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Preliminary Estimate of the Cost of Ethanol Production for SSF Technology

N. D. HINMAN, D. J. SCHELL,
C. J. RILEY,* P. W. BERGERON, AND P. J. WALTER

Fuels and Chemicals, Research and Engineering Division, Solar Energy Research Institute, Golden, CO 80401

ABSTRACT

The Solar Energy Research Institute (SERI) recently completed a detailed engineering and economic analysis of the simultaneous saccharification and fermentation (SSF) based wood-to-ethanol process. The reference-case design was based on a plant capacity of 1920 dry t/d and a wood cost of $42/dry t. For this case, the preliminary estimate of the production cost of the ethanol product is about $1.22/gal. The combined effects of optimizing SSF enzyme loading, increasing plant capacity to 10,000 dry t/d, and reducing wood cost to $34/dry t are to reduce the preliminary estimate of the production cost to about $0.95/gal. Other technological improvements may further reduce the production cost. Certain technical assumptions, inherent in the analysis, are being investigated further.

Index Entries: Ethanol production costs; simultaneous saccharification and fermentation; ethanol from biomass.

INTRODUCTION

Ethanol has received considerable attention over the years as an octane booster, fuel extender, or neat liquid fuel. There is heightened interest in ethanol as a transportation fuel. Lignocellulosic materials have promise as a substrate for ethanol production in the United States because of their low cost and their huge potential availability.

*Author to whom all correspondence and reprint requests should be addressed.

Lignocelulosic materials are composed of carbohydrate polymers known as cellulose and hemicellulose, plus lignin and smaller amounts of other materials. Agricultural residues, municipal solid waste, underutilized standing forests and residues from logging operations, energy crops, such as short-rotation woody crops and herbaceous crops, and waste streams from industrial operations are examples of this largely untapped source of renewable material.

The use of domestic lignocellulosic substrates for fuel ethanol production could increase fuel flexibility, reduce the related strategic vulnerability of our petroleum-based transportation fuel system, reduce the net accumulation of CO_2 in the atmosphere, and improve urban air quality. Thus, ethanol from lignocellulosic materials holds great promise as a new industry in the United States and has the potential for making a significant contribution to the solution of major problems facing our country.

The purpose of this study was to carry out an engineering and economic analysis of the current conceptual wood-to-ethanol process. A detailed analysis was performed on a reference-case process having a plant capacity of 1920 dry t/d and a hardwood feedstock at a cost of $42/dry t. Using the design and economic information from the reference case, a spreadsheet model of the wood-to-ethanol process was developed. This model was used to examine the effects of many process and cost variables on ethanol production cost.

METHODOLOGY

Process Design

Introduction

The current conceptual design of the wood-to-ethanol process is a simplified, straightforward process that contains significant improvements over processes developed in the early 1980s. As shown in Fig. 1, the basic units of this process consist of feed handling, pretreatment, cellulase production, xylose and cellulose fermentations, and ethanol purification. In this study, several alternative technologies were considered for pretreatment, cellulase production, and xylose and cellulose fermentations. The technologies selected for each of these basic units were as follows:

Unit	Technology
Pretreatment	Dilute sulfuric acid
Cellulase production	Batch culture with *Trichoderma reesei*
Xylose fermentation	Genetically engineered *Escherichia coli*
Cellulose fermentation	SSF

The performance data on which the reference case design was based come from SERI and other laboratories. The reported yields are not the

