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Economic Analysis of Selected Lignocellulose-to-Ethanol Conversion Technologies

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Abstract

The objective of this case study was to examine the economics of three lignocellulose-to-ethanol conversion technologies: fast pyrolysis integrated with a fermentation step, simultaneous saccharification and fermentation (SSF), and dilute sulfuric acid hydrolysis and fermentation. All technologies were assumed to have an annual production rate of 25 million gallons of ethanol. The three technologies were compared in terms of capital costs, operating costs, and ethanol production costs. Sensitivity analyses were carried out to study the uncertainties of wood costs and ethanol production rates on ethanol production costs. Final economic analysis showed that fast pyrolysis integrated with a fermentation step is comparable with the other two processes and suggests that it should be considered for further development.

Index Entries: Biomass-to-ethanol; economic analysis; fast pyrolysis; fermentation; acid hydrolysis.

Introduction

Two widely-known lignocellulose-to-ethanol production processes are simultaneous saccharification and fermentation (SSF) *(1)* and dilute sulfuric-acid hydrolysis and fermentation *(2)*. These two processes are illustrated in Figs. 1 and 2. The SSF process considered uses dilute sulfuric acid in its pretreatment *(1)*. Batch culture of *Trichoderma reesei* is utilized in its cellulase production *(1)* and genetically engineered *Escherichia coli* is used to ferment the xylose. *(1)*. Its enzyme loading is 7 IU/g cellulose *(1)*.

In the dilute sulfuric-acid hydrolysis and fermentation, 0.05 g/L of sulfuric acid at 180°C is used for the hydrolysis *(2)*. The fermentation process is assumed to be continuous. Its average hydrolysate sugar concentration

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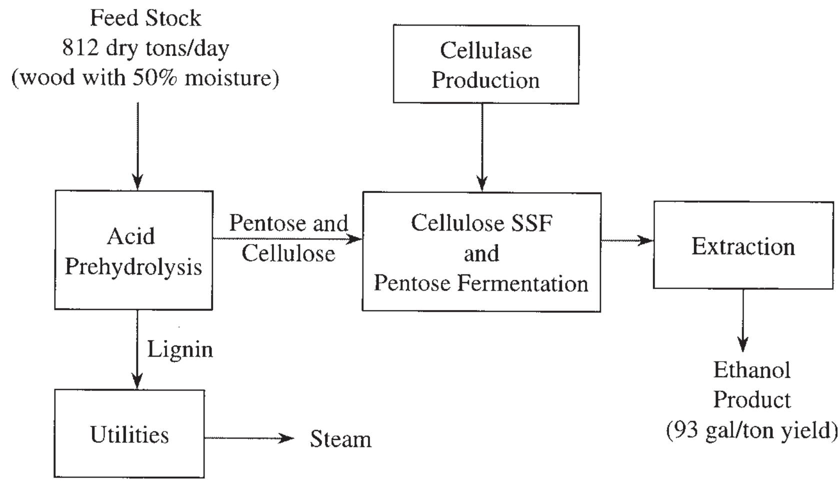

Fig. 1. Simultaneous saccharification and fermentation process flow chart.

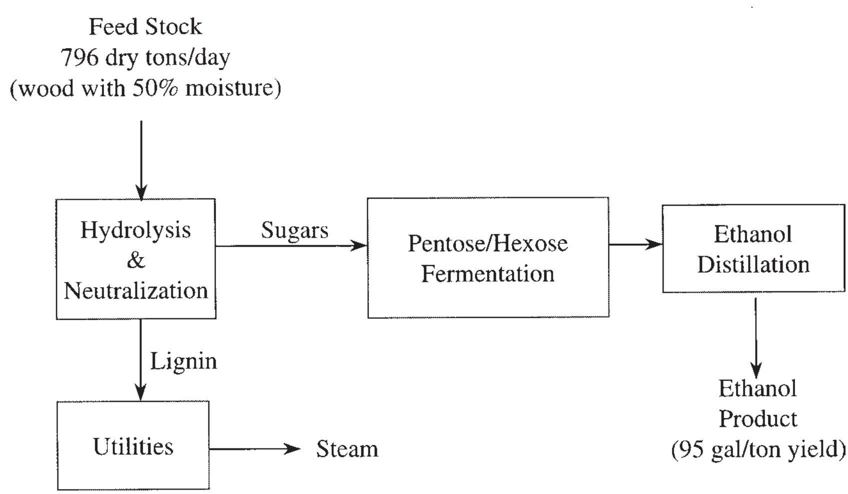

Fig. 2. Dilute sulfuric-acid hydrolysis and fermentation process flow chart.

is assumed to be 103.7 g/L *(2)*. A strain *of Candida shehatae* is used for hexose and pentose fermentation *(2)*.

