Economic analysis of ethanol production from biomass using a hybrid thermal/biological conversion process

by

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ABSTRACT

The objective of this case study is to examine the economics of ethanol production using the Waterloo Fast Pyrolysis process integrated with a fermentation step. The raw materials considered are wood and switchgrass. The pyrolytic ethanol process is evaluated in terms of capital costs, operating costs, and ethanol production costs for each type of feedstocks used. Sensitivity analyses are carried out to study the uncertainties of feedstock costs, ethanol production rates and ethanol yields on ethanol production costs. The economics of pyrolytic ethanol is compared to two other widely-known processes: simultaneous saccharification and fermentation, and dilute acid hydrolysis and fermentation. This analysis indicates that the pyrolytic ethanol process is comparable with the other two processes and suggests that it should be considered for further development.

CHAPTER 1. INTRODUCTION

Biomass, in the form of lignocellulose, is underutilized in the world. It is an inexpensive, abundant and renewable source of value-added chemicals, such as ethanol. Perhaps the most significant advantage of biomass derived fuel is that it does not contribute to the net accumulation of carbon dioxide in the atmosphere. Ethanol is an important precursor to many chemicals. Two common uses of ethanol are as an octane enhancer [1] and as neat fuel [2]. Economic analysis plays an important role in evaluating its commercial potential. Economic analysis identifies high-cost stages in the conversion process, gives preliminary estimates of the total costs involved in the project financing, and estimates profitabilities of such projects.

The objectives of this research are: (i) perform a case study on retrofitting the Waterloo fast pyrolysis process with a fermentation step (pyrolytic ethanol); (ii) introduce a methodology for economic analysis of this integrated process; (iii) perform a sensitivity analyses of the cost of raw material, production capacity and ethanol yield on the production cost; (iv) compare pyrolytic ethanol process economics with two other widely-known processes, simultaneous saccharification and fermentation (SSF) and dilute acid hydrolysis and fermentation (acid hydrolysis), in terms of capital, operating, and production costs of ethanol. The raw materials considered are wood and switchgrass. However, the comparison in part (iv) was made for the case of wood only, since no published data was available for switchgrass.The final product for the process is azeotropic ethanol.

CHAPTER 2. BACKGROUND

Lignocellulosic materials contain of about 65 % cellulose [3], 20-35 % hemicellulose [3] and 7-30 % lignin [3]. The first component, cellulose, is the source of most of the sugar derived from lignocellulose. It is a polymer of glucose (6-carbon sugar) [3]. The second component, hemicellulose, contains the sugar xylose (5-carbon sugar), which can be easily fermented to ethanol [3]. Xylose fermentation can thus supplement the yield of ethanol in the main cellulose-ethanol conversion process. The third component of lignocellulose, lignin, is a large polymer, which has 2 benzene rings (phenol groups) [1]. These phenols can react with methanol to form methyl-aryl ethers, a high-value octane enhancer [1]. The compositions of wood and switchgrass are listed in Table 1.

In lignocellulosic plant materials, the cellulose is enclosed in a protective sheath called the lignin-hemicellulose matrix [1]. This matrix has to be broken down in order to

Table 1. Compositions of Wood and Switchgrass (dry basis)

Feedstock	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Others (%)
Poplar Wood	45	25	25	0.5	4.5
Switchgrass	45	30	15	4.6	5.4

expose the core cellulose component for further processing [1]. There are 5 main steps involved in pyrolytic ethanol process: (i) pretreatment, (ii) pyrolysis, (iii) sugar extraction and cleaning, (iv) microbial fermentation, and (v) ethanol recovery.

Pretreatment

The first step in ethanol production is pretreatment. In the pyrolytic ethanol process, pretreatment removes alkali cations (mostly potassium and calcium) from biomass, which is important to the depolymerization of lignocellulose into in its monomer units in the subsequent pyrolysis step [4]. There are two ways to pretreat the feedstock in pyrolytic ethanol process: (i) acid prehydrolysis of feedstock in 5 % sulfuric acid at 80 - 90 °C for about one hour in a percolating column [5], or (ii) deionization of feedstock in 0.1 % to 0.5 % nitric acid (sulfuric acid or hydrochloric acid can also be used). Acid prehydrolysis results in two sugar streams: pentoses from prehydrolysis step and anhydrohexoses from the pyrolysis step [5]. The latter pretreatment process eventually yields only one sugar stream consisting of a mixture of pentoses and hexoses from the pyrolysis step [5].

After acid prehydrolysis, the slurry of ground biomass and acid is filtered to yield solid residues (mostly cellulose and lignin fractions) and filtrate containing mostly pentose [5]. Deionized water is added to the residues until the pH of the mixture is in the range of 4-5 or higher [5]. Furthermore, the pentose needs to be neutralized before fermentation [5].

Deionization pretreatment of biomass must also be followed by washing in deionized water [5]. For wood with ash content of about 0.5 %, the amount of acid needed is about 0.05 g acid / kg drywood [5].

Pyrolysis

The second step of ethanol production is pyrolysis. This thermal process breaks down the lignocellulose into its monomeric units [6]. Pyrolysis is conducted in a fluidized bed reactor. The operating temperature for pyrolysis of poplar wood is about 400 °C to 650 °C, with vapor residence time of about 1.0 s at atmospheric pressure [5]. During pyrolysis, inert hot gases and solids are contacted with the biomass particles to yield both condensable and non-condensable gases [5]. This non-condensable gas is recycled and further partially oxidized with 130 % excess air to preserve its caloric value and also its organic components [5].

The partial oxidation of the non-condensable gas uses platinum-based catalysts similar to those used to oxidize emissions from internal combustion engines [5]. The partially oxidized non-condensable gas can then used for conveying the feed and for fluidizing the bed after the organic liquid is condensed out [5]. The oxidation releases heat which increases the temperature of the recycle gas stream in the order of 150 °C to 250 °C [5]. The remainder of the heat is supplied indirectly by a preheater, before the gas stream enters the oxidation unit [5]. Further oxidation is not recommended for supplying the remaining heat [5]. This process produces more water, making it more difficult to separate the organic liquid from the organic-water mixture in the extraction stage [5].

Sugar Extraction

The third step of ethanol production is extraction of sugar from the pyrolysis products. A proprietary RTI scrubbing tower is used to extract the pyrolysis volatiles [5]. The water scrubber can recycle the organic-water mixture to adjust the desired sugar concentration of up to 300 g / L [5]. Lignin is also precipitated at this step and is removed by centrifuge [5].

