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ECONOMIC ANALYSIS OF ETHANOL PRODUCTION FROM SWITCHGRASS USING HYBRID THERMAL/BIOLOGICAL PROCESSING

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ABSTRACT

The economics of ethanol production from switchgrass using Waterloo fast pyrolysis with a fermentation step is investigated. Standard chemical engineering methods are used to estimate capital investment and operating costs. Order of magnitude method is employed for preliminary approximation of capital investment. The azeotropic ethanol production capacity used in this case study is 189 million liters / year (50 million gallons / year). All cost figures are updated to 1997 US $. Total capital investment is estimated to be $142 million, while the annual operating cost is about $118 million with an ethanol selling price of $ 0.62 / l ($ 2.35 / gal). This compares to $ 0.58 / l ($ 2.20 / gal) for ethanol from poplar wood as determined in a previous study of the Waterloo fast pyrolysis process. Conservation of energy, especially, in the separation and purification steps, and generation of steam from lignin to meet energy requirements are evaluated in terms of energy saving costs. Additional steam has to be purchased, at $ 0.30 million / year, in order to meet the heat energy requirement of the process. Sensitivity analyses of feedstock cost and yield of sugar fermentation on the selling price of ethanol show that feedstock cost is positively related to ethanol selling price, while the yield has a negative relationship with selling price.

Keyword: switchgrass, fast pyrolysis, ethanol, economics, sensitivity.

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INTRODUCTION

The Waterloo Fast Pyrolysis Process (WFPP) is used to rapidly heat lignocellulose to moderately high temperature (about 500 ° C) to form a mixture of solids, liquids, and gases (3). The non-aqueous phase of the resultant liquids consists of oxygenated compounds that have been investigated as fuel oil and chemical feedstock. Researchers at the University of Waterloo (3) discovered that alkali and alkali earths in biomass act as catalysts to decompose lignocellulose. If these alkalis are removed by dilute acid hydrolysis pretreatment prior to pyrolysis, lignocellulose can be depolymerized to complex sugar (levoglucosan) with very high yields. These sugars can then be hydrolyzed into fermentable sugars. Scott (3) has performed an economic evaluation of the cost of producing fermentable sugars from fast pyrolysis using wood (hybrid poplar) but no economic studies have been performed on the integration of pyrolysis and fermentation technologies.

The objectives of this study are to perform an economic analysis on the production of ethanol from switchgrass using the Waterloo process. The proposed project is flow charted in Figure 1. Switchgrass undergoes an acid pretreatment that removes alkali and hydrolyzes the hemicellulose fraction to pentose. The remaining lignocellulosic fraction is pyrolyzed at 500 °C to yield char, gas, lignin and levoglucosan. The first three products are burned to generate steam while the levoglucosan is hydrolyzed to hexose. The pentose and hexose are fermented to ethanol.

Capital investment, operating costs and selling prices of ethanol for the process are estimated using order of magnitude method. The technology is also evaluated qualitatively for its ability to utilize by-product lignin for steam generation. Sensitivity analyses are also carried out to examine the uncertainties of feedstock cost and yield of sugar fermentation on the selling price of ethanol.

