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Review of Corn Based Ethanol Energy Use and Greenhouse Gas Emissions

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The goal of our research project on ethanol is to determine the long-term potential production scale of corn- and cellulosic-based ethanol in different geographical regions within the United States. Additionally, as the environmental impacts of large-scale ethanol production from starch and cellulosic sources vary regionally, these impacts will also be assessed and considered as one of the factors in determining the scale of ethanol production in these different geographic regions.

The project work to date has looked at a corn-based ethanol production system that includes the agricultural, corn transport, and ethanol processing sectors. A Monte Carlo approach was applied to determine the fossil energy input per gallon of ethanol produced. This approach enables one to account for the variability in system inputs and therefore produces probabilistic or distributive results rather than a single point value, which is common in LCA analyses. This approach was used to address four main questions that have been identified as likely to provide more accurate metrics for determining the impacts and possible benefits of ethanol production and use. The questions raised, in a US context, were:

1. To what extent will the production and use of corn-based ethanol displace petroleum?
2. As natural gas use and its importation are projected to grow, what amount of natural gas is used during ethanol production?
3. What are the overall carbon emission benefits of corn-based ethanol compared to gasoline?
4. How do geographic and climate variations affect the fossil energy consumption and GHG emission results?

The following analysis applies a Monte Carlo approach to address the above questions for the system boundary defined in the attached appendix. This analysis characterizes the current and near-term corn ethanol production energy consumption and greenhouse gas emissions. A description of the agricultural and ethanol-processing data used in this analysis can be found in the attached appendix.

Figure 1 separates the amount of direct system input energy into its main consumption sources: natural gas, purchased electricity, and petroleum. Natural gas, purchased electricity use, and petroleum use represent 82%, 12%, and 6% respectively of the total direct energy use during the production of a gallon of corn-based ethanol. The electric production efficiency is not included in **Figure 1**. Approximately 73% of the natural gas is consumed by the ethanol-processing step, while the remaining amount is consumed mainly during fertilizer production. 58% of the electricity purchased is consumed by the ethanol-processing step, while the remaining amount is consumed while producing corn production inputs, such as fertilizer, and by farm machinery. If an electrical production conversion efficiency of 32% is assumed, the total system primary energy input would be 20.6±2.5MJ/Liter based on the fuels higher heating value[1].

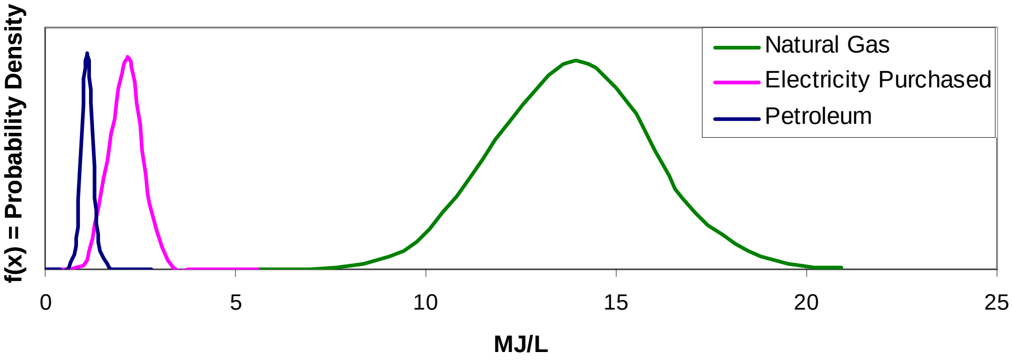

Figure 1 - Total Corn Ethanol Direct Fossil Energy Input Breakdown per Liter of Ethanol Produced

To address the first of the three questions listed, (*To what extent will corn-based ethanol use displace petroleum?)* one needs to determine the amount of petroleum consumed during ethanol production and the amount displaced during the use phase, the difference giving the net amount of petroleum displaced. **Table 1** represents the average amount of petroleum consumed during the production of ethanol if you consider all three sectors; farm, corn transport, and ethanol processing for the system boundary described. The two values represent either the inclusion or the exclusion of the amount of oil consumed during electricity generation. The 2004 US electricity generation energy portfolio was assumed and is defined in the appendix. The values in **Table 1**, which are dependent on the system definition, show that a mean value of 0.03 gallons of oil is consumed to produce a gallon of ethanol. On an energy and volume basis, 1 gallon of ethanol is equivalent to 0.7 gallons of gasoline. Therefore, the consumption of 1 gallon of ethanol displaces 0.67 gallons of gasoline.

