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INVITED REVIEW

The economics of current and future biofuels

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Abstract This work presents detailed comparative analysis on the production economics of both current and future biofuels, including ethanol, biodiesel, and butanol. Our objectives include demonstrating the impact of key parameters on the overall process economics (e.g., plant capacity, raw material pricing, and yield) and comparing how next-generation technologies and fuels will differ from today's technologies. The commercialized processes and corresponding economics presented here include corn-based ethanol, sugarcane-based ethanol, and soy-based biodiesel. While actual full-scale economic data are available for these processes, they have also been modeled using detailed process simulation. For future biofuel technologies, detailed techno-economic data exist for cellulosic ethanol from both biochemical and thermochemical conversion. In addition, similar techno-economic models have been created for *n*-butanol production based on publicly available literature data. Key technical and economic challenges facing all of these biofuels are discussed.

Keywords Biofuel · Biodiesel · Biobutanol · Process economics · Techno-economic analysis · Transportation fuel · Ethanol

Introduction

Biofuels production worldwide is continuing to grow at a very rapid pace. In the USA, ethanol production has more than tripled over the past 5 yr (RFA 2008), from 2.8 billion gallons in 2003 to over 9 billion gallons in 2008. This is used primarily for fuel oxygenate in blend percentages (10% or E10); however, some ethanol is sold as dedicated (85% or E-85) fuel for flexible fuel vehicles. Brazil is the second largest producer worldwide with approximately 5 billion gallons in 2007 (FO Lichts, Kent, UK), but uses the fuel in higher percentage blends, either 20–25% or as high as 100% (E-100). Biodiesel is produced in the USA at lower volumes than ethanol, but is also growing rapidly. Production has increased over tenfold from approximately 25 million gallons in 2004 to an estimated 700 million gallons in 2008 (NBB 2009). Energy policy in the form of a renewable fuel standard (EISA 2007) has helped to maintain strong markets for both of these fuels. Under the Energy Independence and Security Act of 2007 (EISA 2007), 36 billion gallons of renewable fuel are mandated by 2022 of which 15 billion gallons are corn-based ethanol, 16 billion are "cellulosic biofuels", and at least 1 billion gallons are biodiesel. Tax credits for both ethanol and biodiesel are also in place to encourage blenders to use these alternative fuels.

However, recent market price fluctuations for fuels and feedstocks have been quite dramatic. Petroleum prices have ranged from \$20 per barrel in 2002 to record highs over \$140 per barrel in 2008. Average corn prices during this time have also ranged from \$2 per bushel to \$4.20 per bushel (USDA 2008) with spot prices rising over \$8 per bushel. Costs of steel, natural gas, and fertilizer have also experienced dramatic increases during the past 5 yr. In light of these immense price shifts, it becomes increasingly important to understand the production economics of these and other potential biofuels.

For today's commercial biofuels technologies, actual production cost data are available through a variety of sources. The economics of each existing biofuel production

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will differ from one another depending on a variety of specific and local market and technological variations. For example, ethanol plants will pay differing rates for corn, natural gas, and enzymes based on company hedging practices, negotiated contract prices, and regional market conditions. In addition, detailed process and economic models (also called techno-economic models) also exist for these processes and can be used to demonstrate specific economic impacts of certain key parameters.

Production cost data for nonexisting or noncommercial biofuels processes (cellulosic ethanol, corn-based butanol) are less readily available and come largely from detailed techno-economic models and evaluations. Many companies are currently developing these technologies and oftentimes may present cost data through press releases or other simplified formats. However, this type of cost data must be taken at limited value because the assumptions, level of costing detail, and other bases behind the values are oftentimes absent or unvalidated. The assumed years-dollars are also important because inflationary increases can make year to year comparisons difficult. True and meaningful comparisons between fuels and technology variations can only be made when production economic data are presented clearly, transparently, and in sufficient level of detail to be reproducible. Therefore, we applied detailed techno-economics models and evaluations to several current and future biofuel processes.

Development of Concept Design Methodologies and Models for Process Economics

Developing process economics of this sort requires significant amounts of experimental data, modeling toolsets, and engineering expertise. The first step is the development of a conceptual-level design. Conceptual design refers to the engineering decision making that is required to conceive a process from information on the products, feeds, and chemical and physical steps proposed as a basis (Douglas 1989). The effective use of conceptual design methods in the early stages of process design can have a large impact on overall process design and development. There are frequently many process alternatives that can be chosen and many design variables to specify. Conceptual design approaches practically always include both assumptions and heuristics along with numerical modeling and optimization techniques. The conceptual designs for the future biofuels processes described here were largely developed by National Renewable Energy Laboratory (NREL) in collaboration with a number of research partners. The graphical depiction of such designs is referred to as "process flow diagrams" (PFDs).

The material and energy balance and flow rate information for such designs are then generated using process simulation software packages. For these particular applications, Aspen Plus (Aspen Plus 2006) was used. This software contains physical property and thermodynamic data on a large number of chemical compounds. NREL has further developed customized physical property data for biomass constituents such as cellulose, lignin, and xylan (Wooley and Putsche 1996). The material and energy balance data generated by these models are fed into spreadsheets built for capital and operating cost estimation. As documented (Wooley et al. 1999; Aden et al. 2002; Phillips et al. 2007), capital costs are developed for each piece of equipment using a number of sources, including vendor quotations (for more specialized equipments), costing software estimates (for simpler equipment such as pumps and tanks), and engineering company database information. Installation factors are derived from a number of sources as well.

Using published engineering methodology (Peters and Timmerhaus 1991), a discounted cash flow rate of return analysis is generated using capital and operating cost data. The minimum ethanol selling price (MESP; $/gallon) is the minimum price that the ethanol must sell for in order to generate a net present value of zero for 10% internal rate of return (IRR). This makes the MESP slightly higher than a true cost of production.

It should be emphasized that a certain percentage of uncertainty exists around conceptual cost estimates such as these. These values are best used in relative comparison against technological variations or process improvements. Use of absolute values without detailed understanding of the basis behind them can be misleading. Process economics requires a wide range of detailed studies, including conceptual level of process design to develop detailed process flow diagram (based on research data from NREL and other data sources), rigorous materials and energy balance calculations (via commercial simulation tools such as Aspen Plus), capital and project cost estimation (via in house model using spreadsheets), discounted cash flow economic model (via in house model using spreadsheets), and then a final calculation of minimum biofuel selling price.

Process Economics and Comparative Analysis

Commercialized biofuels process economics. Biodiesel is produced worldwide from a variety of feedstocks. Most of the ethanol produced in the USA is derived from corn grain. Brazil uses sugarcane and European Union (EU) countries use wheat and sugar beets as feedstocks for commercial ethanol production. Many parts of Asia use palm oil feedstocks for biodiesel production, while the EU uses oil derived from rapeseed (canola variety) and the USA uses soybean oil and other oil-bearing crops. In this paper, three commercial processes are discussed. Corn ethanol and sugarcane ethanol process economics are discussed in details as representative examples for commercialized ethanol production. For biodiesel production, a soybean-derived biodiesel process is selected as one example for biodiesel process economics.

1. Corn ethanol

Process description

There are two general types of processing: wet milling and dry grind. Dry-grind ethanol plants are much more prevalent; greater than 80% of existing ethanol plants in the USA are dry grind (RFA 2008). Dry-grind processes are less capital and energy intensive than their wet mill counterparts. However, they also produce fewer products. Dry-grind plants produce ethanol and animal feed, known as distillers dried grains (DDG or DDGS). Wet mills, on the other hand, are structured to produce a number of products, including starch, high fructose corn syrup, ethanol, corn gluten feed, and corn gluten meal. As a result, ethanol yields from wet mills are slightly lower (2.5 gal per bushel) than from dry-grind processes (2.8 gal per bushel).

General process diagrams are shown in Fig. 1 for these processes. In a dry-grind process, corn grain is milled and slurried with water and amylase enzymes. The mixture is cooked and mixed with additional enzyme to complete starch hydrolysis to glucose. The subsequent glucose sugars are fermented to ethanol, CO_2, and other minor by-products using various yeast strains. The ethanol is concentrated and purified through a series of distillation and molecular sieve dehydration steps. The by-product solids are dewatered and dried through a series of centrifugation, evaporation, and drying steps.

In wet milling, the corn kernels are first soaked in a mixture of water and SO_2 through a process known as "steeping" in order to allow for separation of the kernel components. Germ, fiber, gluten, and starch are separated from one another through a series of screens, cyclones, presses, and other equipment. Oil can be further extracted from the germ. Enzymes are added to the starch stream for hydrolysis to sugars, and the sugars can be fermented to ethanol, similarly to dry-grind processing.

Process economics

Several sources of data on corn processing economics exist. In 2002, the US Department of Agriculture (USDA 2002) published a "cost of production" survey (Shapouri et al. 2006) where 21 dry-grind corn ethanol plants were asked to estimate their production costs, including both variable and capital expenses. Total average costs ranged from \$0.92/gal to \$0.99/gal. Of that total, \$0.80/gal was the cost for purchasing corn grain feedstock. These averaged cost data for both years 2002 and 1998 are shown in Table 1.

In 2007, FO Lichts conducted a worldwide survey of ethanol production costs (FO Lichts 2007). For the USA during 2006/2007, net production costs of approximately \$400/m^3 (~\$1.50/gal) were documented for corn purchased at \$3.35 per bushel (Table 2). Net production costs for wet mills and dry-grind processes were within 3% of each other. However, the increased cost of capital in 2006 *vs.* 2002 was evident because the net feedstock costs were closer to 60% of the overall cost as opposed to 80% or greater in 2002.