An alternative approach to production of ethanol is pyrolysis of lignocellulose to produce levoglucosan and pentose. After hydrolysis of the levoglucosan, these sugars can be fermented to ethanol *(3)*. The University of Waterloo and Resource Transform International, Ltd. of Ontario, Canada have developed the Waterloo Fast Pyrolysis Process, illustrated in Fig. 3. Scott *(4)* has performed an economic evaluation of the cost of producing fermentable sugars from the process, but these are the first economic studies performed on the integration of pyrolysis and fermentation technologies.

The Waterloo Fast Pyrolysis Process uses 5% sulfuric acid at about 80–90°C in its pretreatment process. Two cultures, *Saccharomyces cerevisiae*

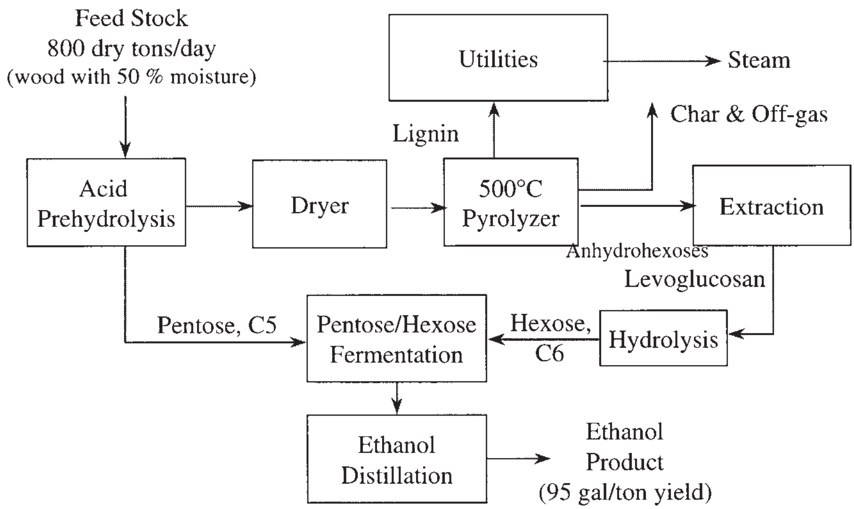

Fig. 3. Waterloo fast pyrolysis and fermentation process flow chart.

and *Pichia stipitis*, are used to ferment the hexose and pentose sugars, respectively.

The objective of this study was to perform a comparative economic analysis of three lignocellulose-to-ethanol technologies: SSF; dilute sulfuric-acid hydrolysis and fermentation (acid hydrolysis); and the Waterloo Fast Pyrolysis Process (fast pyrolysis). The three technologies were compared in terms of their capital costs, operating costs, and production costs of ethanol. The three technologies were also evaluated qualitatively for their ability to utilize by-product lignin for steam generation. Sensitivity analyses were carried out to examine the uncertainties of feedstock costs and production rates on the production cost of ethanol.

Methods

Data for this case study was obtained from published journals *(1–5)*. Because each reference used different assumptions, a common set of assumptions were developed for this case study so that analytical comparisons of the three conversion technologies could be made on the same basis. The general and operating costs assumptions are tabulated in Table 1. Order-of-magnitude method was used to approximate the capital cost of equipment for each of the conversion technologies. This method uses the six-tenth power law exponent to scale capital cost investment from known capital cost data *(6)*. All capital cost data from published journals are assumed to include installation cost, contingency, and fees. More detailed breakdown of capital costs is not possible because bare module costs are not available from the previous studies on which present analysis is based. Working capital makes up 15% of the fixed capital cost, was included in the capital investment *(6)*. An annual capital charge was assumed to be 20% of total capital investment *(1)*. This was calculated using 10% after-tax dis-

