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Analysis of Internal and External Energy Flows Associated with Projected Process Improvements in Biomass Ethanol Production

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ABSTRACT

Possible improvements in biomass ethanol production are described involving heat-pumped distillation, steam-cycle heat integration, elimination of seed fermenters, pretreatment heat integration, advanced pretreatment, thermophilic DMC, and increased carbohydrate yield to 90% of theoretical. Although speculative, a futuristic process incorporating these improvements may be useful for anticipating some features of a technologically mature biomass ethanol process, as well as for comparing ethanol production to more technologically mature energy-conversion processes. Relative to the current state-of-the-art National Renewable Energy Laboratory process design, the futuristic process has 101% higher electricity revenue, 31% higher ethanol revenue, and 35–39% higher overall revenue depending on the assumed ethanol value. The overall first-law thermodynamic efficiency is 43% for the current NREL design and 59% for the futuristic process. A general consideration of the costs associated with the process improvements examined indicates that:

1. Elimination of seed reactors, advanced pretreatment, and thermophilic DMC all have large potential cost reductions independent of their benefits with respect to increased surplus electricity;
2. Steam cycle improvements and pretreatment heat integration are expected to have modest cost benefits that are dependent on increased electricity revenues; and

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3. The relative cost of heat-pumped distillation depends on scale, capital recovery, and electricity value, but is generally similar to the already low cost of conventional distillation provided that the fermentation broth has a reasonably high ethanol concentration.

A comparison of utilizing biomass for ethanol-electricity coproduction and utilizing biomass for dedicated electricity production indicates that these two alternatives have approximately equal economic benefits. At the electricity yields associated with the futuristic process, every 1% displacement of US transportation demand is accompanied by a 0.29% displacement of electricity demand, underscoring the potential significance of electricity coproduced with ethanol in meeting energy needs.

Index Entries: Biomass; ethanol; electricity; efficiency; cogeneration.

INTRODUCTION

Consideration of energy input in relation to energy output is a significant aspect of evaluating energy conversion processes. In the case of fuel ethanol from cellulosic materials (biomass ethanol), energy inputs are associated with feedstock production and transport, process chemicals, plant amortization, and fuel distribution. Recent analyses (*1,2*) indicate that steam generated from combustion of lignin and other process residues is sufficient to supply all process heat and electricity demands, while producing a net excess of electricity that can be exported as a coproduct with ethanol. The ratio of energy output to energy input has been estimated at approximately 5 for current technology based on energy crops, and at >5 for most waste feedstocks (*2*). The potential of the biomass ethanol fuel cycle to make little if any net contribution to CO_2 accumulation is a direct result of this favorable energy ratio.

After over a decade of research and development, technology for production of ethanol from cellulosic materials seems poised to move into the marketplace on an unprecedented scale. Notwithstanding the significant achievements that have brought biomass ethanol to this point, the state of maturity of current technology is such that substantial further improvements are likely. Nonincremental improvements are also necessary if ethanol is to compete with gasoline.

In addition to reduced costs, improvements in ethanol production technology are likely to impact process energy flows and outputs significantly. Specifically, yields of ethanol and especially electricity are likely to increase. This article examines process improvements in terms of anticipated impacts on electricity yields in particular and energy yields in general. Thereafter, associated implications are examined in relation to process economics and energy planning.

CURRENT TECHNOLOGY OVERVIEW

A detailed state-of-the-art process design for ethanol production from cellulosic biomass has recently been carried out by Chem Systems based on process development overseen by the National Renewable Energy Laboratory (NREL; *1*). This design involves annual production of 53.2 million gallons of ethanol (pure basis), with capital costs annualized using a recovery factor of 0.2. In the NREL process, wood chips are milled and held at 160°C with dilute sulfuric acid in the pretreatment step (Fig. 1A). Biological conversion (Fig. 1B) involves fermentation of soluble xylose prior to simultaneous saccharification and fermentation (SSF) of the insoluble cellulose, with associated cellulase production as well as seed fermenters. Compressed air and chilled water are used extensively by the biological conversion steps. The compressed air is used for aeration in the seed fermenters and cellulase production, and the chilled water is used for interstage cooling of the compressed air, for cooling the SSF reactors, and for condensing fermentor off-gas vapor. Ethanol is recovered in the product separation step (Fig. 1C), which involves use of conventional distillation to produce azeotropic ethanol. Dewatered solids from the separation step and other process residues serve as boiler fuel for the steam plant (Fig. 1D). The steam turbine cycle produces process steam at two different pressures for use in the plant, as well as electricity for both internal use and export for additional revenue.