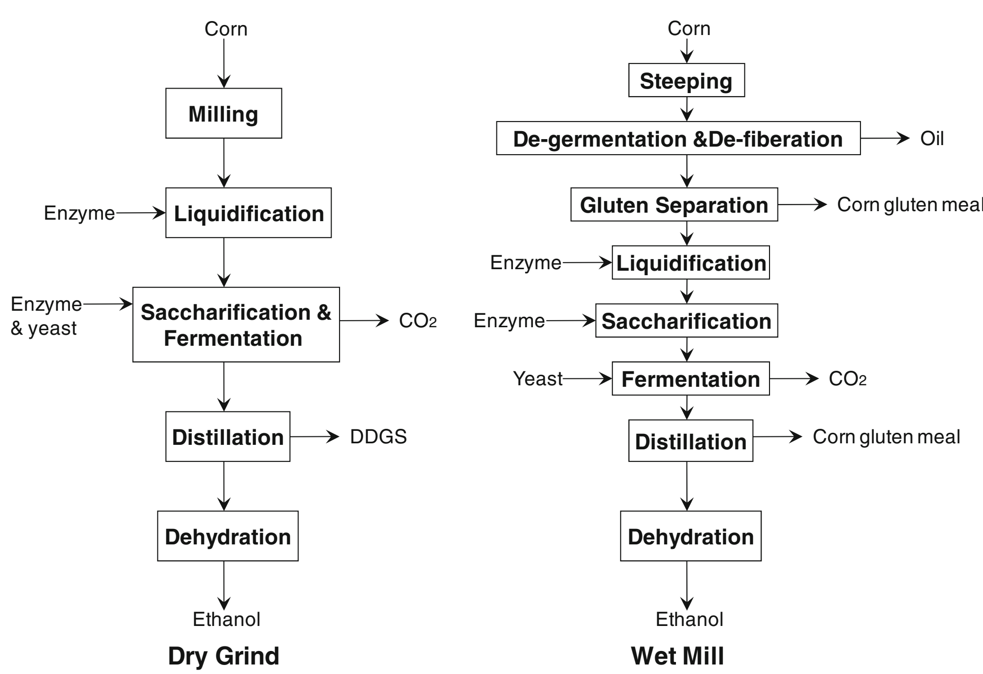


Figure 1. Schematic process flow diagram from corn to ethanol (Bothast and Schlicher 2005).

Table 1. Ethanol production cost in USDA 2002 ethanol production-of-cost survey from US ethanol manufacturers

US average	2002	1998
Feedstock costs ($/gal)	0.8030	0.8151
By-product credit ($/gal)	−0.2580	−0.2806
Net feedstock cost ($/gal)	0.5450	0.5345
Operating cost ($/gal)	0.4124	0.4171
Total cost ($/gal)	0.9574	0.9516

Dry-grind and wet mill techno-economic models also exist as developed by USDA researchers (Kwiatkowski et al. 2006; Ramirez et al. 2009). These models, in general, are good representations of corn ethanol economics. NREL was given a copy of the 2007 version of the dry-grind model by USDA and had used it for several biofuels research projects. For this particular biofuels report, NREL used this model to develop comparative economics between corn ethanol and other biofuels technologies. Baseline assumed values for several key parameters are shown in Table 3. The model was run using these assumed parameter values, which resulted in the modeled costs for ethanol shown in Table 4. The assumed plant design capacity was 45 MM gallons per year ethanol. The operating costs are shown in both $/gallon ethanol and $MM/yr. The corn feedstock cost is the largest single cost contributor as expected. Coproduct DDGS contributes significantly to the net production cost as well, as does natural gas (utilities). Operating costs are based on a yield of 115 gal ethanol yield per dry ton corn. Depreciation of capital is included in the overall operating costs for all models in this paper. The resulting total project investment (TPI) is summarized with other biofuel processes in Table 15.

Table 2. Ethanol production cost in USA, Brazil, and EU (source: FO Lichts 2007)

	2004/2005	2005/2006	2006/2007
Maize ($/bushel)	2.05	2.01	3.35
Maize ($/tonne)	80.71	79.13	131.89
Net feedstock cost ($/gal)			
Dry mill	0.55	0.55	0.90
Wet mill	0.37	0.50	0.72
Net production cost ($/gal) [in USA]			
Dry mill	1.06	1.10	1.54
Wet mill	1.05	1.77	1.50
Net production cost ($/gal) [in Brazil]			
Sugarcane ethanol	0.66	0.92	1.14
Net production cost ($/gal) [in EU]			
Grain-based ethanol	1.54	1.65	2.19
Beet-based ethanol	1.40	2.69	1.83

Table 3. Baseline economic assumptions for corn dry mill ethanol

Economic parameter/prices	Baseline value
Installation factor	3.0 (across all equipment)
Equipment life/depreciation time	20 yr (straight line)
Equipment scaling exponent	0.6
Online percentage	96% (350 d)
Corn price	$3.35/bushel
DDGS price	$95/ton
Caustic price	$0.055/lb ($110/ton)
Enzyme price	$1.03/lb
Gasoline (denaturant) price	$2.00/gal
Sulfuric acid price	$0.05/lb ($100/ton)
Lime price	$0.04/lb ($80/ton)
Makeup water price	$0.00002/lb ($0.167/1,000 gal)
Urea price	$0.10/lb ($200/ton)
Yeast price	$0.85/lb
Electricity	$0.05/kWh
Natural gas	$7.50/MMBtu

2. Sugarcane ethanol

Process description

Brazil's production accounts for 42% of world sugarcane production in 2005 (BNDES 2008). Brazilian cane biorefi-

Table 4. Operating cost of dry mill corn ethanol plant with 45 MM gal/yr production rate

Corn ethanol 45MM gal/yr		
Operating costs ($/gal ethanol)		
Shelled corn		$1.21
Denaturant		$0.04
Other raw materials		$0.05
Utilities		$0.30
Labor, supplies, and overheads		$0.11
Depreciation		$0.14
Coproduct credits		−$0.32
Production cost per gallon		$1.53
Operating costs ($/yr)		
Shelled corn	$57,777,726	
Denaturant	$2,055,982	
Other raw materials	$2,524,366	
Utilities	$14,267,437	
Labor, supplies, and overheads	$5,819,600	
Depreciation	$6,570,000	
Coproduct credits	−$15,037,000	
Total production cost	$73,978,110	

Production cost per gallon is $1.53.

neries began as sugar mills, but had grown to include simultaneous production of ethanol as well. It has been noted that the low cost of Brazilian sugar is largely related to the development of agricultural and industrial technology associated with the expansion of bioethanol production (BNDES 2008). Because both sugar and ethanol coproduction are so closely integrated within these biorefineries, it is difficult, if not impossible, to completely decouple the economics of sugar production from ethanol production.

Sugarcane ethanol is a sugar-based production process that requires one less step than starch-based ethanol production. For corn, the starch must be hydrolyzed to glucose before it can be used by yeast. The sucrose extracted from sugarcane can be used without such a hydrolysis step. Sugarcane cannot be stored for more than a few days, and mills subsequently operate during the harvest period only (6–7 mo) and perform maintenance while down the rest of the year.

A general process diagram for sugarcane ethanol production is shown in Fig. 2. The production process consists of three general steps: sugar extraction from the cane, sugar fermentation to ethanol, and ethanol separation and purification. Sugar extraction is a common step shared by both sugar production and ethanol production trains. Once in the mill, sugarcane is generally washed and sent to preparation and extraction. Extraction is made by roll mills that separate the sugarcane juice from the bagasse, which is sent to the mill's power plant for use as fuel. The bagasse is further pressed through a drying roller which reduces moisture for more efficient combustion in the boilers. The extracted juice is treated and sent through a rotary vacuum filter. The resulting filter cake is applied back on fields as fertilizer, and the sugar is recovered from the decanted slurry. The juice is sent to either sugar production or ethanol production. For ethanol production, the juice is fermented by yeast (*Saccharomyces cerevisae*). Fermentation times range from 8 to 12 h, generating beer with ethanol concentrations from 7% to 10%. Yeast is recovered, treated, and reused. Beer is sent to distillation where ethanol is initially recovered in a hydrated form. This nearly azeotropic hydrated ethanol can further be dehydrated using a number of existing technologies. These include adsorption with molecular sieves and/or extractive distillation with monoethylene glycol (Seabra 2007; BNDES 2008). However, the most common commercial technology in Brazil is extractive distillation using cyclohexane as the entrainer. The decanted cyclohexane-rich stream is recycled internally.

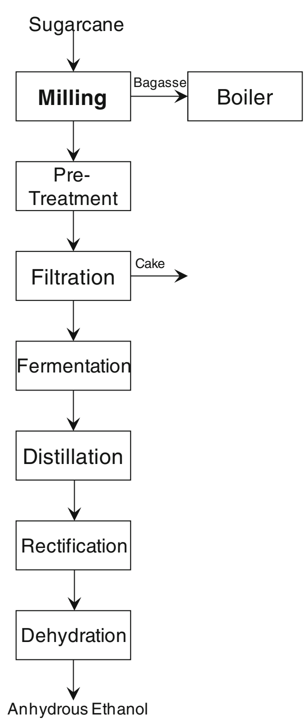


Figure 2. Schematic process flow diagram from sugarcane to ethanol. Sugar production sections not shown.

