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Likely Features and Costs of Mature Biomass Ethanol Technology

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ABSTRACT

Analysis is undertaken motivated by the question: "What are the likely features and cost of a facility producing ethanol from cellulosic biomass at a level of maturity comparable to a refinery?" This question is considered with respect to cost reductions arising from increased scale, lower-cost feedstock, and process improvements in pretreatment and biological conversion, but not other process steps. An "advanced technology" scenario is developed that represents our estimate of the most likely features of mature biomass ethanol technology. A "best-parameter" scenario, intended to be indicative of the potential for R&D-driven cost reductions, is also developed based on the best values for individual process parameters reported in the literature. Both scenarios involve large plants (2.7 million dry t feedstock/yr). Feedstock costs are taken to be $38.60/delivered dry t for the advanced scenario and $34.00/delivered dry t for the best-parameter scenario. Projected selling prices, including operating costs and capital recovery corresponding to a 14.2% return on investment, are 50¢/gal (pure ethanol basis) for the advanced technology case and 34¢/gal for the best-parameter case. These are markedly lower than the 118¢/gal selling price projected for base-case technology, with the largest share of cost reductions due to improved conversion technology. Key conversion technology improvements include, in order of importance, consolidated bioprocessing, advanced pretreatment, elimination of seed reactors, and faster rates. First-law thermodynamic efficiencies based on the biomass high heating value and production of ethanol and electricity are 61.2% for the advanced case and 69.3% for the best-parameter case, as compared to 50.3% currently. Combining advanced ethanol production technology of the type presented here with advanced gas turbine-based power generation is a promising direction for future analysis and may offer still further cost reductions and efficiency increases.

Index Entries: Ethanol; biomass; energy; mature technology; economics.

INTRODUCTION

Humankind is faced with several options as we seek to shift toward increasing reliance on sustainable energy sources in the 21st century. These options differ significantly with respect to technological maturity—that is, the extent to which

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R&D-driven improvements can be expected to reduce costs and improve performance. For many purposes, valid comparison of energy supply options requires that the technologies considered be of like maturity, with full maturity—for which further foreseeable improvements would result in but incremental benefits—often providing the best basis for comparison. Unfortunately, analyses frequently fail to meet this requirement, resulting in erroneous conclusions.

With these considerations in mind, we have undertaken an analysis motivated by the question: "What are the likely features and cost of a facility producing ethanol from cellulosic biomass at a level of maturity comparable to a refinery?" We acknowledge at the outset that this question is difficult to approach and cannot be answered with certainty. The cost of mature technology is, however, among the most important issues for long-term energy planning, and we suspect that it has not been considered to the degree merited in the case of biomass ethanol production.

ANALYTICAL METHODOLOGY

For the purpose of this analysis, process steps are as follows: pretreatment (including feedstock handling and milling), biological conversion (accomplishing in various configurations: cellulase production, cellulose hydrolysis, hexose fermentaton, and xylose fermentation; and including associated seed fermentors, compressed air, and chilled water), distillation, the power cycle (including the boiler, turbine, and related equipment), and other (including environmental, tankage, and miscellaneous). Costs for these steps are broken down into two categories: energy and nonenergy. Nonenergy costs include direct capital and labor as well as items proportional to one or both of these (maintenance at 3.0% of total fixed investment, general plant overhead at 65% of labor and maintenance, direct overhead at 45% of labor, taxes and insurance at 1.5% of total fixed investment). Results are reported on a per-gallon-pure ethanol basis, although the actual distillate is 90% ethanol suitable for use as a neat fuel. The feedstock is assumed to be poplar, a leading candidate for a hardwood energy crop, with composition as reported previously *(1)*.

Results are presented in first quarter (1Q) 1994 dollars, updated to an overall CE *(Chem. Eng.)* cost index value of 364.0. A capital recovery factor of 0.2 is multiplied by the total installed capital cost to give the contribution of capital to the overall selling price. This value is chosen to be consistent with investment returns for mature, low-risk technology. Assuming a 15-yr plant life, 37% tax rate, no sales expenses, and straight-line depreciation over 5 yr for inside battery limit items and depreciation over 15 yr for outside battery limit items, 2-yr construction time with equal investment in each year, production capacity 80% of nameplate in yr 1 of operation and 100% thereafter, the return on investment is 14.2%. With construction time and capacity buildup assumptions based on Chem Systems (Tarrytown, NY) parameters and used in previous National Renewable Energy Laboratory (NREL) analyses, but probably less representative of a mature process (3-yr construction time, with 30% of investment in year 1, 50% in yr 2, and 20% in yr 3; production capacity 60% of nameplate in yr 1, 80% in yr 2, and 100% in yr 3), the return on investment is 10%.

Plant equipment items for pretreatment, biological conversion, and tankage are estimated based on aggregate component costs as given by ICARUS, quotes from vendors, and other standardized costing methods as maintained in a database continually updated by NREL. Bare equipment costs are multiplied by installation factors ranging from 1.3 to 2.5, depending on the equipment type to give total installed cost. Installed cost is multiplied by 1.55 to yield fixed capital investment, with the added cost for proratables, field expenses, home office expenses, construction and fees, and contingency. An additional 10% is added to cover owner's cost and profit. Finally, working capital is added, resulting in total capital investment. The entire costing procedure has been reviewed and validated by Chem Systems for a recent design *(2)*.

