plant is attributed to ethanol according to the portion of crop weight composed of starch. The energy involved in producing ethanol from corn is allocated to ethanol and its coproducts according to the results of a process simulation conducted using ASPEN Plus software. The last two studies use a displacement method. Graboski uses a displacement method to calculate a coproduct credit for the coproducts of both wet- and dry-mill ethanol production (5). This study goes to some lengths to model the effects of increased coproduct production on several potential feed ingredients, using a linear program to minimize cost according to nutritional constraints.

GREET calculates coproduct credits for ethanol using a displacement method. In the case of corn, it assumes the coproduct of dry-milling, DDGS, displaces some whole corn and some soybean meal in animal feed, and that the products of wet-milling, corn gluten meal, corn gluten feed, and corn oil, displace whole corn, nitrogen-in-urea, and soy oil (6). In the case of cellulosic ethanol, the displaced product is the grid-based electricity displaced by the generation and export of electricity through lignin combustion in the ethanol plant. The energy value of the coproduct is thus equal to the primary energy that would have been required to generate this electricity, based on the average fuel mix and efficiency of the United States grid.

EBAMM adopts the displacement model of (5) in its calculation of coproduct energy credits for corn ethanol production. This model was chosen because of the extensively documented, multi-product, nutritionally- and economically-balanced displacement analysis presented. EBAMM adopts the displacement model of (6) in its calculation of coproduct energy credits for the production of cellulosic ethanol because of its simplicity.

Fossil Fuel Use

To move beyond the usual focus on net energy, EBAMM also calculates the total primary energy from coal, natural gas, and petroleum used to produce one MJ of ethanol. The quantities of primary and embodied input energy reported by each study are attributed to specific primary fuels according to the assumptions from (6) about the specific primary energy inputs for each process. Where (6) does not calculate the specific primary energy inputs, such as for manufacturing farm equipment, we assume that the distribution of primary energy inputs for the U.S. economy as a whole is applicable (21).

In order to compare the fossil fuel consumption implications of competing analyses, a consistent platform is constructed in EBAMM by determining the share of primary energy used in material inputs and processes, and applying these shares to the total energy inputs reported in the surveyed studies to estimate the quantities of individual fossil fuels used in ethanol products.

However, because the ethanol production process also results in the production of coproducts that displace substitute products that also require fossil fuels, we also consider coproduct fossil fuel credits.

As discussed above, the most accurate method to calculate these fossil fuel coproduct credits would be to use a general equilibrium model to calculate the net change in fossil fuel use within a system that included the substitute product markets. Unfortunately, the data needed for this calculation are not readily available. For simplicity and consistency, we approximate the allocation of fossil fuel consumption by using the fraction of net energy allocated to coproducts with the model of (5), as discussed above. Thus, if 15% of the net energy is allocated to coproducts, then 15% of the input of each fossil fuel type is also allocated to coproducts.

Greenhouse Gas Emissions

Net greenhouse gas (GHG) emissions to the atmosphere are calculated, including the fossil carbon in fuels like gasoline and diesel but excluding photosynthetic carbon in ethanol that comes from feedstock crops. None of the studies examined consider soil carbon sequestration, so we do not consider it in EBAMM. However, depending on agronomic practices, soil C sequestration can significantly affect net GHG emissions (22). Thus, for ethanol, net GHG emissions reflect only the emissions from feedstock and fuel production. Because the majority of GHG emissions from gasoline and ethanol occur in different stages of the fuel cycle (end use and processing, respectively) both stages must be included to make a meaningful comparison. See the figure in the accompanying paper.

The greenhouse gases considered in EBAMM are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Greenhouse gas emissions are aggregated on a carbon dioxide-equivalent (CO₂e) basis, using the 100-year global warming potential (GWP) factors for methane and nitrous oxide emissions recommended by the Intergovernmental Panel on Climate Change (23). These values are 1 for CO₂, 23 for CH₄, and 296 for N₂O.

Each study sheet calculates GHG emission values using that paper's energy and material input assumptions values and a set of GHG emission factors derived from GREET (6). A similar step is taken in the worksheets adjusted for commensurability. The three EBAMM cases use the most appropriate data and assumptions from the six studies.