Process economics

FO Lichts data for 2006/2007 (Table 2) put sugarcane ethanol costs at \$1.14/gal ethanol, which is lower than corn ethanol produced in the USA. While the USA does not currently produce any ethanol from sugarcane, a USDA 2006 study (Shapouri et al. 2006) estimated what those costs might be. Shapouri and his coworkers estimated sugarcane ethanol production costs in the USA as high as \$2.40/gal based on 2003/2004 sugarcane market prices and estimated processing costs. Feedstock costs were estimated at \$1.48/gal of ethanol, representing 62% of the total ethanol production cost. However, sugarcane feedstock costs in Brazil could be as low as \$0.30/gal of ethanol (Shapouri et al. 2006), which makes sugarcane ethanol more economical in Brazil.

Delivered costs of sugarcane to the biorefinery are estimated at \$21.08/ton by Rodriguez (2007) and Seabra (2007). For yields of 22.7 gal ethanol per ton cane, the feedstock contributes \$0.93/gal ethanol. Other baseline assumptions for production costs are shown in Table 5. The full operating costs for a 45-MM gal/yr process are shown in Table 6 and are largely derived from two economics studies (Rodrigues 2007; Seabra 2007). These studies examined the Brazilian manufacturing process in great detail. Though these biorefineries do not operate year-round, the economics shown assume year-round production for better comparison against other biofuels processes.

Also note that electricity surplus in these processes is not large and is therefore not included in the cost data. This is changing, however, as Brazilian biorefineries continue development and improvement in the overall power management of these facilities. Biomass residue and/or bagasse combustion feeds the cogeneration section to

Table 5. Baseline economic assumptions for sugarcane ethanol process

Economic parameter/prices	Baseline value
Installation factor	3.0 (across all equipment)
Equipment life/depreciation time	20 yr (straight line)
Equipment scaling exponent	0.6
Online percentage	96% (350 d)
Sugarcane price	$28.5/ton
Other chemicals	$0.078/gal ethanol
Gasoline (denaturant) price	$0.043/gal ethanol

optimize the overall power, steam, and electric demands of the mills.

The TPI for the 45 million gallon per year sugarcane ethanol plant is shown in Table 15 alongside the other biofuels processes under comparison. Even though decoupling the economics of ethanol from sugar production is difficult, simplifying assumptions were made for the common areas of feedstock handling juice extraction. It is normal in Brazil for roughly half of the juice to go to sugar and half to ethanol so 50% of the capital in the common area was attributed to ethanol production. Because of this, combined with higher feedstock cost in Seabra and his coworker's study (Rodrigues 2007; Seabra 2007), we

Table 6. Operating cost of sugarcane ethanol, with 45 MM gal/yr production

Sugarcane 45MM gal/yr		
Operating costs ($/gal ethanol)		
Sugarcane		$0.93
Denaturant		$0.04
Other raw materials		$0.08
Water		$0.02
Fuels and lubricants		$0.02
Labor, maintenance		$0.15
Depreciation		$0.05
Production cost per gal		$1.29
Operating costs ($/yr)		
Sugarcane	$42,150,000	
Denaturant	$1,953,801	
Other raw materials	$3,539,760	
Water	$756,800	
Fuels and lubricants	$899,560	
Labor, maintenance	$6,904,080	
Depreciation	$2,185,000	
Total production cost	$58,389,000	

estimated sugarcane cost at $1.29 (Fig. 6) which is higher than FO Lichts (2007)'s prediction.

3. Soybean biodiesel

A diesel engine gets its name from its inventor, Rudolf Christian Karl Diesel. Diesel fuel has traditionally been derived from petroleum refining. Biodiesel, on the other hand, is defined by American Society for Testing and Materials standards as a fatty acid methyl ester produced through transesterification of triglycerides (found in vegetable oils, fats, and greases) with alcohols such as methanol. Biodiesel offers lower emissions than the petrodiesel, which makes it an attractive alternative transportation fuel. Common feedstocks for biodiesel production include soy, canola, camolina, corn, rapeseed, and palm. Peanut, mustard seed, sunflower, and cotton seed present additional potential feedstocks.

The cost of biodiesel varies depending largely on feedstock cost. For instance, biodiesel from soybean can be more than twice as expensive as petrodiesel, although the capital investment for a biodiesel plant is not that significant. The high value of soybean oil makes production of a cost competitive biodiesel fuel very challenging. New feedstocks are undergoing detailed research, such as beef tallow, waste cooking oil, pork lard, yellow grease, etc. (Demirbas 2005). A 10 million gallon per year plant was estimated to cost $2.15/gal biodiesel based on feedstock cost at $0.25/lb (Graboski and McCormick 1998) of soybean oil and the capital cost was also estimated at about $2/gal using 20% discounted cash flow and 100% equity financing assumptions. Four continuous process configurations with HYSYS simulation were studied in detail for biodiesel capital and production cost comparison by Zhang et al. (2003) using waste oils, with cost ranging from $644 to $884/ton (~$2.10–2.90/gal). At a value of $0.52/kg ($0.24/lb) for feedstock soybean oil, Hass et al. (2006) predicted biodiesel production cost at $2.00/gal using Aspen simulation and cash flow calculation. Although previous researchers have used different plant scale, the soybean biodiesel production cost over the past years lies in $2.00–2.50/gal range with similar feedstock pricings.

Process description

The most common way to make biodiesel is by transesterification, which refers to a catalyzed chemical conversion involving vegetable oil and an alcohol to yield fatty acid alkyl esters (i.e., biodiesel) and glycerol as by-product. Methanol is the most commonly used alcohol. Transesterification reactions can be alkali, acid, or enzyme catalyzed. Among these three technologies, alkali catalyzed is the most common. The production process contains the following major steps: raw material handling, transesterification, methanol recovery and recycle, biodiesel and glycerol separation, purification of both biodiesel and by-product glycerol, and wastewater treatment. The simplified PFD is shown in Fig. 3.

Process economics

The soybean oil pricing is the dominant factor for the biodiesel cost as shown in Table 8. Even when soybean oil is priced below \$0.20/lb, the feedstock still dominated more than 70% of overall biodiesel cost. The coproduct glycerin of 80% purity is assumed to be roughly equivalent to \$0.15/gal biodiesel produced based on Energy Information Administration (EIA) data (EIA 2004); however, the price of glycerin can often offset the high feedstock price to a certain degree.

Baseline economics assumptions are listed in Table 7, together with feedstock and coproduction glycerin pricings. The IRR after tax is assumed 10% and equity of total investment is 100%. The operating cost of soybean biodiesel is calculated in the model to be \$2.55/gal for a 45-MM gal biodiesel plant, shown in Table 8. The TPI of a soybean biodiesel process is also listed in Table 15. From the cost analysis of soybean biodiesel, it is obvious that the feedstock cost of oil is the largest single component of biodiesel production costs. To make biodiesel cost competitive to petrodiesel, low cost feedstocks and their availability are the key. It is necessary to understand the process economics from the variety feedstocks, in addition to soybean biodiesel. Shown in Fig. 4, soybean prices from \$0.10–0.88/lb contribute 75% to 95% of overall operational cost.

Table 7. Baseline economic assumptions for soybean diesel process

Economic parameter/prices	Baseline value
Installation factor	3.0 (across all equipment)
Equipment life/depreciation time	20 yr (straight line)
Equipment scaling exponent	0.6
Online percentage	96% (350 d)
Soybean oil price (\$/lb)	\$0.30
80% glycerin price (\$/gal biodiesel)	\$0.15
Methanol price (\$/lb)	\$0.13
Sulfuric acid price	\$0.05/lb (\$100/ton)
Sodium methoxide catalyst price (\$/lb)	\$0.45
Makeup water price	\$0.00002/lb (\$0.167/1,000 gal)
Electricity	\$0.05/kWh
Natural gas	\$7.50/MMBtu
IRR	10%
Equity	100%

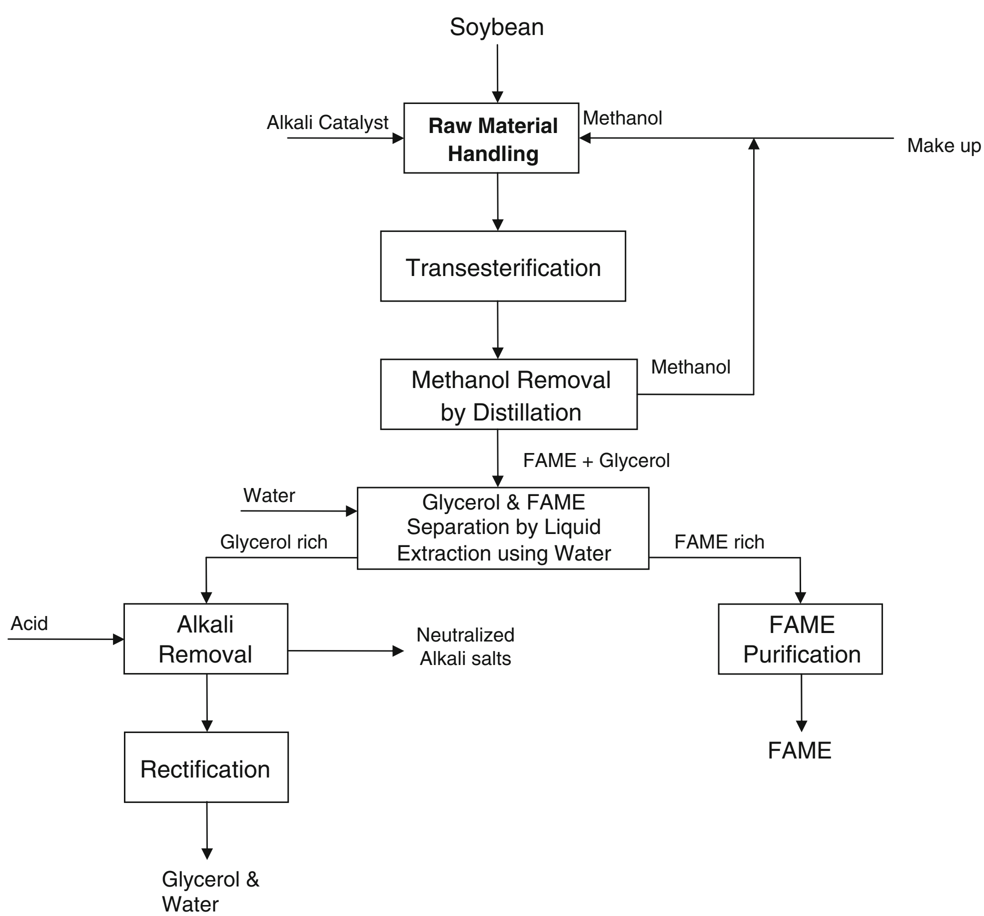


Figure 3. Schematic process flow diagram from soybean to biodiesel.