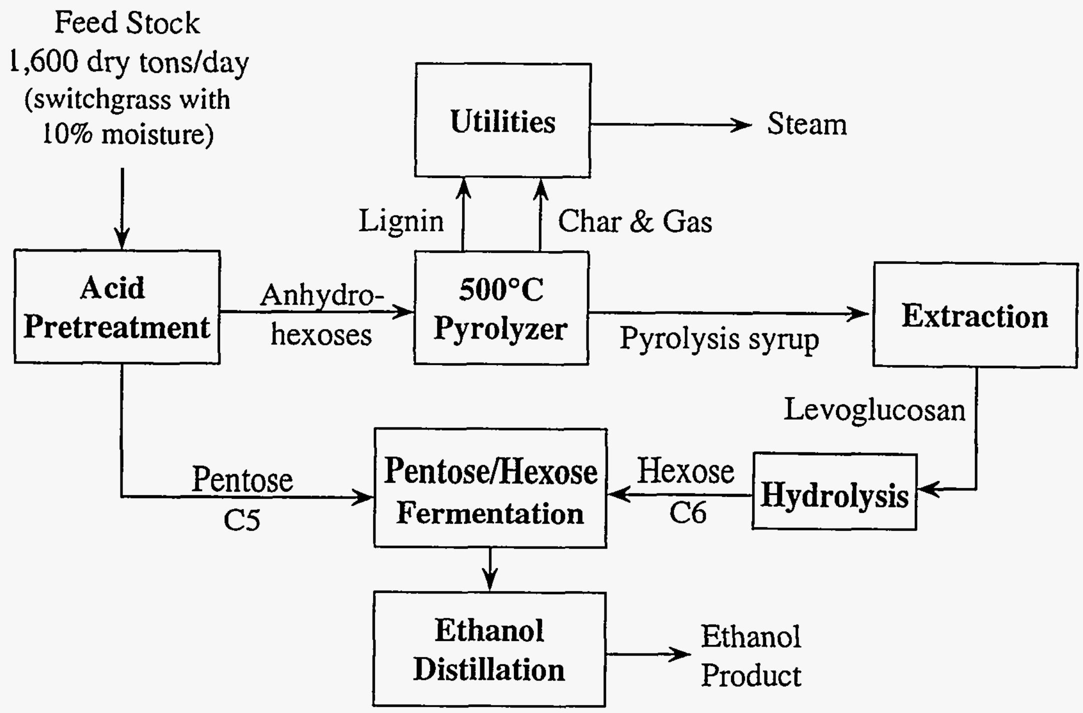

Figure 1. Waterloo Fast Pyrolysis Process.

METHODOLOGY

Data for this case study is obtained from published literature (1-3). A common set of assumptions are developed for the analysis. General and operating cost assumptions (5) are listed in Table 1, while the feed composition assumptions are listed in Table 2. Experimental yield data are not available for alkali-free pyrolysis of switchgrass. Although such data is available for hybrid poplar (3). Accordingly, yields of hemicellulose and pyrolysis products for switchgrass were estimated from switchgrass compositional data and yield data for pyrolysis of hybrid poplar. The estimated yields of various products from switchgrass pyrolysis are listed in Table 3. For an annual production rate of 189 million liters of ethanol (50 million gallons), switchgrass feed rate of about 1.5 million dry kg / day (1600 dry ton / day) is required.

Table 1. General and Operating Cost Assumptions.

General Assumptions:
Grassroot plant type
Unspecified location
330 Operating days
1997 US $
189 Million liters of azeotropic ethanol production
Operating Cost Assumptions:
Supervisory : 15 % of operating labor
Maintenance & repair : 6 % of fixed capital
Laboratory charges : 15 % of operating labor
Local tax : 1.5 % of fixed capital
Insurance : 0.7 % of fixed capital
Overhead : 60 % of Sum of operating labor, supervisory, and maintenance
Depreciation : 10 % of fixed capital
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

Table 2. Switchgrass Composition (Dry Basis).

Component	Mass Fraction (%)
Cellulose	45
Hemicellulose (Xylose)	30
Lignin	15
Other*	10

* include protein, oils, mineral matter (such as silica and alkali).

Table 3. Yields of Pyrolysis Products and Composition of Organic Liquid.

Pyrolysis products:	Yields (% switchgrass 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
Others	14

Order of magnitude method is employed to estimate the capital investment for equipment used in the fast pyrolysis process. This method uses the six-tenth power law exponent to scale capital cost investment from known capital cost data (5). Startup and working capital, making up about 5 % and 15 %, respectively, of the fixed capital cost, are included in the capital investment. Capital charge is estimated to be 20 % of total capital investment. This is based on straight-line depreciation, 15-year plant life, and 3-year construction period (1). The accuracy of the estimated capital, operating costs and the selling price of ethanol is about +/- 30.0 % (5).

As part of the major operating costs, the feedstock is assumed to be purchased at $ 55 / dry Mg ($ 50.00 / dry ton). Switchgrass is further comminuted and dried at approximately $ 8.2 / dry Mg ($ 7.50 / dry ton) and $ 0.22 / dry kg / % moisture removed during drying ($ 0.20 / dry ton / % moisture), respectively. The feedstock is assumed to have an initial moisture content of 50 % and has to be dried to 10 % moisture for pyrolysis.

Electricity requirement for the fast pyrolysis technology is purchased at $ 0.04 / kWh. Lignin boilers and equipment used to produce steam, either for sale or consumption, are included in the utility capital cost. Steam is sold and purchased at $ 9.92 / 1000 kg ($ 4.50 / 1000 lb). The amount of lignin available for steam generation is listed in Table 2.

The energy demands in the entire process are identified for following major process areas: pretreatment, pyrolysis, and ethanol recovery. Energy sources to meet these demands include lignin, char and off-gas from pyrolysis. The pie charts below show the distribution of the heat energy demand and supply. Total energy demand is approximately 2.75×10^{15} J (2.61×10^{12} Btu), while total energy sources is about

2.66×10^{15} J (2.50×10^{12} Btu). Thus there is a net energy shortage of about 9.00×10^{13} J (8.5×10^{10} Btu).