Table 1 presents a cost and energy breakdown for the base-case process. It may be noted that biological conversion is the most costly overall and has the largest energy cost, with pretreatment a close second in both categories. Biological conversion is the most technically immature (i.e., has the greatest potential for improvement; *2*), with pretreatment being the next most immature and all the other steps being substantially more mature. Taking into account both cost contribution and technological maturity, biological conversion and pretreatment clearly present the largest cost reduction opportunities, probably in this order.

The value of the electricity that could be produced by burning lignin-rich process residues is 29.20¢/gal (Table 1). However, the 13 MW of net exported electricity in the base case has a value of 8.03¢/gal after allowing for electricity and steam consumption by the process. Reduction of process energy consumption thus represents a significant opportunity to both realize added revenue and to produce an additional valuable energy product.

OPPORTUNITIES FOR REDUCING INTERNAL ENERGY DEMAND

Opportunities are examined in approximate order of ease of implementation. That is, those considered first require little development

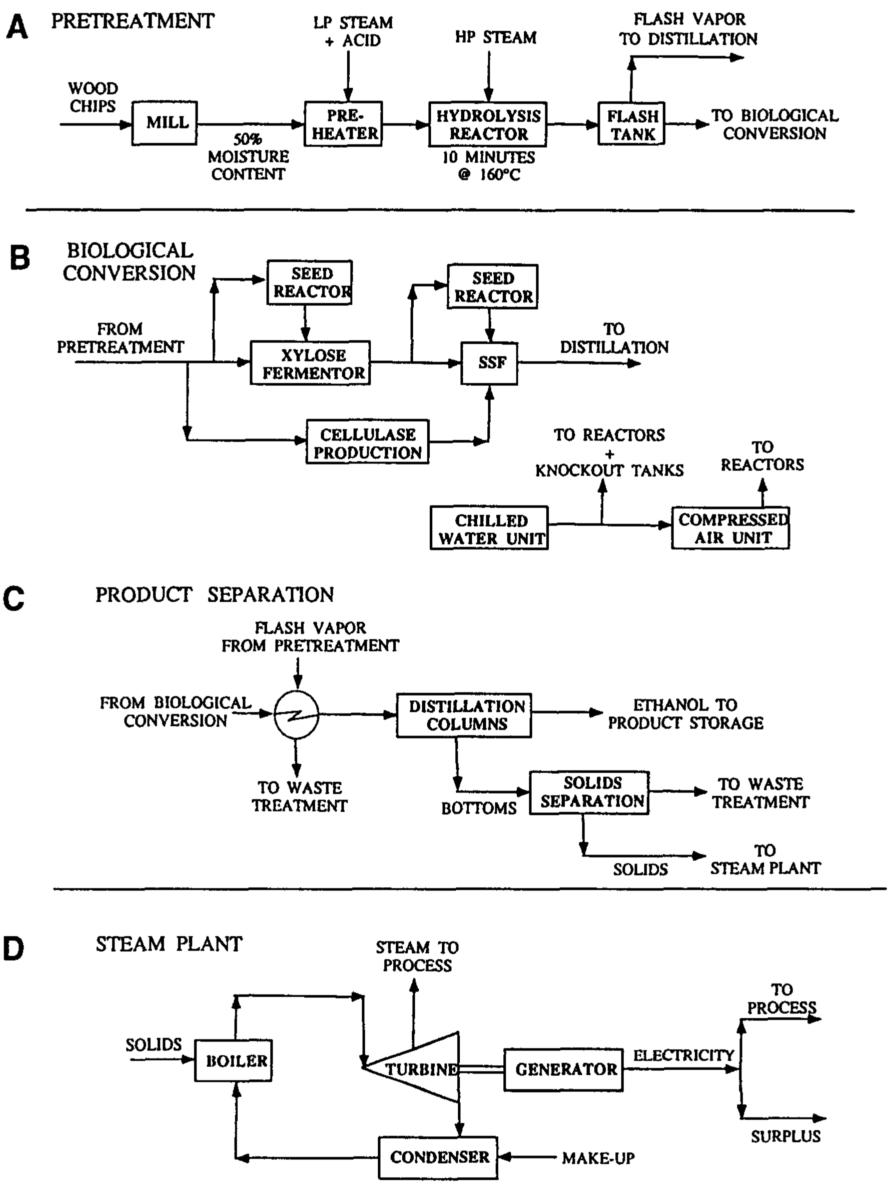

Fig. 1. State-of-the-art process flow diagram. From (*1*).

beyond pilot plant verification, whereas those considered last involve substantial research and development before they could be utilized. Energy flows are considered in this section; commentary on cost implications is offered subsequently.