Table 8. Operating cost of 45 MM gal/yr soybean biodiesel plant

Soybean biodiesel 45MM gal/yr	
Operating costs ($/gal biodiesel)	
Feedstock (raw soybeans)	$2.21
Raw materials	$0.26
Utilities	$0.06
Labor supplies	$0.01
General works	$0.14
Subtotal operating costs	$2.70
Coproduct credits	−$0.15
Gross operating costs	$2.55
Operating costs ($/yr)	
Feedstock (raw soybeans)	$99,506,040
Raw materials	$11,673,531
Utilities	$596,000
Labor supplies	$6,389,064
General works	$121,455,000
Subtotal operating costs	$26,826,018
Coproduct credits	$94,628,982
Gross operating costs	$121,455,000

Going forward—economical challenges. Commercial biofuels to date have been very successful in garnering larger and larger shares of the fuel markets. However, many economic challenges still remain for these fuels. Feedstock availability is one issue. While many million acres of US cropland are devoted to soybean and corn production, much of these are used in competing processes such as animal feeding and/or livestock. It may prove difficult for corn ethanol, for example, to grow to more than 15 billion gallons per year without substantially impacting exports or other markets. Another issue facing conventional biofuels is the decoupling of feedstock costs and biofuel prices. Because these biofuels are largely blended into petroleum fuels at lower concentrations, their prices track those of gasoline or diesel. However, feedstock prices track with other commodity grain prices. Therefore, history has presented several instances of high feedstock costs coupled with low ethanol prices, which can cause producers to have negative margins and lose money.

A final issue facing commercial biofuels is one of perceived value and sustainability. Enormous debate over the potential benefits of biofuels has taken place around concepts of net energy, water use and quality, food *vs.* fuel issues, and most recently, land-use change impacts. Fervor on these topics are likely to only increase as time goes on, but new developments in cellulosic biofuels and advanced biofuels hold promise in this discussion.

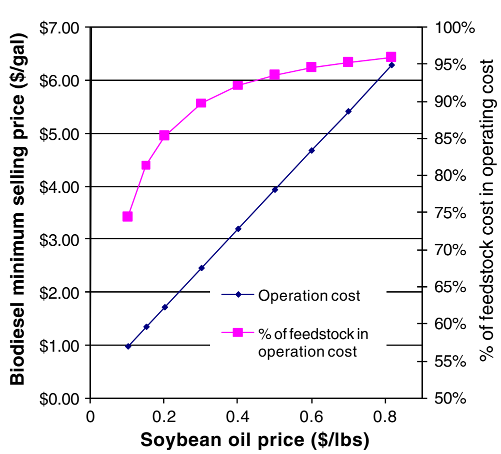


Figure 4. Soybean oil price is the dominant factor for soybean biodiesel price.

Future biofuels process economics. The future biofuels process economics shown here encompass both future fuels (butanol) as well as new feedstocks (lignocellulosic biomass). Various lignocellulosic materials, such as wood, agricultural residues, and energy crops, have the potential to be valuable raw materials for economical and compatible biofuel processes. Agricultural residues include wheat straw, sugar cane bagasse, and corn stover. Forest residues include sawdust, and dedicated energy crops include salix, switchgrass, and miscanthus. The lignocellulosic materials and subsequent conversion processes are sufficiently abundant and have potential to significantly reduce environmental impacts compared to today's technologies. Transportation biofuels such as hydrocarbons or cellulosic ethanol, if produced from low-input biomass grown on agriculturally marginal land or from waste biomass, could provide much greater supplies and environmental benefits than food-based biofuels (Hill et al. 2006). Therefore, various process design studies have been proposed over the last decade on ethanol production from lignocellulosic materials. However, process economics data are still relatively limited. In this paper, two representative lignocellulosic ethanol processes were selected for techno-economic analysis: biochemical conversion and thermochemical conversion.

Advanced biofuel development is as important as the development of alternative feedstocks. Advanced fuels, meaning nonethanol fuels, are high energy and high performance biofuels that include higher molecular weight alcohols (such as butanol and isobutanol) as well as infrastructure compatible hydrocarbons produced from either thermochemical (Fischer–Tropsch fuels) or biochemical (fermentation-derived hydrocarbons) pathways. Biobutanol will likely be the first of these biofuels to reach global markets (Spake 2007). One specific partnership active in this area is the collaboration between BP and DuPont (BP News 2006). Active and rapid technology development by these groups has led to initial construction of a US $400 million world-scale biofuels plant in Hull, UK. Initially, the plan will have the capacity to produce 420 million liters (110 million US gallons) of bioethanol annually from locally grown wheat but could subsequently be converted to biobutanol production. Several other companies are active in this area, including EEI (D. Ramey), Cobalt, Gevo, and Tetravitae. In this paper, process economics for *n*-butanol production from corn grain are shown based on Aspen Plus modeling and detailed economic analysis.

1. Cellulosic ethanol via biochemical conversion route

Process description

The biochemical design and cost estimates are based on an updated version of the NREL design report (Aden et al. 2002) for conversion of corn stover to ethanol. This design uses dilute acid pretreatment followed by enzymatic hydrolysis and cofermentation with recombinant *Zymomonas mobilis*. The corn stover is first treated with dilute sulfuric acid catalyst at a high temperature (190°C) for a short time (average at 2 min), liberating the hemicelluloses sugars and other compounds. Before going into enzymatic hydrolysis, proper conditioning is required for acid neutralization and detoxification prior to the biological portions of the process. Detoxification is only applied to the liquor fraction of the pretreated biomass and not the solids. Solids from pretreatment will be internally washed before remixed with the detoxified liquor for saccharification and fermentation. A purchased cellulase enzyme is added to the hydrolyzate at an optimized temperature for enzyme activity. If saccharification and fermentation steps are conducted at different temperatures, a cooling step is required to ensure growth of fermenting organism *Z. mobilis* at anaerobic condition. Between 3 and 7 d are required to convert most of the cellulose and xylose to ethanol. The "beer" liquor with ~4–8 wt.% of ethanol is then sent to recovery and purification, which uses standard adsorption technology. The solids after fermentation are separated and combusted in a fluidized bed combustor to produce high pressure steam for electricity credits and process heat. This is very similar to systems at Brazilian sugar mills and North American pulp and paper mills.

The process design presented (Fig. 5) reflects the best available estimates for performance of an enzyme-based process with the current status of NREL research efforts. The process includes four general steps:

(a) Conversion of feedstocks to sugar. Corn stover is the model feedstock in this study. The approach used to accomplish this step normally distinguishes different process technologies (or configurations) for the overall process design, since it is the most critical and challenge step or steps. This includes the areas of pretreatment and/or hydrolysis both chemical and enzymatic.
(b) Fermentation of sugars to ethanol. The fermenting organism *Z. mobilis* recombinant bacterium is used to co-ferment all sugars simultaneously to ethanol.
(c) Ethanol recovery area. High purity ethanol (99.5 wt.%) is produced in the recovery area, using distillation columns, a molecular sieve unit, and water evaporation units. Although it is an energy intensive operation, the temperature gradient from the first distillation column (beer column) can be used as a driving force for energy intensification in the area. Recycled water streams with reasonable levels of impurities are introduced into different areas such as pretreatment of feedstocks, in order to optimize the water and/or steam usage.
(d) Residue use. The solids from distillation (largely lignin), the concentrated syrup from the evaporator, and the biogas from anaerobic digestion are com-

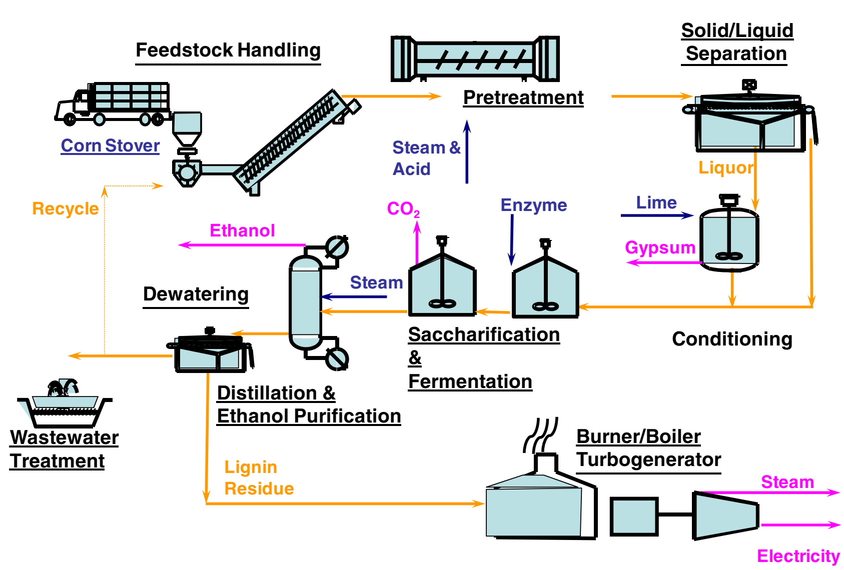


Figure 5. Schematic process flow diagram from corn stover to ethanol (Aden et al. 2002).

busted in a fluidized bed combustor to produce high pressure steam for electricity production and provide process steam or heat. Excess electricity credits are included in the cost analysis.

