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Alternative Liquid Fuels Simulation Model (AltSim)

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Abstract

The Alternative Liquid Fuels Simulation Model (AltSim) is a high-level dynamic simulation model which calculates and compares the production and end use costs, greenhouse gas emissions, and energy balances of several alternative liquid transportation fuels. These fuels include: corn ethanol, cellulosic ethanol from various feedstocks (switchgrass, corn stover, forest residue, and farmed trees), biodiesel, and diesels derived from natural gas (gas to liquid, or GTL), coal (coal to liquid, or CTL), and coal with biomass (CBTL). AltSim allows for comprehensive sensitivity analyses on capital costs, operation and maintenance costs, renewable and fossil fuel feedstock costs, feedstock conversion ratio, financial assumptions, tax credits, CO_2 taxes, and plant capacity factor. This paper summarizes the structure and methodology of AltSim, presents results, and provides a detailed sensitivity analysis.

The Energy Independence and Security Act (EISA) of 2007 sets a goal for the increased use of biofuels in the U.S., ultimately reaching 36 billion gallons by 2022. AltSim's base case assumes EPA projected feedstock costs in 2022 (EPA, 2009). For the base case assumptions, AltSim estimates per gallon production costs for the five ethanol feedstocks (corn, switchgrass, corn stover, forest residue, and farmed trees) of $1.86, $2.32, $2.45, $1.52, and $1.91, respectively. The projected production cost of biodiesel is $1.81/gallon. The estimates for CTL without biomass range from $1.36 to $2.22. With biomass, the estimated costs increase, ranging from $2.19 per gallon for the CTL option with 8% biomass to $2.79 per gallon for the CTL option with 30% biomass and carbon capture and sequestration.

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AltSim compares the greenhouse gas emissions (GHG) associated with both the production and consumption of the various fuels. EISA allows fuels emitting 20% less greenhouse gases (GHG) than conventional gasoline and diesels to qualify as renewable fuels. This allows several of the CBTL options to be included under the EISA mandate. The estimated GHG emissions associated with the production of gasoline and diesel are 19.80 and 18.40 kg of CO_2 equivalent per MMBtu (kgCO_2e/MMBtu), respectively (NETL, 2008). The estimated emissions are significantly higher for several alternatives: ethanol from corn (70.6), GTL (51.9), and CTL without biomass or sequestration (123 – 161). Projected emissions for several other alternatives are lower; integrating biomass and sequestration in the CTL processes can even result in negative net emissions. For example, CTL with 30% biomass and 91.5 % sequestration has estimated production emissions of -38 kgCO_2e/MMBtu.

AltSim also estimates the projected well-to-wheel, or lifecycle, emissions from consuming each of the various fuels. Vehicles fueled with conventional diesel or gasoline and driven 12,500 miles per year emit 5.72 - 5.93 tons of CO_2 equivalents per year (tCO_2e/yr). Those emissions are significantly higher for vehicles fueled with 100% ethanol from corn (8.03 tCO_2e/yr) or diesel from CTL without sequestration (10.86 to 12.85 tCO_2/yr). Emissions could be significantly lower for vehicles fueled with diesel from CBTL with various shares of biomass. For example, for CTL with 30% biomass and carbon sequestration, emissions would be 2.21 tCO2e per year, or just 39% of the emissions for a vehicle fueled with conventional diesel.

While the results presented above provide very specific estimates for each option, AltSim 's true potential is as a tool for educating policy makers and for exploring "what if?" type questions. For example, AltSim allows one to consider the affect of various levels of carbon taxes on the production cost estimates, as well as increased costs to the end user on an annual basis. Other sections of AltSim allow the user to understand the implications of various polices in terms of costs to the government or land use requirements. AltSim's structure allows the end user to explore each of these alternatives and understand the sensitivities implications associated with each assumption as well as the implications for bottom line economics, energy use, and greenhouse gas emissions.

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Introduction

There has been a significant growth in biofuel use over the past decade, driven by both policy and economics. The initial push came in the late 90's as policy makers sought a suitable substitute for MBTE, a gasoline additive used to reduce tail-pipe emissions, but which was later shown to be a groundwater contaminant. The 2005 Energy Policy Act (EPACT) established a goal of 4 billion gallons of biofuels by 2006 and 7.5 billion gallons by 2012. Due to favorable economics and tax policies, the 2006 target was surpassed, The Energy Independence and Security Act (EISA) of 2007 revised and extended the goals of EPACT, setting a target of 36 billion gallons of biofuels by 2022. Of that, 15 billion gallons can be met by traditional biofuels, such as corn or other starch-based ethanol. The remainder is expected to come from non-conventional biofuels, such as cellulosic ethanol and possibly diesel derived from coal and biomass. Under Title II of EISA, fuels that release 20% fewer GHG emissions can qualify as renewable fuels. EISA also gave responsibility to the EPA to develop a baseline estimate for lifecycle emissions for gasoline or diesel sold or distributed as transportation fuel in 2005, to allow for comparison of the alternatives.

The Alternative Liquid Fuels Simulation Model (AltSim) is a high-level dynamic simulation model which calculates and compares the production and end use costs, energy balances, and greenhouse gas emissions for several, alternative liquid transportation fuels. These fuels include: corn ethanol, cellulosic ethanol from various feedstocks, biodiesel, and diesels derived from natural gas (gas to liquid, or GTL), coal (coal to liquid, or CTL), and coal with biomass (CBTL). AltSim allows for comprehensive sensitivity analyses on capital costs, operation and maintenance costs, renewable and fossil fuel feedstock costs, feedstock conversion ratio, financial assumptions, tax credits, CO_2 taxes, and plant capacity factor. AltSim also includes policy tools to allow for consideration of greenhouse gas offset policies, production tax credits, and land use requirements. The main goal is to allow interested stakeholders to understand the complicated economic and environmental tradeoffs associated with the various options.

AltSim is written in Powersim Studio Enterprise 2007[4], a dynamic simulation-modeling software package. The model's easy to use policy screens allow the user to explore "What-if?" questions, such as:

- Under what conditions can corn-based ethanol compete economically with conventional gasoline – and how sensitive are the results to changes in corn prices?
- What alternatives result in lowered emissions of greenhouse gases relative to gasoline and diesel?
- In the absence of emission charges, which options can compete with gasoline produced from $80/bbl oil? From 150 $/bbl oil?

[4] Powersim Studio Enterprise 2007 is a product of the Powersim Corporation: www.powersim.com

– How would carbon taxes affect the overall economic competitiveness of various options?

– Can corn-based ethanol compete with various alternatives without a production tax credit? If not, what is the cost to taxpayers of maintaining the production tax credit?

– How might adoption of a mandatory renewable fuels policy affect the amount of available arable land if corn ethanol is the sole source of alternative fuels?

This paper provides an overview of the model structure, base case results and detailed sensitivity analyses on capital costs, feedstock prices, and feedstock efficiencies.

Model Structure and Assumptions

AltSim estimates the production and end use costs, energy balances, and greenhouse gas emissions (GHG) for each fuel included in the model. A key goal of the model is to allow users to understand the complicated economic and environmental tradeoffs associated with the various options.

The model is organized into three main sections: production, end use, and scenario analysis. Each section is accessed by clicking on the corresponding hyperlink at the top of any screen, such as the one shown in Figure 1. There is no requirement to start the model with the production section; one can just explore the end use analysis section. The production section calculates the production costs, energy balances, and greenhouse gas emissions for each of the options. The energy balance and greenhouse gas emissions calculations include energy and emissions associated with the production and delivery of the feedstock to the production facility, as well as the energy and associated emissions from the production process itself. The production section includes options for conducting thorough sensitivity analyses for all variables. The end use section estimates costs (per mile and per year), energy balances, and greenhouse gas emissions for driving vehicles powered by fuels generated through a variety of production pathways. For example, the greenhouse gas emissions associated with vehicle use include all emissions associated with the production of the fuel and then combustion by the vehicle. These well-to-wheel estimates do not include any emissions associated with delivering the fuel to the vehicle, nor do they include any emissions or energy associated with building the vehicles. The scenario analysis section includes options for: greenhouse gas tax policy, land use requirement calculations, co-product analysis, production tax credits, and an option for comparing options against a baseline cost or greenhouse gas emission level (i.e., emisisons 20% below those of conventional gasoline). Each of these options is discussed more completely later in this paper.

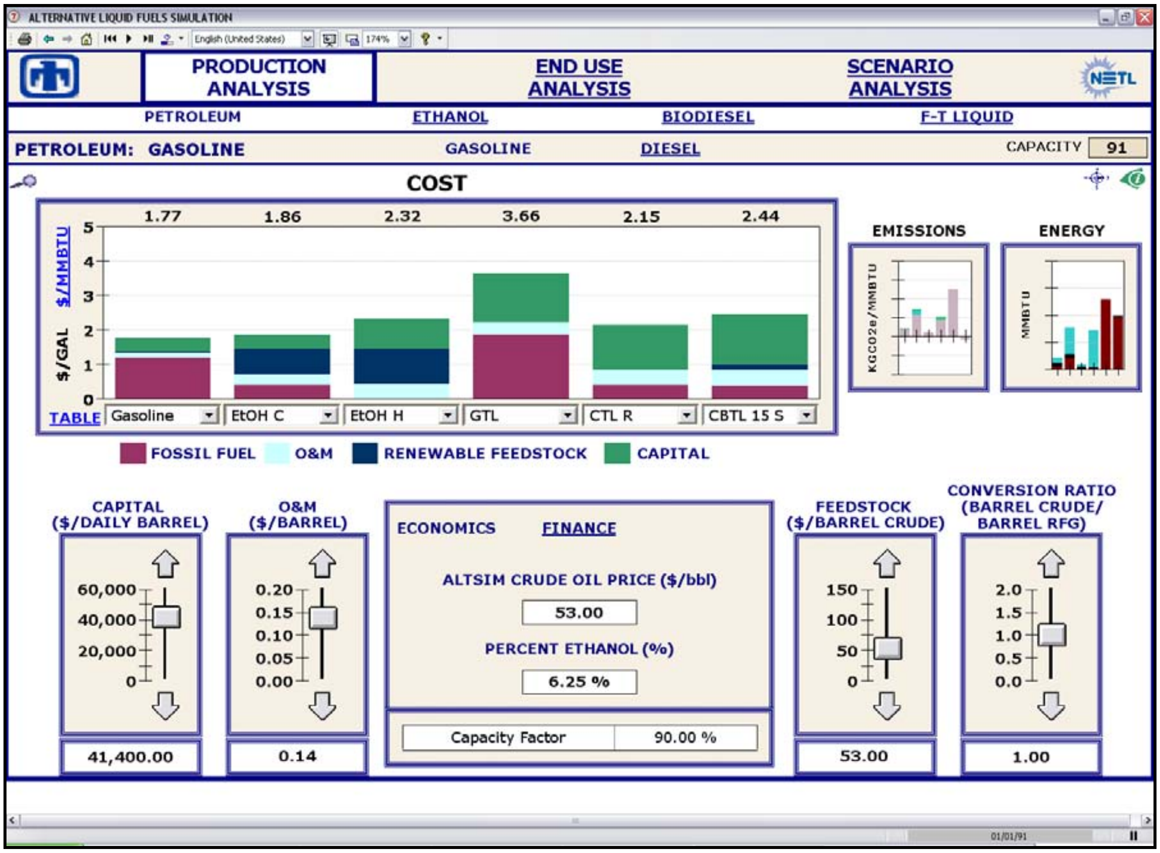

Figure 1. AltSim production analysis screen, showing links to end use and scenario analysis at the top of screen.

For the production estimates, the base case relies on estimated costs for newly constructed facilities. Wherever possible, these estimates are based on industry estimates for new facilities. For those technologies not yet implemented on a commercial scale, as is the case for CTL, CTBL, and cellulosic ethanol, we rely on industry and governmental estimates of the likely costs.

The 18 fuel production pathways options included in AltSim are listed in Table 1. This table includes the labels used in AltSim and their definitions (ie, EtOH C is corn-based ethanol), the type of fuel (E100 is 100% ethanol), the plant type (dry-milled ethanol production facility), and the feedstock (corn). AltSim graphically displays six fuel options at a time. The default fuels are: gasoline, corn-based ethanol, herbaceous ethanol (EtOH H), natural gas to liquid diesel (GTL), CTL with recylcle and without sequestration (CTL R), and CTL with 15% biomass and sequestration (CBTL 15 S). The pull down menus below each fuel type allow the user to display other fuels.

Table 1. Fuel options included in AltSim, including label names, plant type, fuel specification, and feedstock.

AltSim Label	Label Definition	Plant Type	Fuel Specification	Feedstock
Gasoline	Reformulated Gasoline	Refinery	Reformulated (6.5% ethanol)	Crude
Diesel	Ultra Low Sulfur Diesel	Refinery	ULSD (<5PPM)	Crude
EtOH C	Corn Ethanol	Dry Milled	100% Ethanol	Corn
EtOH T	Farmed Tree Ethanol	Thermochemical	Cellulosic Ethanol	Farmed Trees
EtOH H	Herbaceous Ethanol	Fermentation	Cellulosic Ethanol	Switchgrass
EtOH CS	Corn Stover Ethanol	Fermentation	Cellulosic Ethanol	Corn Stover
EtOH FR	Forest Residue Ethanol	Thermochemical	Cellulosic Ethanol	Forest Residue
Biodiesel	Biodiesel	Fermentation	Biodiesel	Soy Oil
GTL	Natural Gas To Liquid	Recycled	Fischer-Tropsch Diesel	Natural Gas
CTL O	Coal to Liquid Once Through	Once Through	Fischer-Tropsch Diesel	Bituminous Coal
CTL O S	Coal to Liquid Once Through w/ CCS	Once Through	Fischer-Tropsch Diesel	Bituminous Coal
CTL R	Coal to Liquid Recycled	Recycled	Fischer-Tropsch Diesel	Bituminous Coal
CTL R S	Coal to Liquid Recycled w/ CCS	Recycled	Fischer-Tropsch Diesel	Bituminous Coal
CBTL 8 S	Coal/ 7.7% Biomass to Liquid w/ CCS	Recycled	Fischer-Tropsch Diesel	Bituminous Coal/ Switchgrass
CBTL 15 S	Coal/ 15% Biomass to Liquid w/ CCS	Recycled	Fischer-Tropsch Diesel	Bituminous Coal/ Switchgrass
CBTL 30 S	Coal/ 30% Biomass to Liquid w/ CCS	Recycled	Fischer-Tropsch Diesel	Bituminous Coal/ Switchgrass
BTL S	Biomass to Liquid w/ CCS	Recycled	Fischer-Tropsch Diesel	Bituminous Coal/ Switchgrass

AltSim includes several ethanol (EtOH) options, including ethanol derived from corn, farmed trees, herbaceous crops (switchgrass), corn stover (residue after corn kernels removed), and forest residue. Each of the ethanol options are unique processes and hence have unique costs. Only one option for converting natural gas to liquid (GTL) is included. Several coal to liquid (CTL) processes are included. In addition to fundamental differences in technologies (once through (O) vs. recycle (R)), other CTL options modelled include carbon capture and sequestration (S) and various levels of biomass mixing (8%, 15%, 30%, and 100%). The assumed energy content for the fuels, on a lower heating value (LHV) basis, are summarized in Table 2. When fuels are blended, the energy content is based on a weighted average calculation. In AltSim, the gasoline is assumed to contain 6.5% ethanol; the corresponding energy content is thus lower than 100% gasoline.

Table 2. Energy content of various fuels, Btu/gallon (LHV basis).

	Fuel Energy Content (Btu/gallon)
Gasoline	116,090
Diesel	131,229
Ethanol (100%)	76,330
Biodiesel (100%)	119,550
Fischer-Tropsch (FT) Diesel	118,905

The base case technical and economic assumptions associated with each of the 18 production pathway options are summarized in Table 3. These include capital costs, O&M costs, feedstock costs, feedstock conversion ratio, capacity factors, and other basic financial assumptions. Energy cost assumptions are summarized in Table 4. Additional details about each technology are discussed in subsequent sections. As output for certain technologies, including the ethanol and biodiesel plants, are usually reported in terms of gallons-per-day rather than the more traditional barrels-per-day, this convention is maintained in AltSim. The tables clearly indicate the units used for each technology.

As the EISA standard calls for 36 billion gallons of renewable fuels by 2022, we use estimated fuel and feedstock costs in 2022. These estimates are taken from the EPA's 2009 proposed Amendments to the Renewable Fuel Standard Program (referred to as RFS2) (EPA, 2009). While these serve as the base case assumptions in this version of AltSim, the user can easily change these assumptions to explore alternative futures. Feedstock and fuel price sensitivities are discussed more completely in the sensitivity analysis section.

Production costs are reported on both a per gallon ($/gallon) and energy content ($/MMBtu LHV) basis. Production costs are also referred to as "plant gate" costs and do not include distribution costs. AltSim estimates end user costs for typical vehicles fueled with the various fuel options. End user costs are reported both in terms of $/mile and $/year for typical vehicles. Likewise, energy balances and associated greenhouse gas emissions are reported on both a well to plant gate and end use basis. When added together, these are very similar to well-to-wheel estimates, but do not include either energy or greenhouse gas emissions associated with fuel distribution. This is largely due to the structure of AltSim which focuses on the production and end use, and ignores the overall distribution of fuels to the end use location.

Table 3. Cost and performance characteristics for alternative liquid transportation fuel options included in AltSim (2007 $).

Fuel Option	Capital	O&M	Feedstock		Conversion Ratio		Capacity Factor
		($/gal)	Fossil Fuel	Biomass	Fossil Fuel	Biomass	
Gasoline	41,400 (($/dbbl)	0.14	53 ($/bbl)		1 (bbl/bbl)		90%
Diesel	110,108 ($/dbbl)	0.14	53 ($/bbl)		1 (bbl/bbl)		90%
Ethanol (Corn)	904 ($/dgal)	0.31		3.34 ($/bu)		0.36 (bu/gal)	90%
Ethanol (Farmed Trees)	944 ($/dgal)	0.24		101.34 ($/ton)		0.0125 (ton/gal)	90%
Ethanol (Switchgrass)	1979 ($/dgal)	0.41		77.15 ($/ton)		0.0131 (ton/gal)	90%
Ethanol (Corn Stover)	1246 ($/dgal)	0.2		88.71 ($/ton)		0.0143 (ton/gal)	90%
Ethanol (Forest Residue)	944 ($/dgal)	0.24		70.00 ($/ton)		0.0125 (ton/gal)	90%
Biodiesel	439 ($/dgal)	0.24		0.23 ($/lb)		7.41 (lb/gal)	90%
GTL	113,571 ($/dbbl)	0.35	6.21 ($/MMBtu)		11.36 (MMBtu/bbl)		90%
CTL O	105,711 ($/dbbl)	0.4	27.52 ($/ton)		0.76 (ton/bbl)		90%
CTL O S	115,227 ($/dbbl)	0.41	27.52 ($/ton)		0.76 (ton/bbl)		90%
CTL R	100,523 ($/dbbl)	0.26	27.52 ($/ton)		0.43 (ton/bbl)		90%
CTL R S	104,151 ($/dbbl)	0.28	27.52 ($/ton)		0.42 (ton/bbl)		90%
CBTL 8 S	111,801 ($/dbbl)	0.44	27.52 ($/ton)	77.15 ($/ton)	5.27 (ton/bbl)	8.30 (ton/bbl)	90%
CBTL 15 S	112,487 ($/dbbl)	0.44	27.52 ($/ton)	77.15 ($/ton)	2.38 (ton/bbl)	13.48 (ton/bbl)	90%
CBTL 30 S	126,806 ($/dbbl)	0.5	27.52 ($/ton)	77.15 ($/ton)	2.78 (ton/bbl)	6.37 (ton/bbl)	90%
BTL S	225,170 ($/dbbl)	0.89	27.52 ($/ton)	77.15 ($/ton)		0.97 (ton/bbl)	85%

Table 4. Fuel cost assumptions (2007 $).