Heat-Pumped Distillation

Consideration of a Mollier diagram (Fig. 2) indicates that roughly half of the electricity that could be generated from a kilogram of high-pressure steam is lost when steam is extracted for distillation. Thus, separation

Table 1
Cost and Energy Breakdown: State-of-the-Art Biomass Ethanol Production

	Cost contribution, ¢/gal		
Item	Capital, capital-related, and labor	Energy[a]	Total
Raw materials			
Primary feedstock			50.53
Secondary raw materials			10.79
Subtotal			61.32
Processing			
Pretreatment[b]	17.98	7.83	25.81
Biological[c]	21.38	8.25	29.63
Distillation	2.33	4.35	6.68
Power cycle	27.00	−29.20	−2.20
Other[d]	6.16	0.74	7.65
Subtotals		−8.03	67.57
Grand total			128.9

Basis: Costs from (*1*) for a poplar energy crop, 53.2 mm gal/yr pure ethanol.
[a] All energy flows converted to their electricity equivalent, valued @ 4¢/kWh.
[b] Includes SSF, cellulase production, xylose fermentation, and associated seed fermentors, compressed air, and chilled water.
[c] Includes wood handling (principally size reduction).
[d] Environmental, tankage, miscellaneous; the difference between capital and energy costs and the total is owing to 0.75 ¢/gal for gypsum disposal.

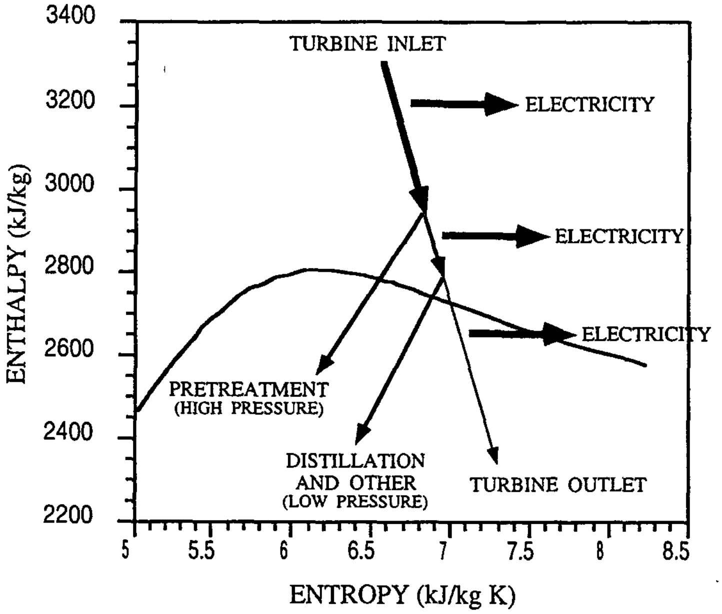

Fig. 2. Mollier diagram for steam explosion in biomass ethanol production.

technologies that use less steam will increase surplus electricity and associated revenues. The heat-pumped distillation process described by Lynd and Grethlein (3) and Torres et al. (4) is one such technology. As presented in Fig. 3A, vapor is extracted at the feed point, compressed and condensed in the reboiler, and the condensate returned above the feed point. The external heat required by the reboiler is approximately inversely proportional to the rectifying section operating line slope, m. Figure 3B indicates that this slope, and hence the steam requirement is substantially reduced when heat pumps are employed.

For the 4.4 wt% ethanol feed in the base case (relative to liquid components), the steam demand for heat-pumped distillation is 29.5 t/h, a reduction of 62% from the conventional case. Although the electricity demand for the heat-pumped case increases to 1.7 MW, this is more than compensated by the increased electricity production owing to the lower steam demand, with a net increase in surplus electricity of 2.8 MW corresponding to a 1.7¢/gal increase in revenue (electricity at 4¢/kWh throughout).

The distillate for the heat-pumped configuration depicted in Fig. 3A is limited to about 90 wt% ethanol because of the pinch point at high ethanol mole fraction. For neat fuel applications, such as anticipated in the base-case design, this should pose little difficulty, since 90 and 95 wt% hydrous ethanol are expected to have unmeasurable differences in engine performance save for energy density (Roberta Nichols, Ford Motor Co., personal communication). Heat-pumped distillation may be combined with pervaporation or molecular sieves should anhydrous ethanol be desired.

Steam Cycle Heat Integration

Boiler feed-water heaters using extracted process steam can increase the overall steam cycle efficiency, with an associated increase in gross electricity output of several MW. In this study, two feed-water heaters are examined (Fig. 4). The first uses low-pressure process steam as a heat source, and the second uses distillate vapor from product separation. In the state-of-the-art process, the distillate vapor is not hot enough to be of any use and is condensed using cooling water. However, it is possible to operate the distillation column at a pressure of 300 kPa, thus raising the distillate vapor to a useful temperature of about 105°C.

At 300 kPa, and with heat flows corresponding to the case where heat-pumped distillation is utilized, there is more than enough latent heat in the distillate vapor to raise the boiler feed water to 100°C. Boiler feedwater preheating as described herein increases net electricity output by 4.3 MW, resulting in a revenue increase of 2.6¢/gal.