Process economics

The biochemical (Aden et al. 2002) and thermochemical (Phillips et al. 2007) ethanol design reports from NREL were completed 5 yr apart. As a result, costs for much of the equipment and raw material inputs (chemicals, etc.) were developed using different year's dollars. Because of inflation and other factors, the time value of money for each year changes. Therefore, it was necessary to put all costs in the same year's dollars in order to make them all more directly comparable. This was done using a factored indexing approach for capital costs, chemical costs, and labor costs as described by Aden and coworkers and Phillips and coworkers using well-known cost indices. The cost indices for nonlabor costs have risen significantly since 2003 due to a variety of international demands for materials and increased energy costs. For this comparison, all costs are shown using year-$2007. Similar approach has been applied to the other four processes discussed in the paper. Operating costs were calculated (Table 9) based on the following assumptions of 45 MM gal ethanol production per year plant size with ethanol yield of 90 gal per dry ton feedstock (corn stover). The internal rate of return after tax is assumed 10% and equity of total investment is 100%. The assumed plant operates 350 d per year for a total of 8,400 h. Total project investment is listed in Table 15 and is depreciated in 20 yr. Detailed baseline economics assumptions can be found by referring to the Aden et al. 2002 study.

The costs are further broken down into respective process areas as shown in Fig. 6. In the biochemical process, the lignin residue boiler and turbogenerator section represent a huge portion of the overall capital costs; however, much of this are offset by the heat and power generated for the process. Therefore, the net cost of this process area is diminished. The next largest net cost area of the biochemical process is pretreatment and conditioning, accounting for $0.25/gal (or 19%) of the overall cost. Much of this is due to the high capital cost of the pretreatment reactors needed for dilute sulfuric acid. The largest single operating cost, however, remains the feedstock cost itself.

2. Cellulosic ethanol via thermochemical conversion route (Phillips et al. 2007)

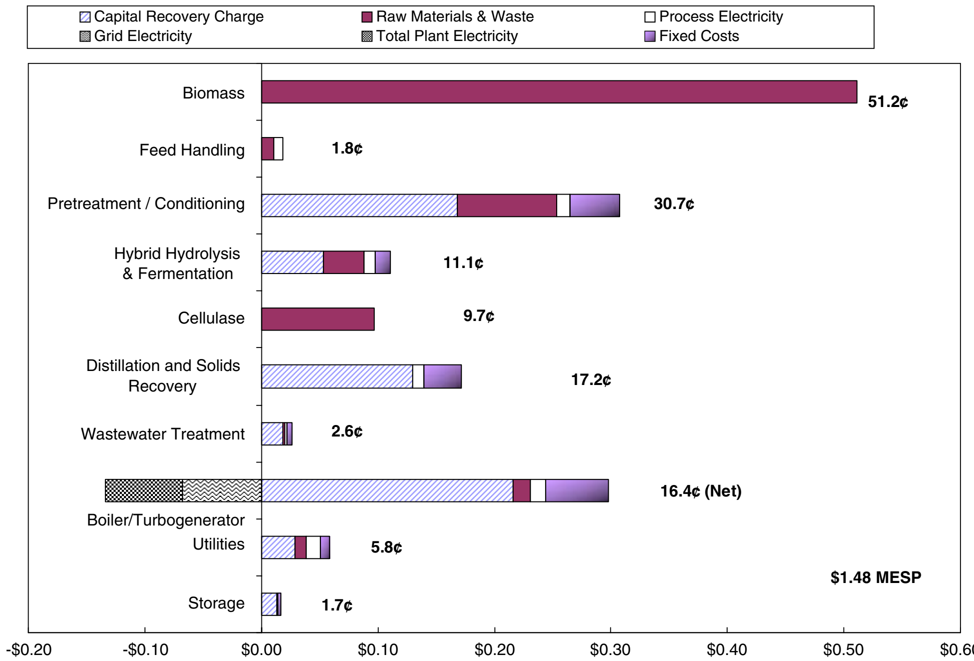
Process description

The thermochemical design is illustrated in Fig. 7 and uses a different feedstock than the biochemical design. Wood chips instead of corn stover are converted to ethanol and other higher alcohols though a series of solid-phase and gas-phase reactions. Wood chips are brought to the plant and then screened, milled, and dried. The wood is then gasified using a circulating fluidized bed indirect gasification system. Biomass char and a small slipstream of unreformed synthesis gas are combusted and this heat is transferred to the gasifier through the circulation of hot sand (olivine) between the two process vessels. The crude synthesis gas (syngas) is primarily composed of CO, H_2, CO_2, CH_4, tars, and water. The tars (including benzene) are then reformed into useful syngas using a fluidize-able tar reforming catalyst. Deactivated reforming catalyst is separated from the effluent syngas and regenerated online similarly to fluidized catalytic cracking technology used in petroleum refining. The hot syngas is cooled through a series of heat exchange and water scrubbing steps. The scrubber removes impurities such as particulates and residual tars. This scrubber water undergoes primary treatment onsite to recover a portion of the quench water, while the rest is sent offsite for further wastewater treatment. The cooled syngas is compressed to 435 psi before it enters an amine unit to remove a majority of the acid gases (CO_2, H_2S) present. The CO_2 is vented to the

Table 9. Conversion cost of biochemical conversion of corn stover to ethanol

Cellulosic ethanol biochem 45MM gal/yr	
Operating costs ($/gal ethanol)	
Feedstock	0.51
CSL	0.03
Cellulase	0.10
Other raw materials	0.11
Waste disposal	0.02
Electricity	−0.07
Fixed costs	0.16
Capital depreciation	0.18
Average income tax	0.13
Average return on investment	0.32
Production cost per gal	1.48
Operating costs ($/yr)	
Feedstock	23,000,000
CSL	1,400,000
Cellulase	4,400,000
Other raw material costs	2,500,000
Waste disposal	700,000
Electricity	−3,000,000
Fixed costs	$7,000,000
Capital depreciation	$8,000,000
Average income tax	$5,900,000
Average return on investment	$14,300,000
Total operating costs ($/yr)	$64,200,000

Figure 6. Biochemical costs distributed by process area.



atmosphere and the sulfur is captured in its elemental form using a Klaus-like unit called LO-CAT.

The cleaned and conditioned syngas is further compressed to the required synthesis pressure and sent through a fixed-bed molybdenum sulfide-based catalyst to synthesize a variety of mixed alcohols. After synthesis, the alcohols are cooled and condensed away from the unconverted syngas. The unconverted syngas is recycled to the tar