The anhydrosugars extracted need to be hydrolyzed to simple sugars before fermentation. Acid hydrolysis is one approach to producing simple sugars [5]. Another possibility is to use high temperature water hydrolysis at 205 °C with short reaction times [5]. This method produces a mixture of glucose and a small amount of isomeric hexoses [5]. However, high temperature water hydrolysis method has not been tested in pilot runs and has not been used to hydrolyze the anhydropentoses [5].

Formic and acetic acids formed during pyrolysis need to be neutralized or steam stripped [5]. Also some inhibitors present need to be removed using activated carbon before fermentation [5].

Microbial Fermentation

The third step in ethanol production is microbial fermentation. Microorganisms ferment in order to release energy in the form of ATP to sustain their activities, like cell multiplication, respiration, etc. [3]. Fermentation process can be represented by the following equation:

$$\text{Carbohydrates} + \text{Cells} = CO_2 + \text{Ethanol} + \text{Cell Mass} \quad [3]$$

Not all of the carbohydrate substrates are converted into ethanol during microbial fermentation. Some of the carbohydrate substrates yield cell mass and CO_2 [3]. The net conversion rate is about 47 % (mass of ethanol/mass of carbohydrates) [3].

Microorganisms have limitations during fermentation especially in terms of substrate specificity, concentration and oxygen requirements [1, 3]. Genetic engineering plays an important role in developing an improved system of microorganisms that optimizes ethanol production.

In pyrolytic ethanol, the bulk sugar component is levoglucosan, as shown in Table 2. Laboratory tests have shown that pyrolysis oil, with inhibitors removed using activated carbon, can be fermented readily with common bakers' yeast in about 1.5 hours [5].

Ethanol Recovery

The fourth step in ethanol production is ethanol recovery or distillation. In this case study, distillation with silicone membrane (180 μm thick, tubular module) is employed [7]. Ethanol vapors are swept from the membrane surface by air [7]. Ethanol condensation temperature is taken to be -2 °C [7] and the temperature of recovery buffer tank is assumed to be 30 °C [7].

The concentration of fermentable sugars affects distillation processing cost. A study was done by SERI of comparing SHF (separate hydrolysis and fermentation) process and SSF. It showed lower sugar concentration (about 4.5 %) due to higher degree of enzyme inhibition led to higher distillation processing costs in SHF than in SSF with a sugar concentration of about 10 % [1].

Table 2. Yields of Pyrolysis Products and Composition of Organic Liquid [4]

Pyrolysis Products	Yields (% wood mf)
Organic liquid	80
Water	6.9
Char	6.7
Gas	6.4
Organic Liquid:	Mass Fractions (%)
Levoglucosan	30
Other sugars	17
Pyrolytic lignin	19
Other	14

CHAPTER 3. METHODOLOGY

Data for this case study was obtained from published journals [1-5, 7-8]. Since 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 later. The general assumptions are listed in Table 3.

The capital cost data from the published journals [1-4, 7] were estimated at different production capacities and using different equipment cost indices. Order-of-magnitude method was used to approximate the equipment capital cost for each of the

Table 3. General Assumptions [2]

Grassroot plant type
Unspecified location
330 Operating days / year
1997 US $
Constant chemistry, theoretical yields and fermentation efficieny of 92 % (for scale up purporses)
25 million gallons of azeotropic ethanol production

conversion technology. This method used the six-tenth exponent to scale capital cost investment from known capital cost data [8]. The capital costs were also updated to 1997 US $ using appropriate equipment cost indices, listed in Table 4. Working capital, making up 15 % of the fixed capital cost, was included in the capital investment [8]. The fixed capital investment was calculated by the following expression:

$$F_x = F_a \times \left(\frac{x}{a}\right)^{0.6} \times \left(\frac{I_j}{I_k}\right)$$

where:

F_x is the unknown fixed capital investment with capacity x and in year j

F_a is the known fixed capital investment with capacity a and in year k

I_j is the Marshall and Swift cost index for year j

I_k is the Marshall and Swift cost index for year k

All equipment capital cost data from different literature included direct field and indirect costs. The accuracy of the estimated fixed capital investment is greater than ±30.0 % [8].

Table 4. Marshall and Swift Equipment Annual Cost Indices [9]

1990 = 915.1
1991 = 930.6
1992 = 943.1
1993 = 964.2
1994 = 993.4
1995 = 1027.5
1996 = 1039.2
1997 = 1056.8

The operating cost assumptions are listed in Table 5. The operating costs were assumed to be directly proportional to the plant production rates:

$$O_v = O_w \times \left(\frac{V}{W}\right)$$

where:

O_v is the operating cost for production rate, V

O_w is the operating cost for production rate, W

Table 5. Operating Cost Assumptions

Operating Cost Assumptions:
Operating labor : 3 % of total expenses
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 operating labor, supervisory, and maintenance
Administrative cost : 25 % of overhead
Distribution & selling cost : 10 % of total expenses
Research & development : 5 % of total expenses
Annual Capital Charge : 20 % of total capital investment[1]

[1] Based on 37 % income taxes, 15-year plant life, 3 year construction period, and straight line depreciation.

As part of the major operating costs, the feedstocks were assumed to be purchased at \$ 42 / dry ton poplar wood and \$ 50 / dry ton switchgrass. Raw material were further comminuted and dried according to feedstock assumptions listed in Table 6. These costs were approximately \$ 7.50 / dry ton for comminution (see Appendix A) and \$ 0.20 / dry ton / % moisture (see Appendix A) removed during drying.

Electricity requirement for the pyrolytic ethanol process was assumed to be purchased at $ 0.04 / kWh. By-product lignin was burned to produce steam either for sales or consumption. Steam was sold and purchased at $ 4.50 / 1000 lb. The amount of lignin available for steam generation was listed in Table 6.

Scott et al. assumed a plant based on the WFPP process that consumes 100 tonnes dry poplar wood / day to produce 24, 000 tonnes/year of glucose equivalent and pentoses [4]. Using process assumptions of constant chemistry and theoretical yields, this translates to about 3 million gallons ethanol / year (see Appendix B). Therefore, for 25 million gallons ethanol / year, the scaled-up capacity was estimated to require 834 tonnes dry poplar wood / day. The scaled-up capacity for the process using switchgrass was also assumed to be 834 tonnes dry switchgrass / day since its sugar compositions were comparable to that of wood (see Table 1). A schematic diagram of WFPP combined with a fermentation process is shown in Figure 1.