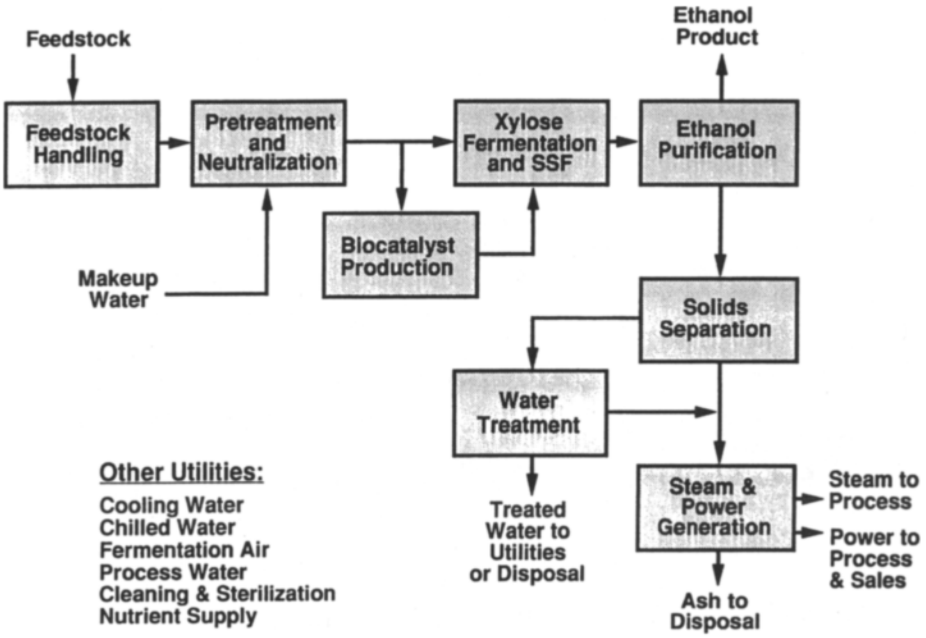

Fig. 1. Biomass-to-ethanol process.

best ever achieved, but rather conservative and reproducible values that form a reasonable basis for a design, reflecting the current state of process development. For dilute sulfuric acid pretreatment, yields and process conditions were taken from work conducted at SERI (*1*); performance data developed at SERI (*2*) for a genetically engineered *E. coli* developed by L. Ingram of the University of Florida was used for xylose fermentation; cellulase production was carried out using data from several laboratories (*3,4*); and data for SSF were obtained from SERI researchers (*5–7*). Specific technical and engineering assumptions were made in areas where data and information were lacking.

Design Basis

The design basis of the base-case process follows.

• Plant type	Grass roots, Nth plant
• Costs	1990 dollars
• Plant location	Unspecified
• On-stream time	8000 h/yr
• Feed	1.0-in wood chips
• Nominal capacity	160,000 lb dry wood/h (1920 dry t/d)
• Feed composition (dry basis)	46.2 wt% cellulose
	24.0 wt% xylan
	24.0 wt% lignin
	5.6 wt% solubles
	0.2 wt% ash

• Moisture content	50.0 wt%
• Product	Azeotrophic ethanol denatured with 5% gasoline
• Lignin utilization	Boiler fuel
• Environmental	Cooling tower blowdown sent to evaporation pond
	Gypsum and boiler ash sent to off-site disposal
	Fermentation CO_2 vented to atmosphere after ethanol and VOC recovery
	Process waste-water treatment by anaerobic digestion followed by aerobic treatment and clarification
• Utilities	
• Steam	On-site generation from lignin and other waste organics
• Electricity	On-site generation from high-pressure steam extraction turbine
	Excess sold over the fence

Design Procedure

For the reference case, 19 detailed process flow sheets were prepared for the entire plant, including inside battery limits as well as off-sites. Detailed material balances were calculated for all areas of the plant, and a complete utility summary was prepared. A complete list was compiled with sizes and specifications for more than 230 pieces of equipment, including spares. Owing to the space limitations of this article, it is not possible to provide a detailed description of the process design basis and the technical assumptions incorporated in the analysis. The authors may be contacted for additional information.

Economics

Introduction

SERI developed investment and cost of production estimates for a reference case plant producing 58.5 million gal/yr of denatured ethanol product based on a hardwood feedstock. The plant is based on the process design described above.

Capital Investment

The investment cost for the base case was developed by determining bare equipment costs for each piece of equipment. Costs of major pieces of equipment were obtained from recent vendor quotes (*8*) as well as from other data sources, which include cost estimates and engineering studies carried out under subcontract to SERI (*9–14*). From the bare equipment costs, the fixed capital investment was estimated using installation factors. These factors are based on vendor information, data for fermentation-type plants, and information from earlier cost estimates (*8*). Fixed capital investment includes direct field costs (labor and materials for purchased equipment, equipment setting, piping, civil, steel, instrumentation, electrical, insulation, painting, and buildings) and indirect costs (engineering, construction overhead, and contractor's fee).