In EBAMM, the GHG calculations follow the format of the net energy calculations. For each of the inputs and steps in agricultural production and conversion to ethanol at the biorefinery, the net CO₂e emissions are calculated. For many inputs, these emissions are essentially the sum of emissions of CO₂ from primary energy use. However, for some inputs the model accounts for other important sources of GHGs. For instance, the use of nitrogen fertilizer results in GHG emissions in two stages: fertilizer manufacture (primarily CO₂ emissions from energy use) and fertilizer application (primarily from N₂O emissions from nitrification and denitrification processes in soil). In EBAMM, GHG emissions for nitrogen fertilizer are calculated on a per hectare basis as shown in S-8 through S-10 below.

$$\begin{aligned} & \text{Nitrogen fertilizer emissions (kgCO}_2\text{e/ha)} \\ & = \text{Fertilizer production emissions(kgCO}_2\text{e/ha)} + \text{Soil related emissions(kgCO}_2\text{e/ha)} \end{aligned} \quad (\text{S-8})$$

$$\begin{aligned} & \text{Fertilizer production emissions (kgCO}_2\text{e/ha)} \\ & = \text{Fertilizer manufacturing emissions factor (kgCO}_2\text{e/kgN)} \\ & \quad \times \text{Nitrogen application rate (kgN/ha)} \end{aligned} \quad (\text{S-9})$$

$$\begin{aligned} & \text{Soil related emissions (kgCO}_2\text{e/ha)} \\ & = \text{Nitrification/ denitrification emissions factor (kgCO}_2\text{e/kgN)} \\ & \quad \times \text{Nitrogen application rate (kgN/ha)} \end{aligned} \quad (\text{S-10})$$

Similarly, agricultural lime (CaCO_3) application results in GHG emissions from both production energy use and in-soil reactions that release carbon as carbon dioxide. These latter emissions are poorly understood and are a significant source of uncertainty. We use the average of emission factors for limestone and dolomite applications recommended in the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Worksheet 5-5. For other agricultural inputs, data from (6) are used, including pesticides, transportation, and on-farm energy. The estimate of GHG emissions due to irrigation relies on (24) and (6).

Emissions from energy used in the ethanol facility are based on emissions factors for each energy type and combustion technology as given in (6). Where studies reported only total primary energy, emissions have been calculated based on coal and natural gas emissions factors for wet and dry milling facilities and the percentage of ethanol production using each of these methods as reported in (6).

While a few of the papers reviewed here provide estimates of the energy embodied in the on-farm and biorefinery capital, primary energy sources are not reported. We base our estimate on the carbon content of the mix of fuels used in the United States economy in total. We use this same emissions factor for other under-specified reported energy data, including process water and seed production (21).

As with net energy, GHG emissions from ethanol are compared in EBAMM to the emissions from the production and use of conventional gasoline. We assume near-term production and combustion technology.

The additional use of ethanol due to the Energy Policy Act of 2005 is not expected to bring very much unfarmed land into cultivation, although some shifts in production from one crop to another will occur (18). Significantly greater use of biofuels might shift marginal or unused lands into crop production, however, potentially resulting in significant changes in net GHG emissions due to land use changes alone. The possibility of importing ethanol suggests that land use changes as a result of U.S. ethanol use could occur outside of the country, raising concerns about, for instance, the conversion of rainforest into plantations for fuel production (25). Estimating the magnitude of such effects would be very difficult, requiring analysis of land productivity and availability, commodity markets, and other factors, none of which are

considered in the studies evaluated here (1). For these reasons, we ignore GHG emissions due to potential changes in land use.

We approximate the allocation of GHG emissions using the fraction of net energy allocated to coproducts with the model of (5), as discussed above. Thus, if 15% of the net energy is allocated to coproducts, then 15% of net GHG emissions are also allocated to coproducts. For most factors, this simplifying assumption will be roughly correct, as GHGs track fairly consistently with energy use. However, there is considerable uncertainty associated with the net GHG effects of some emission sources, including agricultural nitrogen and lime applications, and changes in legume (soybean) cropping. More research is needed to resolve these issues (26).