Table 6. Feedstock Drying/Comminution and Lignin wt % Availability for Steam Generation Assumptions [5]

Feedstock drying/comminution assumptions :
Wood: 15 % moist., 1.5 mm chip size (as received 50 % moist., 24.5 mm chip size) Switchgrass: 15 % moist., 1.5 mm in length (as received: 50 % moist)
Lignin wt % available for steam generation :
Wood: 13.9 wt % of feedstock Switchgrass: 13.9 wt % of feedstock

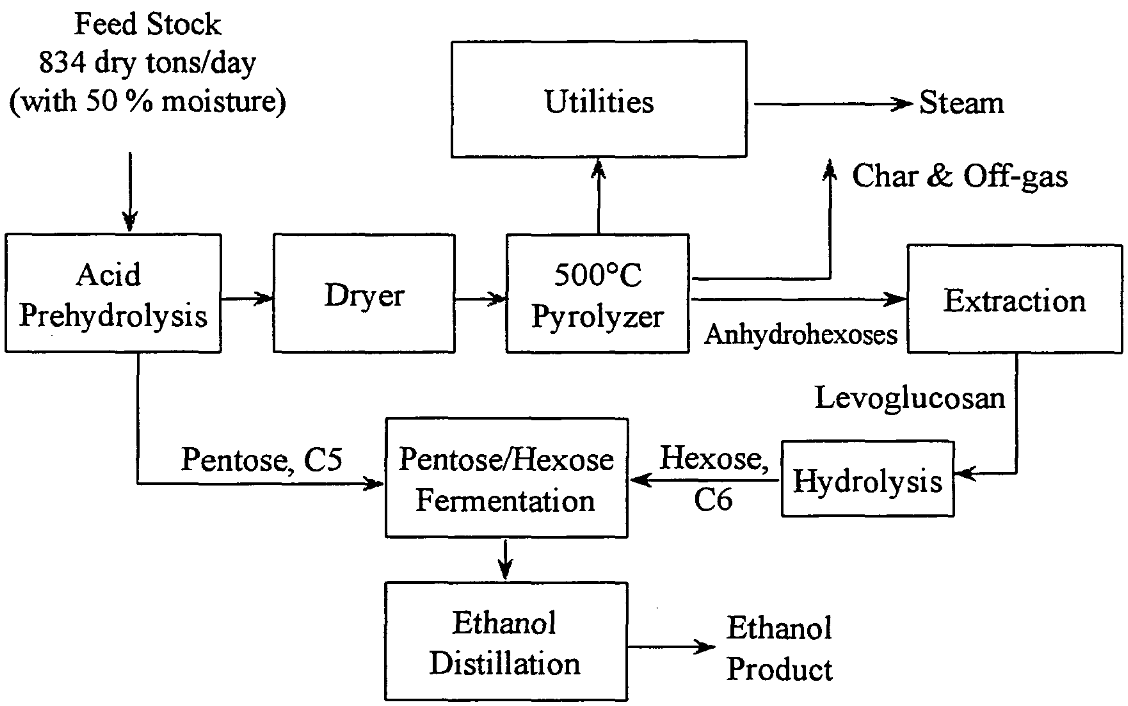

Figure 1. WFPP Combined with a Fermentation Step

The heat energy demands for the WFPP process are identified as: pyrolysis and distillation. Possible energy sources to meet these demands included lignin, char and off-gas from pyrolysis. Figures 2 and 3 show the distribution of energy demand and supply. Total energy demand was approximately 1.1 x 10^{12} Btu (see Appendix C) for wood while total energy requirement was about 1.8 x 10^{12} Btu (see Appendix C). Figures 4 and 5 show the energy demand and supply for switchgrass (see Appendix C). Thus, wood processing has an energy deficit of about 7 x 10^{11} Btu while switchgrass has a deficit of 6 x 10^{11} Btu.

