Switchgrass to Ethanol: A Field to Fuel Approach

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Mohua Haque is a graduate research assistant, and Francis M. Epplin is Charles A. Breedlove professor. This material is based on work supported in part by USDA Special Research Grant award 2008-34417-19201from the National Institute of Food and Agriculture. Additional funding was provided by the U.S. Department of Energy and USDA Biomass Research and Development Initiative. The project is also supported by the USDA National Institute of Food and Agriculture, Hatch grant number H-2574. Support does not constitute an endorsement of the views expressed in the paper by the USDA. Professional paper AEP-1003 of the Oklahoma Agricultural Experiment Station.

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association 2010 AAEA,CAES, & WAEA Joint Annual Meeting, Denver, Colorado, July 25-27, 2010.

Abstract

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The U.S. Energy Independence and Security Act of 2007 mandates the production of 16 billion gallons of cellulosic biofuels by 2022. Desirable feedstock properties, biomass to biofuel conversion rate, and investment required in plant and equipment differs depending on which of several competing technologies is used. The objective is to determine the breakeven ethanol price for a cellulosic biorefinery. A comprehensive mathematical programming model that encompasses the chain from land acquisition to ethanol production was constructed and solved. For a capital requirement of $400 million for a 100 million gallons per year plant and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price is $1.91 per gallon: $0.20 for land rental and switchgrass production; $0.14 for feedstock harvest; $0.18 for feedstock storage and transportation; $0.75 for biorefinery operation and maintenance; and $0.64 for biorefinery investment. Biomass to ethanol conversion rate and the cost of biorefinery construction, operation, and maintenance are critical issues.

Key words: biorefinery; breakeven price; cellulosic ethanol; mathematical programming; switchgrass

JEL codes: Q42, Q48

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Introduction

In a frequently referenced *Science* article published in 1991, Lynd et al. hypothesized that given continued investment in research, by the year 2000, technology would be developed enabling the production of cellulosic ethanol for a wholesale selling price of $0.60 per gallon ($1.19 in 2009 dollars). In 2006 Pacheco reported to a U.S. Senate committee that "…Our goal is to reduce the cost of producing cellulosic ethanol from $2.25 a gallon in 2005, to $1.07 in 2012. …" In anticipation of an economically viable feedstock production and conversion system, the U.S. Energy Independence and Security Act (EISA) of 2007 included a provision that by 2022, 16 billion gallons of cellulosic biofuels, primarily cellulosic ethanol, be produced and blended with gasoline. Since, no unsubsidized commercial sized facilities were operating in 2009, it seems reasonable to conclude that development of a commercially viable system for production of cellulosic ethanol has not progressed as rapidly as anticipated.

The United States Environmental Protection Agency (USEPA) has the responsibility for implementing the provisions of EISA. They have identified six methods or technical categories for producing ethanol from cellulose (biochemical enzymatic hydrolysis; thermochemical/catalytic; thermochemical/biochemical; strong acid hydrolysis; dilute acid, steam explosion; consolidated hydrolysis and fermentation) (USEPA 2010, p. 115). These methods have several important differences that influence field to fuel economics. The (a) desirable feedstock properties, (b) biomass to ethanol conversion rate and (c) investment required in plant and equipment differs across systems.

For cost-efficient operation these systems would require a flow of feedstock throughout the year. Enzymatic hydrolysis requires specific enzymes to convert a given type of feedstock and a homogeneous mixture of feedstock would be preferable (Wei, Pordesimo, and Batchelor 2007). Gasification (thermochemical) can handle a wider variety of feedstocks. Net feedstock costs could be expected to be greater for conversion systems that have narrower tolerances on biomass characteristics. Characteristics that define feedstock quality remain to be determined.

There is considerable variability in expected conversion rates. For example, the USEPA (2010) reports conversion rates of 72 gallons per dry ton (p. 721), 90 gallons per dry ton (p. 285), and 92.3 gallons per dry ton (p. 286), depending on system and maturity of the system. Schmer et al. (2008) used 91 gallons per dry ton. Coskata (2010) reports that their semi-commercial facility produces 100 gallons of ethanol per dry ton. For a given size biorefinery, total feedstock requirements, acres required, transportation distances, and feedstock cost would differ greatly between a plant that achieved 100 versus one that produced only 70 gallons per dry ton.