The total capital investment includes fixed capital investment, miscellaneous fees, start-up costs, and working capital. Start-up costs are 5% of fixed capital cost, and working capital is based on a formula that takes into account warehouse/spare inventory, accounts receivable/payable, and cash on hand.

Annual Cash Costs

Cash costs include expenditures for wood, raw materials, utilities, labor, maintenance, plant overhead, property taxes, and insurance. For the base case, the cost of wood was assumed to be $42/dry t, and materials costs were at the current market value. Labor rates were assumed to be $29,400/yr to $40,000/yr, and direct overhead was at 45% of labor. Maintenance costs were at 3% of fixed capital investment, and general plant overhead was at 65% of labor plus maintenance. Taxes and insurance were 1.5% of fixed capital investment.

Annual Capital Charge

The annual capital charge was at 20% of the total capital investment. This charge is approximately equivalent to a 10% after-tax discounted cash flow rate of return with the following parameters: income taxes at 37%, 15-yr plant life, 3-yr construction period, and straight-line depreciation.

RESULTS OF REFERENCE CASE ANALYSIS

Capital Investment

A breakdown of the total capital investment for the reference case is shown in Table 1. The fixed capital investment is estimated at $128 million, and the total capital investment is estimated at $141.2 million. Utilities account for 41.4% of the fixed capital. In fact, the boiler and turbo generator alone account for 29.9% of the fixed captial. The pretreatment area accounts for 18.5% of the fixed capital, and the SSF area accounts for 16.3%. The remaining 23.8% is divided between the other six plant areas and miscellaneous items.

Steam Consumption/Production

All stream requirements for the plant are provided by the combustion of lignin and waste organics. Total steam produced for the reference case is 434,000 lb/h of 1100 psia steam. From this, 41,400 lb/h of 150 psig and

Table 1
Estimated Reference Case Capital Investment

Plant area	MM$
Wood handling	7.16
Pretreatment	23.68
Xylose fermentation	6.16
Cellulase production	2.76
SSF	20.93
Ethanol recovery	3.99
Off-site tankage	4.09
Environmental systems	3.96
Utilities	53.14
Miscellaneous	2.52
Fixed capital investment	128.39
Start-up costs	6.42
Working capital	6.40
Total capital investment	141.22

223,800 lb/h of 50 psig steam are extracted in a turbo generator, and electricity is generated. Steam is used primarily by the ethanol recovery and pretreatment units. The total steam energy consumed per gallon of ethanol product is 35,700 BTU.

Electricity Production/Consumption

All power requirements for the plant are provided by cogenerated power from lignin and other waste organics. Total electricity produced for the reference case is 36.1 mW, of which 23.1 mW is consumed by the plant. The remaining 13.0 mW is sold at $0.04/kWh. The utilities area consumes 46.9% of the electricity, mainly by the chilled water system and air compressors. The next largest users are the mills in the wood-handling area. This area consumes 32.9% of the electricity. Total electricity consumed per gallon of ethanol product is 3.16 kWh.

Production Costs

A summary of the costs of production for the reference-case plant is shown in Table 2. For this case, the preliminary estimate of the cost of ethanol production is about $1.22/gal, which includes a $0.07/gal credit for electricity sales. The annual capital charge is the largest component of this cost, representing 37.5% of the cost. The wood cost at $42/dry t is the second largest cost at 35.6% of the total cost. Materials are 10.9% of the cost, and the remaining 16.0% is divided between maintenance, labor, overhead, and taxes/insurance. The estimated production cost minus the wood is $0.76/gal.

Table 2
Estimated Base-Case Cost of Production*

	MM$/yr	¢/Gal
Wood	26.88	45.9
Materials	8.14	14.1
Gypsum disposal	0.40	0.7
Electricity	(4.15)	(7.1)
Water	0.14	0.2
Labor/supervision	1.57	2.7
Maintenance	3.85	6.6
Direct overhead	0.71	1.2
General overhead	3.52	6.0
Insurance, property tax	1.93	3.3
Total cash cost	42.99	73.4
Annual capital charge	28.24	58.3
Total cost of production	71.23	121.7

POTENTIAL IMPROVEMENTS TO REFERENCE-CASE ECONOMICS

Optimization of the Reference Case

A spreadsheet model of the SSF-based biomass-to-ethanol plant was developed from the design and equipment cost information from the reference case. This model was used to perform preliminary optimizations of certain reference case operations.