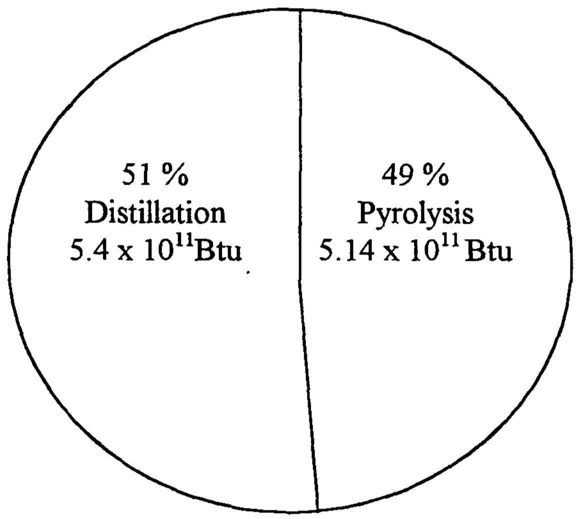

Figure 2. Energy Demand When Using Wood as Feedstock

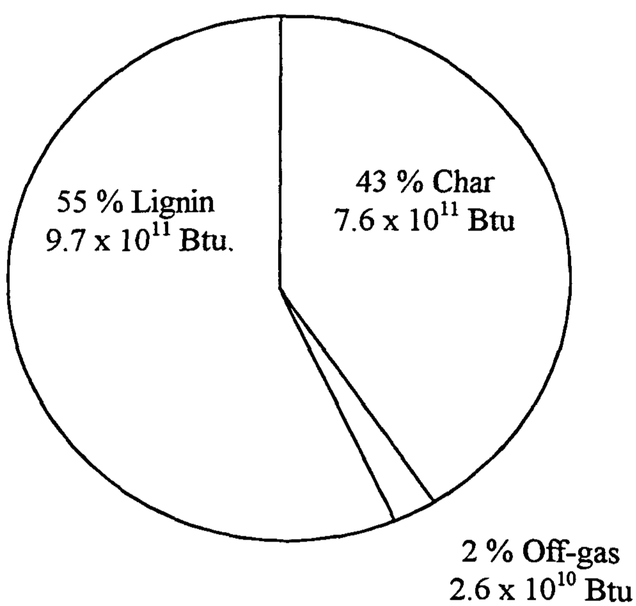

Figure 3. Energy Sources When Using Wood as Feedstock

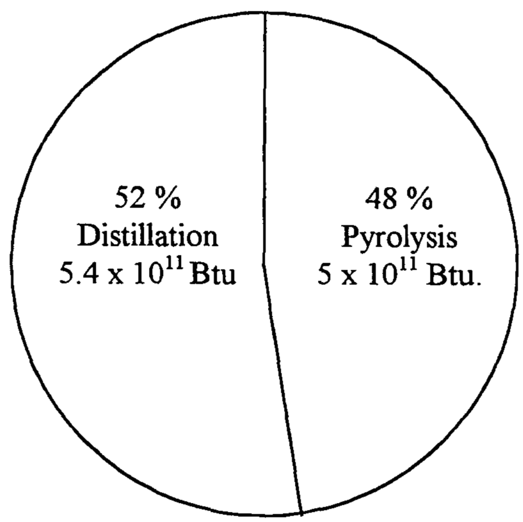

Figure 4. Energy Demand When Using Switchgrass as Feedstock

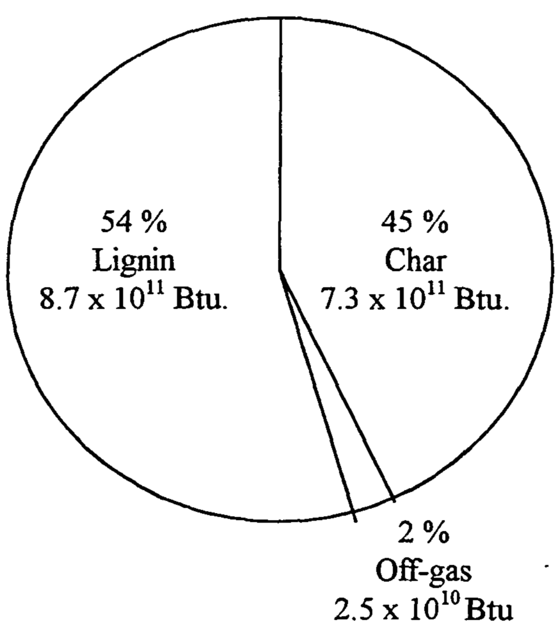

Figure 5. Energy Sources When Using Switchgrass as Feedstock

CHAPTER 4. RESULTS AND DISCUSSION

The breakdown of the capital costs for wood and switchgrass are listed in Table 7. The operating cost breakdown is tabulated in Table 8. Overall annual ethanol production cost for wood was about \$ 1.83 / gal and approximately \$ 1.95 / gal for switchgrass. Two factors accounted for the difference in the overall annual production costs of ethanol: (i) feedstock costs, and (ii) lignin contents. Wood cost about \$ 8 / dry ton more than switchgrass. Furthermore, wood has higher lignin content than switchgrass by about 10 %. This latter fact allows wood feedstock to provide more steam credits than switchgrass feedstock.

Sensitivity analyses of feedstock costs, production rates and ethanol yields on ethanol production costs are shown in Figures 6 - 8. The wood-to-pyrolytic ethanol process was more competitive than using switchgrass at all production rates and ethanol yields. The effect of feedstock costs on production costs were similar for the two cases.

Table 7. Capital Cost Breakdown for Wood and Switchgrass

Plant Areas	Capital Cost ($ million)
WFPP System	15
Fermentation	29
Ethanol Recovery	13
Utilities*	12
Off-Site Tankage	3
Fixed Capital	72
Working Capital	11
Total Capital Investment	83

* see Appendix D.

Table 8. Operating Cost Breakdown for Wood and Switchgrass for 25 Million Gallons Ethanol / Year Production Rate

Cost Elements:	Annual Operating Cost ($ million)	
	Wood	Switchgrass
Direct Costs:		
Wood	11.56	13.76
Comminution/Drying	4.00	4.00
Utilities:		
Steam	-3.20*	-2.70*
Electricity	4.78*	4.78*
Operating Labor	0.87	0.96
Supervisory	0.13	0.14
Maintenance/Repair	4.32	4.32
Indirect Costs[a]:	4.78	4.84
General Expenses[b]:	5.17	5.64
Total Expenses:	29.16	32.12
Annual Capital Charge:	16.56	16.56
Production Cost of Ethanol ($ / gal)	1.83	1.95

[a] Includes overhead, local taxes and insurance.

[b] Includes administrative costs, distribution and selling, research and development.

* See Appendix D.