Capital costs required to construct a commercial-scale biorefinery depends on the conversion technology. The USEPA (2010) reported estimates of expected capital costs computed by the Department of Energy's National Renewable Energy Laboratory (NREL). NREL estimated expected capital cost of $232 million for a biochemical conversion plant with an annual capacity of 56 million gallons (USEPA 2010, p. 751). For a thermochemical plant designed to produce an ethanol yield of 63 million gallons per year NREL estimates an expected capital cost of $257 million (USEPA 2010, p. 763). The capital investment requirements for both of these systems would be in excess of $4 per gallon of annual capacity. Consistent with these estimates a Rapier (2008) reports that Coskata expects a capital cost for their technology of $400 million for a 100 million gallon per year facility.

Prior to investing millions of dollars in a cellulosic biorefinery, prudent investors would expect to have information about the most economical conversion method, approximate investment cost to build a plant, ethanol yield per ton of biomass (ethanol yield depends on feedstock quality and method of conversion), and they would expect assurance that a flow of feedstock that meets the quality standards of the facility will be available at a price that provides a high probability of a positive return on investment.

Progress has been made towards the development of the production and harvest of dedicated energy crops such as switchgrass and miscanthus, and the harvest of crop residues such as corn stover. The standard paradigm for evaluating the economics of cellulosic ethanol has followed the pattern used to evaluate grain ethanol. However, producing, harvesting, storing, and delivering cellulosic biomass and converting it to ethanol is fundamentally different from producing and marketing corn grain, and producing ethanol from grain. The infrastructure for corn grain was well developed prior to implementation of public policies designed to increase the production of fuel ethanol. A similar infrastructure does not exist for cellulosic biomass such as switchgrass.

A number of studies have reported estimates of feedstock production, harvest, storage, and transportation cost (Brechbill and Tyner 2008; Duffy 2007; English, Short, and Heady 1981; Epplin 1996; Epplin et al. 2007; Gallagher et al. 2003; Glassner, Hettenhaus, and Schechinger 1998; Graham et al. 2007; Khanna, Dhungana, and Brown 2008; Perrin et al. 2008; Petrolia 2008; Vadas, Barnett, and Undersander 2008). In general these studies have not considered quality characteristics other than dry matter and have assumed that the value to a biorefinery of a dry ton of switchgrass would be equal to the value of a dry ton of corn stover independent of month of harvest or length of time in storage. This is one result of the lack of information flow from scientists and engineers conducting the processing research regarding feedstock quality parameters.

Estimating only delivered dry matter cost may be appropriate for a system that requires a feedstock that is relatively homogeneous and easily storable such as corn grain. However, (a) cellulosic biomass feedstock is not homogeneous, (b) ethanol yield depends on feedstock quality and method of conversion, (c) the optimal composition of feedstocks may not be the same across all potential conversion methods, and (d) plant investment cost varies depending on the conversion technology used. Hence, determination of the most efficient system requires a holistic field to products model that simultaneously considers land procurement, feedstock production, harvest, storage, transportation, processing, and the value of final products. Modeling each of the competing conversion systems using a field to fuel approach could provide useful information to compare the expected economics of each system and identify unique bottlenecks.

The objective of this study is to determine the ethanol price necessary for a lignocellulosic biorefinery to breakeven. The modeling system enables a determination of the optimal feedstock production, harvest, investment in harvest machines, storage, and transportation strategy, and optimal biorefinery location and size. Given the uncertainty regarding biorefinery capital requirements and the uncertainty regarding the number of gallons of ethanol that could be produced per dry ton by a commercial sized facility, the breakeven ethanol price is computed for 12 different combinations of investment cost and conversion rates.

Data Descriptions and Assumptions

The study is based on the assumption that a biorefinery would depend entirely on switchgrass as a single feedstock and be located in Oklahoma. USEPA (2010) estimates that by 2022 eleven cellulosic ethanol biorefineries that use switchgrass as the feedstock will be operating in Oklahoma. The model is limited to the eastern 55 Oklahoma counties as production regions. Tall grasses such as switchgrass are not common in the native prairies of the westernmost 22 counties. Field trials would be required to determine if pure stands of switchgrass would persist on the soils and in the climate of these counties (Gopal 2009; Wu 2009;). Eleven candidate biorefinery locations are included. These locations were selected considering biomass relative density and availability of road infrastructure.