Supporting Text

Data trends

All the studies evaluated here use average historical data for the primary analysis, although agricultural practices and biofuel production technologies vary from location to location, and over time. Thus, evaluations of the future use of biofuels should be explicit about their assumptions, and should consider how future trends and the use of average or marginal data could influence results. Of the six studies, only (5) presents projections of future trends. These projections foresee efficiency gains in corn yield, on-farm energy use, and ethanol plant energy use and yields, resulting in an improved energy profile.

Figure S-1 below plots average corn yield in the United States over the last 35 years and a linear regression trend line. Figure S-2 shows the variability in corn yield by county in Iowa for 2002-4.

These figures illustrate some of the problems associated with using average historical data to consider possible increases in biofuel production in the future. The first problem is that using average historical values implicitly assumes there will be no change in agricultural yields (production per unit area of farmed land). Figure S-1 shows that average corn yield on U.S. farms has increased by 3.5% annually over the last 35 years. Projections about the potential role of corn ethanol in the future must at least implicitly assume a future trend. The yield values used in the six studies evaluated here are all quite similar and are all close to the actual yields observed in 2000-2003. Thus, using these studies to consider future ethanol production assumes future corn yields will be similar to those enjoyed in the recent past – neither improvements nor declines in production can be expected. However, the necessary conditions for this assumption to be true are not described or tested.

Assumptions about future trends in farm productivity may be more important for the cellulosic case because the cultivation of switchgrass and other potential energy crops is not nearly as advanced as the cultivation of traditional food crops such as corn. Thus the potential for crop yield improvements in the overall performance of cellulosic ethanol may be greater than for corn ethanol. The *Cellulosic* case is based on the “Herbaceous” case in (6), which uses recent crop yield data and therefore may underestimate the net energy value of cellulosic ethanol in the future.

A second problem is that similar trends exist in conversion yield, which has the added advantage that these improvements are not be subject to environmental constraints (e.g. nutrient loss, soil quality) as agricultural yields are. Scaling up of the ethanol industry will entail additions to ethanol production capacity that will be newer and more advanced than today's average value, raising average productivity over time. Further, increasing production of ethanol will continue to cause technological innovation and learning-by-doing, as has happened in other industries (27, 28). Because all studies and cases examined here use recent data, they implicitly assume no improvements in biorefinery technologies and thus likely underestimate NEV and petroleum displacement in the future, and overestimate net GHG emissions.

Some of the literature on ethanol contains secondary citations which hide the original source and vintage of data that in some cases is obsolete. The importance of trends in agricultural and biorefinery technologies illustrated in Figure S-1 makes this problem especially troubling. (See Table S-4 below.)

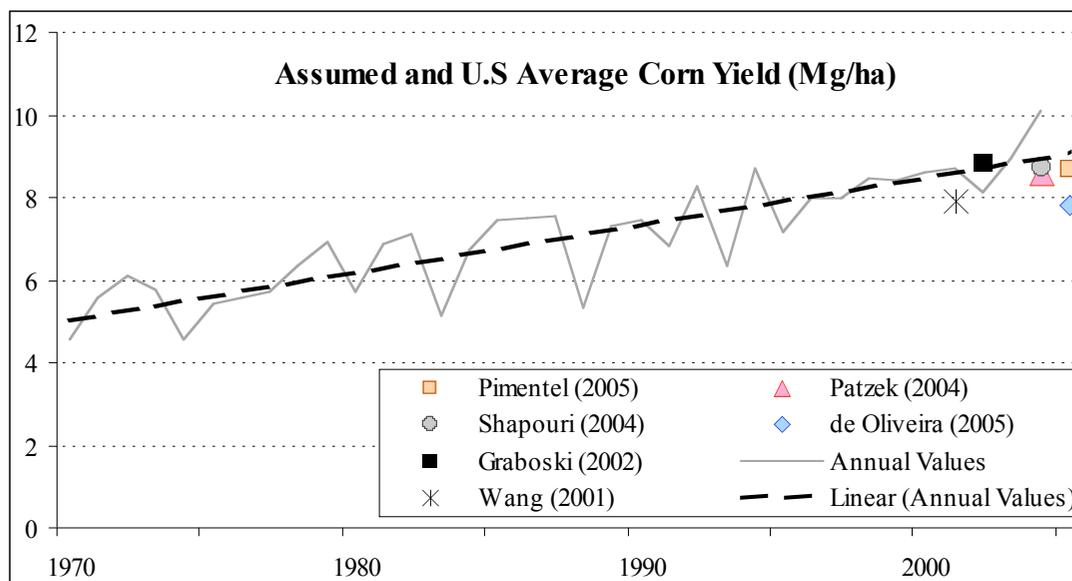


Figure S1: Trend in corn yield and assumed values (29)