Elimination of Seed Fermenters

Seed fermenters for cellulose and xylose consume more than 80% of all compressed air and more than 39% of all chilled water duty (including

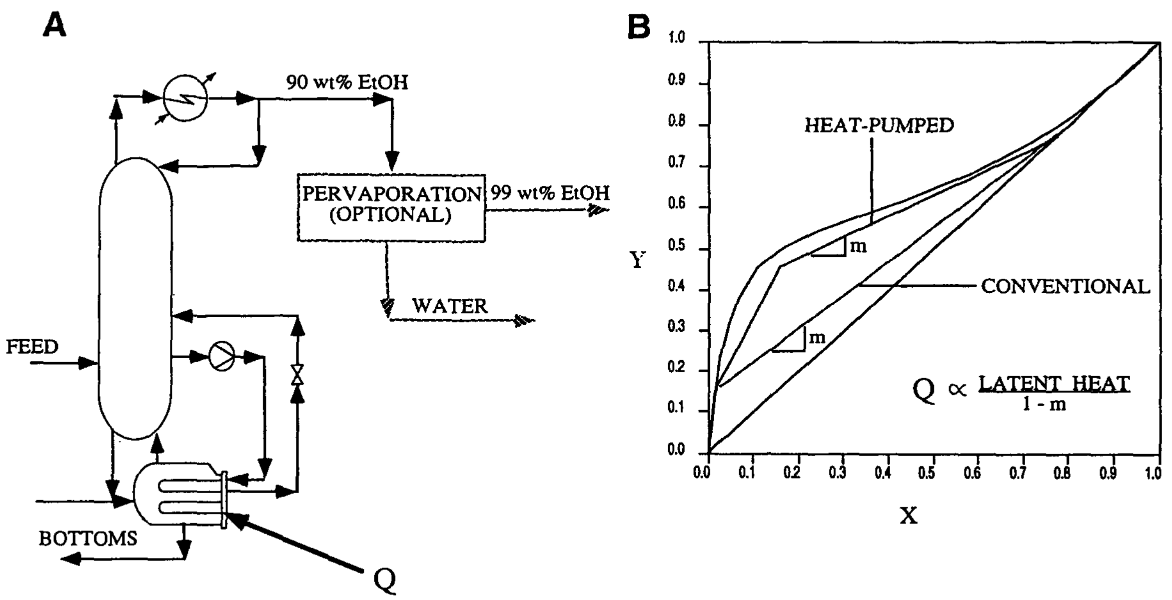

Fig. 3. Heat-pumped distillation and optional pervaporation. (**A**) Flow diagram; (**B**) McCabe-Thiele diagram.

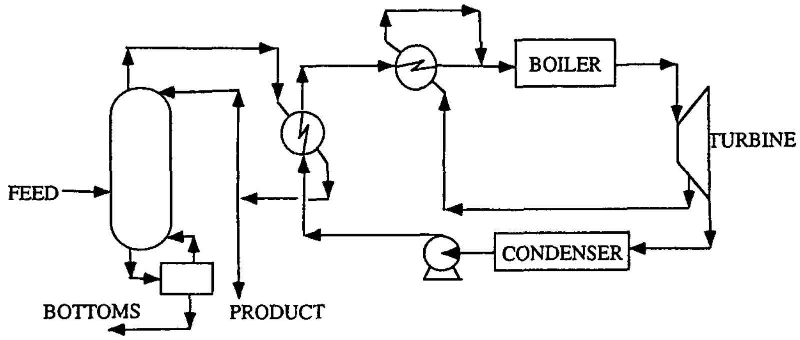

Fig. 4. Steam cycle heat integration.

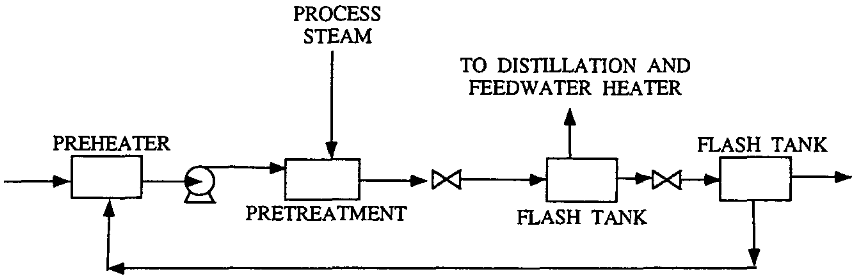

Fig. 5. Pretreatment heat integration.

chilled water used in interstage cooling). Together, these seed fermenter-associated energy requirements account for about 4.6 MW of internal electricity demand. Continuous fermenters essentially obviate the need for seed fermenters and are very likely to become standard as process technology matures. This statement is supported by: (1) the recent work of South et al. (*5,6*) that provides both analytical and experimental evidence that seed fermenters are unnecessary for continuous SSF processing, and (2) the observation that most of the installed capacity in the corn ethanol industry uses continuous fermenters (*7*). Elimination of seed fermenters would be accompanied by 4.6 MW of additional surplus electricity and 2.8¢/gal additional revenue.