Switchgrass biomass yield estimates for each of 55 counties for each of nine harvest months were synthesized from several sources (Graham, Allison, and Becker 1996; Fuentes and Taliaferro 2002; Haque, Epplin, and Taliaferro 2009; Wu 2009). In Oklahoma, the harvest season may begin in July and extend through March. However, harvests during April, May, and June are not expected since it is anticipated that harvest during these months would damage plant growth for subsequent years. Maximum expected yield is obtained by harvesting in either September or October. Expected yield from harvest in July is 80 percent of maximum and land harvested in May will require more fertilizer (Haque and Epplin 2010). If switchgrass is left to stand in the field beyond October, dry matter losses of five percent per month are expected from November through March.

In the model, switchgrass production is restricted to two land classes: cropland and improved pasture land. Data from the census of agriculture were used to determine acres of cropland and improved pasture (USDA 2002). The expected switchgrass yields were assumed to be the same on improved pasture land as on cropland. This assumption follows from the finding that switchgrass yield is limited more by available moisture and the length of the growing season than by soil quality (Gopal 2009; Wu, 2009).

Restrictions are included in the model to limit switchgrass production in each county to no more than ten percent of the county's cropland and no more than ten percent of the county's improved pasture land. Another assumption is that the use of this cropland and improved pasture land can be acquired at a long-term lease rate of $60 and $40 per acre per year, respectively. The average 2005-09 cropland cash rental for Oklahoma non-irrigated cropland ranged from $28-$31 per acre, and the average 2005-09 pasture land cash rental for Oklahoma ranged from $8.50-$10.50 per acre (USDA 2009). The assumptions of $60 and $40 per acre for cropland and pasture land lease rates are made to account for the need to entice land owners to enter into a long-term lease that would be necessary for the perennial grass and to recognize that land lease rates in the vicinity of a biorefinery would increase in response to the plant's existence. Switchgrass production cost estimates are based on establishment and maintenance budgets prepared by Haque, Epplin, and Taliaferro (2009).

Harvest days per month by county were obtained from Hwang et al. (2009). Harvest costs were estimated based on the harvest unit concept described by Thorsell et al. (2004) and modified by Hwang (2007). Harvest machines (windrowers, tractors, rakes, balers, bale stackers) and machinery ownership and operating costs were updated to 2010 levels. A feedstock transportation cost equation was estimated from data provided by Wang (2009).

The biorefinery is assumed to operate 350 days per year. Storage losses at the biorefinery and in the field are assumed to be one percent per month. Another assumption is that bales stored in the field would be covered with a plastic tarp. The cost of field storage is estimated to be $2 per ton regardless of the number of months the material is in storage.

No feedstock quality attribute other than dry matter was considered. It was assumed that switchgrass dry matter would be of equivalent value to the biorefinery independent of harvest month and time in storage. For the base model a conversion rate of 100 gallons of ethanol per dry ton of switchgrass was assumed. Sensitivity analysis was conducted by solving the model with alternative conversion rates of 60, 80, and 120 gallons per dry ton.

The model was designed to consider three plant sizes: 25, 50, and 100 million gallons per year. For the base model, biorefinery investment costs of \$189.5, \$275, and \$400 million were assumed for the 25, 50, and 100 million gallons per year facilities, respectively. These estimates of capital required are \$7.58, \$5.50, and \$4.00 per gallon of annual capacity for the three sizes. Values assumed for selected parameters are reported in Table 1.

Annual plant operation and maintenance costs including the cost of labor, utilities, chemicals, other required variable inputs, taxes, repairs, and insurance were assumed to be \$0.75 per gallon of production. USEPA (2010, p. 751) estimates a cost for these inputs of approximately \$0.68 per gallon. The value of co-products was assumed to be equal to disposal cost. The expected life for the biorefinery was set at 20 years, and the discount rate at 15 percent.

