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Feasibility, economics, and environmental impact of producing 90 billion gallons of ethanol per year by 2030

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Abstract –This paper addresses a national interest in investigating the potential of displacing a large fraction of U.S. gasoline use by 2030 with ethanol. This study assesses the feasibility, implications, limitations, and enablers of producing 90 billion gallons ethanol per year by 2030. We developed a dynamic supply chain model, the Biofuels Deployment Model (BDM), and conducted sensitivity analyses to determine the parameters that most affect the feasibility, cost-competitiveness, and greenhouse gas impact of large-scale ethanol production. Though we found no theoretical barriers to achieving the stated goal, we identified a number of practical obstacles that need to be addressed. In particular, investment in cellulosic ethanol production needs long-term protection against oil and feedstock price volatility. Capital costs are significant, and investment risk needs to be managed. Technology improvements, particularly in cellulosic conversion yields, are critical and must be sustained over a number of years. Finally, large-scale development of energy crops is necessary.

Keywords: cellulose, supply chain, system dynamics, sensitivity analysis, biofuels.

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Introduction

Biofuels have been proposed as an alternative transportation fuel that has the potential to increase energy security, improve the environmental footprint of transportation, and help fill the increasing global need for fuel. Ethanol is the focus of this study not because we necessarily believe it to be the best alternative fuel option, but because it is a prominent option that is developed enough for analysis. Ethanol is of particular interest not only because it has a foothold in the current transportation fuels market as corn-based ethanol, but also because cellulose-based ethanol has significant long-term potential. There has been national interest in investigating the potential of ethanol to replace 30% of present U.S. light duty vehicle energy use by 2030, amounting to approximately 60 billion gallons of ethanol (EIA, 2009). This study assesses the feasibility, implications, limitations, and enablers of greatly exceeding this target to produce and deliver 90 billion gallons of ethanol (equivalent to ~60 billion gallons of gasoline per year) by 2030. Previous studies have addressed the potential of biomass (Perlack et al., 2005) or the energy and environmental impact of biofuels (Farrell et al., 2006) (Hammerschlag, 2006) (Hedegaard et al., 2008) (von Blottnitz and Curran, 2007) but not the supply chain rollout needed to achieve ethanol production targets; therefore, the focus of this study was the evolution of the supply chain over time. The supply chain components included in this study were land use changes for feedstock production, production of biomass feedstocks, storage and transportation of these feedstocks, conversion of feedstocks to ethanol at biorefineries, transportation of ethanol, blending with gasoline, and distribution to retail outlets.

This feasibility study addresses three basic questions: i) Is it feasible to achieve a 90 billion gallon production volume, considering land use and availability, cost of capital required, and logistics challenges and constraints associated with this level of production? ii) What factors affect the cost-competitiveness of cellulosic ethanol with gasoline? iii) What are the greenhouse gas and energy footprints associated with this level of ethanol production? In addition, we identified potential risks that impact cellulosic ethanol's production and competitiveness goals. A companion study addressing the water impact of large-scale ethanol production is to be published separately (Tidwell et al., in preparation).

Methods

Tools

We used a range of data sources and analysis tools to address the main questions. In particular, we developed a 'Seed to Station' system dynamics model (Biofuels Deployment Model – BDM) to explore the feasibility of any given production level of ethanol (Malczynski et al., 2009). The primary purpose of the model is to understand how certain variables affect the cost and volume of ethanol production from biomass sources and to identify needed resources. The model also allows one to understand how some of these variables interact. The model has no predictive capability because it is based on cost minimization, and markets that make enormous impacts on cost (for example, energy markets or the markets for construction materials) are not modeled. Rather than having predictive capacity, given specific (and uncertain) assumptions, the model allows a study of variable sensitivity, providing a better understanding of the forces at work in the development of a national bioethanol production capability.

BDM models the evolution over time of the complete ethanol supply chain, tracking thousands of variables and their evolution from 2006 to 2030. However, the output metrics of primary interest for this paper are feedstock and ethanol volumes, costs, and greenhouse gas emissions. Given an exogenous (i.e., specified externally to the model) demand for ethanol production rising from current levels to 90 billion gallons in 2030, the BDM dynamically calculates the associated land use changes, volumes and costs of feedstock production and logistics, build-up of conversion plants, volumes and costs of ethanol production and distribution, greenhouse gas emissions, energy use, and water use. Our baseline analysis includes production of cellulosic ethanol from residues and energy crops from 2006 to 2030; corn ethanol is limited to 15 billion gallons per year, but growth in cellulosic ethanol production is accelerated beyond 2007 legislation (EISA, 2007) to enable 90 billion gallons per year by 2030.