One of the optimizations examined was the complex relationship between cellulase enzyme concentration in SSF, cellulose conversion in SSF, and fermentation time. In the reference case, seven international units (IU) of cellulase per gram of cellulose were used in SSF, whereas an optimal use is about 13 IU. At this level, the ethanol production cost drops by about $0.07/gal. Although the costs associated with the cellulase production unit increase, the higher cellulose conversion level in SSF more than offsets these costs.

Effect of Increased Plant Capacity

The potential effect of increased plant capacity on production cost is shown in Table 3. Here it can be seen that increasing plant capacity from 1920 dry t/d to 10,000 dry t/d decreases the production cost by $0.14/gal, given the same average feedstock cost for both plant sizes. If the average feedstock cost increases with increasing plant size owing to higher transportation costs, the economies of scale shown in Table 3 would be reduced. On the other hand, economies of scale in plant equipment were assumed

Table 3
Effect of Plant Capacity
on Estimated Production Cost

Plant capacity, dry t/d	Production cost, $/gal
1920 (ref. case)	1.22
5000	1.12
10,000	1.08
20,000	1.04

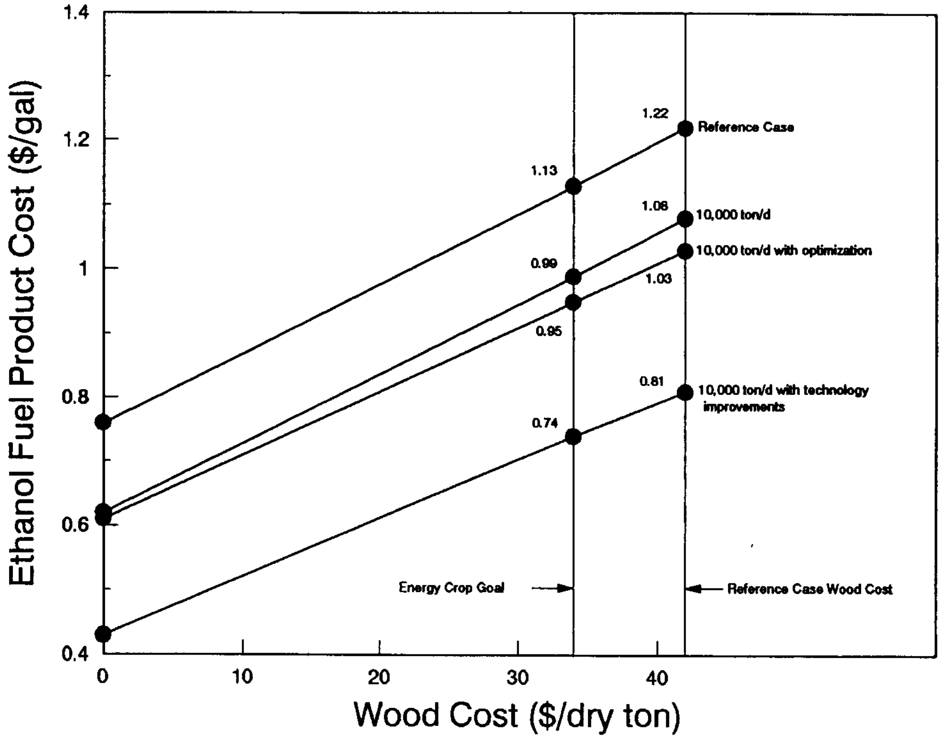

Fig. 2. Effects of plant size, optimization, and technological improvements vs wood cost.

only for the ethanol recovery, environmental systems, and utility areas of the plant. If the equipment in the wood-handling, pretreatment and fermentation areas also exhibit economies of scale, then the overall plant economies of scale will improve.

Effect of Wood Cost

The effect of wood cost on the production cost relative to the reference case is shown in Fig. 2. This figure shows that, at $34/dry t (the goal of the Biomass Production Program), the production cost is lowered $0.09/gal, whereas at zero feedstock cost, the production cost is lowered $0.46/gal.