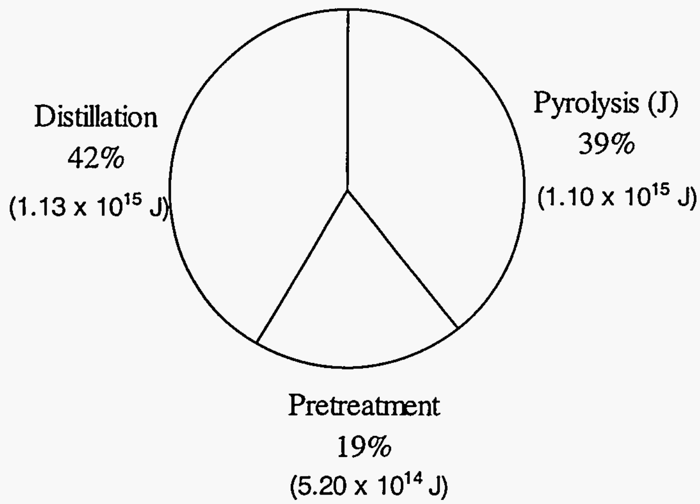

Figure 2. Pie Chart of Energy Demands for the Major Process Areas.

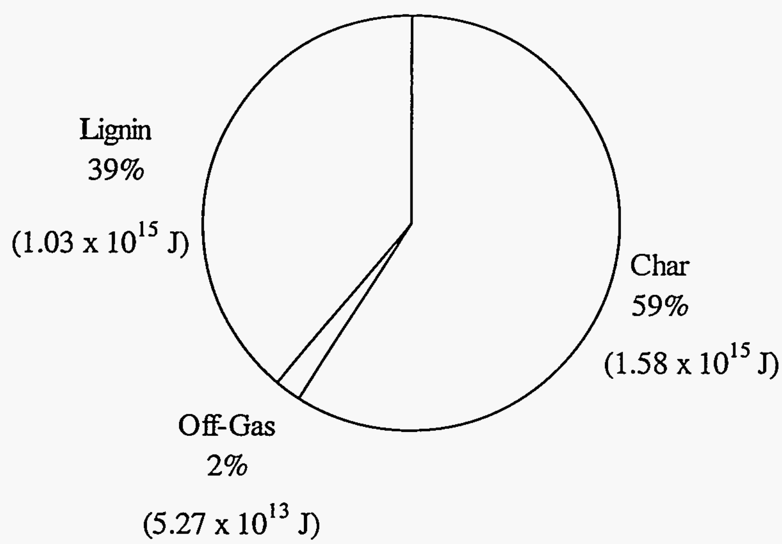

Figure 3. Pie Chart of Energy Sources.

RESULTS

Capital and operating costs are listed in Table 3. Total capital investment for the fast pyrolysis technology with a suitable fermentation is estimated to be \$ 142 million. The annual operating cost, for the production of 189 million liters of ethanol (50 million gallons), is estimated to be \$ 118 million with an ethanol selling price of about \$ 0.62 / liter of ethanol (\$ 2.35 / gallon).

Previous economic analysis (4) estimated the selling prices, using wood as the feedstock, to be \$ 0.58/l (2.20 / gal) by fast pyrolysis and \$ 0.59/l (\$ 2.24/gal) by SSF. The difference in the selling prices could be accounted for by the higher cost of switchgrass, which was assumed to be about \$ 0.055 / dry kg (\$ 50.00 / dry ton), while the cost of wood used in (4) was about \$ 0.046 / dry kg (\$ 42/dry ton). In addition, wood had a higher composition of lignin than switchgrass, by about 7 %.

Sensitivity analysis of feedstock cost on selling price of ethanol is illustrated in Figure 2. Selling price of ethanol increases with increasing feedstock cost. At feedstock cost of \$ 0.22 / dry Mg (\$ 20 / dry ton), the selling price of ethanol is about \$ 0.52 / l (\$ 2.19 / gal). As the feedstock cost is increased to \$ 0.46 / dry Mg (\$ 42 / dry ton), the selling price of ethanol is increased to \$ 0.59 / l (\$ 2.25 / gal). For every \$ 1.00 / dry Mg (\$ 9.07 / dry ton) of feedstock increase, the selling price of ethanol increases by about \$ 0.03 / liter (\$ 0.11 / gal).