Data Acquisition and Model Inputs

The land use data for this project originated from the United States Department of Agriculture's (USDA) Economic Research Service. We assume that all idle land is available, some fraction of which is conservation reserve program land. Crop land as pasture is also available. No land currently used in crop production is available for cellulosic feedstock production, and corn for ethanol was capped at production levels needed for 15 billion gallons per year. Short rotation woody crops were restricted to a maximum of 15% of non-grazed forest land (including private and government-owned lands). Agricultural residues available were limited to a 35% recovery of corn stover and wheat straw.

Crop characteristics data, including state-by-state crop yields, availabilities, and projected yield improvements were obtained from available historical data, literature reports, and exchanges with subject matter experts. (Perrin et al., 2008) (USDA, 2006)

(USDA, 2007) (Perlack, 2008) (Perlack et al., 2005) (NBP, 2007) (USDA, 2008) Crop costs were estimated from recent reports and discussions with industry (Foreman, 2006) (Perez-Verdin et al., 2007) (Walsh and Becker, 1996) (Brechbill and Tyner, 2008) (Ceres, 2008).

Feedstock-to-ethanol conversion data were estimated from a combination of recent studies (Aden et al., 2002) (Phillips et al., 2007) (Tiffany and Eidman, 2003) (Hsu, 2008), discussions with industry (Mascoma, 2008) (POET, 2008) (Coskata, 2008) and calculations of theoretical ranges. Capital costs were similarly estimated from a combination of recent reports (NREL, 2008) (IEA, 2008) (OPEC, 2007) (PennWell, 2008) and discussions with industry (Mascoma, 2008) (POET, 2008) (Coskata, 2008).

Estimates of transportation and distribution costs and energy use were derived from recent studies (Searcy et al., 2007) (Jenkins et al., 2008) (Brechbill and Tyner, 2008), data (BNSF, 2008), and a linear programming distribution optimization model exogenous to the BDM. Note that ethanol costs were calculated based on estimated costs of production, transportation, or conversion at each step of the supply chain, with anticipated minimum rates of return incorporated into the costs. The price of ethanol, which would be affected by supply and demand, was not calculated.

Estimates of greenhouse gas emissions and emissions factors were derived from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model (Wang, 2008) for the fuels, fertilizers, herbicides, and pesticides used in all steps of the supply chain. For this study, we did not consider the emissions due to land use changes, as this is still widely debated in the literature. We also did not account for any uptake by the plants during feedstock production nor consider the emissions in the combustion of the fuel, as these would have a nearly zero net effect. The emissions estimates for gasoline and ethanol at each stage, as used in the sensitivity analysis described below, are shown in Figure 1.

Key model input values are found in Table 1.

Sensitivity analysis methods and approach

A reference case was defined using baseline values for input parameters, and sensitivity analyses relative to the reference case were carried out to determine the influence of key input parameters on the time-dependent behavior of the system. Such knowledge is important for at least two distinct reasons. First, a parameter that is known to have a strong effect on the results is a potential lever that can be adjusted to achieve a desired outcome. Secondly, the extent to which results are reliable depends on how precisely the parameters are known; hence, the sensitivity analysis is a method for targeting those parameters that require fine-tuning.

The analysis was conducted for three principal metrics: (a) the total ethanol production volume in the final year of the simulation (2030); (b) the accumulated cost difference between the ethanol produced over the life of the simulation and the gasoline that it replaced; and (c) the difference between the GHG emissions associated with ethanol production over the life of the simulation and those associated with the displaced gasoline. These were deemed to be reasonable measures of the overall success of a gasoline replacement program. In addition, because corn ethanol technology is relatively well established but that for cellulosic ethanol is not, a cellulosic cost difference metric was defined as the accumulated cost difference between cellulosic ethanol produced over the life of the simulation and the gasoline that it replaces. To capture measures of temporal performance (which could create an insurmountable bottleneck) of the emerging cellulosic ethanol industry, a crossover year metric was defined as the year in which cellulosic ethanol became less expensive than gasoline. These secondary metrics were not used in the screening activities to be discussed below, but they were used in parameter studies.

From the entire list of input parameters to the model, three subsets were constructed, each consisting of those parameters that were thought to be potentially important in influencing model behavior in one of the three primary metrics.

The next step, denoted as importance screening, was designed to provide a further down-selection of parameters in the three topical areas. First and second-order sensitivity coefficients for each parameter, relative to the appropriate primary metric, were calculated. The calculation was done by computing values for the metric at both the baseline parameter value and at values equally spaced above and below the baseline, followed by a spreadsheet-based computation of the first two coefficients in a Taylor series expansion about the baseline. In order to allow comparisons involving different metrics and different parameters, each sensitivity coefficient was nondimensionalized with the appropriate baseline values. When these computations were completed, those parameters not showing a significant value for either the first- or second-order sensitivity coefficient were excluded from further consideration.

