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Integrative Investment Appraisal of a Lignocellulosic Biomass-to-Ethanol Industry

Gelson Tembo, Francis M. Epplin, and Raymond L. Huhnke

While theoretically more efficient than starch-based ethanol production systems, conversion of lignocellulosic biomass to ethanol is not without major challenges. A multi-region, multi-period, mixed integer mathematical programming model encompassing alternative feedstocks, feedstock production, delivery, and processing is developed. The model is used to identify key cost components and potential bottlenecks, and to reveal opportunities for reducing costs and prioritizing research. The research objective was to determine for specific regions in Oklahoma the most economical source of lignocellulosic biomass, timing of harvest and storage, inventory management, biorefinery size, and biorefinery location, as well as the breakeven price of ethanol, for a gasification-fermentation process. Given base assumptions, gasification-fermentation of lignocellulosic biomass to ethanol may be more economical than fermentation of corn grain. However, relative to conventional fermentation processes, gasification-fermentation technology is in its infancy. It remains to be seen if the technology will be technically feasible on a commercial scale.

Key words: biomass, biorefinery location, ethanol, integrative investment appraisal, logistics, mixed integer programming

Introduction

Ethanol production in the United States increased from 900 million gallons in 1990 to 1.6 billion gallons in 2000. Most of this growth in production can be attributed to public policies subsidizing the use of ethanol as (*a*) a fuel substitute when blended with gasoline, and other public policies that mandated the use of (*b*) fuel additives of oxygen-containing molecules in gasoline in stipulated regions of the United States to improve the local atmosphere.

A gallon of ethanol contains 78,000 Btu. A gallon of unleaded gasoline contains 125,000 Btu. In terms of energy, 1.6 gallons of ethanol would be required to replace one

Gelson Tembo is a research fellow with Michigan State University's Food Security Research Project. Francis M. Epplin is professor, Department of Agricultural Economics, and Raymond L. Huhnke is professor, Department of Biosystems and Agricultural Engineering, both at Oklahoma State University. The authors wish to thank Charles Taliaferro, Department of Plant and Soil Sciences, Arland Johannes and Randy Lewis, School of Chemical Engineering, and Danielle Bellmer and Timothy Bowser, Department of Biosystems and Agricultural Engineering, Oklahoma State University, and Ralph Tanner, Department of Botany and Microbiology, University of Oklahoma, for providing assistance and parameter estimates. Anonymous referees provided numerous helpful comments.

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gallon of unleaded gasoline. The average price of unleaded gasoline as traded on the New York Board of Trade from 1990 to 2001 was $0.63 per gallon. By this measure, if ethanol had to compete with unleaded gasoline based on Btu content, it would have to be produced for $0.40 per gallon. Over the period from 1990 to 2001, the average price for fuel grade ethanol was $1.20 per gallon. In the absence of federal and state policies that provide subsidies for blends containing 10% ethanol, ethanol has not been an economical substitute for gasoline.

As an oxygenate, ethanol competes with the petroleum-derived additive methyl tertiary-butyl ether (MTBE). MTBE has been the major additive of choice in those regions of the United States where oxygenate use has been mandated. However, as a result of environmental concerns, the use of MTBE may be substantially reduced. If public policy continues to require oxygenated fuels, and if no substitute oxygenate is developed, the demand for ethanol may increase.

Most of the ethanol produced in the United States is from fermentation of corn grain. Critics such as Pimentel et al. (p. 539) contend that "Ethanol produced from corn clearly is not a renewable energy source...."[1] Conversion technologies used in the grain-based fermentation systems are approaching their inherent theoretical limits (National Research Council). Two alternative methods for producing ethanol have been proposed. Both methods are based upon the use of low-valued lignocellulosic biomass (LCB) such as crop residue and perennial grasses (Lynd et al.; National Research Council; Vollebergh; Wyman). One of the alternative technologies is enzymatic-fermentation. The second alternative method to convert LCB to ethanol is gasification-fermentation. LCB may be gasified in fluidized beds to produce synthesis gas (composed primarily of CO, CO_2 and H_2). Synthesis gas can be bubbled into a bioreactor and converted by anaerobic bacteria to ethanol and other commodities such as acetic acid and butanol (Phillips, Clausen, and Gaddy; Rajagopalan, Datar, and Lewis).

An LCB system could use: (*a*) virtually all types of harvested plant material; (*b*) feedstock produced on less productive land; (*c*) feedstock produced by perennials; and (*d*) material which would ordinarily be considered waste, such as waste from wood products processing and crop residue (Hall and Scrase; Hohmann and Rendleman; Keeney and DeLuca; Mauguiri; President's Committee of Advisors on Science and Technology; Pimentel 1991). Theoretically, an LCB-based system would be much more efficient than conversion of corn grain. However, McAloon et al. concluded the cost of enzymatic-fermentation of corn stover would be 1.7 times greater than the cost of corn grain fermentation. This suggests, if conversion of LCB to ethanol is to be feasible, either an alternative feedstock or an alternative conversion technology will be required. While the potential economics of enzymatic-fermentation have been studied by McAloon et al., to date, the economics of LCB gasification-fermentation technology have not been investigated.

The objective of this research is to determine for a specific region the most economical source of biomass, timing of harvest and storage, inventory management, biorefinery size, and biorefinery location, and to identify the breakeven price of ethanol for a gasification-fermentation process. An integrated model encompassing alternative feedstocks, feedstock production, field losses, harvest, storage, storage losses, transport, biorefinery

[1] For more information regarding the debate over the efficiency of corn grain fermentation to ethanol, see Johnson and Libecap; Pimentel (2002); Shapouri, Duffield, and Graboski; and Shapouri, Duffield, and Wang.

size, and biorefinery location was developed. This type of model may be used to identify key cost components and potential bottlenecks, reveal opportunities for reducing costs, and identify LCB-based biorefinery constraints.

This study differs from prior studies in several respects. Specifically, the model and case study (*a*) considers a variety of feedstocks; (*b*) recognizes that an LCB biorefinery would require a steady flow of feedstock, and breaks the year into 12 discrete periods (months); (*c*) recognizes that different feedstocks have different harvest windows, and the dry matter yield of species depends upon the time (month) of harvest; (*d*) recognizes that storage losses will occur, depending upon location of storage and time of storage; and (*e*) incorporates multiple biorefinery sizes and locations to enable investigation of the tradeoff between economies of biorefinery size and feedstock transportation costs. For a given case study area, the model is designed to determine the number, size, and distribution of LCB-based biorefinery processing capacity necessary to maximize industry net present worth, the optimum quantities of LCB stocks and flows, and the most important cost items in the system. An overview of the model is presented in the next section.

A major potential advantage of an LCB gasification-fermentation biorefinery is its ability to gasify at a single facility a variety of feedstocks, including agricultural residues such as corn stover, native perennial grasses, existing introduced perennials such as fescue and bermudagrass, and dedicated energy crops such as switchgrass. Use of a variety of feedstocks has many potential advantages. Harvest windows differ across species, allowing the use of specialized harvest and collection machinery throughout many months and reducing the fixed costs of harvest machinery per ton of feedstock. Similarly, a variety of perennial species would enable a diversified landscape and would reduce the potential for insect and disease risk inherent with monocultures. The potential for environmental problems, such as soil loss and pesticide and fertilizer runoff, is relatively less for perennial grasses than for corn grain. Perennial grasses may be grown on land not suitable for grain production.