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[1] Ethanol HHV = 23.4 MJ/Liter

	Consumption of Petroleum in gallons (Excluding Electricity Generation)	Consumption of Petroleum in gallons (Including Electricity Generation)
Production of 1 gallon of ethanol	0.025±0.003	0.030±0.003

Table 1 – Gallons of Petroleum Fuels Consumed to Produce a Gallon of Ethanol, based on HHV

Natural gas is the main fossil fuel consumed to produce a gallon of ethanol as shown in **Figure 1**. The second question recognizes that as US natural gas consumption continues to rise so does its importation and thus our dependence on a foreign resource. **Table 2** represents the average amount of natural gas consumed during the production of a liter of ethanol. The two values again represent either excluding or including the amount consumed during electricity generation. The 2004 US electricity generation energy portfolio is again assumed to determine the amount of additional natural gas consumed due to electricity generation.

	Consumption of Natural Gas in MJ/L (Excluding Electricity Generation)	Consumption of Natural Gas in MJ/L (Including Electricity Generation)
Production of 1 Liter of ethanol (23.4 MJ/L)	13±2	14±2

Table 2 - Natural Gas Energy Consumed to Produce a Liter of Ethanol, based on HHV

The third question to address is, *Does using ethanol as an alternative transportation fuel lower greenhouse gas emissions compared to gasoline usage?* There are two main issues to consider when answering this question:

1. The difference in ethanol-blended gasoline heating values and their effect on vehicle fuel consumption, and

2. The effects of co-product credits on the greenhouse gas emissions results.

Table 3 shows the heating values and fuel consumption for different ethanol gasoline fuel blends. Ethanol has 30% less energy content per unit volume, and therefore higher ethanol blends have lower overall heating values and thus higher fuel consumption.

	Energy Content *(MJ/L)*	**Fuel Consumption** *(L/100-km)*
Gasoline	33	8.6[2]
E10	32	8.8
E85	25	11.5
E100	23	12.2

Table 3 - Heating Values and Fuel Consumption for Different Ethanol Blends, based on HHV

Table 4 shows the amount of greenhouse gases emitted during the production and use of both ethanol and gasoline, not including co-product credits. These results show no overall benefit in GHG emissions from a life cycle point of view. GHG emission results including co-product credits are discussed later in this report.

	Fuel Production	**Fuel Use**	**Total**	**Total**
	gCO_2-equ/L	gCO_2-equ/L	gCO_2-equ/L	gCO_2-equ/MJ
Ethanol	2,430±330	0	2,430±330	106±14
Gasoline	660[3]	2,400	3,060	93±9[4]

Table 4 – Average GHG Emissions Based on Fuel Production and Use Phases

For ethanol production all the greenhouse gas emissions are attributed to the production phase since the amount of CO_2 released during combustion is assumed to be the amount absorbed during photosynthesis. For gasoline production and use the majority of emissions occur during the fuel-use phase, which is approximately 4 times higher than the production sector emissions.

The type of feedstock and how it's grown is a major factor in determining the associated GHG emissions. For example, ethanol produced from sugarcane in Brazil, emits 480 gCO_2-equ/L of ethanol produced not including any co-product credits associated with producing excess electricity from bagasse[5]. When compared to producing corn ethanol, that is an 80% decrease in GHG emissions. One reason for this is that Brazil's agricultural industry is labor intensive while the US agricultural industry is highly mechanized and therefore consumes more fossil fuels. This is one example of how the feedstock choice and the way in which it is grown can affect the energy use and GHG emission output.