Note that for the production volume metric only, the target value for cellulosic ethanol production was set to near infinity, rather than the reference value, for every year from 2006 onward for the sensitivity analysis. This was done in order to assess the effect on production in the absence of artificial constraints, which would otherwise obscure the true sensitivities.

The next step, denoted as interaction screening, was applied to the parameters remaining after the importance screening to determine the sensitivity coefficients more accurately and to assess the interactions between parameters. In this case, a Monte Carlo approach was used to generate values of the metric at a large number of points covering the entire range of interest of a given parameter. Just as importantly, all of the parameters from the importance screening associated with a given metric were varied simultaneously in order to allow determination of interactions; for practical reasons, however, the interaction coefficients were limited to those of lowest (i.e., second) order. The processing of the Monte Carlo results was performed by a Fortran program that used a least-squares method to find the best fit to the "data" in terms of a second-order multiparameter Taylor series expansion about the default vector. Examination of all of the results from these analyses resulted in a final reduction of the parameter list for detailed analysis.

In the last step, each of the remaining parameters (or combinations thereof) was varied systematically over its entire range in order to ascertain its detailed influence on the metric in question. These calculations were similar to those in the previous step, but the goal was to graphically see the behavior, especially nonlinear behavior or anomalies occurring away from the reference point.

Results

Reference case

The reference case was used as a baseline in the screening activities and as a basis for more detailed analyses. As shown in Figure 2, this case achieves the 90 billion gallons of ethanol annual production target in 2030 using less than 800 million dry tons of cellulosic feedstock in that year. The feedstock choice is determined by feedstock availability and least cost of ethanol production. Costs are driven by feedstock production yields, conversion yields, and conversion costs. For this reference case, cellulosic ethanol is not cost-competitive with gasoline at crude oil prices below $90/barrel. The greenhouse gas savings for the reference case (Figure 2) are approximately 400 million tonnes CO2 equivalent/year for 90 billion gallons of ethanol—approximately the equivalent of 25% of emissions from the current fleet of gasoline vehicles or of 87 coal-fired power plants (EPA). The cumulative greenhouse gas savings for the reference case from 2006 to 2030 are 3.46 billion tonnes CO2 equivalent.

Capital required for the ethanol supply chain for 90 billion gallons/year (equivalent to 60 billion gallons/year gasoline) for the period from 2006 to 2030 is estimated to be $390 B, dominated by the cost of 630 added cellulosic biorefineries. As shown in Figure 3, this averages out to approximately $5/gallon of annual production capacity of cellulosic ethanol. Capital required for 25 years of sustained new production of petroleum in the Gulf of Mexico is estimated to be roughly $6 per gallon of ethanol equivalent of production capacity.

Ethanol production volume

The sensitivity analysis for the ethanol production volume showed conversion yield as the key parameter influencing this metric. Availability of short rotation woody crops also had a significant impact on the production volume. The interaction of these two parameters also emerged as significant from the interaction screening. The combined impact of feedstock availability and conversion yield on ethanol production was further investigated by using a low, reference, and high conversion yield for three cases: when all feedstocks are available, when short rotation woody crops are not available, and when no energy crops at all are available (Table 2.) When all feedstocks are available, the 90 billion gallons/year target is met for all values of overall conversion yield over the range of 74 gallons/dry ton to 115 gallons/dry ton. Figure 4 shows the conversion yield sensitivity graphically, plotted with the maximum available feedstock for the three studied cases. However, at the bottom of the conversion yield range, the required harvest amount approaches one billion tons per year (Figure 4). When short rotation woody crops are not available, ethanol production volume is limited to less than the 90 billion gallons/year target—70 billion gallons/year (55 billion gallons/year cellulosic ethanol + 15 billion gallons/year corn ethanol) at the reference case conversion yield. If no energy crops are available, i.e., only agricultural and forest residues can be used for cellulosic ethanol production, then we estimate the production volume at the reference case conversion yield to be 30 billion gallons/year of cellulosic ethanol (45 billion gallons/year total ethanol production), which meets only half of the 90 billion gallons/year target.

Cost-competitiveness of ethanol with gasoline

Sensitivity analyses were conducted to explore not only the parameter space in which cellulosic ethanol is cost-competitive with gasoline, but also the sensitivity of its cost-competitiveness to key parameters. For all of these calculations, the 2030 production volume target was 90 billion gallons of ethanol (15 billion gallons from corn starch, 75 billion gallons from cellulose.)