	Cost ($/Unit)
Electricity (kWh)	0.05268
Coal (MMBtu)	1.94
Gas (MMBtu)	6.21

Production Cost Calculations

Production costs are esimated using a levelized cost of energy (LCOE) approach. LCOE calculations estimate the per unit ($/gallon, $/kWh) cost of production over the economic lifetime of the technology being considered. Specifically, this calculation takes the capital costs, associated financing costs, O&M, fuel costs, and any externality costs (such as GHG taxes) and calculates a per unit production cost. The LCOE is often used as an economic measure of energy costs as it allows for comparison of technologies with different capital and operating costs, construction times, and capacity factors. The LCOE calculation is given by:

$$LCOE = \frac{I * FCR}{Q} + \frac{O\,\&\,M}{Q} + \frac{E}{Q} \qquad (1)$$

where:
- I = Total financed capital costs
- FCR = Fixed charge rate
- Q = Annual plant output (i.e, gallons/yr)
- O&M = Fixed and variable operating and maintenance costs
- E = Externality costs, such as CO_2 and other GHG.

The methodology for calculating the capital cost component is consistent across all technologies in AltSim. Financing costs assume that capital expenditures are uniformly distributed over the time of construction, and assume a default real interest rate during construction of 4.65%.[5] Once operational, annual capital costs are determined by multiplying the total capital cost, including finance costs, by a fixed charge rate (FCR), which represents the percentage of capital costs that must be recovered each year:

$$FCR = \frac{CRF[1 - bT\sum_{n=1}^{M} V_n/(1+d_{WACC})^n - t_c]}{(1-T)} + p_1 + p_2 \qquad (2)$$

where: CRF = capital recovery factor

[5] All interest and discount rates in AltSim are expressed in real dollar terms, meaning they are adjusted for inflation. The alternative is to use nominal rates in combination with an assumed inflation rate.

b	= fraction of investment that can be depreciated (initially is 100%)
T	= effective tax rate (comprised of federal and state taxes; default 38.5%)
M	= Depreciation period (5 to 20 years)
V_n	= fraction of depreciable base in year n
r_{WACC}	= real discount rate initially set at 10%)
t_c	= tax credit (initially zero)
p_1	= annual insurance cost (initially zero)
p_2	= other taxes (initially zero)

The fixed charge rate (FCR) typically ranges from 0.11 and 0.17 and represents the percentage of capital costs that must be recovered each year in order to cover all investment costs, including return on debt and equity. For example, for a $1 million capital investment and a FCR of 0.15, the annual capital requirement for that investment is $150,000.

The real discount rate is based on a weighted average cost of capital (WACC) approach that takes into account the portions of the total cost that is debt (borrowed commercially) or equity (investor) financed. The WACC calculation is given by:

$$WACC = \frac{E}{V} * r_e + \frac{D}{V} * r_d * (1 - T) \tag{3}$$

where:

E/V	= percent of total project equity financed
r_e	= equity financing rate
D/V	= percent of total project debt financed
r_d	= debt financing rate (pre-tax)
T	= effective tax rate

The default case assumes 60%/40% debt/equity financing, a debt financing rate of 4.56% and equity financing rate of 20%, a rate that is commensurate with riskier investments.

The capital recovery factor (CRF) is calculated using:

$$CRF = r_{WACC} * \frac{(1 + r_{WACC})^n}{(1 + r_{WACC})^n - 1} \tag{4}$$

r_{WACC}	= real weighted average cost of capital
n	= economic plant life (initially 20 years).

Depreciation follows the United States' Modified Accelerated Cost Recovery System (MACRS). Under IRS regulations, most utility type investments use either a 15- or 20-year depreciation schedule. Certain investments, such as renewables, are allowed to use a five-year depreciation schedule. This effectively lowers the annual capital requirements for these investments.

The Production Technologies

AltSim allows the user to compare the production and end use costs, energy balances, and carbon dioxide emissions for 18 different fuels: gasoline, diesel, ethanol from corn, ethanol from other feedstocks (herbaceous (switchgrass), corn stover, farmed trees, or forest residue), biodiesel, and Fischer-Trospsch diesels (GTL, CTL, and CBTL). While Tables 3 and 4 summarized economic and technical assumptions used in the AltSim base case, this section provides more detail about the technologies and the assumptions used for each in AltSim.

Ethanol from Corn

The Energy Independence and Security Act (EISA) of 2007 mandates the increased use of biofuels, reaching 36 billion gallons by 2022. Of that, up to 15 billion gallons can be met by conventional biofuels, such as ethanol from corn. Most of this ethanol is blended with gasoline in ratios of less than 10%. While automakers have produced over 5 million flex fuel vehicles, capable of running on 85%/15% ethanol to gas blend (E85), few stations outside of the Midwest offer E85.

The EPA reported in April 2009 that a total of 169 ethanol plants, with a combined capacity of 10.5 billion gallons per year, were operational. An additional 19 plants with a capacity of 1.9 billion gallons are currently idled due to unfavorable economics. An additional 36 plants, with a capacity of 2.4 billion gallons, are under construction (although some of those have also been idled by economic uncertainty) (EPA, 2009). .

As so many ethanol plants have been constructed in recent years, the economics are fairly well known. AltSim relies largely on the technical and economic assumptions available in the trade literature and from confidential sources. The base case assumptions in AltSim assumptions are for a 275,000 gallon per day dry mill ethanol facility. Dry mill plants account for 80% of all ethanol production facilities in the U.S. (Wang et al., 2007). As part of the dry milling process, corn kernels are ground into a flour or "meal." Enzymes and water are added, creating a "mash." The enzymes break down the starch into sugar, which is then fermented and distilled, resulting in a 190 proof alcohol (ethanol). A denaturant is added to the ethanol to make it unfit to drink. A byproduct of the distillation process is distiller's grains (DSG), which can be sold as a feed for livestock.

AltSim assumes a capital cost of $904 per daily gallon, capacity factor of 90%, and a feedstock conversion ratio of 0.36 bushels per gallon. The default case assumes a distiller's grain credit of 0.45 cents/gallon, based on grain and moisture contents of 10 and 15.5%, respectively. Other key assumptions are summarized in Table 3.

Cellulosic Ethanol

While most ethanol produced in the U.S. is derived from corn, and from sugar cane in Brazil, other lignocellulosic feedstocks may be better candidates for ethanol production. AltSim includes options for producing ethanol from several alternative lignocellulosic feedstocks, including: herbaceous crops (such as switchgrass), corn stover (the leftover leaves and the stalks from corn), farmed tree crops, and forest residue.

Ethanol can be produced from these feedstocks using either biochemical or thermochemical processes. The biochemical process utilizes enzymes to break down the biomass prior to fermentation, whereas the thermochemical process relies on heat and pressure to gasify the biomass prior to alcohol synthesis. Two of the AltSim options use the biochemical process (corn stover and switchgrass) and two use the thermochemical process (forest residue and farmed trees).

While both processes are widely discussed and documented, they are yet to be proven on a commercial scale. Approximately 25 pilot or demonstration plants exist (EPA, 2009). In 2007, the DOE awarded grants totaling $385 million for six commercial-scale cellulosic ethanol refineries with a potential combined production capacity of 130 million gallons. Two of those companies have since forfeited their funding. Just one facility, owned by Range Fuels, with a capacity of 40 million gallons per year is currently under construction. The first phase of this thermochemical cellulosic ethanol facility, located in Georgia, will have a capacity of 10 million gallons per year and is scheduled to be in operation by December 2009. The feedstocks for this plant will be wood waste and switchgrass.

Biochemical Cellulosic Production

Lignocellulose is composed mainly of cellulose, hemicellulose, and lignin. The basic process of producing ethanol begins with a pretreatment phase that uses both physical (crushing) and chemical means. During the next phase, hydrolysis, enzymes are used to convert the cellulose chains into glucose molecules. For some biochemical processes, this enzyme is created during the process; in other processes, the enzyme must be added. Fermentation of the sugars and distillation results in a 99.5% ethanol stream (Laser et al., 2009).

As these facilities are very much still in the pilot or demonstration phase, the default assumptions of AltSim rely on technical reports.

A 2003 NREL study (Aden et al.) provides a techno-economic analysis of biochemical cellulosic ethanol production using corn stover. The NREL study is for a 69.3 million gallon per year (190,000 gallons/day) facility utilizing dilute acid prehydrolysis. This facility would require a biomass feed rate of 90,039 kg/hr (15% moisture content). The total project investment was estimated at 197 million in 2000 dollars. The NREL analysis assumes enzyme costs would decrease from 32 to 8 cents/gallon by 2022. Feedstock costs are assumed to be $30 per dry ton. Natural gas was assumed as the process fuel. The plant would produce excess electricity (beyond what is required internally) of about 2.28 kWh per gallon ethanol produced, which is sold back to the grid.

Based on a 100% equity financed project with a discount rate of 10%, Aden et al. concludes that this plant could produce ethanol for $1.07 per gallon.   The report acknowledges a large degree of uncertainty in this estimated cost on the order of -10% to +25%.

AltSim uses the base NREL technical and economic assumptions with two exceptions. Based on conversations with experts, about the likely costs of enzymes and the uncertainty surrounding these costs, AltSim assumes the enzymes are 0.40 $/gallon. This obviously increases the projected cost per gallon by 32 cents and is an area where costs may be significantly lower in the future. The price used by NREL for corn stover is also considered low. Corn stover is currently used as feed for cattle. Its use as a feedstock for ethanol production will make it susceptible to the same type of upward price pressure seen in corn prices. AltSim assumes an initial feedstock cost of $88 per dry ton, based on the RFS2 market price for 2022.

Laser et al. (2007) utilized the NREL (2003) methodology to analyze a technology that uses switchgrass as a feedstock but that also produces the enzymes necessary to break the cellulose from the lignin fibers. In this process, the switchgrass is first exposed to sulfuric acid which dissolves a portion of the lignin and the hemicellulose. Enzymes are produced from this pretreated biomass through a process requiring the addition of whole corn steep liquor, a co-product of the corn wet milling industry. The cellulose is hydrolyzed to glucose using this enzyme. The resulting glucose is then fermented and distilled to produce a stream of 99.5% pure ethanol. The process requires both steam and electricity, which is produced on site. The excess electricity is sold to the grid. Laser et al. estimate 11.5 MW of exported power for a 365,500 gallons per day plant. This plant would have a daily input of 5000 dry tons of switchgrass, considerably larger than the corn stover facility discussed by Aden et al, but still smaller than the Arthur Daniel Midlands corn ethanol plant in Decatur, IL (15,500 dry tons/ day). The estimated total project investment for this facility is $603 million. Based on 35%/65% debt/equity split, with debt interest rate of 7%, and 15% return on equity, Laser et al. estimate production costs of $1.71 per gallon. The higher estimated cost than Aden et al. is partially due to higher assumed discount rates.

Laser et al. note that future technology advancements will likely drive projected production costs lower. Their “mature technology” case, which assumes superior strains of switchgrass through breeding, and an integrated combined cycle power production, reduces the production cost to $0.77/gallon.

Thermochemical Cellulosic Production

A companion study to 2003 NREL study for the biochemical production process reviews the feasibility and costs of producing ethanol from forest residue using a thermochemical approach in the 2012 timeframe (Phillips et al., 2007). Forest residue was chosen as the feedstock based on its expected availability as noted in the "Billion ton Vision", an April 2005 report from the USDA. The plant requires 2205 dry tons of feedstock per day, or 772,000 dry ton/year. Steps in the process include: feed preparation, gasification, gas cleanup and conditioning, and alcohol synthesis and purification. Byproduct char and some of the product gas provide the heat and power necessary for the gasification process. The benefit of this approach is that no outside fuels are necessary. However, 28% of the syngas produced is diverted back into the process, lowering the alcohol output by 38%.[6]

Philips et al. chose this indirect steam gasification process over a partial oxidation gasifiers (POX) approach which would require a large quantity of pure oxygen. POX is, however, another option for ethanol production but is not considered further in AltSim.

Through this indirect gasification process, biomass is converted to mixture of syngas (synthesis gas), tars, and a solid char (fixed carbon residual). Sulfur and other impurities are removed from the syngas. Unless sequestered, the CO_2 is vented. Elemental sulfur is stockpiled for disposal. The syngas is converted to alcohols in a fixed bed reactor that requires a catalyst, such as MoS_2. This process results in a distribution of alcohol product types, including methanol, ethanol (71%), and pentanol. These other alcohols are considered co-products. Philips et al. assumes a co-product credit for these alcohols of $1.15/gallon.

The estimated total project investment of 1,974 million in 2000$ for a 69.3 million gallons per year ethanol plant. The feedstock requirements are 2,000 tons per day (dry). Utilizing the same economic framework of Aden et al., Phillips et al. estimate an ethanol production cost of $1.07 per gallon ($2000) The authors suggest even larger uncertainty for the capital costs than is the case for Aden report: +30% to -10%. For the feedstock, they assume forest residue available at $35 per dry ton in 2012.

AltSim relies on the base case assumptions of this study for both the forest residue and farmed tree options.

[6] Alternatively, natural gas could be used as the process fuel, increasing the output of ethanol. The energy/economic tradeoff of this option may be explored in future versions of AltSim.

Biodiesel

Biodiesels refer to a renewable diesel produced from fats and oils using a process called esterfication.[7] Many home users produce biodiesel from used restaurant oils. While recycling restaurant grease and oils is one option for producing biodiesel, it is not feasible on a large scale. Large scale producers have to rely on feedstocks such as soybeans, canola, palm oil, and rapeseed. Another possible feedstock, although not yet commercially viable, is algae. Early and McKeown (2009) estimate that 3.8 billion gallons of biodiesel were produced in 2008. Just over half of this amount was produced in EU countries using rapeseed as the basic feedstock. In the US, 711 million gallons were produced, largely from soybeans.

Haas et al. (2007) provide a techno-economic analysis of the large scale production of biodiesels from soy oil. They describe a three step process: chemical transesterification that converts vegetable oils to fatty acid methyl esters and glycerol, purification of the methyl esters to meet biodiesel standards, and recovery of the glycerol for sale as a co-product. They estimate that a ten million gallon per year biodiesel facility would cost $11.3 million. Based on their economic assumptions they estimate a production cost of $2.00/gallon and note that the soy oil feedstock and the other raw materials used in the process accounts for 88%, or $1.89 per gallon, of that cost. While this study breaks out the capital, O&M, and feedstock costs, it does not account for several important economic assumptions, including the debt/equity financing, taxes, or required returns on investment. These omissions may not matter too much for a process where 88% of the cost is attributable to feedstock costs however, but are considered by the AltSim model.

Coal to Liquid (CTL) and Coal and Biomass to Liquid (CBTL)

Given the large reserves of coal in the U.S. and elsewhere, there is considerable interest in developing coal to liquid (CTL) technologies. The technology to create liquid transportation fuels from coal has long existed. Germany relied heavily on synthetic fuels during WWII to fuel their planes. Approximately 92% of their aviation fuel and more than half of their transport fuel came from synthetic fuel plants (DOE, 2008). The first of many synthetic fuel legislation in the U.S., the Liquid Fuels Act of 1944 authorized $30 million for the "…construction and operation of demonstration plants to produce synthetic liquid fuels from coal, oil shales, agricultural and forestry products, and other substances (DOE, 2008)."

CTL is produced commercially in South Africa and supplies about 30%, or about 205,000 barrels per day, of that country's transportation energy demand (Sichinga, 2005). A clear benefit of CTL is its low sulfur content (<5 ppm). However, if CTL

[7] Other methods for producing biodiesel exist, such as hydrotreated renewable diesel (HRD), but are not included in AltSim.

produced without carbon capture and storage (CCS) it would have higher carbon emissions than from petroleum products.

Several technical studies estimate the costs for constructing CTL or CBTL plants in the U.S. (Gray, 2005; Williams et al. 2006; Williams, 2007; and NETL, 2009). The basic process for converting solid carbon-based feedstocks to a liquid fuel is known as Fischer-Tropsch synthesis, illustrated in Figure 2. The CBTL process is similar but includes a biomass preparation process. For both, the feedstock is first gasified in presence of pressurized steam and oxygen. The resulting synthesis gas is cooled and cleaned before entering a reactor where the syngas is converted in the presence of a catalyst to Fischer-Tropsch Liquids. Unreacted syngases can be used to produce electricity or can be recycled through the plant to maximize the liquid output. As the sulfur present in the coal is removed by this process, the resulting diesel has very low (<5 ppm) sulfur content, classifying the diesel as Ultra low sulfur diesel (ULSD).

Altsim includes two competing CTL technology options: a once through process designed to coproduce diesel and electricity from coal as described by Williams (2007); and a recycle process designed to maximize liquid fuel production as described by NETL (2009).

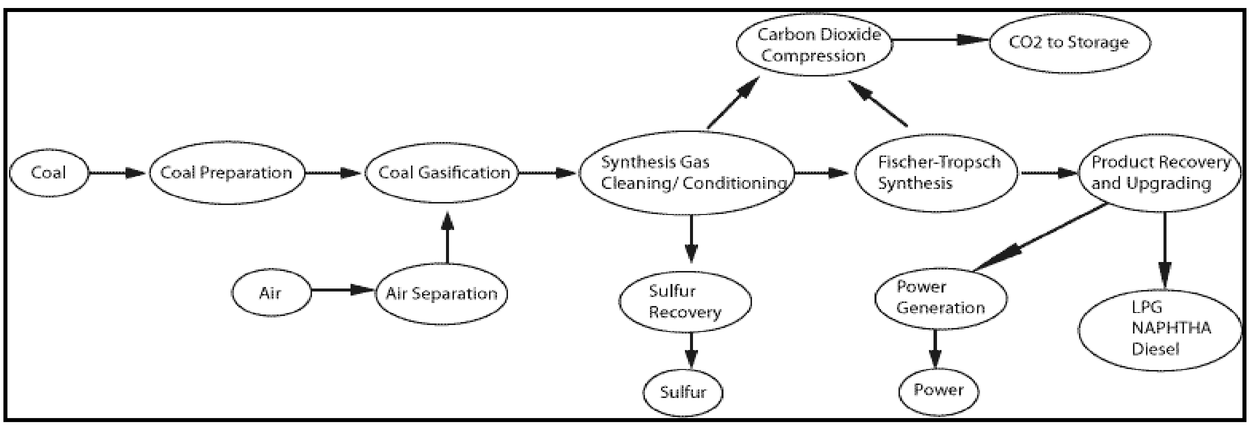

Figure 2. Basic CTL process.

The once through process is described by Williams (2007). Williams refers to these plants as polygeneration plants, producing both F-T fuels, including gasoline, diesel, as well as electricity. Each scenario includes an option for carbon capture and storage (CCS) where CO_2 is compressed to 150 bar and transported 100 km to a site where CO_2 is either stored in a saline aquifer 2 km underground or used for enhanced oil recovery (EOR). Williams assumes that commercially available components are used for the coal-to-liquid portion of the plants. Certain components for the biomass portion rely on Williams estimates for future, mature technologies.

For all technology scenarios, Williams financing assumptions use a debt/equity split of 55%/45% with an interest rate on debt of 4.4% real and a discount rate on equity of 14% real, resulting in a capital charge rate of 15%.

For the CTL processes, Williams estimates that each 2.99 GJ of coal input results in 1.0 GJ of Fischer-Tropsch liquids and 0.38 GJ of electricity, and an efficiency rating of 46%. For the CBTL scenarios, biomass accounts for 28% of the feedstock input on an energy basis. In this scenario, 2.17 GJ of coal and 0.86 GJ of biomass yield 1.0 GJ of Fischer-Tropsch liquids and 0.45 GJ of electricity, for an efficiency of 48%. According to Williams, the addition of the biomass components actually decreases the total capital costs as a smaller coal gasifier is required, which is more expensive than the biomass gasifier. When accounting for the GHG emissions, Wiliams assumes GHG emissions associated with the electricity are equivalent to stand alone IGCC plants[8] either with or without CO_2 venting[9].

The assumed total project investment for the CTL without CCS system is $1,850 million. The addition of CCS capability to that plant adds approximately 9%. Williams' estimates for these costs are based on the work of Ogden (2002). Ogden's analysis considers carbon capture from large-scale hydrogen and electricity facilities utilizing either natural gas or coal as a feedstock. The captured carbon is then compressed to 15 megapascals (MPa) (2176 psi) for pipeline transmission as a supercritical fluid and injected into underground reservoirs. The total costs include pipeline transport costs, the costs of drilling and operating the wells, and surface piping that connects various disposal wells in large operations. The CBTL system, with CCS, is estimated to cost $1,884 million.