For distillation, with 99.5% recovery from a 5 wt% feed, the ASPEN simulation of Grethlein and Nelson *(3)* was used to estimate column size, steam requirements, and capital costs. Distillation bottoms are centrifuged, and the solids (containing lignin and other residual solids at 50% moisture) are sent to the boiler. Power cycle equipment consists of a fluidized bed combuster designed by Radian (Austin, TX), with control of SO_2, CO, and NO_x, and particulate emissions, as well as elements of a conventional Rankine-type power cycle. The boiler efficiency (steam/HHV of boiler fuel) is about 0.68 with minor variation depending on boiler fuel composition. The overall power cycle efficiency (gross electricity production/HHV of boiler fuel not used to produce process steam) is 25.8%. Boiler ash is disposed of via landfill.

The waste-water treatment section, also updated from previously published NREL designs, is based on a design developed by C2HM HILL (Denver, CO). This section receives the fraction of distillation bottoms thin stillage that is not recycled to the process (40% for both the current process and advanced process), condensed flash vapors from pretreatment, and CIP waste water. COD factors for each component are used to calculate the overall COD burden, and an anaerobic digester is used to produce methane and CO_2 from the biodegradable organics in the combined waste stream, as well as H_2S from any sulfates that may be present (e.g., from gypsum). The disharge COD in the anaerobic digester effluent is specified at 600 mg/L. The off-gas is sent to the boiler, along with dewatered solids. The effluent is polished in an aerobic treatment operation and discharged to publically owned treatment works.

This analysis considers larger biomass ethanol plants than previously analyzed at this level of detail. For expediency, costs for larger plants were based on process components for smaller-sized plants, with adjustment through the use of scaling exponents. In general, much of the equipment in a biomass ethanol plant with capacity exceeding 50 million gal is approaching maximum per unit sizes, and so economies of scale in going to larger plants will be limited. This is, however, probably not the case for the power cycle, which has the largest capital costs in current designs and assumes even greater relative importance in advanced designs. In light of these factors, a scaling exponent of 1.0 was used for pretreatment and biological conversion, a 0.8 exponent for other plant components downstream of biological conversion (distillation, residue processing, waste treatment, and tankage), a 0.7 exponent for the power cycle (W.R. Cambell, Foster Wheeler Energy Corp., Clifton, NJ), and a 0.3 exponent for labor. A more detailed consideration of the issue of the scaling would significantly reduce the uncertainty inherent in this analysis.

POINT OF DEPARTURE—CURRENT TECHNOLOGY

We take as a point of departure NREL's base-case design for ethanol production from a poplar energy crop using simultaneous saccharification and fermenta-

Table 1
Biomass Ethanol Cost Summary—Base-Case Technology

	Selling price breakdown				
	¢/Gal			% of Total	
	Capital, labor and related	Energy	Total	Processing	Overall
Raw materials					
Feedstock			45.97	—	39.0
Other			9.78	—	8.3
Subtotal			55.75		47.3
Processing					
Pretreatment	13.75	6.55	20.3	32.7	17.2
Biological	18.60	6.00	24.6	39.6	20.9
Cellulase production	1.55	1.67	3.22	5.2	2.7
SSF	13.83	3.34	17.17	27.7	14.6
Pentose conversion	3.22	0.99	4.21	6.8	3.6
Distillation	2.74	5.10	7.84	12.6	6.7
Power cycle	28.61	-26.96	1.65	2.7	1.4
Other	7.34	0.36	7.70	12.4	6.5
Subtotal	71.04	-8.95	62.09	100.0	52.7
Grand total			117.84		100.0

Some sums are inconsistent owing to round-off error.
Feedstock: 658,000 dry t/yr.
Plant capacity: 60.1 million gal/yr.
Installed capital cost: $150.3 million (1Q, 1994).

tion (SSF). The poplar feedstock cost is $42/dry t, as in the earlier design. General features of the design are similar to those presented previously by Hinman et al. *(1)*. Costs are somewhat lower than in the previous design, reflecting improvements made in the intervening period between the two studies. Changes from the Hinman et al. design include an updated bioler/steam cycle system with integrated condensate heat recovery, an updated waste-water treatment section, distillation design changes to give a nondenatured product containing 10% water, lower installed costs for fermentation vessels, updated installation factors, and increased plant scale (from 52.7 million gal/yr to 60.1 million gal/yr).

Table 1 presents a cost and selling price summary for the current NREL design. The projected selling price is 117.8¢/gal, based on the sum of operating costs and allowance for capital recovery as described in Analytical Methodology. Dominant cost elements include raw materials, biological conversion (most notably SSF), pretreatment, and the capital cost for the power cycle. Process energy is consumed as steam at two pressures and as electricity. In Table 1 and elsewhere in this article, we represent the composite cost of energy demands for the various process steps in terms of lost electricity revenue—that is, the revenues that would have been realized had the electricity required by a particular process step been sold as exported electricity and had the steam required by a particular process step been expanded to generate exported electricity. Electricity is valued at 4¢/kWh throughout.

Table 2 presents a utilities summary for the base case. Of the 26.96¢/gal of electrical generating potential represented in the boiler feed, consistent with the assumed boiler and power cycle efficiencies, process requirements account for 18.01¢/gal leaving 8.95¢/gal of electricity revenues from electricity export. Pretreatment and biological conversion (principally for cooling, compressed air for aerobic cellulase and seed production, and agitation) account for the largest share of lost electricity revenue, with distillation smaller but significant. The first-law thermodynamic efficiency of the process (energy as ethanol and electricity/high heating value of the feedstock) is 50.3%.