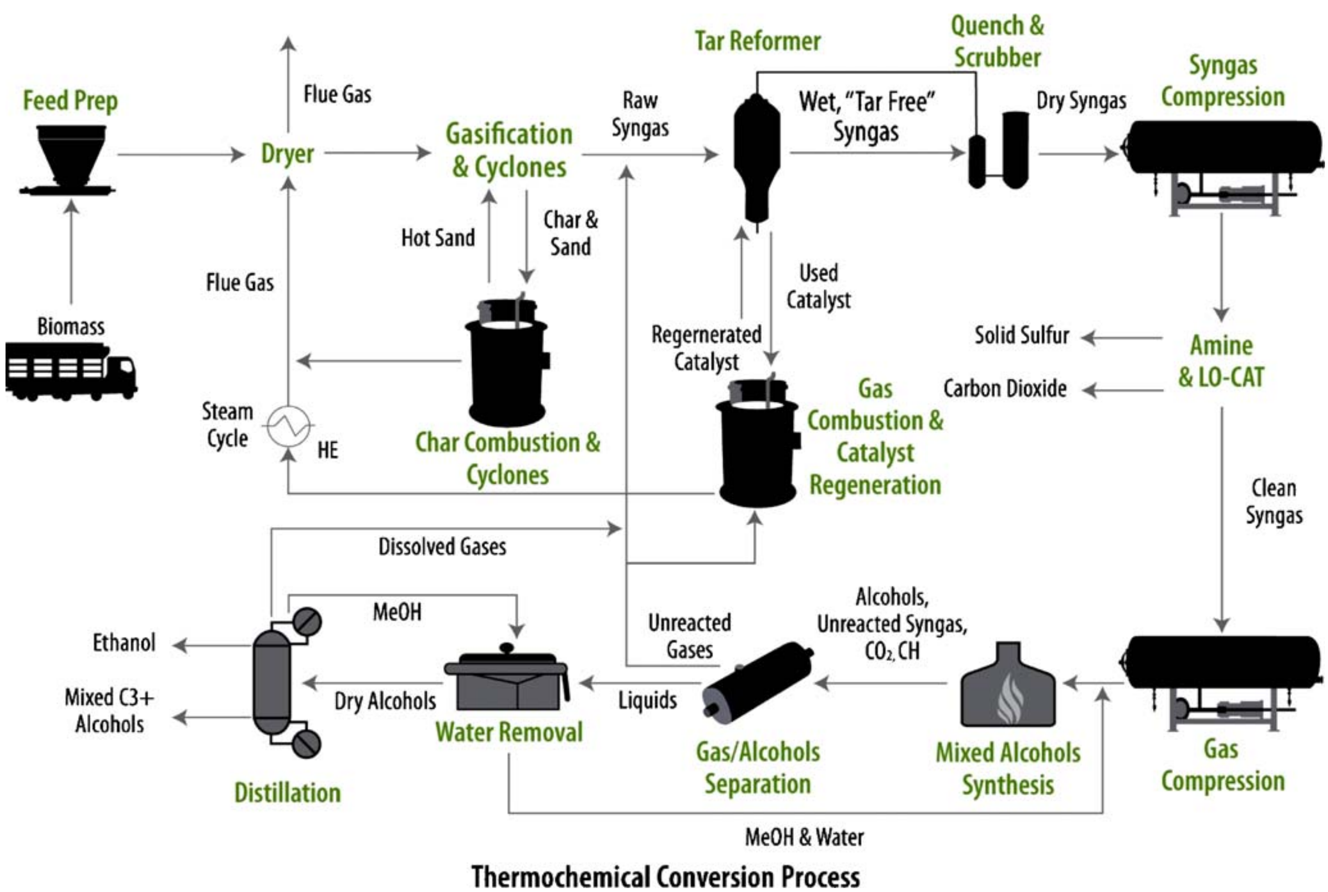


Figure 7. Schematic process flow diagram from corn stover to ethanol (Phillips et al. 2007).

reformer while the condensed alcohols undergo distillation and purification to recover pure ethanol. Methanol is recovered and recycled to the synthesis reactor in order to boost ethanol and higher alcohol yields. The C3+ alcohols are then sold as a coproduct based on an assumed fuel value ($1.15/gal). In this design, the steam cycle is integrated throughout the process while driving compressors and generating electricity as well.

Process economics

Operating costs were calculated for a 45 million gallon per year facility and are shown in Table 10. The internal rate of return after tax is assumed 10% and equity of total investment is 100%. The plant operates 350 d per year for a total of 8,400 h. The TPI of this size plant is shown in Table 15. Detailed baseline assumptions can be found in Phillips et al. 2007.

For both cases of biochemical and thermochemical conversion, the single largest cost component is the biomass feedstock, though the absolute contribution in $/gallon differs because of the different ethanol process yields. For the thermochemical process, the largest cost area is the tar reforming and syngas conditioning section, which accounts for $0.38/gal (or 28%) of the overall cost (Fig. 8). Reductions in costs for pretreatment and syngas cleanup and conditioning will lead to significant reductions in the overall cost of ethanol for each process. This also helps to depict why each of these respective areas is a key focus of process R&D.

A direct comparison of the costs (Table 11) is shown for biochemical and thermochemical ethanol processes. Process alcohol yields are also shown. Note that while the feedstocks are different for each process, identical delivery costs ($46/dry ton) are assumed. The MESP ($/gallon) is slightly lower for the thermochemical process despite having lower ethanol yields than the biochemical process. One primary reason for this is that the total alcohol yield from thermochemical production is slightly higher than for biochemical production, and the higher alcohols coproduct return, a larger coproduct credit than the power credit the biochemical process receives. Subtracting the coproduct credits from the respective MESP values results in ethanol costs that are almost identical, especially within the margin of uncertainty for these models.

Table 10. Conversion cost of thermochemical conversion of wood chips to ethanol

Cellulosic ethanol thermochem 45MM gal/yr		
Operating costs ($/gal product)		
Feedstock		$0.57
Catalysts		$0.00
Olivine		$0.01
Other raw materials		$0.02
Waste disposal		$0.01
Fixed costs		$0.24
Coproduct credits		−$0.21
Capital depreciation		$0.19
Average income tax		$0.14
Average return on investment		$0.34
Total operating costs (cents/gal)		$1.32
Operating costs ($/yr		
Feedstock	$25,800,000	
Catalysts	$100,000	
Olivine	$300,000	
Other raw material costs	$200,000	
Waste disposal	$200,000	
Fixed costs	$10,900,000	
Coproduct credits @ $1.15/gal	−$9,300,000	
Capital depreciation	$8,400,000	
Average income tax	$6,400,000	
Average return on investment	$15,400,000	
Total operating costs ($/yr)	$58,400,000	

3. Corn butanol

Fermentation of sugar-containing substrates to acetone, butanol, and ethanol (ABE) is well known. These solvents were produced by fermentation at commercial quantities in the early-to-mid-1900s using *Clostridium acetobutylicum*, a solvent-producing gram-positive bacteria. At times, acetone was the product of focus and butanol was a by-product. After the mid-1950s, petroleum became a more cost-preferred feedstock for producing butanol. The ABE plants simply could not compete and were forced to shut down. However, with the onset of rising petroleum prices and new biotechnology, biological butanol production may become the more cost-effective technology once again. In the long run, the butanol production via biomass may be more economical than petrochemical industry as a transportation fuel with much larger scale than in the past.

The old fermentation processes were batch processes with low productivity and solvent concentration. Molasses or corn mash was generally used as feedstocks. More recent research has been aimed at developing a continuous process with high product yield, concentration, and productivity. From this research, initial economics of ABE produced from corn starch hydrolysate were compared against propylene-based butanol. Under certain scenarios, the economics for butanol looked promising at the time. Another well-known strain, *Clostridium beijerinckii* (or *C. butylicum*) produces solvents in approximately the same ratio as *C. acetobutylicum*, but isopropanol is produced in place of acetone. These strains are spore formers and obligate anaerobes with relatively simple growth require-

Table 11. Cost comparison between biochemical and thermochemical ethanol production from biomass

	Biochemical	Thermochemical
Year-dollars ($)	$2,007	$2,007
Feedstock	Corn stover	Wood chips
MESP ($/gallon)	$1.48	$1.32
Total installed cost ($MM)	$92	$121
Total project investment ($MM)	$183	$241
Delivered feedstock cost ($/dry ton)	$46	$46
Coproduct credit	Electricity ($0.05/kWh)	Higher alcohols (C3+) $1.15/gallon)
Coproduct credit/gallon EtOH	$0.09	$0.21
Ethanol production (MM gal/yr)	45	45
Total alcohol production (MM gal/yr)	45	52.8
Ethanol yield (gal/dry ton feed)	89.7	80.1
Total alcohol yield (gal/dry ton feed)	89.7	94

ments. Blaschek et al. (2005) have significant research experience with "hyper-producing" versions of such strains. Ramey and Yang (2004) have also been successful in producing higher butanol yields by separating the fermentation into two separate steps: an acidogenesis phase and a solventogenesis phase, where different organisms are used during each phase.

Butanol's higher energy density and transportation advantages compared to ethanol provide incentive for investment from industry. In addition to BP and DuPont collaborations on butanol isomers, Cobalt Biofuels announced it raised $25 million in equity to accelerate the commercialization of *n*-butanol, an advanced biofuel (Cobalt News 2008). Another startup company, Gevo, is currently focused on the development of advanced biofuels and renewable chemicals that are based on isobutanol and its hydrocarbon derivatives (Gevo News 2009) using a microorganism recently licensed from Cargill. TetraVitae Bioscience's focus is the production of biobutanol using a proprietary fermentation process and enhanced microorganism platform and claims making significant improvements over conventional approaches (TetraVitae Bioscience 2009). UK-based Green Biologics and Mumbai-based Laxmi Organic Industries have signed an agreement to build a commercial-scale biobutanol plant in India and the demonstration plant is expected to produce 1,000 metric tons (2.2 million pounds) of butanol a year starting in 2010 (Cleantech 2008). In general, technological advances are being focused on engineering strains for higher butanol productivity and yield through minimization or elimination of the metabolic pathways that lead to acetone and ethanol production. Engineering advances are also being employed

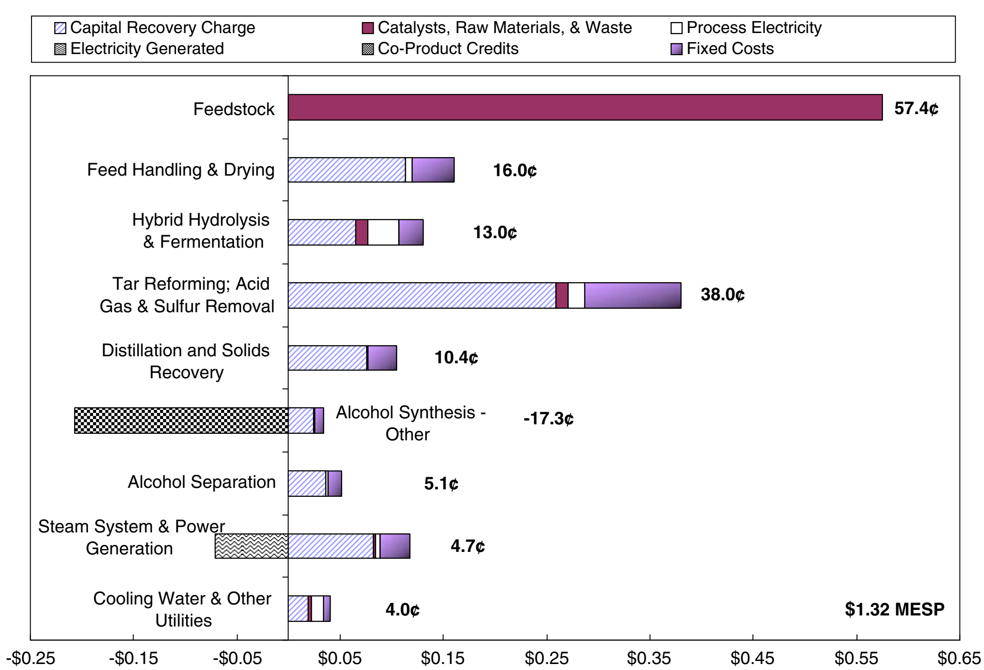


Figure 8. Thermochemical costs distributed by process area.

to help overcome the toxicity challenges that these systems have seen in the past.