While theoretically more efficient than enzymatic-fermentation of corn grain, gasification-fermentation of LCB to ethanol is not without major challenges. In contrast to corn grain, LCB is bulky and difficult to transport. It is relatively simple for ethanol plants processing corn grain to obtain feedstock. Managers may post a competitive price and corn grain will be delivered by the existing marketing system. Corn grain is also relatively easy to store. Managers of corn grain-to-ethanol plants may use existing futures markets to manage feedstock price risk. These options would not be available to managers of an LCB-to-ethanol biorefinery.

If an LCB gasification-fermentation facility with intentions of operating throughout the entire year relied strictly on corn stover as the feedstock, a massive quantity of material must be harvested in a relatively short period of time. Storage space must be sufficient to store a year's supply of material if the biorefinery is to operate throughout the entire year. As noted by Schechinger, in Iowa and elsewhere in the U.S. Corn Belt, corn stover harvest may be complicated by mud and snow. Schechinger, who was involved with the management of a pilot corn stover collection project conducted near Harlan, Iowa, has written that the collection, storage, and transportation of a continuous flow of corn stover is a "logistical nightmare."

For a conversion ratio of 75 gallons of ethanol per ton of biomass, a biorefinery with a capacity of 100 million gallons per year would require one and one-third million tons of biomass annually. A total of 224 truckloads of 17 dry tons of biomass would be required per day, assuming 350 operating days per year. Prior to investing in a biorefinery, arrangements likely would be made to assure a reliable flow of feedstock by contracting with individual growers, or with a group of growers through a cooperative arrangement, or through long-term land leases similar to those employed by the U.S. federal government with the Conservation Reserve Program. In addition to assuring feedstock quantities and quality, a plan for providing a steady flow of feedstock to the biorefinery is needed.

Prior studies of LCB-to-ethanol industry appraisal have considered only the enzymatic-fermentation technology, only a single feedstock, and pay little attention to the logistics associated with feedstock production, field losses, transportation, storage, storage losses, and feedstock inventory management. For example, McAloon et al. assume a posted price of $35 per ton would result in a steady year-round flow of corn stover to a processing facility in a manner similar to the process by which corn grain flows to existing facilities.

English, Short, and Heady, and Gallagher and Johnson estimated the nutritive value, harvest cost, and transportation cost of corn stover. English, Short, and Heady, and English et al. estimated these three components to be about $12.50 per ton in 1975 dollars. Gallagher and Johnson's 1999 estimate is from $17–$19 per ton. Neither study provided an estimate of what it would cost to convince farmers to permit the material to be removed. In each of these studies, the corn stover harvest window, storage location, transportation, and storage losses are largely ignored.

For comparison, Glassner, Hettenhaus, and Schechinger describe a corn stover collection project conducted near Harlan, Iowa. The delivered price for the stover ranged from $32 to $36 per dry ton. Graham, English, and Noon modeled switchgrass as a single feedstock. In two related studies, Nienow et al., and Nienow, McNamara, and Gillespie modeled willow as a single source feedstock for co-firing with coal. Finally, while Kaylen et al. consider a number of potential feedstocks, harvest and storage logistics are aggregated in their analysis.

The Conceptual Model

The objective function for the multi-region, multi-period, mixed integer appraisal model proposed here is given as:

$$(1)\qquad NPW = \left\{ \sum_{m}^{12} \left(\sum_{j}^{J} \sum_{s}^{S} \sum_{g}^{G} \rho_g q_{jsgm} - \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{f=1}^{F} \sum_{h=1}^{2} \alpha_{kh} A_{ikfhm} - \sum_{i=1}^{I} \sum_{k=1}^{K} \gamma_k xs_{ikm} - \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{k=1}^{K} \tau_{ij} xt_{ijskm} \right) - \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{ft=1}^{2} TAFC_{s,ft} \beta_{js} \right\} * PVAF,$$

where quantity of process outputs (q), acres of biomass harvested (A), tons of biomass stored (xs), and tons of biomass transported between production regions and biorefinery locations (xt) are choice variables, and NPW is the net present worth of the industry; $\beta_{js} \in \{0, 1\}$ are binary variables, equal to one if a plant of size s is optimum at location j and zero otherwise, where $s = \{1, 2, ..., S\}$ and $j = \{1, 2, ..., J\}$. Subscripts $i = \{1, 2, ..., I\}$, $g = \{1, 2, ..., G\}$, and $f = \{1, 2, ..., F\}$ index biomass production region, product type, and level of fertilizer applied to the harvested biomass acres, respectively. The structure of the harvesting operation and type of facility at the plant (for processing or for storage) are indexed by $h = \{1, 2\}$ and $ft = \{1, 2\}$, respectively. Subscript $k = \{1, 2, ..., K\}$ indexes species of biomass feedstocks. To facilitate modeling of monthly variations in biomass availability, the model is set up to use the month as the planning period, indexed by the letter $m = \{1, 2, ..., 12\}$.

Output price, ρ_g, may be positive for biorefinery outputs such as ethanol, acetic acid, or a positive externality, or negative when g is a negative externality.[2] Parameters α, γ, and τ represent unit cost of producing and harvesting an acre of biomass on leased land, cost of storing a ton of biomass for one month, and unit cost of transporting a ton of biomass from production region i to biorefinery j, respectively. *TAFC* is the amortized annual cost of constructing and operating the facilities. $PVAF = ((1 + r)^T - 1)/(r(1 + r)^T)$ is the present value of an annuity factor, where T is useful plant life in years, and r is the discount factor. In terms of biomass yields and production costs, each of the T years is assumed to be identical. Changing the project life alters (*a*) the amortized annual cost of constructing and operating the biorefinery and (*b*) the net present worth of the project. This formulation allows a single-year model with monthly periods to evaluate the multiple-year investment decision.

Equation (1) is maximized, subject to several system constraints. Land constraints are imposed as:

$$(2) \qquad \sum_{f=1}^{F}\sum_{h=1}^{H}\sum_{m=1}^{12} A_{ikfhm} - \sum_{l=1}^{L} BP_{ikl} * LAND_{ikl} \leq 0, \quad \forall\, i, k,$$

where $LAND_{ikl}$ is total acres of land suitable for production of feedstock k at production region i, which includes land currently under k and/or, if permissible, land displaced from other existing cropping activities. Subscript $l = \{1, 2, ..., L\}$ indexes the categories of land suitable for k if more than one. Equation (2) uses the index BP, $0 \leq BP \leq 1$, to limit the portion of available land that can be harvested for ethanol production in each production region.

The quantity (tons) of each biomass species available for delivery to biorefineries from the harvested acres is computed as:

$$(3) \qquad \sum_{f=1}^{F} x_{ikfhm} - YAD_{km} * \sum_{f=1}^{F} A_{ikfhm} BYLD_{ikf} = 0, \quad \forall\, h, i, k, m,$$

where x is quantity of biomass in tons, *BYLD* is biomass yield (tons per acre) after adjusting for the biomass retained to mitigate erosion and fulfill conservation compliance requirements. *YAD* is a yield adjustment factor that satisfies $0 \leq YAD \leq 1$. *YAD* is agronomically determined to adjust for biomass quantity and quality variations by month of harvest, with the highest value (equal to one) at optimal harvest times. An additional constraint is imposed to ensure no acres are harvested when $YAD = 0$:

$$(4) \qquad \sum_{f=1}^{F} A_{ikfhm} = 0 \quad \text{if } YAD_{km} = 0, \quad \forall\, h, i, k, m.$$

[2] For the current application, given the lack of data, potential benefits and costs of outputs other than ethanol were ignored. The model is designed to accommodate inclusion of additional outputs when more precise information becomes available.