A third problem is that the six studies of biofuel production use average national or state estimates for agricultural yield, even though yields vary over a great range for any given crop, as illustrated in Figure S-2. This variability raises several questions: Where will agricultural lands that are shifted into energy production from other uses fall in this distribution? Where in the distribution in yield for current uses does that land currently fall? (That is, What will be the effect of shifting crops from land that is poor for corn but good for switchgrass?) What about idle land that is newly put into production? The ability to analyze these data is limited by the resolution of available data; further insights from national or even state-level data may be limited and may not be worth pursuing at this time.

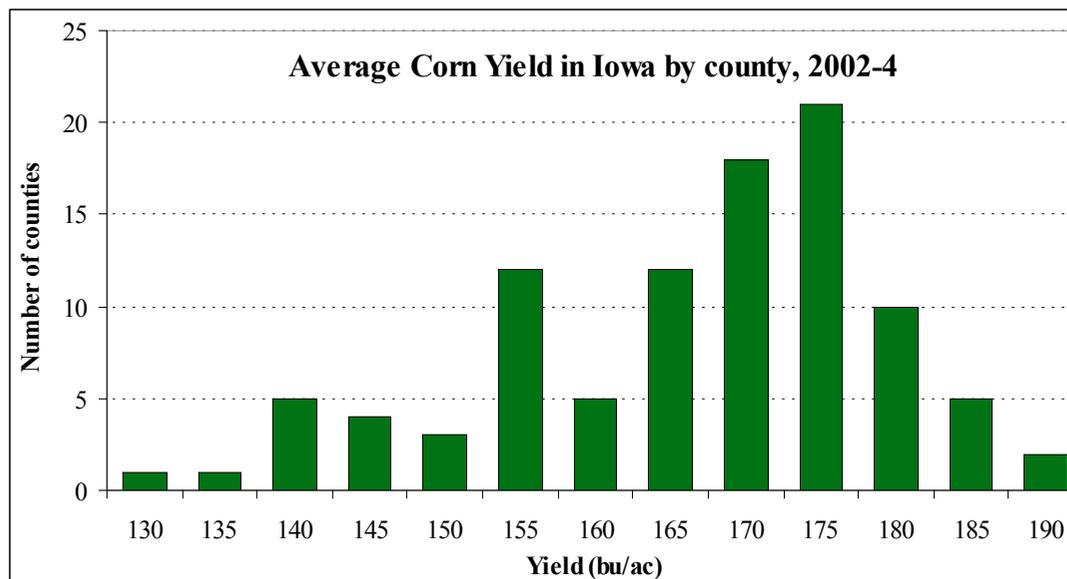


Figure S2: Variability in corn yield by county in Iowa (29)

Sensitivity Analysis

The relatively simple structure of EBAMM makes uncertainty analysis fairly straightforward. To evaluate the sensitivity of summary values (net energy, net GHG emissions) to the choice of parameter values, we computed the elasticity of the summary value with respect to each input parameter. The elasticity was calculated as the percent change in the summary value given a one percent increase in the input parameter. As elasticities vary with the magnitude of the values considered, there was variance across the studies. However, the analysis yielded a set of parameters that consistently showed the highest elasticities. Although the order sometimes shifted between studies, the top six were consistent across all studies. They are:

- refinery energy (often reported only as an aggregate net energy value)
- farm yield
- refinery yield
- coproduct credit
- nitrogen energy
- nitrogen application rate

We did not compute elasticities of petroleum consumption with respect to input parameters because there is little petroleum used in ethanol production, and most of it is attributable to the various transportation parameters where liquid fuels are used.