Importance and interaction screenings conducted using the cost difference metric demonstrated that energy input prices have the largest effect on the cost-competitiveness of ethanol; increases in conversion yield and reductions in capital and feedstock costs lower ethanol costs and thus improve the cost metric. The price of energy was implemented as a meta-parameter, an energy price multiplier being uniformly applied to the baseline prices of crude oil, natural gas, LPG, and electricity. For ease of visualization, the corresponding price of crude oil will be used as a proxy for the meta-parameter of energy price in the graphs presented.

Though energy prices were varied uniformly as a single meta-parameter, the price of crude oil is the most influential of the energy prices to the cost-competitiveness of cellulosic ethanol relative to gasoline. Any cost savings due to cellulosic ethanol replacing gasoline are eliminated if the price of crude oil drops below approximately $90/barrel.

The capital costs involved in the construction of cellulosic ethanol plants are uncertain, but current costs are estimated to be as high as $7 per gallon of annual capacity of ethanol. Construction costs two decades from now are unknown. Corn ethanol plants use a mature technology and require approximately $2 in capital per gallon of annual capacity of ethanol. Varying the conversion capital costs over the range of $2-$7/ gallon capacity results in a $0.60/gallon ethanol change in the overall fuel cost. Our reference case, which results in an average cellulosic conversion capital cost of $3.45/ gallon of annual ethanol capacity, assumes significant technology and engineering improvements.

As expected, increases in the conversion yield improve cost metrics. As a point of reference, corn grain ethanol yields average approximately 90 gallons/ton. The theoretical biochemical yield from cellulose and hemicellulose is 172.5 gallons/dry ton, while the maximum yield from the thermochemical process is 206 gallons/dry ton. However, the practical maximum yields for conversion processes using cellulose are estimated to be 120 gallons/dry ton, due to losses from non-converted feedstock material and external energy inputs. There are no data on production-scale cellulosic processes, as there are no such processes in existence, but the current estimates based on laboratory yields are in the range of 63-72 gallons/dry ton (Hsu, 2008). Our reference case has an overall average yield (2006-2030) of 95 gallons/dry ton and thus assumes significant technical advances over time. Sensitivity analysis showed that the cost difference between achieving a moderate improvement of yield (75 gallons/dry ton) and achieving the maximum practical yield corresponds to approximately a $0.20/gallon impact on cost of ethanol.

The rate at which the conversion yields improve also has an effect on cost-competitiveness. In our model, conversion yields have an initial and final (mature) value. In the reference case, conversion yields mature in 2020. However, delaying the maturity of conversion yield has an impact on cost-competitiveness of cellulosic ethanol. As measured by the cellulosic cost difference metric, a delay of five years is estimated to reduce the accumulated cost savings by 9%, and a delay of ten years is estimated to reduce the accumulated cost savings by 24% from the reference case.

The cost to purchase and deliver feedstock can also significantly change the calculated cost to produce cellulosic ethanol. The reference case has an average feedstock cost of $43/dry ton. Variations of 50% to 200% of the reference value were tested, and they produced a nearly $0.70/gallon variation in final ethanol cost. At 200% of the reference value, the feedstock cost approaches $90/dry ton, higher than most current feedstock costs.

The best and worst case scenarios for conversion yield, feedstock cost, and capital costs can be combined to illustrate the range of ethanol costs and the sensitivity to input energy prices, as shown in Figure 5. At $100/barrel oil, the best case scenarios produce a 50 cents/gallon ethanol savings over the reference case ($1.20/gallon vs. $1.70/gallon of ethanol). The worst case scenario is cost-competitive with gasoline only when oil is more than $165/barrel.

Multi-parameter Monte Carlo analysis was used to investigate the temporal sensitivity of cost to four key parameters via the crossover year metric. Energy price and feedstock cost were varied using low, reference, and high values for conversion yield and capital costs. The results were binned into 3 groups: conditions that lead to crossover within 5 years (prior to 2014), crossover between 5 and 15 years (2014-2024), and crossover after 15 years (after 2024). Figure 6 shows that capital costs have a much larger effect on the crossover year than does conversion yield. At low capital costs, cellulosic ethanol is cost-competitive with gasoline at reference values for energy prices and feedstock cost. Conversion yield has little effect on the crossover year at low capital costs. At high capital costs, energy prices need to be higher than those of the reference case to produce cost competitive ethanol within 15 years. Conversion yields do affect the metric at high capital costs, with a wider range of energy prices and feedstock costs that produce a crossover within 15 years.