To ensure no more biomass is shipped from any production region than is actually available at the time of shipment, the following constraint is imposed:

$$(5) \qquad \sum_{j=1}^{J}\sum_{s=1}^{S} xt_{ijskm} + xs_{ikm} - \theta_{ik} xs_{ikm-1} - \sum_{f=1}^{F}\sum_{h=1}^{2} x_{ikfhm} \leq 0, \quad \forall\, i, k, m,$$

where xt represents tons of biomass shipped from region i to refinery j. The parameter θ_{ik} is the proportion of biomass k which is usable following one month of in-field storage at production region i and is computed as $\theta_{ik} = 1 - det_{ik}$, where det_{ik} is monthly deterioration rate for feedstock species k when stored at production region i. Specifically, equation (5) tells the model that, in each month and at each source, the sum of quantity shipped to plants and quantity put in storage of each biomass feedstock, k, cannot exceed the sum of current production and usable portion of stored biomass. No storage upper bounds are assumed for in-field storage.

Defined on an annual basis for each production region, equation (6) stipulates that quantity of biomass shipped out plus biomass lost in in-field storage balance with total biomass produced in the year, i.e.:

$$(6) \qquad \sum_{f=1}^{F}\sum_{h=1}^{H}\sum_{m=1}^{12} x_{ikfhm} - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{m=1}^{12} xt_{ijskm} - (1 - \theta_{ik}) * \sum_{m=1}^{12} xs_{ikm} = 0, \quad \forall\, i, k,$$

where all the variables and parameters are as previously defined.

At each plant, the respective capacity constraints for processing and on-site biomass storage are defined as:

$$(7) \qquad q_{jsem} - CAPP_s \beta_{js} \leq 0, \quad \forall\, j, m, s$$

and

$$(8) \qquad \sum_{k=1}^{K} xs_{jkm} - CAPS_s \beta_{js} \leq 0, \quad \forall\, j, m, s,$$

where $CAPP$ is monthly processing capacity in gallons of ethanol and $CAPS$ is on-site storage capacity in tons of biomass per month. Subscript e refers to ethanol, where $e \subset g$. If $\beta_{js} = 1$, $CAPP_s\beta_{js} = CAPP_s$, and total ethanol production at each plant in that month will be bounded by $0 \leq q_{jsem} \leq CAPP_s$ [equation (7)]. Similarly, total biomass storage at the plant will be bounded by $0 \leq \Sigma_{k=1}^{10} xs_{ikm} \leq CAPS_s$ [equation (8)]. Optimal levels of ethanol produced and biomass stored at the plant will be determined in the solution. If $\beta_{js} = 0$, expressions $CAPP_s\beta_{js}$ and $CAPS_s\beta_{js}$ will also be equal to zero, by definition. Because neither q_{jsem} nor xs_{jkm} can assume negative values, they both must also be equal to zero.

An appropriate production function must be used to model transformation from raw materials (biomass) to end products (ethanol) and by-products. If we assume a Leontief production function (fixed input-output coefficients), for example, the output supply constraint can be expressed as:

$$(9) \qquad q_{jsgm} - \sum_{k=1}^{K} \lambda_{kg} xp_{jskm} \leq 0, \quad \forall\, g, j, m, s,$$

which imposes a direct fixed-proportion relationship between processed biomass, xp, and each of the outputs. Each product and by-product has its own transformation coefficient,

$\ddot{e}$, which will also vary by feedstock species used. The inequality in equation (9) enables allowance for production losses.

A Leontief production possibilities frontier is imposed between ethanol and each by-product, designated by:

$$(10) \qquad q_{jsem}\lambda_{kg} - q_{jsgm}\lambda_{ke} = 0, \quad \forall g, j, k, m, s.$$

Equation (10) also implies that any quantity of ethanol produced would result in a corresponding amount of the by-products. These by-products may have positive or negative value.

With respect to the region under study, the model can include any number of plants at each prospective location, as long as *NPW* is maximized. However, it is sometimes desirable to place an upper bound on the number of plants to be located in any one area. If the solution determines a particular plant size is too small, for example, limiting the number of plants may have the advantage of forcing the model to consider increasing the plant size as opposed to locating additional small plants. The former is easier to implement and may take advantage of scale economies. To illustrate, the following constraint can be imposed to permit multiple plants in the area under study, but at most $\bar{\beta}_j$ plants at each location:

$$(11) \qquad \sum_{s=1}^{S} \beta_{js} \le \bar{\beta}_j, \quad \forall j,$$

where $\bar{\beta}_j$ is specified by the analyst. To restrict the maximum number of plants that can be located in the case study area, equation (11) needs to be summed over j.

The model is structured with monthly periods. In each planning period (the month), total quantity of biomass available at each plant may not exceed the sum of all the biomass transported to the plant and the undeteriorated portion of the biomass stored on-site from the previous month:

$$(12) \qquad \sum_{i=1}^{I} xt_{ijskm} + \theta_{jk} xs_{jkm-1} - xs_{jkm} - xp_{jskm} \ge 0, \quad \forall j, k, m, s,$$

where xs_{jkm} denotes tons of biomass feedstock k stored at biorefinery location j in month m. The parameter θ_{jk} is the proportion of biomass k that is usable following one month of on-site storage at biorefinery location j and is computed as $\theta_{jk} = 1 - det_{jk}$, where det_{jk} is monthly deterioration rate for feedstock species k when stored at biorefinery location j.

Similar to equation (6), equation (13) imposes annual balance between total biomass shipped to the biorefinery and the sum of biomass processed and the biomass lost in on-site storage:

$$(13) \qquad \sum_{i=1}^{I} \sum_{m=1}^{12} xt_{ijskm} - (1 - \theta_{jk}) * \sum_{m=1}^{12} xs_{jskm} - \sum_{m=1}^{12} xp_{jskm} = 0, \quad \forall j, k, s,$$

where all the variables and parameters are as previously defined. To ensure no unexpected biomass supply interruptions occur during any of the planning periods, a minimum biomass inventory level can be imposed for each plant:

$$(14) \qquad \sum_{k=1}^{K} xs_{jkm} - MBINV_s \ge 0, \quad \forall j, m, s,$$

where $MBINV_s$ is minimum biomass inventory for plant size s. Finally, nonnegativity conditions are imposed on choice variables. That is, acres harvested, all biomass variables, and all output levels are restricted to be nonnegative:

$$(15) \qquad A_{ikfhm}, x_{ikhm}, xs_{ikm}, xs_{jkm}, xt_{ijskm}, xp_{jskm}, q_{jsgm} \geq 0.$$

Given some base values of all the parameters, the above model determines a base solution by maximizing equation (1), subject to equations (2)–(15). Any questions the researcher and other decision makers may have can be modeled by replacing the affected relationships and parameters by the hypothesized ones. The impact of the hypothesized relationships can then be determined by comparing the new solution to the base solution, ceteris paribus.