Pretreatment Heat Integration

It may be possible to eliminate low-pressure steam demand for pretreatment without increasing the demand for high-pressure steam. As shown in Fig. 5, a two-stage let-down can provide low-pressure flash vapor at a temperature high enough to displace about 20% of the process steam demand associated with distillation. In addition, near-atmospheric flash vapor can be recycled to preheat the milled wood chips by direct injection, thus eliminating the demand for low-pressure steam for pretreatment. These measures result in 2.5 MW of additional surplus electricity and 1.5¢/gal additional revenue.

Although conceptually simple, pretreatment heat integration is potentially complicated by the presence of byproducts that may foul heat exchangers. To minimize this complication, we have chosen not to recycle the vapor from the first flash within pretreatment, which would result in the accumulation of byproducts. Even so, considerable pilot-scale work will be necessary to demonstrate the feasibility of pretreatment heat integration.

Advanced Pretreatment

Most investigations of pretreatment have employed wood milled to a particle size significantly smaller than that of standard chips, with large associated energy requirements. The base-case design assumes dry milling to 2 mm prior to pretreatment. However, there is some indication that such milling may not be necessary. For example, Heitz et al. (*8*) report high enzymatic hydrolysis yields for wood chips pretreated at 220°C for 2 min in the absence of added acid. Recalling that we are engaged in examining futuristic technology with subsequent process modifications involving greater degrees of uncertainty and required R&D, it is deemed appropriate to consider the case where milling prior to pretreatment is replaced by milling after pretreatment. This would result in an approx 95% reduction in the milling power requirement (Estaban Chornet, personal communication).

Currently, effective pretreatment of woodchips without prior milling has only been demonstrated to our knowledge at temperatures >200°C. Although it may be possible to achieve pretreatment at lower temperatures without prior milling, with significant likely advantages, we consider the high temperature case here. Pretreatment at 220°C would increase the intermediate flash vapor to the point where it could replace all of the low-pressure process steam demand, with a small portion remaining for boiler feed-water preheat. However, these reductions in low-pressure process steam demands would be accompanied by a substantial increase in high-pressure process steam demand and in the required extraction pressure. The net effect of reduced electricity demand and reduced gross electricity output is an increase in surplus electricity of 2.5 MW with an accompanying revenue increase of 1.5¢/gal.

Thermophilic DMC

As reviewed elsewhere (*9,10*), use of thermophilic bacteria could be one route to obtaining the large cost reductions necessary of biomass ethanol to become competitive with gasoline if the disadvantages of currently available strains can be circumvented. Only the potential impacts of using thermophiles on utilities consumption will be considered here.

Even if seed fermenters are eliminated, biological conversion still consumes 9 MW of power in the base case, with compressed air and chilled water accounting for 5.6 MW and fermentation vessel agitation 2.8 MW.

Use of thermophilic organisms would eliminate the need for all remaining compressed air, because thermophiles are anaerobic and produce their own cellulase, as well as essentially all chilled water, because thermophiles operate at 55–60°C and thus can be cooled using readily available heat sinks and incomplete preheating of the fermentor feed. In light of elimination of cellulase production, the higher hydrolysis rates of thermophilic systems, and the potential for consolidating cellulose and pentose processing, a 67% reduction of mixing power is also assumed, although this has a smaller impact than elimination of compressed air and chilled water. These reductions would increase the surplus electricity by 7.5 MW and the revenue by 4.5¢/gal.

Increased Carbohydrate Yield to 90% of Theoretical

Increased ethanol yield has been a common feature of most process improvements over the last decade and is very likely to continue to be so in the future. Furthermore, two of the specific process improvements considered thus far, elimination of seed fermentors and elimination of cellulase production (the latter associated with thermophilic DMC), would be accompanied by yield increases. Thus, for the purpose of anticipating a truly mature ethanol production process, it would seem appropriate to consider the impact of improved process yields. We have chosen to conside the case where the yield of ethanol is 90% of theoretical based on the feed carbohydrate content, corresponding to a 31% increase over the base case. We regard this value to be a practical upper limit on what can foreseeably be achieved using a biological process in light of factors, such as diversion of carbohydrate to cells, loss of carbohydrate to byproducts during pretreatment, and the likelihood that a small cellulose fraction will not be rendered reactive by pretreatment.

As examined in the subsequent section, increased ethanol yields have a positive impact on overall revenues, but have an adverse effect on electricity revenues. The reduction in electricity revenues accompanying increased ethanol yield results from a higher distillation steam requirement as well as a lower amount of fuel going to the boiler.