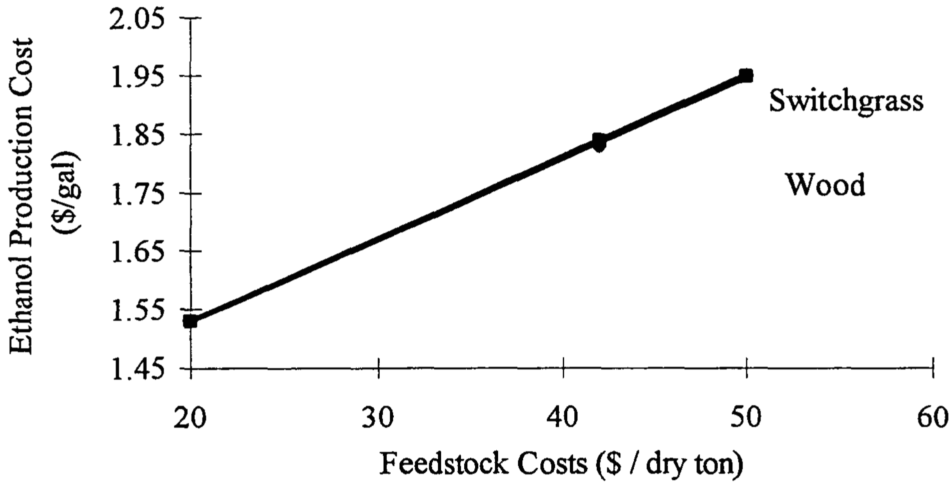

Figure 6. Sensitivity of Feedstock Costs on Ethanol Production Cost

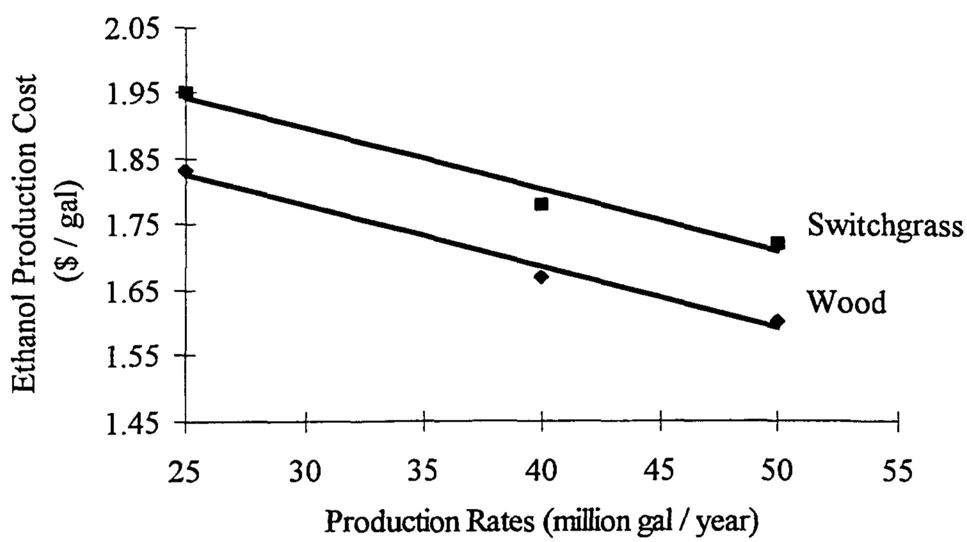

Figure 7. Sensitivity of Production Rates on Ethanol Production Cost

The slopes of the curves shown in Figures 7 - 9 are tabulated in Table 9 to illustrate the influence of various process factors on production costs. Feedstock cost has positive linear relationship with ethanol production cost. Production rate has negative linear relationship with ethanol production cost, which is consistent with the economies of scale concept. Ethanol yield has negative linear relationship with ethanol production cost. Annual ethanol production cost is most sensitive to feedstock costs.

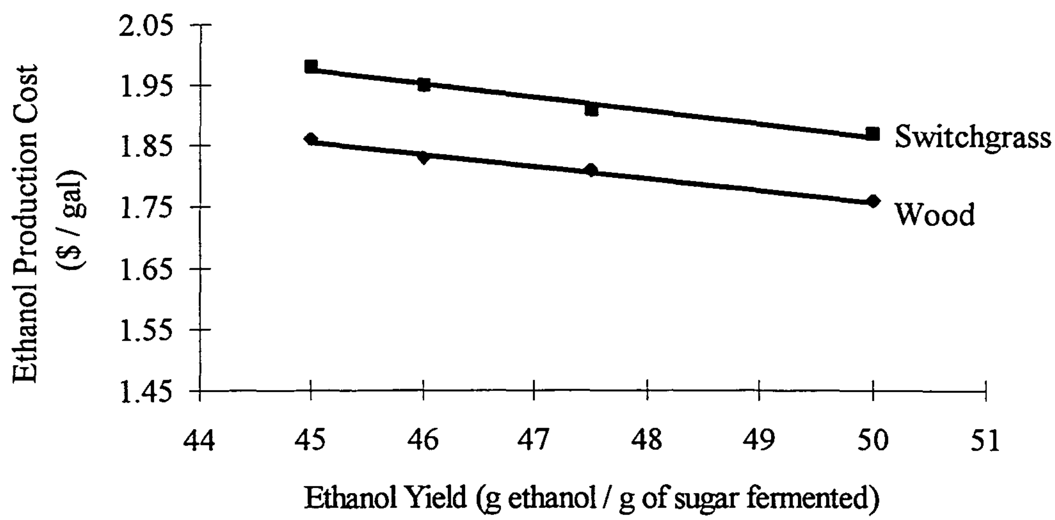

Figure 8. Sensitivity of Ethanol Yield on Ethanol Production Cost

Table 9. Average Slopes for the Sensitivity Analysis Curves

	Wood or Switchgrass
Feedstock Costs	$0.014 \left(\frac{\$/gal}{\$/dry\ ton} \right)$
Production Rates	$-0.0094 \left(\frac{\$/gal}{million\ gal} \right)$
Ethanol Yields	$-0.0192 \left(\frac{\$/gal}{\%} \right)$

Comparisons of Conversion Technologies

To justify the economics, the pyrolytic ethanol process was compared with two other widely-known processes: simultaneous saccharification/ fermentation (see Figure 10) and acid hydrolysis/fermentation (see Figure 11) processes. They were compared in terms of capital, operating, and ethanol production costs. The comparison was based on wood as a feedstock since published data on switchgrass was not available. Capital cost and operating cost comparisons are listed in Tables 10 and 11, respectively.

In terms of capital costs, pyrolytic ethanol was the most expensive, while SSF was the least expensive process. Sensitivity analyses of wood costs and production rates on ethanol production costs are shown in Figures 12 and 13 respectively. Wood cost has positive linear relationship to ethanol production cost, while production rate has negative linear relationship with ethanol production cost, once again consistent with the concept of economies of scale. From Table 11, pyrolytic ethanol has significantly higher annual capital charge than SSF and acid hydrolysis. This contributes to its steeper slope in Figure 13.