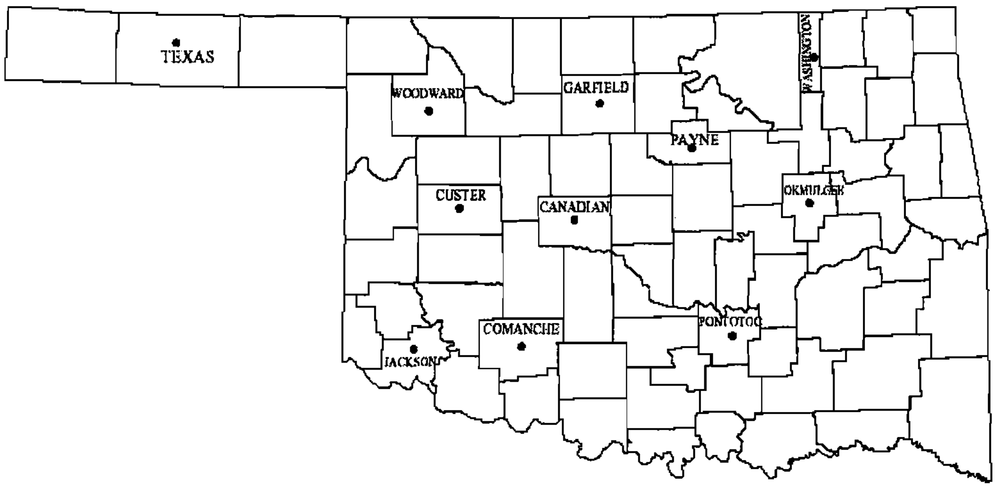
The model integrates a combination of formulations including sequencing, storage, inventory, location, investment, and equilibrium with known life (McCarl and Spreen). Harvest, storage, and transportation activities are sequenced to provide a flow of material to the biorefinery. This sequencing provides "within-period (year) dynamics." LCB may be harvested and placed in storage in 9 of the 12 months, and LCB may be removed from storage for use in each of the 12 months. Alternatively, LCB may be transported and processed in the harvest month. Decisions regarding LCB production, harvest, storage, and transportation, and ethanol production are assumed to be made repeatedly in all years. McCarl and Spreen characterize this formulation as a "representative single period" model because resource, technology, and price data are assumed to be constant and a long-run steady state solution is assumed to be obtainable. The "typical period" (year) is modeled as "equilibrium" with known life. Year-to-year adjustments are not modeled. The location, size, and number of biorefineries are endogenously determined. However, all plant size and plant location decisions are made under the assumption that all investment takes place at the beginning of the 15-year life.

One shortcoming of mixed integer programming problems is that duality is not well defined. In most cases, an optimal integer solution occurs at a point interior to the continuous feasible region. Hence, conventional range analysis cannot be performed (McCarl and Spreen, chapter 15, p. 12; Hillier and Lieberman). However, it is possible to implement a grid search procedure to determine the approximate breakeven price for ethanol.

Empirical Considerations and the Case Study

The state of Oklahoma was selected as the area for the case study (figure 1).[3] Oklahoma is an ideal state for a study of this type for several reasons. First, the state has a variety of potential LCB feedstocks, including plant residue, indigenous native prairies, and improved pastures. In addition, cropland could be used to produce dedicated feedstock crops such as switchgrass. Oklahoma has 14.9 million acres that are in native prairie

[3] The boundaries are arbitrary and the model could be changed by either removing regions or by adding regions. However, there are often practical reasons for using political boundaries. It is not uncommon for public policy and incentives to differ across state borders. For example, in 1996, an Oklahoma producers tax credit law was passed. This legislation gives a value-added processing tax credit to farmers and ranchers who invest in an agricultural processing venture. For every dollar Oklahoma agricultural producers invest in an agricultural processing venture, they receive a 30% tax credit. The tax credit is limited to Oklahoma farmers and ranchers. The incentive was enacted to increase agricultural processing plants. A group of producers may form a cooperative venture to produce ethanol and qualify for the tax credit. In 2003, another Oklahoma law was passed which provides for an additional tax credit of $0.20 per gallon of ethanol produced in an Oklahoma facility. Hence, there were practical reasons for limiting the study to Oklahoma.



Note: Each of Oklahoma's 77 counties was designated as a potential production region. Potential plant locations were limited by the model to Canadian, Comanche, Custer, Garfield, Jackson, Okmulgee, Payne, Pontotoc, Texas, Washington, and Woodward counties.

Figure 1. Oklahoma study area: Potential biorefinery sites (11 counties)

grass, 4.7 million acres in improved pasture, one million acres in the federal government's Conservation Reserve Program, and 8.5 million acres of harvested cropland. Annual precipitation ranges from more than 50 inches in the southeast to less than 20 inches in the northwestern panhandle. Second, the soils and climate of the state are such that harvest of potential feedstock could be conducted across many months. Third, as demonstrated by participation in the Conservation Reserve Program, landowners are willing to engage in long-term land leases. Fourth, the energy business is important to Oklahoma. When Oklahoma became a state in 1907, it ranked first in U.S. oil production. Currently, Oklahoma ranks third in U.S. production of natural gas. The designated delivery point for New York Mercantile Exchange crude oil futures contracts is located at pipeline oil and gas storage facilities in Cushing, Oklahoma.

A description of data for the empirical application is included in the appendix. Table 1 highlights the ceteris paribus changes used for eight alternative scenarios. Each was implemented by changing one of the base assumptions or estimates. The alternatives considered include (*a*) determining a breakeven price of ethanol, (*b*) doubling land costs, (*c*) doubling biorefinery investment costs, (*d*) doubling the per mile feedstock transportation costs, (*e*) changing the project life to 10 years, (*f*) changing the project life to 20 years, (*g*) using a discount rate of 5%, and (*h*) using a discount rate of 25%.

Base Model Results

Results from the base model, which includes about 400,000 activities in 56,000 equations, are reported in tables 2–5. Given the assumptions of the base model, five large (100 million gallons per year) biorefineries would be optimally located—one each in Comanche, Garfield, Okmulgee, Pontotoc, and Washington counties (table 2). One medium sized (50 million gallons per year) biorefinery would be located in Woodward County.

Table 1. Assumed Levels of Selected Parameters by Scenario

Item	Base[a]	Break-even	Double Land Costs	Double Plant Costs	Double Shipping Costs/Mile	Project Life 10 Years	Project Life 20 Years	Discount Rate 5%	Discount Rate 25%
		SCENARIO							
Ethanol Price ($/gallon)	1.25	0.758							
Land Lease Rates ($/acre/year):									
Native Pasture	20		40						
Improved Pasture	40		80						
Cropland	60		120						
Biorefinery Investment ($000s):									
25 million gallons/year	58,824			117,647					
50 million gallons/year	100,000			200,000					
100 million gallons/year	170,000			340,000					
Transportation Cost Equation: ($ per 17-ton truckload round trip = $34.08 + $ per round trip mile)	1				2				
Project Life (years)	15					10	20		
Discount Rate (%)	15							5	25
Upper Limit on Acres per County per Species (%)	10								
Truck Capacity (dry tons)	17								
Conversion Rate (gallons of ethanol/dry ton)	75								
Potential Plant Locations (number)	11								
Production Regions (number)	77								

[a] Values included in the base column were used for all scenarios except where exceptions are specified.