When determining the amount of GHG emissions for different ethanol gasoline fuel blends, the following equation was applied, in which *E* represents emissions per unit

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[2] Average US passenger car fuel consumption rate, 27.5 mpg

[3] General Motors Corporation, Argonne National Lab, BP, ExxonMobil, Shell*: Well-to-Tank Energy Use and Greenhouse Gas Emissions of Transportation Fuel*, pg B-3, June 2001

[4] Assumed a 10% standard deviation and a normal distribution

[5] UNICAMP, *GHG Emissions in the Production & Use of Ethanol in Brazil: Present Situation (2002)*

volume. The percent ethanol and gasoline represent the amount of each fuel in the blend. As previously noted there are no emissions attributed to the ethanol-use phase. Fuel emission factors were taken from the DOE and EIA website[6].

$$Total\ Emissions = (E_{Ethanol\ production})(\%Ethanol) + (E_{Gasoline\ prooduction} + E_{Gasoline\,use})(\%Gasoline)$$

Using the above equation and the values in **Table 4**, **Figure 2** was created to compare the GHG emissions from different ethanol gasoline fuel blends with gasoline per km traveled. The results in **Figure 2** represent the same system boundary defined in the appendix and do not include co-product credits. Using the average gasoline GHG emission values in **Table 4** and assuming a 10% standard deviation, the gasoline probability distribution curve in **Figure 2** was generated.

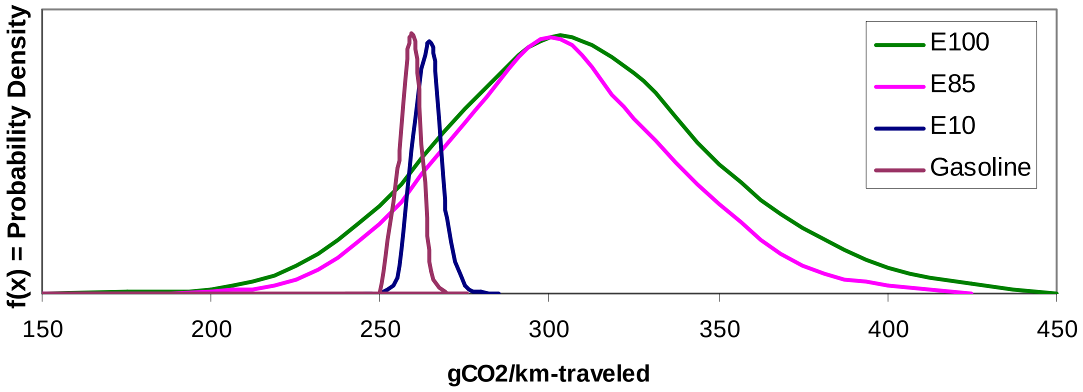

Figure 2 - GHG Emissions of Ethanol Gasoline Fuel Blends

The standard deviation increases with an increasing ethanol content which is represented by the wider gap curve. This is because there is larger variability in the ethanol input values. **Figure 2** shows that without co-product credits ethanol-gasoline-blended fuels do not reduce GHG emissions. This is because the GHGs are emitted during the ethanol production processes only and not the use phase and therefore are highly dependent on the system boundary being analyzed. Note of course, that a given amount of ethanol, whether used as E100 or blended, still displaces the same amount of gasoline on a volume basis.

Two additional conclusions can be made from **Figure 2**:

1. In low ethanol-blended fuels the GHG emissions are dominated by the use phase emissions, and
2. In high ethanol-blended fuels the GHG emissions are dominated by the production phase emissions

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[6] U.S DOE/EIA, *Instructions for Form 1605: Voluntary Reporting of Greenhouse Gases, 1998, Appendix B*

The results so far have not included co-product credits because it is important to understand what the fossil energy consumption and GHG emissions are without including a major assumption of energy and emission displacement. It is not clear, nor has it been demonstrated, that co-products produced from ethanol production are a replacement product. If ethanol production and use clearly displaced fossil energy consumption and GHG emissions, even without co-product credits, this would not be of much concern, but based on the previously shown results this is not the case. Therefore, careful understanding and application of co-product credits must be done to accurately represent what is happening in the market. The following figures examine the impacts on energy consumption and GHG emissions when co-product credits are considered.