FUTURE TECHNOLOGY

Foreseeable cost reductions relative to current technology arise from three factors: increased scale, decreased feedstock cost, and improved conversion technology. Anticipating costs for feedstock production and conversion involve the particularly challenging matter of projecting impacts of future R&D. We present here two approaches. The first approach involves taking best values for individual process parameters from the literature, and then assuming that through future R&D, these can be realized simultaneously. The second approach uses results reported in the literature in conjunction with judgment to come up with a set of process parameters that are less than or equal to the values used in the first approach. We intend the first "best-parameter" approach to be indicative of the potential for R&D driven cost reductions, whereas the second "advanced technology" approach represents our estimate of the most likely features of mature biomass ethanol technology.

Scale

Production of ethanol from cellulosic materials is very likely to involve considerably larger plants than those most often considered for near-term application. For both the advanced and best-parameter scenarios, we assume a scale of 2.74 million dry t/yr of feedstock. This feedstock utilization rate corresponds to annual ethanol production of 295 million gal/yr at yields associated with the advanced case, and 350 million gal/yr at yields associated with the best-parameter case. This scale is chosen to be comparable to that of the largest corn-based ethanol plant in production currently, the 330 million gal capacity Archer Daniels Midland Co. plant in Decatur IL *(4)*.

It may be noted that the assumed plant scale is far below that constrained by feedstock delivery. As an illustration, the volume of feedstock that can be produced from a hypothetical land area with a 50-mile radius (commonly used in this type of analysis and corresponding to the maximum transport distance typical of corn ethanol plants) producing an energy crop at a productivity of 10 t/acre/yr (the goal of the Oak Ridge Program) at yields representative of an advanced process is calculated as follows:

$$\pi \times (50 \text{ miles})^2 \times (640 \text{ acres/mile}^2) \times (10 \text{ t/acre} \cdot \text{yr}) \times (100 \text{ gal/t}) = 5.03 \times 10^9 \text{ gal/yr} \quad (1)$$

Table 2
Energy and Utilities Breakdown—Base-Case Technology

	Process requirements				Efficiency (first law)		
	Steam usage, lb/gal ethanol		Power usage	Energy cost—¢/gal,	% Feedstock HHV		
	50 psig	150 psig	kWh/gal ethanol	lost electricity rev.	Ethanol	Electricity	Total
Pretreatment	4.19	5.66	0.99	6.55	46.1	4.2	50.3
Biological			1.50	6.00			
Distillation	21.44		0.33	5.10			
Other			0.09	0.36			
Power cycle[a]				–26.96[a]			
Exported power			–2.24	–8.95			

[a]Values correspond to the electricity produced if steam were not extracted for the process.

Thus, production of 250 million gal/yr corresponds to fractional energy crop coverage of 5% for advanced energy crop productivities (10 t/acre/yr), and 10% for productivities representative of current technology (5 t/acre/yr).

Feedstock

For a biomass ethanol facility at the level of maturity of a refinery, it is reasonable to assume that technology for feedstock production will also be advanced relative to that available today. In the case of conversion technology (considered below), we believe it reasonable to project rapid improvements given adequate resource investment, and it is also probably reasonable to think in terms of cost asymptotically approaching that associated with a hypothetical "mature" technology for which further R&D offers incremental benefits. This framework may well be less appropriate for energy crops. The rate of R&D progress on biomass feedstocks is constrained by the time it will take to develop low-cost energy crops and associated cultivation practices, which in turn is constrained by the long generation time of energy crops. It may be noted that this generation time is roughly two orders of magnitude longer than that of the microorganisms on which conversion technology is based. In addition, there is unlikely to be a limit to energy crop improvements that can be realized in the lifetimes of those living today. This statement is supported by the observation that we are far from realizing the genetic potential of even conventional crops that have been the target of a century of development, and thus, further R&D-driven productivity improvements can be projected (personal communication, Marie Walsh, Oak Ridge National Lab).

With these observations in mind, one could make a case for using a very low feedstock cost in the best-parameter scenario, or even the advanced scenario, as defined here. However, costs have only been projected to 2020, so reductions beyond that time frame become more speculative. In addition, 25 yr hence is sufficiently distant for many planning purposes that it may be appropriate to use projections for the 2020 time frame as a surrogate for mature technology. Consistent with this approach, and based on consultation with Marie Walsh and others at the Biofuels Feedstock Development Program at the Oak Ridge National Laboratory, a cost of $38.6/delivered dry t is used here for the advanced technology scenario (corresponding to the average future cost value projected by Perlack and Wright *[5]*). This corresponds to the projected cost in the 2020 time frame based on a three- to fourfold increase in R&D expenditures, but probably does not represent a limiting value if expenditures were yet higher. With respect to the best-parameter scenario, it has little meaning to use the single best cost or productivity value for a particular test plot in a particular year, which can be very high. Instead, we use $34/delivered dry t, corresponding to the national average productivity goal of the Biofuels Feedstock Development Program (Janet Cushman, Oak Ridge National Laboratory, personal communication).