Table 2. Biorefinery Locations and Size Selected and Locations Not Selected, by Scenario

	SCENARIO								
Description	Base	Break-even	Double Land Costs	Double Plant Costs	Double Shipping Costs/Mile	Project Life 10 Years	Project Life 20 Years	Discount Rate 5%	Discount Rate 25%
Locations and Plant Size Selected by the Model: L = Large M = Medium S = Small	Comanche (L) Garfield (L) Okmulgee (L) Pontotoc (L) Washington (L) Woodward (M)	Washington (L)	Custer (L) Garfield (L) Okmulgee (L) Pontotoc (L) Washington (L)	Garfield (L) Pontotoc (L) Washington (L)	Canadian (L) Garfield (L) Okmulgee (L) Pontotoc (L) Washington (M) Jackson (S) Woodward (S)	Comanche (L) Garfield (L) Okmulgee (L) Pontotoc (L) Washington (L) Woodward (M)	Comanche (L) Garfield (L) Okmulgee (L) Pontotoc (L) Washington (L) Woodward (M)	Custer (L) Garfield (L) Okmulgee (L) Pontotoc (L) Washington (L) Comanche (M) Texas (S)	Custer (L) Garfield (L) Okmulgee (L) Pontotoc (L) Washington (L)
Locations Not Selected by the Model:	Canadian Custer Jackson Payne Texas	Canadian Comanche Custer Garfield Jackson Okmulgee Payne Pontotoc Texas Woodward	Canadian Comanche Jackson Payne Texas Woodward	Canadian Comanche Custer Jackson Okmulgee Payne Texas Woodward	Custer Comanche Payne Texas	Canadian Custer Jackson Payne Texas	Canadian Custer Jackson Payne Texas	Canadian Jackson Payne Woodward	Canadian Comanche Jackson Payne Texas Woodward

This annual production capacity of 550 million gallons of ethanol (table 3) has an expected net present worth of $1,143 million over a 15-year expected plant life. The six biorefineries would process 7.3 million tons of biomass annually harvested from 2.56 million acres. Table 5 reports the acres harvested by species. For the base model, biomass is harvested from each of the nine potential feedstocks including wheat straw, corn stover, native prairies, introduced forages, and switchgrass. As a result of the restriction on the proportion of land that can be harvested in each county (10%), biomass would be procured from 75 of the state's 77 counties.

Table 4 provides the level of costs incurred to produce a gallon of ethanol. For the base model, the total costs are estimated to be $0.89 per gallon. Land rental costs are estimated to be $0.15 per gallon (17% of the $0.89), field costs $0.05 (6%), harvest costs $0.07 (8%), in-field storage $0.08 (9%), cost of transporting the biomass from the field to the biorefinery $0.16 (18%), and the biorefinery cost of $0.39 (44%). The major cost items include biorefinery construction, operation, and maintenance (44%), biomass transportation from the field to the biorefinery (18%), and land rent (17%).

Optimal Biomass Inventory Management

The results indicate feedstocks would be harvested from June through October. This is consistent with the highest levels of the yield adjustment factor (*YAD* = 1.00) for most of the feedstocks. The *YAD* remains high (i.e., *YAD* ≥ 0.95) during most of the harvest period for native prairies, improved pasture grasses, and switchgrass. Crop residues, however, can only be harvested during the months the main crop is being harvested. Thus, wheat straw and corn stover have high yield adjustment factors (*YAD* = 1.00) only in the periods June–July and September–October, respectively. For all other months, *YAD* = 0 for these crop residues. From November until June, all the shipments are drawn from in-field storage.

With each biorefinery operating at full capacity, a constant quantity of feedstock will be processed in each month. For example, each large biorefinery will convert about 111,000 tons of biomass per month. In any particular month, this may be harvested and delivered directly to the plant or may be obtained from in-field or on-site storage. The model uses the biomass balance relationships at the production counties and at the plants, and interactions between them, to determine the optimal shipment and storage patterns.

Biomass is optimally shipped from the production counties to biorefineries in each of the 12 months of the year. The quantity shipped in any particular month depends, to a great extent, on the feedstock balances at the plants. Total on-site storage for the six plants is about 144,000 tons in all six plants in May, and optimally zero in June, July, and August.[4] By assumption, the model is set up to permit zero inventory [$MBINV_s = 0$, $\forall s$, in equation (14)]. In each of the months September through April, the on-site storage facilities will pass on to the following month a quantity of biomass equal to the full storage capacity less storage losses. The model is structured so that both storage losses in the field and storage losses at a conversion facility are considered. However, precise estimates of storage losses over time for all the species considered are not available; as more precise data are developed, the consequences of storage losses can be more precisely determined.

[4] On-site storage capacity is 57,692 tons, 28,846 tons, and 14,423 tons of biomass for large, medium, and small plants, respectively.

Table 3. Summary of Results for Each Scenario

Scenario	Net Present Worth ($000s)	Number of Plants	Gallons Ethanol (000s)	Tons Processed (000s)	Acres per Year (000s)	Number of Biomass Species
Base Scenario	1,143,155	6[a]	550,000	7,333	2,563	9
Breakeven	0[b]	1	100,000	1,333	429	5
	(-100%)	(-83%)	(-82%)	(-94%)	(-79%)	(-44%)
Double Land Costs	695,802	5	500,000	6,667	2,074	8
	(-39%)	(-17%)	(-9%)	(-9%)	(-2%)	(-11%)
Double Plant Costs	115,483	3	300,000	4,000	1,180	6
	(-90%)	(-50%)	(-45%)	(-45%)	(-42%)	(-33%)
Double Shipping Costs/Mile	730,441	7	500,000	6,667	2,397	9
	(-36%)	(+17%)	(-9%)	(-9%)	(-18%)	(0%)
Project Life 10 Years	844,486	6	550,000	7,333	2,563	9
	(-26%)	(0%)	(0%)	(0%)	(0%)	(0%)
Project Life 20 Years	1,291,646	6	550,000	7,333	2,563	9
	(+13%)	(0%)	(0%)	(0%)	(0%)	(0%)
Discount Rate 5%	2,781,217	7	563,481	7,513	2,751	9
	(+243%)	(+17%)	(+2%)	(+2%)	(+7%)	(0%)
Discount Rate 25%	448,549	5	500,000	6,667	2,393	9
	(-61%)	(-17%)	(-9%)	(-9%)	(-7%)	(0%)

Note: Percentage changes from the base values are included in parentheses.
[a] Five 100 million and one 50 million gallons per year plants.
[b] The grid search procedure incremented the price of ethanol to determine the price level at which net present worth is equal to zero.