In addition, because (1) and (23) suggest that agricultural N₂O emissions may be one of the most uncertain parts of this problem, we performed a sensitivity analysis of this factor in our model. Using the full range of GWP values for N₂O reported in (23), net GHG emissions for the *Today* EBAMM case range from about –10% to +40% relative to the value we report. The upper value includes direct N₂O from fertilizer in the soil as well as downstream N₂O from applied N that has

volatilized and been redeposited elsewhere or leached into water and become N₂O later. This sensitivity analysis reflects uncertainties in emissions factors, not uncertainties in N application rates, which do vary by region and county and would have a large impact on total GWP/MJ. However, the uncertainties in the IPCC factors reflect global variation, and the upper end of that range has been critiqued methodologically (26).

Moreover, there exist several potential sources of N₂O in corn agriculture that are not part of any of the six studies because they focus on energy and not GHGs. For instance, the application of manure, or the incorporation of crop residues (stover) increase N availability, leading to additional N₂O emissions. Growing legumes does the same. Because corn is often grown in rotation with soybeans, residual N fixed by soybeans could be partially attributed to corn production because it reduces the need for inorganic sources of N. Finally, the conversion of wetlands to agricultural land is associated with N₂O production. Overall, there is deep uncertainty about the net GHG implications of ethanol production.

These sensitivity analyses suggest two key implications. First, we can state with reasonable confidence that corn ethanol (or ethanol from other feedstock crops that rely on large amounts of N fertilizer) is unlikely to provide significant reductions in net GHG emissions relative to gasoline, while cellulosic ethanol is likely to provide significant reductions. Second, relatively little petroleum is used to produce ethanol from either corn or cellulosic material, so using ethanol as a transportation fuel reduces petroleum supply requirements.

EBAMM cases

In order to evaluate the importance of assumptions about trends and average values in the analysis of ethanol, three EBAMM cases were created: *Ethanol Today*, *CO₂ Intensive*, and *Cellulosic*. System boundaries for these cases were selected to make them commensurate with the adjusted values for the six papers using the best available data. Thus, data from (5) are used for the energy embodied in farm machinery and inputs packaging, and data from (3) are used for the energy embodied in the biorefinery, process water use, and effluent restoration.

The *Ethanol Today* scenario assumes typical current practices for corn ethanol, including the current mix of wet and dry milling, current crop and ethanol yields, and current input (e.g. nitrogen fertilizer) energy intensities. Most of the data are taken from (6). While the *Ethanol Today* scenario need not be (and we think is not likely to be) representative of future ethanol production, it is useful as a benchmark for comparison across studies, because it uses the most reliable data and requires the fewest additional assumptions.

The *CO₂ Intensive* scenario uses the same assumptions as the *Ethanol Today* case except that the corn production data is for the most energy-intensive major producing state in 2001, Nebraska, and the corn is assumed to be shipped by rail to a lignite-fueled ethanol plant in North Dakota. This scenario is based on a project currently under construction and is meant to illustrate the sensitivity of model results to two significant parameters that could be affected by a major expansion of corn-based ethanol production: the expansion of corn-growing on more marginal lands, and fuel-switching in ethanol production (30). The *Cellulosic* scenario uses data found in

(6) for the production of ethanol from switchgrass, and is adjusted to be consistent with the system boundaries used by EBAMM.

Errors, Omissions, and Inconsistencies

The construction of EBAMM required extensive, detailed examination of the six studies we evaluated, which brought to light some errors, omissions, and inconsistencies in the data. Those that we consider significant are shown in Table S2 below, and described in the associated notes.

Table S2. Errors, Omissions, and Inconsistencies

Source	Parameter	Problem	Note
(2)	Ethanol yield	Inconsistent data	1
(2)	On-farm labor	Invalid assumption and double counting	2
(3)	Nitrogen fertilizer production energy	Misreported data	3
(3)	Embodied energy of ethanol plant capital	Obsolete, unverifiable, misreported and inconsistently used data	4
(3)	Herbicide application	Misreported data	5
(3)	On-farm labor	Invalid assumption	6
(3)	Steam and electricity use in corn ethanol production	Obsolete, inaccurately cited data	7
(3)	Steam and electricity use in cellulosic ethanol production	Unsupported assumption	8
(3)	Cellulosic ethanol conversion efficiency	Obsolete, inaccurately cited data	9
(3)	Phosphorus, Potassium, Lime, herbicide, insecticide, farm input transportation	Questionable, unverifiable data	10
(7)	Seed energy	Incorrect citation	11
(31)	All Table 1 N fertilizer values	Incorrect unit conversions	12