Greenhouse Gas Emissions

Sensitivity analysis showed that the GHG savings metric is most sensitive to the overall conversion yield and the energy assumed to be generated at the conversion plants, with some interaction noted. Both of these directly affect the amount of energy used in conversion and therefore the total GHG emissions per gallon of ethanol. Increasing the conversion yield and increasing the boiler efficiency (which decreases the amount of energy generation needed) have the largest impact on ethanol GHG emissions savings relative to gasoline. An increase in overall conversion yield of 10 gallons/dry ton results in approximately a 3% increase in GHG emissions savings. A 6% change in the boiler efficiency results in similar GHG emissions savings from energy generation. Sensitivity analyses over a range of input values showed only modest effects on greenhouse gas emissions.

Discussion

The reference case reaches the 90 billion gallons of ethanol per year goal by 2030, and it can be cost-competitive with gasoline if the price of oil remains above $90/barrel. However, sensitivity analyses revealed that there are five conditions that need to be satisfied in order for 90 billion gallons of ethanol to be feasible. First, to reach production volumes, i) conversion technology must mature to maintain increases in conversion yields, and ii) feedstock from dedicated energy crops must be developed. In addition, to assure cost-competitiveness with gasoline, iii) ethanol prices must be protected against low oil prices and oil price volatility, iv) feedstock costs must remain low and stable, and v) capital costs must be manageable and investment risk mitigated.

Production volume was shown by the sensitivity analysis to be highly dependent upon conversion yield, which in turn affects the amount of biomass needed. The harvest amount at the minimum conversion yield studied here is equivalent to the biomass available under the most optimistic scenario in the report of Perlack et al (Perlack et al., 2005). However, the minimum conversion yield of 74 gallons/dry ton is above currently attainable yields (Hsu, 2008), so even the minimum conversion yield considered here will require technological improvement to occur. Significant reductions in feedstock availability (modeled here by removing short rotation woody crops or by removing all energy crops from the analysis) reduced ethanol production to below the 90 billion gallons/year target, even at a high conversion yield of 116 gallons/dry ton. Using current conversion yields would reduce these production volumes even further. Thus, conversion yield and feedstock availability drive the ability to reach large cellulosic ethanol production volume targets. Both of these parameters require significant development, over a period of time, to achieve the values considered in this study. Aggressive conversion technological improvement and rapid development of a cellulosic ethanol feedstock industry will be critical.

The most influential parameter in cellulosic ethanol's cost-competitiveness with gasoline is the price of energy, which is clearly a highly uncertain parameter. Of the primary energy prices, the price of crude oil is the most influential for cost-competitiveness; as the price of crude oil increases, cellulosic ethanol becomes more cost-competitive with gasoline. It is important to note that our simulation did not attempt to model the gasoline market price; the gasoline price was fixed during the simulation and was not impacted by the production of ethanol. However, it would be reasonable to assume that production of a significant volume of ethanol would put downward pressure on the price of gasoline and thereby negatively impact cost metrics. Also, the price of gasoline was fixed during the reference simulation, whereas current energy prices exhibit significant volatility.

Feedstock costs, conversion yield, and capital costs also play significant roles in the cost-competitiveness of ethanol with gasoline. The best case scenario studied here showed a 50 cents/gallon savings over the reference case ($100/barrel oil), but this scenario is not sufficient to make ethanol profitable at December 2008 gasoline prices. It cannot be overemphasized that the best case scenario parameters ($22/dry ton feedstock, 116 gallons/dry ton yield, $1.73/gallon capacity capital) are unlikely, especially in combination.

It is also important to note that ethanol will not be cost-competitive immediately. For any scenario there will be a number of years, during which the technology matures, when ethanol is more expensive to produce than gasoline. For ethanol to become viable, consideration must be given as to how to mitigate losses over a number of years and still sustain improvements in the industry.

For the GHG emissions calculated (ignoring land use changes), a key finding is that incremental changes to the current ethanol production processes result in only modest decreases in GHG emissions. Additionally, increases in corn ethanol production volumes result in only modest decreases in GHG emissions. In this study, the largest reduction in GHG emissions was achieved by increasing the volume of cellulosic ethanol produced. There is a limit, however, to the amount of cellulosic ethanol that could be produced without significantly changing the assumptions underlying the GHG emissions calculations (e.g., the amount of fertilizer needed for nutrient loss through removal of residues and the amount of energy required for transport, harvest, and processing) as sub-optimal lands are incorporated into cellulosic production.