Williams estimates the production cost for F-T liquids, in terms of gallon of gasoline equivalence on LHV basis, of 1.33 $/gallon for CTL without CCS, 1.68 $/gallon for CTL with CCS, and 1.74 $/gallon for CBTL with CCS.

The technologies included in the NETL (2009) report focus on the maximum production of liquid fuels, rather than co-products, including electricity. This was done, according to NETL, to "simplify the analysis by eliminating the need to allocate production costs and GHG emissions to another significant byproduct." The main difference with the technology analyzed by Williams is that the unreacted syngas is recycled back into the process in order to maximize the amount of carbon converted to diesel.

The NETL report considers 11 different options with different combinations of technology and feedstock. These options include CTL plants with and without carbon capture and sequestration (CCS); CBTL plants utilizing various percentages of coal and biomass (8%, 15%, and 30% biomass) with and without CCS; and a BTL plant with 100% switchgrass. The NETL modeled pathway options range in size from 5,000

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[8] Williams et al. notes this allocation is "somewhat arbitrary" (Williams et al, 2006).
[9] Uses IGCC with carbon capture emisison estimates for once through option with sequestration.

barrels per day (BPD) of liquid transportation fuel to 50,000 BPD depending on the biomass requirements. The NETL study found that the 50,000 BPD facility was the preferred option for the CTL facilities, but limited the size of plants using biomass due to biomass resource constraints – basically, the amount of biomass available within a 30-50 mile radius of the plant.

The NETL report analyzes well-to-wheel greenhouse gas emissions associated with each technology, with the goal of determining whether they could qualify as renewable fuel under Title II, Subtitle A of the EISA 2007. Under EISA, fuels that release 20% fewer GHG emissions can qualify as renewable fuels. The NETL report concludes that this is possible for those CTL technologies with CCS that include at least 8% biomass Without the biomass share, none of the CTL options, even with the CCS, would meet the EISA standard.

Figure 3 summarizes the economic results from the NETL study. Specifically, the NETL results show production costs for the CTL option with CCS of 2.49 $/gallon. The figure also shows that the CTL option with 8% biomass results in a 20% reduction in life cycle GHG emissions and has an estimated cost of about 2.75 $/gal. In general, NETL concludes that the cost of CCS is very inexpensive, increasing the estimated costs by as little as 7 cents/gallon (CTL+CCS). NETL concludes the BTL option is not competitive unless GHG taxes exceed 138 \$/mtCO_2e (or about 1.70$/gallon on diesel fuel).

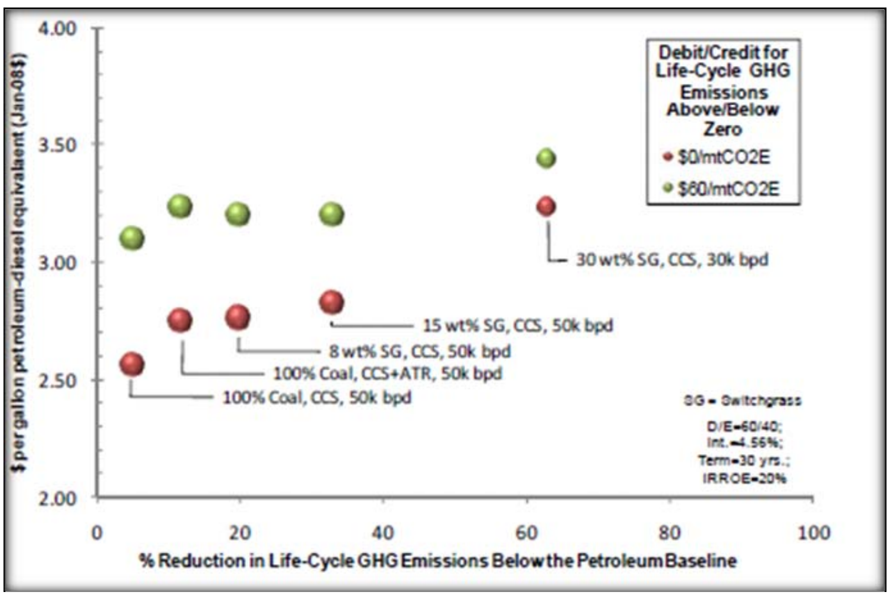

Figure 3. Estimated production costs and associated GHG reductions for the NETL options (Source: NETL, 2009).

The NETL estimated production costs are higher than those of Williams. A significant part of this difference is due to financing assumptions. The NETL paper assumes a 60/40 debt equity split, an interest rate of 4.56%, 30 year economic life, and a 20%

return on equity financing. Williams uses a 55/45 debt equity split, a 4.4% debt financing rate, and a 14% equity financing rate.

Altsim includes several options from the NETL report: CTL with no CCS; CTL with CCS;CTL with 8, 15, and 30% biomass and CCS; and BTL with CCS. The technical and economic assumptions are summarized in Table 3.

Conventional Refinery Options

AltSim relies on estimates of Gary and Handwerk (2001) for construction of a new refinery in the U.S. Gulf Coast region. The total investment for the assumed Gulf Coast facility is $1.9 billion for 100,000 barrels per day of capacity. As the authors note, these estimates are fairly generic and subject to large variation and inflationary pressures. The original estimates are in 1999 $; these numbers were converted to 2007 $ using GDP price inflators. The use of GDP price inflators likely underestimates the true costs in field, as prices for construction of facilities with large steel and cement requirements have increased rapidly in recent years due to the huge worldwide surge in demand. Using a different index, such as the Chemical Engineering Plant Cost Index or the Nelson-Farrar Refinery Index, would like yield higher estimated costs. However, as these indices were not used for other technologies, they were not used here. The user can explore the effects of higher assumed capital costs on the estimated production costs of gasoline and diesel.

The EPA RFS2 uses econometric relationships to estimate the cost of both gasoline and diesel. The estimated wholesale gasoline and diesel prices are given by:

Gasoline ($/gal) = 7.7 + 2.95 * Crude ($/bbl)

Diesel ($/gal) = 3.46 – 17.0 * Crude ($/bbl)

Based on these estimates, for crude at 53 $/bbl (the 2022 estimated price), wholesale gasoline and diesel costs would be 1.64 $/gal and 1.66 $/gal respectively.

Energy Balances and CO_2 Emissions

AltSim tracks the energy use and resulting greenhouse gas emissions associated with the production and end use of each fuel. With a few key exceptions discussed below, AltSim relies on coefficients from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, developed at Argonne National Laboratory. GREET tracks the total consumption of energy by fuel type, the emissions of greenhouse gases and other criteria pollutants for over 100 fuel production pathways.[10] GREET attempts to capture the energy used at every step of production. For example, in the case of corn-based ethanol, GREET includes the energy associated with growing and harvesting the corn, including the energy used in fertilizer and pesticide production, the transport of the corn to the plant, the processing required to convert the corn to ethanol, and the energy to transport the ethanol to the point of end use.

An example from Wang et al. (2007) illustrates the complexity. Wang et al. (2007) summarizes the total energy needed to produce corn-based ethanol using the existing mix of wet milled (20%) and dry milled (80%) plants. This example illustrates the detail and complexity of tracking energy use through the various production pathways. The dry mill plants require 36,000 Btu of fuel for each gallon of ethanol produced. 80% of the process fuels used in the dry mill plants is natural gas, 20% is coal. Wet mill plants average 45,960 Btu for each gallon of ethanol produced. For these wet mill plants, 60% of the process fuel is natural gas and 40% is coal. The current plants also consume 0.88 kWhr of electricity for each gallon of ethanol produced. Wang et al. assumes this is met from the grid and uses national averages for calculating fuel percentages (52% coal, 16% natural gas, 20% nuclear, 3% residual oil, 1% biomass, and 8% hydro). Wang et al. conclude that to produce one million Btu of ethanol from corn requires a fossil fuel input (coal, oil, and natural gas) of 0.78 MMBtu.

As this example illustrates, a possible criticism of the GREET data is that the coefficients are average values. Actual fuel use may vary widely depending on such factors as fertilizer and pesticide use, crop yields, harvesting efficiency, and distance of crops to the plant. Nevertheless, the GREET values are widely quoted and provide a good baseline for comparing and contrasting energy use and resulting emissions from alternative pathways.

While the GREET model includes estimates for the production of each fuel type included in AltSim, some of the estimates are based on a more generic process than is ideal. For example, GREET models one technology for CTL and one technology for CBTL, whereas AltSim includes several specific options for CTL and CBTL. Therefore, for these technologies, AltSim relies on the estimates provided by the option specific reports. The CTL O and CTL O S energy and GHG estimates are derived from Williams (2007). The remainder of the CTL and CBTL options are taken from NETL (2009). One limitation with the NETL report is lack of specifics regarding variations in the energy balances for each specific technology. It is expected that more specific estimates will be included in future versions of this work.

NETL recently completed a comprehensive study on the lifecycle greenhouse gas emissions associated with the production of diesel and gasoline (NETL, 2008). The motivation for the study was Title II, Subtitle A, Sec. 201 of EISA 2007 which included a call for development of such a baseline. The NETL report notes the existence of a large

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[10] AltSim uses version 1.8. GREET and all documentation is available at: www.greet.anl.gov.

disparity in estimates in the literature, ranging from 11.8 to 37.5 kg CO_2e/MMBtu for diesel. NETL attributes the large variation to "differences in study boundary conditions, type of data used in the analysis, technology represented, geographical representation of key processes (national average, regional, or site-specific), time-related coverage (age of data used in the analysis), and/or the allocation procedures used to assessing emissions to operations with more than one valuable product (such as the petroleum refinery)." Their analysis estimates total well to tank emissions for diesel and gasoline of 19.6 and 18.4 kgCO2e/MMBtu, respectively. These estimates are used as the base case assumptions for AltSim, although AltSim provides an option for using the GREET coefficients instead (16.5 kgCO2e/MMBtu for gasoline and 11.04 kgCO2e/MMBtu for diesel).

AltSim tracks three main greenhouse gases: carbon dioxide, methane, and nitrous oxides. As each gas has different atmospheric residence times and overall effectiveness at absorbing infrared radiation and therefore affecting climate change, they are weighted according to their global warming potentials (GWP). AltSim relies on the 100 year GWP coefficients recommended by the Intergovernmental Panel on Climate Change (IPCC, 2007), Table 5. Based on these GWPs, a gram of CH_4 is equivalent to 25 grams of CO_2.

Table 5. Global warming potentials for GHGs included in AltSim.

Pollutant	Abbreviation	Global Warming Potential (GWP)
Carbon Dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	298

Navigating AltSim and Base Case Results

The model is organized into three main sections: production, end use, and scenario analysis. Each section is accessed by clicking on the corresponding hyperlink at the top of any screen, such as the one shown in Figure 4. A step by step guide to navigating within the model is included in the Appendix to this report. There is no requirement to start the model with the production section. The production section calculates the production costs, energy balances, and greenhouse gas emissions for each of the options. The energy balance and greenhouse gas emissions calculations include energy and associated emissions associated with the production and delivery of the feedstock to the production facility, as well as the energy and associated emissions from the production process itself. The production section includes options for conducting thorough sensitivity analyses for all variables. The end use section focuses on the costs, energy use, and greenhouse gas emissions at the vehicle level. For example, the greenhouse gas emissions associated with vehicle use are those associated with the combustion of the fuel. They do not include any emissions associated with producing or delivering the fuel to the vehicle, nor do they include any emissions or energy associated with building the vehicles. The scenario analysis section includes options for: greenhouse gas tax policy, land use requirement calculations, co-product analysis, production tax credits, and an option for comparing options against a baseline cost or greenhouse gas emission level (i.e., emissions 20% below gasoline).

AltSim's user interface allows users to quickly change key basic assumptions to test the sensitivity of the base case results. Figure 4 shows a representative screen from the production analysis section of the model. This particular screen is for ethanol production from corn. From this screen, one can vary capital and O&M costs, feedstock costs ($/bushel corn), and conversion ratio (bushel of corn per gallons of ethanol). The page also provides access to more detailed financial assumptions. Hyperlinks along the top allow the user to change screens. For example, clicking on "petroleum" takes the user to the gasoline and diesel specific production screens. Each production screen shows three graphs: production costs, energy balance, and GHG emissions. To make one of the smaller graphs larger, simply click on that graph.

The production economics screens show the estimated cost per gallon for each of the alternative liquid fuels. Pull down menus under each column in the figure allow the user to select which fuels to display on the screen. The same data is available in tabular form by clicking the "Table" hyperlink, found in the left-hand corner of most graphs in AltSim. Figure 5 illustrates the tabular output. The model also allows comparison of the fuels on an energy content basis ($/MMBtu) by clicking on the "$/MMBtu" hyperlink. As illustrated by Figure 6, the production cost by energy content reveals a significant difference. Specifically, on a volumetric basis, AltSim estimates corn ethanol costs $1.86 per gallon[11], comparable to gasoline production costs for crude at $57.00 per barrel. On an energy content basis, corn ethanol is $24.32 per MMBtu, compared to $16.23 $/MMBtu for gasoline produced from $57 per barrel.

[11] Does not include production tax credit, currently legislated at $0.45/gallon.

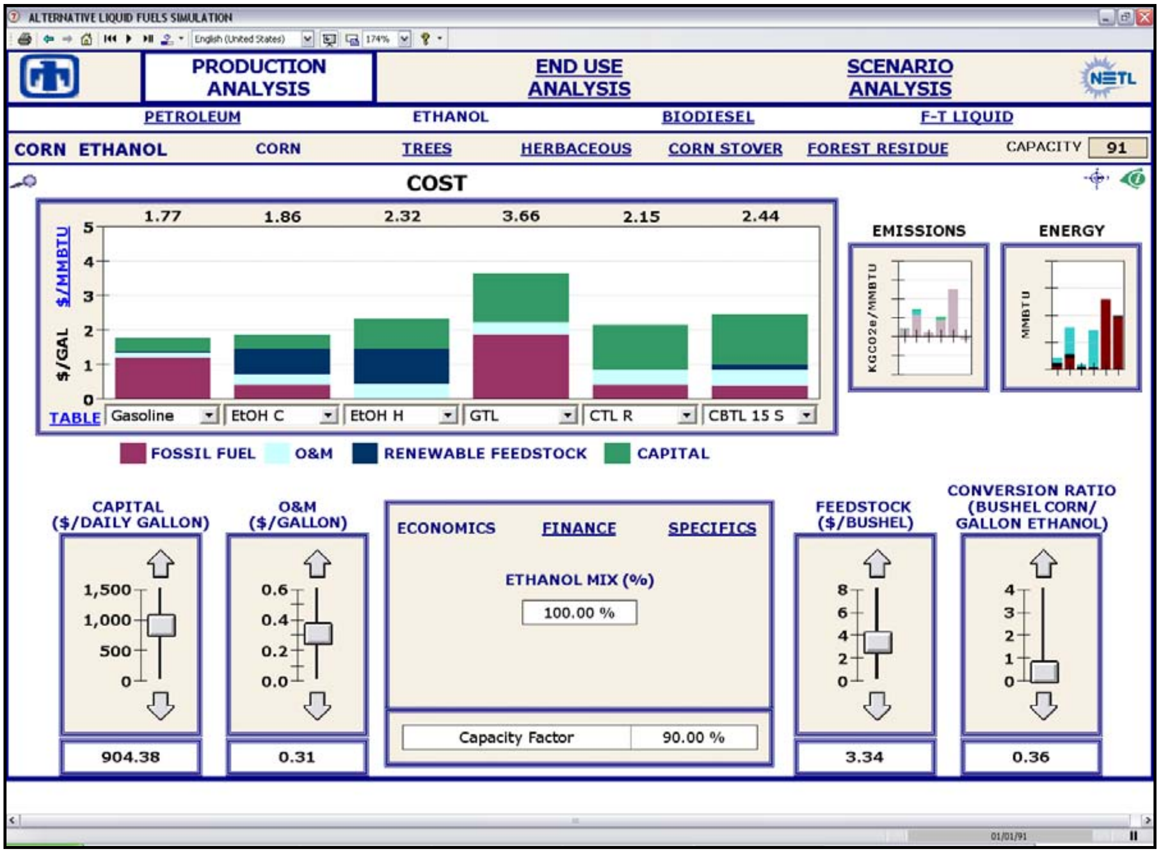


Figure 4. Representative AltSim production analysis screen (corn ethanol) showing production costs for selected fuels on volumetric basis ($/gallon).

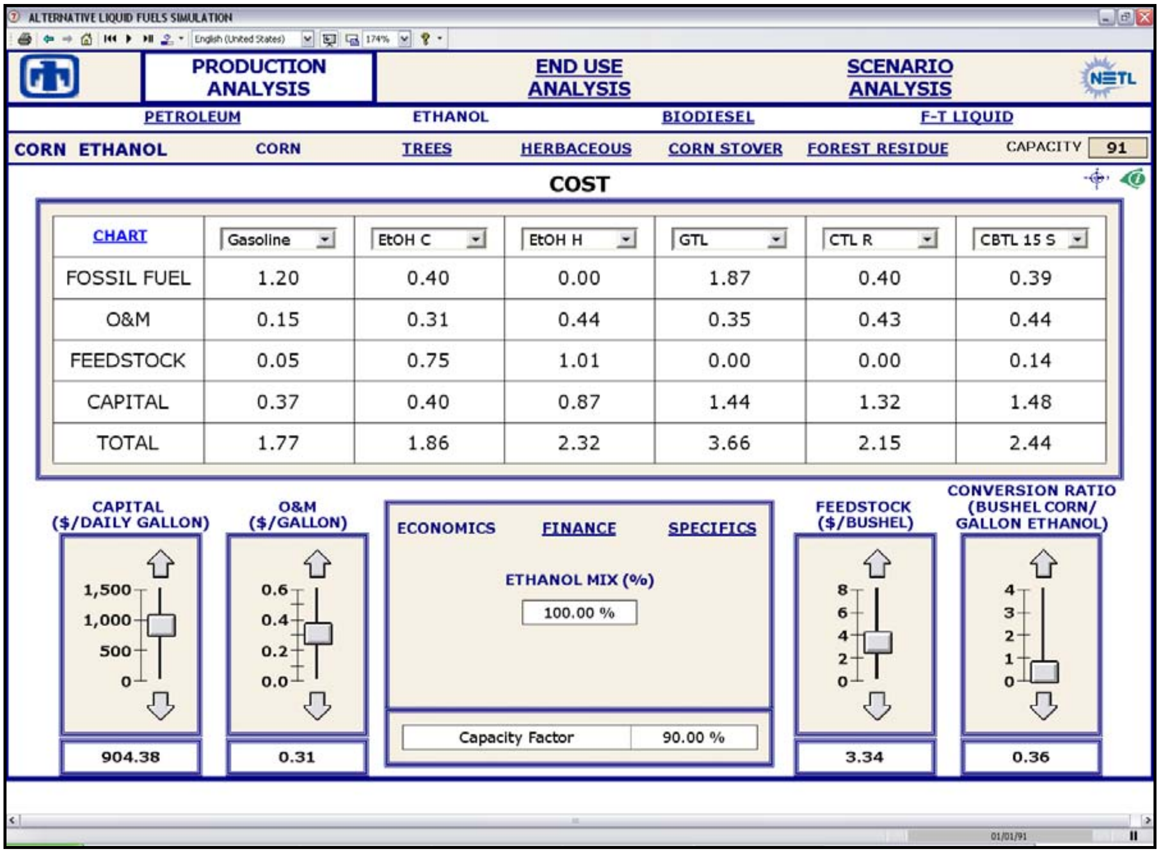


Figure 5. Representative AltSim production analysis screen (corn ethanol) showing production costs for all fuels on volumetric basis ($/gallon) in tablular format.