Procedure

A multi-region, multi-period, monthly time-step, mixed integer mathematical programming model similar to the models described by Tembo, Epplin, and Huhnke (2003), Epplin, Mapemba, and Tembo (2005), Mapemba et al. (2007), and Mapemba et al. (2008) was constructed. The objective function is to maximize the net present value of the system with a discount rate of 15 percent subject to the constraint of a single biorefinery. The model is designed and solved to determine the area and quantity of switchgrass harvested by county, the number of harvest machines, and the cost to procure, harvest, store, and transport a flow of switchgrass biomass to an optimally located and optimally sized biorefinery. Binary variables are included to enable the model to determine the most economical plant location and plant size.

Integer variables are used to enable the model to endogenously determine the optimal number of harvest machines. The model includes about 73,400 activities and 10,700 equations.

It is assumed that plant investment costs would occur in year zero. Biomass harvest and delivery, plant operation, and ethanol production begins in year one and continues through year 20. Activities in years one through 20 are assumed to be identical.

A grid search procedure was used to determine breakeven price of ethanol at which net present value of the industry is equal to zero. The model accounts for differences in yield and nitrogen fertilizer requirements across harvest months. Shipment and processing of feedstock can be done in any of the twelve months of the year. Harvested feedstock can be transported directly from the field to the plant or can be placed in field storage for transport and use in later months.

As noted, for the base model, biorefinery investment costs of $189.5, $275, and $400 million were assumed for the 25, 50, and 100 million gallons per year facilities, respectively. Given the uncertainty regarding capital requirements, models were also solved with these values halved ($95, $138, and $200 million) and doubled ($284, $413, and $600 million). Each of these three capital requirements scenarios was modeled for four alternative biomass to ethanol conversion rates: 60, 80, 100, and 120 gallons of ethanol per ton. A total of 12 capital requirement-conversion rates were considered.

Results

For each of the 12 capital requirement-conversion rates considered, the model selected the 100 million gallons per year biorefinery rather than either the 25 or 50 million gallons per year facility. And, the model selects Pontotoc County for the plant location rather than any of the other ten alternative locations. In the region, the cost economies of the larger processing plant offset the additional transportation costs that result when procuring feedstock from greater distances.

Table 2 includes breakeven ethanol prices for each of the 12 capital requirement-conversion rates considered. Table 3 includes results of total biomass harvested; total number of acres harvested, and estimated delivered cost of feedstock. For a capital requirement of $400 million and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price for the 100 gallons per year biorefinery is $1.91 per gallon. Decreasing capital requirements to $200 million, reduces the breakeven price of ethanol by $0.32 per gallon. Similarly, increasing plant investment cost from $400 to $600 million, increases the breakeven price of ethanol by $0.32 per gallon. This $0.32 is the $2 per gallon investment cost difference amortized over 20 years at the assumed discount rate of 15 percent.

As the conversion rate increases from 60 to 80 to 100 to 120 gallons of ethanol per ton, the estimated feedstock cost per gallon decreases from $0.92 to $0.66 to $0.51 to $0.42 per gallon. The net result is that the breakeven ethanol price decreases by $0.26 per gallon when the conversion rate increases from 60 to 80 gallons per ton. Similarly, the breakeven prices decrease by $0.14 and $0.10 per gallon as the conversion rate increases from 80 to 100 and from 100 to 120 gallons per ton, respectively. Conversion rate is critical to the economics of the system.

For a conversion rate of 60 gallons per dry ton, 1.7 million tons of biomass is required (Table 3). More than 350,000 acres would be required to produce the feedstock. However, for a conversion rate of 120 gallons per dry ton, the model selects 171,856 acres to produce the 0.85 million required tons. More biomass is harvested than processed to compensate for storage losses.

Table 3 shows the estimated feedstock delivered cost to the optimally located biorefinery for each of the four biomass to ethanol conversion rates. As the conversion rate increases from 60 to 80 to 100 to 120 gallons of ethanol per ton, the total cost of delivered feedstock decreases from $55.20 to $52.80 to $52.00 to $50.40 per dry ton, respectively. These costs include land rent, establishment, fertilizer, harvest, storage, and transportation. Transportation and harvest cost comprise the largest component of feedstock delivered cost. As the conversion rate increases from 60 to 80 to 100 to 120 gallons per ton, transportation costs decreases from $0.35 to $0.23 to $0.18 to $0.14 per gallon of ethanol. Transportation costs account for 33 to 38 percent of the delivered feedstock cost. Harvest costs account for 24 to 29 percent of the delivered feedstock cost.