Explanatory notes for Table S2

- Pages 523 and 560 report a theoretical maximum ethanol conversion yield from typical, 15%-moisture corn (2.42 gal/kg) that is below the actual average industry yields reported by USDA (based on industry surveys) for both dry and wet milling operations (2.5 and 2.8 gal/bu respectively; weighted average of 2.68 gal/bu) (31). The practical yield of ethanol from moist corn reported in (2) (0.32 L/kg corn) is 20% below the actual recorded average yield of all US ethanol plants in 1998 (0.39 L/kg moist corn).
- Page 529 presents an estimate of on-farm labor energy input as a fraction of the caloric intake of workers. Although calculated slightly differently from (3), this approach is also based on the invalid assumption that that a portion of an average corn production worker's annual caloric intake can be counted as an energy input to corn production. In addition, in (2) this

figure is added to a labor energy value from (31). Because both of these figures are derived from USDA NASS labor data, (2) is in effect counting labor energy twice.

3. Table 1 reports N fertilizer energy as 2,448,000 kcal for 153 kg N, which converts to 66.9 MJ/kg and refers to (2) as the source. However (2) reports only 54.4 MJ/kg. This higher value is 23% greater than the cited source, and 13% greater than next highest reported value among studies reviewed here.
4. Table 2 presents data from (3) for the energy embodied in stainless steel, structural steel, and cement. These data are cited as taken from (32). No calculations or references are given for these values in (32), and these values cannot be checked or verified. Further, in (3) these data are either incorrectly reported or adjusted in an unreported and inconsistent way. Of the 15 instances these values are used in (3), ten data are significantly different than those used in (32). These problems are illustrated below.

Values reported in (32):

Stainless steel (pipe)	68	MJ/kg
Structural steel	50	MJ/kg
<u>Cement</u>	<u>8</u>	<u>MJ/kg</u>

Values reported in (3) said to be based on (32):

Corn ethanol plant:		
Stainless Steel	17	MJ/kg
Steel	17	MJ/kg
<u>Cement</u>	<u>4</u>	<u>MJ/kg</u>
Cellulosic ethanol plant:		
Stainless Steel	63	MJ/kg
Steel	64	MJ/kg
<u>Cement</u>	<u>8</u>	<u>MJ/kg</u>
Biodiesel plant:		
Stainless Steel	60	MJ/kg
Steel	49	MJ/kg
<u>Cement</u>	<u>8</u>	<u>MJ/kg</u>

5. Table 2 reports an herbicide application rate of 6.2 kg/ha, citing a website entitled "History of U.S. Corn Production." This website contains two sentences relating to pesticide use, citing data from ten and twenty years previous, "*Total and per acre use of pesticides for all crops reached their peak in the early 1980's and has since declined (ERS, 1994). Corn accounted for 55% of the 410 millions pounds of herbicides used in 1986.*" (33) These data do not support the value given in (2). The USDA's "historical track records" indicate that in 1986, 30.5 million acres of corn were harvested (29). Dividing this area into the herbicide application reported above yields an average application of 3.4 kg/ha. The value reported in (2) is 82% larger than this, and more than double the next highest value reported in any of the other studies reviewed here, and no explanation is given for the difference.
6. Table 1 reports energy input of on-farm labor, assuming that a portion of an average corn production worker's annual caloric intake can be counted as an energy input to corn

production. However, the majority of this food energy would have been consumed by the worker anyway no matter what their employment. Therefore, this assumption is invalid. Furthermore, if the assumption were valid, counting the non-renewable energy input into labor as caloric intake is incorrect. To quantify the energy input into labor, it would be more appropriate to consider the life cycle non-renewable inputs to food production rather than the caloric energy of the food itself. But we believe this to be moot.