CUMULATIVE IMPACTS OF PROCESS IMPROVEMENTS

Although speculative, a futuristic process incorporating the above improvements may be useful for anticipating some features of a technologically mature biomass ethanol process, as well as for comparing ethanol production to more technologically mature energy-conversion processes. Figure 6 presents the cumulative impact of the process improvements examined in terms of kilowatt hours of electricity equivalent per ton dry biomass. The electricity equivalent of process steam is calculated based on the electricity that could have been generated had the steam not

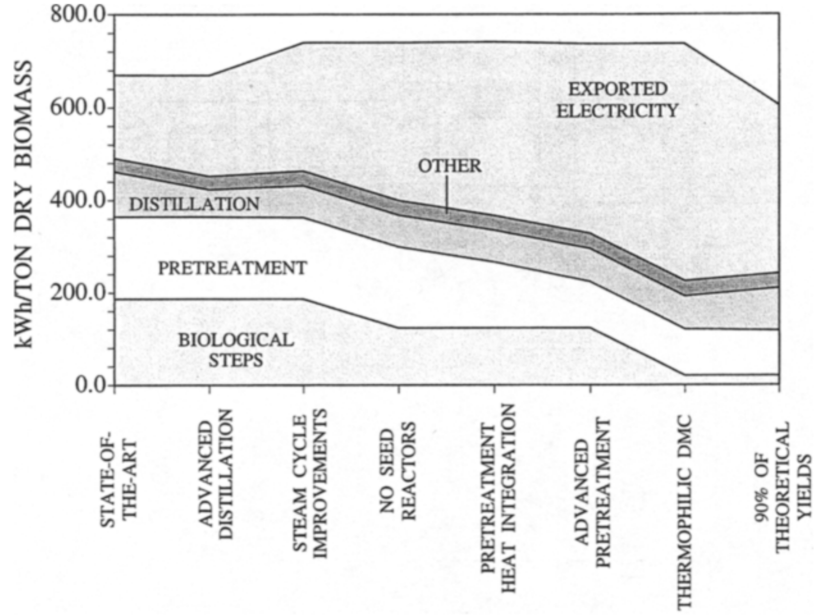

Fig. 6. Energy allocation in relation to process improvements.

been extracted. It may be seen that the overall effect is to shift the allocation of energy from primarily meeting internal demand to export for sale. Reduction of the energy demand for biologically mediated steps is the largest factor responsible for this shift, followed by reduced demand for pretreatment.

Figure 7 presents energy flows for the base-case and futuristic processes, with respective first-law efficiencies of 43 and 59%, respectively. Higher efficiencies are calculable using indices that incorporate either product value or fossil fuel displacement.

As presented in Table 2, the futuristic process has 31% higher ethanol revenue and 101% higher electricity revenue. At the current ethanol price of $1.20/gal, the overall revenue is 35% higher for the futuristic process, whereas the increase is 39% for ethanol valued at 65¢/gal. For the futuristic process, electricity accounts for 15% of total revenue. More conservative assumptions about the ethanol yield increase would be accompanied by a higher increase in electricity revenues. Lower temperature pretreatment would result in higher electricity revenues with no loss of ethanol revenue.

It may be noted that the net cost of utilities (annualized capital and operating costs less electricity revenues) decreases from $17.5/t for the base case to $10.1/t for the futuristic process. This illustrates the important point that although a process step, such as utilities, may be mature technologically, it is still possible to affect significant cost reductions by improvements in other less mature process steps.