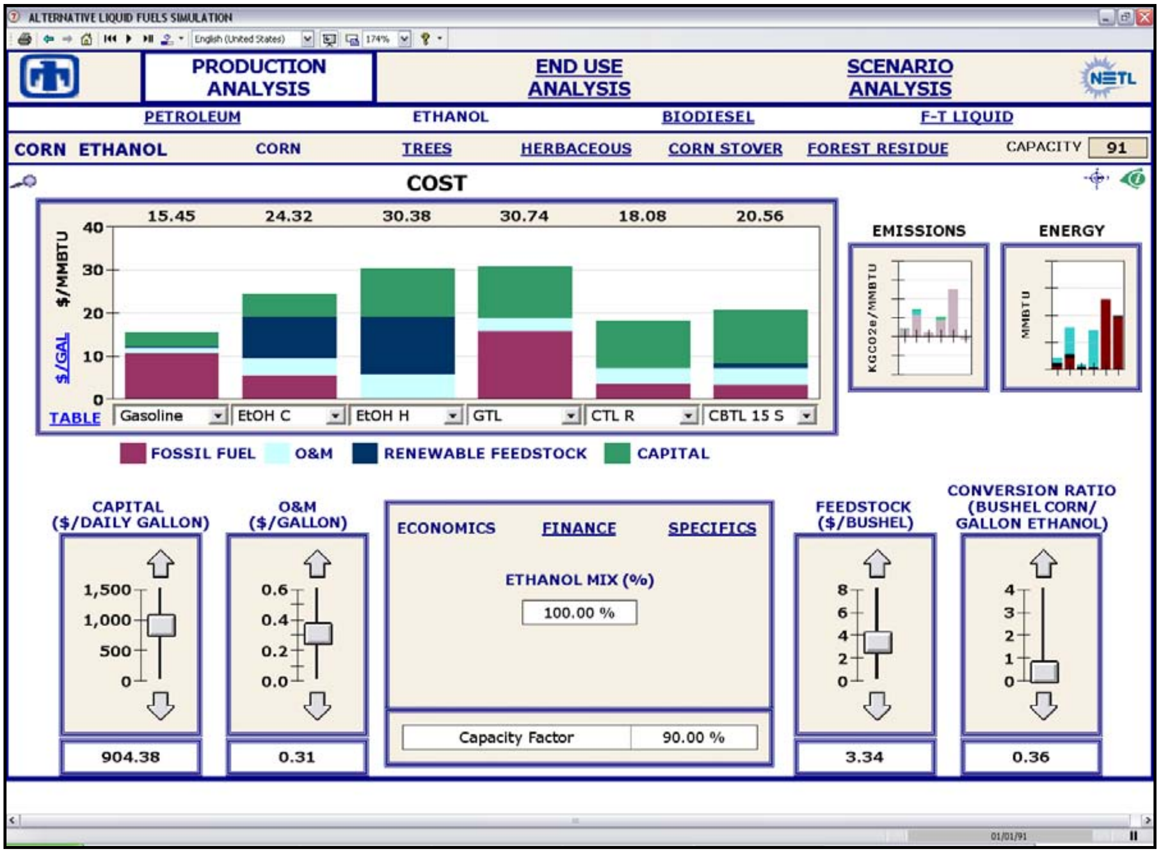


Figure 6. Representative AltSim production analysis screen (corn ethanol) showing production costs for all fuels on energy content basis ($/MMBtu).

The financial summary screen for each technology summarizes the key financial assumptions. Figure 7 shows the financial screen for corn ethanol production. From this page, the user can adjust tax rates, debt/equity financing assumptions, discount rate, construction time, depreciation period, and plant life. AltSim's default debt/equity financing ratio is 60%/40% with an assumed debt financing rate of 4.56% and an equity financing rate of 20%. The default federal and state tax rates are 35% and 6%, for an effective tax rate of 38.5%.

In addition to the financing assumptions, Figure 7 also illustrates the energy balance screen. The energy balance screen shows the energy consumed during production of each MMBtu. For the corn ethanol example shown, the production of one MMBtu of ethanol requires 0.76 MMBtu of energy inputs (0.19, 0.08, and 0.49 MMBtu of coal, oil, and natural gas respectively) during the production process. Note this is energy consumed during the production process; an alternative way of stating this energy balance would be that there is 1.76 MMBtu in for each 1.0 MMBtu out. AltSim focuses on the energy consumed during the production process broken down by fossil fuel input type. This screen also provides a checkbox to include any renewable input, such as solar used for photosynthesis.

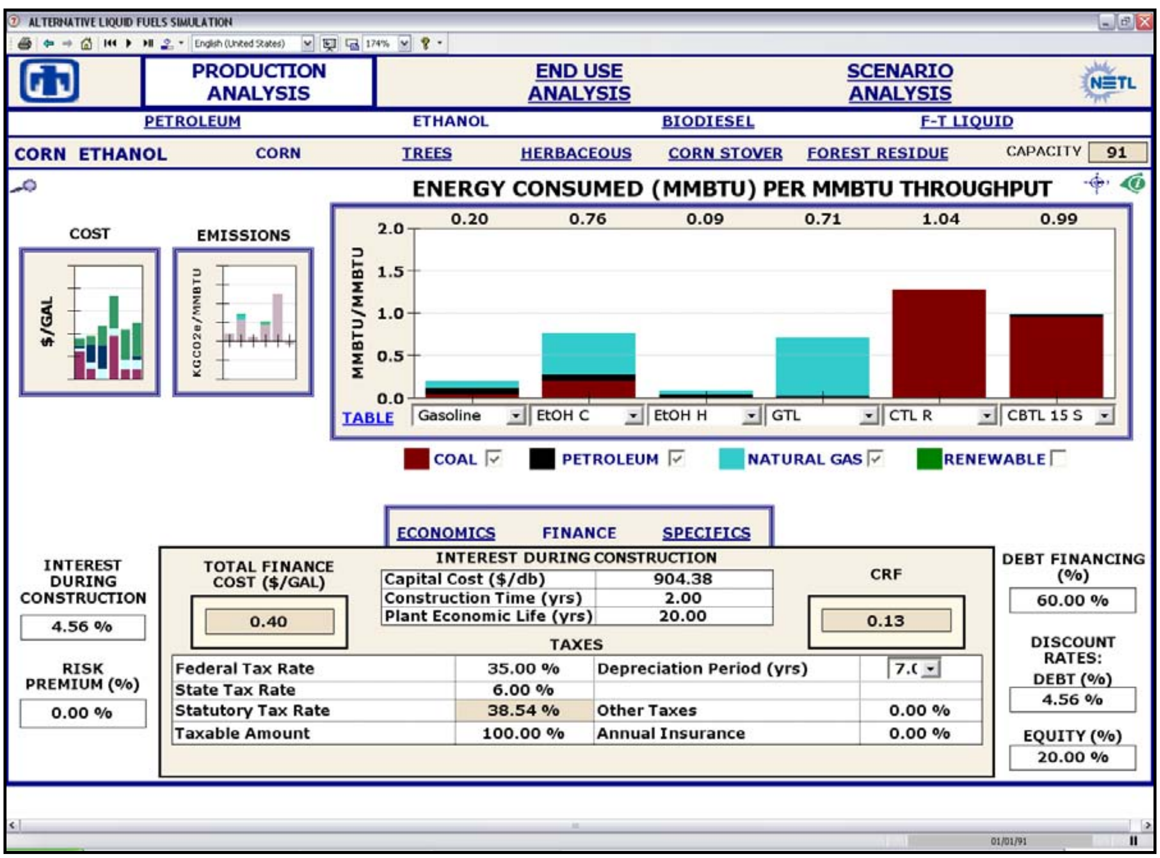
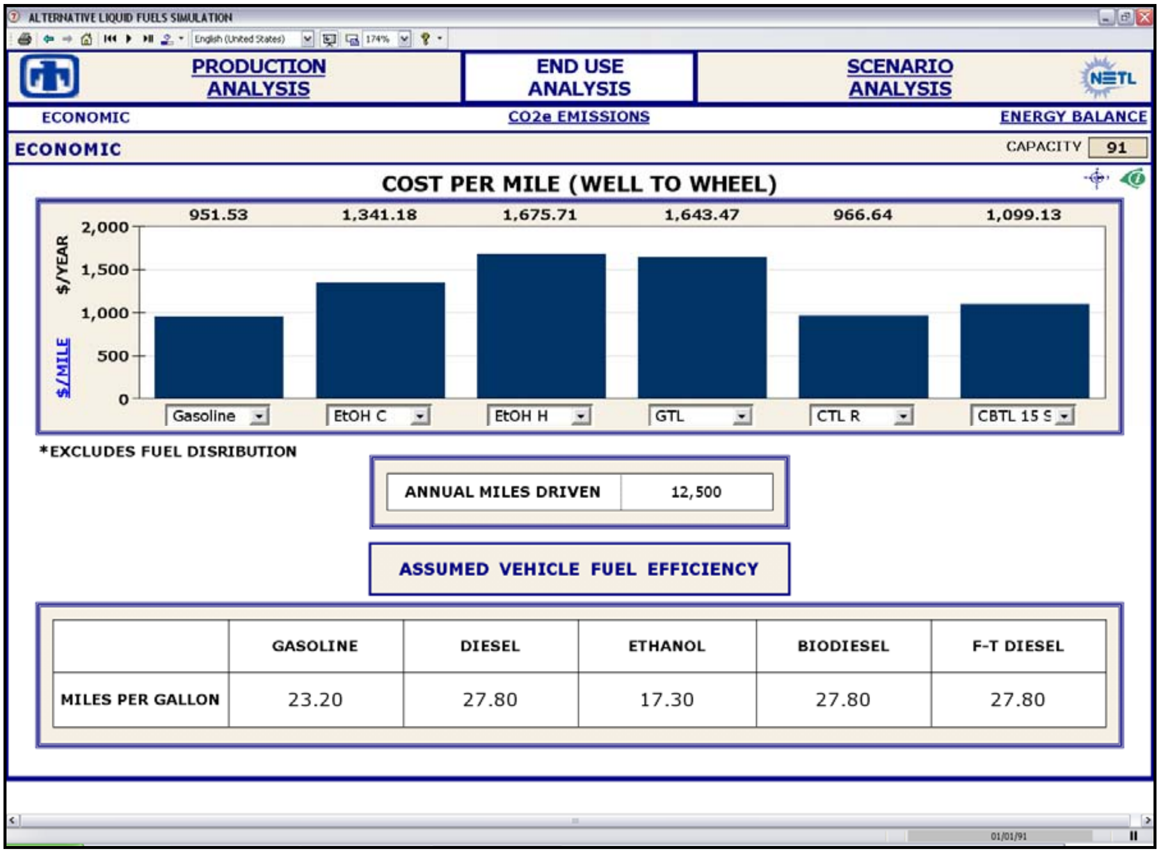


Figure 7. Financial assumptions and energy balance screen for corn ethanol.

The end use analysis section compares per mile and annual fuel costs for average vehicles in the U.S. For example, the annual cost to fuel a gasoline-powered vehicle that gets 23.1 mpg and is driven 12,500 miles per year is $952, Figure 8. The annual fuel costs for an ethanol-fueled vehicle would be $1,341 per year. The end use analysis section also includes estimates of the total GHG released during the annual operation of these vehicles and the total energy required to produce the fuel for these vehicles.



	GASOLINE	DIESEL	ETHANOL	BIODIESEL	F-T DIESEL
MILES PER GALLON	23.20	27.80	17.30	27.80	27.80

Figure 8. Representative AltSim end use analysis screen showing annual costs associated with driving a vehicle 12,500 miles.

Figure 9 illustrates the estimated well-to-wheel (WTW) GHG emissions associated with the various fuel options, not including fuel distribution. These estimates are given in both grams of CO_2 equivalent (CO_2e) per mile or annual totals for representative vehicles. For example, cars rated at 23.1 mpg using gasoline emit 475 g CO_2e per mile. Similar vehicles fueled with 100% ethanol from corn have lower fuel economy because of the lower energy content of ethanol. The CO_2 emissions associated with a vehicle running on 100% ethanol would be 642 g CO_2e per mile, or 35% higher. The situation is somewhat improved if the ethanol is derived from switchgrass (373 g CO_2 per mile, 21% below the gasoline fueled vehicle), or biodiesel from soy (411 g per mile, or 13.5% less).

Figure 9 also shows that CTL could result in significantly higher emissions of CO_2 if the CTL production does not include carbon capture and sequestration. For the CTL-R option, the emissions would be 89% higher without CCS than with CCS(868 g CO_2 per mile compared to 457 g for diesel from crude). Including biomass in the CTL process drastically reduces emissions. The CBTL-derived diesel option with 15% biomass and carbon capture and sequestration results in emissions of 297 g per mile, or 35% lower than diesel from crude.

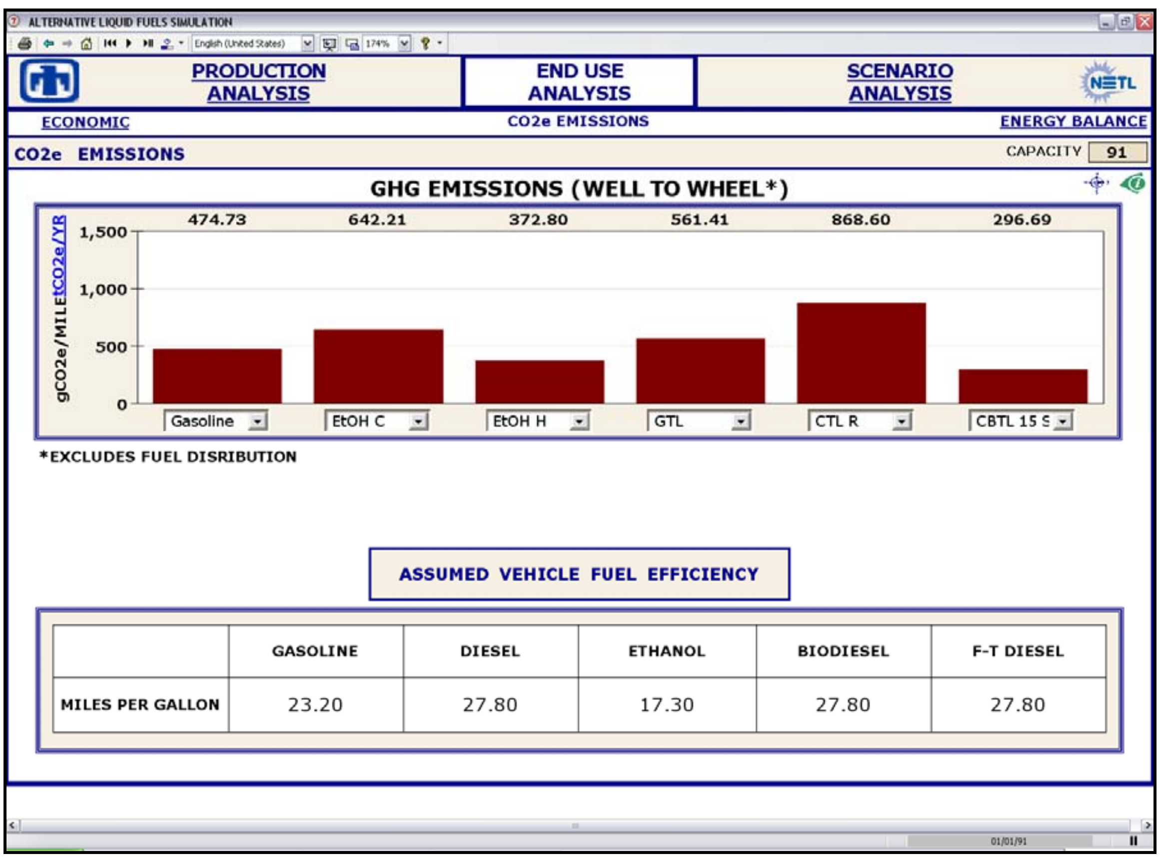


Figure 9. End use emissions screen (without sequestration).

The scenario analysis section includes options for: greenhouse gas tax policy, land use requirement calculations, co-product analysis, production tax credits, and an option for comparing options against a baseline cost or greenhouse gas emission level (i.e., emissions 20% below gasoline).

Figure 10 shows the "land requirements for corn ethanol" screen. This screen shows that replacing 10% of current U.S. gasoline demand with ethanol from corn would require 32.3 million acres of cropland, equivalent to 37% of current corn cropland or 7% of currently farmed land. One can use this screen to determine that it would take the entirety of the current corn crop to replace about 27% of our current gasoline consumption.

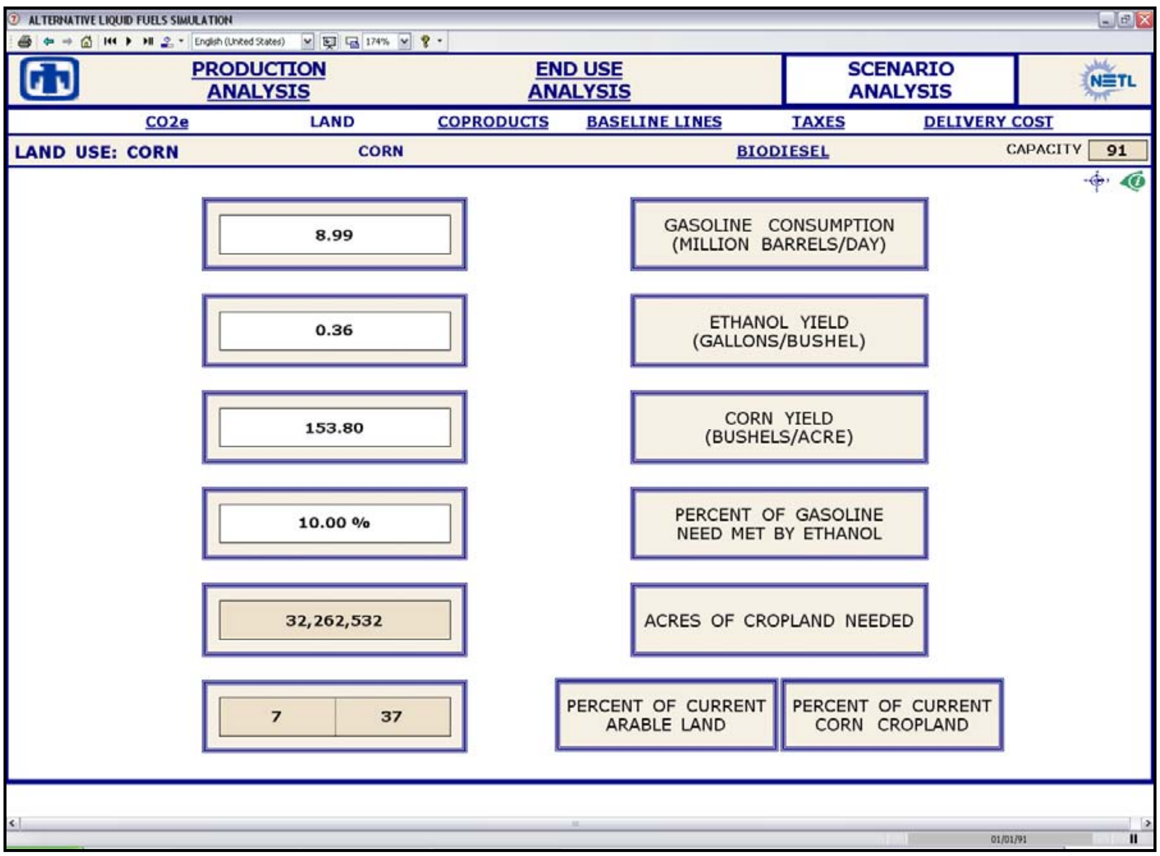


Figure 10. Land required for producing ethanol from corn.

Figure 11 illustrates the use of the baseline GHG lines feature. Both existing and proposed legislation include requirements for GHG emissions targets for fuels. Under EISA, fuels that release 20% fewer GHG emissions can qualify as renewable fuels. This screen allows the user to explore which fuels can meet various GHG reduction targets. This example shows that herbaceous ethanol and CBTL technologies with at least 8% biomass and 91.6% sequestration would meet the standard.