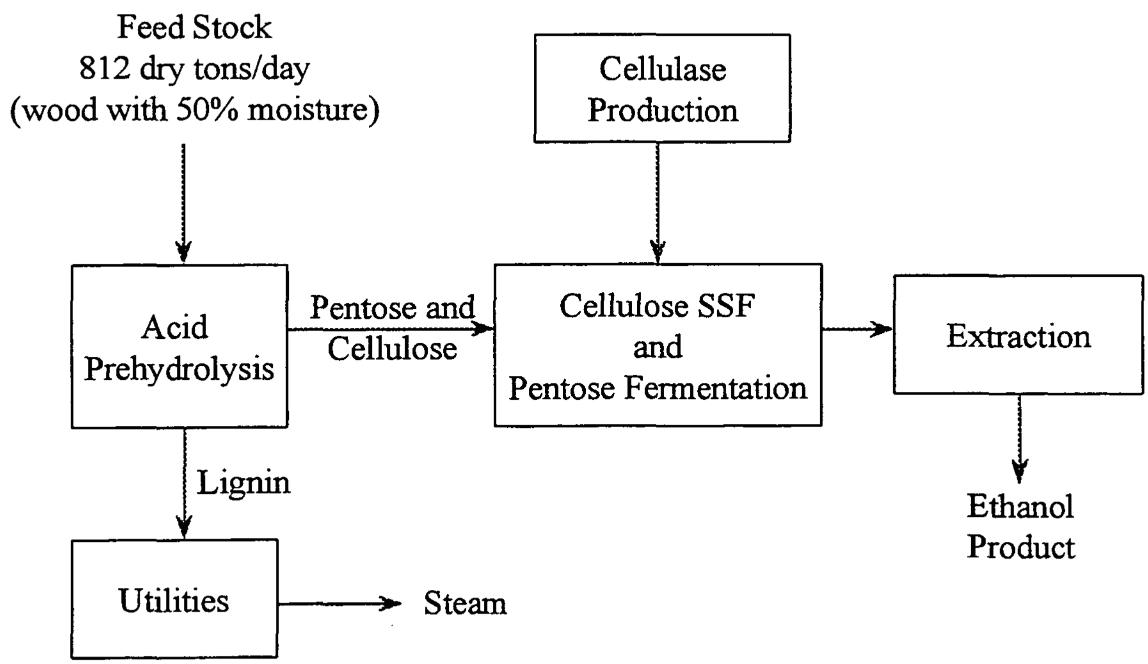

Figure 9. Simultaneous Saccharification and Fermentation Process

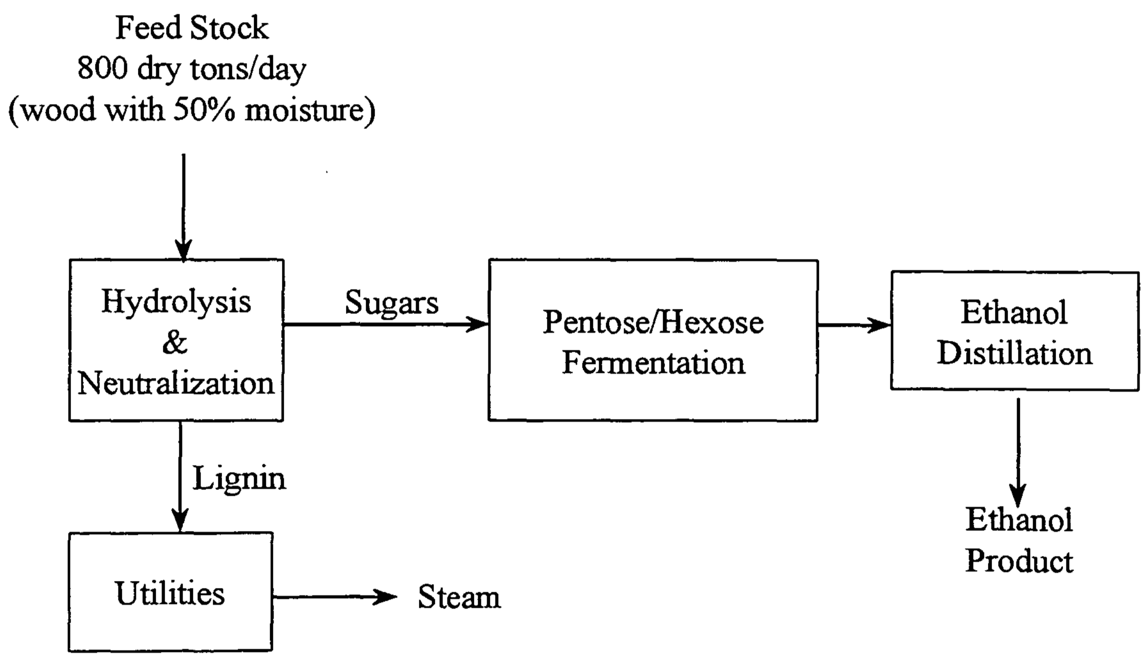

Figure 10. Dilute Acid Hydrolysis and Fermentation Process

Table 10. Capital Cost Comparisons

Plant Areas	Capital Cost ($ million)
Pyrolytic Ethanol:	
WFPP System	15
Fermentation	29
Ethanol Recovery	13
Utilities*	12
Off-Site Tankage	3
Fixed Capital	72
Working Capital	11
Total Capital Investment	83
SSF:	
Pretreatment	16
Pentose Fermentation	4
Cellulase Production	2
SSF	14
Ethanol Recovery	3
Utilities*	12
Off-Site Tankage	3
Fixed Capital	54
Working Capital	8
Total Capital Investment	62
Dilute Acid Hydrolysis:	
Hydrolyser	2
Fermentor	28
Ethanol Recovery	14
Utilities*	12
Off-Site Tankage	3
Fixed Capital	58
Working Capital	9
Total Capital Investment	67

* see Appendix D.

Table 11. Operating Cost Comparisons.

Cost Elements:	Annual Operating Cost ($ million)		
	Pyrolytic Ethanol	SSF	Acid Hydrolysis
Direct Costs:			
Wood	11.56	11.25	11.09
Comminution/Drying	4.00	2.00	1.98
Utilities:			
Steam	-3.20*	-2.75*	0.00*
Electricity	4.78*	1.70*	4.20*
Operating Labor	0.87	0.64	0.84
Supervisory	0.13	0.10	0.13
Maintenance/Repair	4.32	3.26	3.50
Indirect Costs[a]:	4.78	3.59	3.96
General Expenses[b]:	5.17	3.78	4.86
Total Expenses:	29.16	21.23	27.92
Annual Capital Charge:	16.56	12.48	13.43
Production Cost of Ethanol ($ / gal)	1.83	1.35	1.65

[a] Includes overhead, local taxes and insurance.

[b] Includes administrative costs, distribution and selling, research and development.

* See Appendix D.