Conversion Technology

The largest anticipated cost reductions are associated with conversion technology. This situation arises because the most expensive steps in biomass ethanol production—biological conversion, pretreatment, and the power cycle—also have the greatest potential for improvement through R&D. The analysis presented here considers conversion technology improvements in biological conversion

Table 3
Process Parameters and Features for Base-Case, Advanced, and Best-Parameter Cases

Process area	Units[a]	Current[b]	Advanced[c]	Best-parameter[c]	Refs.[d]
Scale	MMgal	60.1	294.9	349.7	*5*
Feedstock cost	$/t	42	38.6	34	*See text*
Availability[e]	%	91.3	91.3	95.9	*5*
Pretreatment					
Milling	–	Yes	No	No	*6*
Solids loading	wt%	35	20	50	*7*
Pentosan solubilization	%	93	100	100	*8*
Pentosan recovery	%	80	90	97	*9*
Glucose loss to byproducts	%	0.1	0	0	*8*
Biological					
Cellulose hydrolysis fermentation	%	72	83	95	
Hydrolysis yield	%		92	98	*10*
C6 Fermentation yield	%		90	97	*11*
C5 Fermentation yield	%	85.5	90	97	[f]
Ethanol concentration	g/L	45	50	120	*12*
Hydrolysis reaction time	Days	7			
SSF	Days		3.0		
DMC	Days		1.5	0.75	*13*
Seed fermentors	–	Yes	No	No	*14*
Consolidated processing	–	No	Yes	Yes	*15*
Distillation		———No change———			
Power Cycle		———No change———			
Waste-water treatment and other		———No change———			

[a]Percent is expressed relative to theoretical.
[b]The basis for current technology is presented in ref. *2*.
[c]The basis for advanced technology and best-parameter cases is discussed in the text.
[d]References are for the best-parameter case only.
[e]Author's estimate based on current practice in the corn ethanol industry.
[f]The value reported in ref. *11* for the C6 fermentation yield is used for the C5 fermentation yield in the best-parameter case.

and pretreatment only. Comments concerning the potential of cost reductions via power cycle improvements are presented in the discussion, but no detailed analysis is offered. Table 3 presents a summary of design variables and features associated with pretreatment and biological conversion for the current technology case, the advanced case, and the best-parameter case.

Table 4
Biomass ethanol cost and Selling Price Summary—Best-Parameter Case

	Selling price breakdown				
	¢/Gal			% of Total	
	Capital, labor and related	Energy	Total	Processing	Overall
Raw materials					
Feedstock			27.95	—	81.6
Other			0.83	—	2.4
Subtotal			28.78		84.0
Processing					
Pretreatment	1.68	1.79	3.47	63.3	10.1
Biological	0.52	0.44	0.96	17.5	2.8
Distillation	1.28	2.78	4.06	74.1	11.8
Power cycle	11.61	−17.84	−6.23	−113.7	−18.2
Other	3.02	0.20	3.22	58.8	9.4
Subtotal	18.11	−12.63	5.48	100.0	15.9
Grand total			34.27		99.9

Some sums are inconsistent owing to round-off error.
Feedstock: 2,738,000 dry t/yr.
Plant capacity: 349.7 million gal/yr.
Installed capital cost: $222.1 million (1Q, 1994).

Best-Parameter Case

The projected selling price for the best-parameter case is 34.3¢/gal, based on the parameters in Table 3 and the already described analytical framework. A cost and selling price summary for the best-parameter case is presented in Table 4, and an energy and utilites breakdown in Table 5. General differences between the best-parameter case relative to the base case are very similar to changes between the advanced technology case relative to the base-case, considered below.

Advanced Technology Case

The process parameters describing the advanced technology case are chosen based on our estimate of the most likely features of mature biomass ethanol technology. Since these choices involve judgment, rationale is presented in some detail.

Pretreatment

In general, features resulting in significant pretreatment cost reductions include: reduced or eliminated milling, elimination of acid addition, achievement of high pentosan recovery, and production of a hydrolysate with minimal inhibitory effect on fermentation. Since available data indicate that these features of advanced pretreatment technology may be embodied in liquid hot water (LHW) pretreatment (also called aquasolv *[10,16,17]*), our choice of process conditions is influenced by those at which this process has been studied. In so doing, we acknowledge

Table 5
Energy and Utilities Breakdown—Best-Parameter Case

	Process requirements				Efficiency (first law)		
	Steam usage, lb/gal ethanol		Power usage	Energy cost—¢/gal,	% Feedstock HHV		
	50 psig	350 psig	kWh/gal ethanol	lost electricity rev.	Ethanol	Electricity	Total
Pretreatment	4.61	2.17	0.02	1.79	61.4	7.9	69.3
Biological			0.11	0.44			
Distillation[a]	8.77		0.31	2.78			
Other			0.05	0.20			
Power cycle[a]				-17.8[b]			
Exported power			-3.16	-12.63			

[a] The value shown does not include flash vapor recovered from pretreatment, which provides a significant portion of the distillation steam requirement.
[b] Value corresponds to the electricity produced if steam was not extracted for the process.

both that these conditions have not been optimized (also performance could thus improve), and also that available data on LHW pretreatment are not sufficient to establish this process as the preferred pretreatment technology, especially in the near term.

Successful pretreatment, in the sense of rendering crystalline cellulose accessible and reactive on enzymatic hydrolysis, has been demonstrated in the absence of extensive milling in the case of both steam explosion (e.g., *see* ref. *6*) and LHW pretreatments *(10)*. Base-case technology, employing dilute-acid hydrolysis, requires extensive milling to reduce the mean particle size to 1 mm. Although mechanistic understanding of pretreatment is incomplete, it is possible that the dilute-acid process requires small particles in order for acid to penetrate fully, whereas steam explosion and LHW pretreatments can be effective at larger particle sizes because they do not involve exogenously added acid.