Process description

While several designs and process variations have been explored in literature, very little modeling has been done using rigorous physical property models. Simple assumptions of how components are expected to fractionate and separate, for example, can often be proven wrong through such an approach. After analyzing several conceptual designs, NREL developed its own conceptual design for ABE production. The USDA corn dry mill ethanol model was used as a basis for modeling. The ethanol fermentation and downstream recovery was replaced with a butanol fermentation using *Clostridium*. A complex sequence of distillation steps was then added to separate and purify the acetone, butanol, and ethanol components from the water. Nonrandom two-liquid modeling package was used to more accurately predict the liquid/liquid interactions that would take place in a system such as this. As with corn ethanol, the by-product from this process is animal feed. While DDGS from yeast-based production is common, bacterial-based DDGS would have to undergo animal feeding trials. H_2 is also produced from clostridial strains of this sort. This is collected and purified using commercial pressure-swing adsorption (PSA) technology. In this fashion, five total products are produced: ethanol, hydrogen, DDGS, acetone, and butanol.

The process is depicted in Fig. 9, adopted initially from the corn dry mill process. Corn is milled first then sent to liquefaction. After liquefaction, microorganisms are added to ferment the glucose to acetone, butanol, and ethanol mixture. Total residence time in the fermentors is 72 h. The gas stream from the fermentors goes through a PSA unit to recover hydrogen, which is sold as coproduct. The whole beer is degassed and sent to distillation systems. About 85% water is removed from the dehydration column then recycled back to liquefaction. Downstream distillation columns further separate acetone, ethanol, and *n*-butanol from residual water, combined with process options of extractive distillations, molecular sieve, or pervaporation membrane units.

Process economics

Qureshi and Blaschek published ABE butanol production costs at $1.56/gal based on $1.80 per bushel corn feedstock cost (Qureshi and Blaschek 2000). If the feedstock is raised to $3.35/bushel (FO Lichts 2007), their estimated butanol cost is about $2.10/gal, which is similar to what is estimated in the model reported here.

The economics (annualized cost of production, not cash flow analysis) for corn ethanol production are calculated in an Excel spreadsheet. The material and energy balance data

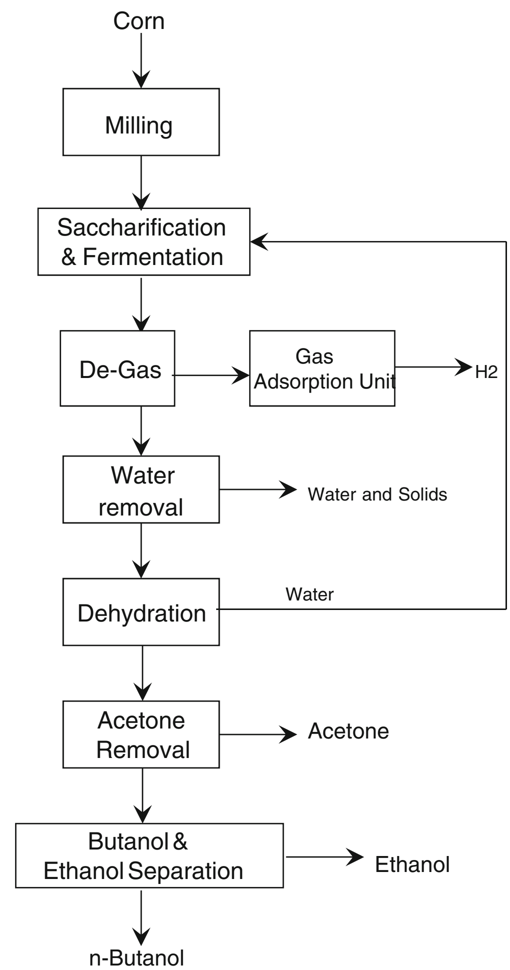


Figure 9. Simplified process flow diagram of corn butanol.

obtained from the Aspen Plus simulation is used in the spreadsheet to size and cost the specified capital equipment. It is also used to calculate the fixed (labor and supplies) and variable (raw materials) operating costs of the plant. The economics have been updated to reflect year-$2007. The specific costing data sources are originally gathered by USDA and represent a combination of vendor specifications, costing program results, and chemical and utility list prices. Overall economic process assumptions are listed in Table 12.

The resultant process economics are shown in Table 13. For a 45-MM gal/yr butanol plant using $3.35/bushel corn, the production cost of $1.96/gal *n*-butanol results and a yield of 1.36 gal/bushel (57 gal/dry ton corn) are calculated. With a total installed cost of $138 MM, this equates to just over $6.10/annual gallon, shown in Table 15. These results are a fairly accurate depiction of the economics during early 2007. The comparison of process economics of corn ethanol and corn butanol is listed in Table 14. Using almost identical baseline economic assumptions, the yield of corn ethanol is almost

Table 12. Baseline economic assumptions for corn butanol process economics

Economic parameter/prices	Baseline value
Installation factor	3.0 (across all equipment)
Equipment life/depreciation	20 yr (straight line)
Equipment scaling exponent	0.6
Online percentage	96% (350 d)
Corn price	$3.35/bushel
Acetone price	$0.45/lb
Ethanol price	$0.35/lb
Hydrogen price	$1.30/lb
Caustic price	$0.055/lb ($110/ton)
Enzyme price	$1.03/lb
Sulfuric acid price	$0.05/lb ($100/ton)
Lime price	$0.04/lb ($80/ton)
Makeup water price	$0.00002/lb ($0.167/1,000 gal)
Urea price	$0.10/lb ($200/ton)
Yeast price	$0.85/lb
Electricity	$0.05/kWh
Natural gas	$7.50/MMBtu

twice as to corn butanol. However acetone, ethanol, and hydrogen coproducts in corn butanol process contribute more significantly to the net production cost than coproducts do to the corn ethanol process. These results in a production cost of $1.96/gal butanol compared with $1.53/gal ethanol produced from corn. Also note that the TPI is also doubled for the corn butanol process compared

Table 13. Butanol cost from a 45-MM gal/yr plant from corn

Corn Butanol 45MM gal/yr	
Operating costs ($/gal butanol)	
Shelled corn	$2.46
Denaturant	$0.00
Other raw materials	$0.11
Utilities	$0.97
Labor, supplies, and overheads	$0.44
Depreciation	$0.43
Coproduct credits	−$2.45
Production cost per gallon	$1.96
Operating costs ($/yr)	
Shelled corn	$110,829,994
Denaturant	$0
Other raw materials	$5,036,590
Utilities	$43,457,545
Labor, supplies, and overheads	$19,959,364
Depreciation	$19,262,217
Coproduct credits	−$110,443,187
Total production cost	$88,102,522

to corn ethanol, simply due to low feedstock yield, and a more complicated separation of liquid mixtures of acetone, ethanol, butanol, and water from the fermentation beer with low solvent concentrations.

Cellulosic butanol potentials. Using corn grain to make butanol is a logical technology progression because much of the technology is already commercial. However, further increases in biofuel production (ethanol and butanol) to meet the goals of the renewable fuels standard can be produced from cellulosic biomass, such as corn stover, corn fiber, wheat straw, barley straw, and energy crops like switchgrass and miscanthus. While *C. beijerinckii* (Parekh et al. 1999) and *C. acetobutylicum* (Lin and Blaschek 1983) have been used primarily for butanol production, *C. beijerinckii* BA101 has also been used to treat corn fiber hydrolysate (Qureshi et al. 2008) and soy molasses (Qureshi et al. 2001) for butanol production. *C. beijerinckii* P260 was used to wheat straw by Qureshi et al. 2007. *C. acetobutylicum* P262 has been used to corn stover (Parekh et al. 1988) and wheat straw (Marchal et al. 1984). *Clostridium saccharoperbutylacetonicum* has been used for bagasse and rice straw (Soni et al. 1982). Newly engineered *Escherichia coli* strains as the microbial cultures have been developed to produce isobutanol (Atsumi et al. 2007, 2008; Hanai et al. 2007), in addition to *n*-butanol production. It should be noted that butanol-producing cultures are able to use a wide variety of carbohydrates, such as cellobiose, sucrose, glucose, fructose, mannose, lactose, dextrin, starch, xylose, and arabinose (Qureshi and Thaddens 2008). There is no reported cost data for cellulosic butanol production available yet.