When considering the GHG benefits of using ethanol, co-product credits for animal feed production are often given. There are different methods for applying these credits so two cases were considered. First, the displacement method, which assumes a 20% co-product credit and second, the process energy method that allows for a 40% co-product credit[7]. These two scenarios represent the most conservative and aggressive methods used, respectively**.** **Figure 3** and **Figure 4** show the GHG emissions for different ethanol gasoline blends for an assumed 20% and 40% co-product credit, respectively.

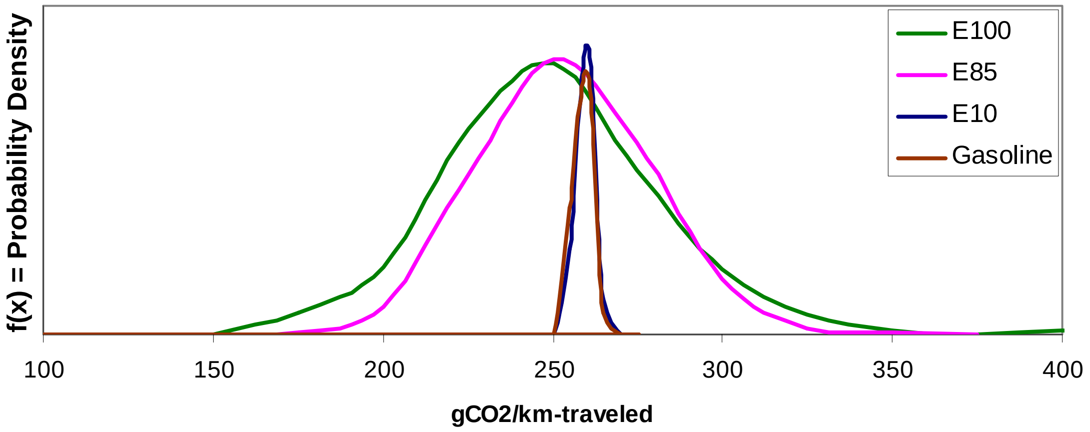

Figure 3 - GHG Emissions of Ethanol Gasoline Fuel Blends, with a 20% Co-Product Credit

As the percentage of co-products credits increases the higher ethanol-blended fuels shift to the left and have a GHG benefit when compared to gasoline for both scenarios. **Table 5** summarizes the results shown in Figures 3-5. When no co-product credits are used the different ethanol blends emit more GHG's when compared to gasoline. As co-product credits are apportioned, ethanol-blended fuels show a reduction in GHG emissions when compared to gasoline.

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[7] Wang, Michael. "Updated Energy and GHG Results for Fuel Ethanol", 2005.

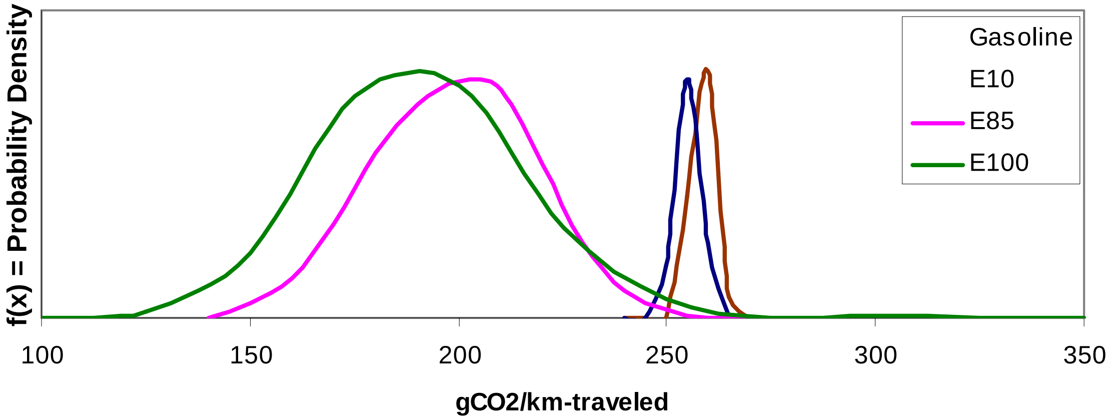

Figure 4 - GHG Emissions of Ethanol Gasoline Fuel Blends, with a 40% Co-Product Credit