Many pretreatments, including dilute acid, achieve relatively high degrees of pentosan solubilization (as indicated by little residual pentosan). However, recovering hydrolysis products in undegraded form as fermentable sugars or oligomers is a major challenge for pretreatment processes. Mok and Antal *(8)* have recently reported an average of 90% pentosan recovery for LHW treatment of 10 different biomass sources, and we use this value for the advanced technology case. We note that yet higher values might be achievable, but also that lower values are characteristic of dilute-acid and steam-explosion pretreatments, which have been studied more extensively than LHW processes.

Glucose losses via thermochemical degradation are 0.1% in the base case, and are assumed to be zero in the advanced case. The latter is consistent with the LHW work of Mok and Antal, which analyzed for, but could not detect, glucose degradation products. Hydrolysates resulting from dilute-acid pretreatment as well as other well-characterized pretreatments have a considerable inhibitory effect on fermentation *(18)*. However, only a slight inhibitory effect was observed for LHW pretreatment *(10)*, consistent with the possibility of higher rate processing *(see below)*.

We use conditions as investigated by Mok and Antal *(8)* and van Walsum et al. *(10)*: a 2-min exposure at 220°C without acid. Most LHW pretreatment data have been obtained at low solids loadings, and it is possible that solids loading is an important factor underlying the observed differences between steam-explosion and LHW pretreatment. We assume a solids loading of 20 wt%, noting that LHW pretreatment has been successfully demonstrated at 10 wt% and that the upper limit for effective performance has not been considered. Although there is considerable uncertainty with respect to the solids loading value, overall cost sensitivity to this variable is not great provided that a loading of at least 15 wt% can be utilized.

In addition to elimination of milling, higher sugar recovery, and the absence of inhibition, further differences between the base-case and advanced pretreatment technology scenarios include, for the advanced case: lower-cost for materials of construction, lower-costs for process chemicals, and eliminated gypsum disposal. All of these arise because of the elimination of acid addition. Some degree of pH adjustment might be necessary to make LHW hydrolysates compatible with fermentation requirements. However, this would entail costs a small fraction of those for pH adjustment in the base case, which are already rather small.

In the advanced technology case, pretreated material is flashed in three stages. Some of the vapor from a 150-psia flash is used to preheat feedstock slurry via direct injection prior to pretreatment. The remainder of the 150-psia vapor and all of the vapor from a 50-psia flash are used to meet distillation steam demand partially via condensation on the tube side of a reboiler, with the resulting condensate returned to the steam cycle. Vapor from an atmospheric pressure flash is used to preheat the feed to distillation.

Biological Conversion

The advanced case hydrolysis yield (production of hexose sugars from hexan) value (92%) is taken from the average value observed by van Walsum et al. *(10)*, using LHW pretreatment and SSF. This is in no sense a limiting value, since near-quantitative yields can be observed for pretreated substrates under appropriate conditions.

The fermentation yields are assumed to be 0.46 gal ethanol/g sugar fermented, or 90% of theoretical. Less-than-theoretical ethanol yields are expected even in advanced cases because of the need to produce cells and in the case of direct microbial conversion processes cellulase, and the tendency of most microbes to produce at least small amounts of byproducts (e.g., glycerol, acetic acid). Yeasts routinely achieve yields on the order of 90% of theoretical conversion for soluble glucose, and *Zymomonas* achieves higher yields (Table 3). A higher value might be assumed for the advanced case since cell yields can be expected to diminish under conditions present in a continuous fermentor producing ethanol from cellulosic biomass. At the same time, we apply 90% yields to all sugars, whether they be hexose or pentose, major (e.g., glucose, xylose) or minor (e.g., galactose, arabinose) biomass components—representing an extension of the current state-of-the-art.

We assume an ethanol concentration of 5 wt%. This might appear conservative, since it is well known that yeast and *Zymomonas* produce ethanol concentrations of 10 wt% or more. We believe that several factors support a lower value. These include:

1. Production of ethanol concentrations >5 wt% has not been observed to our knowledge at the temperatures at which SSF is normally operated (~37°C, in order to minimize cellulase cost) or by thermophilic bacteria (*19;* attractive candidates for direct microbial conversion (DMC), discussed below);
2. The difficulty of processing and delivering slurries increases with increasing solids concentration, which normally determines the fermentor ethanol concentration, so there is some advantage to not pushing this variable to the limit; and
3. Ethanol tolerance may be difficult to modify using molecular genetics, since it has not been shown to be under the control of a single gene.

In summary, although it would certainly be possible to operate using higher ethanol concentrations even with currently available organisms, we think the benefits of operating at moderate ethanol concentrations are likely to continue to outweigh the costs. Analysis of distillation cost and energy requirements for the advanced case (presented subsequently) supports the notion that operation at 5 wt% ethanol is not a large cost burden on the overall process.

The SSF reaction time in the base-case design is 7 d. This value is the result of optimization to reduce costs rather than fundamental kinetic limitations, as reflected by the fact that SSF of pretreated hardwood can be completed in a day at very high cellulase loadings (e.g., 50–100 U/g cellulose, personal communication, Colin South, Biometics, Inc.). Shorter reaction times are not used because the smaller associated SSF vessels would be more than offset by the higher cost of cellulase.

Through one or a combination of several improvements, it is possible to imagine the optimum reaction time for SSF decreasing in the future. In particular, either improved pretreatment resulting in more reactive fiber or lower-cost cellulase production methods would have this effect. We estimate that a 3-d reaction time is indicative of the potential of advanced SSF technology resulting from significant, but by no means revolutionary or ultimate, advances.