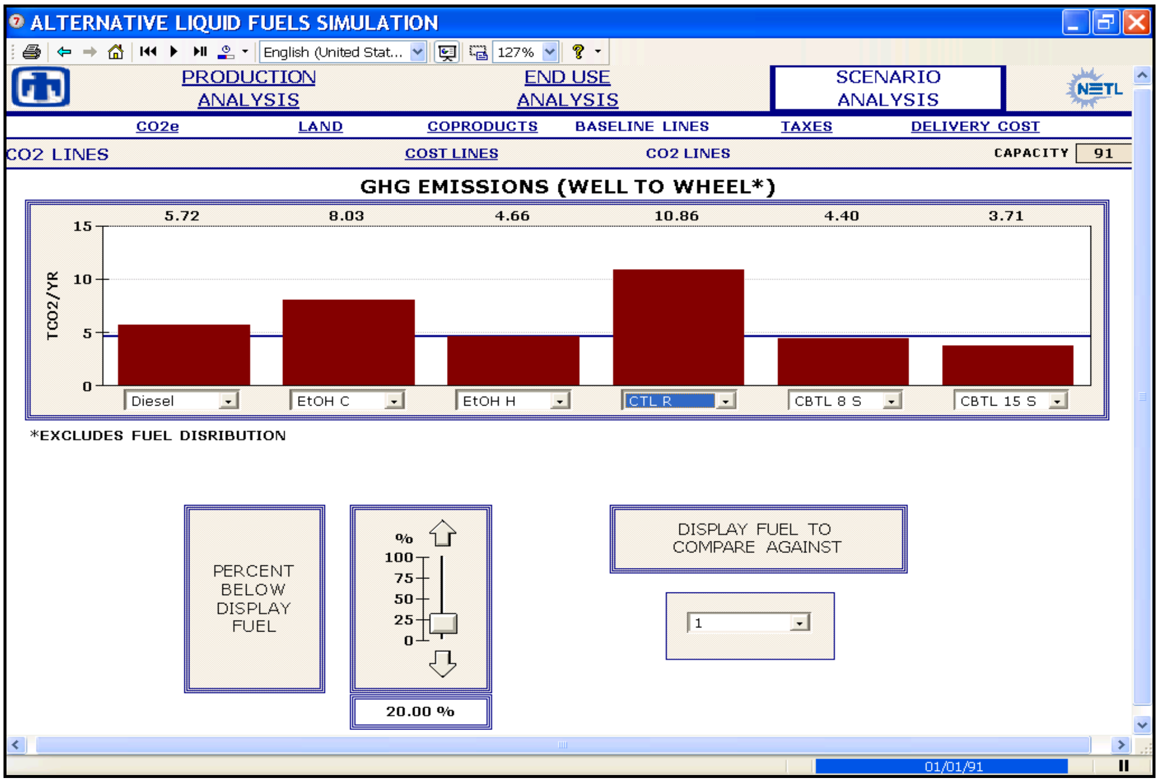


Figure 11. GHG emission baseline analysis screen showing fuels with life cycle emissions at least 20% below diesel.

Results and Sensitivity Analysis

The previous section displayed a representative set of screens showing base case results. This section provides a more comprehensive overview of the results and sensitivies for all options. Table 6 summarizes estimated production costs by fuel on both a volumetric ($/gallon) and energy content ($/MMBtu) basis. These base case production costs do not include renewable tax credits, carbon dioxide pricing, or distillers grain credit

For the base case assumptions, AltSim estimates per gallon production costs for the five ethanol feedstocks (corn, switchgrass, corn stover, forest residue, and farmed trees) of $1.86, $2.32, $2.45, $1.52, and $1.91, respectively. The projected production cost of biodiesel is $1.81/gallon. The estimates for CTL without biomass range from $1.36 to $2.22. The lower estimates are for the once through CTL technologies described by Williams et al. With biomass added to the process, the estimated costs increase, ranging from $2.19 per gallon for the CTL option with 8% biomass to $2.79 per gallon for the CTL option with 30% biomass and carbon capture and sequestration. While the economic results presented here are based on the EPA projected feedstock costs in 2022, AltSim allows the user to quickly vary key assumptions and explore the sensitivity of the outputs to changes in those key input parameters.

The results suggest that several of the CTL options could be lower cost fuel options than most of the ethanol alternatives. It is important to note, however, that most of these CTL options are are not yet commercially viable. Hence, these results must be viewed with caution. The assumptions are based on reports and estimated costs and efficiencies. AltSim is ideal for testing the sensitivity of the various assumptions and viewing those results in real time on the screen.

Table 6. Comparison of base case results in volumetric ($/gallon) and energy content ($/MMBtu).

	$/gallon	$/MMBtu
Gasoline	1.77	15.45
Diesel	1.72	13.13
Corn Ethanol	1.86	24.32
Cellulosic Ethanol (Farmed Trees)	1.91	25.07
Cellulosic Ethanol (Switchgrass)	2.32	30.38
Cellulosic Ethanol (Corn Stover)	2.45	32.05
Cellulosic Ethanol (Forest Residue)	1.52	19.94
Biodiesel	1.81	13.87
Gas to Liquid (GTL)	3.66	30.74
Coal to Liquid Once Through (CTL O)	1.36	11.42
Coal to Liquid Once Through w/ Sequestration (CTL OS)	1.57	13.17
Coal to Liquid Recycled (CTL R)	2.15	18.08
Coal to Liquid Recycled w/ Sequestration (CTL R S)	2.22	18.65
Coal +8% Biomass to Liquid w/ Sequestration (CBTL 8 S)	2.19	18.43
Coal +15% Biomass to Liquid w/ Sequestration (CBTL 15 S)	2.44	20.56
Coal +30% Biomass to Liquid w/ Sequestration (BTL S)	2.79	23.45
Biomass to Liquid w/ Sequestration (BTL S)	5.99	50.37

Table 7 summarizes the energy balances for each option in terms of energy consumed during the production process for each MMBtu of output. Several of the alternatives are very energy intensive, which results in higher GHG emissions during the production process as well. For example, 0.76 MMBtu of fossil fuels are consumed for each MMBtu of corn-based ethanol produced. The CTL and CBTL options are also very energy intensive, requiring approximately 1.0 MMBtu for each MMBtu of output. An alternative way to express these energy balances is in terms of total energy in over energy out. Expressed in this manner, corn-based ethanol requires 1.76 units of energy input for every one unit of output. Unfortunately, this version of AltSim does not allow for differentiation of energy balances for the various CBTL options, as neither the NETL study or the GREET model provide the detail necessary. This may be addressed in future versions of AltSim.

Table 7. Energy consumed per MMBTU of product for each production pathway. .

	Energy Consumed (MMBtu) per MMBtu Throughput
Gasoline	0.20
Diesel	0.14
Corn Ethanol	0.76
Cellulosic Ethanol (Farmed Trees)	-0.01
Cellulosic Ethanol (Switchgrass)	0.09
Cellulosic Ethanol (Corn Stover)	0.05
Cellulosic Ethanol (Forest Residue)	0.23
Biodiesel	0.11
Gas to Liquid (GTL)	0.71
Coal to Liquid Once Through (CTL O)	1.04
Coal to Liquid Once Through w/ Sequestration (CTL OS)	1.04
Coal to Liquid Recycled (CTL R)	1.04
Coal to Liquid Recycled w/ Sequestration (CTL R S)	1.10
Coal + Biomass to Liquid w/ Sequestration and Biomass to Liquid w/ Sequestration (CBTL S and BTL S)	0.99*

*GREET Energy balance does not differentiate by biomass content.

Table 8 compares the greenhouse gas emissions (GHG) associated with both the production and consumption of fuels generated through the various production pathways. The estimated GHG emissions associated with the production of conventional gasoline and diesel are 19.80 and 18.40 kg of CO_2 equivalent per MMBtu ($kgCO_2e$/MMBtu), respectively. The estimated emissions are significantly higher for several alternatives: ethanol from corn (70.6), GTL (51.9), and CTL without biomass or sequestration (123 – 161). Projected emissions for several other alternatives are lower; including biomass and sequestration in the CTL processes can even result in negative net emissions. For example, CTL with 30% biomass and sequestration has estimated production emissions of -38 kgCO_2e/MMBtu.

AltSim also estimates the projected well-to-wheel, or lifecycle, emissions associated with each fuel option.   Emissions associated with the manufacture of the vehicle itself are not included. Vehicles fueled with conventional diesel or gasoline and driven 12,500 miles per year are responsible for 5.72 - 5.93 tons of CO_2 equivalents per year (tCO_2e/yr). Those emissions are significantly higher for vehicles fueled with 100% ethanol from corn (8.03 tCO_2e/yr) or diesel from CTL without sequestration (10.86 to 12.85 tCO_2/yr). Emissions could be significantly lower for vehicles fueled with diesel from CTL with various shares of biomass. For example, for CTL with 30% biomass and carbon sequestration, emissions would be 2.21 tCO2e per year, or just 39% of the emissions for a vehicle fueled with conventional diesel. On an energy content basis, ethanol produced from corn results in significantly higher emissions (70.6 kgCO2e/MMBtu) than associated with producing gasoline or diesel from crude. Production emissions associated with the CTL options vary from 161 kgCO2e/MMBtu for the once through CTL process (CTL O) to negative emissions for those options that include sequestration. For example, the estimated production emissions for CBTL with 30% biomass and sequestion are -38 kgCO2e/MMBtu.

Table 9 also provides a comparison of estimated emissions for gasoline and diesel using baseline emissions profiles given by GREET and NETL. The NETL coefficients (AltSim's base case assumption) result in higher emissions than using those associated with GREET. For example, the estimated production emissions for gasoline using the GREET coefficients are 16.50 kgCO2e/MMBtu compared to 19.80 kgCO2e/MMBtu using the NETL coefficients (20% difference). The difference in terms of end use are not as large: 5.73 tCO_2/yr using GREET compared to 5.93 tCO_2/yr using the NETL coefficients, a 3.4% difference.

Table 8. Comparison of base case results for GHG emissions.

	Production GHG (kgCO2e/ MMBtu)	End Use GHG (ton CO2e/year)
Gasoline (GREET)	16.50	5.73
Gasoline (NETL)	19.80	5.93
Diesel (GREET)	11.04	5.29
Diesel (NETL)	18.40	5.72
Corn Ethanol	70.62	8.03
Cellulosic Ethanol (Farmed Trees)	1.62	4.22
Cellulosic Ethanol (Switchgrass)	9.56	4.66
Cellulosic Ethanol (Corn Stover)	5.00	4.41
Cellulosic Ethanol (Forest Residue)	21.14	5.30
Biodiesel	9.05	4.79
Gas to Liquid (GTL)	51.89	7.02
Coal to Liquid Once Through (CTL O)	161.00	12.85
Coal to Liquid Once Through w/ Sequestration (CTL OS)	17.00	5.15
Coal to Liquid Recycled (CTL R)	123.71	10.86
Coal to Liquid Recycled w/ Sequestration (CTL R S)	11.66	4.87
Coal +8% Biomass to Liquid w/ Sequestration (CBTL 8 S)	3.00	4.40
Coal +15% Biomass to Liquid w/ Sequestration (CBTL 15 S)	-10.00	3.71
Coal +30% Biomass to Liquid w/ Sequestration (CBTL S)	-38.00	2.21
Biomass to Liquid w/ Sequestration (BTL S)	-82.00	-0.14

Table 9. Comparison of emission sources (Kg CO_2e/ MMBtu).

	GREET	NETL	ALTSim
Gasoline Production	16.5	19.8	19.8
Gasoline End Use	76.5	76.6	76.5
Diesel Production	11.0	18.4	18.4
Diesel End Use	71.9	76.7	71.9

Table 9 illustrates the difference between each source of conventional fuel. AltSim is initially set to use NETL's emission coefficients for production. There is a significant production difference between NETL and GREET. The difference between NETL and AltSim end use emissions is due to the lower assumed miles per gallon in AltSim. In the case of diesel, NETL assumes a 31.9 mile per gallon fuel economy, while AltSim uses a 27.8 mpg rating from GREET. The effect of fuel economy on vehicle emissions can be observed in more detail with Figure 26.

Sensitivity Analysis

AltSim's sensitivity analysis screens are useful for examing various scenario-related questions such as: at what crude price could ethanol from corn compete with gasoline on an energy content basis and without production tax credits? The base case assumptions result in projected production costs for corn based ethanol of $24.32 per MMBtu compared to $15.45 for gasoline from crude priced at $53/barrel. AltSim suggests the price of crude would have to approach $100/bbl before corn-based ethanol could compete.

Table 10 is a summary table showing the sensitivity of the base case results to a 10% change in the capital, O&M, and feedstock costs, conversion efficiencies, and capacity factors. For example, every 10% increase in crude oil cost increases the production cost for gasoline by $0.27 per gallon, or $2.29 per MMBtu. For ethanol produced from corn, a 10% increase in feedstock cost results in a $0.28 per gallon increase. The GTL, CTL, and CBTL are particularly sensitive to changes in the capital costs.

Table 10. Production cost sensitivity analysis.

Fuel	$/gallon	$/MMBtu
Reformulated Gasoline	1.77	15.45
Capital ±10%	±0.03	±0.30
O&M ±10%	±0.01	±0.14
Feedstock ±10%	±0.11	±1.03
Conversion ±10%	±0.11	±1.03
Capacity factor -10%	+0.04	+0.28
Low Sulfur Diesel	1.72	13.13
Capital ±10%	±0.04	±0.25
O&M ±10%	±0.02	±0.13
Feedstock ±10%	±0.13	±0.96
Conversion ±10%	±0.13	±0.96
Capacity factor -10%	+0.04	+0.32
Corn Ethanol	1.86	24.32
Capital ±10%	±0.04	±0.52
O&M ±10%	±0.03	±0.40
Feedstock ±10%	±0.12	±1.57
Conversion ±10%	±0.07	±0.97
Capacity factor -10%	+0.05	+0.65
Farmed Tree Cellulosic Ethanol	1.91	25.07
Capital ±10%	±0.04	±0.54
O&M ±10%	±0.03	±0.31
Feedstock ±10%	±0.13	±1.66
Conversion ±10%	±0.13	±1.66
Capacity factor -10%	+0.06	+0.68

Table 10. Production cost sensitivity analysis (cont.).

Herbaceous Cellulosic Ethanol	2.32	30.38
Capital ±10%	±0.09	±1.14
O&M ±10%	±0.04	±0.54
Feedstock ±10%	±0.10	±1.33
Conversion ±10%	±0.10	±1.33
Capacity factor -10%	+0.10	+1.42
Corn Stover Cellulosic Ethanol	2.45	32.05
Capital ±10%	±0.05	±0.71
O&M ±10%	±0.02	±0.26
Feedstock ±10%	±0.12	±1.66
Conversion ±10%	±0.12	±1.66
Capacity factor -10%	+0.06	+0.89
Forest Residue Cellulosic Ethanol	1.52	19.94
Capital ±10%	±0.04	±0.55
O&M ±10%	±0.03	±0.31
Feedstock ±10%	±0.09	±1.15
Conversion ±10%	±0.09	±1.15
Capacity factor -10%	+0.05	+0.68
Biodiesel	1.81	13.87
Capital ±10%	±0.01	±0.03
O&M ±10%	±0.01	±0.03
Feedstock ±10%	±0.04	±0.26
Conversion ±10%	±0.04	±0.26
Capacity factor -10%	+0.01	+0.03
GTL	3.66	30.74
Capital ±10%	±0.14	±1.21
O&M ±10%	±0.03	±0.29
Feedstock ±10%	±0.18	±1.57
Conversion ±10%	±0.18	±1.57
Capacity factor -10%	+0.17	+1.51
CTL O	1.36	11.42
Capital ±10%	±0.12	±1.05
O&M ±10%	±0.02	±0.22
Feedstock ±10%	±0.07	±0.59
Conversion ±10%	±0.07	±0.59
Capacity factor -10%	+0.15	+1.31

Table 10. Production cost sensitivity analysis (cont.).

CTL O S	1.57	13.17
Capital ±10%	±0.13	±1.14
O&M ±10%	±0.03	±0.25
Feedstock ±10%	±0.07	±0.59
Conversion ±10%	±0.07	±0.59
Capacity factor -10%	+0.17	+1.43
CTL R	2.15	18.08
Capital ±10%	±0.13	±1.11
O&M ±10%	±0.04	±0.38
Feedstock ±10%	±0.04	±0.34
Conversion ±10%	±0.04	±0.34
Capacity factor -10%	+0.16	+1.39
CTL R S	2.22	18.65
Capital ±10%	±0.13	±1.15
O&M ±10%	±0.04	±0.39
Feedstock ±10%	±0.04	±0.33
Conversion ±10%	±0.04	±0.33
Capacity factor -10%	+0.17	+1.44
CBTL 8 S	2.19	18.43
Capital ±10%	±0.13	±1.12
O&M ±10%	±0.05	±0.38
Coal Feedstock ±10%	±0.04	±0.32
Biomass Feedstock ±10%	±0.01	±0.06
Coal Conversion ±10%	±0.03	±0.28
Biomass Conversion ±10%	±0.00	±0.04
Capacity factor -10%	+0.17	+1.39
CBTL 15 S	2.44	20.56
Capital ±10%	±0.15	±1.34
O&M ±10%	±0.05	±0.37
Coal Feedstock ±10%	±0.04	±0.33
Biomass Feedstock ±10%	±0.02	±0.13
Coal Conversion ±10%	±0.03	±0.24
Biomass Conversion ±10%	±0.01	±0.11
Capacity factor -10%	+0.19	+1.55
CBTL 30 S	2.79	23.45
Capital ±10%	±0.16	±1.40
O&M ±10%	±0.05	±0.43
Coal Feedstock ±10%	±0.03	±0.28
Biomass Feedstock ±10%	±0.03	±0.24
Coal Conversion ±10%	±0.03	±0.26
Biomass Conversion ±10%	±0.03	±0.22
Capacity factor -10%	+0.21	+1.75

Table 10. Production cost sensitivity analysis (cont.).

BTL S	5.99	50.37
Capital ±10%	±0.33	±2.79
O&M ±10%	±0.09	±0.75
Biomass Feedstock ±10%	±0.18	±1.51
Biomass Conversion ±10%	±0.18	±1.51
Capacity factor -10%	+0.44	+3.72

The following graphs illustrate the key sensitivities over a larger range.
For gasoline and diesel, the key sensitivity is feedstock cost, Figures 12 and 13. The base case assumes a crude cost of $53/bbl. As crude prices increase, the alternatives become more attractive. CTL O, CTL O S, and ethanol from forest residue are still cost competitive for crude prices at around $40/bbl. Holding corn prices constant (and everything else except crude prices), corn based ethanol only becomes competitive above crude prices of $57. Diesel from the CBTL 30 S option becomes competitive with diesel from crude at around $100 per barrel. In reality, increased crude prices will also affect the estimated production costs for other options. For example, increased gasoline prices would likely drive up corn prices and the production estimates for ethanol. Such feedbacks are not considered in AltSim, as we rely on projected market value of feedstock costs as discussed previously.

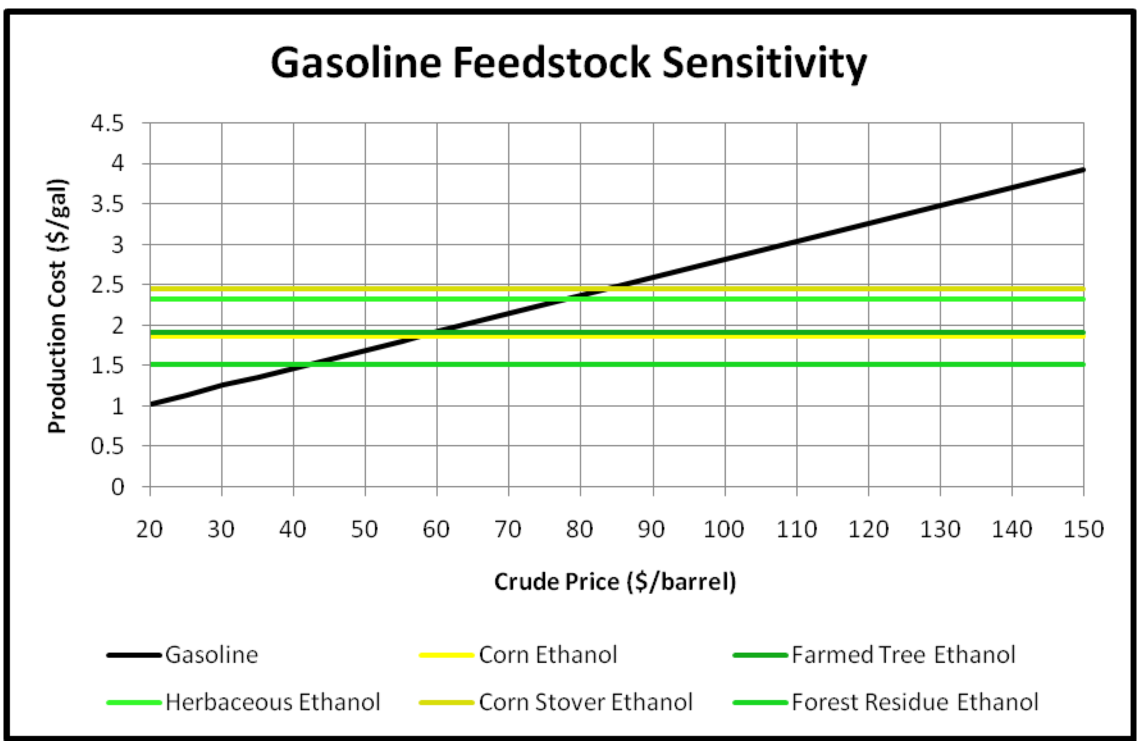


Figure 12. Gasoline feedstock sensitivity.