Table 4. Capital and Operating Costs.

Plant Areas	Capital Cost	Cost Elements	Operating Cost
	($ million)		($ million)
WFPP System	22.81	Direct Operating Costs:	
Fermentation	56.12	Raw Material:	
Ethanol Recovery	7.01	Switchgrass	26.40
Utilities	26.20	Comminution/Drying	8.18
Off-Site Tankage	6.03	Materials	6.78
Fixed Capital	118.16	Utilities:	
Start Up Costs	5.91	Steam (250 psig)	0.30
Working Capital	17.72	Electricity	4.72
		Cooling Water	0.12
Total Capital	141.80	Operating Labor	1.14
		Supervisory	0.17
		Maintenance & Repair	7.09
		Laboratory Charges	0.17
		Indirect Operating Costs:	
		Overhead	5.04
		Local Taxes	1.77
		Insurance	0.83
		Depreciation	11.82
		General Expenses:	
		Administrative costs	1.26
		Distribution & Selling Costs	8.92
		Research & Development	4.46
		Total Expenses	89.16
		Annual Capital Charge	28.36
		Total Operating Costs	117.52
		Ethanol Produced (million liter)	189.27
		Selling Price of Ethanol (in $ / l)	0.62

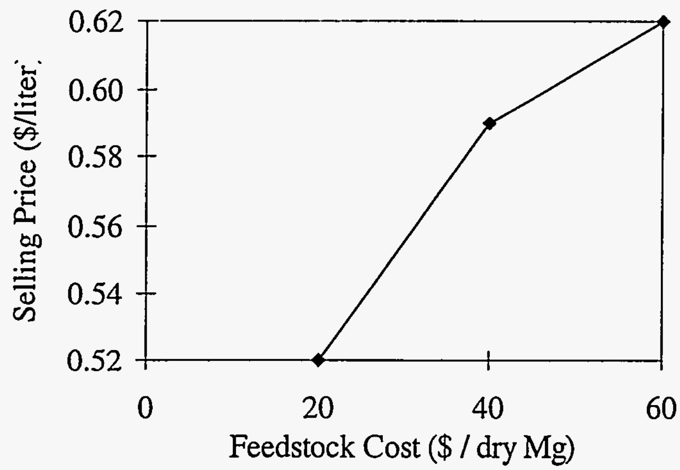

Figure 2. Sensitivity Analysis of Feedstock Cost on Selling Price of Ethanol.

Figure 3. illustrates the sensitivity analysis of the yield of xylose and glucose fermentation. Selling price of ethanol is negatively related to the yield of sugar fermentation. At 92 % yield, the selling price of ethanol decreases to about $ 0.59 / liter ($ 2.23 / gal). At a higher yield of 95 %, the selling price of ethanol decreases to about $ 0.57 / liter ($ 2.15 / gal). Finally with a theoretical yield of 100 %, the ethanol selling price is reduced to about $ 0.54 / liter ($ 2.04 / gal).

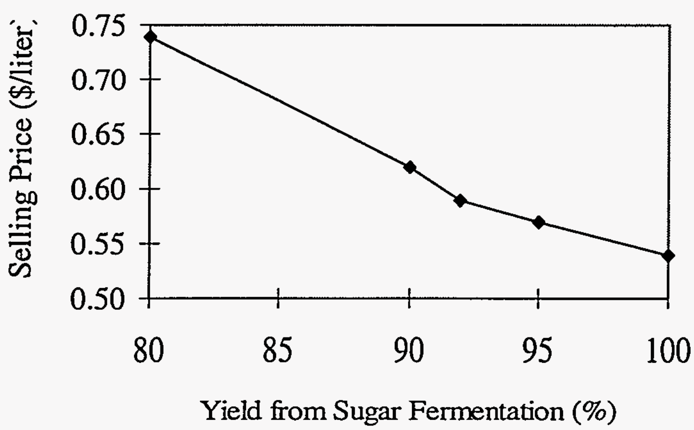

Figure 3. Sensitivity Analysis of Yield from Sugar Fermentation on Selling Price of Ethanol.

CONCLUSIONS

The economic analysis provides an estimate for the selling price of ethanol as \$ 0.62 / l (\$ 2.35 / gal) using fast pyrolysis of switchgrass to produce 189 million liters (50 million gallons) of ethanol. This selling price is slightly higher than that for ethanol from hybrid poplar. Further research should be conducted to verify its feasibility, and the conservation of energy in the separation and purification steps on a pilot scale.

ACKNOWLEDGMENTS

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