For the case of DMC, where cellulase and ethanol production are produced in one unit operation by a single microbial community, it is likely that somewhat higher rates could be achieved relative to SSF. This is supported by data from the literature, such as that of Lynd et al. *(13)*, which shows high conversion of pretreated hardwood in as little as 12 h. In addition, one might support this notion by an independent line of reasoning. Although cell yields (mass cells/mass sugar fermented) are on the order of fivefold lower for the anaerobic organisms in a DMC process compared to aerobic cellulase producers, the amount of substrate used to produce cellulase in a DMC system is on the order of 20-fold higher. This statement is supported by the observation that 5% or less of total feedstock is used to produce cellulase in a system producing cellulase and ethanol separately, such as SSF, whereas all of the substrate is processed by cellulase-producing organisms in DMC. Furthermore, the specific activity (per mass protein) is known to be very high for some DMC organisms (e.g., *Clostridium thermocellum [20]*). We choose for our advanced case a more conservative fermentation, 1.5 d, than observed by Lynd et al. *(13)*, in light of the very low substrate concentrations used in that work (<1 wt%) and the expectation that inhibition will become important at more realistic concentrations.

The base-case process design includes cultivation of yeast in aerobic "seed reactors." These are used to produce biomass that is subsequently fed to continuous SSF reactors. Continuous SSF in the absence of seed fermentors, with endogenous yeast biomass production, has been demonstrated *(14)*. Furthermore, we note that already-discussed features of the advanced case, the absence of an inhibitory hydrolysate and shorter reaction times, are conducive to yeast growth and thus consistent with the elimination of seed reactors.

Consolidated bioprocessing refers to achieving cellulase production, cellulose hydrolysis, hexose fermentation, and pentose fermentation in one process step—the salient feature of DMC processes. In addition to improving the ethanol selectivity of thermophilic bacteria or other organisms/defined consortia capable of coproducing ethanol and cellulase as well as utilizing pentoses, an entirely distinct approach is to begin with an excellent ethanol producer, such as yeast of *Zymomonas mobilis*, and modify it so that it can produce cellulase and utilize pentoses. Moreover, both of these approaches should in principle be amenable to molecular genetics, since a relatively small number of genes are involved. The recent progress in conferring pentose-fermenting capability to yeast *(21)* and *Zymomonas (22)* provides yet further support for realism of developing organisms for consolidated processing, although we caution that developing organisms capable of utilizing cellulose is likely to be more difficult. Given these considerations, we see considerable basis for including consolidated processing in the advanced case.

Using the process parameters and features summarized in Table 3 and justified in the discussion above, we estimated costs for the advanced technology case using the analytical framework developed at NREL. Table 6 presents a cost and selling price breakdown for the advanced technology case. It may be seen that the overall

Table 6
Biomass Ethanol Cost and Selling Price Breakdown—Advanced Technology

	Selling price breakdown				
	¢/Gal			% of Total	
	Capital, labor and related	Energy	Total	Processing	Overall
Raw materials					
Feedstock			35.84	—	71.3
Other			0.95	—	1.9
Subtotal			36.79		73.2
Processing					
Pretreatment	3.22	5.63	8.85	65.5	17.6
Biological	1.95	1.00	2.95	21.8	5.9
Distillation	1.79	2.83	4.62	34.2	9.2
Power cycle	14.06	-22.03	-7.97	-59.0	-15.8
Other	4.74	0.32	5.06	37.5	10.1
Subtotal	25.76	-12.25	13.51	100.0	27.0
Grand total			50.30		100.2

Feedstock: 2,738,000 dry t/yr.
Plant capacity: 294.9 million gal/yr.
Installed capital cost: $268.4 million (1Q, 1994).

cost of production is 50.3¢/gal. The cost of production is dominated by raw materials, as expected for a commodity product produced by mature technology. Pretreatment is the most expensive step in the advanced technology case, followed by "other" (primarily environmental and tankage). Biological conversion and distillation are both quite small cost factors.

Figure 1 compares allocated costs for the base-case and advanced processes, and underscores a number of large differences. The cost of biological conversion, the most expensive process step for current technology, is reduced almost 10-fold in the advanced case. A similarly large cost reduction occurs for other raw materials, consistent with no requirements for acid or limestone in the advanced case, and reduced requirements for microbial nutrients, because no cells are grown aerobically in the advanced case. Pretreatment costs are reduced by much less (approximately twofold), resulting in pretreatment becoming a much more dominant cost component in the advanced case. Although distillation technology is not changed, the allocated cost of distillation shows a marked decrease because energy requirements are supplied by pretreatment flash vapor in the advanced case. Exported electricity revenues roughly double for the advanced case, with power cycle capital decreasing on a per-gal basis because of increased ethanol yields.