For a capital requirement of $400 million and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price is $1.91 per gallon. This includes $0.10 (5.02 percent of the $1.91) for land rental, $0.10 (5.36 percent) for field cost, $0.14 (7.14 percent) for harvest, $0.004 (0.22 percent) for field storage, $0.18 (9.22 percent) for transporting the biomass from the field to the biorefinery, $0.75 (39.27 percent) for plant operation and maintenance and $0.64 (33.51 percent) for capital recovery. These findings suggest that efforts to reduce cost should focus on conversion rate and on the cost of biorefinery construction, operation, and maintenance.

Discussion

Ethanol contains less energy (75,700 Btu) per gallon than unleaded gasoline (115,000 Btu) (U.S. Department of Energy 2009). When ethanol is blended with gasoline at levels of ten percent or less, it has value as an oxygenate in addition to its energy value. However, when used in greater proportions in engines with compression ratios designed for unleaded gasoline, the lower Btu content results in a proportionately lower mileage. If the EISA mandates are achieved, ethanol production will exceed the quantity required for ten percent blends. At this level of use the marginal value of ethanol could be expected to be based on its energy content relative to gasoline. By this measure, the estimated \$1.91 breakeven ethanol price would be equivalent to a wholesale price of \$2.90 per gallon for unleaded gasoline.

A simple ordinary least squares regression of the annual price of gasoline (U.S. Energy Information Administration 2010a) on the price of crude oil (U.S. Energy Information Administration. 2010b) (1989 to 2009) results in the following equation: gasoline (\$ per gallon) = 0.05 + 0.0259 x crude oil price (\$ per barrel). By this measure for a crude oil price of \$110 per barrel the expected price of gasoline is \$2.90 per gallon. Based strictly on energy equivalence, ethanol priced at \$1.91 would be cost completive when the price of crude oil exceeds \$110 per barrel.

Unlike corn-ethanol, a business plan for a cellulosic ethanol production system should consider the total chain from field to final products. Given the investment required in harvest machines and the need to provide a continuous flow of biomass throughout the year, based on our modeling results, an efficient business plan built on use of a perennial grass feedstock such as switchgrass would include a highly coordinated harvest, storage, and delivery system, with harvest extended over as many months as permitted by species and weather.

The ultimate challenge is to formulate a profitable field-to-fuel business model. A number of discussions have occurred regarding the “chicken and egg” problem with a dedicated energy crop such as switchgrass or miscanthus and cellulosic biorefineries. That is, a rational land owner would not establish perennial grasses such as switchgrass until a biorefinery is built and long term contracts are offered. However, rational investors would be reluctant to invest in a biorefinery that did not have a reasonably certain supply of feedstock for the life of the plant.

Results of the model suggest that (in the absence of government imposed distortions) a cost-efficient switchgrass feedstock biorefinery system could engage in long term contracts with land owners to lease a sufficient quantity of land to provide for feedstock needs prior to, or simultaneously with, construction of a biorefinery.

Switchgrass production in post establishment years does not require many activities, one trip per year for fertilizer followed by a single harvest per year. Cropland and improved pasture land could be converted from current use to cellulosic biomass feedstock production in a manner similar to what occurred when millions of acres were converted from cropland and enrolled in the Conservation Reserve Program (CRP). The difference being that the biorefinery rather than the government would be the lessee and would be responsible for pay the leasing cost.

The CRP was established in 1985. USDA provided CRP participants with an annual per acre rent and half the cost of establishing a permanent land cover (usually grass or trees) in exchange for 10 or 15 year leases. During the first three enrollment periods in March, May, and August of 1986, more than eight million acres were contracted. An additional 13.9 million acres were contracted in February and July of 1987. Within two years after the 1985 legislation, more than 22 million acres were under contract. This suggests that if an economically competitive biorefinery technology is developed, entrepreneurs could prepare a field-to-fuel business model and contract and convert millions of acres from current use to the production of dedicated energy crops in a relatively short period of time.