Corn Ethanol GHG Emissions Compared to Gasoline (gCO_2/km-traveled)			
	No Co-Product Credits	**20% Co-Product Credits**	**40% Co-Product Credits**
E10	+2%	0%	-2%
E85	+20%	-4%	-23%
E100	+23%	-4.5%	-30%

Table 5 – Corn Ethanol GHG Emissions Compared to Gasoline

The previous results have shown that the amount of GHG savings for ethanol fuel blends is highly dependent on the system boundary and the assumed co-product credits. An additional factor that affects these results is the effect of geographic variation on input parameters within the agricultural and corn transport sector. The current analysis applies to the state of Iowa, which is the top corn-producing state in the United States. As the ethanol market continues to grow, corn from different parts of the US will be used as a feedstock for additional ethanol production. Therefore, as one considers different states and regions within the US, the input parameters such as, yield, fertilizer application, and irrigation will vary, and this can affect the energy ratio and GHG savings.

Figure 5 shows the fossil energy inputs per liter of ethanol produced, on a higher heating-value basis, where the higher heating value of ethanol is 23 MJ/liter. Values for the specific inputs are state specific, but this still represents the same system boundary defined in the appendix and with no co-product credits. While Iowa is the top corn-producing state, Nebraska and Georgia represent the 3rd and 26th corn-producing states respectively. **Figure 5** demonstrates that corn produced in Georgia, a potential area for the expansion of corn production, requires 35% more fossil energy. For this case there is not the same net energy benefit as corn grown in Iowa, which can be seen as the best-case scenario.

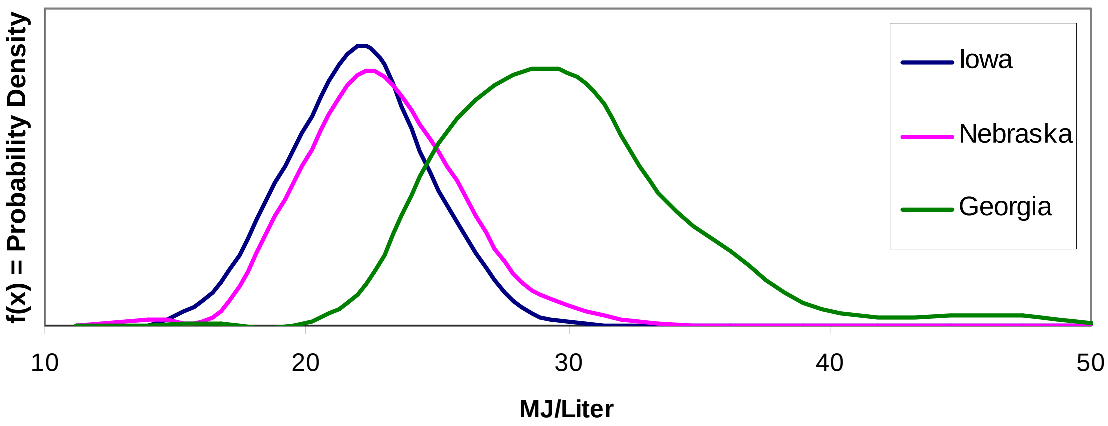

Figure 5- Total Ethanol Production Energy per Liter by State

Figure 6 shows the GHG emissions for the same set of assumptions and inputs values for these three states. The same trend is obviously seen as GHG emissions correlate to energy use. Gasoline GHG emissions for comparison is 90 gCO_2/MJ which corresponds to the Iowa average GHG emission result. One example of an input parameter difference between the states that has a major impact is fertilizer application. States with lower soil quality, such as Georgia, require more fertilizer per acre, which is the highest energy and GHG emission agricultural input. **Figure 6** shows that without considering co-product credits, whether corn is taken from another state or whether corn production is expanded to another state that is less energy efficient at producing corn, their GHG emissions increase. This increase can easily reach a point at which ethanol production emissions are greater than current gasoline emissions, even when including co-product credits. Co-product credits provide the opportunity to reduce this effect but the benefits are sensitive to the type of allocation method assumed. **Figure 5 and 6** both show how geographic variation affects the net energy input and GHG emissions when producing ethanol, and therefore location needs to be considered when determining the potential impacts of corn ethanol production and use.