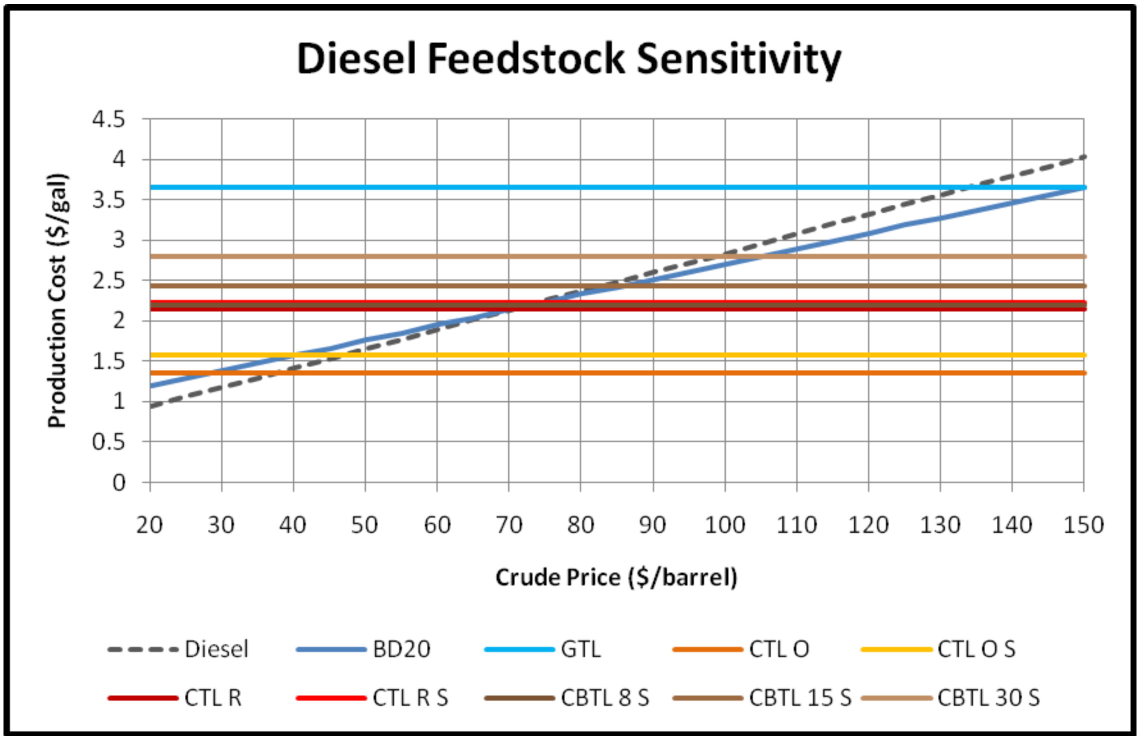


Figure 13. Diesel feedstock sensitivity.

Figure 14 illustrates the sensitivity of corn ethanol to feedstock costs. At corn prices above $5 per bushel, corn ethanol is no longer competitive with any of the gasoline substitutes. As recently as 2006, the cost of corn (Figure 15) was down around $2.00/bushel which made corn ethanol competitive with all cellulosic ethanol and considerably cheaper than gasoline produced from $50 per barrel crude. Average corn prices climbed from $3.32/bushel in August of 2007 to $5.24/bushel in August 2008; a 63% rise in a year (USDA). For the RFS2 forecast average corn price of $3.34, corn ethanol is not competitive with gasoline refined from $53/bbl crude. This does not include any production tax credits or other subsidies, such as the $0.45 per gallon federal subsidy. It is important to note that these graphs do not capture the linkages between commodity prices. Commodity prices often move together in the markets. Such movements must be explored manually in AltSim, as the prices within the model are not linked.

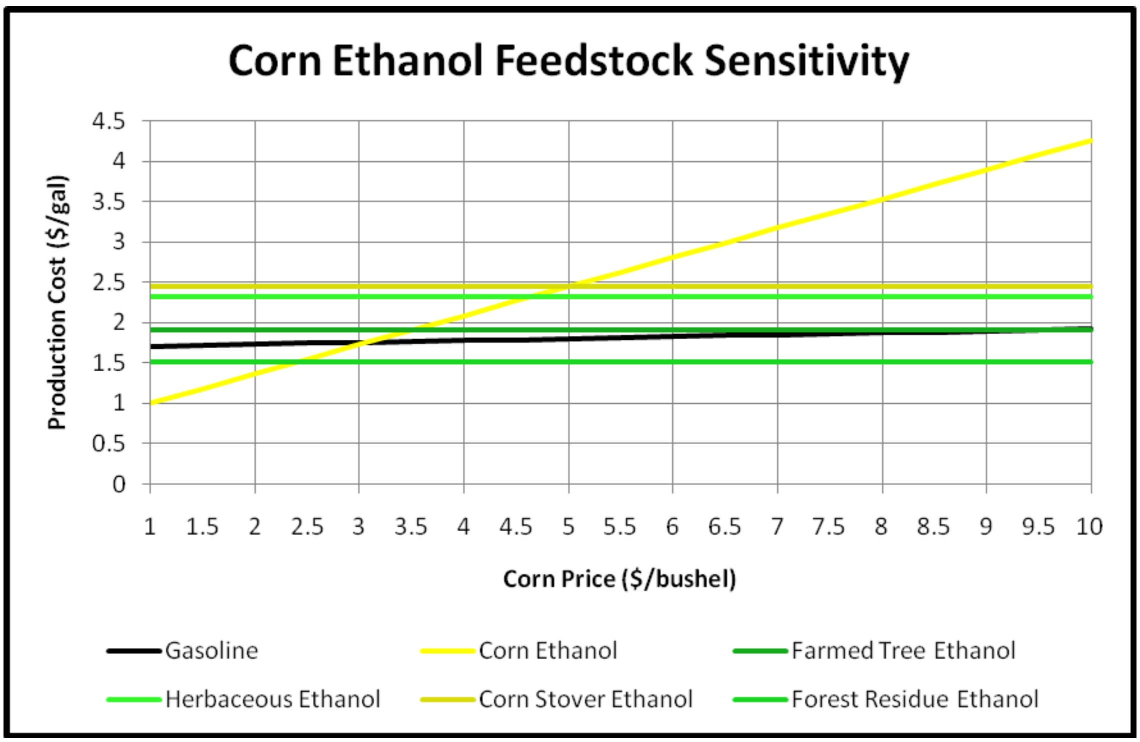


Figure 14. Corn ethanol feedstock sensitivity.

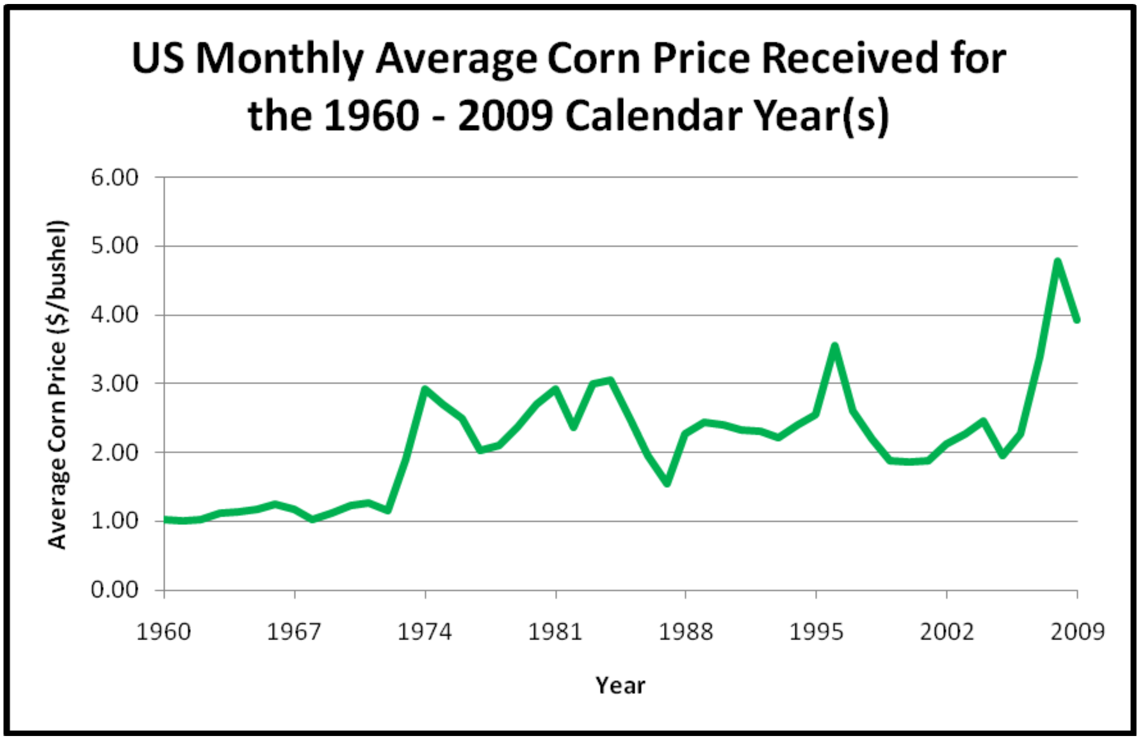


Figure 15. Historical corn prices (Source: USDA, 2008).

The biodiesel base case assumes a 20% blend rate with diesel, referred to as B20. At that blend rate, the biodiesel results are not particularly sensitive to feedstock cost, Figure 16. However, the production costs are very sensitive to feedstock costs in the case of B100 (100% biodiesel) as also illustrated in Figure 16. B100 becomes competitive with the B20 for soy prices around $0.17/pound. For the base case assumption of $0.23/pound, biodiesel is not currently competitive with any of the technologies. This analysis does not include production tax credits or other subsidies. The federal tax credit for biodiesel (B100) is $1.00 per gallon, which as Figure 16 illustrates, is necessary to make B100 a competitive option. This price sensitivity reveals why small-scale production of biodiesel from free or inexpensive feedstocks, such as waste vegetable oil, makes economic sense.

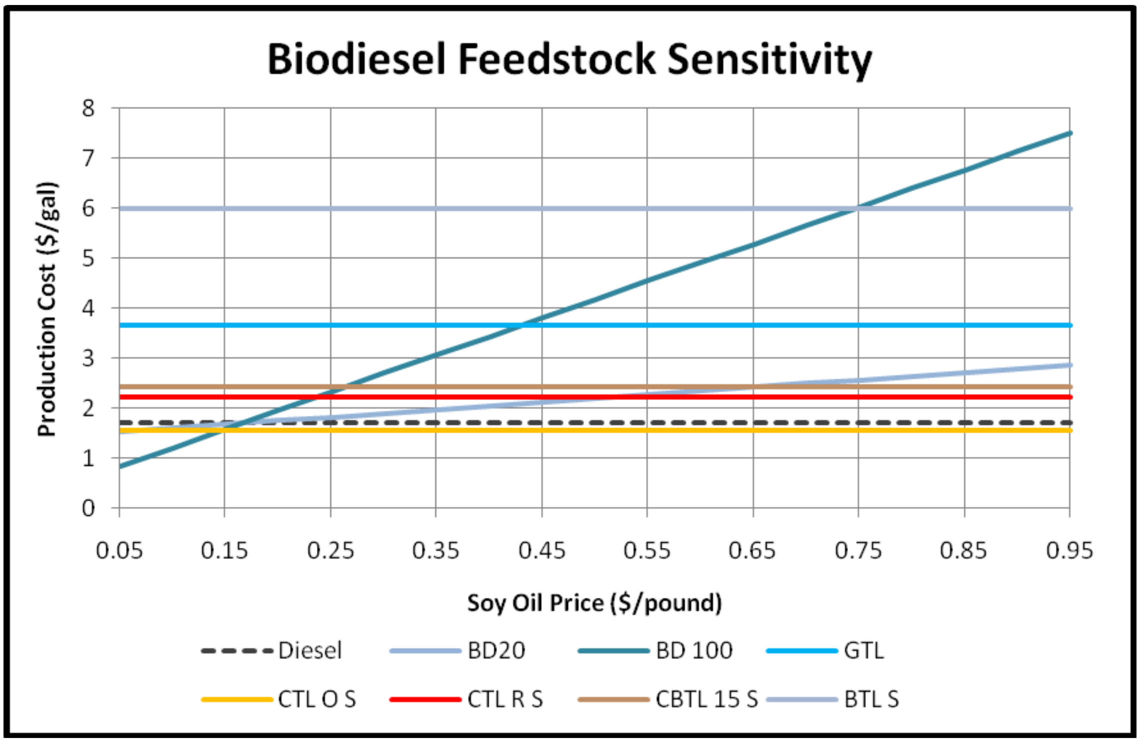


Figure 16. Biodiesel feedstock sensitivity.

Figure 17 shows the affect of varying feedstock costs for several of the gasoline substitutes on a percentage basis. The solid lines illustrate the results of this sensitivity analysis; the dashed lines show the base case results. While there are large changes in production costs as feedstock costs increase, the relative competitiveness of the options change little. As the feedstocks for crude and corn ethanol are at relatively low prices compared to just a year ago, the graph reveals how changes in feedstock cost can drastically change a technology's economic viability. For crude oil prices half as expensive as the base case ($26.5), only forest residue ethanol can be competitive.

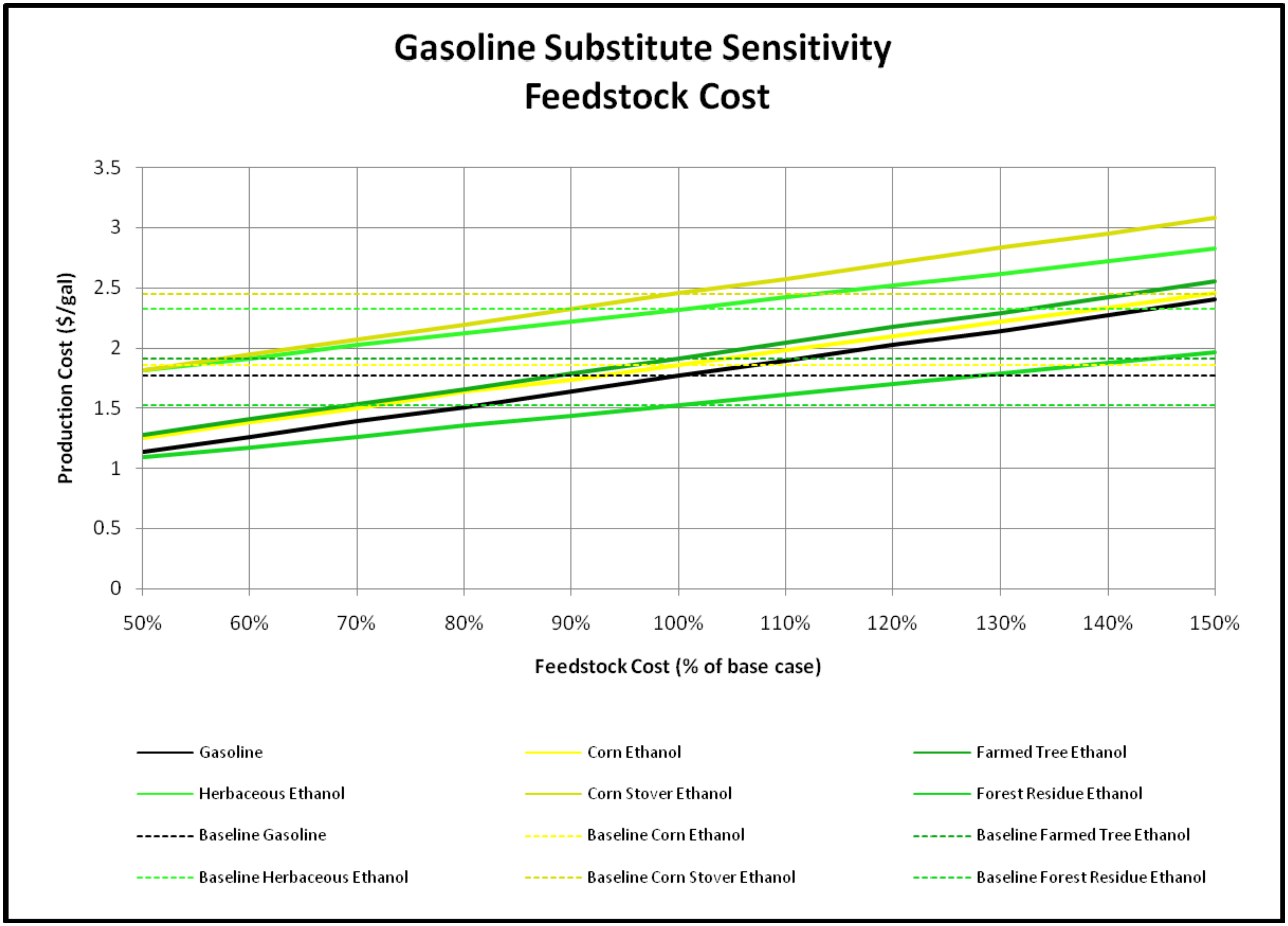


Figure 17. Gasoline substitute feedstock sensitivity (100% is the base case).

Figure 18 illustrates the sensitivity of capital costs for several of the substitutes and gasoline in percentage terms. The solid lines indicate the production costs at each level of capital cost; the dashed lines are the base case results. The base case is where the capital costs are 100% of base. This analysis suggests that while production costs are sensitive to changes in capital costs, the relative competitiveness does not change much for similar percentage changes in capital costs. For the base case, corn ethanol and gasoline are very close in production cost. This result does not change as capital costs change. Herbaceous ethanol's larger sensitivity to capital costs allows it to become viable with the base case farmed tree ethanol at 50% of base case capital.