Table 4. Level and Percentage of Costs Incurred to Produce a Gallon of Ethanol, by Scenario

Scenario	Land Rent	Field Costs[a]	Harvest Costs	In-Field Storage	Shipping Costs	Plant Costs[b]	Total Costs
	<------------------------			Cost by Item ($/gallon)[c]			------------------------>
Base Scenario	0.15	0.05	0.07	0.08	0.16	0.39	0.89
	(17%)	(6%)	(8%)	(9%)	(18%)	(44%)	(100%)
Breakeven	0.12	0.02	0.06	0.01	0.17	0.38	0.76
	(16%)	(3%)	(8%)	(1%)	(22%)	(50%)	(100%)
Double Land Costs	0.28	0.05	0.06	0.08	0.16	0.38	1.01
	(28%)	(5%)	(6%)	(8%)	(16%)	(38%)	(100%)
Double Plant Costs	0.15	0.04	0.07	0.01	0.15	0.76	1.18
	(13%)	(3%)	(6%)	(1%)	(13%)	(64%)	(100%)
Double Shipping Costs/Mile	0.15	0.05	0.07	0.04	0.27	0.40	1.00
	(15%)	(5%)	(7%)	(4%)	(27%)	(40%)	(100%)
Project Life 10 Years	(0.15	0.05	0.07	0.08	0.16	0.44	0.95
	(16%)	(5%)	(7%)	(8%)	(17%)	(46%)	(100%)
Project Life 20 Years	0.15	0.05	0.07	0.08	0.16	0.37	0.87
	(17%)	(6%)	(8%)	(9%)	(19%)	(42%)	(100%)
Discount Rate 5%	0.15	0.06	0.07	0.07	0.16	0.27	0.78
	(19%)	(8%)	(9%)	(9%)	(21%)	(35%)	(100%)
Discount Rate 25%	0.14	0.05	0.06	0.04	0.15	0.48	0.93
	(15%)	(5%)	(7%)	(4%)	(16%)	(52%)	(100%)

[a] All costs associated with establishing (for switchgrass only) and maintaining feedstock fields.
[b] All costs associated with construction, operation, and maintenance of on-site storage and processing facilities.
[c] The values in parentheses are percentage of total cost per gallon of ethanol production. Values may not sum to 100% due to rounding error.

Table 5. Acres Harvested by Species per Year, by Scenario

	SCENARIO								
Biomass Type	Base	Breakeven	Double Land Costs	Double Plant Costs	Double Shipping Costs/Mile	Project Life 10 Years	Project Life 20 Years	Discount Rate 5%	Discount Rate 25%
Wheat Straw	246,970		61,220	5,732	182,526	246,970	246,970	253,110	203,870
Corn Stover	9,760		744	134	838	9,760	9,760	9,760	7,678
Tall Native Prairies	726,666	325,384	726,666	540,542	726,666	726,666	726,666	726,666	726,666
Mixed Native Prairies	508,741	9,169	397,291	47,781	508,741	508,741	508,741	508,741	508,741
Short Native Prairies	93,021				53,121	93,021	93,021	254,700	30,631
Old World Bluestem	150,372		60,775		97,867	150,372	150,372	170,565	87,891
Bermudagrass	221,415	1,200	221,415	62,061	221,415	221,415	221,415	221,415	221,415
Tall Fescue	67,728	23,392	67,728	60,833	67,728	67,728	67,728	67,728	67,728
Switchgrass	537,894	69,854	537,894	462,680	537,894	537,894	537,894	537,894	537,894
Total Acres	2,562,567	428,999	2,073,733	1,179,763	2,396,796	2,562,567	2,562,567	2,750,579	2,392,514

With the plants using 100% processing capacity, (5 × 111,111) + (1 × 55,556) = 611,111 tons of biomass will be processed each month. If storage is optimally zero in month m but was at full capacity in month $m - 1$, then a total of 611,111 − 0.999 × [(5 × 57,692) + (1 × 28,846)] = 294,122 tons of biomass would need to be shipped in from the production counties to satisfy processing needs only. If storage was optimally at full capacity in month $m - 1$ and has to be fully replenished in month m while satisfying the processing needs, then a total of 294,122 + [(5 × 57,692) + (1 × 28,846)] = 611,428 tons of biomass would need to be delivered to the six biorefineries in month m. This is the case for months October through April. In July and August, because storage was zero in the preceding month (June and July, respectively), all the processing needs (611,111 tons of biomass) would be satisfied by direct delivery from the production counties. In June, about 0.999 × 143,555 = 143,411 tons would be obtained from May's on-site storage, and the remaining 467,700 tons would be shipped directly from the field. In September, both storage and processing activities have to be at full capacity, starting with zero biomass inventory from August. This requires a direct delivery of 611,111 + 317,306 = 928,417 tons of biomass.

Results from the Alternative Models

As shown in table 1, eight alternative scenarios are considered. Each was implemented by changing one of the base assumptions or estimates, ceteris paribus.

Breakeven Price of Ethanol

From the results of the grid search for a threshold price of ethanol, the breakeven price of ethanol was determined to be about $0.758 per gallon (table 4). Over the period 1990–2001, the average price for fuel grade ethanol was $1.20 per gallon. If the base assumptions are correct, at a price of $1.20 per gallon, LCB gasification-fermentation may be less costly than fermentation of corn grain. However, a gallon of gasoline contains 1.6 times as much energy as a gallon of ethanol. Hence, by this measure and method of conversion, in the absence of subsidies, a gallon of ethanol would not be competitive in terms of energy equivalent with gasoline when gasoline prices are less than $1.21 per gallon. As noted, the average price of unleaded gasoline as traded on the New York Board of Trade from 1990 to 2001 was $0.63 per gallon.

For the breakeven scenario, 50% of the total cost would be incurred as a result of construction, operation, and maintenance of a single 100 million gallons per year biorefinery located in Washington County (table 2). A total of 429,000 acres would be harvested to provide the 1.3 million tons of biomass (table 3). For this situation, the model processes biomass from only five of the nine species.

Table 6 includes a listing of the acres of each species harvested by month for the breakeven scenario. Biomass from tall native prairies would be harvested in each month from July through February. Switchgrass would also be harvested from July through February with the exception of August. The use of species with wide harvest windows would permit use of specialized harvest equipment throughout much of the year. The model does not select crop residues, wheat straw, and corn stover. The biorefinery is located in Washington County in the northeast part of the state (see figure 1). Most of the wheat straw is produced in the western half of the state, and most of the corn stover

Table 6. Acres of Each Species Harvested by Month for the Breakeven Scenario

	Species Harvested				
Harvest Month	Tall Native Prairies	Mixed Native Prairies	Bermudagrass	Tall Fescue	Switchgrass
January	19,519	262			13,318
February	144,532				13,814
March					
April					
May					
June				23,391	
July	33,113	1,563			1,467
August	37,037				
September	35,337	4,491	1,200		8,193
October	14,935	597			11,847
November	21,367				9,903
December	19,543	2,256			11,312
Annual Total	325,383	9,169	1,200	23,391	69,854

is produced in the three panhandle counties. Given the assumptions of the model, including the narrow harvest windows for wheat straw and corn stover relative to the wide harvest window (July through February) for native prairie grasses and switchgrass, it is less costly to locate the biorefinery near the tall grass prairies.

Double Land Costs

For the base model, it was assumed native prairies could be leased for $20 per acre per year, improved pastureland for $40 per acre per year, and cropland for $60 per acre per year (table 1). These values were increased to $40, $80, and $120 per acre per year for native prairies, improved pastureland, and cropland, respectively. Relative to the base scenario, net present worth is maximized with five rather than six biorefineries with the reduction of the plant in Woodward County (table 2). The net present worth over the 15-year life would drop by 39% to $695 million (table 3). Cost per gallon of ethanol is expected to increase by 13% from $0.89 per gallon to $1.01 per gallon. If land costs were doubled, the land rent proportion of total costs of producing a gallon of ethanol would increase from 17% to 28% (table 4).