Table 1
General and Operating Cost Assumptions

General Assumptions:
Grassroot plant type
Unspecified location
330 Operating days / year
1997 US $
25 Million gallons of azeotropic ethanol
Operating Cost Assumptions:
Supervisory : 15 % of operating labor
Maintenance & repair : 6 % of fixed capital
Local tax : 1.5 % of fixed capital
Insurance : 0.7 % of fixed capital
Overhead : 60 % of Sum of operating labor, supervisory, and maintenance
Administrative cost : 25 % of overhead
Distribution & selling cost : 10 % of total expense
Research & development : 5 % of total expense
Annual Capital Charge : 20 % of total capital investment

counted cash flow rate of return *(1)*, 37% income taxes *(1)*, 3-yr construction period *(1)*, 15-yr plant life, straight line depreciation *(1)*, and zero scrap value. The accuracy of the estimated capital, operating costs, and production cost of ethanol was ±30% *(6)*.

As part of the major operating costs, the feedstocks were assumed to be purchased at $42/dry ton for all conversion technologies. Raw wood was further comminuted and dried according to feedstock assumptions listed in Table 2. These costs were approximately $7.50/dry ton for comminution, and $0.20/dry ton/% moisture removed during drying.

Electricity requirement for each conversion technology was purchased at $0.04/kWh. By-product lignin was burned to produce steam either for sale or consumption. Steam was sold and purchased at $4.50/1000 lb. The amount of lignin available for steam generation is listed in Table 2.

Results

Comparisons of capital investments are shown in Table 3. SSF has the least capital cost of $64 million, whereas acid hydrolysis process has a

Table 2
Feedstock and Lignin Assumptions for Steam Generation

Feedstock Drying/Comminution Assumptions :
Feedstock as received : 50 % moisture, 25.4 mm chip size
Note: Dilute sulfuric acid & SSF processes do not require additional processing.
Fast pyrolysis requires chips to be reduced to 1.5 mm chip size & dried to 15 % moisture after pretreatment
Lignin wt % available for steam generation :
Fast Pyrolysis 15 wt % of feedstock
SSF 25 wt % of feedstock
Dilute sulfuric acid 25 wt % of feedstock

Table 3
Capital Cost Investment Comparisons

Fast Pyrolysis		SSF		Acid Hydrolysis	
Plant Areas	Capital Cost (in million $)	Plant Areas	Capital Cost (in million $)	Plant Areas	Capital Cost (in million $)
WFPP System	12	Pretreatment	16	Hydrolysis	2
Fermentor	22	Pentose Fermentor	4	Fermentor	27
		Cellulase Production	2		
		SSF	16		
Ethanol Recovery	11	Ethanol Recovery	3	Ethanol Recovery	14
Utilities	12	Utilities	12	Utilities	12
Off-Site Tankage	3	Off-Site Tankage	3	Off-Site Tankage	3
Fixed Capital	60	Fixed Capital	56	Fixed Capital	58
Working Capital	9	Working Capital	8	Working Capital	9
Total Capital	69.	Total Capital	64	Total Capital	67

Table 4
Operating Cost Comparisons

	Fast Pyrolysis	SSF	Acid Hydrolysis
Total Capital Cost (in $ million)	69	64	67
Annual Operating Cost (in $ million)			
Wood	11.09	11.25	11.03
Steam	1.15	-4.50	-2.95
Electricity	1.20	1.37	1.25
Operating Labor	0.27	0.58	0.30
Supervisory	0.04	0.09	0.05
Maintenance & repair	3.52	3.36	3.48
Indirect Operating Costs[a]	3.67	3.64	3.58
General Expenses[b]	4.40	3.49	3.63
Annual Capital Charge	13.80	12.80	1334
Total Annual Operating Costs	39.21	32.09	33.70
Production cost of Ethanol (in $ /gal)	1.57	1.28	1.35

[a]Indirect operating costs include: overhead, local taxes, insurance.
[b]General expenses include administrative, distribution, selling, research and development costs.
All cost figures in 1997 US $.