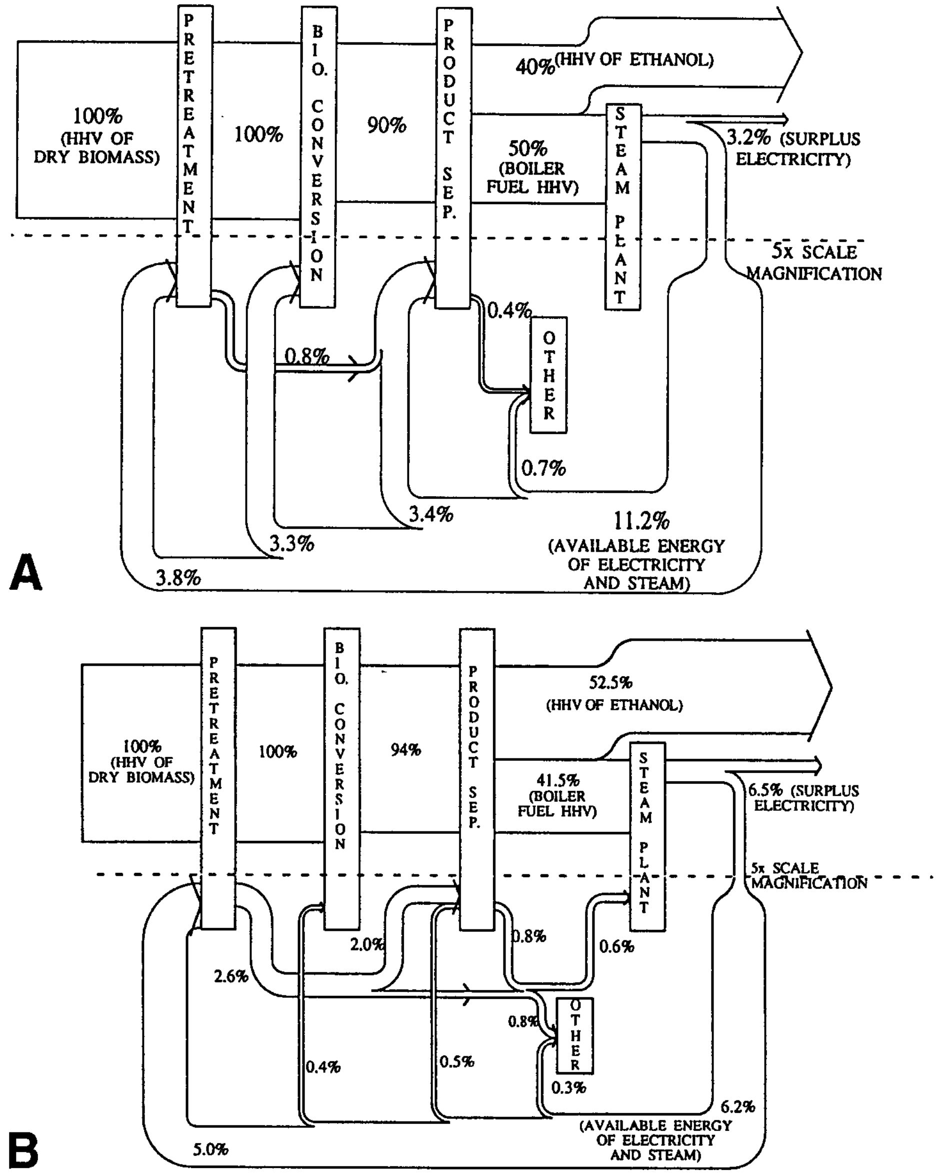

Fig. 7. Energy flow diagram for biomass ethanol production. (**A**) State-of-the-art; (**B**) futuristic. From (*1*). Available energy of steam is the difference between the energy of the steam and the energy of water at ambient conditions.

COMMENTARY ON COSTS ASSOCIATED WITH PROCESS IMPROVEMENTS

Although it would be highly informative, a detailed cost analysis is outside the scope of this analysis. At a general level, the process improvements considered fall into three categories.

Table 2
Product Revenue

	$/Ton biomass		
	Current	Futuristic	%Increase
Ethanol @$1.20/gal	109.7	143.7	31
(@$0.65/gal)	(59.4)	(77.8)	
Electricity[a]	7.2	14.5	101
Total	116.9	158.2	35
	(66.6)	(92.3)	(39)

[a] Electricity valued at 0.04 $/kWh.

Elimination of seed reactors, advanced pretreatment, and thermophilic DMC all have large potential cost reductions independent of their benefits with respect to increased surplus electricity. In general, these improvements would involve elimination of process components (seed fermenters, most milling equipment, cellulase production, and some ethanol production fermentors). The higher pressures required for pretreatment vessels in the futuristic case would tend to raise costs. However, this effect would likely be more than offset by the somewhat smaller vessels, the lower cost materials of construction (owing to the absence of added acid), and eliminated cost of acid associated with the futuristic case.

Steam cycle improvements and pretreatment heat integration are expected to have modest cost benefits that depend on increased electricity revenues. Both involve additional heat exchangers that are expected to pay for themselves. Increasing the pressure of the distillation columns in order to use the distillate vapor for boiler feed-water preheating (associated with the steam cycle improvements) would involve larger costs owing to larger distillation feed preheaters, a larger reboiler, and a larger distillation feed pump. However, these are likely more than offset by reduced column diameters, a more efficient heat pump, and by elimination of the cooling water demand associated with the distillation condenser.

A moderately detailed analysis by the authors of heat-pumped distillation revealed that this approach roughly doubled the capital cost for product separation for both 90 and 99 wt% final products. For the scale, capital recovery factor, and electricity value parameters assumed in the base case, the increased electricity revenues associated with the heat-pumped approach are almost exactly canceled by the increased capital cost. Thus, substitution of heat-pumped distillation is essentially price-neutral for the base-case parameters, and would be expected to have some advantage over conventional distillation in situations with some combination of larger-scale, lower capital recovery factor, and increased electricity value. The heat-pumped approach would also become more advantageous for dilute feeds. The data and analyses presented herein underscore the point that the impacts of distillation are rather minor in terms of both cost and energy. Considering the base case, the annualized capital and operating cost exclusive of steam is 2.3¢/gal, and distillation is the fourth largest process energy flow (behind exported electricity, biological steps, and pretreatment). In light of these considerations, it is perhaps not surprising that significant reductions of the already low cost of distillation are difficult to achieve.