Double Plant Costs

For the base model, biorefinery investment costs of $59 million, $100 million, and $170 million were assumed for the 25, 50, and 100 million gallons per year facilities, respectively (table 1). For the double plant costs scenario, these investment costs were doubled to $118, $200, and $340 million for the small, medium, and large size facilities, respectively. As shown in table 2, relative to the base model, when plant costs are doubled, it is optimal to build three rather than seven biorefineries. Large facilities are optimally constructed in Garfield, Pontotoc, and Washington counties. The net present worth over the 15-year time horizon declines by 90% to $115 million (table 3). The cost to produce a gallon of ethanol increases by 33% from $0.89 to $1.18. The investment required to construct a biorefinery is clearly a very important variable relative to the economic success of the venture.

Double Shipping Costs

The transportation cost equation developed by Bhat, English, and Ojo was used to estimate the cost to transport biomass from the fields where harvested to the biorefinery. The estimated marginal cost of $1 per mile per truckload was doubled to $2 for this scenario. As reported in table 2, when this change is made, the optimal number and size of biorefineries changes. The base model selected five sites for location of large plants and one site for the location of a medium sized plant. When the marginal transportation cost is doubled, the model selects four sites for large plants, one site for a medium sized plant, and two sites for a small, 25 million gallons per year biorefinery. As expected, there is a tradeoff between feedstock transportation distance and biorefinery size. The two small plants are located in Jackson and Woodward counties in western Oklahoma where the expected biomass per acre yields are lower, and hence biomass production is less dense. This is the only scenario in which a plant is located in Jackson County.

Doubling the shipping costs increases the cost to produce a gallon of ethanol by 12% from $0.89 to $1.00 per gallon (table 4). Most of this increase is due to the increase in the marginal change in transportation costs. However, biorefinery costs increase somewhat as the smaller facilities lose some economies of size.

Change in Project Life

In the base model a project life of 15 years is assumed. In terms of biomass yields and production costs, each of the 15 years is assumed to be identical. Changing the project life alters (*a*) the amortized annual cost of constructing and operating the biorefinery and (*b*) the net present worth of the project. When the project life is decreased to 10 from 15 years, the net present worth declines by 26% (table 3). However, when the project life is increased to 20 years, the net present worth increases by 13%. If the project life is changed from 15 to 10 years, the cost to produce a gallon of ethanol increases from $0.89 to $0.95 as a result of the increase in annual amortized cost of the biorefinery (table 4). Alternatively, if the project life is increased from 15 to 20 years, the cost to produce a gallon of ethanol decreases from $0.89 to $0.87.

Change in Discount Rate

A discount rate of 15% was used in the base model. In a manner similar to changing project life, changing the discount rate alters (*a*) the amortized annual cost of constructing and operating the biorefinery and (*b*) the net present worth of the project. Changing the discount rate changes the optimal location, size, and number of biorefineries. Relative to the base model, when the discount rate is decreased to 5%, it is optimal to build an additional small biorefinery in Texas County, a large biorefinery in Custer County, change the size of the facility in Comanche County from large to medium, and to not locate a biorefinery in Woodward County (table 2).

Decreasing the discount rate from 15% to 5% increases the net present worth over the 15-year life of the project by 243% (table 3) and decreases the cost to produce a gallon of ethanol by 12% from $0.89 to $0.78 per gallon (table 4). With a discount rate of 5%, the model is also constrained by the restriction limiting harvested acres to 10% of the total available acres per region (county). The result is that some of the biorefineries are optimally used at less than 100% capacity. Ethanol production in the large biorefineries in Custer, Okmulgee, and Washington Counties is optimally at 97.9%, 96%, and 94.6% of full capacity. Thus, rather than produce 575 million gallons of ethanol, the five large, one medium, and one small facilities produce 563 million gallons.

Increasing the discount rate from 15% to 25% decreases the net present worth over the 15-year life of the project by 61% (table 3) and increases the cost to produce a gallon of ethanol by 4.5% from $0.89 to $0.93 per gallon (table 4). More than half (52%) of the cost to produce a gallon of ethanol is incurred with biorefinery investment and operation. An increase in the discount rate also reduces the optimal number of biorefineries relative to the base model from six to five (table 2).

Conclusions

Prior to investment in a facility which would require several thousand tons of feedstock per day, it seems reasonable to expect that a plan for acquisition and delivery of a steady flow of material would be developed. For the model, it was assumed that landowners would be willing to engage in long-term leases similar to leases used by the U.S. federal government with the Conservation Reserve Program.

A major advantage of gasification-fermentation over conventional grain fermentation technology is that a variety of feedstocks—including agricultural residues, native perennial grasses, existing stands of introduced perennials, and dedicated energy crops—may be gasified by the same facility. The mixed integer programming model confirms the use of a variety of feedstocks has several advantages. Harvest windows differ across species, permitting the use of specialized harvest and collection machinery throughout many months, and reducing the fixed costs of harvest machinery per ton. Use of a variety of species would enable a diversified landscape and would reduce the potential for insect and disease risk inherent with monocultures. The potential for environmental problems such as soil loss as well as pesticide and fertilizer runoff is relatively less for perennial grasses than for corn grain.

For most variables, the largest response was recorded when the system was subjected to a breakeven price of ethanol, followed by the scenario in which plant costs were doubled. Net present worth, number of plants, gallons of ethanol produced, tons of biomass harvested, acres harvested, and number of biomass species varied with scenario. The base results are quite robust with respect to increases in opportunity cost of land and transportation costs of biomass. However, the industry will be faced with more challenges associated with plant costs. Clearly, the cost of constructing and operating a biorefinery is crucial in determining whether this type of industry will be economically competitive.

The breakeven price of ethanol was determined to be about $0.758 per gallon, which is substantially less than the 1990 to 2001 average price of $1.20 per gallon. This finding suggests, if the base assumptions are correct, LCB gasification-fermentation may be less costly than fermentation of corn grain. If ethanol is to be used as an oxygenate, production by LCB gasification-fermentation may develop. However, since a gallon of gasoline contains 1.6 times as much energy (Btu) as a gallon of ethanol, in the absence of subsidies, ethanol would not be competitive in terms of energy equivalent with gasoline when gasoline prices are less than $1.21 per gallon—nearly twice as much as the 1990 to 2001 average gasoline price of $0.63 per gallon.

Limitations

This study has several limitations and shortcomings. It remains to be seen if the gasification-fermentation technology will be technically feasible on a commercial scale. Relative to enzymatic-fermentation processes, this technology is in its infancy. The technology as envisioned has been demonstrated on a laboratory scale. However, much research remains to be done. To develop a more precise estimate of the gasification-fermentation biorefinery investment costs, it will be necessary to construct a pilot plant. Because a pilot plant has not been constructed, it is not known if this technology will ever be economically viable. It is not known if it will be more efficient than the enzymatic-fermentation processes.

The estimates are contingent upon the assumption that a biorefinery could efficiently use a variety of feedstocks, a hypothesis which remains to be tested. It was also assumed that thousands of acres could be leased and managed by an integrated firm. Institutional constraints (local, state, or federal legislation) could be imposed which would restrict the business ties between feedstock production and feedstock processing.