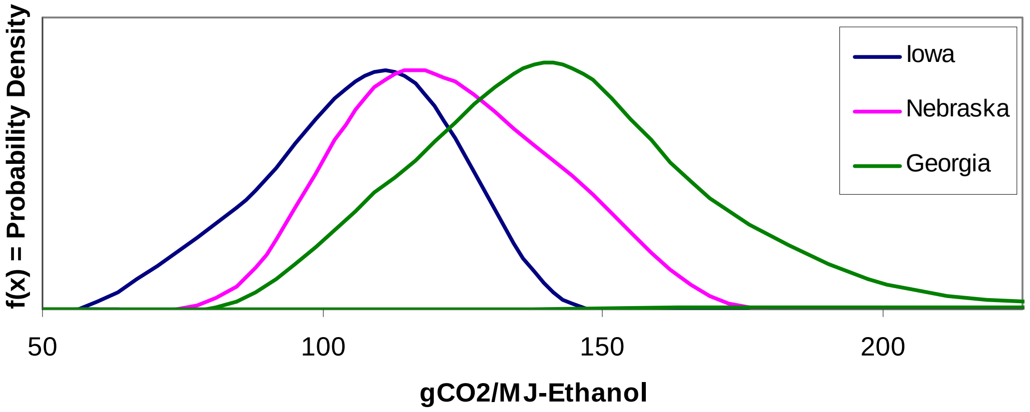

Figure 6 - System GHG Emissions by State

A caution with allocating co-product credits is that it assumes, regardless of the allocation method, that the co-product is displacing a good that is already in the market place and therefore displacing the amount of fossil fuel consumed and GHG emissions released during its production. This is a bold assumption, as it is often not known what effect a new replacement product may have on the market it enters. It may replace current production or it may over saturate the market and drive prices down and thus not displace fossil fuel consumption or greenhouse gas emissions. To date, corn-based ethanol does not present a clear environmental benefit without allocating co-product credits, and therefore the certainty that those credits are warranted and are correctly accounted for is key for truly making this a green fuel alternative.

Question Summary

1. To what extent will corn-based ethanol displace petroleum?

   Producing ethanol from corn consumes 0.03 gallons of petroleum during ethanol production when the oil consumed during electricity generation is included. On an energy basis l gallon of ethanol is equivalent to 0.7 gallons of gasoline. Therefore, over its life cycle 1 gallon of ethanol displaces 0.67 gallons of petroleum, assuming the in-use efficiency is the same.

2. As natural gas use and its importation are projected to grow, what amount of natural gas is used during ethanol production?

   Natural gas consumption represents 66% of the total corn ethanol production energy, when the electric production efficiency (32%) and US energy fuel portfolio are included. Therefore, as ethanol production continues to rise the demand for natural gas will also increase. This could become a national security issue if natural gas imports continue to rise as well.

3. What are the overall carbon emission benefits of corn-based ethanol compared to gasoline?

   If co-product credits are not included, using ethanol does not show any significant GHG emission benefit. When looking at ethanol gasoline fuel blends on a per-km-traveled basis, GHG emissions increase with fuel ethanol percentage above conventional gasoline GHG emissions. Only when co-product credits are considered does corn ethanol begin to see GHG benefits on an energy equivalent basis compared to gasoline. On a volume basis, for a given amount of ethanol the same amount of gasoline is displaced regardless of how it is blended.

4. How do geographic and climate variations affect the fossil energy consumption and GHG emission results?

   As corn ethanol production continues to grow, corn will either be grown by other states or corn production will increase in places that have available land. The agricultural production energy that is needed to grow corn is highly dependent on the geographic location and climate. Therefore, as areas with lower yield and higher agricultural inputs are utilized the fossil energy requirements will increase as well as GHG emissions.