A utility breakdown for the advanced case is presented in Table 7. Steam usage for pretreatment is higher for the advanced case than it is for base-case technology (Table 2), consistent with the lower solids loading used. Power requirements are much lower for pretreatment, because of the elimination of milling, and

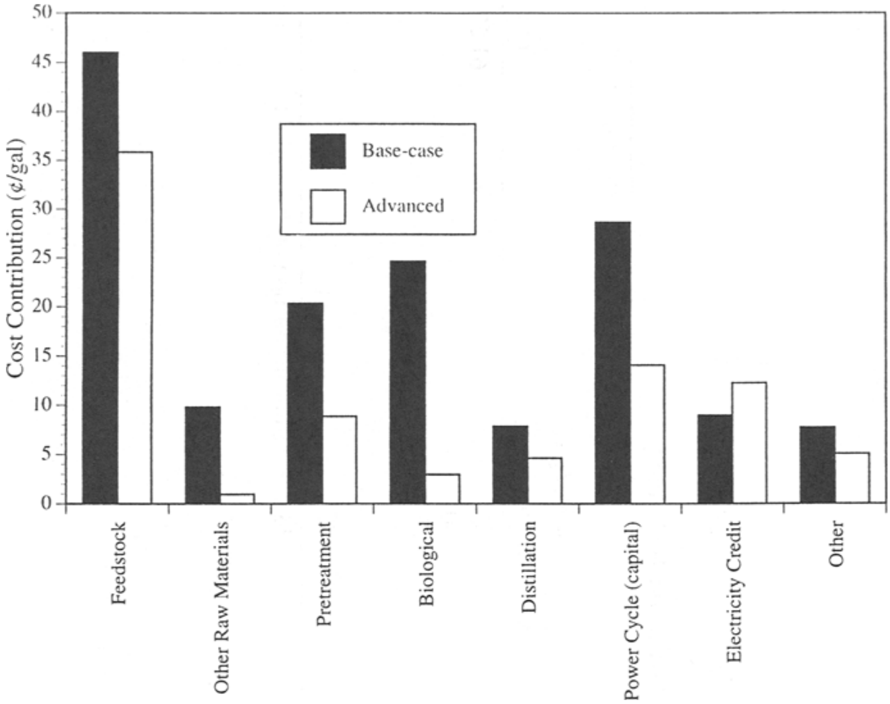

Fig. 1. Comparison of allocated costs for base-case and advanced technology.

for biological conversion, because of the elimination of cooling and compressed air and reduction in agitation requirements. The overall thermodynamic efficiency of the advanced process is 61.2%.

SENSITIVITY ANALYSIS

The impacts of individual process improvements and selected combinations of improvements are presented in Table 8. It may be seen that progress made since the previous NREL base-case was reported results in a 13.5¢/gal improvement. Increasing the plant scale decreases the projected price by 15.9¢/gal to 102¢/gal, while lowering the feedstock cost reduces the price a further 3.7¢/gal to 98.3¢/gal. Increased availability (assumed on only for the best-parameter case; corresponding to decreasing plant down-time from 32 d/yr to 15 d/yr), decreases the price by an additional 2.6¢/gal.

Relative to the 98.3¢/gal projected selling price for the base case adjusted for scale and feedstock, individual process modifications have cost reductions as follows: heat integration, 2.3¢/gal, advanced pretreatment, 15.4¢/gal; cofermentation (combining C5 fermentation and SSF), 7.4¢/gal; elimination of seed reactors, 12.2¢/gal; consolidated bioprocessing, 21.7¢/gal.

Cost reductions for individual improved performance parameters, also relative to the feedstock- and scale-adjusted scenario with a selling price of 98.3¢/gal, are: increased yield (to hydrolysis = 92%, C5 and C6 fermentation to 90%—as used in the advanced case), 3.6¢/gal; a more aggressive yield scenario (hydro-

Table 7
Energy and Utilities Breakdown—Advanced Technology

	Process requirements				Efficiency (first law)		
	Steam usage, lb/gal ethanol		Power usage	Energy cost—¢/gal,	% Feedstock HHV		
	50 psig	350 psig	kWh/gal ethanol	lost electricity rev.	Ethanol	Electricity	Total
Pretreatment	14.91	6.61	0.06	5.63	54.4	6.8	61.2%
Biological			0.25	1.00			
Distillation[a]	8.82		0.32	2.83			
Other			0.08	0.32			
Power cycle				-22.03[b]			
Exported power			-3.06	-12.25			

[a]The value shown does not include flash vapor recovered from pretreatment, which provides a significant portion of the distillation steam requirement.
[b]Value corresponds to the electricity produced if steam was not extracted for the process.

lysis yields = C5 fermentation yields = C6 fermentation yields = 95%),10.0¢/gal; decreased hydrolysis time (to 3 d), 5.5¢/gal; decreased hydrolysis time to 1.5 d, 7.7¢/gal; and high temperature fermentation, 0.2¢/gal.

Cost reductions for combinations of improvements are: nonbiological only, 19.8¢/gal; advanced SSF—biological only, 24.8¢/gal; advanced SSF—biological and nonbiological improvements, 41.2¢/gal; thermophilic DMC–biological only, 31.5¢/gal; thermophilic DMC—biological and nonbiological improvements (corresponding to the advanced case), 48.1¢/gal; and improvements corresponding to the best-parameter case, 63.9¢/gal.

Within the context of the improvements considered, process improvements are by far the most important component contributing to the lower-cost of the advanced scenario, with cost reductions three times those associated with larger scale and over 10 times those associated with less expensive feedstock. It may be seen that consolidated bioprocessing, improved pretreatment, and continuous operation have the largest cost impacts among the individual improvements incorporated into the advanced design. Improvements in biological processing, the largest overall cost-reduction contributor, result primarily from the assumption of consolidated processing. The path to achieving consolidated processing involves combining the properties of separate existing microorganisms into a single organism or system of organisms, which is the distinguishing feature of genetic engineering. The authors offer the perspective that few experts would doubt the achievability of creating organisms compatible with consolidated processing given a sufficient effort.