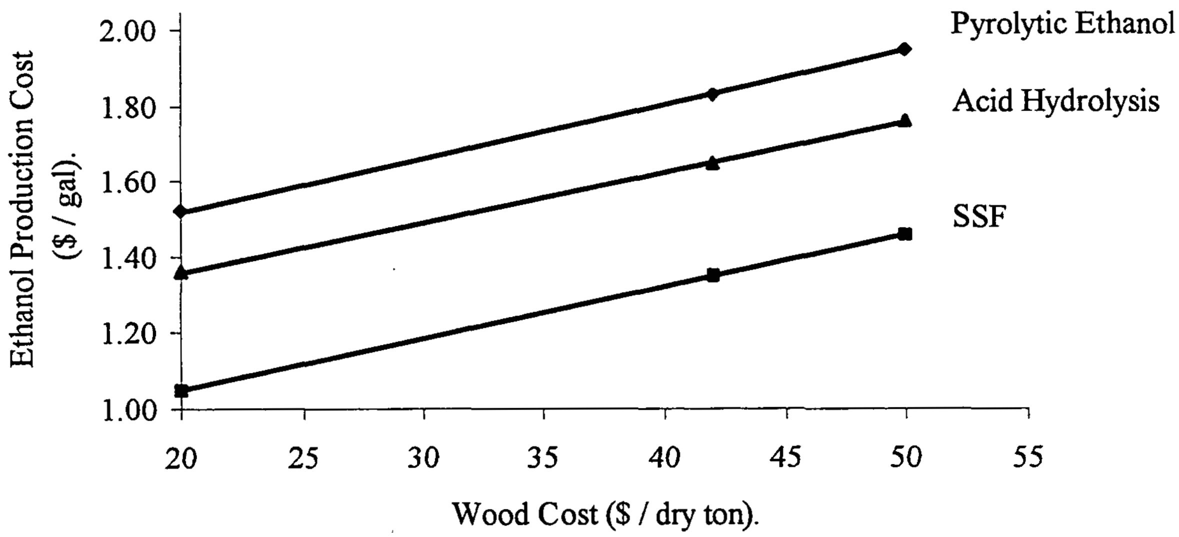

Figure 11. Sensitivity of Wood Costs on Ethanol Production Costs

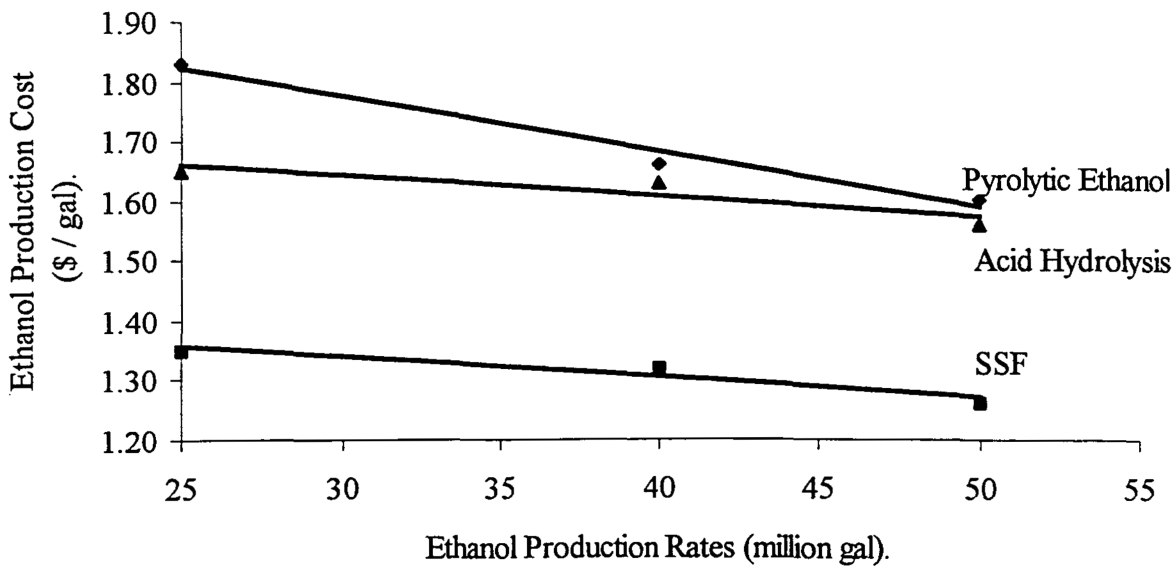

Figure 12. Sensitivity of Production Rate on Ethanol Production Cost

CHAPTER 5. CONCLUSIONS

In the final analysis, wood is more competitive as a raw material than switchgrass as indicated by the final ethanol production costs. But switchgrass is more expensive as a feedstock compared to wood. As shown by the sensitivity analysis of feedstock costs on ethanol production cost, switchgrass can compete with wood as potential raw material, if both have the same feedstock costs.

Taking into account the error associated with order of magnitude method, which is greater than $\pm 30\%$ [8], capital, operating and production costs of pyrolytic ethanol can be said to be comparable to those of acid hydrolysis and SSF.

Further research in the area of pyrolytic ethanol should be carried out to verify its feasibility in ethanol production and also its ability to utilize lignin to produce steam for both consumption and sales.

APPENDIX A. ESTIMATION OF DRYING AND COMMINUTION COSTS

From Reed [10], "kiln drying" is defined as moisture reduction from 50% to 10%, which requires about 2.67 million Btu per dry ton of wood or 1335 Btu/lb. Thus per unit % moisture reduction, the amount of heat energy needed is approximately 33 Btu/dry lb wood/% moisture or 66000 Btu/dry ton wood/% moisture. The cost of drying is then estimated using natural gas cost ($ 3 / MMBtu), which gives approximately $ 0.20 /dry ton wood/% moisture.

$ 15/dry ton of wood is assumed as the combined cost of comminution and drying. Using our cost of drying , $ 0.20 /dry ton wood/% moisture, for 35 % moisture reduction, this costs about $ 7 / dry ton wood, which is about 50 % of the combined cost of drying and comminution. Thus, 50 % of the combined cost of drying and comminution or $ 7.50 / dry ton is used as the cost of comminution.

APPENDIX B. ESTIMATING SUGAR CONVERSION TO ETHANOL

From Scott et al [4], 24, 000 tonnes of glucose, its equivalents, and pentoses per year are produced from WFPP. Assuming ethanol yield to be 0.46 g ethanol/g of sugar fermented [5] and its density to be 0.8 g/ cm^3 [11], the following calculation is done:

$$\left(\frac{24,000\ \textit{tonne sugars}}{1\ \textit{year}}\right)\times\left(\frac{907,200\ g}{1\ \textit{tonne}}\right)\times\left(\frac{0.46\ g\ \textit{ethanol}}{1\ g\ \textit{sugar fermented}}\right)\times\left(\frac{1\ cm^3}{0.8\ g}\right)\times\left(\frac{1\ \textit{gallon}}{3,785\ cm^3}\right)$$

= 3 million gallons ethanol / year.

APPENDIX C. ESTIMATING ENERGY SOURCES AND DEMANDS

According to Bridgwater et al. [12], there are 2 sources from which heat energy requirements for the WFPP model can be derived: char and off-gases. However, lignin , a third potential heat energy source, is available [2, 7]. Energy obtainable from char is estimated to be 2.93 GJ/tonne d.a.f wood with 15 % moisture (75 % effficiency) [12]. Energy from the off-gas is estimated to be 0.1 GJ/tonne d.a.f wood with 15 % moisture (75 % efficiency) [12]. Bridgwater et al. [12] uses a feedrate of 200 tonnes d.a.f. wood with 15 % moisture per day. Lignin, the third energy source, is assumed to have a heating value of 12, 700 Btu/lb. Scott et al. [4] estimated 4, 600 tonnes per year of lignin produced as by-product from WFPP. All the energy sources are scaled to 834 dry tons of wood per day capacity for wood and switchgrass.

Energy from char:

$$\left(\frac{2.93\ GJ}{tonne}\right)\times\left(\frac{200\ tonnes\ d.a.f\ wood}{day}\right)\times\left(\frac{330\ days}{year}\right)\times(1-0.005\ ash)\times\left(\frac{834\ dry\ tonnes\ wood\,/\,day}{200\ d.a.f\ wood\,/\,day}\right)$$

$= 8.02 \times 10^{14}$ J or 7.60×10^{11} Btu.