Conclusion

As policy is made mandating ethanol production and use, estimating current and near-term energy and environmental impacts of corn ethanol in the US is necessary. Corn ethanol, while a not achieving significant GHG savings compared to gasoline, can be seen as a stepping stone to ethanol produced from cellulose. While ethanol produced from cellulose is not yet commercially available, energy and GHG savings have been projected.

The next phase of this research will examine the potential production scale of corn ethanol production, and its impacts on energy use and GHG emissions. The energy and GHG emissions associated with the production of ethanol from cellulosic sources will also be analyzed. This research will also examine and geographically categorize how location and climate can affect both the energy requirement in the agricultural and processing sectors and their respective GHG emissions.

Future Work

This same Monte Carlo approach has been applied to cellulosic ethanol production from switchgrass in the US. Fossil energy use, GHG emissions, petroleum displacement, natural gas consumption, and geographic variation models have been created and analyzed. An additional report or paper summarizing these models and results will be available by mid to late January 2007.

Please contact Tiffany Groode at tgroode@mit.edu for further questions[8]

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[8] This research is sponsored by BP but does not reflect the position or policy of BP

Appendix

System Boundary

This section describes the system boundary that was used in this analysis. Items such as building infrastructure, human labor, and machinery production energy were not included as these quantities are uncertain and relatively small when their long lifetimes are taken into account. The conclusions drawn from this analysis are applicable to current and near-term corn ethanol production in the Midwest portion of the US, as mainly Iowa data from the USDA databases was used.

Agricultural sector includes:

1. Corn seed production
2. Nitrogen, phosphate, and potash fertilizer production and application
3. Lime production and application
4. Herbicide and insecticide production and application
5. Farm machinery fuel consumption

Corn transport sector includes:

1. Diesel fuel consumption assuming a 100-mile roundtrip from the corn storage station to the ethanol-processing plant

Ethanol-processing sector includes:

1. Natural gas and electricity inputs to convert corn to ethanol
2. An ethanol yield of 2.5 gal of ethanol per bushel of corn was assumed
3. Enzyme, chemical, and yeast production energy were excluded

Data Sets

USDA and ERS agricultural data sets from 1995-2004 were used to characterize variables such as yield, fertilizer application, and farm machinery fuel consumption for the state of Iowa, the highest corn-producing state. The ethanol-processing energy distributions were created using reported plant natural gas and electricity consumption values in *USDA's 2002 Ethanol Cost-of-Production Survey*, July 2005.

System Greenhouse Gas Emissions

Greenhouse gas emissions were calculated for all energy flows considered within the system boundary. Nitrous oxide emissions associated with fertilizer use also included within the GHG calculation. Fossil fuel emission factors were taken from the DOE and EIA website. The electricity generation energy portfolio of the US was used to determine the fuel energy use and GHG emissions associated with purchased electricity.

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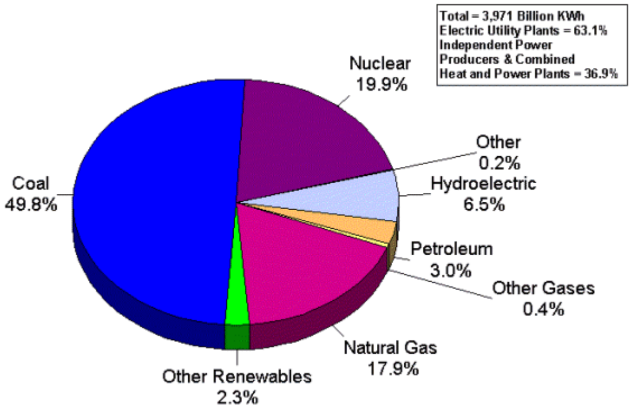
Figure 1-A describes the US Electricity Energy Portfolio in 2004. These energy percentages were used to determine the amount of natural gas and petroleum that was consumed during the corn ethanol production processes due to electricity consumption.



Note: Conventional hydroelectric power and hydroelectric pumped storage facility production minus energy used for pumping.

Figure 1-A – US Electricity Generation Energy Portfolio

Source - www.eia.doe.gov/cnef