capital cost of $67 million. Fast pyrolysis has the highest capital cost ($69 million). Operating cost comparisons are shown in Table 4. Taking into consideration the accuracy of the order-of-magnitude method, the production costs for all the technologies are essentially the same at this level. Analysis of steam usage indicates that the SSF and the acid hydrolysis processes are better able to recover lignin to generate steam for external sales than the fast pyrolysis process. Sensitivity analyses of feedstock supply costs and production rates on ethanol production cost are shown in Figs. 4 and 5. SSF remains the most competitive of the three processes, at all feedstock supply costs and ethanol production rates. Feedstock supply cost is linearly and positively related to ethanol production cost: for every $10/dry ton change in wood price, ethanol production cost changes by about $0.13/gal on average.

Consistent with the economy of scale assumption, ethanol production cost declines as the ethanol production rate is increased. For every 10 million gallon increase in the production rate, ethanol production cost decreases on average by about $0.08/gal.

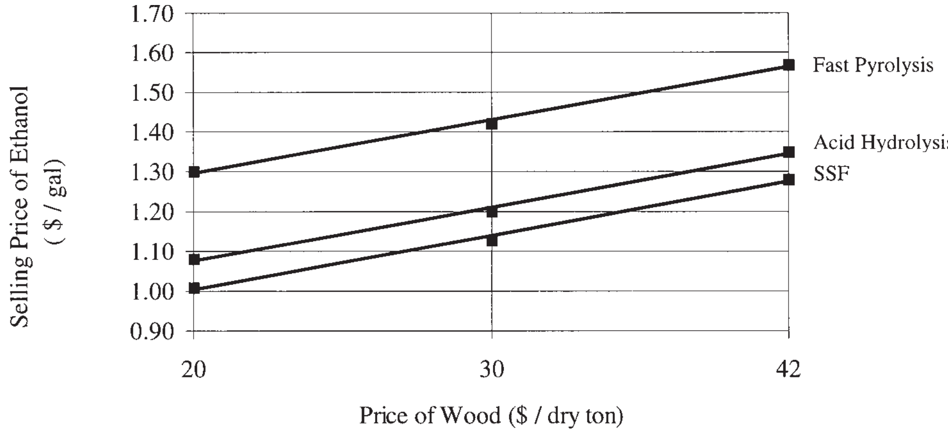

Fig. 4. Sensitivity analysis of wood price on ethanol production cost.

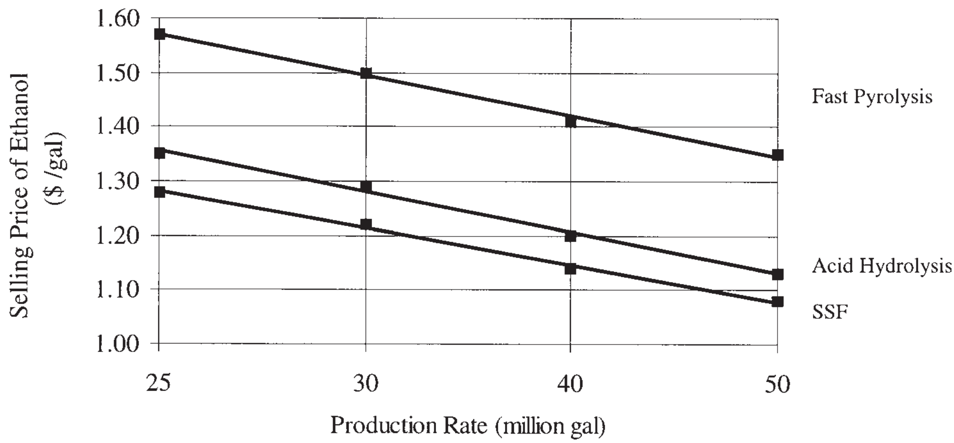

Fig. 5. Sensitivity analysis of ethanol production rate on ethanol production cost.

Discussion

From an overall economic analysis, the cost of the fast pyrolysis process is comparable to the SSF and the acid hydrolysis processes, in terms of capital costs, operating costs, and ethanol production costs. Further research in the area of the fast pyrolysis process should be conducted to verify its feasibility in ethanol production and to examine the possibilities of recovering its by-products, especially lignin.

Acknowledgments

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