A similar calculation was done for switchgrass, taking into consideration its different ash content of 4.6 %. This gave about 7.3 x 10^{11} Btu.

Energy from off-gas:

$$\left(\frac{0.10\,GJ}{tonne}\right)\times\left(\frac{200\,tonnes\,d.a.f\;wood}{day}\right)\times\left(\frac{330\,days}{year}\right)\times(1-0.005\,ash)\times\left(\frac{834\,dry\,tonnes\,wood\,/\,day}{200\,d.a.f\;wood\,/\,day}\right)$$

= 2.6 x 10^{10} Btu.

A similar calculation was done for switchgrass, taking into consideration its ash content of 4.6 %. This gave about 2.5 x 10^{10} Btu.

Energy from lignin:

$$\left(\frac{4,600\,tonnes\,lignin}{year}\right)\times\left(\frac{834\,tonnes\,dry\,wood\,/\,day}{100\,tonnes\,dry\,wood\,/\,day}\right)\times\left(\frac{2,000\,lb}{tonne}\right)\times\left(\frac{12,700\,Btu}{lb}\right)$$

= 9.7 x 10^{11} Btu.

A similar calculation was done for switchgrass, taking into consideration that switchgrass has 10 % less lignin than wood. This gave 8.7 x 10^{11} Btu.

Energy requirement for pyrolysis is estimated to be about 1.98 GJ/tonne d.a.f. wood with 15 % moisture [12]. Only one reference was found [13] that contained information on distillation energy requirement. Lynd et al [13] estimated distillation energy requirement based on SSF process with production rate of 60.1 million gallons ethanol per year and a feed rate of 658, 000 dry tons wood per year. The distillation energy requirement was estimated to be 21.44 lb steam per gal ethanol. This figure, scaled accordingly to the feed capacities, is used to approximate the distillation energy requirements for pyrolytic ethanol and acid hydrolysis processes. Heating value of steam is taken to be 1, 000 Btu/lb.

Energy for pyrolysis using wood:

$$\left(\frac{1.98\,GJ}{tonne}\right)\times\left(\frac{200\,tonnes\,d.a.f\ wood}{day}\right)\times\left(\frac{330\,days}{year}\right)\times(1-0.005\,ash)\times\left(\frac{834\,dry\,tonnes\,wood\,/\,day}{200\,d.a.f\ wood\,/\,day}\right)$$

= 5.4 x 10^{14} J or 5.14 x 10^{11} Btu.

A similar calculation was done for switchgrass taking into consideration its ash content of about 4.6 %. This gave 5 x 10^{11} Btu.

Energy for distillation using wood or switchgrass:

$$\left(\frac{21.44\,steam\,lb}{gal\ ethanol}\right)\times\left(\frac{60.1\times10^{6}\ gallons\,ethanol}{year}\right)\times\left(\frac{1,000\,Btu}{lb\ steam}\right)\times\left(\frac{275,220\,dry\,tonnes\,/\,year}{658,000\,dry\,tonnes\,/\,year}\right)$$

= 5.4 x 10^{11} Btu.

APPENDIX D. ESTIMATING STEAM AND ELECTRICITY OPERATING COSTS

Steam cost is assumed to be \$ 4.50 / 1000 lb.

For pyrolytic ethanol using wood:

$$\left(\frac{7 \times 10^{11}\ Btu}{year}\right) \times \left(\frac{\$4.50}{1,000\,lb}\right) = \$\ 3.20 \text{ millions / year of steam credits.}$$

A similar calculation was done for switchgrass with net excess steam of 6 x 10^{11} Btu. This gave steam credits of \$ 2.70 millions / year.

According to Qureshi et al. [7], the acid hydrolysis process utilized all of the steam from boiling of lignin and did not generate steam for sales.

Hinman et al. [2] estimated the economics of the SSF process based on production rate of 58.5 million gallons of ethanol per year and a feed rate of 1, 920 dry tons wood per day. The SSF process produced an estimated 434, 000 lb/h of steam [2] or 3.44 x 10^9 lb/year of steam. Assuming the latent heat of steam to be 1, 000 Btu/lb, the total amount of steam energy produced by SSF is 3.44 x 10^{12} Btu per year. It consumed

35, 700 Btu per gallon ethanol product [2] or 2 x 10^{12} Btu of steam per year. Thus the net steam energy available for sales is 1.44 x 10^{12} Btu per year, this is equivalent to $ 6.5 millions of steam credits per year. Scaling the steam credits to the appropriate production capacities:

$$\left(\frac{\$6.5\ million\ steam\ credits}{year}\right)\times\left(\frac{25\ million\ gallons\ ethanol\,/\,year}{58.5\ million\ gallons\ ethanol\,/\,year}\right)\times\left(\frac{330\ days\,/\,year}{333\ days\,/\,year}\right)$$

= $ 2.75 million / year of steam credits.

Utility capital costs for SSF include the cost of turbo generator for electricity generation [2]. However, in this analysis, electricity is assumed to be purchased for any power requirement. The breakdown of the utility capital cost was not available in the case of SSF. No utility capital cost for the pyrolytic ethanol process was available. The utility capital cost for the acid hydrolysis case was used as an estimate since it did not include a turbo generator capital cost, scaled (using six-tenth rule) to the appropriate feed capacities, and updated to 1997 US $ for each conversion technology.

Data on electricity requirement for the pyrolytic ethanol process was not available. The electricity requirement for the acid hydrolysis process was used as an estimate for pyrolytic ethanol process and scaled directly with the appropriate feed capacity, as follows:

Pyrolytic ethanol electricity operating cost:

$$\left(\frac{\$2,640,000\ \textit{acid hydrolysis electricity}}{\textit{year}}\right)\times\left(\frac{834\ \textit{dry tonnes wood / day}}{500\ \textit{dry tonnes wood / day}}\right)\times\left(\frac{330\ \textit{days / year}}{335\ \textit{days / year}}\right)\times\left(\frac{1056.8}{964.2}\right)$$

= \$ 4.78 million / year of electricity cost.

For the SSF process, electricity requirement was about 1.68 kWh per gallon of ethanol product [2] or 1 x 10^8 kWh per year. Using electricity cost of \$ 0.04 / kWh, this translates into \$ 4 million per year. Scaling the electricity costs for 25 million gallons of ethanol capacity gives \$ 1.7 million per year of electricity costs.

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