COMPARISON OF ETHANOL ELECTRICITY COPRODUCTION TO DEDICATED ELECTRICITY PRODUCTION

Two prominent alternatives for biomass utilization are production of ethanol for use as a transportation fuel with coproduction of electricity and production of electricity as the sole useful energy product. It is of interest to compare the economics of these two processes.

We have examined the operating margin (revenues minus annualized capital costs, $/t biomass) for both ethanol electricity coproduction and dedicated production of electricity, with two scenarios considered for each. For coproduction, one scenario involves the state-of-the-art process with ethanol at its current price of $1.20/gal, whereas the second scenario involves the futuristic process defined herein with ethanol at a value expected to be competitive with gasoline, 65¢/gal. Capital costs for the second scenario are calculated based on the difference between the product revenue and the cost of feedstock and raw materials, and thus are not based on specific technological assumptions save that production for 65¢/gal is possible. For dedicated electricity production, the first scenario involves the same steam plant size as in the state-of-the-art ethanol plant, whereas the second scenario involves the same feedstock flow rate as for the ethanol plants. The first scenario requires little scale adjustment relative to the ethanol plant; the second scenario is somewhat more uncertain in that it involves adjustment for a scale difference of about 2. However, the second scenario is perhaps more equitable in that it allows dedicated electricity production to enjoy the same scale advantages as the ethanol plants. The cost of the steam plant is based on the steam plant used in the ethanol process, with a scaling exponent of 0.7 used for the second electricity scenario.

As may be seen from Fig. 8, the analysis is relatively insensitive to the choice of scenario, and indicates that coproduction of ethanol and electricity has an equal operating margin relative to dedicated electricity production at an electricity selling price of about 4¢/kWh. Since this is an entirely representative value for electricity, the implication of this analysis is that coproduction of ethanol and electricity is approximately equally attractive in comparison to dedicated electricity production from an economic viewpoint. Since ethanol-electricity coproduction has a higher

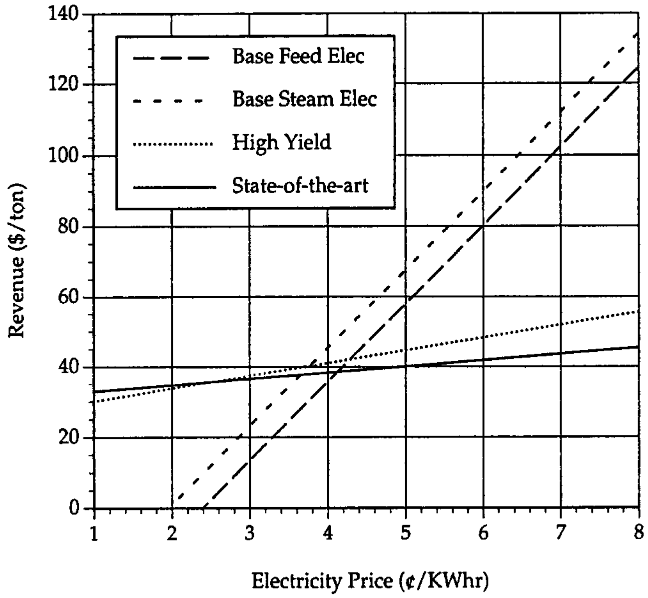

Fig. 8. Economic comparison of ethanol electricity coproduction with dedicated electricity production. A 40% efficiency is assumed for the dedicated electricity plant. Capital costs for the dedicated electricity plant with the same steam plant size as the base-case ethanol plant are increased by 10% owing to larger sizing of the same components necessary to accommodate the increased power output. The cost of feedstock and raw materials is $41.1/metric t for futuristic ethanol electricity coproduction. *See text* for further explanation.

capital cost and higher revenue relative to dedicated electricity production at the same scale, we anticipate that larger scale or a lower cost of capital would favor the coproduction alternative.

In closing, we note that the coproduction of electricity along with ethanol could be highly significant from an energy supply perspective. At the ethanol and electricity yields associated with the futuristic process defined herein, every 1% displacement of current (1990) US transportation sector energy demand would be accompanied by a 0.29% displacement of total electricity demand. As an illustration, conversion of 19 quads of wood with the yields of the futuristic process defined herein would result in 10 quads of ethanol (45% of transportation demand) as well as 1.2 quads of electricity (13% of electricity demand) with a total fossil fuel displacement of 13 quads.

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