There are significant risks involved in reaching a 90 billion gallons/year goal of ethanol production, in particular, volatility in oil and feedstock prices. These risks may negatively impact investment into development of a large-scale cellulosic ethanol industry if not mitigated. Potential policy options that warrant further investigation include well-planned market incentives and carbon pricing as well as federal investment in research and development and commercialization, especially when oil prices are low.

Conclusions

This study found that there are no theoretical barriers to reaching large volumes (~90 billion gallons/year) of ethanol production. However, there are practical barriers that need to be overcome, and a sustained effort over a period of time will be necessary to achieve large production goals. Sustained technology improvement in feedstock development and conversion technology is critical. Other practical considerations, such as capital availability and cost, are also significant.

Sensitivity analysis revealed that it is feasible for cellulosic ethanol to be cost competitive with gasoline if oil prices are above approximately $90/barrel. Significant improvements in conversion yield and significant decreases in feedstock and capital costs can help make cellulosic ethanol more cost-competitive at lower oil prices. However, sustained low oil prices would make it difficult for cellulosic ethanol to be cost-competitive with gasoline without government support.

Greenhouse gas savings are relatively insensitive to the technology development changes modeled here.

This study addressed the feasibility of large-scale ethanol production; however, many options exist for diversification of transportation fuels. Further studies that similarly address the feasibility of other fuel options are needed to investigate the potential future of alternative transportation fuels.

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Table 1. Key Biofuel Deployment Model input parameters

Parameter	Units	Values	
Conversion Yields			
Biochemical (Ag residues)	E95 gallons/dry ton	58 (initial)	84 (final)
Biochemical (Herbaceous)	E95 gallons/dry ton	55 (initial)	84 (final)
Thermochemical	E95 gallons/dry ton	74 (initial)	106 (final)
BioThermal	E95 gallons/dry ton	100 (initial)	117 (final)
Corn	E100 gallons/bushel	2.68 (initial)	3.00 (final)
Capital for conversion plant			
Biochemical	$/gallon	6.16 (intial)	3.3 (final)
Thermochemical	$/gallon	6 (initial)	4 (final)
BioThermal	$/gallon	5 (initial)	3 (final)
Corn	$/gallon	1.5 (initial)	2.0 (final)
Annual capacity per cellulosic plant	million gallons/year	30 (start)	150 (final)
Energy Prices			
Annual Average Oil Price	$/barrel	actual (2006-2007)	100 (2008+)
Annual Average Natural Gas Price	$/thousand cubic ft	actual (2006-2007)	8.61 (2008+)
Annual Average Electricity Price	$/KWh	actual (2006-2007)	0.0643 (2008+)
Annual Average LPG Price	$/gallon	actual (2006-2007)	2.38 (2008+)
Feedstock Yield Improvements			
Corn	%/year	1.5	
Ag Residue	%/year	0 - 1.5	
Herbaceous	%/year	3	
Short Rotation Woody Crops	%/year	1.5	
Forest Residue	%/year	0	

Table 2: Maximum annual cellulosic ethanol production in billion gallons per year (BGY)

	Low yield (74 gallons/dry ton)	Reference case (95 gallons/dry ton)	High yield (116 gallons/dry ton)
All feedstocks available (agricultural & forest residues, herbaceous energy crops, and woody crops)	>75 BGY	>75 BGY	>75 BGY
No short rotation woody crops (agricultural & forest residues and herbaceous energy crops)	38 BGY	55 BGY	67 BGY
No energy crops (agricultural & forest residues)	21 BGY	30 BGY	37 BGY

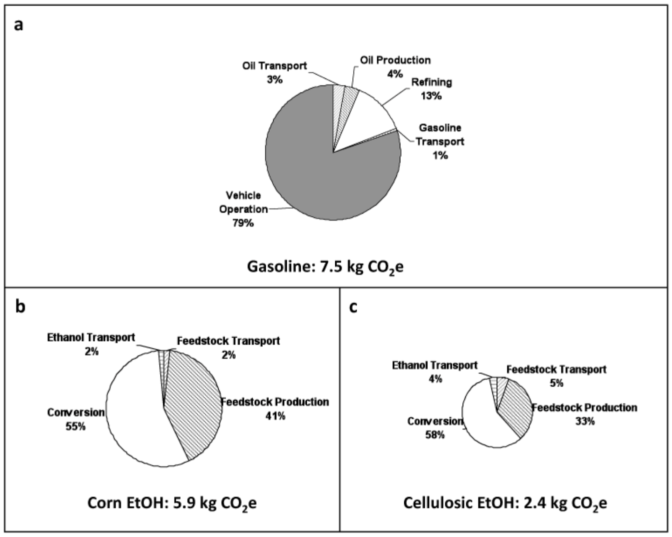

Figure 1. GHG emissions estimates per gasoline-equivalent gallon for a) gasoline, b) corn ethanol, and c) cellulosic ethanol. GHG emissions for cellulosic ethanol are estimated to be less than that for corn ethanol. GHG emissions for corn ethanol are estimated to be less than that for gasoline.