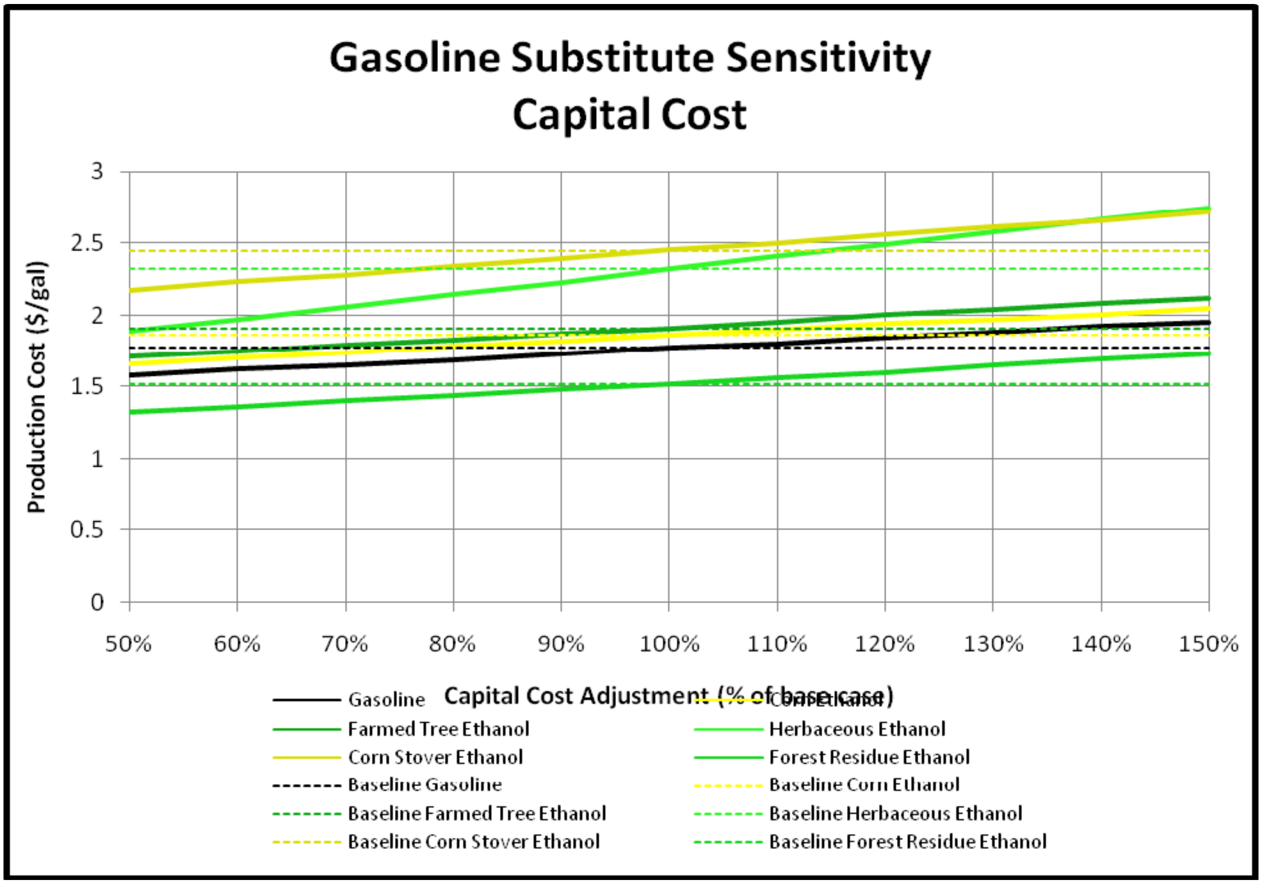


Figure 18. Gasoline substitute capital cost sensitivity (100% is the base case).

Figure 19 shows both the capital and feedstock cost sensitivities for GTL. Initial plans for Shell's Pearl GTL plant in Qatar suggested capital costs in the $50,000/daily barrel range ($6 billion for a 140,000 barrels per day plant) and assumed that the natural gas was a stranded resource worth about $0.50 per MMBTU. Based on those assumptions, AltSim estimates a production cost of $1.12/gallon (the GTL stranded asset scenario). A second scenario considers a higher value for the natural gas (the GTL Qatar value approach) based on the assumption that the natural gas can be liquefied and transported to the European markets. AltSim calculates the cost of transporting the natural gas to market (Kessler, 2005) and subtracts this cost from the current market price to get the value of this "stranded resource." The third scenario employs production costs for a full market value for the natural gas (GTL market value approach). As these different scenarios illustrate, GTL can be cost competitive for the "Qatar Value" and "stranded natural gas scenarios"; however at current market value it would take unrealistically reduced capital costs to allow GTL to be competitive. Estimated capital costs have climbed significantly in recent years, pushing the production cost for GTL up significantly.

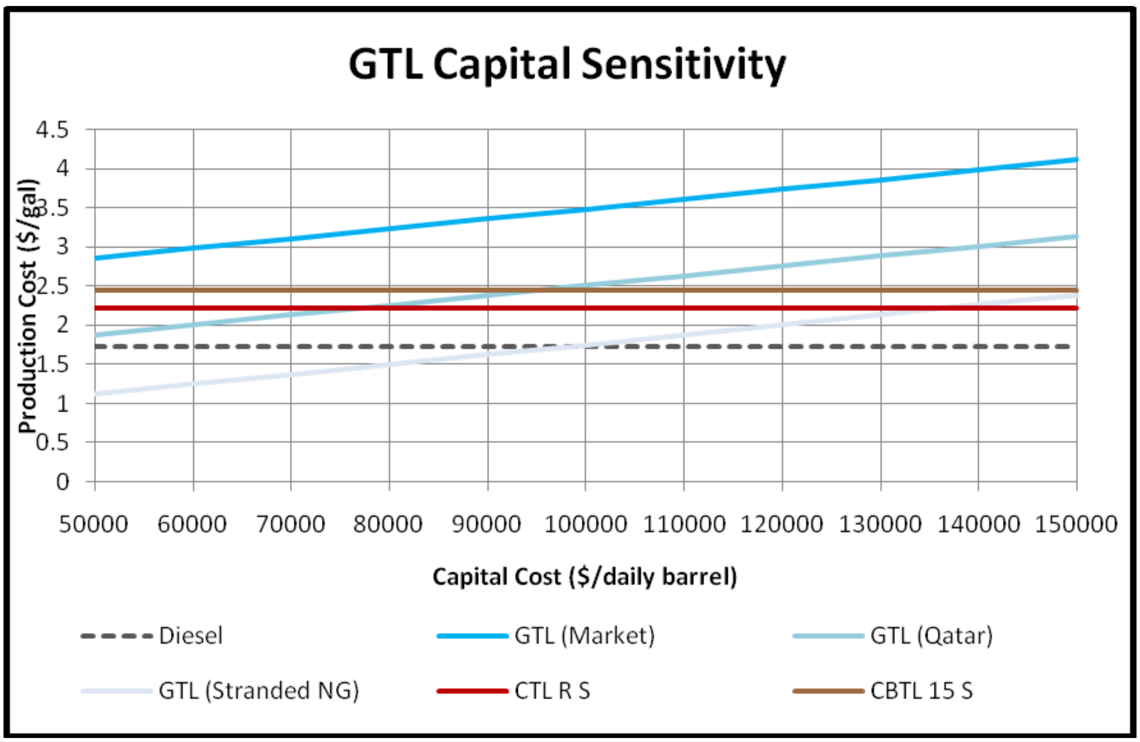


Figure 19. GTL capital sensitivity.

As substitutes for replacing conventional diesel, CTL and CBTL are very competitive options in the base case (Figure 20).   The key sensitivity for these two alternatives is capital cost. In the absence of carbon dioxide pricing, CTL O S diesel is cheaper than conventional diesel unless capital costs for CTL O S increase by 15%. AltSim includes reference assumptions from two plant designs for CTL, once through and recycled. Figure 20 illustrates the significant difference for these two sets of assumptions. Production cost estimates are significantly cheaper for the once through design. As neither type of plant has been built, the estimates have a large degree of uncertainty. Resolving this uncertainty will be important for understanding the likely competiveness of either option relative to conventional sources. This analysis shows, however, that at low crude prices, it will take significant reductions in capital costs for CTL R and CBTL options to be cost competitive. Figure 20 also illustrates that the BTL results are even more sensitive to changes in capital costs than CTL or CBTL and would require a reduction of more than 50% in capital cost to become economically viable.

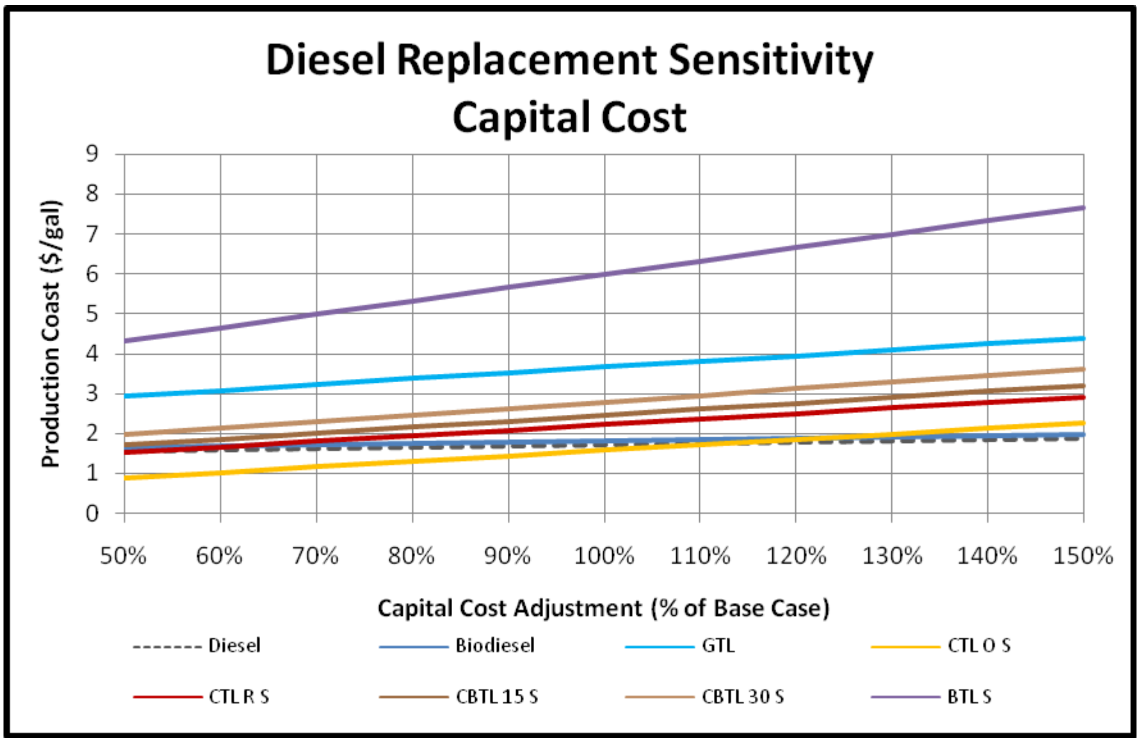


Figure 20. Diesel substitute capital sensitivity.

A major concern for any alternative fuel is the potential GHG emissions. The results shown here suggest that emissions could actually increase if conventional gasoline or diesel were replaced by corn-based ethanol or CTL without biomass and carbon capture and sequestration. This section considers the use of carbon taxes or fees at both the production level and the end use level to show how such policies would affect the relative economic competitiveness of the various options.

Figures 21, 22, and 23 consider the impact of taxes or fees on GHGs (carbon dioxide equivalents (CO_2e)) released during the production process (not from vehicle tailpipes). Those technologies which release more GHG during the production process are more affected by the additional fees. For the gasoline substitutes, corn ethanol is the most sensitive to a tax; a hundred dollar per ton adds $0.54 per gallon to the estimated production cost. The GHG has less of an impact on the other ethanol fuels.

As for the diesel substitutes, the high emissions from non-sequestered CTL technologies are very sensitive to the tax; a $100/ton tax results in a additional $1.92 per gallon and $1.47 per gallon for CTL O and CTL R respectively. CBTL 15 S, CBTL 30 S and BTL S actually have a negative GHG balance as they are able to sequester carbon that was taken out of the atmosphere by switchgrass during its growth. This results in a tax credit, reducing the production cost by $0.11 for CBTL 15 S, $0.45 for CBTL 30 S, and $0.98 for BTL S at a tax of $100/ton. This doesn't change their relative competitiveness compared to other technologies, however it does allow CBTL 30 S to come within $0.01 of CBTL 15 S production cost at $100/ton.

Figures 21 – 23 also illustrate the sensitivity of the results to the choice of the baseline GHG coefficients for diesel and gasoline (NETL vs. GREET). As noted in the discussion of assumptions regarding greenhouse gas emissions, AltSim relies on the coefficients derived by NETL in their 2008 report. These estimates are higher than assumed by GREET. When comparing the two GHG baselines for the petroleum fuels (NETL vs. GREET), it is interesting to note that while the difference may be minor in terms of GHG emissions, it does make an economic impact in a CO_2e tax scheme. As seen in Figure 23, the difference between the two is $0.037 for gasoline and $0.096 for diesel at the 100$/ton tax level. Due to the extreme nature of diesel substitutes' GHG emissions, either high or low, the ten cent difference does not change the competitiveness of the substitutes, despite being larger than the gasoline variation.

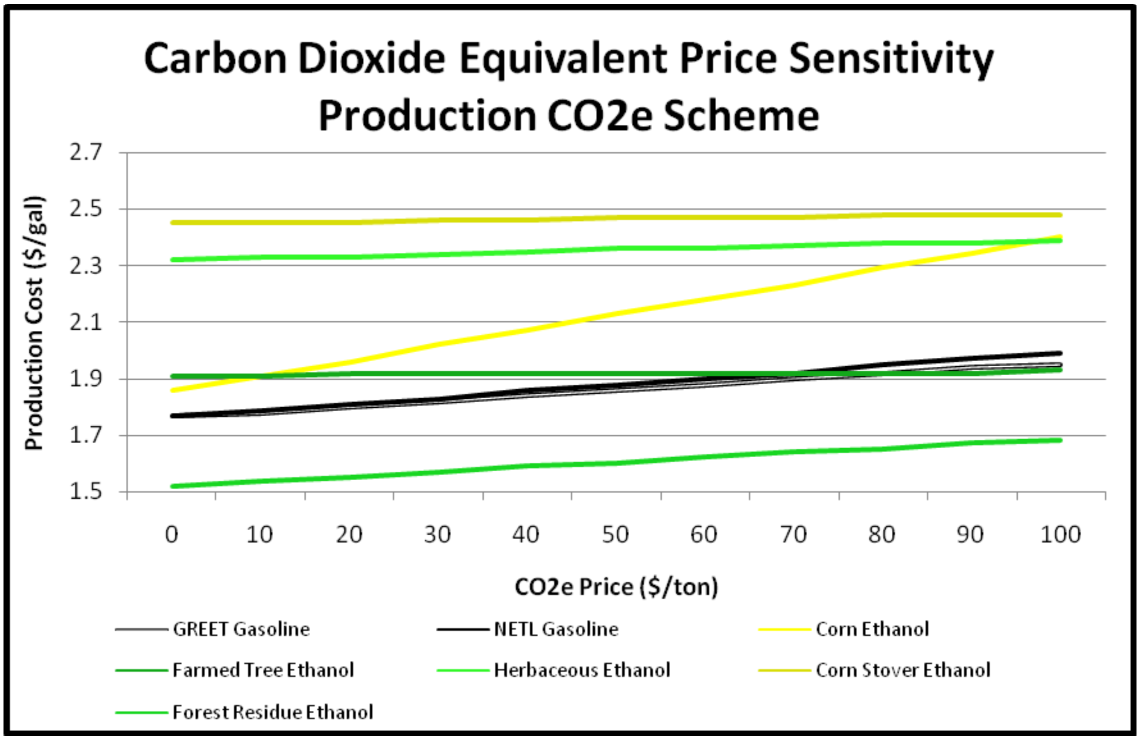


Figure 21. Carbon taxation at production level for gasoline substitutes.

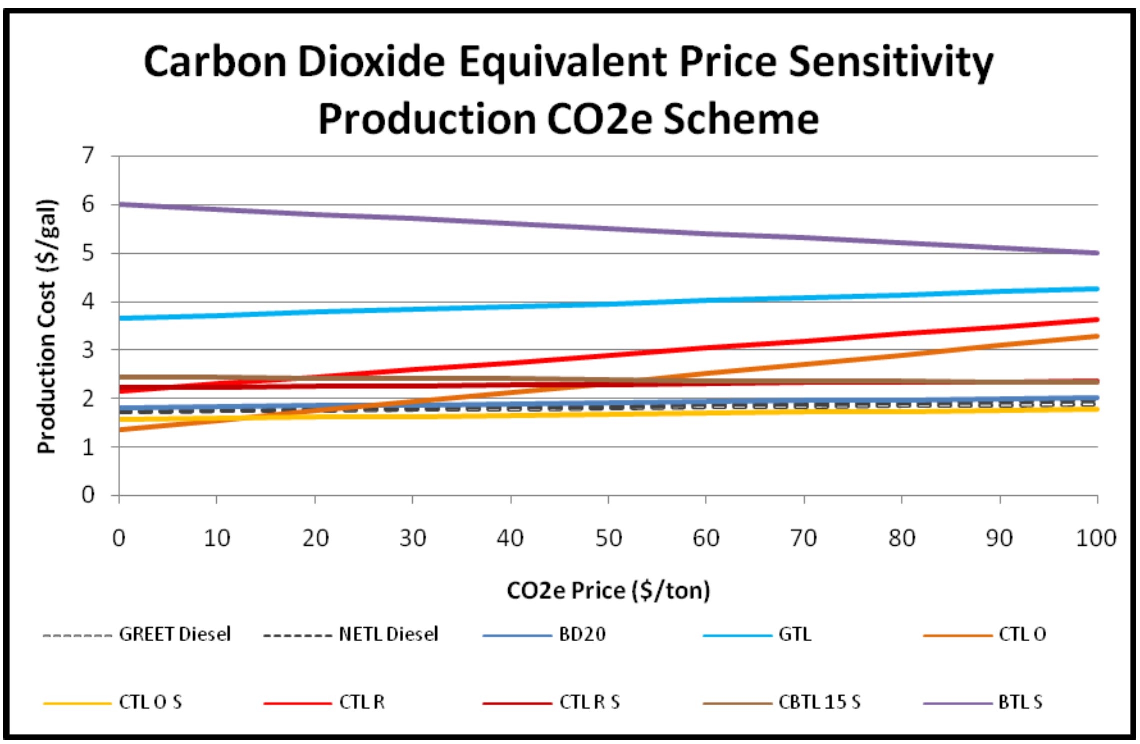


Figure 22. Carbon taxation at production level for diesel substitutes.

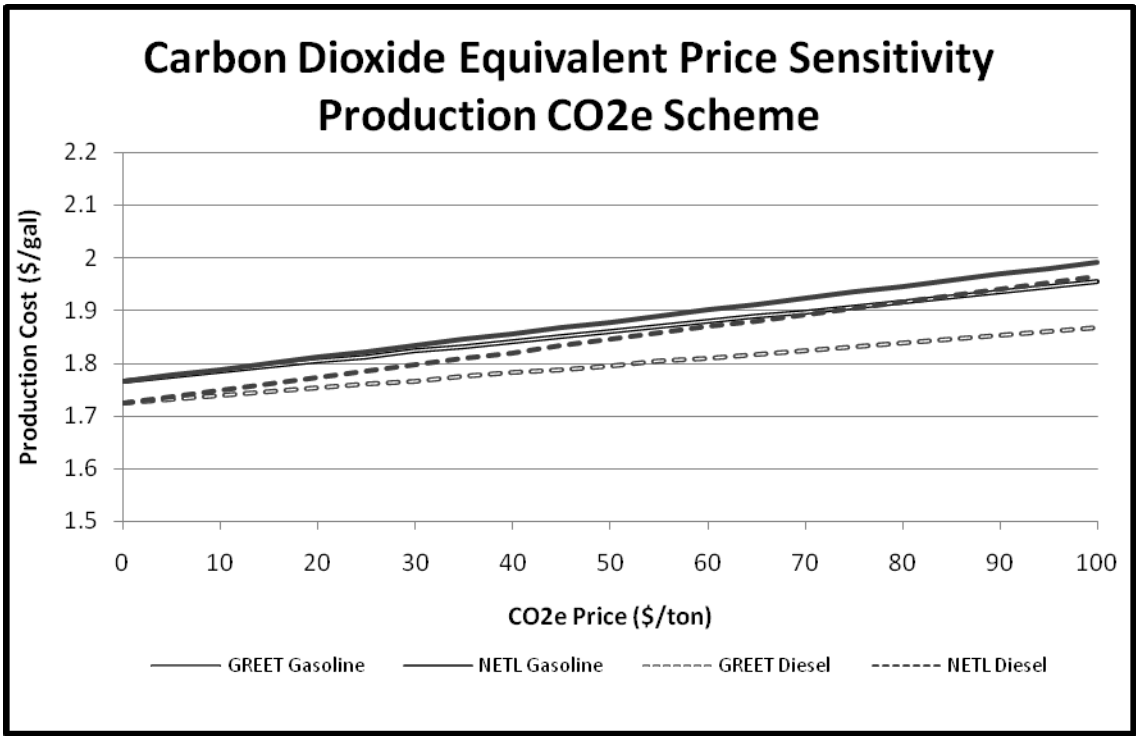


Figure 23. Comparison of NETL and GREET baselines and carbon taxation.