7. The citation used in the notes to Tables 2 and 5 for energy for ethanol production is a website listed as "Illinois Corn Growers Association 2004," whereas the actual source is over a decade older (34) and which is available in an updated version at www.ilsr.org.
8. On page 68, (3) argues that although “[t]he energy and dollar costs of producing ethanol can be offset partially by the by-products produced... these energy credits are contrived because no one would actually produce livestock feed from ethanol at great costs in fossil energy and soil depletion.” As noted earlier, current ethanol plants do, in fact, sell by-products and current designs for cellulosic biorefineries include the use of the combustible fraction of lignin for electricity generation (including offsite sales) and waste heat recovery.
9. In the notes for Table 5, recent claims by an ethanol technology vendor (Arkenol) that 2 kg of wood cellulose are needed to produce one liter of ethanol is rejected in part because “Others are reporting 13.2 kg of wood per liter of ethanol (DOE, 2004).” This citation is a website (www.eere.energy.gov/biomass/dilute_acid.html) that includes in its first paragraph the following text:

“...As indicated earlier, the first attempt at commercializing a process for ethanol from wood was done in Germany in 1898. It involved the use of dilute acid to hydrolyze the cellulose to glucose, and was able to produce 7.6 liters of ethanol per 100 kg of wood waste (18 gal per ton). The Germans soon developed an industrial process optimized for yields of around 50 gallons per ton of biomass...”

The value of 13.2 kg/L reported by (3) is based on this 107-year old data; 100 divided by 7.6 yields the 13.2. While this value is *not* used in subsequent calculations, it *is* used as the sole justification for an otherwise arbitrary choice of an important parameter (see the section on sensitivity analyses above) without being clear about how it was calculated or noting that it is based on obsolete data.

10. In Table 1, numerous reported values lack any citation or explanation, including embodied energy in: phosphorus, potassium, lime, herbicide and insecticide. Several of these values are 20-50% higher than values reported by other sources.
11. In Table 1, (4) is cited, but the values are from (35) (See note 20).
12. In Table 1, the entire column of Nitrogen Fertilizer Production values is incorrectly converted from the English-unit version of the paper to SI, using $(x \text{ BTU/lb}) / (948.45 \text{ BTU/MJ}) / (2.205 \text{ lb/kg})$ to compute MJ/kg. The correct conversion multiplies, rather than divides, the last term, i.e. $(x \text{ BTU/lb}) / (948.45 \text{ BTU/MJ}) * (2.205 \text{ lb/kg})$. So, for example, the N energy value reported by the 2002 version of the paper, 18392 BTU/lb is converted to 8.80 MJ/kg when the correct value is 45.75 MJ/kg. However, it appears that

totals were converted directly to SI as totals, rather than by adding up the incorrectly converted values. Thus, the reported final results are correct despite the intermediate error.

Table S3. EBAMM Results

Data for six studies of corn ethanol and three cases using the EBAMM model and published data. Values for gasoline account for coproducts.

Reference	EBAMM results for selected studies						EBAMM cases		
	Patzek 2004	Pimentel <i>et al.</i> 2005	de Oliveira <i>et al.</i> 2005	Shapouri <i>et al.</i> 2004	Graboski 2002	Wang 2001	Ethanol Today	CO ₂ Intensive	Cellulosic
Petroleum inputs (MJ/MJ)									
Original values	0.26	0.25	0.14	0.04	0.05	0.09			
Commensurate values	0.19	0.19	0.08	0.05	0.07	0.10	0.06	0.20	0.08
Net GHG emissions (gC/MJ)									
Original values	121	116	98	61	99	71			
Commensurate values	104	97	82	80	107	74	87	101	11
Net energy (MJ/L)									
Original values	-5.0	-6.1	1.6	8.9	3.9	6.9			
Commensurate values	-1.6	-3.7	4.8	8.0	3.1	6.1	4.5	1.0	23
Percent of published net energy									
Original values	100.0%	99.9%	100.0%	100.0%	100.5%	100.2%	-	-	-
Coproduct credit (MJ/L)									
Original values	0	0	0	7.3	4.1	4.0	4.1	4.1	4.8
Commensurate values	4.1	1.9	4.1	7.3	4.1	4.0	4.1	4.1	4.8

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8. The term "Cellulosic" is used because it is the most intuitive even though this case is based on the use of switchgrass (*Panicum virgatum*), also called "Herbaceous" in (6). Using other crops (e.g. poplar trees) to produce cellulosic ethanol would likely produce different results.
9. NEV is presented only graphically in (2).
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