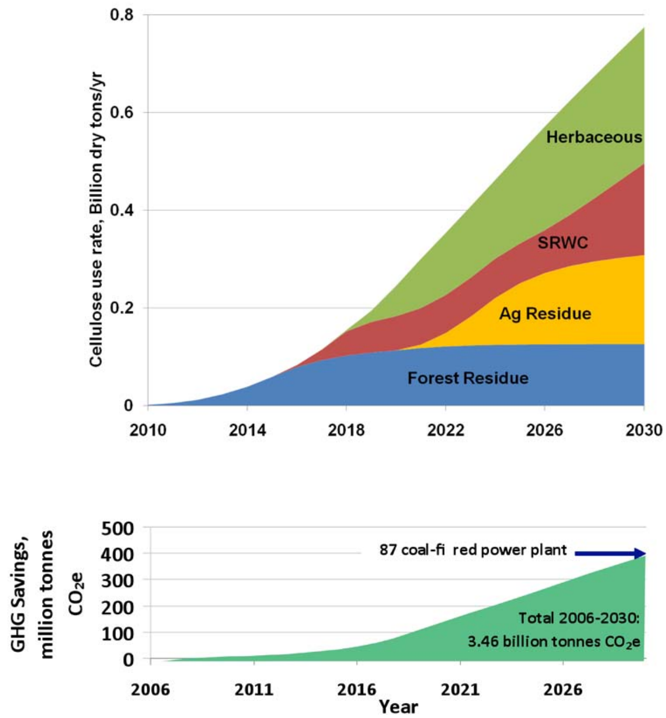

Figure 2. Reference case: Biomass used to produce 90 billion gallons of ethanol in 2030 and the associated GHG savings due to displacement of gasoline by this amount of ethanol. The feedstock used is determined by feedstock availability and cost considerations. Costs are driven by feedstock production yields, conversion yields, and conversion costs.

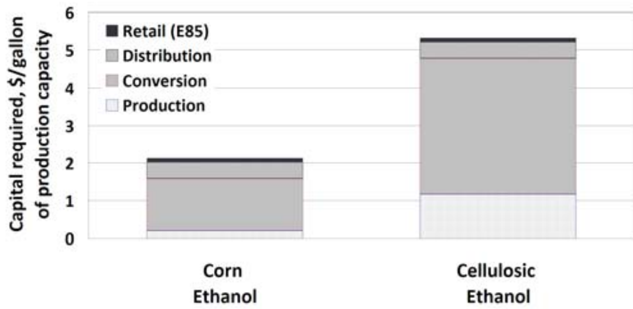

Figure 3. Capital investments required for new production of fuel, per additional gallon of production capacity of corn ethanol and cellulosic ethanol. Capital investment is averaged for 2006-2030. The capital investment required for cellulosic ethanol in this time is more than double that for corn.

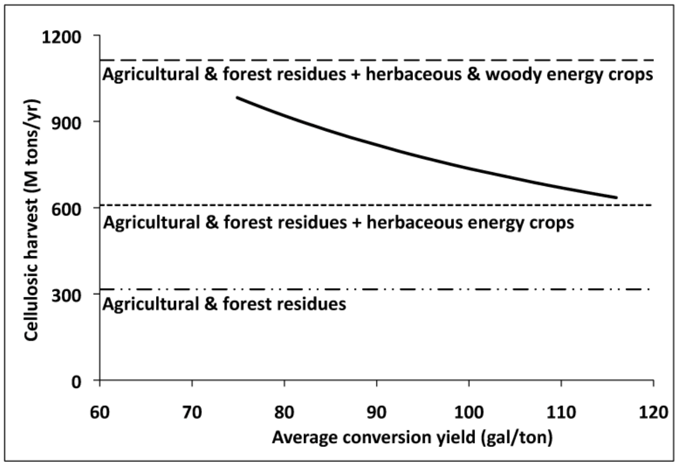

Figure 4: Cellulosic harvest requirement for production of 90 billion gallons per year of ethanol (75 billion gallons per year of cellulosic ethanol) as a function of conversion yield. Dashed lines represent feedstock availability for three scenarios considered. Biomass required decreases as conversion yield increases. Both residues and both energy crops considered are needed to reach production of 75 billion gallons per year of cellulosic ethanol.