The data on cost elements presented in Table 6 demonstrate that process improvements result in lowered per-gal feedstock, processing, and capital costs, as well as greater electricity revenues. These data also demonstrate that as the technology matures, the process becomes considerably more feedstock intensive and less capital intensive.

DISCUSSION

The advanced technology case developed here reflects our estimate of the most likely cost associated with mature biomass ethanol technology considering improvements in biological conversion and pretreatment. If the 50¢/gal ethanol selling price projected for advanced technology were realized, this would have a very large impact on ethanol use and market penetration. We take these to be sufficiently self-evident that they need not be elaborated here.

We acknowledge the difficulty of calibrating the degree of technological realism or optimism implicit in an analysis of this type. In this context, we note that the advanced case is by no means ultimate, as underscored by the lower-costs for the best-parameter case and the exclusion of improvements in process steps other than pretreatment and biological conversion.

We believe it probable that there is scope for considerable R&D-driven process improvements and associated cost reductions with respect to the process steps that are not considered in this analysis: distillation, the power cycle, and waste treatment. It is likely that the potential for cost reductions through improving the power cycle is particularly large. In support of this, we note that both the boiler efficiency (steam production/high heating value of boiler fuel = about 68%) and the efficiency of electricity generation (gross production for both process requirements and export/high heating value of the boiler fuel not used to generate process steam

Table 8
Sensitivity Analysis for Process Improvements

	Cost elements, ¢/gal pure ethanol						
	Feedstock	Operating[a]	Electricity revenue	Total operating	Capital	Grand total	Plant capacity, MM gal ethanol/
Previous NREL (per gal denatured product)	45.9	34.6	7.1	73.4	48.3	121.7	58.5
Previous NREL (per gal pure ethanol)	51.0	34.7	7.9	77.8	53.7	131.4	52.7
Update, adjust scale, and feedstock							
1. New NREL	46.0	30.8	9.0	67.8	50.0	117.9	60.1
2. Increased scale	46.0	23.9	9.0	60.9	41.1	102.0	250.1
3. Reduced feedstock cost	42.3	23.9	9.0	57.2	41.1	98.3	250.1
4. Increased availability	42.3	23.2	9.0	56.5	39.2	95.7	262.7
Individual improvements							
Process modifications							
5. Heat Integration	42.3	23.9	11.4	54.8	41.2	96.0	250.1
6. Advanced pretreatment	39.7	18.3	6.5	51.5	31.4	82.9	266.4
7. Cofermentation	41.7	20.3	8.9	53.1	37.8	90.9	253.5
8. Eliminate seed fermentors	40.7	19.2	9.9	50.0	36.1	86.1	259.4
9. Consolidated bioprocessing	39.8	14.9	10.3	44.4	32.2	76.6	265.4

Performance parameters[b]							
10a. Increased yield (90/92/90)[2]	40.4	22.9	8.0	55.3	39.4	94.7	261.3
10b. Increased yield (95/95/95)[2]	37.6	21.3	7.1	51.6	36.7	88.3	281.4
11a. Decrease hydrolysis time (3 d)	42.3	22.7	9.2	55.8	37.0	92.8	250.1
11b. Decrease hydrolysis time (1.5 d)	42.3	22.3	9.4	55.2	35.4	90.6	250.1
12. High-temperature fermentation	42.3	23.8	9.0	57.1	41.0	98.1	250.1
Combined improvements							
13. Nonbiological (5 + 6)	39.7	17.8	10.6	46.9	31.6	78.5	266.4
14. Advanced SSF, biological only (7, 8, 10a, 11a)	39.0	14.7	9.3	44.4	29.1	73.5	271.0
15. Advanced SSF, bio. + nonbio. (13, 14)	36.7	10.3	11.0	36.0	21.1	57.1	288.2
16. Thermophilic DMC, biological only (9, 10a, 11b, 12)	38.1	12.9	10.1	40.9	25.9	66.8	277.2
17. Advanced (13 + 16)	35.8	8.5	12.3	32.0	18.2	50.2	294.9
18. Best-parameter *(see text)*	28.0	6.3	12.6	21.7	12.7	34.4	349.7

[a]Includes raw materials other than feedstock, labor-proportional operating costs (direct overhead, general plant overhead), and capital-proportional operating costs (maintenance, general plant overhead, taxes, and insurance).

[b]Values refer to yields for hexose fermentation, enzymatic hydrolysis, and pentose fermentation, respectively.

= about 25.8%) have significant room for improvement. An option with particular potential is use of a combined cycle gas turbine (CCGT) for the power cycle rather than a conventional Rankine cycle. As presented by Larson *(23)*, electricity production from biomass via CCGT technology is projected to achieve very high efficiencies (e.g., 40–45%) and to involve costs that are relatively insensitive to scale. Thus, substitution of CCGT power cycle can be expected to more than double electricity revenues, already significant at 12.3¢/gal in the advanced case, compared to a conventional power cycle. Particularly at large scales, such as that of the advanced technology case presented here, there is a distinct possibility that the increased electricity revenues associated with use of a gas turbine power cycle will more than offset higher capital costs. Use of such a highly efficient power cycle would have the added effect of substantially increasing the already high thermodynamic efficiency of biomass conversion to ethanol and electricity. A detailed consideration of this topic would be an important extension of this work.

Although we believe our projections for advanced technology are defensible, we also wish to emphasize that the advanced case developed in this article is not our projection of what is realistic today, but rather our projection of what is likely to be realistic at some date in the future. That date depends entirely on the level of effort expended to advance the technology.

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