Figures 24 and 25 consider taxes or fees on total (production + tail pipe) GHG emissions for each technology. Rather than examining the change in production cost in $/gal or $/MMBtu, this example focuses on the cost per 12,500 miles driven, the estimated annual driving distance. The cost per year also takes into account the fuel efficiencies associated with these technologies, which partially mitigates the CO_2e pricing as lower emitting fuels have relatively low fuel efficiencies. BTL S is the most expensive option at all CO_2e tax levels, despite being the only technology to sequester more carbon than the GHGs it emits, and thereby benefiting most from the CO_2e tax. CTL O starts as the low cost option, but with a tax of $12.15 or greater, CTL O S becomes the low cost option. A $50/ton CO_2e tax would approximately double the annual cost for using diesel from CTL O (610 to 1253 $/year). BD20 becomes competitive with diesel at $80/ton using the NETL base case.

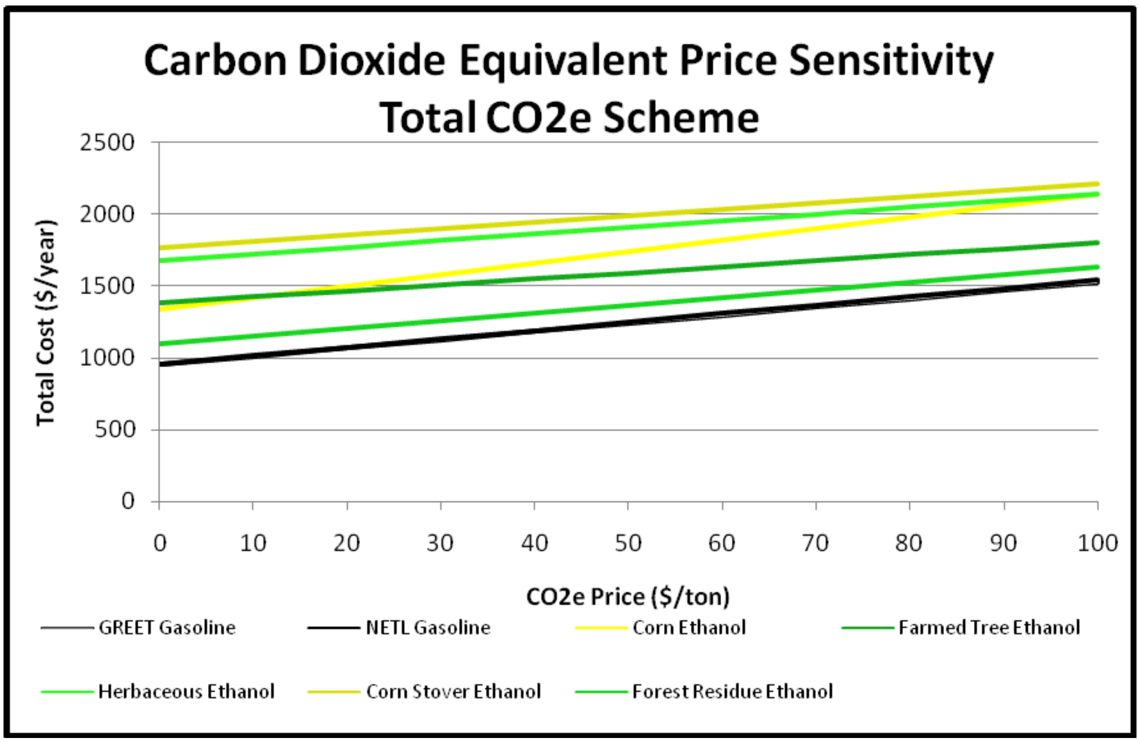


Figure 24. Carbon taxation for well to wheel GHG emissions for gasoline substitutes.

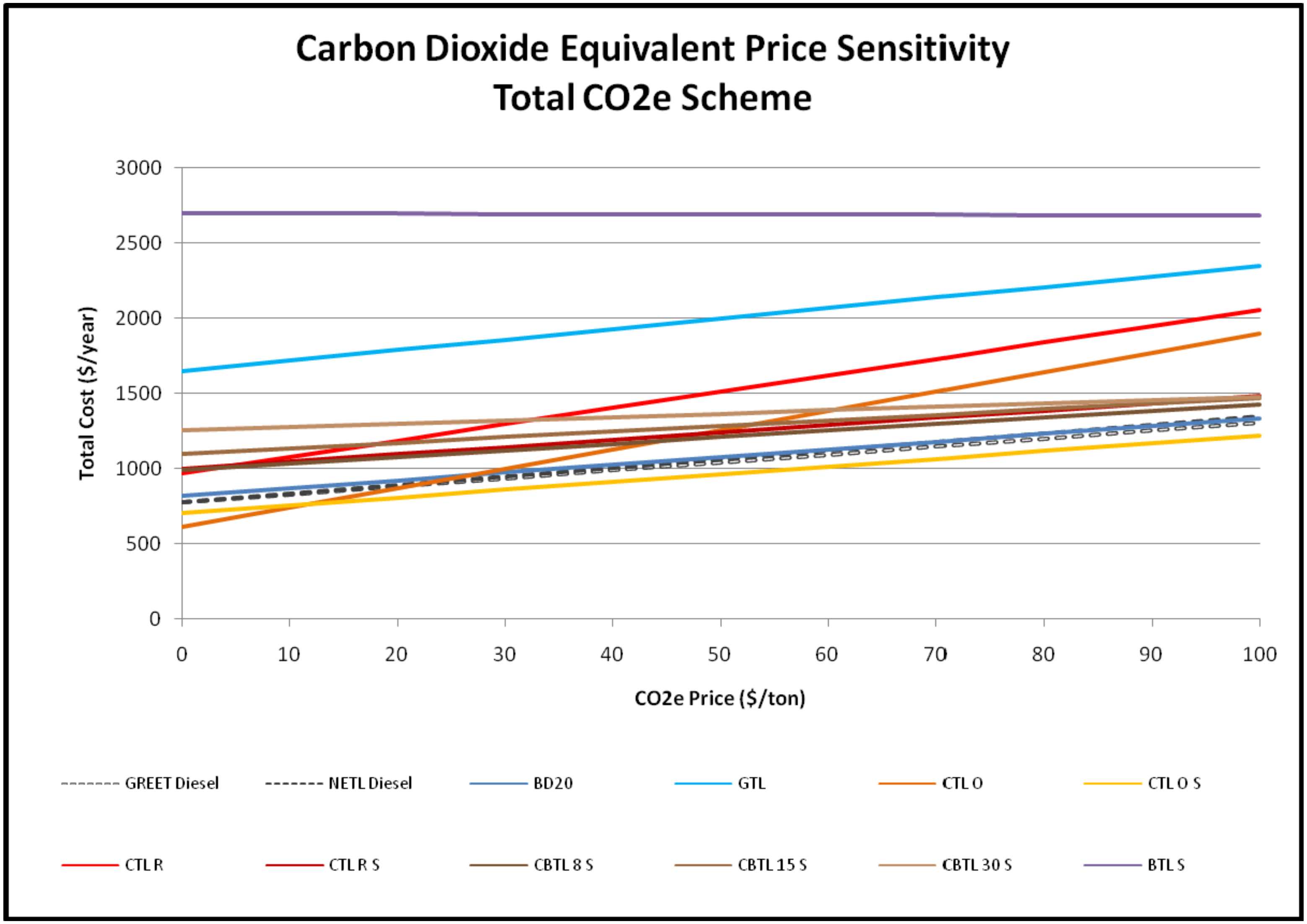


Figure 25. Carbon taxation for well to wheel GHG emissions for diesel substitutes.

AltSim can also be used to test the sensitivity of fuel economy assumptions on calculated production costs. Figure 26 compares the fuel efficiency of gasoline compared to the base production costs of the other technologies in terms of annual cost to the consumer. As the fuel efficiency improves, gasoline becomes more competitive with the other technologies on a $/ year basis. A 10 mile per gallon increase in fuel efficiency would make the annual costs for gasoline lower than for all alternatives except CTL O diesel. Of course, the fuel efficiency of gasoline-fueled vehicles would not increase alone; the point of this graph is to show that increasing fuel efficiencies is another method for lowering per mile costs of driving. Adopting a national fuel standard of 40 mpg would result in similar fuel costs per mile as a policy of switching to CTL O diesel. A similar analysis could be done for the other fuel options in AltSim.

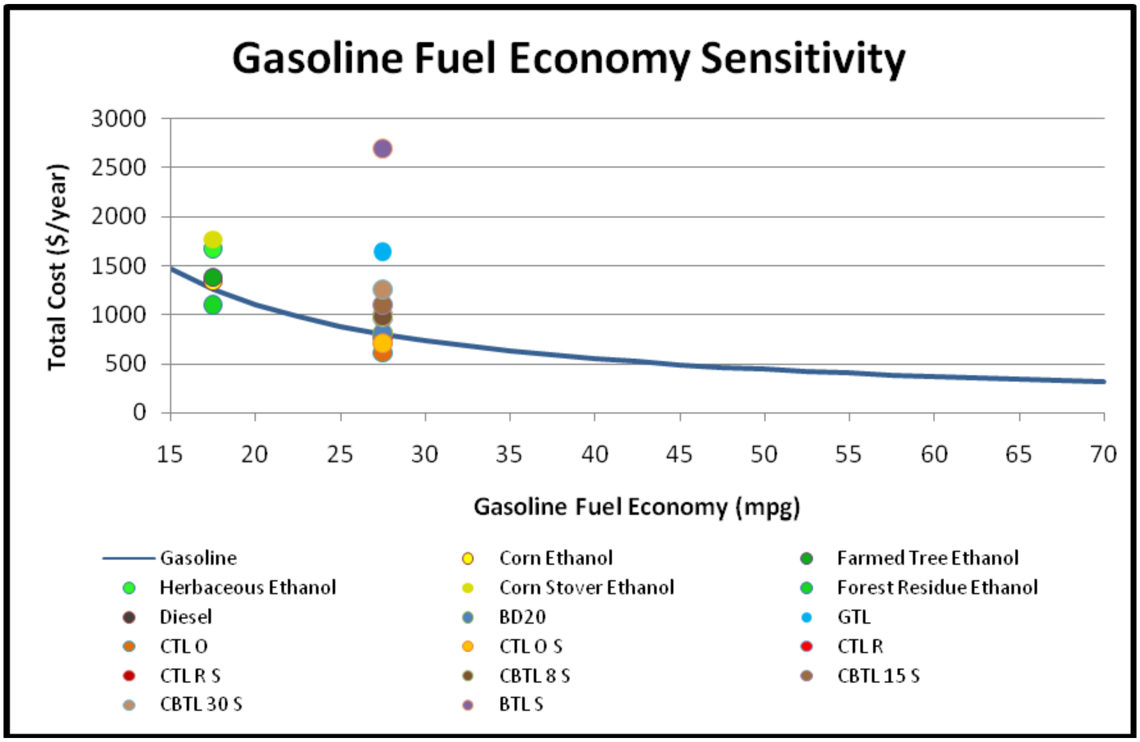


Figure 26. Annual fuel cost sensitivity for fuel economy (base case results for all other fuels).

Total miles driven annually is another key factor represented by Figure 27. AltSim assumes each vehicle currently travels 12,500 miles per year (vertical line). A 10% reduction in miles driven would save $95/year for gasoline. Changing the miles driven does not affect the relative competitiveness of the base results.

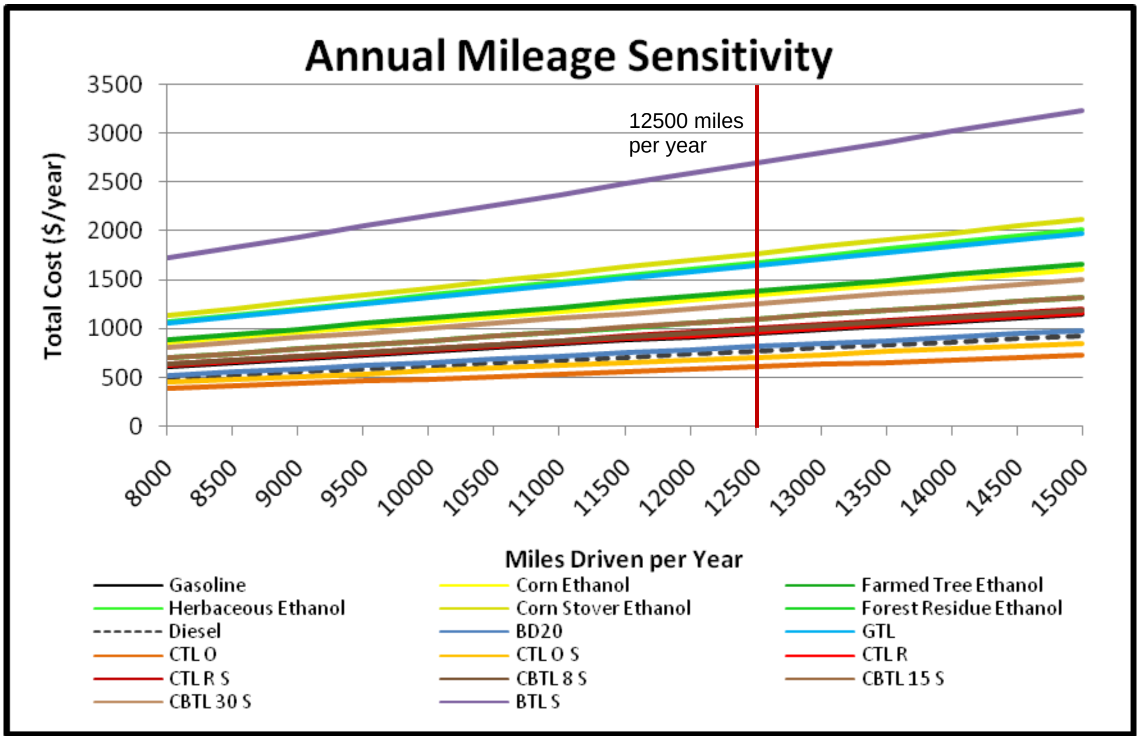


Figure 27. Annual fuel cost sensitivity for miles driven.

Conclusion

The Alternative Liquid Fuels Simulation Model (AltSim) is a high-level dynamic simulation model which calculates and compares the production and end use costs, greenhouse gas emissions, and energy balances of several alternative liquid transportation fuels. These fuels include: corn ethanol, cellulosic ethanol from various feedstocks (switchgrass, corn stover, forest residue, and farmed trees), biodiesel, and diesels derived from natural gas (gas to liquid, or GTL), coal (coal to liquid, or CTL), and coal with biomass (CBTL). AltSim allows for comprehensive sensitivity analyses on capital costs, operation and maintenance costs, renewable and fossil fuel feedstock costs, feedstock conversion ratio, financial assumptions, tax credits, CO_2 taxes, and plant capacity factor. This paper summarizes the structure and methodology of AltSim, presents results, and provides a detailed sensitivity analysis.

The Energy Independence and Security Act (EIAS) of 2007 sets a goal for the increased use of biofuels in the U.S., ultimately reaching 36 billion gallons by 2022. AltSim's base case assumes EPA projected feedstock costs in 2022 (EPA, 2009). EISA allows fuels emitting 20% less greenhouse gases (GHG) than conventional gasoline and diesels to qualify as renewable fuels. This allows several of the CBTL options to be included under the EISA mandate. For the base case assumptions, AltSim estimates per gallon production costs for the five ethanol feedstocks (corn, switchgrass, corn stover, forest residue, and farmed trees) of $1.86, $2.32, $2.45, $1.52, and $1.91, respectively. The projected production cost of biodiesel is $1.81/gallon. The estimates for CTL without biomass range from $1.36 to $2.22. With biomass, the estimated costs increase, ranging from $2.19 per gallon for the CTL option with 8% biomass to $2.79 per gallon for the CTL option with 30% biomass and carbon capture and sequestration. While the economic results presented here are based on the EPA projected feedstock costs in 2022, AltSim allows the user to quickly vary key assumptions and explore the sensitivity.

AltSim compares the greenhouse gas emissions (GHG) associated with both the production and consumption of the various fuels. The estimated GHG emissions associated with the production of gasoline and diesel are 19.80 and 18.40 kg of CO_2 equivalent per MMBtu (kgCO_2e/MMBtu), respectively. The estimated emissions are significantly higher for several alternatives: ethanol from corn (70.6), GTL (51.9), and CTL without biomass or sequestration (123 – 161). Projected emissions for several other alternatives are lower; including biomass and sequestration in the CTL processes can even result in negative net emissions. For example, CTL with 30% biomass and sequestration has estimated production emissions of -38 kgCO_2e/MMBtu.

AltSim also estimates the projected well-to-wheel, or lifecycle, emissions for vehicles consuming each of the various fuels. Vehicles fueled with conventional diesel or gasoline and driven 12,500 miles per year are responsible for 5.72 - 5.93 tons of CO_2 equivalents per year (tCO_2e/yr). Those emissions are significantly higher for vehicles fueled with 100% ethanol from corn (8.03 tCO_2e/yr) or diesel from CTL without sequestration (10.86 to 12.85 tCO_2/yr). Emissions could be significantly lower for vehicles fueled with diesel from CTL with various shares of biomass. For example, for CTL with 30% biomass and carbon sequestration, emissions would be 2.21 tCO2e per year, or just 39% of the emissions for a vehicle fueled with conventional diesel.

While the results presented above provide very specific estimates for each option, its true potential is as a tool for educating policy makers and for exploring "what if?" type questions. For example, AltSim allows one to consider the affect of various levels of carbon taxes on the production cost estimates, as well as increased costs to the end user on an annual basis. Other sections of AltSim allow the user to understand the implications of various polices in terms of costs to the government or land use requirements. AltSim's structure allow the end user to explore each of these alternatives and understand the sensitivities implications associated with each assumption as well as the implications for bottom line economics, energy use, and greenhouse gas emissions.

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Appendix: Running the Model

System Requirements

AltSim can be installed directly onto most Windows-based computers. The model is written in Powersim Studio 2007, a dynamic simulation modeling language.

Starting the Model and Running a Base Case

The CD includes the necessary Powersim Studio 2007 software to run AltSim.

To install the Powersim software, follow these steps:

1. PLACE the CD in the appropriate computer drive on the target computer, locate and open the file “**PS2007**” on the CD.

2. FOLLOW the installation instructions for Powersim Studio 2007.

3. ENTER the long serial number listed on the CD cover when prompted on the Customer Information page.

4. ACCEPT the license agreement to use the software.

5. CHOOSE the Complete installation option.

6. CLICK install.

AltSim can run either from the CD, but will run faster if copied to the computer. Double click on the file “**AltSim v. 2.0.sip**” to open the model. To open the model while the Powersim Studio software is running, choose files of type “.sip” in the “Open” window. Locate the file “**AltSim v. 2.0.sip**” and click “Open” to run the model.

The model opens to the title page, Figure A-1. The user advances from this point by clicking on the large arrow labeled **Model** in the lower right hand corner of the screen. The base case assumptions are viewed by clicking **Assumptions**. The next screen is the opening **Production Analysis** screen for conventional fuels. Clicking on any of the blue links on this page will take the user to other liquid fuel options, such as ethanol.

Figure A-28. AltSim title page.

Model Operation

PLAY — Click to start model simulation or click during simulation to stop.

REWIND — Click to reset simulation.

PLAY/PAUSE — Click to advance the model one step.

Model Navigation

MAIN TOOL PANEL – Click on desired model section (Production Analysis, End Use Analysis, Scenario Analysis) to navigate there.

HYPERLINK – Any underlined word acts as a hyperlink. Click on any hyperlink to navigate to the specified location.

BACK - Back — Click to return to previously visited screen.

Distribution:

1	MS0735	Tom Drennen, 06316
1	MS0899	Technical Library, 9536 (electronic copy)