Companies may be reluctant to lease sufficient quantities of land to provide for feedstock needs and/or the public or elected representatives may place impediments limiting their ability to do so. One example is the current harvest month restrictions placed on harvest of biomass from CRP lands. Another example is the USDA’s Biomass Crop Assistance Program (BCAP) which implies a disconnect between feedstock production and biorefineries. Policies such as BCAP send the wrong message implying that converting land from current use to the production of feedstock is the responsibility of someone other than the biorefinery. Ambiguities as to what determines feedstock quality and how to provide a flow of feedstock throughout the year are likely to be resolved much more quickly if the annual payment to the land owner is set. Leased land would enable the biorefinery to manage feedstock quality and harvest to optimize the field to fuel process.

Public policy could be modified to enable companies to subcontract existing CRP acres, subject to approval from land owners, from the USDA. Policies that restrict harvest timing could be relaxed. The USDA could maintain the contract and continue to make rental payments to the land owners. Policies could be adjusted to enable companies to either use existing species or to establish other species on the land. The companies would be responsible for activities including harvest and for reimbursing the USDA for the rental fees.

CRP type contracts could be made directly between the companies and land owners. Public policy could facilitate these contracts by enabling the use of the USDA Farm Service Agency and USDA Natural Resources and Conservation Service infrastructure to identify suitable acres for contract. Since land owners may be skeptical of contracting with a startup, given the history of bankruptcies in ethanol businesses, additional policies could be implemented to enable the USDA to provide an insurance mechanism to facilitate contract insurance. Experts from USDA's Risk Management Agency could contribute to designing insurance to mitigate moral hazard issues.

The USEPA has identified six methods or technical categories for producing ethanol from cellulose. Desirable feedstock properties, biomass to ethanol conversion rate, and investment required in plant and equipment differs across systems. When data become available, the comprehensive holistic farm to field model could be used to compare the economics of these conversion systems to determine which are most likely to be successful and contribute to fulfilling the EISA mandates. If feedstock quality attributes in addition to dry matter are important, and if data are available regarding these attributes for each potential feedstock for harvest and storage situations likely to be encountered, the model could be enhanced to determine a more precise estimate of the ethanol price required to breakeven with feedstock production and processing cost.

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Table 1: Values for Selected Variables for the Twelve Alternatives

Item	Alternatives											
	Expected Capital Cost				Low Capital Cost				High Capital Cost			
Biorefinery capital investment												
Small plant (million $)	189	189	189	189	94.5	94.5	94.5	94.5	283.5	283.5	283.5	283.5
Medium plant (million $)	275	275	275	275	137.5	137.5	137.5	137.5	412.5	412.5	412.5	412.5
Large plant (million $)	400	400	400	400	200	200	200	200	600	600	600	600
Conversion rate (gallons of ethanol/dry ton)	60	80	100	120	60	80	100	120	60	80	100	120
Operation & maintenance cost ($/gallon)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Biorefinery processing capacity												
Small (million gallons/year)	25	25	25	25	25	25	25	25	25	25	25	25
Medium (million gallons/year)	50	50	50	50	50	50	50	50	50	50	50	50
Large (million gallons/year)	100	100	100	100	100	100	100	100	100	100	100	100
Project life (years)	20	20	20	20	20	20	20	20	20	20	20	20
Discount rate (%)	15	15	15	15	15	15	15	15	15	15	15	15
Land lease rate ($/acre/year)												
Cropland	60	60	60	60	60	60	60	60	60	60	60	60
Improved pasture land	40	40	40	40	40	40	40	40	40	40	40	40
Maximum proportion of land leased per county (%)												
Cropland	10	10	10	10	10	10	10	10	10	10	10	10
Improved pasture land	10	10	10	10	10	10	10	10	10	10	10	10
Potential plant locations (number)	11	11	11	11	11	11	11	11	11	11	11	11
Production regions (number)[a]	55	55	55	55	55	55	55	55	55	55	55	55
Harvest months per year	9	9	9	9	9	9	9	9	9	9	9	9

[a] The model considered 55 Oklahoma counties as production regions. Switchgrass is the only feedstock considered.