Table 4
Effect of Specific Individual Improvements on Estimated Production Cost of Fuel Ethanol

Improvement	Decrease from reference case of \$1.22/gal, ¢/gal
Yield-related	
Improve SSF yield to 90% from 72%	15.0
Improve xylose-to-ethanol yield to 95% from 85%	2.4
Improve xylan-to-xylose yield to 90% from 80%	3.5
Capital-related	
Decrease SSF time to 2 d from 7 d	6.7
Decrease xylose fermentation time to 1 d from 2 d	1.3
Decrease cellulase fermentation time to 2 d from 6 d	1.3
Noncapital-related	
Decrease milling HP by 35%	1.5
Increase onstream time to 95% from 91.3%	2.6

Combined Effect of Optimization, Increased Plant Capacity, and Lower Feedstock Cost

The combined effects of the cellulase production/SSF optimization and increasing plant capacity to 10,000 dry t/d as a function of feedstock cost are shown in Fig. 2. Here it is seen that, for a SSF/cellulase optimized plant at 10,000 dry t/d capacity and a feedstock cost of \$34/dry t, the production cost of ethanol is lowered by \$0.27/gal.

Improvements to Technology

Improvements to the reference-case biomass-to-ethanol technology can reduce the cost of production by

1. Increasing the conversion of available carbohydrate to ethanol;
2. Increasing the revenue from electricity;
3. Adding revenue from other coproducts;
4. Decreasing capital-related costs; or
5. Decreasing noncapital-related cash costs.

Using the spreadsheet model, the effects of many specific performance improvements in the reference case were investigated separately as well as in combination. The effects of some of the individual improvements are shown in Table 4. Improvements of yields, particularly SSF yields, have significant impact on the production cost. Reduction of SSF fermentation time also has a significant effect. The combined effect of the individual improvements is shown in Table 5 for the cases of plant capacities

Table 5
Combined Effect of Individual Technical
Improvements on Estimated Production Cost of Ethanol

Case	Production cost, $/gal
Base case of wood at $42/dry t and capacity at 1920 dry t/d	1.22
Technical improvements shown in Table 5, wood at $42/dry t and capacity at 1920 dry t/d	0.91
Technical improvements shown in Table 5, wood at $34/dry t and capacity at 1920 dry t/d	0.84
Technical improvements shown in Table 5, wood at $42/dry t and capacity at 10,000 dry t/d	0.81
Technical improvements shown in Table 5, wood at $34/dry t and capacity at 10,000 dry t/d	0.74

of 1920 dry t/d and 10,000 dry t/d, and wood costs of $42/dry t and $34/dry t. The production cost is for the large plant, and the low wood cost is $0.74/gal.

Many other technological improvements besides those shown in Table 4 are possible. They include

1. Use of feedstocks with higher carbohydrate content;
2. Further reduction of power for milling;
3. Reduced power for mixing;
4. Reduced capital for pretreatment;
5. Reduced power and capital for air compression;
6. Increased efficiency of the boiler/turbo generator;
7. Improved heat integration;
8. Reduced inoculum preparation costs;
9. Advanced bioreactor designs; and
10. Direct microbial conversion.

There are many possible combinations of feedstock cost, plant size, and technological improvements that result in substantially lower ethanol production costs.

CONCLUSIONS

In 1980, the production cost of ethanol was estimated at $3.60/gal; today the preliminary estimate of the cost for a reference-case design is $1.22/gal. This current reference-base cost assumes a feedstock cost of $42/dry t and a plant capacity of 1920 dry t/d. However, certain technical assumptions inherent in the analysis must be investigated before the analysis can be finalized.

For a plant employing a currently optimized cellulase enzyme level in SSF, using wood at $34/dry t and having a capacity of 10,000 dry t/d, the production cost of fuel is estimated to be 34% below the reference-case cost. Improvements in yield will have a significant impact on the production cost. Substantial improvements in yield are possible and are being achieved in the laboratory. Technological improvements that result in lower capital-related costs and/or noncapital-related costs will also have a significant impact on production cost.

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