Comparison on process economics. The TPIs for the six biofuel processes discussed in the paper are listed in Table 15 for comparison at the plant scale of 45 MM gal production/yr. For TPI per gallon biofuel production, corn butanol costs more than any of the other processes due to both low yield and high installed equipment cost under current technologies.

Once converted to a production cost with energy equivalence to gasoline (Table 16), the modeled butanol production cost is more similar to the food-based commercial processes' production cost. Although both cellulosic ethanol processes have not achieved commercial scale yet and are still in the development stages, the process economics with higher TPI still look very promising.

Process intensification. Numerous ways of improving the overall efficiencies and intensities of biofuels processes are being explored for both current and future biofuels. In addition, the colocation of cellulosic facilities with existing conventional facilities is being examined. As part of an on-

Table 14. Economic results comparison for corn dry mill ethanol and *n*-butanol

	Corn to ethanol	Corn to butanol
Annual ethanol production cost	$1.53/gal	$1.96/gal
Plant size (fuel production, MM gal/yr)	45.00	45.00
Yield (gal/bushel)	2.77	1.36
Capital costs—installed ($MM)		
Feed handling and milling	$4.05	$5.99
Liquefaction and saccharification	$3.56	$5.31
Fermentation	$10.97	$19.99
Distillation	$13.56	$22.60
Water recycle and solids handling	$25.85	$63.08
Storage	$1.53	$7.32
Utilities and other	$6.23	$9.21
Total	$65.75	$133.51
Operating costs ($/gallon)		
Shelled corn	$1.21	$2.46
Denaturant	$0.04	$0.00
Other raw materials	$0.05	$0.11
Utilities	$0.30	$0.97
Labor, supplies, and overhead	$0.11	$0.44
Depreciation	$0.14	$0.43
Coproduct credits	−$0.32	−$2.45
Total	$1.53	$1.96

going collaboration between USDA-ARS and NREL, several conceptual options for integrating these technologies were explored and summarized in a report (Wallace et al. 2005). Biomass in corn ethanol boiler systems in place of natural gas is being used in Minnesota. Not only does this help to begin integrating biomass into existing systems but it also avoids high natural gas prices and fluctuations. If gasifier systems, such as one being implemented by Chippewa Valley Ethanol Co., Benson, MN, are used, they provide the next step toward integrating cellulosic ethanol production into conventional systems.

Similarly, within cellulosic biofuels processes themselves, opportunity exists for integrating biochemical and thermochemical technologies to increase the overall efficiency of a biorefinery (Fig. 10). This has been demonstrated through the Role of Biomass in America's Energy Future project. While capital costs for these systems will likely be large, the increased energy efficiency of such systems can lead to attractive economics for certain modeled scenarios. Specifically, the thermochemical section can provide combined heat and power production by gasifying the lignin residue from a biochemical process while simultaneously producing additional liquid fuels. The overall yields of alcohols and the total process efficiencies have been shown to increase beyond current designs.

While the benchmark biochemical cellulosic ethanol design uses purchased cellulase enzymes, the option for including onsite enzyme production is also a viable technological consideration. Realistically, enzyme cost targets in the range of $0.30/gal at the commercial scale should be achievable in the near future by avoidance of transportation and formulation costs (Merino and Cherry 2007). In such scenario, on-site or near-site enzyme production is essential, where enzymes are produced using reduced-cost feedstocks, transported short distances, and not stored for extended periods of time. The least expensive alternative in this situation involves the direct use of whole fermentation broth (including cell mass) to circumvent expensive cell removal and enzyme formulation steps. To

Table 15. Total project investment of all six processes

Total capital investment ×1,000

45MM gal/yr biofuel	Corn ethanol	Sugarcane ethanol	Soybean diesel	Corn butanol	Corn stover ethanol (biochem)	Wood chips ethanol (thermochem)
Total installed equipment cost	$65,745	$43,700	$11,681	$138,317	$91,901	$120,637
Warehouse and site development	$6,575	$4,589	$1,168	$13,832	$9,190	$12,064
Total installed cost	$72,320	$48,290	$12,849	$152,148	$101,091	$132,701
Indirect costs						
Field expenses	$14,464	$9,658	$2,570	$30,430	$20,218	$26,540
Home office and construction fee	$18,080	$12,072	$3,212	$38,037	$25,273	$33,175
Project contingency	$14,464	$9,658	$2,570	$30,430	$20,218	$26,540
Total capital investment	$119,328	$79,676	$21,201	$251,045	$166,800	$218,956
Other costs (startup, permits, etc.)	$11,933	$7,968	$2,120	$25,104	$16,680	$21,896
Total project investment	$131,261	$87,644	$23,321	$276,149	$183,480	$240,852
TPI per gal biofuel ($/gal)	$2.92	$1.95	$0.52	$6.14	$4.08	$5.35

Table 16. The process economics comparison of all six processes

45MM gal/yr biofuel	Corn ethanol	Sugarcane ethanol	Soybean diesel	Corn butanol	Corn stover ethanol (biochem)	Corn stover ethanol (thermochem)
Total production cost ($M/yr)	$74	$58	$121	$88	$64	$58
Total project investment ($M)	$131	$88	$23	$276	$183	$241
Production cost ($/gal)	$1.53	$1.29	$2.55	$1.96	$1.48	$1.32
Energy density (BTU/gal)	76,330	76,330	119,550	99,837	76,330	76,330
Production cost with energy equivalent to gasoline ($/gal)	$2.33	$1.95	$2.48 equivalent to gasoline; $2.74 equivalent to diesel	$2.28	$2.25	$2.00

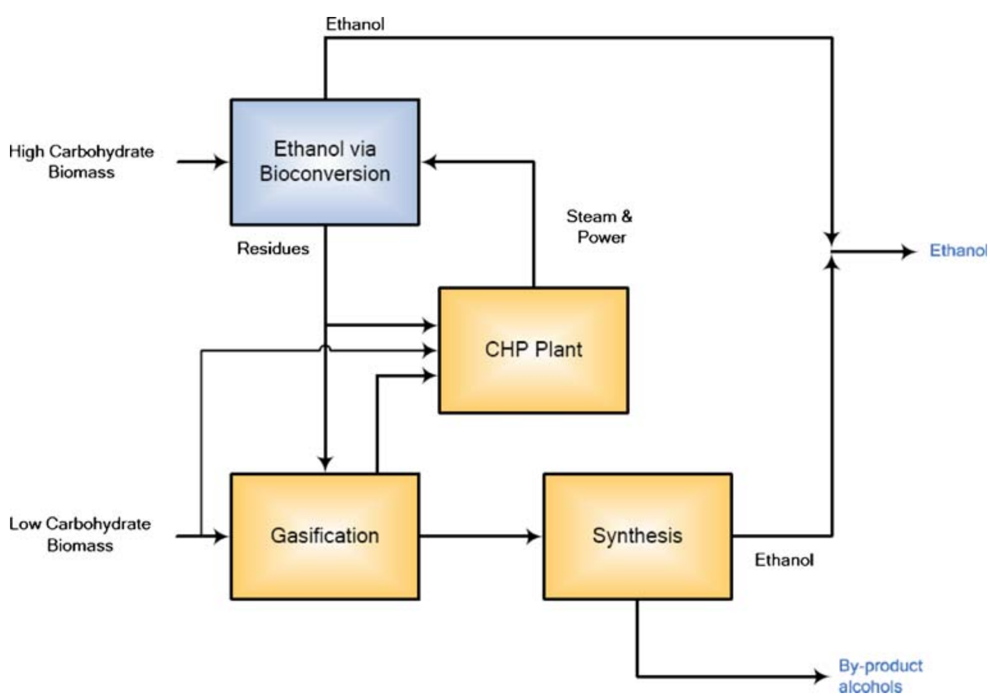
Energy density data from Argonne GREET 1.8 model (http://www.transportation.anl.gov/modeling_simulation/GREET/index.html).

investigate this possibility, they compared the use of whole fermentation broth and cell-free broth as catalysts; results strongly indicated that there is no difference in terms of enzymatic performance for both preparations with equivalent dose. Most current commercial cellulase products are sold as cell-free stabilized concentrates. Although these formulations meet market needs with regard to application and cost, for many enzyme products, it is uncommon for the recovery cost and formulation costs to be a major portion of the overall cost. It then follows that no postfermentation processing has the lowest cost. Performance in saccharification was indistinguishable among fresh whole fermentation broth, fresh fully recovered and formulated product, and 28-d-old fermentation broth. These results suggest that typical recovery and formulation costs can be eliminated for use in biorefinery operations, especially in an integrated plant that both makes and uses the cellulase enzymes (Dean et al. 2006).

Conclusions

The process economics for commercial biofuels processes are presented here and are fairly well understood throughout the industry. For these processes, the feedstock cost comprises a very large fraction of the overall production cost, and the overall capital costs are not particularly large compared to other processes or industries. Techno-economic models exist for these processes that appropriately depict the proper process behavior, results, and economics. This knowledge in techno-economic analysis of biofuels can also be applied to future biofuels processes that are not yet commercial. This includes not only the cellulosic processes but also advanced biofuels processes, such as butanol. While feedstock costs are the single largest portion of the overall cost for cellulosic processes, capital costs are much higher for these processes because of the increased difficulty presented by the deconstruction and use

Figure 10. Conceptual configuration for a combined biochemical/thermochemical biorefinery.



of these materials. Significant opportunity for improving both existing and future biofuels economics will come from a variety of sources including better process intensity and integration of multiple technologies.

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