Further analysis is also needed to identify more precisely yields and nutrient content by month of harvest for each of the potential feedstocks. Additionally, future work is required to determine if the yields of the potential feedstocks can be maintained over time and to develop more precise estimates of storage losses. However, the logistics of producing, harvesting, storing, transporting, and providing a continuous flow of feedstock to a conversion facility will be important in arriving at the ultimate cost, independent of the method of conversion. Finally, as more precise estimates of the key parameters are refined, the model as developed could be used to establish more accurate estimates of the breakeven cost.

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Appendix: Data for the Case Study

In the empirical implementation, each of the state's 77 counties was considered to be a potential biomass production source. In terms of the indices for the model, $g = 4$ products (ethanol plus three by-products with an assumed value of zero); $h = 2$ harvest structures; $i = 77$ production regions (Oklahoma counties); $j = 11$ potential biorefinery locations; $k = 9$ species for feedstock; $m = 12$ months; $s = 3$ potential biorefinery sizes (25, 50, and 100 million gallons of ethanol per year). Figure 1 in the text gives a map of the state showing the 77 production regions (counties) and 11 potential biorefinery locations.

The base model uses approximately 400,000 activities in 56,000 equations to determine a net present worth (*NPW*). To accommodate the possibility of one of three potential biorefinery sizes in each of 11 potential locations, the model included 33 binary variables. These integer variables necessitated the use of a mixed-integer programming algorithm. The GAMS/CPLEX mixed-integer programming solver was used (Brooke, Kendrick, and Meeraus). The matrix of constraint coefficients for the base model has more than 1.8 million nonzero cells; however, it is sparse with less than 0.01% nonzero elements. Solution time varied depending upon the model. The base model required about four hours to solve with a Pentium® III 550 MHz processor.

Text table 1 identifies levels for several key parameters. Over the period from 1990 to 2001, the average U.S. price for fuel grade ethanol was \$1.20 per gallon. For the base model, a price of \$1.25 was used. Under the base model, it was assumed that native prairies could be leased for \$20 per acre per year, improved pastureland for \$40 per acre per year, and cropland for \$60 per acre per year. These lease rates exceed market rates. For example, more than one million acres in the state are enrolled in the Conservation Reserve Program at an average rental rate of \$32 per acre (USDA/Farm Service

Agency 2001). The USDA/National Agricultural Statistics Service (2000) also reports the average cash rent in Oklahoma in 2000 was \$26 per acre for non-irrigated cropland and \$7.80 per acre for pasture.

Estimates of establishment costs (switchgrass only) and maintenance costs were developed. Agricultural machinery cost software was used to determine harvest costs and field machinery specifications (Huhnke). Estimates of storage costs and losses and in-field losses if harvest is delayed, were obtained through consultations with agricultural engineers and agronomists, respectively.

The base model includes three potential plant sizes: small (25 million gallons of ethanol per year), medium (50 million gallons of ethanol per year), and large (100 million gallons of ethanol per year). Precise estimates of the cost of constructing and operating a commercial gasification-fermentation biorefinery are unknown. After consultation with engineers, for the base model, costs of \$100 million and \$1.5 million were assumed for processing and on-site storage facilities, respectively, with a biorefinery capacity of 50 million gallons of ethanol per year. It was assumed, based upon consultations with engineers, that doubling capacity would increase construction costs by 70%. Operating and maintenance costs were computed as 2% and 5% of total construction costs for storage and processing facilities, respectively.

From Bhat, English, and Ojo's work, the cost of transporting a 17 dry-ton truckload of biomass was computed as

$$TRC_{ij} = 34.08 + 1.00\delta_{ij},$$

where TRC_{ij} is the estimated cost of transporting a 17 dry-ton truckload of biomass from production region i to biorefinery j, and δ_{ij} is the round-trip distance in miles. The average per dry-ton transportation cost [τ_{ij} in equation (1)] can then be calculated by dividing by the assumed truck capacity of 17 dry tons. A dry matter content of 85% is assumed for all feedstocks. The assumed net weight of the trucks is substantially less than the 27 tons routinely hauled by grain and oil well service trucks over roads in the state.

For a 20-mile haul, the estimated transportation costs are very similar to those reported by Gallagher and Johnson. Bhat, English, and Ojo's intercept (a fixed load charge) results in per mile estimates which are greater for shorter trips and less for longer trips. This is a plausible assumption. Gallagher and Johnson's estimation that a pickup and 10-mile trip would cost exactly twice as much as a pickup and five-mile trip is less appealing. However, if an LCB biorefinery requiring a continuous flow of feedstock were constructed, a dedicated fleet of vehicles specifically designed to transport LCB would likely be used. Additional research would be required to determine more precise estimates of transportation costs for these conditions. As these estimates become available, they could be incorporated into the model.

Other assumptions are included in text table 1. The index *BP* in equation (2) was set equal to 10% in the base model. This places an upper bound on the proportion of available land that can be harvested for ethanol production in each county. For example, up to 10% of the improved pasture land in a county was assumed to be available for lease at the base lease rate of \$40 per acre. Based upon results from laboratory gasification-fermentation scale studies, it was also assumed that a dry ton of feedstock could be converted to 75 gallons of ethanol. However, it remains to be seen if this conversion rate can be achieved.

Feedstock categories considered include crop residues (wheat straw, corn stover), native prairies (short grass, mixed, tall grass), improved pasture (tall fescue, old world bluestem, bermudagrass), and a dedicated energy crop (switchgrass). Data from the agricultural census and *Oklahoma Agricultural Statistics* (Oklahoma Department of Agriculture) were used to determine existing acres of wheat, corn, native prairies, improved pastures, and cropland. A survey of professional forage specialists was conducted to disaggregate native prairie acreage into acres of tall grass, mixed, and short grass prairies by county. Acres of improved pastures were disaggregated into acres of tall fescue, old world bluestem, and bermudagrass.

Regression functions estimated with data reported by Steiner, Schomberg, and Morrison were used to compute wheat straw and corn stover yield estimates from average grain yields. Corn and wheat grain mean yield estimates were computed as 1993–97 five-year averages for each county (Oklahoma Department of Agriculture). Yield estimates for native prairies were obtained through a survey of professional agronomists in the respective production regions (counties). Yield estimates for switchgrass and improved pastures under different fertility regimes were obtained through consultations with agronomists.

Published yields of hay crops were not used. Hay does not provide an appropriate comparison because the nutrient content—specifically the protein content of hay—is a crucial component in determining its value. Hence, hay is optimally harvested prior to plant maturity. As forages mature, the percentage of protein declines while the tonnage increases. Smith describes the general relationship between protein content and dry matter yield. For example, when harvested for hay at the heading stage of growth, Smith found smooth bromegrass produced 1,720 pounds per acre of dry matter with a protein content of 10.24%. When permitted to mature, smooth bromegrass plants produced 2,354 pounds per acre of dry matter (37% increase) with a protein content of 7.44% (27% decline). Brummer and Rill reported a similar finding for native prairie grass. When prairie grass harvest was delayed from June 29 to August 10, they found crude protein declined 15% but dry matter yield increased 60%.

Consequently, if crops were harvested for biomass production, harvest likely would be delayed substantially beyond the point at which they would be harvested for hay, and dry matter yields would be substantially greater than published hay yields. Feedstock deterioration is estimated to be 0.5% and 0.1% per month for in-field and on-site storage, respectively. Additional details may be found in Tembo.