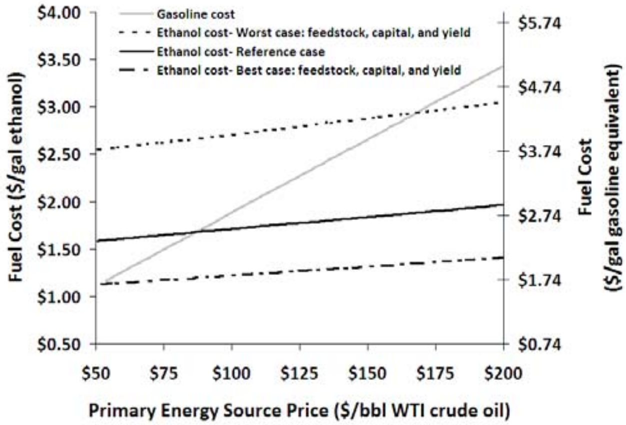

Figure 5. Effect of energy price on ethanol cost for best, reference, and worst cases of feedstock costs, capital costs, and conversion yield. Note that energy costs were uniformly varied as a single meta-parameter but that price of crude oil is used as a proxy for ease of visualization. For the reference case, ethanol is only cost-competitive with gasoline at oil prices lower than $90/barrel.

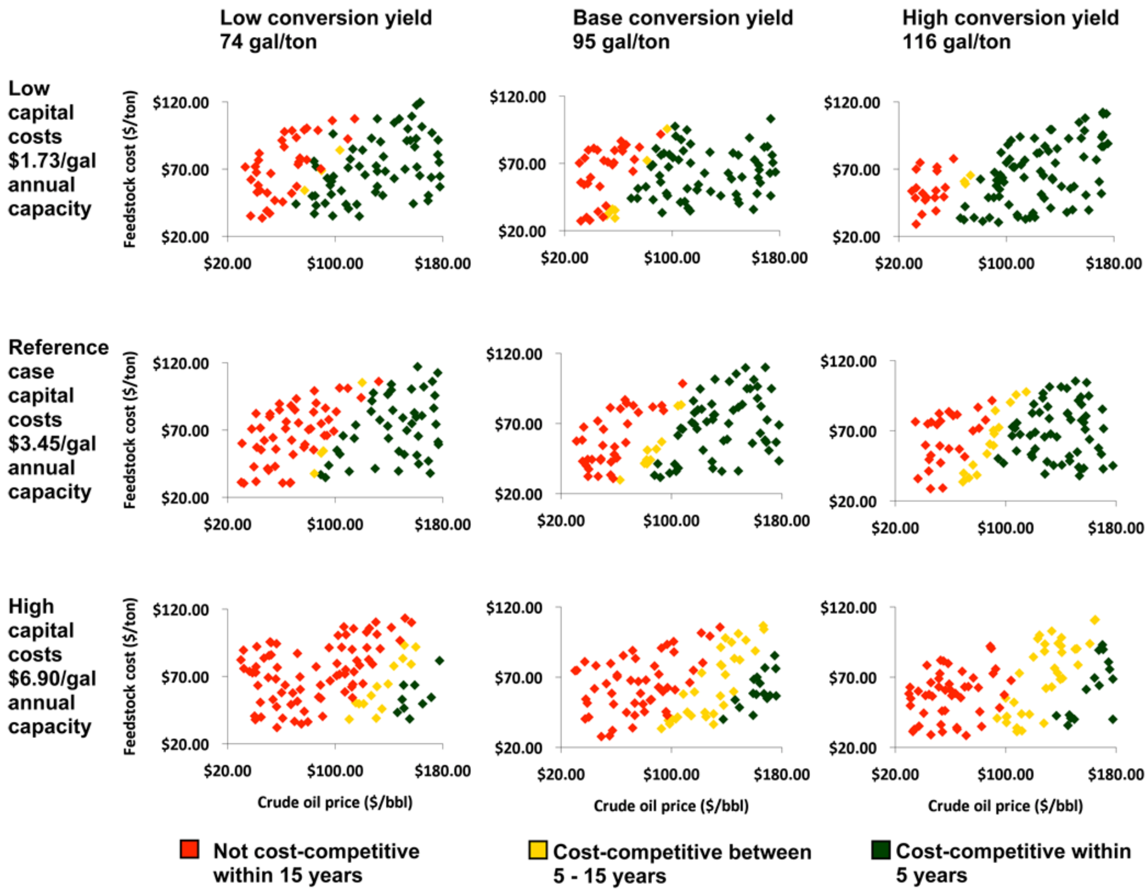

Figure 6. Speed at which ethanol becomes cost-competitive with gasoline as a function of conversion yield, capital cost, crude oil price, and feedstock cost.