Table 2: Estimated Ethanol Breakeven Price ($ per gallon) for Three Levels of Capital Investment Requirements and Four Biomass to Ethanol Conversion Rates

Investment Cost (million $)	Conversion Rate of Ethanol (gallons/dry ton)			
	60	80	100	120
200	1.99	1.73	1.59	1.49
400	2.31	2.05	1.91	1.81
600	2.63	2.37	2.23	2.13

Note: Breakeven prices of ethanol is defined to be the price at which the net present value of the biorefinery system is equal to zero.

Table 3: Biomass Harvested, Acres Harvested, and Estimated Cost of Delivered Feedstock for Four Biomass to Ethanol Conversion Rates

Conversion Rate of Ethanol (gallons/dry ton)	Biorefinery Size (gallons/year)	Total Biomass Harvested (dry tons)	Total Land Harvested (acres)	Cost of Delivered Feedstock ($/ton)
60	100,000,000	1,691,486	351,474	55.20
80	100,000,000	1,268,733	260,678	52.80
100	100,000,000	1,015,256	207,752	52.00
120	100,000,000	845,876	171,856	50.40

Note: For a given conversion rate, the optimal biorefinery size, total biomass harvested, and total number of acres harvested, are the same regardless of investment cost.

Table 4: Components of Cellulosic Ethanol Production Cost

Investment Cost (millions $)	Conversion Rate of Ethanol (gallons/dry ton)	Land Rent	Field Storage Costs	Transportation Costs	Field Costs	Harvest Costs	Plant Costs[a]	Total costs
		($ per gallon)						
200	60	0.17	0.01	0.35	0.17	0.22	1.07	1.99
		(8.43%)	(0.34%)	(17.41%)	(8.71%)	(11.30%)	(53.80%)	(100%)
200	80	0.12	0.005	0.23	0.13	0.17	1.07	1.73
		(7.19%)	(0.30%)	(13.38%)	(7.43%)	(9.86%)	(61.86%)	(100%)
200	100	0.10	0.004	0.18	0.10	0.14	1.07	1.59
		(6.04%)	(0.26%)	(11.08%)	(6.44%)	(8.58%)	(67.60%)	(100%)
200	120	0.08	0.003	0.14	0.08	0.12	1.07	1.49
		(5.14%)	(0.23%)	(9.42%)	(5.63%)	(7.73%)	(71.85%)	(100%)
400	60	0.17	0.01	0.35	0.17	0.22	1.39	2.31
		(7.26%)	(0.30%)	(15%)	(7.51%)	(9.74%)	(60.19%)	(100%)
400	80	0.12	0.005	0.23	0.13	0.17	1.39	2.05
		(6.07%)	(0.25%)	(11.29%)	(6.27%)	(8.32%)	(67.81%)	(100%)
400	100	0.10	0.004	0.18	0.10	0.14	1.39	1.91
		(5.02%)	(0.22%)	(9.22%)	(5.36%)	(7.14%)	(73.04%)	(100%)
400	120	0.08	0.003	0.14	0.08	0.12	1.39	1.81
		(4.23%)	(0.19%)	(7.75%)	(4.64%)	(6.37%)	(76.82%)	(100%)
600	60	0.17	0.01	0.35	0.17	0.22	1.71	2.63
		(6.38%)	(0.26%)	(13.18%)	(6.59%)	(8.65%)	(65.03%)	(100%)
600	80	0.12	0.005	0.23	0.13	0.17	1.71	2.37
		(5.25%)	(0.22%)	(9.77%)	(5.42%)	(7.20%)	(72.15%)	(100%)
600	100	0.10	0.004	0.18	0.10	0.14	1.71	2.23
		(4.30%)	(0.18%)	(7.89%)	(4.59%)	(6.11%)	(76.92%)	(100%)
600	120	0.08	0.003	0.14	0.08	0.12	1.71	2.13
		(3.60%)	(0.16%)	(6.59%)	(3.94%)	(5.41%)	(80.31%)	(100%)

[a] Plant cost includes cost of investment and operating and maintenance costs of $0.75 per gallon. The values in parentheses are percentage of total cost per gallon of ethanol production. Values may not sum to 100% due to rounding error.